LEABHARLANN CHOLÁISTE NA TRÍONÓIDE, BAILE ÁTHA CLIATH | TRINITY COLLEGE LIBRARY DUBLIN
Ollscoil Átha Cliath | The University of Dublin

Terms and Conditions of Use of Digitised Theses from Trinity College Library Dublin

Copyright statement

All material supplied by Trinity College Library is protected by copyright (under the Copyright and Related Rights Act, 2000 as amended) and other relevant Intellectual Property Rights. By accessing and using a Digitised Thesis from Trinity College Library you acknowledge that all Intellectual Property Rights in any Works supplied are the sole and exclusive property of the copyright and/or other IPR holder. Specific copyright holders may not be explicitly identified. Use of materials from other sources within a thesis should not be construed as a claim over them.

A non-exclusive, non-transferable licence is hereby granted to those using or reproducing, in whole or in part, the material for valid purposes, providing the copyright owners are acknowledged using the normal conventions. Where specific permission to use material is required, this is identified and such permission must be sought from the copyright holder or agency cited.

Liability statement

By using a Digitised Thesis, I accept that Trinity College Dublin bears no legal responsibility for the accuracy, legality or comprehensiveness of materials contained within the thesis, and that Trinity College Dublin accepts no liability for indirect, consequential, or incidental, damages or losses arising from use of the thesis for whatever reason. Information located in a thesis may be subject to specific use constraints, details of which may not be explicitly described. It is the responsibility of potential and actual users to be aware of such constraints and to abide by them. By making use of material from a digitised thesis, you accept these copyright and disclaimer provisions. Where it is brought to the attention of Trinity College Library that there may be a breach of copyright or other restraint, it is the policy to withdraw or take down access to a thesis while the issue is being resolved.

Access Agreement

By using a Digitised Thesis from Trinity College Library you are bound by the following Terms & Conditions. Please read them carefully.

I have read and I understand the following statement: All material supplied via a Digitised Thesis from Trinity College Library is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of a thesis is not permitted, except that material may be duplicated by you for your research use or for educational purposes in electronic or print form providing the copyright owners are acknowledged using the normal conventions. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

An Assessment of the Performance of Willow Evapotranspiration Systems for the Treatment of On-site Wastewater in Ireland

By

Seán Curneen B.A., B.A.I.



A Thesis submitted to the University of Dublin for the degree of Doctor of Philosophy

Department of Civil, Structural and Environmental Engineering

University of Dublin

Trinity College

Dublin

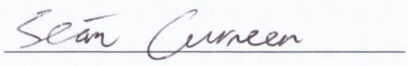
TRINITY COLLEGE
5 JAN 2015
LIBRARY DUBLIN

Thesis 10766

Declaration

I hereby declare that the work contained in this thesis is my own work, and has not been submitted as an exercise for a degree at this or any other university.

I also give the library permission to lend or copy this thesis, upon request, for academic purposes. This permission covers only single copies made for study purposes, subject to normal conditions of acknowledgment.



May 2014

Seán Curneen

Executive Summary

In Ireland, domestic wastewater from approximately 400,000 dwellings is treated by on-site systems which are all designed to distribute the treated effluent to groundwater via the subsoil on the site. Low permeability subsoils can result in lack of percolation and thus ponding of the effluent on the surface with potential surface water pollution around the site. In such cases, the only options available are discharge of wastewater to surface water (requiring a Water Pollution Act discharge licence, which local authorities are reluctant to grant) or installation of a zero discharge system. There is a reluctance in Ireland among local authorities to permit the use of zero discharge willow evapotranspiration systems as viable treatment systems given the lack of long-term performance data relevant to Ireland, or any information or guidance provided in the EPA wastewater treatment manual pertaining to the systems.

A four year research study was undertaken to examine and compare the performance of willow evapotranspiration (ET) systems in low permeability subsoils, in treating domestic wastewater. ET is the removal of water from the soil surface to the atmosphere via a combination of evaporation, which is the direct movement of the water from the soil, and transpiration, which describes the movement of water within the plants. Treatment and removal of wastewater is achieved by a combination of evapotranspiration and nutrient absorption, primarily via the willow trees. Eight systems in County Wexford were constructed (with additional systems in Counties Leitrim and Limerick), consisting of a sealed basin in which the hydraulic load was stored. The storage medium was comprised of the excavated subsoil and a gravel layer in which the wastewater was distributed by means of either percolation or pressurised pipes. The wastewater being treated was either septic tank effluent or secondary treated effluent. The surfaces of the systems were planted with different varieties of willow clones at a density of 3 plants/m^2.

The ET rates were determined by means of a mass balance equation and compared to the reference evapotranspiration, this being the evapotranspiration from a hypothetical grass reference crop. It was found that the usable storage capacity in the clay subsoil was quite low, ranging from 9.5 - 21% by volume. As a result, the basin did not have the capacity to store all the hydraulic loading and flooding of the systems occurred. The relatively high rainfall levels compounded this effect. The low porosity of the soil also had the effect of reducing ET from the system.

The ET rates from the willow systems varied greatly from system to system. The highest ET rates came from the three earliest established systems, and ranged from 358 mm to 929 mm (per year). However, these values were conservative due to the fact that ET could not be determined on days in which overflow from the system was deemed to have occurred. When compared to the reference ET for each site, it was determined that the expected annual ET from a system was approximately 2.2 times (the crop coefficient) the reference value. Tree development had the singular greatest impact on ET. It had the effect of greatly reducing the impact of other factors such as radiation, wind speed, rainfall, effluent loading, aspect ratio of the system, and geographical location in Ireland. The ET rates for systems with sub optimal tree development ranged from 341 mm to 827 mm (per year). The estimated annual ET from these systems was approximately 1.5 times greater than the reference ET, which was significantly lower than the value for the better performing willow systems.

Nutrient removal was found to be quite high on systems with well-developed trees and was, to varying degrees, lower for the systems with poorer established trees. Total-N removal rates ranged from 67% to 99%, while PO_4-P removal ranged from 94% to >99%. However, it should be noted that there was a significant degree of uncertainty in the various aspects of these measurements. There did appear to be some salt accumulation on systems receiving effluent compared to the background systems. However, concentrations were still relatively low and there was no detrimental effect observed on the willow trees on any of the sites.

As part of the research, guidelines on the design and construction of willow systems in County Wexford have been developed based upon the results of these trials. It was deemed that the design of a zero discharge system suitable for wastewater treatment for a single house will be very difficult to achieve in an Irish climate. As such, the guidelines were designed on the basis of minimising the volume of overflow while keeping within reasonable practical and financial constraints. A hydraulic model was used to assess the likelihood of wastewater overflow occurring from a system. The hydraulic level within the system was predicted on a monthly basis, assuming that effluent entered the system from the bottom and rainfall entered from the top, with minimal mixing between the two. It was shown that although overflow will occur during the winter months, it would mostly consist of rainfall and not wastewater (as the rainfall is at the top of the system and the wastewater is at the bottom). So, although the willow systems do not provide overall zero discharge, they can maintain zero discharge of effluent and thus represent a robust wastewater treatment solution on sites with low permeability subsoils in Ireland.

Acknowledgements

Firstly, I would like to thank my project supervisor Dr. Laurence Gill for his constant support and guidance throughout the research. His tireless work ethic, ability to come up with ideas, uncanny knack to pull money out of the woodwork, and constant optimism throughout the project were greatly appreciated. I think everyone will look back on his time as Head of the Department with fond memories, with the Department days out and the Christmas parties a particular highlight.

Thank you to Wexford County Council for providing me with the funding which enabled me to undertake this research and in particular to Brendan Cooney who was pivotal in spearheading the research.

Thanks to everyone in the department who helped out (especially with the planting) along the way (apologies for all the blistered hands). I also wish to thank Kev and Martin for their help in the lab. Special recognition must go to Pat Veale whose help, in both the field and the lab, was greatly appreciated.

I would like to thank all of my Pearse Street office colleagues and friends from the past few years. Aisling, Andy, Davie, Franz, John, Mairéad, Mary, Stevie, and Ted – you've all been *great craic*. Thanks to Mac for being a great house mate and friend for the last year. Thanks to Kavo – everyone in the office was in agreement in saying that maximum productivity always coincided with your visits. Thanks to members of the book club for all the literary insight - no doubt it greatly aided with the authoring of this thesis. Also, thanks to Paraic for being a great friend over the last few years – the moral support, table tennis and comfort of living with a fellow sick-note was always enjoyable!

I'd like to give a special mention to Maria for being so supportive in the last few months. I don't think anyone else had to listen to as much whinging and bellyaching!

Finally, I wish to thank my family for all their support along the way. A special thanks to my parents, James and Róisín for all the encouragement and (financial!) backing throughout my years of education. I'm also grateful to my brothers and sisters, Kate, Áine, Róisín, James and Fintan for all their help – and also to Bruce for hours of entertainment.

Table of Contents

Declaration i
Executive Summary iii
Acknowledgements v
Table of Contents vii
List of Figures xv
List of Tables xxvii
Abbreviations xxxv
Nomenclature xxxv
1 Introduction 3
1.1 Background 3
1.2 Scope of Research 4
1.2.1 Aims and Objectives 4
1.2.2 Methodology and Work Programme 5
1.3 Thesis Outline 7
2 Literature Review 11
2.1 Introduction & Background 11
2.2 On-site Treatment 12
2.2.1 Wastewater Production 14
2.2.2 Septic Tank Design and Operation 15
2.2.3 Septic Tank Treatment Performance 17
2.2.4 Soil Treatment Unit (Percolation Area) 18
2.2.5 Secondary and Tertiary Treatment 20
2.2.6 Percolation Tests and Systems Options 21
2.3 Low Permeability Subsoils 22
2.3.1 Subsoils 23
2.3.2 Subsoil Permeability 24
2.4 Willow 27
2.4.1 History of Willows & Overview of Phytoremediation 27
2.4.2 Evapotranspiration 29
2.4.3 Willow System Treatment of Wastewater Pollutants 34
2.4.4 Zero Discharge Willow Systems 47
2.4.5 Willows - Establishment and Maintenance 51
3 Methodology 59
3.1 Introduction 59
3.2 Site Selection 59

3.2.1 On-site Assessment 60
3.2.2 Visual Assessment 60
3.2.3 Trial Hole 61
3.2.4 Percolation Test 61
3.2.5 Occupancy 62
3.3 Design Criteria 63
3.3.1 Wastewater flow into system 63
3.3.2 Meteorological Data 63
3.3.3 Preliminary Sizing 64
3.3.4 Construction Details 65
3.4 Test Sites 68
3.4.1 Sites A and B: Fardystown, Co. Wexford 71
3.4.2 Site C: Borehovel, Co. Wexford 72
3.4.3 Site D: Ballask, Co. Wexford 73
3.4.4 Site E: Jamestown, Co. Wexford 73
3.4.5 Site F: Ballywilliam, Co. Wexford 75
3.4.6 Site G: Ardcavan, Co. Wexford 76
3.4.7 Site H: Duncormick, Co. Wexford 76
3.4.8 Site I: Carrigallen, Co. Leitrim 77
3.4.9 Site J: Ballylanders, Co. Limerick 78
3.5 Proprietary Treatment Systems 78
3.5.1 Septic Tank 78
3.5.2 Puraflo® Effluent Treatment System 79
3.5.3 Envirocare P6 Treatment System 80
3.5.4 Enviropak Biological Aerated Filter (BAF) System 80
3.6 Construction of Willow System 81
3.6.1 Excavation 81
3.6.2 Liner 82
3.6.3 Distribution Layer 84
3.6.4 Inspection Well, Refilling and Berms 86
3.7 Instrumentation 88
3.7.1 Monitoring of Willow System Influent and Water Level 88
3.7.2 Tipping bucket flow gauge 88
3.7.3 Water Level Meter 89
3.7.4 Water Level Monitoring within Willow System 90
3.7.5 Meteorology Instrumentation 90
3.8 Water Sampling and Analysis 92
3.8.1 Sample Collection 92

3.8.2 Chemical Analysis 92
3.8.3 Bacteriological Analysis 93
3.9 Willow Establishment and Maintenance 94
3.9.1 Planting 94
3.9.2 Coppicing 94
3.9.3 Weed Control 95
4 Site Characteristics - Meteorological, Effluent Loading and Soil Porosity 99
4.1 Introduction 99
4.2 Meteorological Data 99
4.2.1 Sites A & B Fardystown 99
4.2.2 Site C Borehovel 101
4.2.3 Site D Ballask 103
4.2.4 Site E Jamestown 104
4.2.5 Site F Ballywilliam 106
4.2.6 Site G Ardcavan 108
4.2.7 Site H Duncormick 110
4.2.8 Site I Carrigallen (Co. Leitrim) 112
4.2.9 Site J Ballylanders (Co. Limerick) 113
4.2.10 Sensitivity Analysis of Reference Evapotranspiration 114
4.2.11 Variance Analysis 118
4.3 Effluent Loading 127
4.3.1 Sites A Fardystown 127
4.3.2 Site B Fardystown 130
4.3.3 Site C Borehovel 132
4.3.4 Site D Ballask 134
4.3.5 Site E Jamestown 135
4.3.6 Site F Ballywilliam 137
4.3.7 Site G Ardcavan 138
4.3.8 Site H Duncormick 139
4.3.9 Site I Carrigallen (Co. Leitrim) 141
4.3.10 Site J Ballylanders (Co. Limerick) 142
4.4 Comparison of Hydraulic Loading due to Rainfall and Effluent 142
4.5 Soil Porosity 143
4.5.1 Method 1 145
4.5.2 Method 2 147
4.5.3 Method 3 148
4.5.4 Final Porosities 149
4.6 Summary 151

4.6.1 Meteorological Data 151
4.6.2 Effluent Loading 151
4.6.3 Soil Porosity 151
5 Evapotranspiration Results from Willow Systems 155
5.1 Introduction 155
5.2 Method or Analysis/Water Balance 155
5.3 Willow System Evapotranspiration 156
5.3.1 Site A Fardystown 159
5.3.2 Site B Fardystown 170
5.3.3 Site C Borehovel 180
5.3.4 Site D Ballask 190
5.3.5 Site E Jamestown 199
5.3.6 Site F Ballywilliam - System 1 208
5.3.7 Site F Ballywilliam - System 2 215
5.3.8 Site G Ardcavan 223
5.3.9 Site H Duncormick 230
5.3.10 Site I Carrigallen (Co. Leitrim) 237
5.3.11 Site J Ballylanders (Co. Limerick) 243
5.4 Summary 246
5.4.1 Overview of Evapotranspiration Performance 246
5.4.2 Overflow from the Willow Systems 247
5.4.3 Crop Coefficients 247
5.4.4 Conclusions 249
6 Nutrients and Water Quality 253
6.1 Introduction 253
6.2 Background Concentrations 254
6.3 Site A Fardystown 257
6.3.1 Organics 257
6.3.2 Nitrogen 258
6.3.3 Phosphorus 260
6.3.4 Salinity 261
6.3.5 Bacteriological Analysis 263
6.4 Site B Fardystown 264
6.4.1 Organics 264
6.4.2 Nitrogen 266
6.4.3 Phosphorus 268
6.4.4 Salinity 268
6.4.5 Bacteriological Analysis 270

6.5 Site C Borehovel 271
6.5.1 Organics 271
6.5.2 Nitrogen 272
6.5.3 Phosphorus 275
6.5.4 Salinity 276
6.5.5 Bacteriological Analysis 277
6.6 Site D Ballask 279
6.6.1 Organics 279
6.6.2 Nitrogen 280
6.6.3 Phosphorus 283
6.6.4 Salinity 283
6.6.5 Bacteriological Analysis 285
6.7 Site H Duncormick - System 1 286
6.7.1 Organics 286
6.7.2 Nitrogen 288
6.7.3 Phosphorus 290
6.7.4 Salinity 291
6.7.5 Bacteriological Analysis 292
6.8 Site H Duncormick - System 2 293
6.8.1 Organics 293
6.8.2 Nitrogen 295
6.8.3 Phosphorus 297
6.8.4 Salinity 298
6.8.5 Bacteriological Analysis 299
6.9 Summary 301
6.9.1 Organics and Nutrients 301
6.9.2 Bacteria 302
6.9.3 Salinity 303
6.9.4 Accuracy of Results 304
6.9.5 Conclusion 305
7 Mesocosm 309
7.1 Introduction 309
7.2 Materials and Methodology 309
7.2.1 Experimental Setup 309
7.2.2 Water Balance 311
7.2.3 Water Sampling and Analysis 312
7.2.4 Plant Biomass Analysis 313
7.2.5 Statistical Analysis 313

7.3 Results 314
7.3.1 Meteorological 314
7.3.2 Evapotranspiration and Crop Coefficients 316
7.3.3 Biomass 321
7.3.4 Nutrients 322
7.4 Discussion 327
7.4.1 Evapotranspiration and Crop Coefficients 327
7.4.2 Nutrient and Organic Uptake 329
7.4.3 Comparison with Full Scale Systems (Loading Rate) 331
7.4.4 Comparison with Full Scale Systems (Evapotranspiration) 331
8 Analysis and Discussion of Results 337
8.1 Introduction 337
8.2 Effluent Loading Analysis 337
8.3 Willow System Evapotranspiration Comparisons 339
8.3.1 2010 Evapotranspiration Rates 339
8.3.2 2011 Evapotranspiration Rates 340
8.3.3 2012 Evapotranspiration Rates 342
8.3.4 2013 Evapotranspiration Rates 344
8.3.5 Summary of Evapotranspiration 346
8.4 Crop Coefficient Comparison 346
8.5 Effluent Type 348
8.6 Aspect Ratio 351
8.7 Willow Clone Variety 354
8.8 Soil Porosity 355
8.9 Regression Analysis 359
8.9.1 Introduction to Regression 360
8.9.2 Simple Linear Regression 360
8.9.3 Multiple Linear Regression 360
8.9.4 Site C – Regression Analysis 361
8.9.5 Site A – Regression Analysis 365
8.9.6 Site B – Regression Analysis 367
8.9.7 Regression Analysis Summary 369
8.10 Comparison of willow systems on same site 370
8.10.1 Site H Duncormick 370
8.10.2 Site I Carrigallen 371
8.11 Assessment of Clay Liner 372
8.12 Establishment and Development of Clones 373
9 Design Guidelines 379

9.1 Introduction 379
9.2 Design Model 380
9.2.1 Model 383
9.2.2 Overflow 385
9.2.3 Optimum Design 393
9.2.4 Final Design 394
9.2.5 Modelled Hydraulic Level 394
9.2.6 Aspect Ratio 397
9.2.7 Effluent Production 398
9.3 Liner 399
9.4 Distribution Layer 400
9.5 Inspection Well, Berm and Refilling 401
9.6 Willow Planting and Maintenance 401
9.6.1 Planting 401
9.6.2 Coppicing 402
9.7 Summary 403
10 Conclusions and Recommendations 407
10.1 Conclusions 407
10.1.1 Overview 407
10.1.2 Evapotranspiration 408
10.1.3 Nutrients and Water Quality 410
10.1.4 Effluent Loading 410
10.1.5 Meteorological and Subsoil Conditions 411
10.1.6 Mesocosm 411
10.1.7 Design and Construction Guidelines 412
10.2 Recommendations for Further Research 412
10.2.1 System Design Improvement 412
10.2.2 Future Research 413
References 415
Appendix A: 429

List of Figures

Figure 1.1 Layout of sites and willow systems (red indicates effluent flow to the willow system was compromised) 6
Figure 2.1 Conventional septic tank treatment system including percolation area with pathway for potential contaminant migration to groundwater (adapted from Van Cuyk et al., 2001) 13
Figure 2.2 Longitudinal section of typical two-chamber septic tank (EPA, 2000) 16
Figure 2.3 Cross-section of a percolation trench (modified from EPA, 2009a) 19
Figure 2.4 Subsoils map showing different subsoils types across Ireland (modified from Meehan and Lee, 2012) 24
Figure 2.5 (A) Subsoil permeability map of Ireland (adapted from Gsi et al., 2012); 25
Figure 2.6 Crop coefficient for willow (*Salix alba*) over the course of two growing season (modified from Guidi et al., 2008) 31
Figure 2.7 Longitudinal section of zero discharge system (modified from Miljøstyrelsen, 2003) 48
Figure 2.8 Membrane detail along bottom and sides of the willow system (Miljøstyrelsen, 2003) 48
Figure 2.9 Layout of distribution pipes in soil medium (modified from Brix and Arias, 2011) ... 49
Figure 2.10 Area demand for willow system in 20 x 20 km grids (modified from Miljøstyrelsen, 2003) 51
Figure 2.11 Willow cutback after first season (Defra, 2002) 55
Figure 2.12 *Melampsora* rust on willow leaves (Defra, 2002) 55
Figure 2.13 *Phratora vulgatissima* L. - blue willow beetle (adapted from Caslin et al., 2010) 56
Figure 3.1 Cross-section of T-test holes and invert of proposed percolation trench (modified from EPA, 2009a) 62
Figure 3.2 Example of water balance model output for design 65
Figure 3.3 Plan and end elevation of willow system 66
Figure 3.4 Willow system detail 67
Figure 3.5 Test site locations 68
Figure 3.6 Construction plan and instrumentation layout of Sites A and B (Fardystown) 71
Figure 3.7 Aerial view of Sites A and B (with the willow systems highlighted in yellow) 72
Figure 3.8 Construction plan and instrumentation layout of Site C (Borehovel) 72
Figure 3.9 Construction plan and instrumentation layout of Site D (Ballask) 73
Figure 3.10 Construction plan and instrumentation layout of Site E (Jamestown) 74
Figure 3.11 Construction plan and instrumentation layout of Site F (Ballywilliam) 75

Figure 3.12 Construction plan and instrumentation layout of Site G (Ardcavan) 76
Figure 3.13 Construction plan and instrumentation layout of Site H (Duncormick) 77
Figure 3.14 Construction plan and instrumentation layout of Site I (Carrigallen) 77
Figure 3.15 Construction plan and instrumentation layout of Site J (Ballylanders) 78
Figure 3.16 Installation of double chambered septic tank on Site C 79
Figure 3.17 Puraflow® Liquid Effluent Treatment System (cover removed) 79
Figure 3.18 Envirocare P6 Treatment Unit 80
Figure 3.19 A biological aerated filter (BAF) system 81
Figure 3.20 Excavation of basins 82
Figure 3.21 Geosynthetic barrier and impermeable membrane installation 83
Figure 3.22 Installation of gravel trench distribution system 85
Figure 3.23 Installation of gravel layer distribution system 86
Figure 3.24 Connection between pipe from pump and inlet pipe 86
Figure 3.25 Installation of inspection well, berm and refilling of basin 87
Figure 3.26 Tipping bucket distribution design: **(a)** schematic, **(b)** photograph of design installed on Site I and **(c)** photograph of design installed on Site F 89
Figure 3.27 Full weather station on Site I 90
Figure 3.28 Windsonic anemometer and ARG100 tipping bucket rain gauge on Site C 91
Figure 3.29 Coppiced willow shoots 94
Figure 4.1 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Sites A & B 100
Figure 4.2 Daily Penman-Monteith reference evapotranspiration rates (ET_o) for Sites A & B 100
Figure 4.3 Orientation of willow systems with respect to wind speed and direction distribution for Sites A&B 101
Figure 4.4 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site C 101
Figure 4.5 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site C 102
Figure 4.6 Orientation of willow systems with respect to wind speed and direction distribution for Site C 102
Figure 4.7 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site D 103
Figure 4.8 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site D 103
Figure 4.9 Orientation of willow systems with respect to wind speed and direction distribution for Site D 104

Figure 4.10 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site E 105
Figure 4.11 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site E 105
Figure 4.12 Orientation of willow systems with respect to wind speed and direction distribution for Site E 106
Figure 4.13 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site F 107
Figure 4.14 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site F 107
Figure 4.15 Orientation of willow systems with respect to wind speed and direction distribution for Site F 108
Figure 4.16 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site G 109
Figure 4.17 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site G 109
Figure 4.18 Orientation of willow systems with respect to wind speed and direction distribution for Site G 110
Figure 4.19 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site H 110
Figure 4.20 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site H 111
Figure 4.21 Orientation of willow systems with respect to wind speed and direction distribution for Site H 111
Figure 4.22 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site I 112
Figure 4.23 Penman-Monteith reference evapotranspiration rates (ETo) for Site I 112
Figure 4.24 Orientation of willow systems with respect to wind speed and direction distribution for Site I 113
Figure 4.25 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site J 113
Figure 4.26 Penman-Monteith reference evapotranspiration rates (ETo) for Site J 114
Figure 4.27 Comparison of observed and Latin Hypercube simulated ET_o simulations. 117
Figure 4.28 Correlation coefficients for simulated Penman Monteith reference evapotranspiration inputs of meteorological parameters. 117
Figure 4.29 Tornado graph of the regression mapped values of the simulation model inputs. Each value represents the change in daily reference evapotranspiration with a one standard deviation change in a particular input, with all others held constant. 118
Figure 4.30 A summary for the daily reference evapotranspiration rates on Sites A & B 119

Figure 4.31 Distributions of rainfall for each site (mm) 120
Figure 4.32 Distributions of wind speeds for each site (m/s) 122
Figure 4.33 Distributions of net radiation for each site (MJ/m²/day) 124
Figure 4.34 Times series comparison of net radiation (with a 3 week moving average trend line) between Sites A&B, Site F, Site I and Site J 125
Figure 4.35 Distributions of reference evapotranspiration for each site (mm) 126
Figure 4.36 Daily flows to Site A (with 2 week moving average trend line) 128
Figure 4.37 Comparison of daily wastewater flow with daily rainfall over a 1 month period on Site A 128
Figure 4.38 Correlation between daily wastewater flow and daily rainfall over a 1 month period on Site A 129
Figure 4.39 Hydraulic loading to willow system from rainfall and effluent (Site A) 129
Figure 4.40 Daily flows to Site B (with 2 week moving average trend line) 130
Figure 4.41 Comparison of daily wastewater flow with daily rainfall over two different time periods on Site B 131
Figure 4.42 Correlation between daily wastewater flow and daily rainfall over 2 different time periods on Site B 131
Figure 4.43 Hydraulic loading to willow system from rainfall and effluent (Site B) 132
Figure 4.44 Daily flows to Site C (with 2 week moving average trend line) 132
Figure 4.45 Comparison of daily wastewater flow with daily rainfall over two different time periods on Site C 133
Figure 4.46 Hydraulic loading to willow system from rainfall and effluent (Site C) 133
Figure 4.47 Daily flows to Site D (with 2 week moving average trend line) 134
Figure 4.48 Hydraulic loading to willow system from rainfall and effluent (Site D) 135
Figure 4.49 Hydraulic loading to willow system from rainfall and effluent (Site E) 136
Figure 4.50 Daily flows to Site F (with 2 week moving average trend line) 137
Figure 4.51 Hydraulic loading to willow system from rainfall and effluent (Site F) 138
Figure 4.52 Hydraulic loading to willow system from rainfall and effluent (Site G) 138
Figure 4.53 Daily wastewater flows to Site H (with 2 week moving average trendline) 139
Figure 4.54 Hydraulic loading to willow system from rainfall and effluent (Site H - System 1) 140
Figure 4.55 Hydraulic loading to willow system from rainfall and effluent (Site H - System 2) 140
Figure 4.56 Daily wastewater flows to Site I (with 2 week moving average trendline) 141

Figure 4.57 Hydraulic loading to willow system from rainfall and effluent (Site I - System 1 & 2) 142
Figure 4.58 A comparison of the three different methods 150
Figure 5.1 Daily fluctuation in ET_{willow} rates and crop coefficient (K_c) values 157
Figure 5.2 Weekly fluctuations in ET_{willow} rates and crop coefficient (K_c) values 157
Figure 5.3 Fortnightly fluctuations in ET_{willow} rates and crop coefficient (K_c) values 158
Figure 5.4 Water level and daily rainfall for February to December 2010 (Site A) 161
Figure 5.5 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010) 161
Figure 5.6 Water level and daily rainfall for 2011 (Site A) 163
Figure 5.7 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011) 163
Figure 5.8 Water level and daily rainfall for 2012 (Site A) 165
Figure 5.9 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2012) 165
Figure 5.10 Water level and daily rainfall for 2013 167
Figure 5.11 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2013) 168
Figure 5.12 Yearly comparison of mean daily ET_{willow} rates for Site A 169
Figure 5.13 Yearly comparison of monthly K_c values for Site A 170
Figure 5.14 Water level and daily rainfall for 2010 (Site B) 171
Figure 5.15 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2010) 171
Figure 5.16 Water level and daily rainfall for 2011 (Site B) 173
Figure 5.17 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2011) 173
Figure 5.18 Water level and daily rainfall for 2012 (Site B) 175
Figure 5.19 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2012) 175
Figure 5.20 Water level and daily rainfall for 2013 (Site B) 177
Figure 5.21 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2013) 177
Figure 5.22 Yearly comparison of mean daily ET_{willow} rates for Site B 179
Figure 5.23 Yearly comparison of monthly K_c values for Site B 179
Figure 5.24 Water level and daily rainfall for September to December 2010 (Site C) 181

Figure 5.25 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010) 181
Figure 5.26 Water level and daily rainfall for 2011 (Site C) 183
Figure 5.27 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011) 184
Figure 5.28 Water level and daily rainfall for 2012 (Site C) 185
Figure 5.29 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2012) 186
Figure 5.30 Water level and daily rainfall for 2013 (Site C) 187
Figure 5.31 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2013) 187
Figure 5.32 Yearly comparison of mean daily ET_{willow} rates for Site C 189
Figure 5.33 Yearly comparison of monthly K_c values for Site C 189
Figure 5.34 Water level and daily rainfall for 2010 (Site D) 191
Figure 5.35 Water level and daily rainfall for 2011 (Site D) 192
Figure 5.36 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2011) 192
Figure 5.37 Water level and daily rainfall for 2012 (Site D) 194
Figure 5.38 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2012) 194
Figure 5.39 Water level and daily rainfall for 2013 (Site D) 196
Figure 5.40 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2013) 196
Figure 5.41 Yearly comparison of mean daily ET_{willow} rates for Site D 198
Figure 5.42 Yearly comparison of monthly K_c values for Site D 198
Figure 5.43 Water level and daily rainfall for 2010 (Site E) 199
Figure 5.44 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2010) 200
Figure 5.45 Water level and daily rainfall for 2011 (Site E) 201
Figure 5.46 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2011) 202
Figure 5.47 Water level and daily rainfall for 2012 (Site E) 203
Figure 5.48 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2012) 204
Figure 5.49 Water level and daily rainfall for 2013 (Site E) 205

Figure 5.50 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2013) 206
Figure 5.51 Yearly comparison of mean daily ET_{willow} rates for Site E 207
Figure 5.52 Yearly comparison of monthly K_c values for Site E 207
Figure 5.53 Piping running through System 1 on Site F that resulted in leakage at this level 208
Figure 5.54 Water level and daily rainfall for 2011 (Site F - System 1) 209
Figure 5.55 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2011) 209
Figure 5.56 Water level and daily rainfall for 2012 (Site F - System 1) 211
Figure 5.57 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2012) 211
Figure 5.58 Water level and daily rainfall for 2013 (Site F - System 1) 213
Figure 5.59 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2013) 213
Figure 5.60 Yearly comparison of mean daily ET_{willow} rates for System 1 on Site F 215
Figure 5.61 Yearly comparison of monthly K_c values for System 1 on Site F 215
Figure 5.62 Water level and daily rainfall for 2011 (Site F - System 2) 216
Figure 5.63 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2011) 217
Figure 5.64 Water level and daily rainfall for 2012 (Site F - System 2) 218
Figure 5.65 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2012) 219
Figure 5.66 Water level and daily rainfall for 2013 (Site F - System 2) 220
Figure 5.67 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2013) 221
Figure 5.68 Yearly comparison of mean daily ET_{willow} rates for System 2 on Site F 222
Figure 5.69 Yearly comparison of monthly K_c values for System 2 on Site F 223
Figure 5.70 Water level and daily rainfall for 2011 (Site G) 224
Figure 5.71 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2011) 225
Figure 5.72 Water level and daily rainfall for 2012 (Site G) 226
Figure 5.73 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2012) 226
Figure 5.74 Water level and daily rainfall for 2013 (Site G) 228

Figure 5.75 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2013) 228
Figure 5.76 Yearly comparison of mean daily ET_{willow} rates for Site G 230
Figure 5.77 Yearly comparison of monthly K_c values for Site G 230
Figure 5.78 Water level and daily rainfall for System 1 on Site H (March 2012 – August 2013) 231
Figure 5.79 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site H (April 2012 – August 2013) 232
Figure 5.80 Water level and daily rainfall for System 2 on Site H (March 2012 – August 2013) 234
Figure 5.81 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site H (April 2012 – August 2013) 235
Figure 5.82 Water level and daily rainfall for System 1 on Site I (April 2012 – August 2013) 238
Figure 5.83 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site I (April 2012 – August 2013) 239
Figure 5.84 Water level and daily rainfall for System 2 on Site I (April 2012 – August 2013) 241
Figure 5.85 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site I (April 2012 – August 2013) 242
Figure 5.86 Water level and daily rainfall on Site J (November 2012 – August 2013) 244
Figure 5.87 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site J (November 2012 – August 2013) 245
Figure 5.88 Ten-day average ET_{willow} rates (a) and crop coefficients (b) (adapted from Pistocchi et al,. 2009) 248
Figure 6.1 Temporal concentrations (Total N, NH_4-N, NO_3-N, and NO_2-N) during sampling period (Site F – System 2) 255
Figure 6.2 Temporal concentrations (COD, PO_4-P, Cl, and SO_4) during sampling period (Site F – System 2) 256
Figure 6.3 COD removal on Site A throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 258
Figure 6.4 Inorganic-N removal on Site A throughout monitoring period (note log scale) 258
Figure 6.5 NH_4-N and NO_3-N loading in the STE and corresponding mass in the willow system (note log scale) 260

Figure 6.6 PO_4-P removal on Site A throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 261
Figure 6.7 Cl & SO_4 removal on Site A throughout monitoring period (log scale) 262
Figure 6.8 Temporal *E. coli* concentrations during sampling period on Site A 264
Figure 6.9 COD removal on Site B throughout monitoring period 265
Figure 6.10 Inorganic-N removal on Site B throughout monitoring period (note log scale) 266
Figure 6.11 NH_4-N and NO_3-N loading in the STE and corresponding mass in the willow system on Site B (note log scale) 267
Figure 6.12 PO_4-P removal on Site B throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 268
Figure 6.13 Cl & SO_4 removal on Site B throughout monitoring period (note log scale) 269
Figure 6.14 Temporal *E. coli* concentrations during sampling period on Site B 271
Figure 6.15 COD removal on Site C throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 272
Figure 6.16 Inorganic-N removal on Site C throughout monitoring period (note log) 273
Figure 6.17 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site C (note log scale; a value below the minimum value on the y-axis represents zero) 274
Figure 6.18 PO_4-P removal on Site C throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 276
Figure 6.19 Cl & SO_4 removal on Site C throughout monitoring period (note log scale) 277
Figure 6.20 Temporal *E. Coli* concentrations during sampling period on Site C 278
Figure 6.21 COD removal on Site D throughout monitoring period 280
Figure 6.22 Inorganic-N removal on Site D throughout monitoring period (note log scale) 281
Figure 6.23 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site D (log scale; a value below the minimum value on the y-axis represents zero) .282
Figure 6.24 PO_4-P removal on Site D throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 283
Figure 6.25 Cl & SO_4 removal on Site D throughout monitoring period 284
Figure 6.26 Temporal *E. coli* concentrations during sampling period on Site D (note log scale) 286
Figure 6.27 COD removal on Site H (System 1) throughout monitoring period (note log scale) 287
Figure 6.28 Inorganic-N removal on Site H (System 1) throughout monitoring period (note log scale) 288

Figure 6.29 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site H (System 1) (note log scale) 290
Figure 6.30 PO_4-P removal on Site H (System 1) throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero) 290
Figure 6.31 Cl & SO_4 removal on Site H (System 1) throughout monitoring period 292
Figure 6.32 Temporal *E. Coli* concentrations during sampling period on Site H (System 1) 293
Figure 6.33 COD removal on Site H (System 2) throughout monitoring period 294
Figure 6.34 Inorganic-N removal on Site H (System 2) throughout monitoring period 295
Figure 6.35 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site H (System 2) (note log scale) 297
Figure 6.36 PO_4-P removal on Site H (System 2) throughout monitoring period 297
Figure 6.37 Cl & SO_4 removal on Site H (System 2) throughout monitoring period 299
Figure 6.38 Temporal *E. coli* concentrations during sampling period on Site H (System 2) 300
Figure 7.1 Cross sectional detail of container 309
Figure 7.2 Calibration curve for barrel 1 310
Figure 7.3 (A) Willow trees in the middle of the first growing season (2009); (B) Willow trees at the end of the second growing season (2010), with weather station also in view 310
Figure 7.4 Monthly meteorological data for 2010 /2011 /2012 314
Figure 7.5 Correlation between monthly evapotranspiration and temperature 315
Figure 7.6 Correlation between monthly evapotranspiration and wind speed 315
Figure 7.7 Willow evapotranspiration and reference evapotranspiration for 2010 316
Figure 7.8 Willow evapotranspiration and reference evapotranspiration for 2011 318
Figure 7.9 Willow evapotranspiration and reference evapotranspiration for 2012 320
Figure 7.10 Height and stem diameter of willow clones at end of Season 1 and Season 3 321
Figure 7.11 Dry biomass of willow clones at end of Season 1 and Season 3 322
Figure 7.12 Nitrogen uptake by different willow clones 323
Figure 7.13 Phosphorus uptake by different willow clones 324
Figure 7.14 Potassium uptake by different willow clones 325
Figure 7.15 Total organic carbon uptake by different willow clones 326
Figure 7.16 Correlation between ET_{willow} and dry weight of biomass 330
Figure 8.1 Correlation between mean daily ET_{willow} rates and mean daily ET_o rates during the 2012 growing season 343
Figure 8.2 Correlation between mean daily ET_{willow} rates and mean daily ET_o rates during the 2013 growing season 345

Figure 8.3 Comparison of monthly crop coefficients with those reported by Guidi et al. (2008) for willows in the first growing season 347
Figure 8.4 Comparison of monthly crop coefficients with those reported by Guidi et al. (2008) for willows in the second growing season 348
Figure 8.5 Comparison of daily ET_{willow} rate on Site A and Site B (2 week moving average trend line) 349
Figure 8.6 The 'clothesline' effect illustrated by a row of trees planted perpendicular to the prevailing wind direction ((adapted from Brix and Arias, 2011)) 352
Figure 8.7 Comparison of the mean daily wind speeds inside and outside the willow system on Site C (May - August) 353
Figure 8.8 Water level within System A, B, C, and D with the overflow level set at 1.9 m (May - August 2013) 356
Figure 8.9 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site C, for the period 18th June - 26th July 2013) 356
Figure 8.10 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site A, for the period 18th June - 7th July 2013) 357
Figure 8.11 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site B, for the period 9th May - 9th June 2013) 358
Figure 8.12 (A) Refilling of relatively loose soil into basin; (B) Compaction of soil by excavator while constructing distribution drains 358
Figure 8.13 Linear regression plot of the daily ET_{willow} versus the daily ET_o (Summer 2012) 361
Figure 8.14 Linear regression plot of the daily ET_{willow} versus the daily ET_o (Summer 2013) 362
Figure 8.15 Relationship between rainfall and net radiation in Site B (2011) 368
Figure 8.16 (A) Extensive weed growth on Site F (System 1) compared to (B) Site C which saw little weed growth as a result of using a weed proof membrane. 373
Figure 8.17 (A) Surface of the willow system prior to planting; (B) Poor willow establishment due to dry, compact soil; (C) Willow development on Site D two years after originally planting; (D) Three years after originally planting. 374
Figure 9.1 Sample cross sectional area of willow system with relevant porosities 380
Figure 9.2 Second season crop coefficients for Sites A & B compared to those determined by Guidi et al. (2008). 382
Figure 9.3 Water level profile determined by model (using rainfall and ET_o data collected on Sites A & B) 384
Figure 9.4 Water level profile determined by model (after overflow is assumed to be lost from the system) 384

Figure 9.5 Effect of increasing the area on the number of overflow days 385
Figure 9.6 Effect of increasing the depth on the number of overflow days 386
Figure 9.7 Water profile for willow system of and depth 1.5 m and areas area 300 m^2, 500 m^2, 700 m^2; (a) overflow assumed to still be in system, (b) overflow assumed to have been lost from system 388
Figure 9.8 Water profile for willow system of area 500 m^2 and depths 1.8 m and 2.1 m; (a) overflow assumed to still be in system, (b) overflow assumed to have been lost from system. 389
Figure 9.9 Effect of increasing area on the number of overflow days for a willow system receiving effluent from a dwelling with 5PE, 6PE, 8PE, and 10 PE 389
Figure 9.10 Number of days of overflow for different heights of free space for three different depth of willow system 391
Figure 9.11 Expected hydraulic levels in willow evapotranspiration system designed according to the guidelines in County Wexford across an annual cycle. 396
Figure 9.12 Effect of wind speed with increasing crop height for a relatively humid climate (modified from Allen et al., 1998) 397
Figure 9.13 Connection between pipe from pump and inlet pipe; (a) before, (b) after 400
Figure 9.14 An example of a cut back willow stool after the first season 403
Figure 9.15 Coppicing of willow system on three year cycle 403

List of Tables

Table 2.1 Range of raw domestic wastewater influent characteristics (adapted from (EPA, 2009a). 14
Table 2.2 Potential water savings for different toilet systems compared to a reference 9 litre single flush toilet (modified from Dubber and Gill, 2013) 15
Table 2.3 Interpretation of percolation test results (modified from EPA, 2009a) 22
Table 2.4 Willow evapotranspiration for five lysimeter experiments 33
Table 2.5 Evapotranspiration Rates for six willow systems in Denmark. Adapted from (Gregersen and Brix, 2001) 34
Table 2.6 Sample of Total N removal rate (adapted from Perttu and Kowalik, 1997) 35
Table 2.7 Nitrogen removal rates from two separate studies in Poland. 36
Table 2.8 Nitrogen uptake for willow lysimeter experiments. 37
Table 2.9 Sample of phosphorus (as P_2O_5) removal rate (adapted from Perttu and Kowalik, 1997) 39
Table 2.10 Phosphorus uptake for willow lysimeter experiments. 40
Table 2.11 Sample of organic matter (as BOD_5) removal rate (adapted from Perttu and Kowalik, 1997) 42
Table 2.12 Organic matter removal at Gdansk Zoo 42
Table 2.13 Organic removal rates for willow lysimeter experiments 43
Table 2.14 Dry biomass for willow clones receiving various chloride treatments (adapted from Bialowiec et al., 2007) 46
Table 2.15 Objectives of willow breeding programmes (Lindegaard and Barker (1997), cited in Hanley and Karp (2003) 52
Table 2.16 Shoot biomass growth in terms of water used for 3 willow clones (modified from Weih and Nordh, 2002) 53
Table 2.17 Best performing willow clones (in terms of biomass yield) from ten year comparative study (modified from Lindegaard et al., 2011) 54
Table 3.1 Relevant factors considered during visual assessment (adapted from EPA, 2009a) 60
Table 3.2 Subsoil characteristics considered during trial hole inspection (adapted from O' Súilleabháin, 2004) 61
Table 3.3 Overview of test sites 70
Table 3.4 List of willow clones on each site 70
Table 3.5 Hydraulic load projections for Site E 74
Table 3.6 Impermeable Liner Properties Comparison 82
Table 3.7 Meteorological instrument specifications for full weather stations 91

Table 4.1 The type of distributions assigned to each of the meteorological parameters 115
Table 4.2 Correlation Coefficients between meteorological parameters 116
Table 4.3 Distribution type for meteorological parameters 119
Table 4.4 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between rainfall for the different sites 121
Table 4.5 Comparison of rainfall at sites to 30 year average 121
Table 4.6 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between wind speed for the different sites 123
Table 4.7 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between net radiation for the different sites 124
Table 4.8 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between reference evapotranspiration for the different sites 126
Table 4.9 Average daily flows to Site E 136
Table 4.10 Proportion of hydraulic loading from rainfall and effluent 143
Table 4.11 Results for usable water volume storage within soil (Method 1) 147
Table 4.12 Usable water volume storage within soil for each willow system (Method 2) 148
Table 4.13 Usable water volume storage within soil for each willow system (Method 3) 149
Table 4.14 Comparison of usable water volume storage results and final value used 150
Table 5.1 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010) 162
Table 5.2 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011) 164
Table 5.3 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2012) 166
Table 5.4 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2013) 168
Table 5.5 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2010) 172
Table 5.6 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2011) 174
Table 5.7 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2012) 176
Table 5.8 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2013) 178

Table 5.9 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (September to December 2010) 182
Table 5.10 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2011) 184
Table 5.11 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2012) 186
Table 5.12 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2013) 188
Table 5.13 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2011) 193
Table 5.14 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2012) 195
Table 5.15 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2013) 197
Table 5.16 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2010) 200
Table 5.17 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2011) 202
Table 5.18 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2012) 204
Table 5.19 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2013) 206
Table 5.20 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2011) 210
Table 5.21 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2012) 212
Table 5.22 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2013) 214
Table 5.23 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2011) 217
Table 5.24 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2012) 219
Table 5.25 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2013) 221

Table 5.26 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2011) 225
Table 5.27 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2012) 227
Table 5.28 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2013) 229
Table 5.29 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site H (April 2012 - August 2013) 233
Table 5.30 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site H (April 2012 - August 2013) 236
Table 5.31 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site I (April 2012 - August 2013) 240
Table 5.32 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site I (April 2012 - August 2013) 243
Table 5.33 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for on Site J (November 2012 - August 2013) 245
Table 5.34 Total assumed ET_{willow} for each willow system 246
Table 5.35 Number of days that each willow system was overflowing per year 247
Table 6.1 Mean concentration of Total N, NH_4-N, NO_3-N, and NO_2-N for sites not receiving effluent 255
Table 6.2 Mean concentrations of COD, PO_4-P, Cl^-, and SO_4^{2-} for sites not receiving effluent 256
Table 6.3 COD concentrations and cumulative loading for STE and willow system on Site A 257
Table 6.4 Concentrations of different forms of nitrogen in STE and willow system on Site A 259
Table 6.5 Cumulative chloride and sulphate loading in STE and willow system on Site A. 262
Table 6.6 Reduction in total coliform concentrations with respect to STE in the willow system on Site A 263
Table 6.7 Concentrations of *E. coli* measured on 6 different occasions on Site A 263
Table 6.8 COD concentrations and cumulative loading for STE and willow system on Site B 265
Table 6.9 Concentrations of different forms of nitrogen in STE and willow system on Site B 267
Table 6.10 Cumulative chloride and sulphate loading in STE and willow system on Site B 269
Table 6.11 Reduction in total coliform concentrations with respect to STE in the willow system on Site B 270
Table 6.12 Concentrations of *E. coli* measured on 5 different occasions on Site B 270
Table 6.13 COD concentrations and cumulative loading for STE and willow system on Site C 271
Table 6.14 Concentrations of different forms of nitrogen in STE and willow system on Site C 274

Table 6.15 Cumulative chloride and sulphate loading in STE and willow system on Site C 276
Table 6.16 Reduction in total coliform concentrations with respect to STE in the willow system on Site C 278
Table 6.17 Concentrations of *E. coli* measured on 6 different occasions on Site C 278
Table 6.18 COD concentrations and cumulative loading for STE and willow system on Site D 279
Table 6.19 Concentrations of different forms of nitrogen in STE and willow system on Site D 281
Table 6.20 Cumulative chloride and sulphate loading in STE and willow system on Site D 284
Table 6.21 Reduction in total coliform concentrations with respect to STE in the willow system on Site D 285
Table 6.22 Concentrations of *E. coli* measured on 6 different occasions on Site D 285
Table 6.23 COD concentrations and cumulative loading for STE and willow system on Site H (System 1) 287
Table 6.24 Concentrations of different forms of nitrogen in STE and willow system on Site H (System 1) 289
Table 6.25 Cumulative chloride and sulphate loading in STE and willow system on Site H (System 1) 291
Table 6.26 Reduction in total coliform concentrations with respect to STE in the willow system on Site H (System 1) 292
Table 6.27 Concentrations of *E. coli* measured on 6 different occasions on Site H (System 1) 293
Table 6.28 COD concentrations and cumulative loading for STE and willow system on Site H (System 2) 294
Table 6.29 Concentrations of different forms of nitrogen in STE and willow system on Site H (System 2) 296
Table 6.30 Cumulative chloride and sulphate loading in STE and willow system on Site H (System 2) 298
Table 6.31 Reduction in total coliform concentrations with respect to STE in the willow system on Site H (System 2) 299
Table 6.32 Concentrations of *E. coli* measured on 4 different occasions on Site H (System 2) 300
Table 6.33 Total-N removal rates for willow systems by the end of the sampling period 301
Table 6.34 Total PO_4-P removal rates for willow systems 302
Table 6.35 Bacteriological removal rates for the systems receiving STE 302
Table 6.36 Mean concentration of Cl and SO_4 for the willow system samples 303
Table 7.1 Effluent concentrations and quantities 312
Table 7.2 Willow evapotranspiration rates (mm/day) and crop coefficients for different effluent treatments and varieties during the 2010 season 317

Table 7.3 Willow evapotranspiration rates (mm/day) for different treatments and varieties during the 2011 growing season 319
Table 7.4 Willow evapotranspiration rates (mm/day) for different treatments and varieties during the 2012 growing season 320
Table 7.5 Tukey post-hoc test for stem heights after the first season 321
Table 7.6 Nitrogen availability and uptake throughout the first season 323
Table 7.7 Phosphorus availability and uptake throughout the first season 324
Table 7.8 Potassium availability and uptake throughout the first season 325
Table 7.9 Total organic carbon availability and uptake throughout the first season 326
Table 7.10 Effect of different treatments and varieties on ET 327
Table 7.11 Comparison of effluent loading rates between mesocosm and the full scale systems that were receiving effluent 331
Table 7.12 Total ET_{willow} (mm) for period May - September 332
Table 7.13 Mean daily ET_{willow} (mm/day) for period May to September 333
Table 8.1 Effluent loading rate at different sites. 338
Table 8.2 Comparison of the mean daily ET_{willow} (mm/day) in 2010 339
Table 8.3 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2010) 340
Table 8.4 Comparison of the mean daily ET_{willow} (mm/day) in 2011 341
Table 8.5 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2011) 341
Table 8.6 Comparison of the mean daily ET_{willow} (mm/day) in 2012 342
Table 8.7 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2012) 343
Table 8.8 Comparison of the mean daily ET_{willow} (mm/day) in 2013 344
Table 8.9 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2013) 345
Table 8.10 Results from Mann-Whitney U test to assess if there was a significant difference between ET_{willow} for the different growing seasons 350
Table 8.11 Proportion of rainfall and wastewater on Site A and Site B (April - October) 351
Table 8.12 Comparison of daily ET_{willow} between systems on Site F 353
Table 8.13 Results from Mann-Whitney U test to assess if there was a significant difference between the wind speeds inside and outside the willow system on Site C 354
Table 8.14 Model Summary for ET_{willow} on Site C (18^{th} June - 30^{th} August 2013) with predictor variables of rainfall (mm), ET_o, and water level within the system (m) 363

Table 8.15 Model Summary for ET_{willow} on Site C (2012) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s) 364
Table 8.16 Model Summary for ET_{willow} on Site A (14th May - 6th July 2013) with predictor variables of rainfall (mm), ET_o, and water level within the system (m) 365
Table 8.17 Model Summary for ET_{willow} on Site A (14th May - 6th July 2013) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s) 366
Table 8.18 Model Summary for ET_{willow} on Site B (16th April - 24th May 2011) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s) 367
Table 8.19 Model Summary for ET_{willow} on Site B (10th May - 9th June 2013) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s) 369
Table 8.20 Comparison of daily ET_{willow} between the System 1 and System 2 on Site H 370
Table 8.21 One way ANOVA test results for daily ET_{willow} between the System 1 and System 2 on Site I 371
Table 8.22 Results from Mann-Whitney U test to assess if there was a significant difference in ET_{willow} between different sites for the 2011/2012 dormant season 372
Table 9.1 Mean Monthly K_c rates assumed for each month for use in the design model 382
Table 9.2 Willow system parameters used for water profile model 383
Table 9.3 Mean number of days with overflow for different surface areas (across depths ranging from 1.5 - 2.2 m) 386
Table 9.4 Matrix showing the amount of overflow days from the willow system for different area and depth combinations 387
Table 9.5 Matrix showing the effect of varying the area on the amount of overflow generated by four different dwelling sizes 390
Table 9.6 Optimum area for loading from a dwelling with 5PE, 6PE, 8PE, and 10 PE 390
Table 9.7 Effect of varying the depth of free space above the surface of the willow system for three different system depths 391
Table 9.8 Matrix showing the amount of overflow days from the willow system for different reduced rainfall and depth combinations 392
Table 9.9 Design parameters for willow system determined from optimisation 393
Table 9.10 Willow system design dimensions for different PE loading 394

Table 9.11 Effect of an increased effluent loading rate on overflow from the system and the increased area required to negate this effect. 398
Table 9.12 Impermeable membranes and their key properties 399
Table 9.13 Area of liner required for different aspect ratios 400
Table 10.1 Difference between ET_o and ET_{willow} for different sites (mm) 409

Abbreviations

BOD	Biochemical Oxygen Demand
BOD_5	Five-day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
ET_{willow}	Evapotranspiration from the willow system
ET_o	Reference Evapotranspiration
Inorganic-N	Inorganic Nitrogen
K_c	Crop Coefficient
NH_4-N	Ammonium
NO_2-N	Nitrite
NO_3-N	Nitrate
PE	Person Equivalent
Std. Dev.	Standard Deviation
SS	Suspended Solids
TC	Total Coliforms
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TSS	Total Suspended Solids
WS	Willow System

Nomenclature

ET_{willow}	Willow System Evapotranspiration
SE	Secondary Treated Effluent
STE	Septic Tank Effluent

Chapter 1

Introduction

1 Introduction

1.1 Background

On-site treatment and disposal of domestic wastewater is the method of effluent treatment for approximately 400,000 dwellings in Ireland (CSO, 2012). With such a high proportion of households unconnected to a centralised sewerage network, on-site sewage discharge is thought to be a significant contributor to water pollution, particularly to surface water in low permeability soils and subsoils. Given that surface water provides over 80% of all drinking water supplies in Ireland (EPA, 2012a), there is a significant risk to public health posed by such systems in areas with such low permeability soils which are not able to infiltrate the hydraulic and/or organic loading from on-site effluent discharge.

The conventional septic tank treatment process generally involves domestic wastewater flowing into a two-chambered tank in which primary sedimentation takes place along with some anaerobic digestion. The effluent from the tank is then distributed to a soil treatment unit (percolation area) where further physical, chemical and biological treatment processes occur prior to groundwater discharge. The role of the percolation area and its subsoil characteristics is critical in providing a sufficient contaminant attenuation zone and ensuring long-term protection from groundwater pollution.

Low permeability, clayey subsoils do not provide the level of protection required. The lack of sufficiently large pore spaces to allow the necessary unsaturated flow of water within clay subsoil results in low effluent percolation rates. Where such clayey soils occur, saturation of the subsoil due to effluent and rainfall can result in ponding of effluent at the surface which poses a risk to surface water around the site.

Despite the many options of domestic wastewater disposal available on the market in Ireland at the moment, there are still no sustainable treatment methods that can be applied on a site with low permeability subsoil. As a result of this, local authorities and environmental regulators are coming under increasing pressure to come up with a solution to the problem at hand.

1.2 Scope of Research

1.2.1 Aims and Objectives

The project was carried out in response to the current problem Wexford Local Authority has with existing (and potentially new) dwellings discharging on-site wastewater to low permeability subsoils. The new Code of Practice for one-off housing (EPA, 2009a) introduced a minimum field saturated hydraulic conductivity of T=90 ($k_{fs} \approx 0.05$ m/day), below which the discharge of on-site effluent to ground is not permitted. Since this legislation came into being, the local authority is under pressure to remedy existing sites which are in violation of the new guidelines and to provide a solution for new sites in which there exists low permeability subsoils. The problem is not confined to Wexford, with other local authorities in counties such as Leitrim, Limerick and Donegal also in the same predicament.

Willow evapotranspiration systems were seen as possible solution to this problem as they are renowned in Denmark (the country in which the systems were first trialled) for having zero discharge. This would overcome the problem of having discharge that arises from using all current on-site wastewater treatment systems. While there are Danish design guidelines in place (Miljøstyrelsen, 2003), they are not designed to be specifically used in low permeability subsoils and assume a usable void space of >40% in the subsoil. Also, Ireland has much higher rainfall levels and lower evapotranspiration rates compared to Denmark, so using the Danish guidelines in an Irish context would not be appropriate.

As such, the aim of this research project was to conduct a series of rigorous, long term on-site trials in order to assess the evapotranspiration and nutrient removal performance of willow systems constructed in low permeability subsoil in an Irish climate, with a view to producing design and construction guidelines for Wexford Local Authority. Also, as part of the research the effect of different effluent treatments and different willow clones on evapotranspiration was to be examined in a small scale experiment.

The full scale trials were specifically designed with the following objectives:

a) To design and construct a number of full scale willow systems in low permeability subsoil conditions in Co. Wexford, so as to assess the effect of the following parameters on evapotranspiration:
    - Area
    - Aspect ratio
    - Effect of effluent
    - Variety of willow clone
    - Subsoil permeability
    - Meteorological conditions

b) To monitor the systems from a practical point of view, in terms of willow tree establishment and development.

c) To monitor water levels within the systems in order to produce a water balance that could be used to determine the evapotranspiration performance of the systems.

d) To determine the different factors that influence evapotranspiration from the field data.

e) To gain insight into the optimum construction and maintenance of the systems for typical rural houses.

f) To establish a mesocosm experiment to determine the effect of the following factors on evapotranspiration:
    - Type of effluent
    - Variety of willow clone

g) To use the field data to derive a numerical model from which the optimum design for the systems can be ascertained and which will then be recommended in the guidelines.

1.2.2 *Methodology and Work Programme*

To fulfil the objectives set out in Section 1.2.1, willow treatment systems were initially constructed on eight different sites throughout Co. Wexford. Two further sites in Co. Leitrim

and Co. Limerick were added at a later stage in the project. The sites were chosen using guidance from the local authority and were all sites that had failed the falling head percolation test (T-test) as part of the planning application due to low permeability subsoil on the site. The trials were designed to be of a minimum of two years duration to capture seasonal meteorological variations and also to allow the willow trees develop.

A summary of the project, as was carried out, is presented below:

Ten Sites:

- 7 sites with one willow system, 3 sites with two willow systems in parallel (which were used in order to compare parameters under the same meteorological conditions).
- Willow systems receiving STE on seven different sites.
- Willow systems receiving SE on three sites.
- Effluent flow to the systems on three of the sites was compromised to some degree, as highlighted in Figure 1.1.

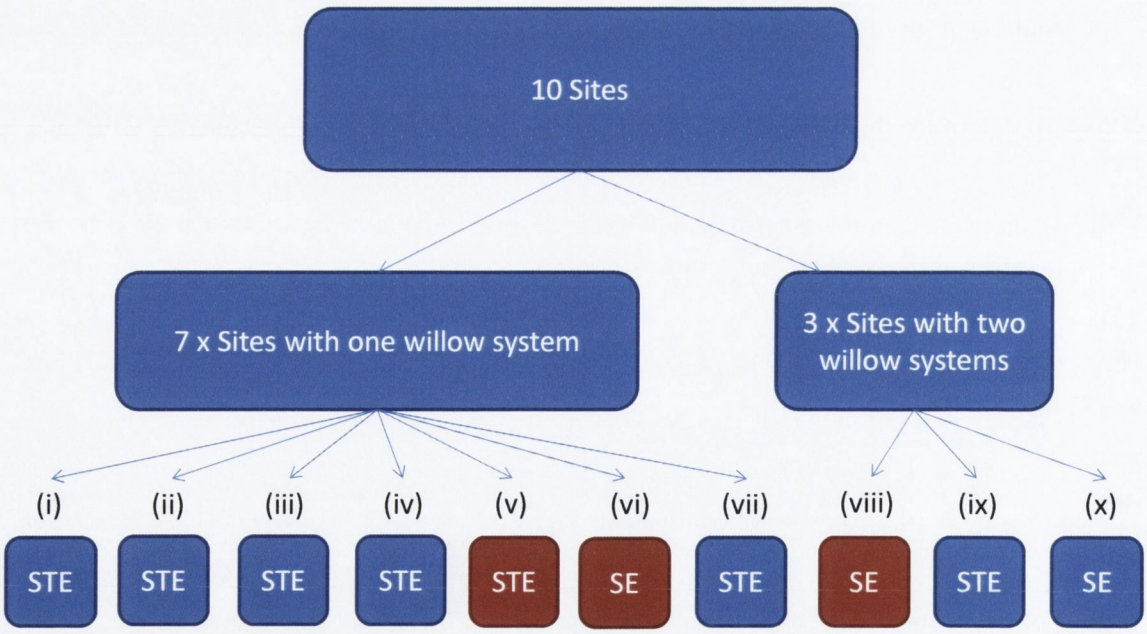


Figure 1.1 Layout of sites and willow systems (red indicates effluent flow to the willow system was compromised)

1.3 Thesis Outline

Chapter 2 contains an extensive literature review focussing on three key areas of the research: (i) an overview of on-site effluent production and current standard on-site wastewater treatment practices and the level of treatment required with respect to subsoil permeability; (ii) low permeability subsoils in Ireland and the bearing they have on water pollution; (iii) the performance of willow in terms of evapotranspiration and nutrient removal, an assessment of the Danish design characteristics for zero-discharge willow systems, and the development and maintenance of willow trees.

Chapter 3 describes the site selection, willow system design process, construction and instrumentation processes as well as sampling and analysis methodologies. Chapter 4 presents the meteorological data, effluent loading rates and soil porosity for each site. Chapter 5 is the primary results chapter and presents the evapotranspiration results and crop coefficients for all of the monitored systems. Chapter 6 presents analysis of the chemical and bacteriological results from the willow systems that were receiving effluent and draws a comparison between them and the systems which were not receiving effluent. Chapter 7 presents the methodology and results for a mesocosm experiment which was conducted as part of the research. The aim of the experiment was to assess the impact three different effluent treatment types had on the evapotranspiration rate of four different willow clones.

In Chapter 8, the evapotranspiration results are analysed and discussed. The effect that factors such as effluent loading, aspect ratio, willow clone variety and soil porosity have on evapotranspiration are assessed. Chapter 9 details the design of a model which determines the required dimensions and specifications for a willow system for different PEs in Co. Wexford.

Finally, Chapter 10 details the conclusions drawn from the research and recommendations for future research.

Chapter 2

Literature Review

2 Literature Review

2.1 Introduction & Background

Over 40% of Ireland's population live outside of urban areas making the country one of the most ruralised in Europe (CSO, 2012). As a result, most of these dwellings are not connected to a public sewer system, and hence require some form of on-site wastewater treatment before disposal to surface water or (more commonly) to groundwater. At present, almost all Local Authorities do not grant discharge consents (required for disposal to surface water) for single house developments due to the burden of monitoring required once such consents are in operation. On-site treatment usually consists of a septic tank, which provides limited anaerobic treatment (Canter and Knox, 1985, Beal et al., 2005) or a secondary aerobic treatment package plant, which then discharge effluent to the subsoil via a percolation area. Under favourable conditions the remaining pollutants in the effluent (BOD, nutrients, pathogens and total suspended solids) should be treated to the required standard in the unsaturated subsoil below the percolation trench (Canter and Knox, 1985). However, in many regions of Ireland the subsoil is of very low permeability (normally due to heavy clay soils) which would not be able to percolate the typical on-site hydraulic loads and so an alternative form of treatment and disposal is required. Such conditions are particularly endemic to Co. Leitrim and Co. Wexford, with a preliminary subsoils map of Ireland (GSI, 2012) highlighting that the counties have approximately 75-80% and 30-40% of their respective areas unsuitable for discharge to ground. Overall it is estimated that approximately 40% of the country has inadequate percolation (either all year round or intermittently during wet weather conditions) due to low permeability subsoils, high water tables and/or low permeability bedrock (EPA, 2012b)

In addition, a new Code of Practice for on-site wastewater treatment in Ireland (EPA, 2009a) has introduced a minimum field saturated hydraulic conductivity of T=90 (equivalent to $k_{fs} \approx 0.47$ m/day), below which the discharge of on-site effluent to ground is not permitted. The field saturated hydraulic conductivity of the subsoil in Ireland is determined by carrying out falling head percolation tests (so-called *T-tests*) on site at the depth of the proposed percolation pipes (Mulqueen and Rodgers, 2001) which result in a T-value (see Section 2.2.6).

County Wexford, which is located in the south east of Ireland, is one such region which has considerable deposits of clay ("marl") subsoils - the Macamore marls from lacustrine clays. In the last decade, during the construction boom, the local authority in Co. Wexford granted

planning permission for single houses, for which on-site treatment consisted of a septic tank and percolation area often located in such subsoil which was not able to take the hydraulic and/or organic loading from the on-site effluent, eventually resulting in discharge of untreated effluent to nearby surface water. However, subsequently many of the streams and rivers throughout the county have been suffering from poor water quality - for example the Environmental Quality Standard (EQS) for phosphorus in rivers in Ireland is set at only 0.035 mg/l (EPA, 2009b) - with on-site effluent considered to be the major contributor to this problem. To address this, Wexford County Council has implemented a series of full-scale trials using zero discharge willow systems to treat and dispose of the effluent - the subject of this research. Due to its relatively high transpiration rate (Hall et al., 1998, Pauliukonis and Schneider, 2001) willow is seen as the obvious crop of choice for wastewater phytoremediation (Rosenqvist et al., 1997, Hasselgren, 1998). Willow has also been shown to be resilient to high polluting substances (Bialowiec et al., 2007, Bialowiec and Randerson, 2010) and so has the necessary rigorousness to cope with the wide ranging pollutants to be found in wastewater.

This Literature Review begins with an outline of the conventional septic tank treatment system including design and treatment performance specifications of each. The importance of suitable subsoil is highlighted, with an outline of the BS5930 classification scheme and a summary of Irish subsoils, with a focus on clayey soils and the problems that arise with such subsoils in terms of on-site treatment.

2.2 On-site Treatment

The standard arrangement for on-site treatment of domestic wastewater is a conventional septic tank system (within which primary treatment is carried out) followed by discharge of the septic tank effluent (STE) to a subsurface disposal field, which, is commonly referred to as a percolation area in Ireland (Figure 2.1) or leach field / drain field elsewhere. The preferred international terminology, however, is Soil Treatment Unit (STU). At this stage of treatment the effluent infiltrates and permeates down through the vadose zone of the percolation area, undergoing physical, chemical and biological processes in the subsoil before entering the groundwater.

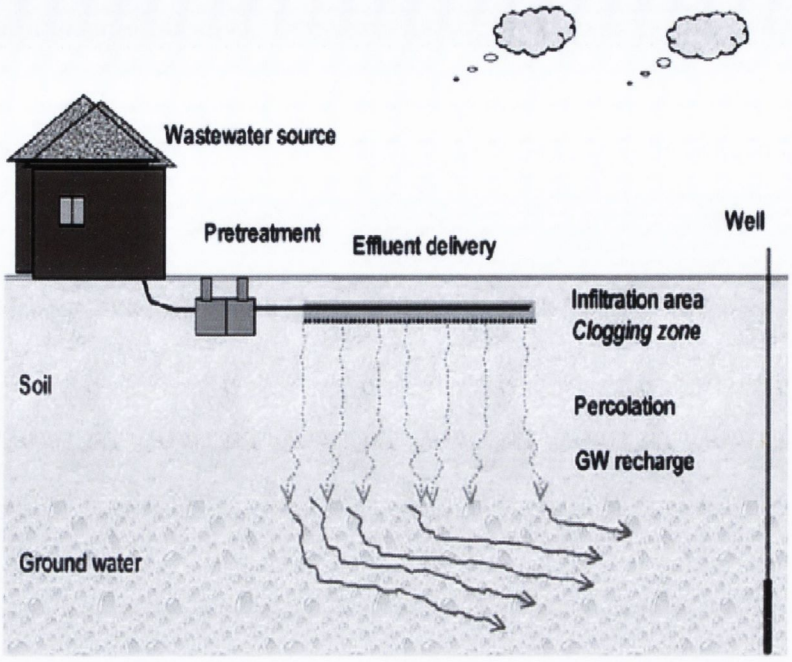


Figure 2.1 Conventional septic tank treatment system including percolation area with pathway for potential contaminant migration to groundwater (adapted from Van Cuyk et al., 2001)

Raw sewage from household comprises of grey water (laundry, bath and kitchen sink) and black water (toilets) and it normally reaches the septic tank via gravity flow from the dwelling. Canter and Knox (1985) report that on average, black water contributes approximately 30% of the Biochemical Oxygen Demand (BOD), 50% of the Suspended Solids (SS), 70% of the Total Kjeldahl Nitrogen (TKN), 17% of the Total Phosphorus (TP) and 30% of the flow from a household. The estimated biological and chemical characteristics of domestic wastewater in Ireland are shown in Table 2.1. In the past, there have been concerns regarding the high concentrations of detergents and inorganic salts in grey water and the damaging effect it might have on bacteria and hence treatment in the tank. However, Grant and Moodie (1995) reported that average concentrations of detergents and inorganic salts from a typical domestic dwelling will not detrimentally affect the functioning of the septic tank. Therefore, it is recommended that all wastes from the household be piped to the septic tank, although it is imperative that water runoff (i.e. rain from roofs, footpaths, driveways) be diverted away from the septic tank to avoid dilution of the wastewater and hydraulic overloading of the system.

Table 2.1 Range of raw domestic wastewater influent characteristics (adapted from (EPA, 2009a)

Parameters	Typical Concentration (mg/l unless otherwise stated)
Chemical Oxygen Demand (COD) (as O_2)	300-1000
Biochemical Oxygen Demand (BOD_5) (as O_2)	150-500
Suspended Solids	200-700
Ammonia (as NH_4-N)	22-80
Total Phosphorus (as P)	5-20
Total Coliforms (MPN/100ml)*	10^6-10^9

*MPN, Most Probable Number

2.2.1 *Wastewater Production*

As hydraulic loading is a critical factor in the design and functioning of a willow system, it is important that an accurate assessment of the expected wastewater production rates at a rural dwelling be drawn up.

Currently, the Code of Practice in Ireland (EPA, 2009a) assumes a mean effluent production per person of 150 litres per capita per day (L/c/day), which should be used when calculating the design load for on-site wastewater treatment systems. This value, which was lowered from 180 L/c/day in the previous Code of Practice (EPA, 2000), is supported by the per capita consumption (PCC) of 147 L/c/day that was obtained from water demand analysis for domestic users in the greater Dublin area (WSP, 2010). However, there is evidence which suggests that the PCC is considerably lower than this for rural dwellings.

A study of 74 households across Ireland, which were served by group water schemes, over a 13 month period (January 2010 - February 2011) revealed an average household consumption of 335 L/day, with a decrease in PCC with increasing household occupancy. During a 4 year study, which focussed on on-site wastewater treatment in Ireland, Gill et al. (2009b) measured the average wastewater flows from 4 different dwellings (4-5 occupants) to be 120 L/c/day. Following further research in this study, which involved monitoring three additional sites, Gill et al. (2009a) measured an average wastewater production rate of 110 L/c/day for the respective dwellings.

2.2.1.1 *Water Saving Technology*

Reduction of wastewater production and hence hydraulic loading on a willow system can be made by the installation of water saving devices in the dwelling. Such devices include low

flush-toilets, low-flow shower heads and low-flow taps as well as water efficient washing machines and dishwashers.

A summary of the potential water savings for different toilet systems compared to a 9 litre single flush toilet is presented in Table 2.2. Nine litres was estimated to be the average volume of water per flush in an Irish and UK context (Liu et al., 2010, WSP, 2010). It can be seen that some of the better performing ones can effect a significant reduction in the amount of effluent being produced in a dwelling. This would almost certainly have benefits in terms of reducing the size of the willow system required, which would also reduce the cost.

Table 2.2 Potential water savings for different toilet systems compared to a reference 9 litre single flush toilet (modified from Dubber and Gill, 2013)

Type of Toilet	Flush Volume (L)	Water Saving (LCD)	Reduction in PCC[1] (%)
Single flush	6	14	9.3%
High efficiency flush	4.8	19.6	13.1%
Dual flush[2]	3/6	24.5	16.3%
Urine diverting dual flush[2]	0.6/4	35.2	23.5%
Vacuum	1	37.3	24.9%
Urine diverting vacuum[2]	0.2/1	40.1	26.8%

[1] Based on average daily per capita consumption (PCC) of 150 L/c/day

[2] Assuming 3 out of 4 flushes (75% of all flushes) are small flushes

The installation of low-flow shower heads has been shown to reduce water use by up to 18 L/c/day, which results in a 11% reduction in PCC (Dubber and Gill, 2013). Furthermore, by using tap aerators, a reduction of between 4% - 10% in PCC can be achieved.

2.2.2 *Septic Tank Design and Operation*

The septic tank is a prefabricated tank usually made from concrete or fibreglass that serves as a combined settling and skimming tank and as an unheated-unmixed anaerobic digester for wastewater (Metcalf and Eddy, 1991). In order to maximise performance of the septic tank, correct sizing is critical. Consequently, tanks are normally sized based on the design flow with one-third of the tank volume providing a 24 hour hydraulic retention time with the other two-thirds set aside for scum and sludge accumulation. This effectively yields a total tank volume equal to three times the daily flow volume (Baumann et al., 1978 cited in Siegrist et al., 2000). Current guidelines (EPA, 2009a) state that the septic tank must be of sufficient volume to provide a hydraulic retention time of at least 24 hours at maximum sludge depth and scum

accumulation to facilitate BOD and solids removal from the wastewater. The degree of sludge accumulation is dependent on the number of occupants in the household, and consequently (British Standards Institute, 1983) and (EPA, 2009a) recommend that the tank capacity be calculated using the following equation:

$$C = 150P + 2000 \qquad \text{Eqn. 2.1}$$

Where, C = capacity of the tank (litres)

P = design population

This equation assumes that the tank is desludged at least once every 12 months. In Ireland a minimum capacity of 2600 litres should be provided (EPA, 2009a), which corresponds to a design for a minimum population of 4 people.

Two-chamber septic tanks (Figure 2.2) are now the legislative standard (EPA, 2009a) in Ireland as they are superior to single-chamber tanks of the same size producing effluent with up to 50% less suspended solids and BOD (Laak, 1980). The main benefit is due mainly to hydraulic isolation to prevent short-circuiting, and to the reduction or elimination of inter-chamber mixing (Canter and Knox, 1985).

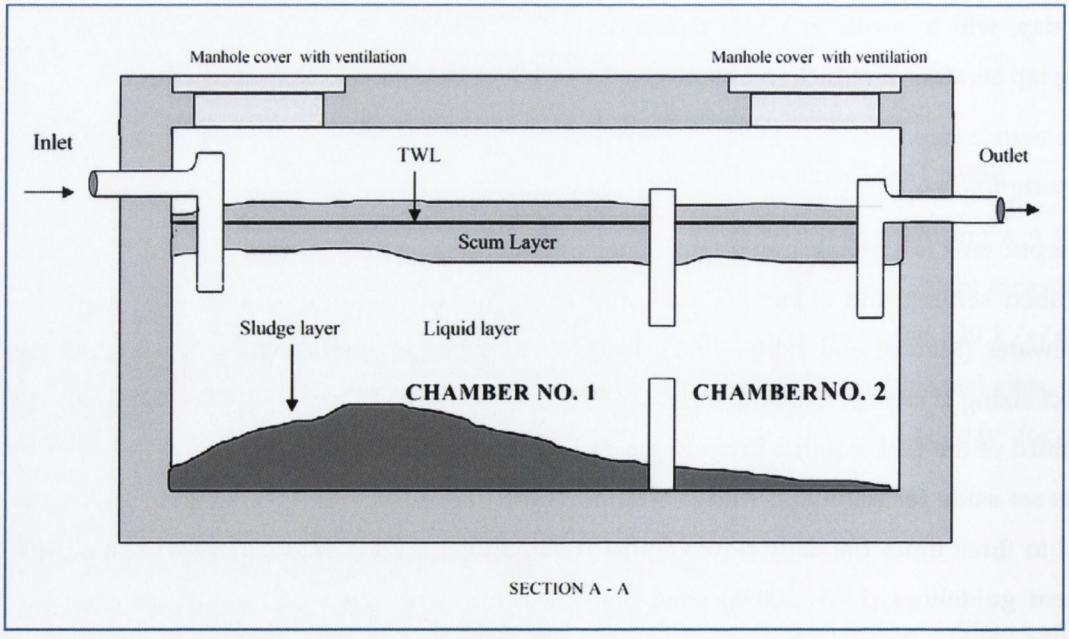


Figure 2.2 Longitudinal section of typical two-chamber septic tank (EPA, 2000)

Successful operation of the septic tank is based around maintaining stagnant conditions that allow for settlement of solids and aid the development of anaerobic conditions for treatment of both stored solids (sludge) and non-settleable components in domestic wastewater. The sludge is partially digested by anaerobic micro-organisms with the liberation of gases, primarily carbon dioxide (CO_2) and methane (CH_4). Aided by these gases, a scum layer, consisting of greases, oils and gas-buoyed solids, forms above the liquid layer and provides an indicator that the tank is operating properly (Daly et al., 1993). The scum layer is beneficial in a number of ways; it maintains anaerobic conditions within the tank by preventing the transfer of oxygen at the air/liquid layer interface and it also helps prevent heat loss from the tank. Septic tanks provide a consistent effluent that can be readily treated further but do not, as is commonly perceived, treat domestic wastewater to standard that requires no further treatment.

2.2.3 *Septic Tank Treatment Performance*

A properly constructed and maintained tank reduces BOD by approximately 15-30% and retains between 50-70% of the solids. Canter and Knox (1985) cite research carried out by Viraraghavan (1976) which found reduction rates of about 50% for BOD and Chemical Oxygen Demand (COD) and less than 25% removal rates for total suspended solids. Meanwhile, (Lawrence, 1973) reported less than a 15% reduction in BOD and a 34-35% reduction of suspended solids. Various other investigations (Patterson et al., 1971, Goldstein and Wenk, 1972, TCC et al., 1998) report 80 mg/l solids in septic tank effluent as typical. The concentration of 155 mg/l solids reported by Gill et al. (2009a) for an Irish dwelling is considerably higher than this.

The anaerobic environment within the septic tank is largely ineffective in reducing the nutrient loading of the wastewater. Nitrogen in the influent is largely in the form of organic nitrogen (org-N) and ammonia (NH_4), which together make up the total Kjeldahl nitrogen (TKN). Under anaerobic conditions, much of this org-N is converted to readily oxidisable ammonium ions (NH_4^+). A typical wastewater influent TKN concentration is 38 mg/l [32% NH_4 : 68% org-N] whilst average effluent TKN concentrations are recorded at similar levels of about 40 mg/l [75% NH_4 : 25% org-N] (Bauer et al., 1981). However, the TKN concentration of 106 mg/l [approximately 70% NH_4 : 30% org-N] reported by Gill et al. (2009a) for an Irish dwelling is considerably higher than these values. So, while the conversion of org-N to NH_4 is promoted in the septic tank environment, the overall removal of total nitrogen (TN) is largely non-existent. Nitrate (NO_3) concentrations are very low (close to zero) in septic tanks, due to the lack if aerobic conditions.

Most of the influent phosphorus is also converted in the anaerobic digestion process, from organic and condensed phosphate (polyphosphate) to soluble orthophosphate (PO_4^{3-}) which passes out in the effluent. Wilhelm et al. (1994a) reported that approximately 76% of the total phosphorus (TP) in the septic tank effluent (STE) was in its PO_4^{3-} form. Canter and Knox (1985) cite research carried out by (Bouma, 1979) which found an average TP concentration of 15 mg/l in the STE of which 85% is in PO_4^{3-} form. Research carried out by Salvato (1992) resulted in a similar concentration of 15 mg/l PO_4^{3-} being found. Research carried out in Ireland found total phosphorus concentrations of 16 mg/l (Keenan, 1983) and orthophosphate concentrations of 29 mg/l and 50 mg/l (Henry, 1990). In two separate reports, Gill et al. (2005) and Gill et al. (2009a) recorded average concentrations of 7.4 mg/l, 7.9 mg/l, 16.6 mg/l and 32.3 mg/l total phosphorus respectively for four different Irish dwellings. Even though septic tank influent in Ireland may be generally more concentrated compared to North America (Gray, 1995), the processes involved in the septic tank are the same and so it would be reasonable to expect similar behaviour of the nutrients under Irish conditions.

From this evidence it is apparent that typical STE contains a high pollutant potential and as a result it requires further treatment before discharge to ground/surface water. There are a number of options available to further treat the effluent once it leaves the septic tank, as outlined below:

- Soil infiltration (percolation) system.
- Secondary Treatment:
    - Pre-treated effluent filtration system, followed by tertiary treatment and/or discharge to subsoil.
    - Prefabricated treatment unit, followed by tertiary treatment and/or discharge to subsoil.

(EPA, 2009a)

2.2.4 *Soil Treatment Unit (Percolation Area)*

Upon leaving the septic tank, the effluent is piped to a distribution box where it should be evenly split, so as to ensure each percolation trench receives equal amounts of effluent. The soil infiltration system is the most important treatment component in a septic tank system, as it is here that the majority of biological, chemical and physical treatment is carried out. Studies have shown (Gill et al., 2007) that greater than 90% removal efficiencies can be achieved for organic constituents (BOD, COD and SS) in suitable subsoils. However, nutrient (N and P) removal is

more limited and variable (USEPA, 1980a, Jenssen and Siegrist, 1990, Van Cuyk et al., 2001, Gill et al., 2009c). Pathogen removal efficiencies can be high, yielding near complete removal of faecal coliform bacteria and greater than 4 log (99.99%) reduction in viruses (Emerick et al., 1997, (cited in Siegrist et al., 2000), Stevik et al., 1999, Van Cuyk et al., 2001, O'Luanaigh et al., 2012)

A cross-section of the typical trench system implemented in Ireland is shown in Figure 2.3. Trenches are shallow, level excavations usually about 850 mm deep and 500 mm wide. The bottom is filled with 8-32 mm washed gravel to a depth of 300 mm, upon which the percolation pipe, maximum length 18 m per trench, is laid at a 1 in 200 slope. The pipe is then surrounded and covered by a depth of 150 mm of gravel, on top of which a geotextile membrane is laid, to prevent the topsoil backfill clogging the aggregate. The porous medium is used to:

- maintain the structure of the trench;
- provide partial treatment of the effluent by facilitating biomat formation;
- distribute the effluent to the infiltrative soil surfaces and
- provide temporary storage capacity during peak flows.

(Kreissel, 1982)

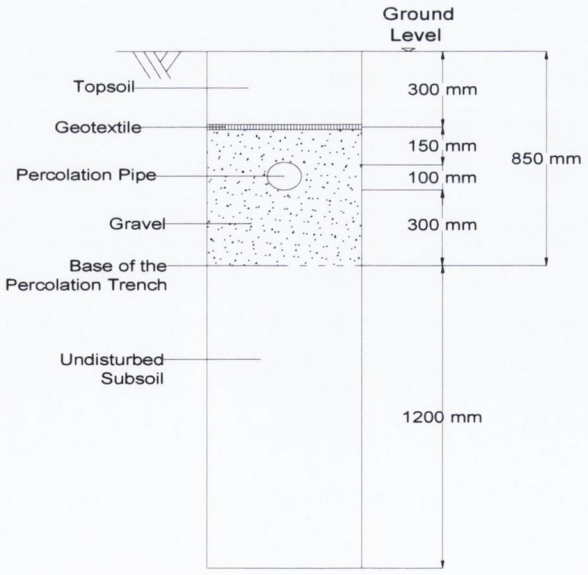


Figure 2.3 Cross-section of a percolation trench (modified from EPA, 2009a)

Research by (Laak et al., 1974, Beal et al., 2005, Beal et al., 2008) Cotteral and Norris (1969) identified subsoil properties, biomat formation and loading rate as the most important factors affecting the performance of a soil absorption system. Subsoil properties will be examined in more detail in Section 2.3.

The biogeochemical mechanisms for treatment and hydraulic performance of a percolation system are complex, especially in an Irish context given the heterogeneity of the soils and aquifers. These mechanisms have been shown to be highly influenced by the biomat layer which forms at the soil-gravel interface along the base and wetted sides of the trench, and in numerous examples it is the hydraulic conductivity of the biomat, and not the subsoil that becomes the dominant variable in wastewater infiltration rates (Mcgauhey et al., 1964, (cited by Wilhelm et al., 1994b), Converse and Tyler, 1994). The biomat zone is formed in three distinct phases:

- Physical: where solids in the effluent physically clog the soil pores;
- Chemical: where soil colloids swell as a result of the chemical processes;
- Biological: where bacteria or bacterial breakdown products reduce pore size.

(Patterson et al., 1971)

Reduced percolation rates through the biomat due to clogging can cause the effluent to pond above the biomat, leaving unsaturated conditions below, allowing for aerobic treatment of the percolating effluent (Bouma, 1975, Siegrist and Boyle, 1987, Beal et al., 2008). Biomat development is closely correlated to the organic loading rate; hence, the provision of secondary treatment before the percolation area reduces the rate and extent of biomat formation, resulting in poorer breakdown of pathogens and other constituents. Conversely, if soil clogging is excessive, for example due to application of high-strength effluents, it can cause hydraulic dysfunction, anaerobic soil conditions and reduced treatment (Van Cuyk et al., 2001).

2.2.5 *Secondary and Tertiary Treatment*

If a site has been deemed unsuitable for the use of a conventional septic tank treatment system, the installation of a secondary treatment system can be considered as a means to create a suitable solution. These systems may be constructed on-site (soil filter system, sand filter system, mounded intermittent filter systems, reed beds) or prefabricated (for example, biological aerated filter [BAF] system, rotating biological contactor [RBC] system, sequencing

batch reactor [SBR] system, membrane bioreactor [MBR] system). These systems are always succeeded by a polishing filter (tertiary treatment) which in many cases is a soil treatment unit, and where used as an alternative to septic tank systems, should be (except for membrane filtration systems) preceded by a primary settlement tank (EPA, 2009a). Many of these systems have primary settlement tanks incorporated into them, negating the need for a separate septic tank. The primary settlement tank provides for the separation and retention of settleable solids and floatable materials, reduces the size of the subsequent biological treatment stage by up to 50%, reduces oxygen demand and thus the power requirement in mechanical aeration systems, and buffers against shock loads (Metcalf and Eddy, 1991). The primary purpose of a tertiary treatment is to reduce the concentration of micro-organisms in the treated wastewater prior to disposal (EPA, 2009a). Tertiary treatment is often achieved by discharge of the secondary treated effluent into the unsaturated subsoil but in areas where subsoils cannot take even secondary treated effluent, tertiary treatment can come in the form of polishing intermittent sand filters, constructed wetlands or packaged tertiary treatment systems.

2.2.6 *Percolation Tests and Systems Options*

The type of treatment system used on a site is primarily decided by the hydraulic assimilation capacity of the subsoil, which in Ireland is determined by an on-site falling head percolation test. The percolation test comprises the measurement of the length of time for the water level to fall a standard distance in the percolation test hole. There are two variants of the percolation test:

- T-test: tests suitability of subsoil at depths greater than 400 mm below ground level.
- P-test: This is carried out at ground level, where there are limiting factors, such as high water table or shallow bedrock or where the T-test result is outside of the acceptable range (>50 for STE; >75 for secondary treated effluent) but less than 90.

(EPA, 2009a)

The different treatment system options available for the range of percolation test results are shown in Table 2.3. In situations where the T-test is in excess of 90 then, irrespective of the P-test result, the site is deemed unsuitable for discharge of treated effluent to groundwater, as it is likely to ultimately result in ponding due to the impervious nature of the underlying subsoil. In such cases, the only options available are discharge of wastewater to surface water (requiring a Water Pollution Act discharge licence, which local authorities are reluctant to grant) or installation of a zero discharge system.

Table 2.3 Interpretation of percolation test results (modified from EPA, 2009a)

Percolation test result	Interpretation
T > 90	Site unsuitable for any on-site treatment system discharging to ground. Site may be deemed suitable for discharge to surface water.[1]
T < 3	Percolation rate is too fast to provide adequate treatment. Site is unsuitable for secondary treatment systems. However, the site is suitable to assimilate effluent treated to tertiary quality. P-test should be undertaken to determine if the site is suitable for secondary system with a polishing filter at ground surface or over ground.
3 ≤ T ≤ 50	Site suitable for septic tank system or a secondary treatment system discharging to groundwater.
50 < T 75	Not suitable for septic tank system. May be suitable for secondary system with a polishing filter at the depth of the T-test hole.
75 ≤ T ≤ 90	Not suitable for septic tank system. Not suitable for polishing filter at depth of T-test hole. P-test should be undertaken to determine if the site is suitable for a secondary treatment system with polishing filter, i.e. 3 ≤ P ≤ 75 at ground surface or over ground.
P < 3	Retention time in subsoil insufficient to provide satisfactory treatment. However, if effluent undergoes tertiary treatment then the site will be suitable to assimilate the hydraulic load. Imported suitable material may be deemed acceptable as part of site works.
3 ≤ P ≤ 75	Site is unsuitable for a secondary treatment system with polishing filter at ground surface or overground.

[1]Most local authorities do not grant water pollution discharge licences to single dwellings.

2.3 Low Permeability Subsoils

In Ireland, the principal aquifers occur in fractured bedrock and in sand and gravel deposits. In general, little attenuation takes place in the bedrock as flow is almost entirely via fissures. Consequently, the subsoil acts as a filter and protective cap for the underlying aquifer, and therefore is the single most important natural feature influencing groundwater vulnerability and groundwater contamination in Ireland (Department of the Environment and Local Government, 1999, Swartz et al., 2003). Large proportions of Irish subsoils are derived from glacial drift and were deposited during the Quaternary period of glacial history. These subsoils play an important role in the underground part of the hydrological cycle, either as aquifers or in the way they affect water percolating into the underlying rock aquifers.

Subsoil is the pathway which forms the link between the source of pollution and the receptor (e.g. aquifer, water course) in the natural environment. Natural pathways are determined by on-site geology, particularly the nature of the subsoil and underlying aquifer. Artificial pathways include drainage ditches, land drains and stream culverts. The characteristics of a pathway are defined by the degree of attenuation between receptor and source. One of the key factors which influence attenuation, and hence the susceptibility of groundwater to contamination by pollutants, along a subsurface pathway is the thickness and permeability of the subsoil.

It has been shown (Swartz et al., 2003, Meehan and Lee, 2012) that subsoils with a high proportion of clay result in low percolation. This is because of the lack of sufficiently large pore spaces to allow the necessary flow of water within it and also because of the charged particle nature of the clay. Where such clayey soils occur, saturation of the subsoil due to a combination of effluent and rainfall can result in ponding of effluent at the surface. This poses a risk to surface water on the site and in water courses around the site. Pathway treatment processes are also limited in low percolation subsoils, as effluent cannot enter the subsurface environment. The following sections will detail the characteristics of low permeability subsoils and also the methods for assessing their permeability.

2.3.1 Subsoils

There are five main subsoil types in Ireland as shown in Figure 2.4:

- Tills
- Sands and gravels
- Lake deposits
- Alluvium
- Peat

This research project is primarily interested in tills (often referred to as boulder clay), as the majority of low permeability soils comes under this broad category of subsoil type. As illustrated in Figure 2.4, till is the most widespread subsoil across Ireland, covering over 43% of the country area at surface, and up to an additional 25% beneath peat or floodplain sediments (Meehan and Lee, 2012). The majority of tills in Ireland are comprised of Quaternary deposits. They are often tightly packed, unsorted, unbedded, and possessing many different particle and stone sizes which are often angular and subangular. They may be categorised according to

dominant petrographical component, or by the grain size of the matrix, or the texture of the till. This is what determines the permeability of the till. A wide range of permeabilities can occur within different till types.

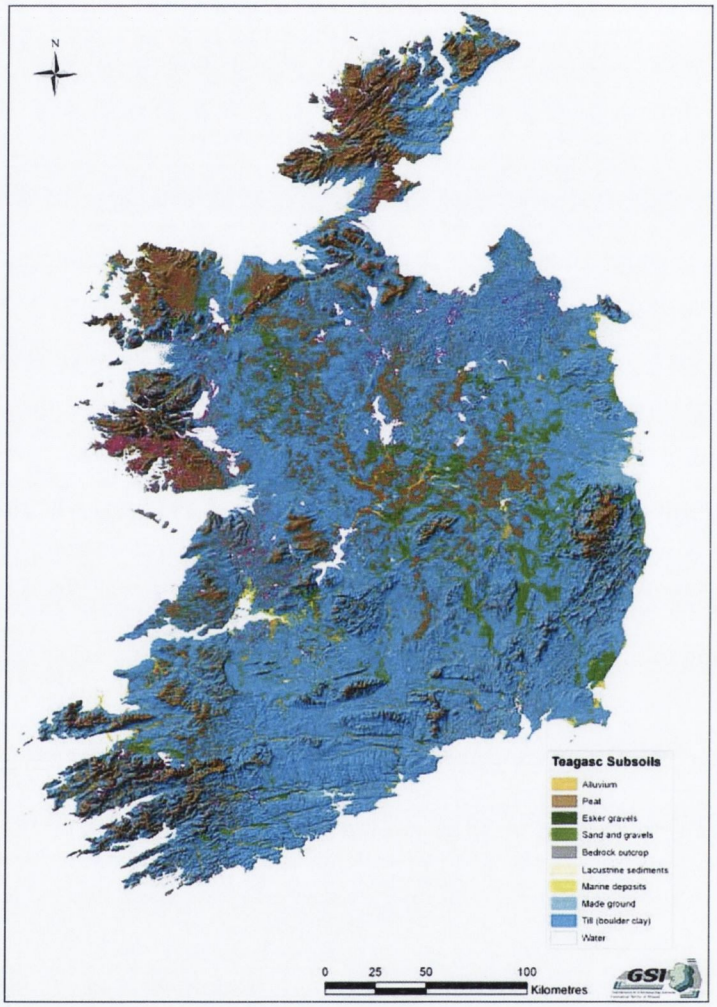


Figure 2.4 Subsoils map showing different subsoils types across Ireland (modified from Meehan and Lee, 2012)

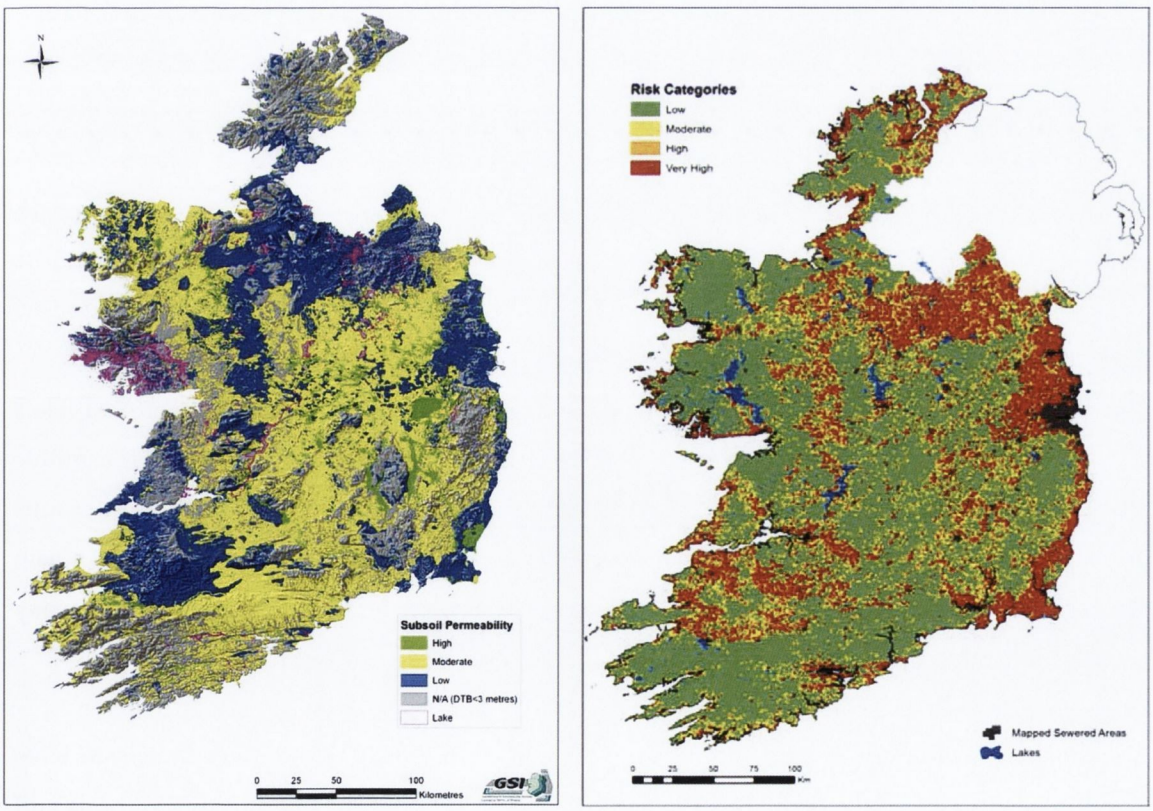
2.3.2 *Subsoil Permeability*

The permeability of subsoil is largely a function of:

- the grain size distribution,
- the amount of clay size particles present,
- the manner in which the grains are packed together.

Subsoil permeability has been mapped across Ireland by the Geological Survey of Ireland as part of the National Groundwater Protection Scheme. The permeabilities mapped are qualitative regional assessments of the subsoil based on how much potential recharge is infiltrating and how quickly potential contaminants can reach groundwater. The provisional map is shown in Figure 2.5 (A) and it can be seen that there is a strong correlation between areas with subsoil of low permeability and the areas shown in Figure 2.5 (B) to have a relatively high risk of water pollution from domestic wastewater treatment systems.

The three characteristics described above detail the engineering behaviour of the material as detailed in the subsoil description and classification method derived from BS 5930: 1999 (Swartz, 1999). This method is used to assess the subsoil permeability at any locality, and is combined with recharge and drainage observations in the surrounding area for a regional, three-dimensional classification. The following sections details with some of the approaches used in assessing the permeability.



(A) (B)

Figure 2.5 (A) Subsoil permeability map of Ireland (adapted from Gsi et al., 2012);
(B) Map of Ireland showing relative risk of water pollution from domestic waste water treatment systems due to inadequate percolation (adapted from EPA, 2012b)

2.3.2.1 *Subsoil Description and Classification Method*

Using this method (which has been derived from BS 5930: 1999), subsoils described as sandy CLAY or CLAY have been shown to have low permeability (Swartz, 1999). Permeability mapping focuses on areas where soil and subsoil thickness are greater than 3 m, since areas with thinner layers of soil/subsoil are automatically considered 'Extremely Vulnerable' with respect to groundwater pollution (EPA, 2012b)

2.3.2.2 *Particle Size Analysis*

The particle size distribution of sediments describes the relationships between the different grain sizes present. Well sorted sediments such as water-lain gravels (high permeability) or lacustrine clays (low permeability) will, on analysis, show a predominance of grain sizes at one end of the scale. Whereas glacial tills have more variability and proportions of different grain sizes are more similar. Despite this, however, studies on grain size analysis for a range of tills in Ireland (Swartz, 1999, O' Súilleabháin, 2000) have shown:

- Samples described as having 'moderate permeability' tend to have less than 12% clay.
- Samples described as having 'low permeability' often have more than 50% fine particles.
- The low permeability samples also tend to have more than 14% clay.
- 'High permeability' sand and gravel subsoils tend to be sorted and have less than 7.5% fines.

2.3.2.3 *Subsoil Parent Material*

The geological composition of the subsoil's parent material (which is often the bedrock) has a very strong influence on the permeability characteristics of the subsoil. Sandstone, for example gives rise to a high proportion of sand size grains in the deposit matrix, which generally results in relatively high permeability. Limestone provides a relatively high proportion of silt, which can result in varied permeability. Shale tills generally have a higher proportion of finer clay particles, resulting in low permeability within the subsoil.

A comparison between Co. Leitrim and Co. Wexford, both which are counties known to have low permeability subsoils, highlights the geological composition of the respective subsoils and how they have a bearing on the respective permeability. The subsoils in Co. Leitrim are comprised mainly of shale, sandstone and limestone, with shale being the most predominant (EPA). Co. Wexford has a slightly broader range of subsoils. It has large areas of shale

dominated subsoil, but also has granite and metamorphic till towards the south east of the county. Many areas on the eastern board of the county have subsoil dominated by estuarine sediments including Irish Sea till, which is characterised by its brown, clay-silt matrix (EPA). The till is highly over-consolidated, very poor draining, which usually results in low permeability conditions.

These three methods are used as part of an overall, integrated approach to get an assessment of a site and hence build up a three-dimensional picture of the regional permeability. The permeability map of Ireland (Figure 2.5A) provides guidance on a regional scale. As a result, it is still important that site investigations take place for specific developments. Hence, the requirement for site specific trial hole assessments and percolation tests as described in Section 2.2.6.

2.4 Willow

As a relatively fast growing species, willow has been grown commercially for biomass production in Sweden since the 1970s. On-going research since then has seen a slight shift in focus from pure biomass production to combining this aspect with phytoremediation and re-use of nutrients from wastewater (Aronsson and Perttu, 2001). So although much of the research has focussed on willow usage as a short rotation crop (SRC), the findings are also of relevance to purpose-built willow wastewater treatment systems. Denmark was the first country to adopt the results from such research and use them in the design of zero discharge willow systems (Gregersen and Brix, 2001). The findings from the initial trial on the systems in that country (as detailed in Section 2.4.4) were positive and eventually resulted in guidelines being produced (Miljøstyrelsen, 2003).

2.4.1 *History of Willows & Overview of Phytoremediation*

Willow belongs to the genus *Salix* and family *Salicaceae*. The word *Salix* comes from the Celtic 'Sal' meaning near and 'lis' meaning water. As its name suggests it has long being regarded as a moisture loving plant, with its riparian tendencies even referenced in the Bible (Old Testament). There are over 450 species of willows, mostly distributed in northern temperate areas (Argus, 1997) and they are primarily in the form of shrubs and small trees. Human use of willow dates back many thousand years, where it was first used in 'wattle and daub' construction of shelter and fencing, basket making and also used for arrow shafts and fish traps.

With its multipurpose advantages, the uses for willow has increased in recent years where it has being used for control of soil erosion, siltation, carbon sequestration, nutrient cycling, biomass production, filtering of sewage and phytoremediation (Verwijst, 2001, Brix and Arias, 2011). This literature review primarily investigates the phytoremediation aspects of willow but will also assess the relative biomass yield of different willow clones, as it has been shown that a strong correlation exists between plant biomass and evapotranspiration rates attained (Martin and Stephens, 2006).

Willow has numerous physiological traits which make it highly suitable for phytoremediation purposes:

- Excellent growth and productivity and a high capacity to convert solar radiation into chemical energy among woody plants under certain climatic conditions (Christersson et al., 1993, Wilkinson, 1999).
- An extensive fibrous root system in many species, with approximately 80% of the fine root hairs found at depths of less than 40 cm and a continuous growth of the fine roots for a large proportion of the growing season (Rytter and Hansson, 1996, Gray and Sotir, 1996, Crow and Houston, 2004).
- It can achieve high rates of evapotranspiration throughout the growing season (Persson and Lindroth, 1994, Lindroth et al., 1995, Ledin, 1998, Guidi et al., 2008).
- Efficient uptake of nutrient compounds (Ericsson, 1981b, Elowson, 1999, Dimitriou and Aronsson, 2011); high filtering capacity for nitrogen and phosphorus (Dimitriou and Aronsson, 2010); ability to facilitate denitrification in the root zone (Aronsson and Perttu, 2001); ability to accumulate high levels of toxic metals, especially cadmium (Klang-Westin and Eriksson, 2003, Dickinson and Pulford, 2005).
- Tolerance of flooded or saturated soils and oxygen shortage in the root zone (Krasny et al., 1988, Aronsson and Perttu, 2001, Jackson and Attwood, 1996, Kuzovkina et al., 2004).
- Ease of vegetative propagation due to preformed root primordial on the stems, and possibility of vegetative reproduction from horizontally lain cuttings (Carlson, 1950, Gray and Sotir, 1996) and vigorous re-establishment from coppiced stumps (Ceulemans et al., 1996, Philippot, 1996).

2.4.2 *Evapotranspiration*

Evapotranspiration is the removal of water from the soil surface to the atmosphere via a combination of evaporation, which is the direct movement of the water from the soil; and transpiration, which describes the movement of water within the plants. ET is expressed in mm per unit time.

Up until 1990, there was no standardised method of calculating reference evapotranspiration. Many of the methods used up until this point were shown to have inaccuracies. The Penman method was found to frequently overestimate ET_o (Allen et al., 1998), while other equations, namely the radiation method, the Blaney-Criddle and pan evaporation methods, showed various degrees of adherence to the reference evapotranspiration. In May of that year, the United Nations Food and Agriculture Organization organised a consultation of experts and researchers to review reference evapotranspiration methods and advise on the use of a standardised method. The panel of experts recommended the use of the Penman-Monteith combination method as the new standard for reference evapotranspiration.

Various other methods show varying degrees of accuracy when compared with the Penman-Monteith method. A formula, developed by Hargreaves (1975), which determines reference evapotranspiration from temperature and global solar radiation has been shown to have a number of short comings by different studies. Amatya et al. (1995) and Trajkovic (2007) reported that for humid regions, the Hargreaves method overestimates reference evapotranspiration compared the Penman-Monteith method. From a study carried out in Spain, Martínez-Cob and Tejero-Juste (2004) reported that the Hargreaves method overestimated reference evapotranspiration rates for sites with low wind speeds. This was backed up by a study carried out by Gavilán et al. (2006) who reported similar findings. Equally, Amatya et al. (1995) reported that the temperature based Thornthwaite formula for calculating reference evapotranspiration under-predicted the annual amount by up to 16%.

2.4.2.1 *Penman-Monteith Reference Evapotranspiration*

Daily reference evapotranspiration (ET_o) is commonly determined with the standardised Penman-Monteith equation (Allen et al., 1998, Allen et al., 2005):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T} + 273\right)u_2(e_s - e)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Eqn. 2.2}$$

Where, R_n = net radiation (MJ/m² /day)

G = soil heat flux density (MJ/m²/day)

Δ = slope of the saturation vapour pressure curve (kPa/K)

γ = psychrometric constant (kPa/K)

T = mean daily air temperature (°C)

u_s = mean daily wind speed at height of 2 m (m/S)

e_s = saturation vapour pressure at mean daily temperature (kPa)

e = mean daily actual vapour pressure (kPa)

The reference evapotranspiration (ET_o) is the evapotranspiration from a hypothetical grass reference crop with an assumed height of 0.12 m and with a readily available water supply. The crop coefficient is a measure of the rate of evapotranspiration achieved by a plant in comparison to the reference evapotranspiration. It is determined by measuring the crop evapotranspiration (ET_c) of crops under standard conditions, disease-free, with optimum soil water conditions and then computing the ratio:

$$K_c = \frac{ET_c}{ET_0} \qquad \text{Eqn. 2.3}$$

When using this approach it is assumed that ET_o accounts for the meteorological effects on ET_c and K_c accounts for plant physiology and management differences between ET_c and ET_o. The factors which can affect the K_c values include differences in plant morphology, plant physiology, the irrigation method used (which can affect the soil moisture distribution), irrigation and rainfall frequency, and dew interception and condensation, which affect canopy resistance (Spano et al., 2009).

The crop coefficient can be a very useful parameter as it allows for easy calculation of the volumes of water (or wastewater) that can be applied to a specific crop which is being used as a treatment system without incurring potential pollutant loss to the environment. Brix and Arias (2011) report an annual crop coefficient of 2.5 for willow, which is the figure used in the design of zero discharge systems in Denmark. However, as shown in a comprehensive study on willow evapotranspiration in a Mediterranean climate by Guidi et al. (2008) and Pistocchi et al. (2009) the crop coefficient is not uniform and varies greatly over the course of a season. As can be seen from Figure 2.6 the crop coefficient was lower for the first season compared to the second

season. This is expected given that in the second season, the plant will be will have an established root system and a greater biomass, hence a higher water demand. The crop coefficient values are low at the start of the season, not rising above the reference ET until mid-June, then rise steadily until peaking at the end of August/start of September, before drop off more rapidly until the end of the growing season.

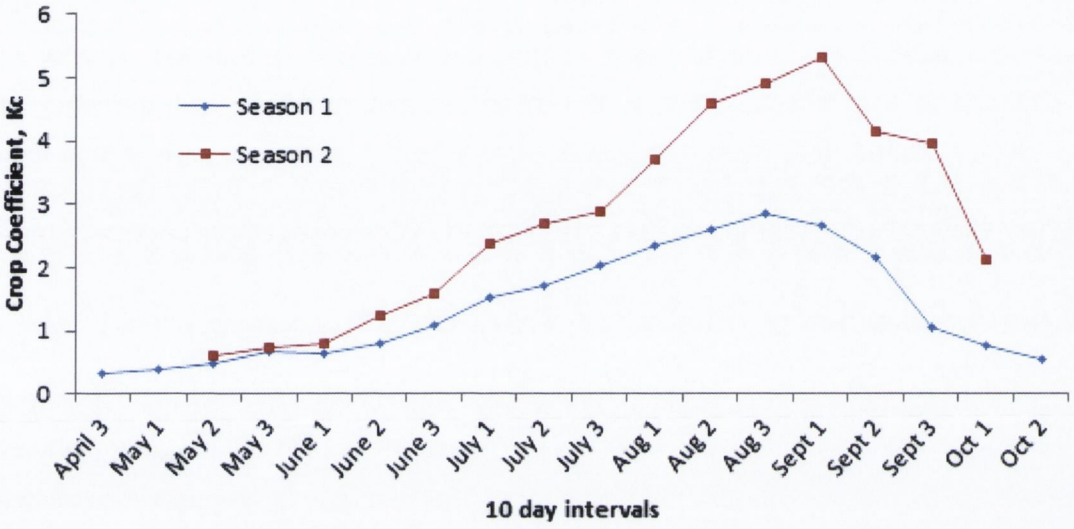


Figure 2.6 Crop coefficient for willow (*Salix alba*) over the course of two growing season (modified from Guidi et al., 2008)

2.4.2.2 *Willow Evapotranspiration*

There have been numerous studies and reports in recent decades investigating the water demands of willow (Lindroth and Båth, 1999, Lindroth et al., 1994, Persson and Lindroth, 1994, Halldin, 1989, Doody and Benyon, 2011) with all concluding that the species consumes large quantities of water relative to most other plants. This was demonstrated in Sweden in the 1980s, where evapotranspiration trials were initiated, coinciding with the start-up of short rotation willow crop plantations in the country. In a multi-site study carried out in the south of the country (Halldin, 1989) determined that the introduction of a willow plantation does put a strain on water resources in the surrounding environment. It was shown that evapotranspiration from the stands surpassed precipitation over the course of the growing season and irrigation was required on all sites. It was also noted that the introduction of willow may help prevent nitrogen leaching into watercourses from agriculture.

Further results from a trial carried out over four years (1985-1988) (Persson and Lindroth, 1994) correlated closely with the previous research, showing that evaporation from the willow stand exceeded the open water evaporation by up to 137 mm (31%) over the growing season. A breakdown of the results into daily average evaporation from the willow stand over the course of the growing seasons gave values of 2.3 to 3.2 mm/day which corresponds to approximately to a total of 416 to 584 mm over the entire season. These results were matched very closely in a further study by Persson (1995), which examined the possibility of simulating evapotranspiration for any given willow stand by modifying meteorological and sites parameters from a reference site. The measured evapotranspiration rates over the course of a growing season in this case varied between 365 and 495 mm. More importantly, it was shown that the evapotranspiration from the willow stand was greater than the reference evapotranspiration.

A detailed experiment carried out in the eastern United States (Pauliukonis and Schneider, 2001), comparing the evapotranspiration rates of weeping willow (*Salix babylonica* L.) with that of red maple (*Acer rubrum* L.) and cattail (*Typha latifolia* L.) over a 3 month (approx.) period produced results which correlated strongly with the findings of previous Scandinavian research. The willow comfortably outperformed the other two species reaching evapotranspiration rates of between 10 and 22 mm/day over the course of the study. Although, it should be noted that these rates were attained at the peak of summertime and so don't take early or late season performance into account.

There have been a number of lysimeter experiments, which examine water consumption of willow, carried out in more recent years; the results of five such studies are shown in Table 2.4. The first of these experiments (Martin and Stephens, 2006) examined the water use of willow subjected to four different soil treatments under water stressed and normal conditions, totalling eight treatments overall. The ET rates for the best performing willow (high fertilisation, no water stress) ranged between 1567 - 5250 mm over the course of the three growing seasons.

These results were very similar to those determined by (Guidi et al., 2008) for willows receiving fertilisation, which saw the ET ranging from 1190 - 1790 mm over the two seasons. The experiment, which compared ET for willow (*Salix alba*) and poplar (*Populus deltoids*) also showed a marked increase in ET caused by fertilisation treatment (51% and 101% increase for willow). The third season of this experiment (Study 'C'), which was examined by Pistocchi et al. (2009) changed the treatment types to low fertilisation and high fertilisation. This reduced the

discrepancy between the ET, with the low fertilisation reaching 607 mm and the high fertilisation reaching 919 mm. However, the low overall ET for the third season was attributed to monitoring equipment breaking down during the trial, resulting in the loss of data.

The ET rates determined by Dimitriou and Aronsson (2010) for willows receiving landfill leachate were somewhat lower than the previous studies discussed. The willows were subjected to two treatments in the first season and two different treatments in the second season. As with Guidi et al. (2008) and Pistocchi et al. (2009) the higher loadings resulted in higher ET for both seasons. The willows fertigated with lower amounts of leachate (and hence nutrients) resulted in ET of only 150 mm for both seasons, while the willows receiving greater amounts of leachate had ET of 565 mm and 850 mm for seasons one and two respectively.

A follow up to this study carried out by Dimitriou and Aronsson (2011), in which the same willow plants were subjected to a similar style of treatments, but with wastewater instead of leachate) resulted in improved ET rates, although still slightly lower than rates attained by Martin and Stephens (2006) and Guidi et al. (2008). The ET rates for the willow subjected to higher fertilisation were 900 mm and 1200 mm for seasons one and two, both of which values were over three times higher than the corresponding low fertilised willow.

Table 2.4 Willow evapotranspiration for five lysimeter experiments

Study	Season	Density (plants/m²)	ET (mm)		ET (l/plant)	
			Treatment		Treatment	
			LF	HF	LF	HF
A	1	4.4	-	1567	-	359
	2	4.4	-	3790	-	868
	3	4.4	-	5250	-	1192
B	1	2	620	1190	310	595
	2	2	890	1790	445	895
C	3	2	607	919	303.5	460
D	1	2	150	565	75	283
	2	2	150	850	75	425
E	1	2	250	900	125	450
	2	2	400	1200	200	600

Sources: (A) (Martin and Stephens, 2006); (B) (Guidi et al., 2008); (C) (Pistocchi et al., 2009); (D) (Dimitriou and Aronsson, 2010); (E) (Dimitriou and Aronsson, 2011)

The only reported ET values for full scale zero discharge willow systems treating on-site wastewater effluent come from trials carried out in Denmark from 1997 to 1999. Reports by

Gregersen and Brix (2001) and (Brix and Arias, 2011) on the experiences of the systems showed the ET rates for six systems over two years (see Table 2.5). The systems, which were planted at an approximate density of 2 plants/m^2 resulted in evapotranspiration ranging from 980 mm - 1270 mm for the first year (April 1997 - March 1998) and 1470 mm - 2090 mm for the second year of the trials (April 1998 - March 1999). These figures are comparable to the ET determined by Guidi et al. (2008) in the lysimeter experiment for willows receiving fertilisation. The precipitation for the 2 years in question was approximately 700 mm and 1,150 mm (which was 400 mm higher than 30 year average (D.M.I)) respectively. As the evapotranspiration from all sites exceeded the rainfall for both years, it was concluded that the difference between the two represents the amount of wastewater that could be added to the system without it overflowing.

Table 2.5 Evapotranspiration Rates for six willow systems in Denmark. Adapted from (Gregersen and Brix, 2001)

Facility	**Evapotranspiration (mm)**	
	Year 1	**Year 2**
1	980	1470
2	1270	2090
3	1140	1650
4	1130	1690
5	980	1660
6	1020	1880

2.4.3 *Willow System Treatment of Wastewater Pollutants*

Following on from removal of the hydraulic load via evapotranspiration, the next aspect of effluent treatment to be assessed is the removal / assimilation of contaminants from the wastewater. As willow wastewater treatment systems are sealed units, pollutant removal within the willow bed occurs by several mechanisms: assimilation of pollutants from the wastewater into the tree biomass (e.g. nutrients and heavy metals); conversion of pollutants to gaseous fractions by natural biochemical cycling processes in the enclosed basin (e.g. nitrogen and organics); natural attenuation / die off (in the case of pathogenic microorganisms). There will also be a net accumulation in the system of chemical such as excess phosphorus, chlorides, etc.

This section will discuss research that has investigated pollution removal/reduction purely from a treatment point of view and also look at pollution/nutrient reduction that has taken

place as a result of adding wastewater to SRC willow grown with biomass yield as the primary focus. Treatment of wastewater was not the main priority in some of the cited research, but it still lends some insight into the treatment capabilities of willow trees.

The most important removal mechanisms for the main pollutants are listed below and will be examined in detail:

- Nitrogen
- Phosphorus
- Organic Matter
- Potassium
- Salinity

2.4.3.1 Nitrogen

Research into phytoremediation of wastewater using willow began in Poland as early as (1969) when Bialkiewicz looked at the treatment efficiency for BOD_5, Total Nitrogen and Phosphorus (P_2O_5) applied to a willow buffer zone. Municipal wastewater was applied via furrows in the willow stand to four different species: *Salix viminalis, S Americana, S. triandra* and *S. purpurea.* As can be seen from Table 2.6 the initial findings from the research showed potential, with an average of 42.6% nitrogen removal over the course of the summer months. This figure dropped slightly to 41.3% for the entire duration of the three year experiment.

Table 2.6 Sample of Total N removal rate (adapted from Perttu and Kowalik, 1997)

Sampling Date	**Total N (mg/L)**	
	Input	**Output**
26-07-1965	49	30
29-07-1965	44	24
23-08-1965	52	40
26-08-1965	52	22
13-09-1965	61	35
16-09-1965	56	29
Mean Removal Efficiency (%)	42.6%	

Further research in Poland ((Ryszkowski, 1990) and (Obarska-Pempkowiak, 1994), both cited by Perttu and Kowalik (1997)), strengthened previous findings regarding nitrogen removal in

willow buffers. The research at Gdansk monitored the stream water flowing into and out of the zoo before and after the willow buffer was installed. As can be seen in Table 2.7 the concentrations for all forms of nitrogen was much lower in the river outflow from the zoo after the construction of the willow buffer zone, with a decrease in Total N from 10.1 mg/l to 2.4 mg/l (although the background concentration of Total N in the river was slightly higher before the willow buffer was installed). The study at Turwia focussed on a stretch of river - one side lined with a 70 m buffer (consisting of willow & poplar) between the farmland and the river, the other side with no buffer. Nitrogen concentrations were measured in the shallow groundwater adjacent to the river on both sides and compared. As can be seen in Table 2.7, while the ammonia concentration was slightly higher on the buffered bank, the nitrate concentration was markedly lower

Table 2.7 Nitrogen removal rates from two separate studies in Poland.

	Parameter	**Concentrations (mg/l)**			
		Before		**After**	
		Input	**Output**	**Input**	**Output**
Gdansk Zoo (A)	Total N	3.1	10.1	2.1	2.4
	NH_4^+	0.0	1.6	0.2	0.1
	Org. N	3.1	8.0	1.3	1.8
	NO_3^-	0.0	0.4	0.6	0.5
		Without Buffer		**With Buffer**	
Turwia River (B)	NH_4^+	1.5		1.8	
	NO_3^-	94.0		9.3	

Sources: (A) (Obarska-Pempkowiak, 1994); (B) (Ryszkowski, 1990)

Research on nitrogen removal by willows continued in Sweden in the 1990s coincided with the growing popularity of using willow short rotation crop for biomass production. Hasselgren (1998) presented an overview of research taking place in Sweden at that time evaluating the use of willow as an alternative to traditional waste management. The drainage water from the stand consisted of 3-7 mg/l total nitrogen, which represented a large decrease from the original loading of 166 kg-N/ha over the season. Elowson (1999) investigated the filter properties of a willow stand applied with polluted drainage water. Although the exact overall nitrogen

retention was not determined, results were positive, with zero NO_3^- concentrations measured in groundwater in areas of the willow stand and zero NH_4^- concentrations measured in all areas.

The Total N treatment efficiencies for willow in a range of lysimeter experiments are presented in Table 2.8. The removal rates for the first growing season are quite poor (Dimitriou and Aronsson, 2010, Aronsson and Bergström, 2001) unless the willow plants had already developed root systems (Dimitriou and Aronsson, 2011). However, once fully established, the willow lysimeters showed excellent nitrogen retention ranging from 82–95%. One of the experiments (Aronsson and Bergström, 2001) did not determine the retention rates, however analysis of the drainage water from the lysimeters showed the same pattern as the other studies - poor treatment of nitrogen in the first season (high concentrations of NO_3^- in drainage water) with much improved treatment for consequent seasons (low concentrations of NO_3- for 2nd season and almost zero for the 3rd season).

Table 2.8 Nitrogen uptake for willow lysimeter experiments.

Study	Year	Season	Treatment	Input Loading (kg-N/ha)	Retention	Output
A	1998	-	A	166	85-95%	-
B	1988	1	A	110	-	High NO_3^- conc.
			B	220	-	High NO_3^- conc.
		2	A	122	-	Low NO_3^- conc.
			B	244	-	Low NO_3^- conc.
		3	A	122	-	$NO_3^- \approx 0$
			B	244	-	$NO_3^- \approx 0$
C	2010	1	A	87	0%	High NO_3^-, low NH_4
			B	262	50%	High NO_3^-, low NH_4
		2	A	126	94%	Low NO_3^-, low NH_4
			B	378	82%	Low NO_3^-, low NH_4
D	2011	1	A	262	95%	NO_3^-& $NH_4 \approx 0$
		2	A	361	95%	NO_3^-& $NH_4 \approx 0$

Sources: (A) (Hasselgren, 1998); (B) (Aronsson and Bergström, 2001); (C) (Dimitriou and Aronsson, 2010); (D) (Dimitriou and Aronsson, 2011)

Results for nitrogen removal in fully operating large scale zero discharge willow systems are not that well known. Gregersen and Brix (2001) and Brix and Arias (2011) both document the experience from the systems which have been operating in Denmark for over a decade. Although there was no measurement of the compounds entering the systems, it was estimated that close to full retention of nitrogen from the wastewater by the willows did occur. This was determined by a mass balance using the assumed influent characteristics against the nitrogen levels in the biomass.

Further research on full scale systems has taken place since the original trials in Denmark with positive results. Wu et al. (2011) looked at a novel domestic treatment package for households in rural China for situations where treatment via percolation was not viable. The system consisted of a sedimentation tank feeding directly into a small 'willow bed' of 1.2 m^2 in area, which had an outflow and was planted with a single willow tree. The measured NH_4-N removal rates from the grey water influent (which provided a nitrate loading of 11,205 kg/ha over the year) were 95% during winter and 96.3% outside of this period. The high removal rate reported during the winter period would throw into question whether removal is down to the willow tree and not the soil, and if the removal rate was sustainable in the long term.

The type of system trialled in northern Sweden by (Rastas Amofah et al., 2012) was similar in design to the Danish systems, however, the willow system was relatively small in area (32 m^2) and had an outflow. The system was loaded with an average of 8 kg-N/ha per day for 2.5 years and an average removal efficiency of 43% was achieved. The relatively low removal could be attributed to the small size of the willow system.

It should be noted that in treatment units such as willow systems, nitrogen removal will also take place in the soil medium within the basin. The primary reduction/transformation processes that take place in the soil are ammonia adsorption, nitrification and nitrate loss via denitrification (Siegrist et al., 2000). Ammonia is the main form of nitrogen in septic tank effluent. Any remaining organic nitrogen is generally mineralised rapidly to ammonium in the upper soil layers. Adsorption of NH_4-N is most effective under anaerobic conditions. In such an environment the ammonium ions are readily adsorbed onto negatively charged soil particles. However, the soil's adsorption capacity is limited as there are only a finite number of exchange sites available within the soil (O' Súilleabháin, 2004).

Under the aerobic conditions of a soil, ammonium will undergo nitrification. Autotrophic bacteria in the soil use O_2 as the electron acceptor in the oxidation of NH_4-N to NO_3-N. Since nitrate is a negatively charged ion it is not attracted to the negatively charged soil colloids. In the absence of oxygen, nitrate can be lost from the system by denitrification if a sufficient supply of organic C is available.

2.4.3.2 Phosphorus

As phosphorus and nitrogen are the two primary nutrients in wastewater, much of the research discussed in the previous section, which dealt with nitrogen removal also has relevant details on phosphorus treatment and removal using willows. Perttu and Kowalik (1997) cites research carried out by Bialkiewicz (1969) in which the treatment efficiency of willow irrigated with wastewater. As can be seen in Table 2.9 a removal rate of 46.8% was achieved over the sampling period of summer 1965. This figure was slightly lower (42.9%) over the course of the entire three years.

Table 2.9 Sample of phosphorus (as P_2O_5) removal rate (adapted from Perttu and Kowalik, 1997)

Sampling Date	**P_2O_5 (mg/L)**	
	Input	**Output**
26-07-1965	10	5
29-07-1965	9	4
23-08-1965	9	5
26-08-1965	10	8
13-09-1965	14	6
16-09-1965	13	6
Mean Efficiency (%)	46.8%	

Perttu and Kowalik (1997) cite further studies in Poland carried out at Gdansk Zoo (Obarska-Pempkowiak, 1994) and on a section of the Turwia River (Ryszkowski, 1990) both of which showed positive findings with regard to phosphorus treatment using willows. The stream water through Gdansk Zoo had been showing an increase in phosphorus (in the form of PO_4^{3-}) from 0.4 mg/l to 0.6 mg/l between entry and exit prior to the installation of a willow buffer. The corresponding values after installation were 0.2 mg/l to 0.1 mg/l. In a separate study, analysis from shallow groundwater samples collected in close proximity to Turwia River between 1984-1986 showed phosphorus concentrations (in the form of PO_4^{3-}) of 0.248 mg/l on the bank with no willow buffer and 0.067 mg/l on the opposite bank which had a willow buffer

distancing the farmland. This represents a 73% decrease in phosphorus concentration. Hasselgren (1998) found similarly positive results when determining low total phosphorus concentrations in drainage water from a willow stand applied with 22 kg-P/ha over the course of a growing season.

The total phosphorus retention rates for different willow lysimeter experiments are shown in Table 2.10. The removal rate of over 95% in all cases appears to be quite high. However, it can be seen in the study carried out by Dimitriou and Aronsson (2010) that a relatively low loading rate was applied (0.54 and 1.62 kg-P/ha) in the first year of growth for both treatment types. This probably accounts for the high retention rate by the newly planted willow. Once established there are multiple examples of the willow retaining approximately 20 kg-P/ha (Hasselgren, 1998, Dimitriou and Aronsson, 2010) and in once instance 29.8 kg-P/ha is retained (Dimitriou and Aronsson, 2011). These results compare favourably to the findings of Cavanagh et al. (2011) which found an average uptake of 21.4 kg-P/ha for a range of treatment types (26 - 127 kg-P/ha) applied to a willow stand in Quebec. It was also demonstrated that increasing phosphorus loading beyond this amount did not result in more phosphorus being absorbed.

Table 2.10 Phosphorus uptake for willow lysimeter experiments.

Study	Year	Season	Treatment	Input Loading (kg-P/ha)	Retention
A	1998	-	1	22	95-96%
B	2010	1	1	0.54	96%
			2	1.62	96%
		2	1	6.7	99%
			2	19.1	99%
C	2011	1	1	21.2	~100%
		2	1	29.8	~100%

Sources: (A) (Hasselgren, 1998); (B) (Dimitriou and Aronsson, 2010); (C) (Dimitriou and Aronsson, 2011)

As with nitrogen there are no definitive results for phosphorus uptake in the full scale zero discharge willow systems in Denmark. However, Gregersen and Brix (2001) and Brix and Arias (2011) assumed full uptake of the phosphorus loading applied by using a mass balance equation. The phosphorus concentration of 10 mg/l that was assumed for the wastewater are

somewhat similar to the concentrations (7.4 mg/l - 32.3 mg/l) reported by Gill et al. (2009a) for Irish on-site wastewater effluent.

From a loading of 1825 kg-P/ha over the course of the year (Wu et al., 2011) showed phosphorus removal rates of 88.2% and 88.6% (winter period and non-winter period respectively) for the willow system filter system trialled at a rural household in China. As with the nitrogen uptake results for this experiment, however, it is not clear to what extent the willow was responsible for the phosphorus reduction, given the high removal rates in the non-growing season. Rastas Amofah et al. (2012) determined a phosphorus uptake of just 23% from an average loading rate of 1.2 kg-P/ha per day for a willow system trialled in northern Sweden. The low removal rate could be attributed to the relatively small size of the willow system (32 m^2).

As with nitrogen, a certain amount of phosphorus removal in a willow system will be as a result of adsorption and mineral precipitation reactions in the soil. The sorption capacity of soils with respect to phosphorus can vary greatly. The clay content of the soil can have a large bearing on the capacity, with Jenssen (2001) reporting that the it can hold for a period of 10 years or more. In contrast, precipitation may provide much higher capacity to fix phosphate, provided that the solution soil chemistry is conducive to the reaction (Jones and Lee, 1979). In research carried out on a treatment system for 44 years, it was shown that the attenuation of phosphate in the subsoil was controlled by mineral precipitation rather than sorption (Harman et al., 1996). Analysis of the soil showed that P-sorption capacity had been reached.

2.4.3.3 Organic Matter

Much of the research focussing on uptake/removal of nitrogen and phosphorus by willow also examines the reduction in organic matter. Perttu and Kowalik (1997) cites Bialkiewicz (1969) which determined BOD_5 removal rates of 88% for wastewater with an average BOD_5 of 168 mg/l applied to a willow buffer zone (an example of the removal rates during the summer of 1965 can be seen in Table 2.11)

Table 2.11 Sample of organic matter (as BOD_5) removal rate (adapted from Perttu and Kowalik, 1997)

Sampling Date	**BOD_5 (mg/L)**	
	Input	Output
26-07-1965	85	11
29-07-1965	109	14
23-08-1965	63	11
26-08-1965	88	27
13-09-1965	150	12
16-09-1965	95	13
Mean Efficiency (%)	94.1%	

Perttu and Kowalik (1997) also cites research by Obarska-Pempkowiak (1994) which shows how the planting of willows adjacent to the stream running through Gdansk Zoo resulted in a marked decrease in the organic matter concentration (both BOD_5 and COD) in the outflow from the zoo (see Table 2.12).

Table 2.12 Organic matter removal at Gdansk Zoo

Parameter	**1991**		**1993/1994**	
	Input	Output	Input	Output
BOD_5 (mg/l)	2.5	3.5	2.5	2.8
COD (mg/l)	2.9	10.0	7.4	4.8

The results from three different lysimeter experiments which examined organic matter removal as part of the research can be seen in Table 2.13. The results from the first two studies listed in the table are quite comparable with the 84-90% TOC (total organic carbon) removal rate determined by Dimitriou and Aronsson (2010) across two different treatment types and two growing seasons quite similar to the 91-98% BOD_5 removal rate approximated by Hasselgren (1998), although neither the loading rate nor concentration of the applied wastewater were given for this experiment. The TOC removal rates of approximately 45% and 70% achieved by Dimitriou and Aronsson (2011) is quite low in comparison to the first two studies. However, this could be as a result of a very low TOC concentration (7.5 mg/l) in the wastewater to begin with.

Table 2.13 Organic removal rates for willow lysimeter experiments

Study	Year	Season	Treatment	Concentration (mg/l)	Input Loading (kg/ha)	Removal
A	1998	-	BOD_5	NA	NA	91-98%
B	2010	1	TOC	565	203	~84%
			TOC	565	609	~90%
		2	TOC	313	707	~90%
			TOC	313	2021	~84%
C	2011	1	TOC	7.5	NA	~45%
		2	TOC	7.5	NA	~70%

Sources: (A) (Hasselgren, 1998); (B) (Dimitriou and Aronsson, 2010); (C) (Dimitriou and Aronsson, 2011)

Wu et al. (2011) showed BOD_5 removal rates of 95% and 96.3% (winter and non-winter seasons respectively) from a loading rate of 110,375 kg-BOD_5/ha/year for a novel willow filter system installed at a dwelling on rural China. However, 32% of this removal was attributed to the sedimentation tank treating the effluent before it entered the willow filter system, and as discussed in the previous two sections, the continuous high removal rate achieved throughout the year does question the level of treatment that can be attributed to the willow itself, rather than to interaction with the soil. Some of the removal is also likely down to natural degradation occurring as the organics are converted to carbon dioxide and methane in the anaerobic environment.

Rastas Amofah et al. (2012) determined a BOD_7 removal rate of 87% for a willow system receiving a daily load ranging between 15-27 kg-BOD_7/ha (averages to an annual loading of 7665 kg-BOD_7) and a corresponding COD removal rate of 80% for a daily loading ranging between 30-70 kg-COD/ha (averages to an annual loading of 18,250 kg-COD/ha).

2.4.3.4 Potassium

The focus in wastewater treatment and reuse traditionally centres in on nitrogen, phosphorus, and organic matter as these can be treated or controlled by normal aerobic/anaerobic treatment processes. However, although potassium does not pose a significant health or environmental threat (USEPA, 1980b), it is one of the essential macrominerals (along with nitrogen and phosphorus) for plant survival. Potassium in wastewater is generally in mineral form that is

readily available for plant uptake (Mengel and Kirkby, 1996), and so the quantity required to sustain willow development needs to be determined.

As there is very little research done on the uptake of potassium itself by willow, usage is usually defined in relation to phosphorus and nitrogen. Ericsson (1981a) reported that a P/N ratio of 0.13 and a K/N ratio of 0.65 (N:P:K of 100:13:65) provides optimum growth for various willow clones. Figures for potassium concentrations in wastewater vary; Arienzo et al. (2009) cites research by Mclaren and Smith (1996) which reports potassium concentrations of 15 mg/l (New Mexico), 12 mg/l (Frankston, Australia) and 15-30 mg/l (Alberta, Canada) for sewage water, while Pettygrove et al. (1985) reports values in the range of 7-15 mg/l. Larsson (2003) reports concentrations ranging between 15-19 mg-K/l (Greece) and 9-15 mg-K/l (Northern Ireland) for primary municipal wastewater. This ties in closely with the findings of Perttu (1993) which showed a N:P:K ratio of 100:14:64.

As well as its biochemical functions, potassium, (Tisdale et al., 1999) and (Whitehead, 2000) (both cited by (Arienzo et al., 2009)) has been shown to improve the tolerance of plants to situations including drought, low temperature and salinity.

2.4.3.5 Salinity

Soil salinity is an issue which affects the vast majority of plants. Glycophytes, which make up the largest proportion of plant life, including willow, have relatively low tolerance to salts . So, from the perspective of treating wastewater using a zero discharge willow system, both the short term response of the willows to the salt quantity being applied via the effluent and the long term effect of increasing salinity within the willow system need to be examined. All salts can affect plant growth but not all will restrict growth; chloride is also a plant nutrient to a certain degree (White and Broadley, 2001) with the optimum amount being 0.03 as a percentage of the total nitrogen added (Ericsson, 1981a cited in Mirck and Volk, 2010). However, this review will focus on the toxic effects of salts on willow growth and development as it is assumed the optimum amount of 0.03% will always be present in typical on-site effluent.

The most common effect of soil salinity is growth inhibition by sodium (Na^+) and chloride (Cl^-). For woody perennials such as willow, the Na^+ is retained in woody roots and stems and it is the chloride (Cl^-) that accumulates in the shoot and is most damaging to the plant, often inhibiting photosynthesis (Flowers, 1988). As well as chloride, the other predominant non-carbonate salt found in wastewater is sulphate (SO_4^{2-}). A typical wastewater chloride concentration is 50 mg/l

(Metcalf and Eddy, 1991), with Withers et al. (2011) and Larsson (2003) determining similar concentrations of 54 mg/l and 50 mg/l respectively. However, concentrations can reach much higher levels depending on the detergent use in a household, as shown by research carried out by Larsson (2003) who determined a chloride concentration of 215 mg/l for a dwelling in Northern Ireland. A multiple site study carried out by Gill et al. (2009a) reported mean concentrations ranging from 56.6 mg/l - 366 mg/l for the different dwellings, although all except one site had a mean concentration which was less than 120 mg/l.

Numerous reports have shown negative effects, such as decrease in biomass, leaf damage and poor survival rates for trees irrigated with leachate containing relatively high concentrations of chloride (Cureton et al., 1991, Ettala, 1988, Mensar et al., 1983, Wong and Leung, 1989).

Stephens et al. (2000) highlighted such effects on the short term response of willow clones subjected to solutions containing very high concentrations of chloride. The experiment applied seven chloride treatments ranging from 0 mg/l (control) to 14,939 mg/l (in approximately 2,500 mg/l increments). All clones receiving solution with a concentration greater than 7469 mg/l showed visual signs of water stress within one day, and all clones receiving the heaviest dose had died within 11 days. All treatments reduced the evapotranspiration by at least 40%, inhibited growth of stem biomass and reduced leaf biomass.

Bialowiec et al. (2003) identified similar, although less pronounced effects to willow clones from leachate (concentrations: 1540 mg-Cl^-/l, 2075.1 mg-SO_4^{2-}/l). The biomass and evapotranspiration responses to 4 dilutions of the leachate (100%, 50%, 25%, control) were examined and it was shown that the application of the two highest concentrated solutions resulted in a marked reduction in biomass growth and transpiration. Further research by the same authors (Bialowiec et al., 2007) reinforced these findings. The evapotranspiration and biomass were monitored for different willow clones receiving varying leachate dilutions. It can be seen that for the first season increased loading only resulted in greater biomass and ET for the clones planted in sand. The clones planted in sand and sewage sludge saw a decrease in biomass and ET for increased loading. During the second season an increase in loading resulted in a decrease for both parameters in all cases, including a remarkable reduction for the dry biomass. The increased chloride loading corresponded with an increase in nitrogen and phosphorus could explain the improved biomass and ET for the willow clones in the sand during the first season. However, it appears that the higher chloride loadings (including additional chloride found in the sand with sewage sludge medium) thereafter negated any

positive effects caused by the addition of extra nutrients. The author attributes the low biomass yield to over nutrition, lack of phosphorus and high salinity.

Table 2.14 Dry biomass for willow clones receiving various chloride treatments (adapted from Bialowiec et al., 2007)

Treatment*	First Vegetation Period			Second Vegetation Period		
	Chlorides (kg/ha)	Biomass (T dm/ha)	ET (mm/day)	Chorides (kg/ha)	Biomass (Tdm/ha)	ET (mm/day)
S1	259	8.0	2.3	320	9.9	3.0
S3	776	6.8	2.6	383	0.2	2.8
S5	1170	7.5	2.9	331	0.1	1.9
SS1	259	7.5	2.7	320	5.1	2.3
SS3	776	3.7	1.4	622	0.3	1.6
SS5	1110	0.8	1.4	393	0.1	2.4

*S1, S3 S5: sand (1, 3, 5 mm/day)

SS1, SS3, SS5: sand with sewage sludge (1, 3, 5 mm/day)

Dimitriou and Aronsson (2010) had much more positive results from a similar lysimeter experiment where willow clones were fertigated with four different leachate dilutions over two seasons. The clones were given leachate that resulted in 391 kg-Cl/ha and 1173 kg-Cl/ha (first season) and 3051 kg-Cl/ha and 9153 kg-Cl/ha (second season) being applied, which are quite similar to the loadings applied by Bialowiec et al. (2007). However, the addition of a more concentrated leachate appeared to have a positive effect in this instance with an increase in ET along with no negative effects reported. The authors also reported chloride retention ranging between 40-55% of the applied loading, although a large proportion of this could be in the soil medium rather than the willow. Another aspect to this experiment was the allowance of drainage from the lysimeters, which would prevent toxic levels of chloride accumulating.

Mirck and Volk (2010) present results from a lysimeter experiment that correlate more closely with those determined by Bialowiec et al. (2007). Along with a control treatment, three willow clones were subjected to 1%, 2%, 5%, 10% and 50% dilutions of leachate with a chloride concentration of 16423 mg/l. Application levels were such that soil moisture was close to field capacity (at ~30%). After ten weeks, application of the 50% solution resulted in a marked reduction in biomass for leaf and stem biomass, although not as severe for root biomass. Apart from the 1% dilution there was a varying drop off trend in leaf and stem biomass for all other dilutions. The significantly lower ET values measured for the 50% dilution compare favourably with the results from Stephens et al. (2000) as discussed previously. It was also noted in this

study that the highest concentrated treatment (50%) resulted in a significantly greater root mass fraction for all three willow clones.

Reports on the findings of investigations into zero discharge willow systems in Denmark provided positive results in regard to long term salinity tolerance of willow. Gregersen and Brix (2001) highlighted no ill effects on the willow clones from salts in the wastewater four years after construction. Although there was no measurement of chloride loadings going into the system or uptake in the willows, no increase in conductivity was noted from readings taken of the water within the system. A decade later Brix and Arias (2011) reconfirmed no negative effects due to salinity, but added that contents of salts in the system are likely to increase over time and the inclusion of a sump from which to pump out salt-containing water is preferential.

2.4.4 *Zero Discharge Willow Systems*

The first reported use of zero discharge willow systems was in the late 1990s in Denmark (Gregersen and Brix, 2001, Brix and Arias, 2011) when trials involving six systems were established and monitored in order to assess their performance under Danish conditions. As a result of this research a guidance document for the design and establishment of willow evapotranspiration systems to cater for a PE of 30 or less was prepared for the Danish EPA (Miljøstyrelsen, 2003). The systems work on the basis of zero discharge, i.e. no wastewater, either treated or untreated enters the surrounding environment from the willow system. Treatment and removal of wastewater is achieved by a combination of evapotranspiration and nutrient absorption, primarily from the willow clones. The technology is still in its relative infancy, as very little further research on the system and its applicability in countries apart from Denmark has been carried out.

2.4.4.1 *Willow System Design*

A Danish zero discharge willow system generally consists of an excavated basin, lined with an impermeable layer, filled with soil and planted with willow cuttings. A standard installation has a surface width of 8 m, with the required length then determined from the area demand grid published in the guidelines (Miljøstyrelsen, 2003). The sides of the basin are sloped a 45° angle which results in the bottom of the basin having a 5 m width (see Figure 2.7).

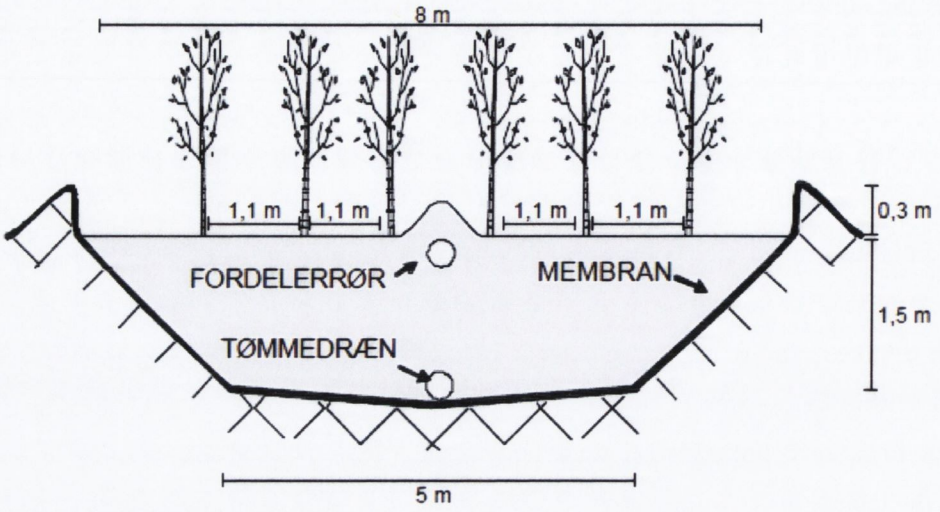


Figure 2.7 Longitudinal section of zero discharge system (modified from Miljøstyrelsen, 2003)

The sides and bottom of the basin are lined with a strong impermeable membrane which is either laid on a 50 mm layer of sand or surrounded by a geotextile membrane. The guidelines recommend using a high-density polyethylene or low-density polyethylene impermeable membrane comprised of one section (or multiple sections welded by a certified technician), have a thickness of at least 0.5 mm and have a manufacturer's 10 year guarantee. The liner is extended above the surface on all sides by 0.3 m (see Figure 2.8) and used to form a berm which prevents ingress of rain and surface water from outside the system.

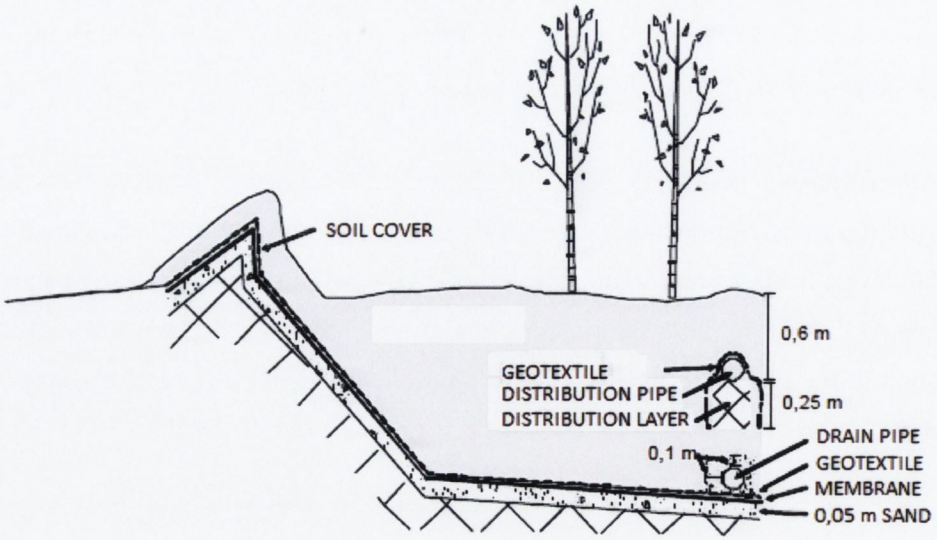


Figure 2.8 Membrane detail along bottom and sides of the willow system (Miljøstyrelsen, 2003)

Distribution of wastewater in the soil medium is carried out using a pressurised pump system. The pressure pipe from the pump is brought 4 m into the system before being connected to the distribution pipe. A pump well is installed in the system to allow for inspection and cleaning. The distribution pipe (32-63 mm diameter) is drilled with 8-10 mm holes at 1 m centres and laid in the centre of the willow system. The distribution pipe is laid at approximately half the overall depth of the basin, but can be laid at a high elevation as long as a soil cover of 0.6 m is maintained to prevent frost damage (Figure 2.9). The piping is placed on a distribution layer consisting of either washed gravel (13-32 mm) or plastic distribution units. The distribution layer is covered with a geotextile membrane to prevent potential clogging from the ingress of soil particles. If the willow system is situated in areas with dense/clayey soils a 0.1 m layer of sand spreading over the entire width of the willow system is placed under the distribution layer. This ensures widespread distribution of the wastewater throughout the system (Miljøstyrelsen, 2003).

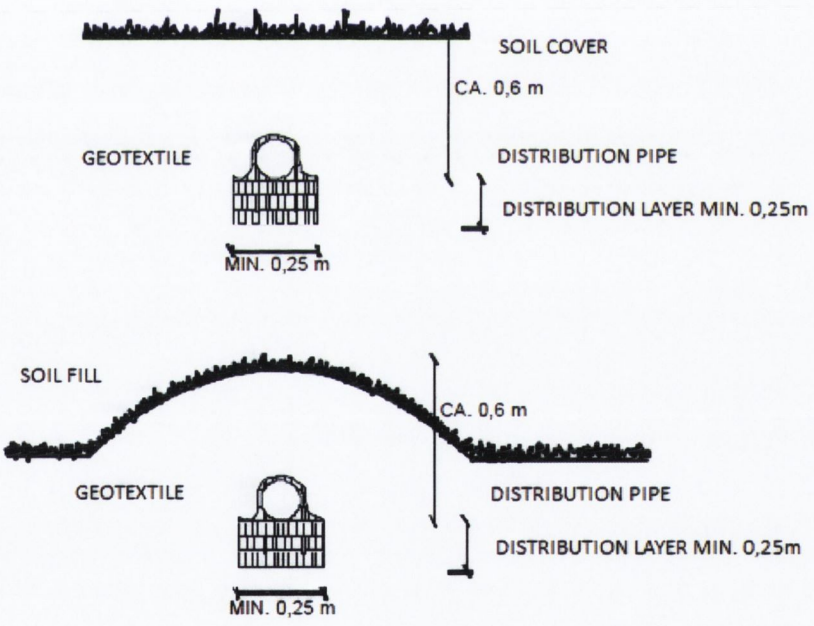


Figure 2.9 Layout of distribution pipes in soil medium (modified from Brix and Arias, 2011)

The Danish guidelines (Miljøstyrelsen, 2003) also recommend the inclusion of a 315 mm diameter inspection well. This is to allow for observation of the water level within the system and provides a means for pumping out the system - something, as Brix and Arias (2011) alluded to, may become necessary if there is a build-up of salts to toxic levels after years of use or if the system floods in the first year of growth.

2.4.4.2 System Sizing

A zero discharge willow system must be designed to remove of all influent in the form of wastewater and rainfall from the system on an annual cycle. On an annual basis the ET should equal the amount of wastewater plus the amount of precipitation falling onto the surface are of the willow system, giving the following water balance for the system:

$$ET = Q_{in} + P \qquad \text{Eqn. 2.4}$$

Where, ET = Evapotranspiration

Q_{in} = Wastewater influent

P = Precipitation

The seasonal variation in precipitation and evapotranspiration are also considered as the system needs to have a large enough capacity to store the effluent and precipitation during the winter months when ET is very low. As a result of the Danish willow system trials, a model was derived whereupon all surface area dimensioning was derived. This model was adjusted for different meteorological conditions throughout the country resulting in a gridded map (see Figure 2.10) being drawn which shows the surface area required in any particular region of the country for 100 m^3 of wastewater effluent. The following prerequisites were assumed for the model:

- The system is 8 m wide at the surface, has a depth of 1.5 m and the sides are sloped at 45°.
- The usable pore volume in the soil is at least 40%.
- The ET from the willows will be 2.5 times the ET_o as calculated by Denmark's Meteorological Institute.
- The calculations are based on the 30 year average for precipitation and ET for the relevant square on the 20 x 20 km grid map.
- The area is calculated such that there will be no accumulation of surface water for a 'normal' year's rainfall, but that a 10 cm accumulation is catered for in the case of a one in ten year rainfall amount.
- The wastewater influent is evenly distributed throughout the year (i.e. the same volume every month).

(modified from Miljøstyrelsen, 2003)

It is apparent from these conditions that the Danish model is based on a strict set of parameter boundaries; most notably the lack of flexibility with regards the pore volume in soil and also the use of a rigid crop coefficient.

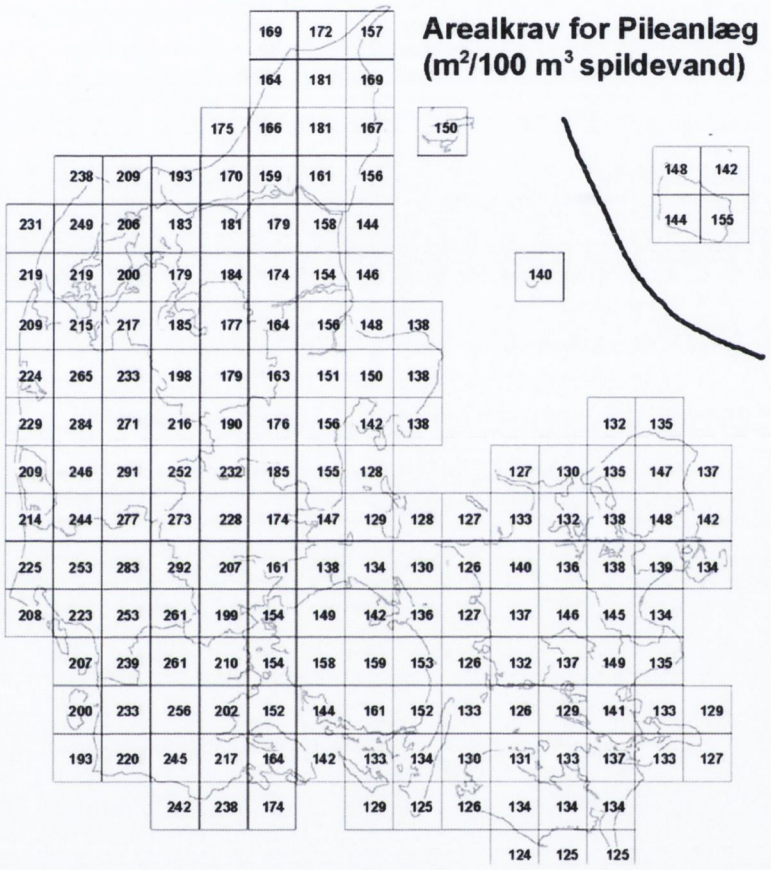


Figure 2.10 Area demand for willow system in 20 x 20 km grids (modified from Miljøstyrelsen, 2003)

2.4.5 *Willows – Establishment and Maintenance*

Most of the guidelines in terms of establishment and maintenance of willow based systems comes from the experience of growing them as a short rotation coppice (SRC) crop. The first experiments with short rotation willow coppice (SRWC) were conducted in Sweden in response to the oil crisis in the 1970s. These experiments were part of a policy of developing renewable energies to lessen the dependence on fossil fuels. Research looking at varieties of fast growing species (including *Alnus, Betulus, Populus* and *Salix*) concluded that willow gave the best results

(Sirén, 1983, Ledin, 1996, Christersson et al., 1993, Hakkila, 1985). These experiments led to the development of various guidelines in different countries over time (Ledin et al., 1996, Tubby and Armstrong, 2002, Defra, 2002, Caslin et al., 2010).

Review of establishment and maintenance practices for short rotation willow coppice will be divided into the following categories:

- Clonal Varieties
- Planting and Weed Control
- Cutback and Coppicing
- Diseases and Pests

2.4.5.1 Clonal Varieties

Willow varieties are currently bred to produce high-yielding, disease and pest resistant varieties with a growth habit that facilitates mechanical harvesting (see Table 2.15). The two main breeding programmes in Europe are located in Sweden (established in 1987) and the United Kingdom (established in 1996).

Table 2.15 Objectives of willow breeding programmes (Lindegaard and Barker (1997), cited in Hanley and Karp (2003)

Factor	Traits
Yield	Increase dry matter yield
	Select tallest clones
	Either 'few and thick' or 'many and thin' stools
Disease and pest resistance	Improve resistance to rust and willow beetles
	Select clones less palatable to mammals
Harvesting ability	Select straight rods with few side branches
Climatic conditions	Select clones suitable to local conditions

Much of the research has focussed on high yielding willow as an energy crop. Intuitively, however, and as detailed in multiple reports (Martin and Stephens, 2006, Guidi et al., 2008, Pistocchi et al., 2009) there is a strong correlation between biomass yield & height of willow clones and evapotranspiration rates attained. So by analysing the reported expected biomass for a particular willow clone can give an indication of the relative evapotranspiration rate which that clone may achieve.

Salix viminalis and its clones comprise the majority of SRC willows currently grown in Europe. It is the favoured species as it has a high growth rate, coppices well, and maintains a good

growth form (Pei et al., 2008). High yields can be achieved through breeding. Most new varieties are fertile and can cross with other species (Hanley and Karp, 2003) and the relative ease with which hybridisation occurs in nature means there is extensive scope to make rapid improvements in yield productivity (Danfors et al., 1998).

Initially, the main clones used were *S. viminalis* and *S. dasyclados* (Larsson, 1998). Early breeding produced a number of varieties, including Orm, Rapp, Ulv, Jorr and Jorrun. Later breeding produced high yielding and disease resistant varieties such as Björn and Tora (Larsson and Pirrwitz, 1998). Tora has the most sustainable high yielding variety in various climate conditions (with the exception of very warm climates) and is considered the industry standard (Lindegaard et al., 2011)

There have been few specific experiments carried out to test for varietal impact on evapotranspiration rates attained by (or even general water usage in) willows. One such study was carried out by Weih and Nordh (2002), which looked at characterising different willow varieties in terms of growth, nitrogen use efficiency (NUE) and water use efficiency (WUE) under different irrigation and fertilisation treatments over several months. The most relevant findings in terms of using willows in zero discharge treatment systems came from the clones subjected to high irrigation and fertilisation treatments. As would be expected, shoot biomass in terms of water used is higher for the clones subjected to low irrigation. Of the higher yielding willow clones under high irrigation & fertilisation, 'Loden' had the lowest biomass growth in terms of water used (0.74 g/l) suggesting that it may attain relatively higher evapotranspiration for a given plant size. However, the effect may be small, as the other two clones (Tora and Tordis) have a higher overall yield which may well make up the difference in terms of overall evapotranspiration (see Table 2.16)

Table 2.16 Shoot biomass growth in terms of water used for 3 willow clones (modified from Weih and Nordh, 2002)

Clone	Plant biomass (mg)	Shoot biomass growth/water (g/l)
Olof	2739 ± 74	0.62
Loden	3272 ± 327	0.74
Tora	3587 ± 344	0.80
Tordis	3754 ± 198	0.87

In terms of biomass yield, the findings of this report tie in with the results of a clone comparison study carried out by Lindegaard et al. (2011). The results from the trial (some of which are shown in Table 2.17) confirm that Tora, Olof and Loden are the better performing clones.

Table 2.17 Best performing willow clones (in terms of biomass yield) from ten year comparative study (modified from Lindegaard et al., 2011)

Clone	Mean biomass yield (Tdm/ha)
Sven	11.5
Tora	11.4
Olof	10.8
Torhild	10.1
Loden	9.8

2.4.5.2 *Planting and Weed Control*

The planting season for willow extends from early spring (February/March) to as late as May and even June, however, planting earlier means earlier establishment and a longer growing season (Dawson, 2007). Longer and thicker cuttings will result in higher number of shoots, taller shoots and a higher biomass production compared to short and thin cuttings (Rossi, 1999, Shield et al., 2008). However, going above a certain size (1.3 - 1.9 cm diameter and 22.9 cm) does not result in any significant improvement in growth (Burgess et al., 1990). The cuttings are usually planted at a commercial standard density of 15,000/ha (i.e. 1.5 per m^2) (Defra, 2002, Caslin et al., 2010), however, Bergkvist and Ledin (1998) showed that a density of 20,000/ha produced highest biomass yields. Increases of greater than 25,000/ha can result in higher stool mortality due to competition between stools (Bergkvist and Ledin, 1998 cites Willebrand and Verwijst, 1993)

Prevention of weed growth in the first season is essential (Defra, 2002, Miljøstyrelsen, 2003, Caslin et al., 2010), as it is tall weeds competing with the willows for light and space, rather than moisture or nutrient stress which limit the stem numbers and length from the stools (Sage, 1999). These factors are usually not an issue in the following seasons as the willows block out light and naturally limit weed growth.

2.4.5.3 *Cutback and Coppicing*

The inserted cutting will produce one to three stems in the first season. During the first winter after planting the stems are cut back close to ground level (see Figure 2.11) to encourage the growth of multiple stems in the following season. Normal coppicing can then take place on a two or three year cycle, with an alternating half or third being coppiced every year. The coppicing should take place after leaf fall and before bud-break, which usually ranges between mid-October and early March (Brix and Arias, 2011).



Figure 2.11 Willow cutback after first season (Defra, 2002)

2.4.5.4 *Diseases and Pests*

Willow leaf rust (*Melampsora epitea)* is one of the major disease problems in willow stands established for biomass or phytoremediation purposes (Royle and Hubbes, 1992, Larsson, 1998, Pei and Mccracken, 2005, Toome et al., 2009). It is particularly an issue in maritime countries (such as Ireland) as it favours conditions of high humidity and temperatures ranging between 16 - 20°C. (Mitchell et al., 1992, Heiska et al., 2007).



Figure 2.12 *Melampsora* rust on willow leaves (Defra, 2002)

The fungal parasite (see Figure 2.12) can reduce biomass yield by as much as 40% due to premature defoliation and lowering frost tolerance of plants (Spiers, 1989, Pei et al., 2003). Planting different varieties of willows (usually at least three) can act as a control measure against the spread of rust; varieties with high resistance to rust can act as a physical barrier to the spread of the disease (Dawson and Mccracken, 1995) and occupy any free space created by any failed varieties.

The borders of the willow system can be sprayed with insecticide in early spring before the beetles get a chance to re-colonise the stand. Routine spraying, however is not recommended, with Dawson (2007) stating ecological impact amongst others as the reason.

Leaf beetles are the principle pest affecting willow plantations, of which *Phratora vulgatissima* L. (blue willow beetle), *Phratora vitellinae* (the brassy willow beetle) and *Galerucella lineola* (the brown willow beetle) are the most abundant (Wickham et al., 2010, cites Hanley and Karp, 2003). The blue willow beetle is shown in Figure 2.13.



Figure 2.13 *Phratora vulgatissima* L. - blue willow beetle (adapted from Caslin et al., 2010)

Chapter 3

Methodology

3 Methodology

3.1 Introduction

At the outset of the project it had been agreed with the local authority (Wexford County Council) to design, construct and monitor zero discharge willow systems on existing dwellings, which had malfunctioning treatment systems due primarily to high T-values on the site (low permeability). This was agreed upon so that all results would be based upon systems receiving effluent and also so that the trees would have sufficient nutrients to sustain development. However, it soon became apparent that there was a limited interest from homeowners due to the relatively high cost of constructing the systems, despite pressure from the local authority. As a result, the majority of the systems under examination as part of this project were constructed at new dwellings whereby the local authority had granted planning permission on the basis that a zero discharge willow system for the treatment of on-site wastewater was designed, installed and monitored by Trinity College Dublin for the purposes of this research project.

The stipulations in full were:

- The willow evapotranspiration treatment system shall be constructed in accordance with the details submitted by Trinity College Dublin.
- The installation of the willow system shall be supervised by a suitably qualified person.
- The applicants shall allow for the monitoring of the willow system for a period of 5 years. The applicants shall allow the installation of any monitoring equipment necessary for such monitoring.

3.2 Site Selection

As part of the planning process all sites were subjected to a site assessment, the results of which were submitted to the local authority as part of the application. On-site assessment comprised of:

- Visual assessment
- Trial hole
- Percolation test

3.2.1 *On-site Assessment*

The site selection process started with Wexford local authority suggesting sites that met general requirements in that the home owner was interested, the subsoil was thought to be of low permeability and the site had a relatively large land area. Following on from these suggestions, an on-site assessment was carried out on the site as part of the design process, the outcome of which decided whether the site was suitable for inclusion as a trial site in this project. The different aspects of the on-site assessment are detailed in the following subsections.

3.2.2 *Visual Assessment*

The first part of the on-site assessment was a visual inspection carried out by the research team. As mentioned above the primary aspects that were looked for on a site was a land area large enough to fit a willow system on and subsoil of low permeability (i. e. a T-value > 90). The expected population that would be living at the house (i.e. the PE) on each site was determined from meeting with the homeowners to verify the current PE (and future PE if expected to change). This allowed for an estimation of the required willow system area and the site could then be checked to see if this area was available. Visual assessment for low permeability, water level depth (for unlined system) and slope of site was carried out using the guidelines from the EPA Code of Practice for Single Houses (see Table 3.1).

Table 3.1 Relevant factors considered during visual assessment (adapted from EPA, 2009a)

Factor	**Significance**
Water level in ditches and wells	Indicates depth of water table
Shape and slope of site	May indicate whether water will collect on or flow away from a site
Presence of watercourse/ponding	May indicate a low permeability subsoil or high water table
Presence and types of bedrock outcrops	Insufficient depth of subsoil into which willow basin can be excavated
Land use and type of grassland surface (if applicable)	Indicator of rate of percolation or groundwater levels
Vegetation indicators	Indicator of rate of percolation or groundwater levels

3.2.3 *Trial Hole*

Following completion of the visual assessment and confirmation that there is sufficient land area a trial hole is excavated to determine:

- Depth to the water table (only an issue for unlined system)
- The depth to the bedrock, and
- The soil and subsoil characteristics

The EPA Code of Practice Guidelines (EPA, 2009a) states that the trial hole should be located adjacent to but not within the proposed percolation area as the disturbed subsoil can create a preferential flow path, which increases the risk of groundwater contamination from percolating wastewater effluent. However, as the willow systems are lined with a waterproof membrane this was not an issue with regards to the sites used in the research. The soil and subsoil characteristics (soil texture, structure, preferential flowpaths, soil density, colouring and layering) were examined in the trial hole using BS 5930 (British Standards Institute, 1999) as part of this integrated approach of on-site assessment (see Table 3.2).

Table 3.2 Subsoil characteristics considered during trial hole inspection (adapted from O' Súilleabháin, 2004)

Characteristic	**Importance**
Soil Texture	Affects physical and chemical processes
Structure	Influences pore space, aeration and flow conditions
Preferential flowpaths	Influences the percolation rate of effluent, level of treatment and subsequently the risk to groundwater
Soil Density	Influences percolation rate
Colour	Indicative of state of aeration of soil
Layering	Effects percolation rate

3.2.4 *Percolation Test*

The on-site assessment was completed by carrying out a T-test at the site in order to verify that the subsoil had a T-value > 90 (see Figure 3.1). Normally the T-test involves excavation of three holes adjacent to the proposed percolation area. However, as with the test hole this was not an issue with the sites selected for this research. The bottom and sides of the hole were rubbed with a wire brush to remove any smearing or compaction caused during the excavation. Each

hole was pre-soaked in clean water within a day before starting the test. The following day the holes were refilled with clean water up to the 400 mm mark and the time was noted. The normal methodology for assessing the percolation rate is then to allow the water to drop to the 300 mm mark and the subsequent time for it to drop to the 200 mm mark level. This should be repeated two more times by twice more refilling the hole to the 300 mm mark and measuring the times taken for to drop back to 200 mm. The average of the three readings is then calculated and divided by four, to give the average time for a fall of 25 mm (the T-value). However, due to the low permeability subsoil the time taken for the first drop from 400 mm to 300 mm was well higher than 5 hours, which according to the Code of Practice (2009a) indicated that the T value was well in excess of 90 which meant that they were suitable for inclusion in this research project. Also, the water levels in all holes failed to drop to the 300 mm mark before the end of each test day.

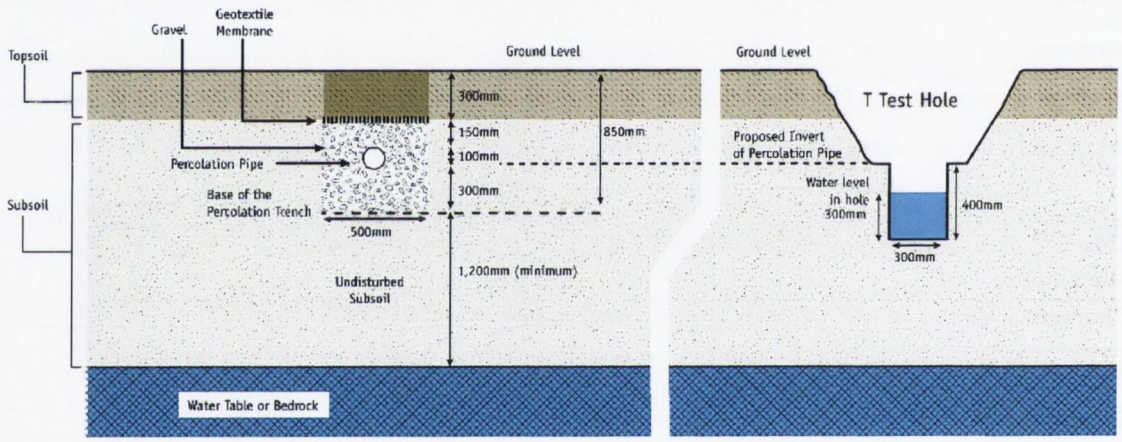


Figure 3.1 Cross-section of T-test holes and invert of proposed percolation trench (modified from EPA, 2009a)

3.2.5 *Occupancy*

The current guidelines in Ireland (EPA, 2009a) dictates that the typical daily hydraulic loading to an on-site treatment system be set at 150 L/person. This figure was lowered from the previous guideline's figure of 180 L/person, a decrease that resulted from the findings of Gill et al. (2005). This field research which was carried out on four sites in Ireland, however, determined that the actual figure is probably considerably less again; with the most common daily flow rate recorded being in the range 100 - 110 L/person. For this project a daily on-site loading of 120 L/person was used when determining the required size of the willow system for

a site, in order to test these systems at realistic levels, given that they were trial systems from which future design guidelines would be determined.

3.3 Design Criteria

As detailed earlier in Section 2.4.4, the only current design guidelines for zero discharge willow systems exist in Denmark (Miljøstyrelsen, 2003). As a result, all of the willow systems constructed in this project, although informed by those guidelines, were designed according to a water balance model developed using realistic Irish climatic data and on-site wastewater loadings (Section 3.3.3). Three of the designs (Sites A&B and Site J) did adhere to the Danish guidelines, while the rest used a modified design for reasons outlined on a case by case basis in Section 3.4.

The willow systems were sized (area and depth) on the basis of a water balance between typical wastewater effluent rates expected from the dwelling, precipitation onto the area and estimated evapotranspiration from the basin over a four year period. A numerical model was built using time realistic varying fluctuations in flows, local meteorological conditions and estimated crop coefficients to determine willow evapotranspiration across a four year period to provide an accurate simulation of the expected balance over the four years.

3.3.1 Wastewater flow into system

The flow into each system was determined on the basis of previous research carried out by Gill et al. (2005) which monitored the flow of wastewater from a total of seven households around Ireland. The flow rates were continually measured on these sites and so normalised flow profiles per person from this were used. The profiles were multiplied by the design population and a daily wastewater consumption figure of 150 L/person (EPA, 2009a) to give a realistic flow pattern into the basin.

3.3.2 Meteorological Data

Four years of detailed meteorological data, including precipitation, humidity, solar intensity, temperature and wind speed, were collected in a previous project from a site in Co. Wexford. This allowed a close estimation of the rainfall input as well as the potential evapotranspiration from the system to be determined.

3.3.3 *Preliminary Sizing*

The systems were sized using the following daily water balance:

$$V_w = R + I - (ET_o . K_c) \qquad \text{Eqn. 3.1}$$

Where, V_w = volume of water/effluent stored within willow system (m^3)

R = rainfall

I = wastewater influent

ET_o = reference evapotranspiration

K_c = assumed crop coefficient (for that time of year)

The results of the water balance across four years using the realistic flows based on the relevant design population and meteorological data were used along with estimated evapotranspiration to determine the volume within the basin at any given time. This produced a profile of the water level throughout the year (Figure 3.2). The evapotranspiration was estimated using historical reference evapotranspiration values for Co. Wexford and using willow crop coefficients taken from literature (Miljøstyrelsen, 2003). The crop coefficients were assumed to be 1 throughout the winter months increasing up to maximum values of 2.65 across the summer months.

Once the volume required was determined, it was then divided by the porosity of the soil expected within the willow system. The net porosity values for the subsoil were estimated at 30% (although this was one of the critical design factors that the full-scale field research was aiming to determine, as discussed later in Section 4.5) was decided upon for the design. When the overall volume (including soil porosity) was determined, the final dimensions of the willow system were compared with using different combinations of area and height. The final design choice is detailed in the following section.

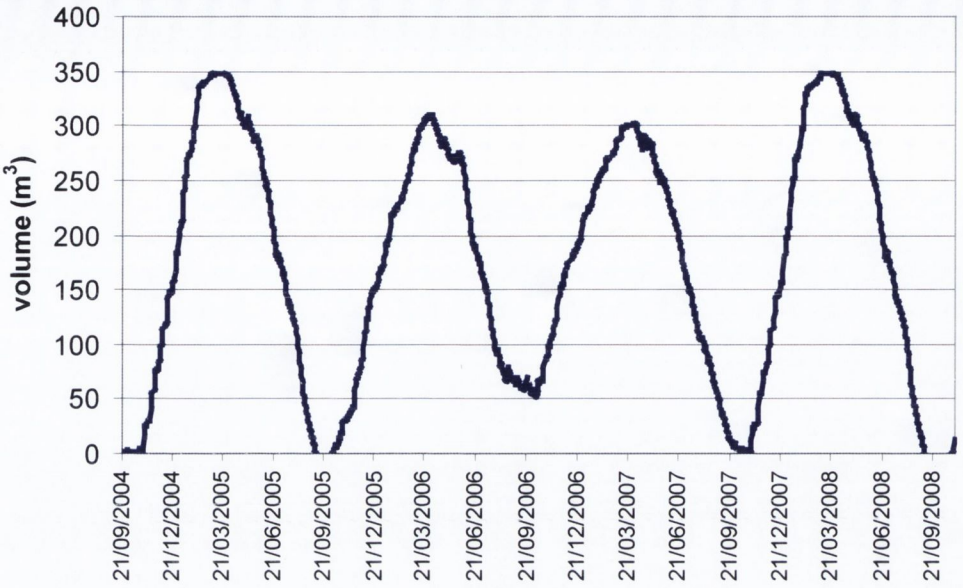


Figure 3.2 Example of water balance model output for design

From the example shown in Figure 3.2 a maximum storage of 350 m^3 would be required for the site in question. So, assuming a soil porosity of 30% an area of 648 m^2 with a depth of 1.8 m (excluding a 0.2 m berm) would be required.

3.3.4 *Construction Details*

The design details are illustrated in Figure 3.3. A soil height of 1.8 m was eventually chosen for the design with an extra 0.2 m made available with the creation of a berm around the perimeter at the top of the willow system (included as a safety feature in case of unforeseen flooding). This extra volume had the added advantage of having 100% pore space given that it was over ground.

The wastewater would be distributed throughout the willow system through 110 mm distribution pipes placed at 3 m centres.

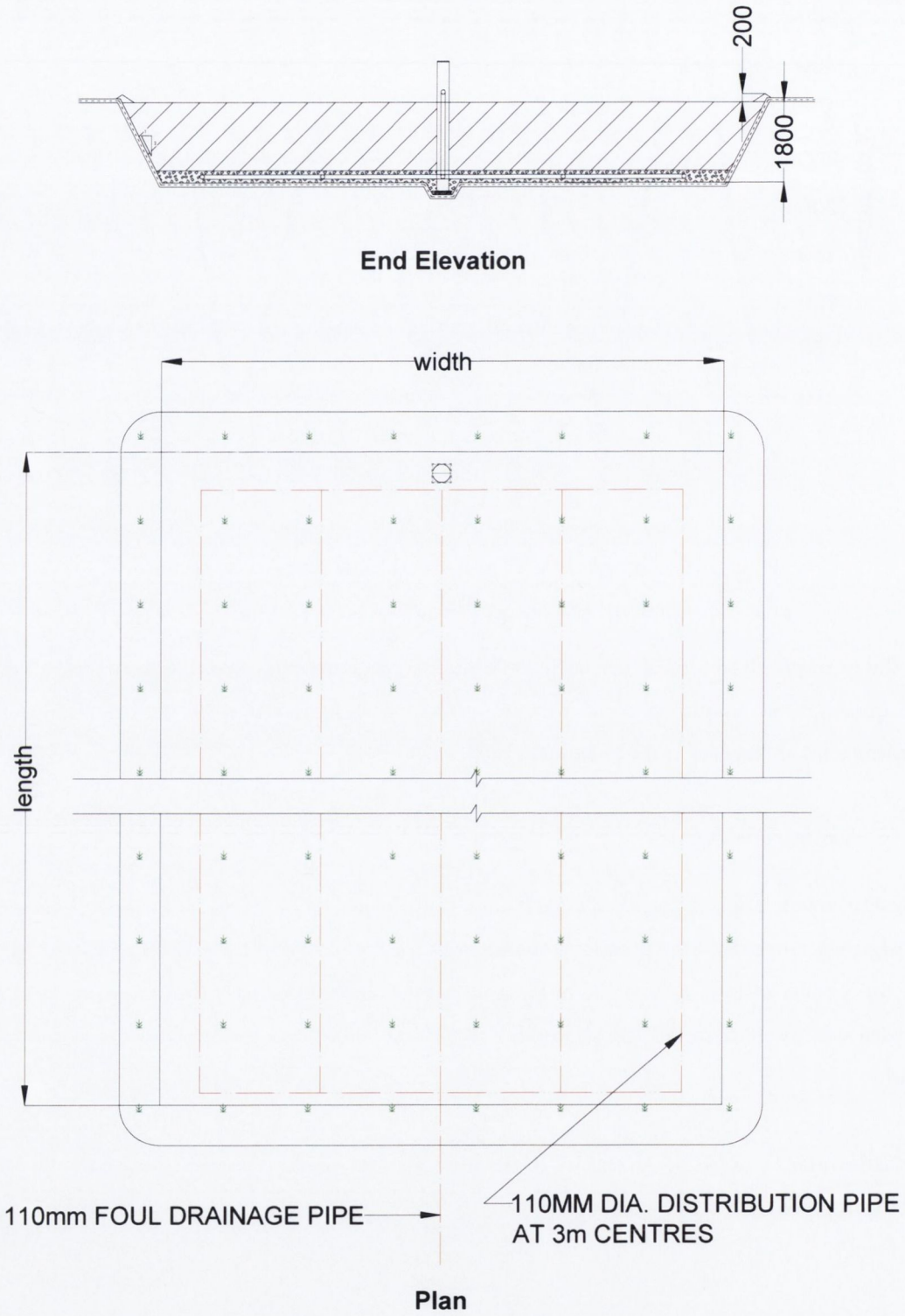


Figure 3.3 Plan and end elevation of willow system

Further details including the placement of the inspection well, gravel distribution layer and the placement of the impermeable membrane and geotextile membrane are shown in Figure 3.4.

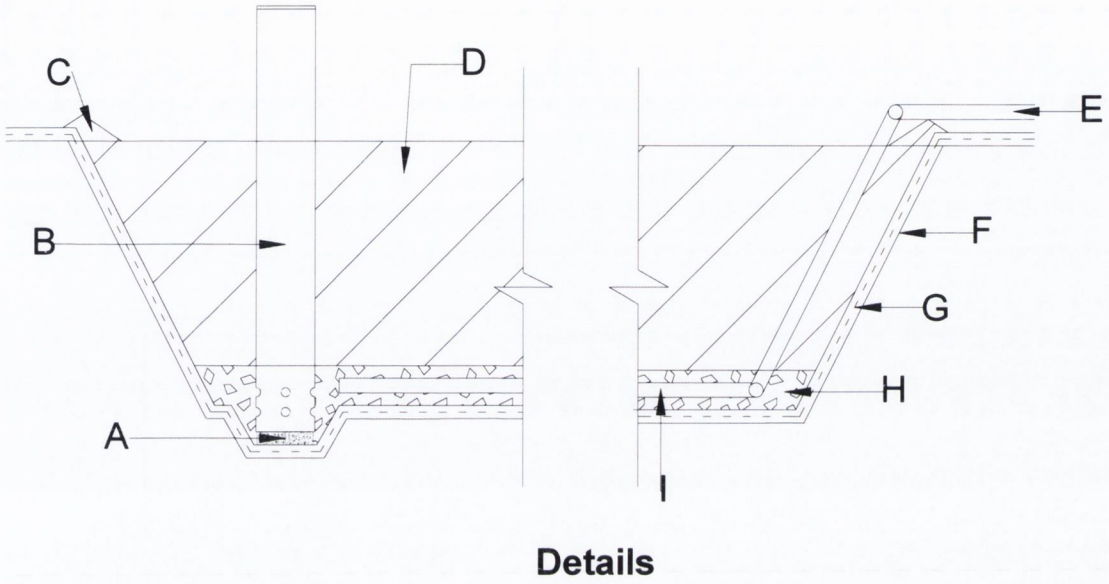


Figure 3.4 Willow system detail

A. Observation pipe sits on concrete slab/block in 200mm deep sump.
B. 300 mm diameter Plastic observation pipe (fitted with removable cap). Pipes is drilled with holes at the bottom to allow ingress of water and then wrapped in geotextile.
C. 200 mm high clay berm constructed over impermeable and geotextile layers, running around willow system perimeter at ground level.
D. In-situ soil refilled over gravel layer.
E. Effluent from proprietary system via 110 mm sewer pipe.
F. Geotextile membrane.
G. Impermeable membrane.
H. 300 mm deep gravel layer (10-30 mm washed gravel)
I. 110 mm diameter distribution pipe at 3 m centres.

3.4 Test Sites

As a result primarily from local authority recommendations, eight sites were selected for the construction and monitoring of 12 separate willow systems. (Note: at Sites F, H and I the effluent was split equally and sent to two separate systems of different design for comparison). In addition to the sites in Co. Wexford, the local authorities in Co. Leitrim and Co. Limerick also showed late interest in carrying out willow system trials (two counties that also suffer from low permeability subsoil) and as a result willow systems were constructed and monitored in these two counties as well. The location of the ten different sites is shown in Figure 3.5.



Figure 3.5 Test site locations

Due to the lack of interest from homeowners with existing dwellings discussed previously and the time taken to process new planning applications within the local authority, establishment of the systems took place on a staggered time frame over two years (May 2009 - May 2011).

The design of the systems was varied across the sites in order to allow a good spectrum of the relevant variables which were of importance to this research to be compared. These variables include:

- area requirement per PE
- aspect ratio
- willow clone variety
- type of influent
- distribution method

Sites A & B were designed with comparison of area requirement per PE in mind with both designed on the basis of 4 PE wastewater production. Site A had an area of 296 m^2 (area per PE of 74 m^2) while Site B had an area of 570 m^2 (area per PE of 143 m^2). The two willow systems on Site F were designed in such a manner so as to allow for aspect ratio comparison. While both willow systems had the same area (800 m^2) the dimensions differed so that one had an aspect ratio of 1.3 (32 m x 25 m) and the other had an aspect ratio of 8 (80 m x 10 m). The effect of varying the influent between STE and SE is examined across all the sites with the systems on seven of the sites receiving STE and the systems on the three remaining sites receiving SE. While practicalities on-site and financial restrictions were the main driving force in deciding the distribution method for a particular site, a good balance was still achieved across the sites.

An overview of the test sites including the number of willow systems per site, construction date, area, type of effluent and the means of effluent distribution are shown in Table 3.3. The willow clones were also varied across the sites, with the intention of singling out better performing varieties. Each willow system was planted with three different willow varieties that would allow the effect of different clones to be determined. The variety selection for the different sites is shown in Table 3.4.

Table 3.3 Overview of test sites

Site	Area per PE	Constructed	Effluent [a]	Area (m^2)	Distribution
A	74	May 2009	STE	296	pumped
B	142.5	May 2009	STE	570	pumped
C	105	April 2010	STE	420	pumped
D	77	May 2010	STE	464	pumped
E	NA	April 2010	STE	24	gravity
F (1)	72	July 2010	Sec	900	gravity
F (2)	72	July 2010	Sec	900	gravity
G	85	Sept. 2010	Sec	340	gravity
H (1)	87	April 2011	STE	260	gravity
H (2)	87	April 2011	STE	260	gravity
I (1)	93	May 2011	Sec	280	gravity
I (2)	93	May 2011	Sec	280	gravity
J	40	May 2012	STE	160	pumped

[a] STE, septic tank effluent; Sec, secondary treated effluent.

Table 3.4 List of willow clones on each site

Site	System	Willow Clone								
		Bjorn	Tora	Jorr	Tordis	Torhild	Sven	Inger	Olof	Native [a]
A	1	√	√	√						
B	1	√	√	√						
C	1		√		√	√				
D	1		√			√			√	
E	1									√
F	1		√		√				√	
	2		√		√				√	
G	1		√			√			√	
H	1		√		√			√		
	2		√		√			√		
I	1		√			√			√	
	2		√		√	√				
J	1		√		√	√				

[a] Native Species: goat willow (*Salix caprea*); grey willow (*Salix atrocinerea*); Bay willow (*Salix pentandra*); Eared Willow (*Salix aurita*)

3.4.1 *Sites A and B: Fardystown, Co. Wexford*

Test sites A and B are located adjacent to each other in Fardystown, Co. Wexford. The willow systems were built in conjunction with two new houses. Both systems receive STE and were designed for 4 PE. The STE was pump fed to the willow systems and underwent pressurised distribution as outlined in Section 3.6.3.1. Site A, which is 296 m^2, was designed by an external consultant prior to this research team's involvement with the trials, whereas Site B, which is 570 m^2, was designed by the Trinity College research team using the water balance model described in Section 3.3.3. The effluent flow was measured using an OTT Thalimedes level meter (see Section 3.7) located in the pump sump. The layout of the two sites can be seen in Figure 3.6 and an aerial photo can be seen in Figure 3.7.

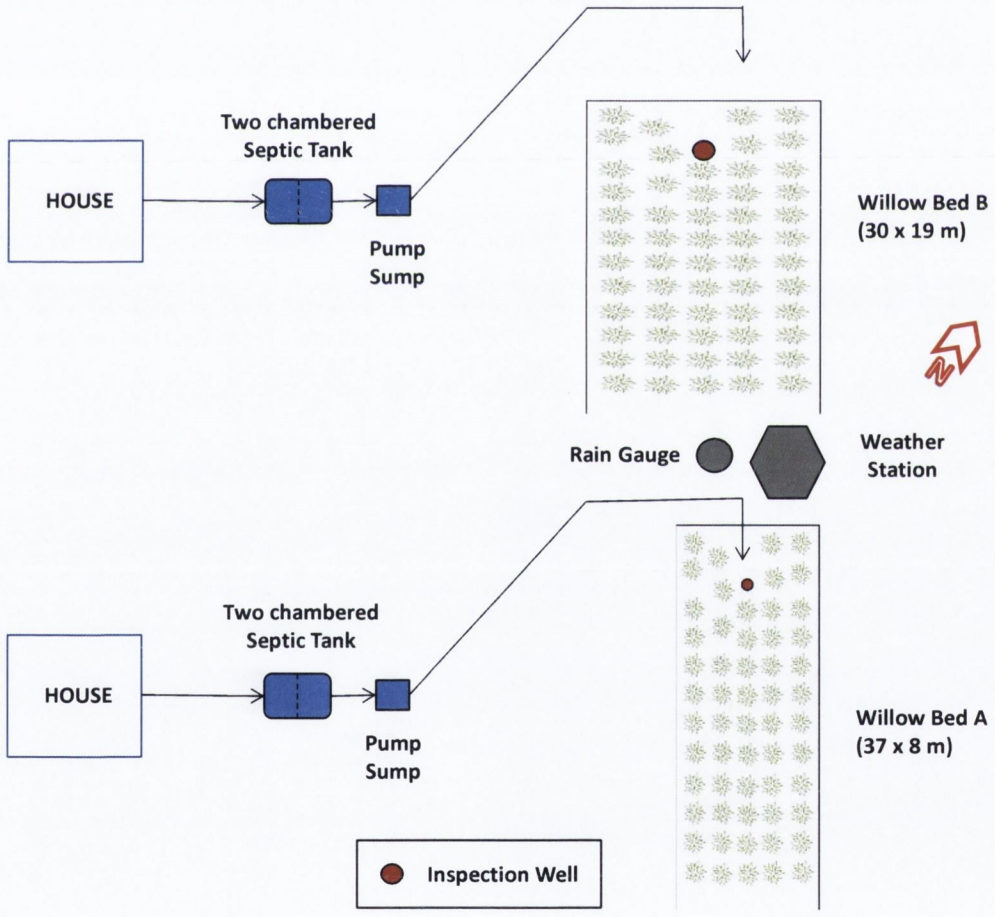


Figure 3.6 Construction plan and instrumentation layout of Sites A and B (Fardystown)



Figure 3.7 Aerial view of Sites A and B (with the willow systems highlighted in yellow)

3.4.2 *Site C: Borehovel, Co. Wexford*

Site C, designed for a PE of 4, receives STE from a pump sump, which undergoes non-pressurised distribution in gravel trenches within the willow system (as outlined in Section 3.6.3.2). The system, which has an area of 420 m², was built in conjunction with the house at the site. Effluent flow was determined by an OTT Thalimedes level meter located in the pump sump as described in Section 3.7. The site layout can be seen in Figure 3.8.

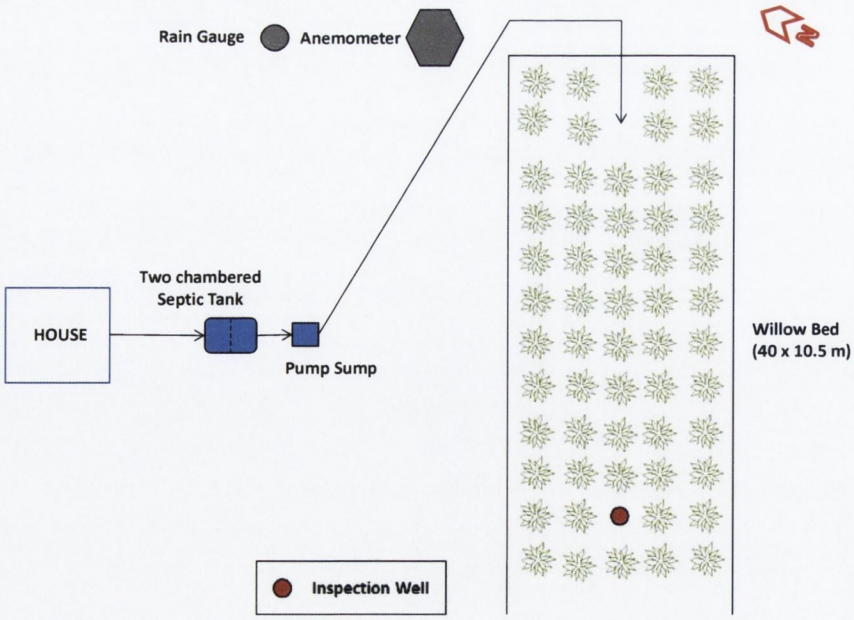


Figure 3.8 Construction plan and instrumentation layout of Site C (Borehovel)

3.4.3 *Site D: Ballask, Co. Wexford*

Site D, designed for a PE of 6, receives STE from a pump sump, which undergoes non-pressurised distribution in gravel trenches within the willow system (as outlined in Section 3.6.3). The willow system, which is 464 m^2 was constructed to replace a failing septic tank and percolation area serving the existing house, with the intention of connecting a newly built house, which replaces the old dwelling, to the system in 2012. Effluent flow was determined by an OTT Thalimedes located in the pump sump as described in Section 3.7. The site layout is shown in Figure 3.9.

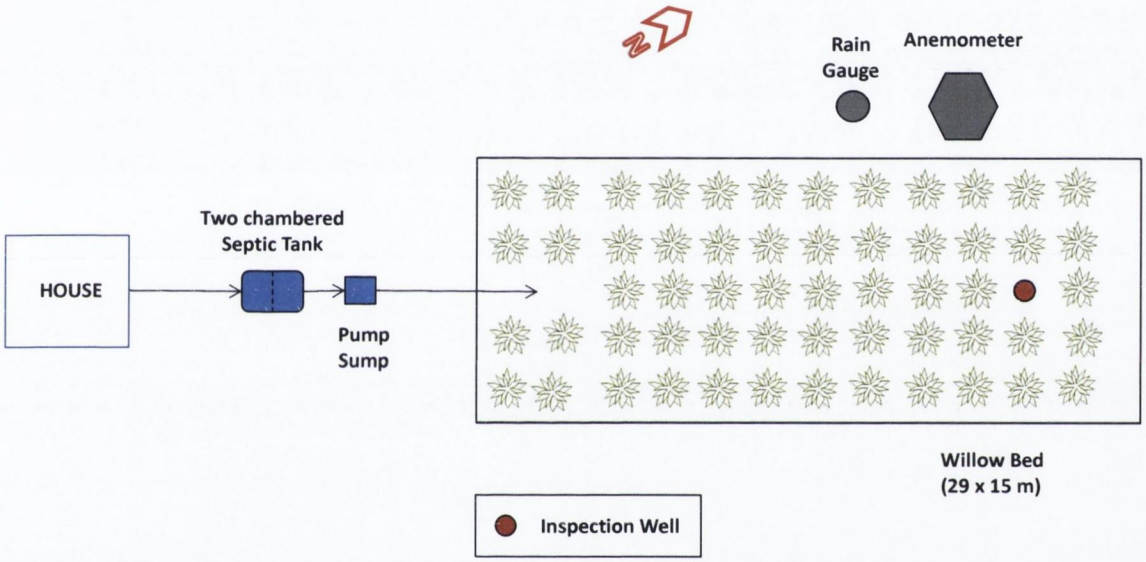


Figure 3.9 Construction plan and instrumentation layout of Site D (Ballask)

3.4.4 *Site E: Jamestown, Co. Wexford*

Site E consists of a small willow system which was designed to serve two stand-alone toilets in an outhouse. The owner of the site was about to open his farm to tours from local primary and secondary schools and required such toilet facilities. It was difficult to determine the exact wastewater volume at the site, however, future visitor numbers were estimated following discussion with the owner of the site an area of 24 m^2 was decided upon based upon a PE of 0.15. The details for the hydraulic load projections are given in Table 3.5. The system receives STE, which was gravity fed, with a tipping bucket providing flow measurements (as detailed in Section 3.7). The site layout can be seen in Figure 3.10.

Table 3.5 Hydraulic load projections for Site E

Month	No. of toilet uses				Cumulative Volume			Total
	School Groups	REPS groups	Wildlife Groups	Staff	Urinal (l)	Small Flush (l)	Full Flush (l)	Litres/month
January	-	-	-	31	29.1	40.7	50.4	120.1
February	-	50	-	28	73.1	102.4	126.8	302.3
March	-	-	30	31	57.2	80.1	99.1	236.4
April	-	-	-	30	28.1	39.4	48.8	116.3
May	200	50	-	31	263.4	368.8	456.6	1088.9
June	400	-	-	30	403.1	564.4	698.8	1666.3
July	-	-	-	31	29.1	40.7	50.4	120.1
August	-	50	-	31	75.9	106.3	131.6	313.9
September	-	-	30	30	56.3	78.8	97.5	232.5
October	-	-	-	31	29.1	40.7	50.4	120.1
November	-	50	-	30	75.0	105.0	130.0	310.0
December	-	-	-	31	29.1	40.7	50.4	120.1

Notes: School groups: 50 per visit (twice per year) for 6 weeks (May to June)
REPS groups: 50 per visit (4 visits per year)
Wildlife groups: 30 per visit (2 visits per year)
Assumed 50% female

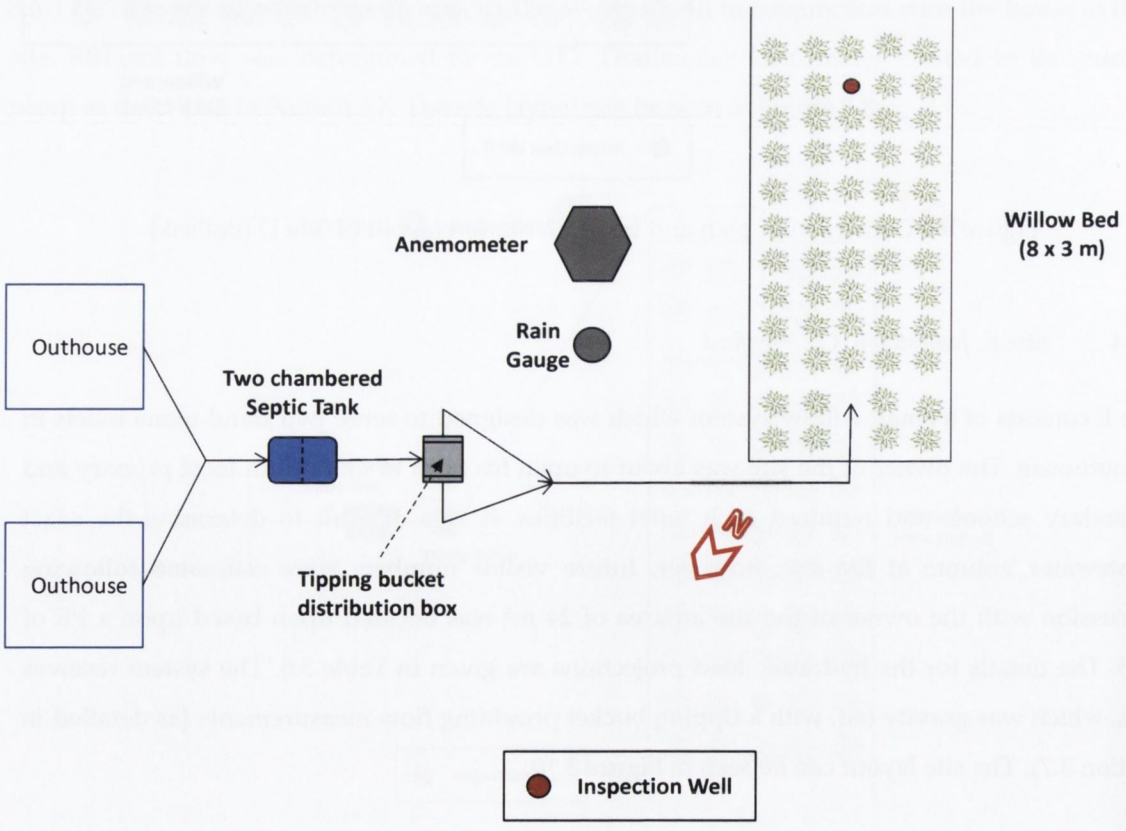


Figure 3.10 Construction plan and instrumentation layout of Site E (Jamestown)

3.4.5 *Site F: Ballywilliam, Co. Wexford*

Site F consists of two willow systems, which are both 800 m^2 and were constructed to replace a malfunctioning raised soil polishing bed. The polishing bed was in place for a number of years prior to the commencement of this project, before the local authority deemed it insufficient for adequate treatment and that a zero discharge system would be required for the site. The systems serve the five existing houses and were designed to cater for 25 PE. The effluent on the site undergoes primary and secondary treatment via an Enviropak Biological Aerated Filter (BAF) System (detailed in Section 3.5.4) before being pumped to a tipping bucket device which splits the effluent between the two willow systems. Distribution of the effluent is non-pressurised in a gravel layer at the base of the willow system as detailed in Section 3.6.3. Of the five houses only two were occupied throughout the duration of this project. Effluent flow was measured using a tipping bucket as detailed in Section 3.7. The layout of the site is shown in Figure 3.11.

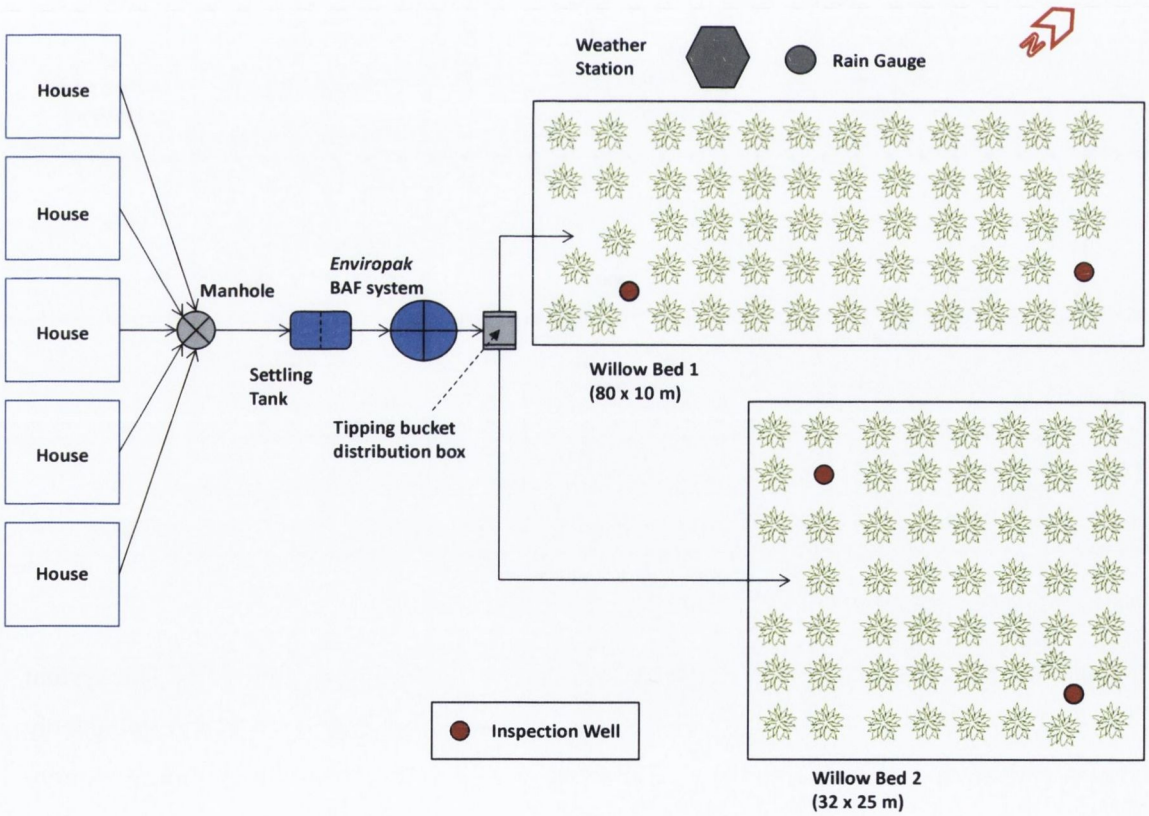


Figure 3.11 Construction plan and instrumentation layout of Site F (Ballywilliam)

3.4.6 *Site G: Ardcavan, Co. Wexford*

The willow system on Site G was designed to replace the constructed wetlands initially specified in the planning proposal. The system, which has an area of 340 m^2 was designed for 4 PE and is receiving secondary treated effluent from a *Puraflo®* peat filter treatment system. Effluent is gravity fed to the willow system, with non-pressurised distribution as outlined in Section 3.6.3. The system employed the use of clay liner. The effluent volume was measured using an OTT Thalimedes level meter located in the pump sump. The layout of the site can be seen in Figure 3.12.

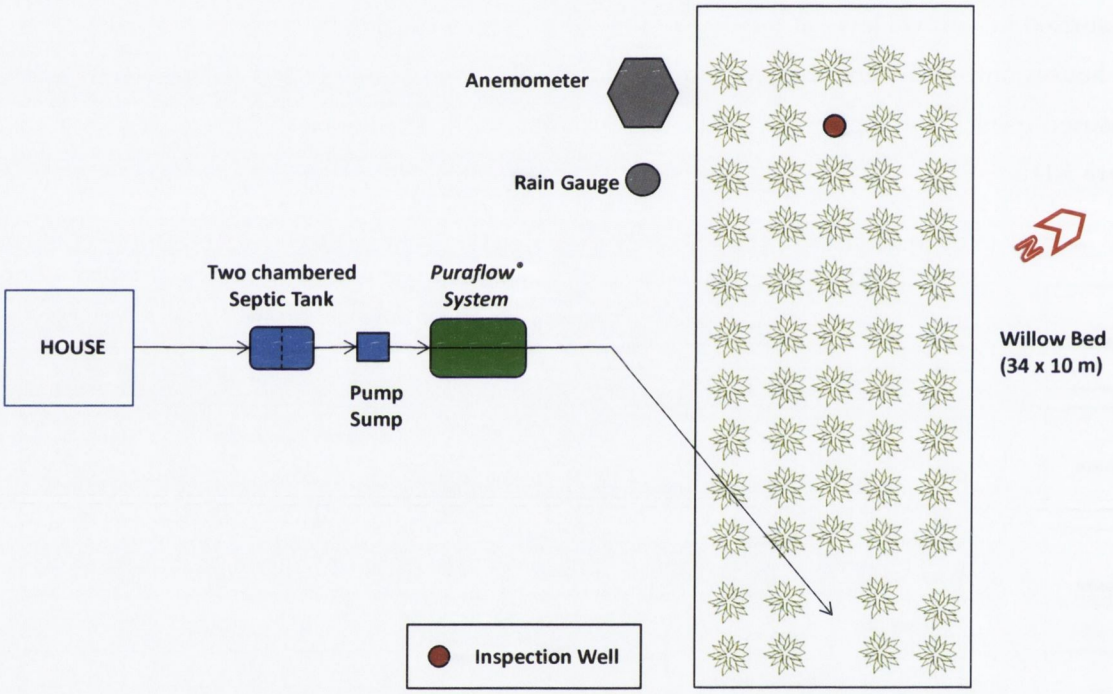


Figure 3.12 Construction plan and instrumentation layout of Site G (Ardcavan)

3.4.7 *Site H: Duncormick, Co. Wexford*

The treatment system at site H was designed to serve a new house with 6 PE. The system consists of two willow systems (each with an area of 260 m^2) receiving STE which is split evenly (using a T-junction splitter valve in the pipe) between each basin. The effluent undergoes non-pressurised distribution to a gravel layer at the base of the willow system, as detailed in Section 3.6.3. The effluent volume was measured using an OTT Thalimedes level meter located in the pump sump. The layout of the site is shown in Figure 3.13.

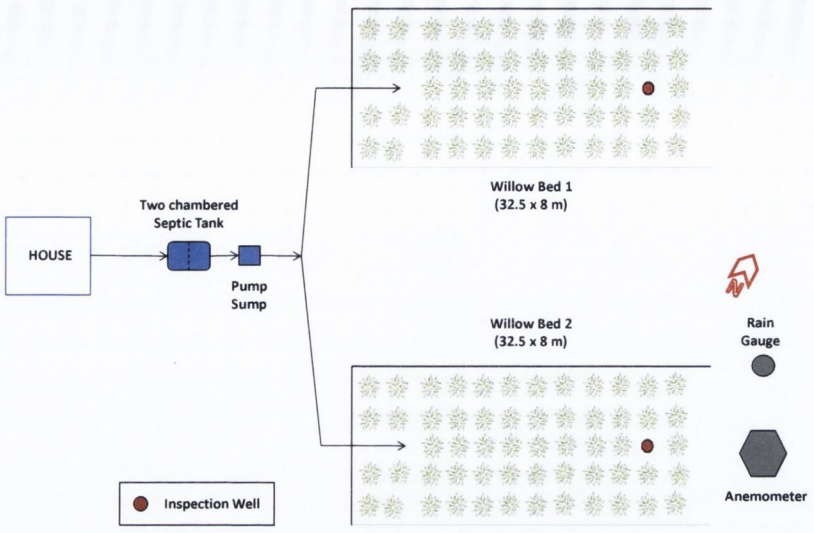


Figure 3.13 Construction plan and instrumentation layout of Site H (Duncormick)

3.4.8 *Site I: Carrigallen, Co. Leitrim*

Site I, which was given approval as a trial site by Leitrim County Council consists of two willow systems (each with an area of 280 m^2) for a PE of 6 receiving secondary treated effluent from an Envirocare P6 Treatment Unit. The effluent is split evenly between the two willow systems in a tipping bucket, which also measures the flow rate (as outlined in Section 3.7.2). From the tipping bucket the effluent is gravity fed to the willow systems where is undergoes non-pressurised distribution to a gravel layer at the base of the system, as detailed in Section 3.6.3. The layout of the site is shown in Figure 3.14.

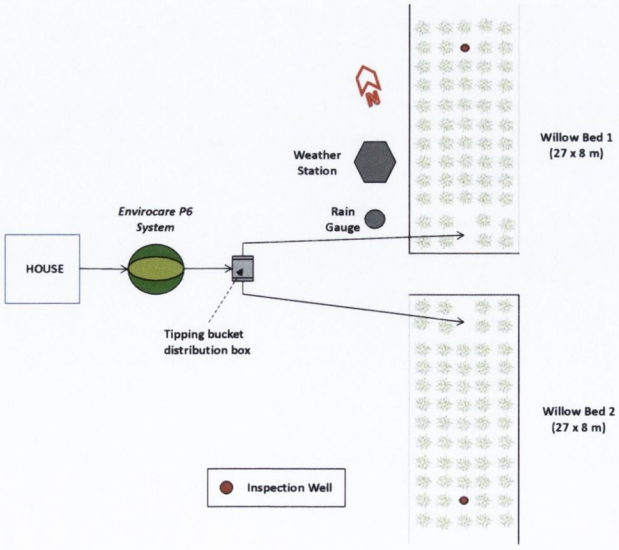


Figure 3.14 Construction plan and instrumentation layout of Site I (Carrigallen)

3.4.9 *Site J: Ballylanders, Co. Limerick*

Site J was given approval as a trial site by Limerick County Council in 2012. The willow system, which has an area of 170 m^2 for a PE of 4 was designed by the same external consultant that designed the willow system on Site A. The willow system receives STE from a pump sump, which then undergoes pressurized distribution throughout an EXPO-NET® BIOBLOCK trickling filter as outlined in Section 3.6.3.1. The layout of the site is shown in Figure 3.15.

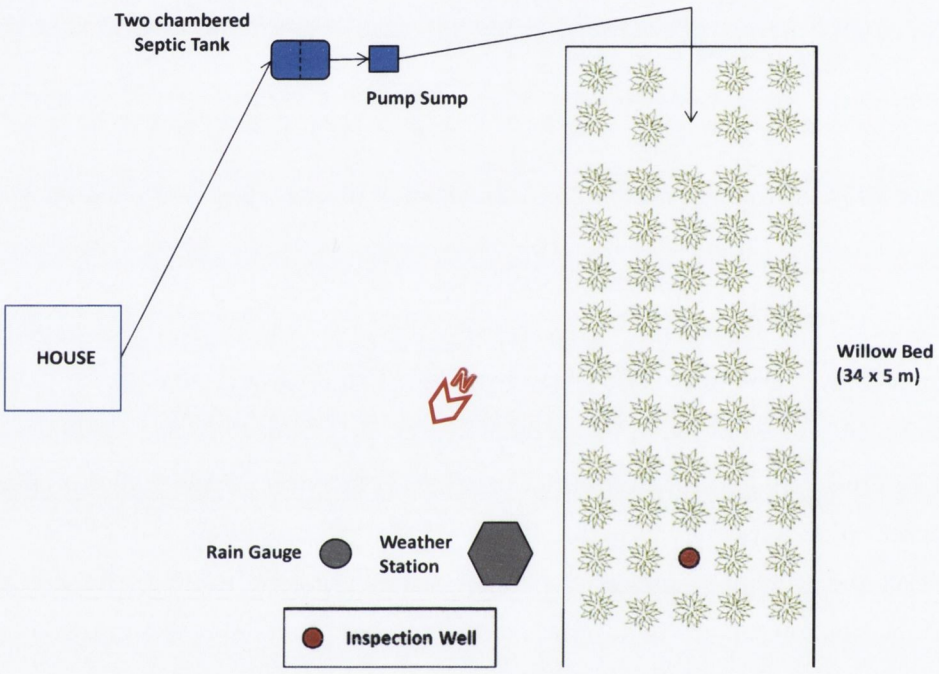


Figure 3.15 Construction plan and instrumentation layout of Site J (Ballylanders)

3.5 Proprietary Treatment Systems

3.5.1 *Septic Tank*

A prefabricated two-chambered, reinforced-concrete septic tank with adequate volume was installed on most of the sites (details on a case by case basis in Section 3.4). In some instances the septic tanks were already in place on the site, while some were installed along with the willow system. The size of tank used on any given site was in line with EPA specifications (EPA, 2009a) and provides an adequate retention time to allow for the settlement of suspended solids based on a national daily design hydraulic loading of 150 L/c/day (EPA, 2009a). The installation of the septic tank on Site C is illustrated in Figure 3.16.



(a) (b)

Figure 3.16 Installation of double chambered septic tank on Site C

(a) Lifting the septic into place

(b) Septic tank in position (with pump sump behind it)

3.5.2 *Puraflo® Effluent Treatment System*

There was a *Puraflo®* secondary treatment unit already in place on Site G before construction of the willow system commenced. The willow system was supplied with the effluent from this unit. The *Puraflo®* is a peat media filter system manufactured by Bord na Móna Environmental Ltd. It consists of a number of modules which contain layers of biofibrous (peat) media. Septic tank wastewater is intermittently dosed evenly; via the pipe distribution network (Figure 3.17) fitted with orifices, on top of the biofibrous media layers. The effluent then percolates through the peat where it is treated by passive biofiltration processes (filtration, adsorption, microbial assimilation). The treated effluent exits the unit via outlet pipework at the bottom, which lead to a sampling chamber, and then leaves the sampling chamber via 110 mm sewer pipe before entering the willow system.



Figure 3.17 Puraflow® Liquid Effluent Treatment System (cover removed)

3.5.3 *Envirocare P6 Treatment System*

Primary and secondary treatment of effluent before discharge to the willow system on Site I was provided by an Envirocare P6 treatment unit manufactured by Kingspan (Figure 3.18). The treatment process is divided up into three distinct processes within the unit. Firstly, course solids are filtered and then retained within the primary zone in the tank for further gradual breakdown. The resulting liquid effluent is then continuously distributed over a plastic suspended filter by an air lift powered by a remotely sited blower. Finally, the solids are allowed to settle and the treated effluent exits the unit, where it flows by gravity to a distribution box, which splits the flow between the two willow systems.

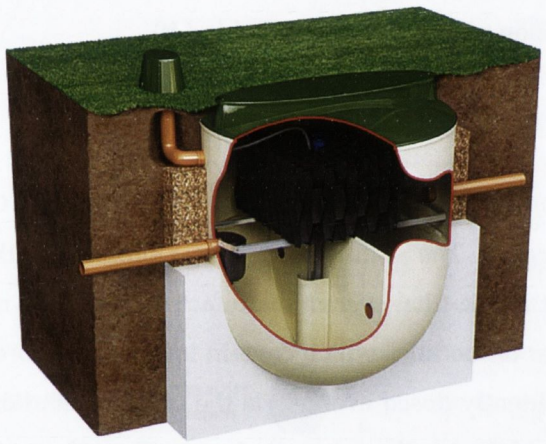


Figure 3.18 Envirocare P6 Treatment Unit

3.5.4 *Enviropak Biological Aerated Filter (BAF) System*

Secondary treatment on Site F was provided by an *Enviropak* Biological Treatment Unit (Figure 3.19) designed for a PE of 50. The unit is divided up into three different components. Firstly, the effluent enters a settlement tank where the solids settle out and undergo some anaerobic digestion. The liquid discharge then goes to the biological aeration media where it undergoes microbial treatment, with the pollutants forming solid particles. Oxygen is supplied to the media via air pumps. The effluent then goes to the clarifier for final settling, and the remaining solids settle out and return to the aeration zone. The treated effluent at the top of the clarifier flows over a weir into a sump from where it is pumped from the system to a distribution box, which splits the flow between the two willow systems.

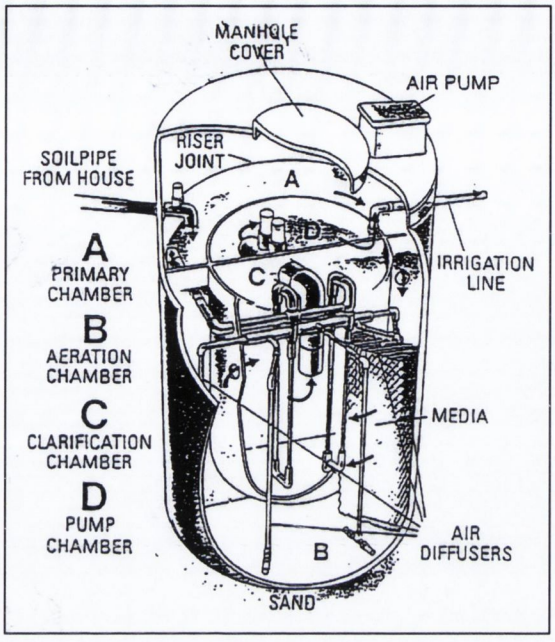


Figure 3.19 A biological aerated filter (BAF) system

3.6 Construction of Willow System

Construction of the willow systems on all sites involved a number of stages which all required much attention to detail. Prior to the excavation of the soil, survey levels were taken upstream of the proposed system location to determine if there was a sufficient hydraulic head to allow for gravity distribution of effluent or whether pumped distribution would be required.

3.6.1 Excavation

The basin was excavated to a depth of 1.8 m (depth from surface to base of willow system). The slopes of the sides of the basin were kept as straight as possible (see Figure 3.20) in order to maximise the storage volume in the system; this is in contrast to the Danish guidelines (Miljøstyrelsen, 2003), which uses a slope of 45°. Any remaining sharp stones were then removed from the basin to aid against puncture of the impermeable membrane.



(a) **(b)**

Figure 3.20 Excavation of basins

(a) Excavated basin on Site D (water table can be seen)

(b) Excavation almost complete on System 1 on Site I

3.6.2 Liner

A geosynthetic barrier (specifications for each site detailed in Section 3.4) was laid along the bottom and sides of the excavated basin, allowing for a 0.1 m overlap between membranes. An excess was left along the top edge of the basin in order to maintain a seal along the berm. The impermeable membrane was the laid on top of the geosynthetic barrier, with an excess kept along the top in the same manner. A comparison of the material properties of the three different liners used at their respective sites is shown in Table 3.6.

Table 3.6 Impermeable Liner Properties Comparison

Liner [a]	**Property**					**Sites**
	Thickness (mm)	Strength at break (MPa)	Elongation at break (%)	Tear Resistance (N/mm)	Puncture Resistance (N)	
1	0.50	>18	>750	>45	>120	F
2	0.75	8	350	30	-	C, D, E, I
3	0.50	13	800	50	120	A & B, H, J

[a] 1, *Wepelen*® Geosynthetic barrier FPP;
2, Butyl Rubber;
3, *GSE Environmental* UltraFlex LDPE

In the case of the impermeable membrane consisting of multiple sections (Liners 1 and 3 respectively), the joints were welded by a qualified professional in order to maintain water-

tightness. A second geosynthetic barrier was laid on top of the impermeable membrane to prevent punctures occurring when the soil is being refilled back into the basin. The installation of the geosynthetic barrier and impermeable membrane is illustrated in Figure 3.21.

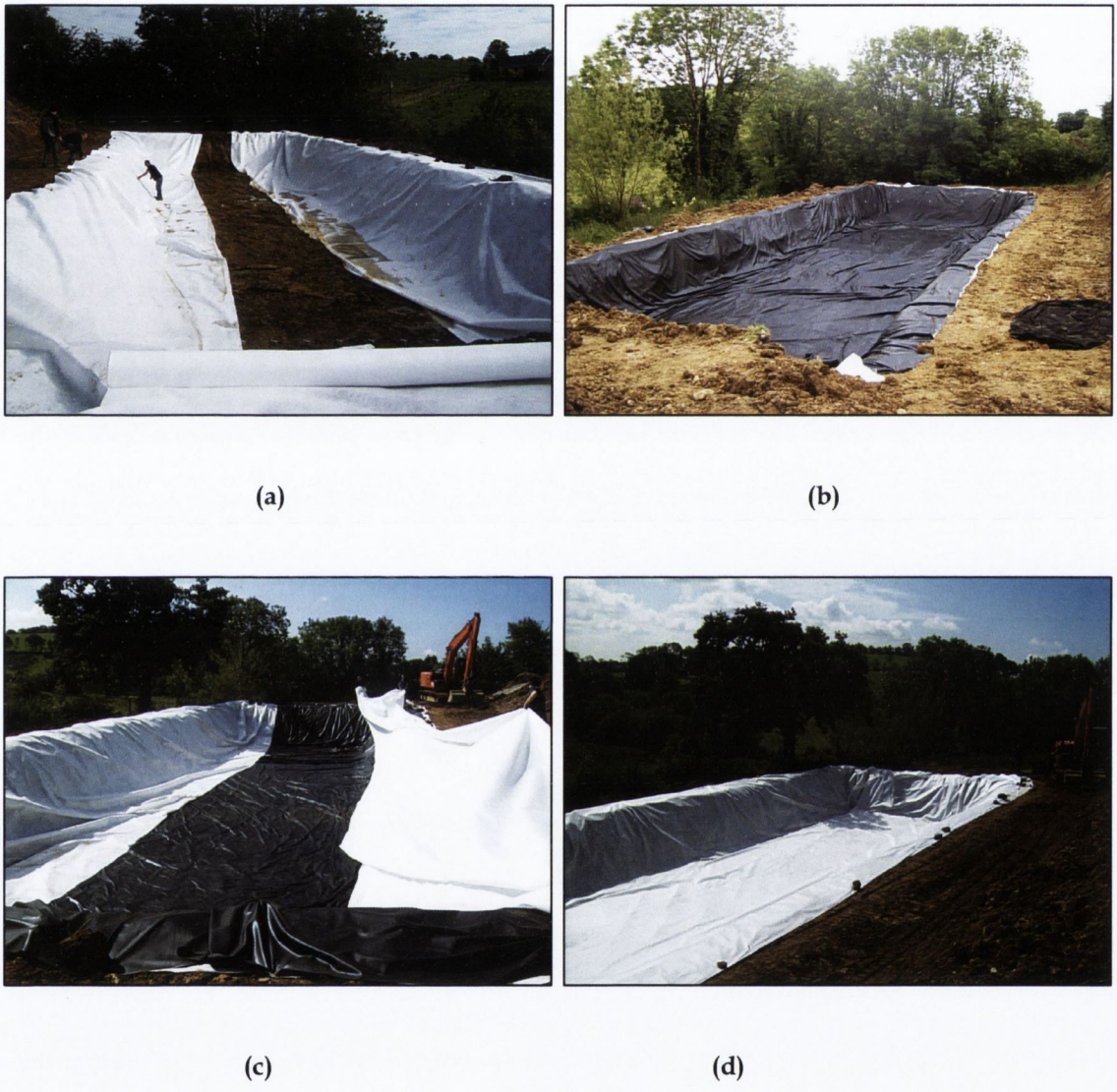


Figure 3.21 Geosynthetic barrier and impermeable membrane installation

(a) Laying of first geosynthetic barrier (under impermeable membrane)

(b) Laying impermeable membrane

(c) Laying of second geosynthetic barrier (over impermeable membrane)

(d) Completed installation of barrier and membrane

3.6.3 *Distribution Layer*

The effluent was distributed throughout the willow system in a high porosity layer situated in the soil medium. There were a number of different variations of this as outlined below.

3.6.3.1 *Pressurised Distribution*

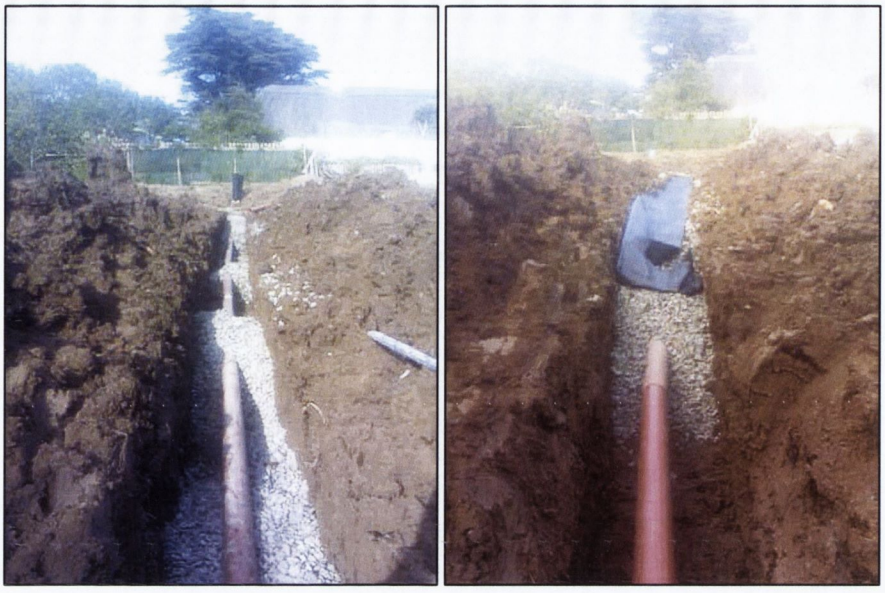
This option was used on the two systems which adhered strictly to the Danish design guidelines. The soil was backfilled in to a depth of 1 m. A 0.1 m layer of washed sand (1-4 mm) was placed on top of the soil. The distribution layer which consists of EXPO-NET® BIOBLOCK 200 (0.275 x 0.275 x 0.55 m) trickling filters are placed end to end along the centre line of the system on top of the sand layer. The blocks are strapped together with cable ties. A semi-rigid 40 mm diameter distribution pipe with drilled percolation holes was strapped to the top of the trickling filter blocks. An excess of 4 m was left at the end of the pipe (which is sealed) to allow it protrude over the surface of the willow system. The start of the pipe is connected to the pressure pipe coming from the pump. The distribution layer and piping was then surrounded in a geosynthetic barrier.

3.6.3.2 *Non-Pressurised Distribution*

This option comprised of Wavin® 110 mm percolation pipes placed in a medium consisting of 8-32 mm washed gravel. There were two variations in the layout of the gravel medium as detailed in the following subsections.

3.6.3.3 *Gravel trench*

The soil was backfilled to a depth of 1.2 m. The gravel trenches (300 mm width x 300 mm depth) were then excavated from this level, along the length of the basin to within 2 m of the ends. The bottom and sides of the trenches were lined with a geosynthetic barrier (to prevent ingress of soil particles into the gravel medium) leaving enough of an excess to loop over the top of the gravel layer. The gravel was added to a depth of 100 mm within the trench and the percolation piping was then laid on top of this with the holes facing down. The trench was then filled to the top with gravel, surrounding the percolation pipe in the process. The excess geosynthetic barrier was looped over the top of the gravel and held in place with mounds of sand placed sporadically along the length of the trench. The trenches were laid out as shown in Figure 3.22 with one inlet pipe (Wavin® 110 mm sewer pipe) serving all the percolation pipes. The trenches were situated at 2 m centres so the number varied per system. This method of distribution was implemented on Sites C, D, E, and G.



(a) (b)

Figure 3.22 Installation of gravel trench distribution system

(a) Percolation pipe being laid at a depth of 100 mm in trench

(b) Semi completed trench showing full depth of gravel and synthetic barrier on top

Gravel layer

This option was used in the later willow systems (Sites F, H, and I) to improve storage volume within the system - the void ratio of the gravel was measured to be 32%. The gravel was laid to a depth of 100 mm on top of the geosynthetic barrier at the base. The percolation pipes were then laid, holes facing down, on top of the gravel, along the length of the willow system. More gravel was added, bringing the overall depth to 300 mm, surrounding the percolation pipes in the process (see Figure 3.23(a)). The gravel layer was then covered with a geosynthetic barrier to prevent ingress of soil particles. The layout of the pipe work can be seen in Figure 3.23 (b). As with the trenches, the percolation pipes were served by one inlet pipe (Wavin® 110 mm sewer pipe).

Effluent was supplied to the non-pressurised distribution system by gravity fall if the site allowed for it, or else via a pump. In the case of a gravity feed, a Wavin® 110 mm sewer pipe stretched from the effluent source (secondary treatment system/tipping bucket/distribution box) to the willow system, connecting with the inlet pipe by means of a Wavin® 110 mm coupler. For the pump feed, the semi-rigid piping (maximum diameter of 40 mm) ran from the pump sump to the willow system and was connected to the inlet pipe using a connection, as shown in Figure 3.24.



(a) (b)

Figure 3.23 Installation of gravel layer distribution system

(a) Laying of 300 mm layer of gravel on top of geosynthetic membrane

(b) Laying percolation pipes within gravel layer



(a) (b)

Figure 3.24 Connection between pipe from pump and inlet pipe

(a) Fitting before semi rigid pipe from pump is attached

(b) Fitting after the pipe has been attached

3.6.4 *Inspection Well, Refilling and Berms*

A 400 x 400 mm concrete tile was placed 2 m from one end, on the base of the willow system. A 2 m length of 300 mm diameter plastic pipe was placed on top of the tile. Slots were cut in the pipe, which was then wrapped in a geosynthetic barrier to allow for the ingress of water, while preventing soil blocking the slots (Figure 3.25(a)). Placement of the inspection well took place

before any gravel or soil has been backfilled into the basin. A cover is placed at the top of the inspection well as a safety measure.

Assuming the gravel layer/trenches were in place, the rest of the soil was backfilled into the basin, bringing it back up to ground level (Figure 3.25(b & c)). For the later systems it was ensured that some topsoil was left to place at the top, to maximise the chances of establishment and development of the willow cuttings.

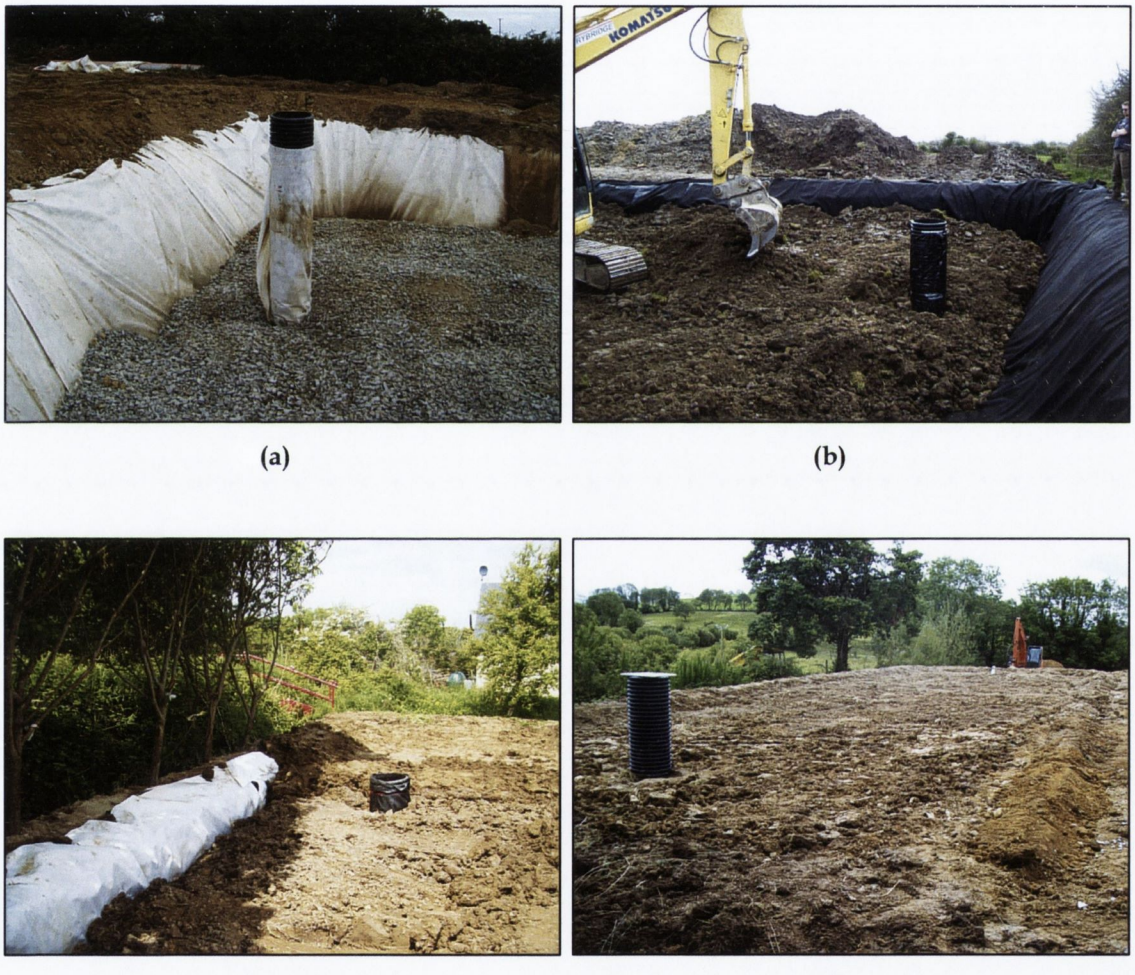


Figure 3.25 Installation of inspection well, berm and refilling of basin

(a) Inspection well wrapped in geosynthetic barrier

(b) Refilling of soil into basin

(c) Semi completed berm around perimeter

(d) Completed willow system.

Overflow protection in the instance of flooding was provided by a berm erected around the perimeter at the top of system Figure 3.25 (d). The berm took the shape of a 300 mm high soil ditch, which also incorporated the excess geosynthetic barrier and impermeable membrane left over from lining the base and sides of the system.

3.7 Instrumentation

3.7.1 Monitoring of Willow System Influent and Water Level

Two different methods were used to measure the overall wastewater production on the test sites. The method used depended on proprietary pre-treatment systems and the properties of the site.

3.7.2 Tipping bucket flow gauge

A tipping bucket device was used to measure flow on the sites that had a sufficient slope to allow for gravity feed from the proprietary system to the willow system. This device had the added advantage of being able to split the flow evenly between systems on sites with two willow systems. The reed switch on the tipping bucket was connected to a Solinist® Rainlogger (Model 3002) datalogger. The effluent was directed onto one side of the tipping bucket via a 110 mm sewer pipe. When a certain volume of effluent collected it would cause the tipping bucket to tip, emptying it, and then allowing the other side of the bucket to start filling (Figure 3.26). Each tipping event was recorded by the datalogger. The flow rate was then calculated on the basis of the number of tips and the known volume of effluent (as calibrated in-situ on each site) required to cause a tip.

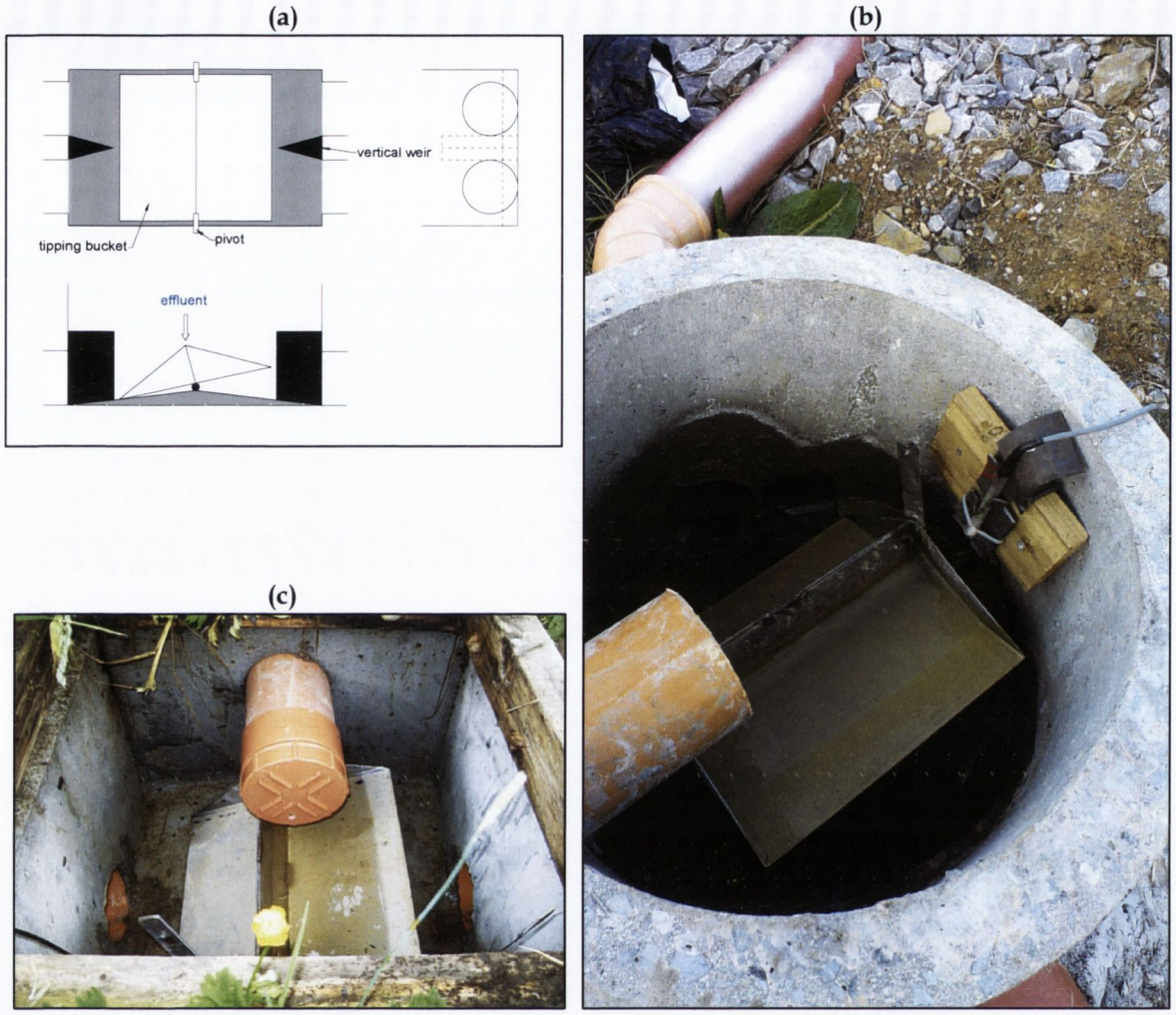


Figure 3.26 Tipping bucket distribution design: **(a)** schematic, **(b)** photograph of design installed on Site I and **(c)** photograph of design installed on Site F

3.7.3 *Water Level Meter*

Pumping of effluent to the willow system was required on sites with an inadequate slope to allow for gravity feed. Upon exiting the proprietary system, the effluent enters a pump sump. The sump houses a submersible pump operating on a float switch. When a certain level of wastewater is reached within the sump, the pump comes on emptying the sump back to the original level. An OTT Thalimedes water level meter (accuracy: ± 0.002 m) was installed in the sump to measure this difference in water level. Changes in the water level are transferred via a float-cable-counterweight-system to the float pulley on the encoder unit. The rotation caused by this action is converted to an electrical signal, which is transferred by the transducer cable to the data logger and then saved as a measured value. The flow rate was calculated on the basis of drops in water level and the known volume of effluent discharged with each drop.

3.7.4 *Water Level Monitoring within Willow System*

The water level within the willow system was measured on an hourly basis using an OTT Orpheus Mini groundwater datalogger (accuracy: ± 1 mm). The instrument consists of a pressure probe which uses the hydrostatic pressure of the water above a relative pressure transducer to determine the water level. A reference value is input at start-up and all subsequent measurements are based on this. The sample interval was set to 20 minutes and the average of three consecutive sample intervals was determined by the datalogger to produce an hourly average.

3.7.5 *Meteorology Instrumentation*

In order to assess the meteorological effects (evapotranspiration and precipitation levels) on the willow systems, relevant data from weather stations and rain gauges were required. Due to the project's financial restrictions it was not possible to erect a full weather station on all sites. As such, full Campbell Scientific weather stations (see Figure 3.27 for an example) were installed on Site A&B (south Co. Wexford) and Site F (north Co. Wexford). The parameters recorded from each station were temperature, relative humidity, wind speed, solar radiation and net radiation. Two additional weather stations (on Site I and Site J) were set up later in the research project when additional funding became available.



Figure 3.27 Full weather station on Site I

A list of the various instruments used to measure the different parameters is shown in Table 3.7. The instruments were either connected to a Campbell Scientific® CR800 datalogger (Sites A&B, I, J) or a Campbell Scientific® CR1000 datalogger (Site F).

Table 3.7 Meteorological instrument specifications for full weather stations

Parameter	Instrument	Manufacturer	Units	Accuracy
Temperature	CS215	CS [a]	°C	± 0.4 °C
Relative Humidity	CS215	CS [a]	%	± 4 %
Wind Speed	03002 RMY [b]	R.M. Young	m/s	± 0.5 m/s
Net Radiation	NR-Lite NR [c]	Kipp & Zonen	W/m²	-

[a] CS, Campbell Scientific®

[b] RMY, R.M. Young Wind Sentry Set

[c] NR, Net Radiometer

Anemometers were erected on all other sites (Sites C, D, E, G, and H) to measure wind speed, as this was reasoned to be the variable likeliest to have the largest variation between sites (Figure 3.28). The anemometers used were Gill Instruments Windsonic Two Dimensional Sonic Anemometers (unit: m/s; accuracy: ± 2% of reading). All other parameters for these sites were acquired from the two full weather stations.



Figure 3.28 Windsonic anemometer and ARG100 tipping bucket rain gauge on Site C

In order to record precipitation levels, an ARG100 tipping bucket rain gauge was installed on all sites (Figure 3.28). These were either connected to a Campbell Scientific® CR800 datalogger (Sites A&B, I, J) or a Campbell Scientific® CR1000 datalogger (Site F) on the sites with a full weather station and to Solinist® Rainlogger (Model 3002) datalogger on the remaining sites. The precipitation was directed onto one side of the tipping bucket via the funnel shaped rain gauge cover. Every 0.2 mm of precipitation caused the tipping bucket to tip and each tipping event was recorded by the datalogger. A general rule of thumb is that the distance to obstructions should be two to four times (Aasc, 1985, USEPA, 1987) the height of the obstruction, so as not to impede collection. However, these guidelines could be ignored to a certain degree for this project as it was the precipitation falling on the willow system rather than the areal precipitation that was of interest. The rain gauge and other meteorological instrumentation were then placed in an appropriate position adjacent to the willow system on each site. The rain gauge funnel and inlet mesh were cleaned and the recorded data downloaded upon regular visits to all sites.

3.8 Water Sampling and Analysis

3.8.1 Sample Collection

Given that the greatest volume of effluent (100 mL) was required for zero dilution bacteriological analysis, water and wastewater samples were firstly transferred directly on site from the 300 mL sample bottles to disposable Colilert®-18 (Section 3.8.3) 100 mL sterile vessels containing sodium thiosulphate. The sample bottles were then topped up and the sample volume was used for the chemical analysis. All 300 mL sample bottles were sterilised prior to each sampling event. After all sample bottles were capped, they were stored in a cooler box and transported directly to the Environmental Engineering Laboratory in TCD for analysis.

3.8.2 Chemical Analysis

Throughout the duration of the field studies, all septic tank, secondary treated effluent and willow system (taken from inspection well within the system) samples were analysed for chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N), orthophosphate (PO_4-P), chloride (Cl) and sulphate (SO_4) using a Merck Spectroquant Nova 60® spectrophotometer and associated USEPA approved reagent kits. Concentrations of organic nitrogen (org-N) and total kjildahl nitrogen (TKN) for the wastewater samples could then be deduced using TN, NH_4-N, NO_2-N and NO_3-N concentration results

derived from laboratory analysis. Eqn. 3.2 was used to determine the inorganic-N concentrations, while Eqn. 3.3 was used to determine the org-N concentrations. TKN concentrations were then calculated through use of Eqn. 3.4.

$$Inorganic\text{-}N = NO_2\text{-}N + NO_3\text{-}N + NH_4\text{-}N \quad \text{Eqn. 3.2}$$

$$Organic\text{-}N = TN - (NO_2\text{-}N + NO_3\text{-}N + NH_4\text{-}N) \quad \text{Eqn. 3.3}$$

$$TKN = Organic\text{-}N + NH_4\text{-}N \quad \text{Eqn. 3.4}$$

3.8.3 Bacteriological Analysis

All water and wastewater samples tested for chemical analysis were also tested for the presence of pathogenic bacteria. Total Coliforms (TC) and *E. coli* are two common indicator organisms of faecal contamination which donate the possible presence of enteric bacteria. Their presence in the designated samples was detected using the IDEXX Colilert®-18 test. Colilert®-18, with its patented Defined Substrate Technology® (DST®), is the only USEPA approved 18 hour test and is currently used for water quality analysis in over 90% of all US State laboratories. DST® uses two nutrient-indicators, ONPG and MUG, as the major sources of carbon in this test and can be metabolised by the coliform enzyme β-galactosidase and the *E. coli* enzyme β-glucuronidase, respectively. As coliforms then grow in Colilert®-18, they use β-galactosidase to metabolise ONPG and change it from colourless to yellow. *E. coli* use β-glucuronidase to metabolise MUG and create fluorescence. Enumeration of TC and *E. coli* was carried out using IDEXX Quanti-Tray®/2000, a semi-automated quantification method based on the Standard Methods Most Probably Number (MPN) model. As each tray provides a maximum count of 2,419 MPN/100 m/l, serial dilutions using sterilised water were prepared in the laboratory for the septic tank and secondary treated effluent samples as well as for a number of the willow system samples.

In the case of coliform analysis, log-unit load removal (where each log represents a decrease of one order of magnitude in pollutant load) is the most commonly used performance indicator and is adopted in both wastewater and willow system analysis.

3.9 Willow Establishment and Maintenance

3.9.1 Planting

The willow cuttings were planted at a density of 3 per m^2. Initially, the willow rods (purchased from Rural Generation Ltd, Derry and Timberpro Ltd, Kells) were cut into 200 mm lengths. However, following poor growth on some sites in the first year it was decided to increase the length of the cuttings to 300 mm for the remaining sites in order to improve their chances of being in adequate soil moisture during dry condtions and prevent the top of them being drowned in flooded conditions (if this occurred during the start-up period). The surface of the willow system was mapped out into 1 m^2 grids using builders line. Three cuttings were then planted in each grid square as per the SRC guidelines. The willow varieties used for each site are detailed in Section 3.4.

3.9.2 Coppicing

After the first year of growth the willows will generally have 1-3 shoots with a maximum height of 2-3 m. Coppicing of all the willows was then carried out, in accordance with standard short rotation coppice guidelines (Caslin et al., 2010, Defra, 2002), in the first dormant season, with all shoots cut back as close to the ground as practically possible (Figure 3.29). This will encourage vigorous growth and multiple shoot development in the following season. Cutback was carried out in a three year cycle thereafter, with alternating thirds of the willow system cut every year.



Figure 3.29 Coppiced willow shoots

3.9.3 *Weed Control*

After the first year of monitoring it was noticed that weed growth was an issue on a number of the sites. In an effort to ascertain the best course of remedial action on heavily weeded sites, an experiment was set up on System 1 on Site F to compare different remedial techniques. The three different methods included covering with weed proof membrane, spraying of weeds with herbicide, and manual removal of weeds. Each of these removal methods was implemented on a 5 x 5 m square of the willow system and the results compared to an area which was left with the weeds intact. The development in of the willow trees in each plot was monitored to see if there was a visual difference. Overall the results from the trial were inconclusive, as the relatively infrequent visits to the site meant some of the method (primarily the manual removal of weeds) was difficult to continuously implement.

Chapter 4

Site Characteristics – Meteorological, Effluent Loading and Soil Porosity

4 Site Characteristics - Meteorological, Effluent Loading and Soil Porosity

4.1 Introduction

This chapter examines the meteorological data and effluent loading onto the willow systems for each site, as well as the soil porosity for the soil within each willow system. Each of these is a key prerequisite to carrying out a detailed water balance for each system. The chapter also includes a description of the soil mineralogy for a number of the sites.

4.2 Meteorological Data

In order to accurately determine the evapotranspiration performance of each individual willow system, the meteorological data between the sites needed to be rigorously assessed. As outlined in the Methodology, full weather stations were installed at two locations (at Sites A&B and at Site F) whilst all other sites had an anemometer and rain gauge installed as it was decided that these parameters were most likely to have greatest local variance. This section examines the calculated reference evapotranspiration, along with the different meteorological parameters for each site. The annual rainfall measured at each site has also been compared to the 30 year (1981 - 2010) average rainfall recorded at Met Éireann's Johnstown Castle weather station in south Co. Wexford. Statistical comparisons of the parameters from the different sites are then carried out at the end of Section 4.2.

In the case of a site not having a full weather station, the net radiation ($MJ/m^2/day$), temperature (°C) and humidity (%) values used in the Penman Monteith equation for the calculation of ET_o were taken from the two full weather stations. This was carried out by determining weighted values based on the distances from a particular site to the two sites with full weather stations. If the site in question was not situated between the two sites with weather stations then the values used were taken directly from the closest site.

4.2.1 Sites A & B Fardystown

Measurement of meteorological data commenced in March 2010 for Sites A & B. Total rainfall measured over the sampling period was found to be 3002.3 mm (March - December 2010: 829.4 mm; 2011: 828 mm; 2012: 1278.9 mm; January - May 2013: 377.7 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 1.95 m/s with speeds

ranging from 0.01 m/s to 7.89 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Sites A & B are shown in Figure 4.1 with the daily reference evapotranspiration shown in Figure 4.2.

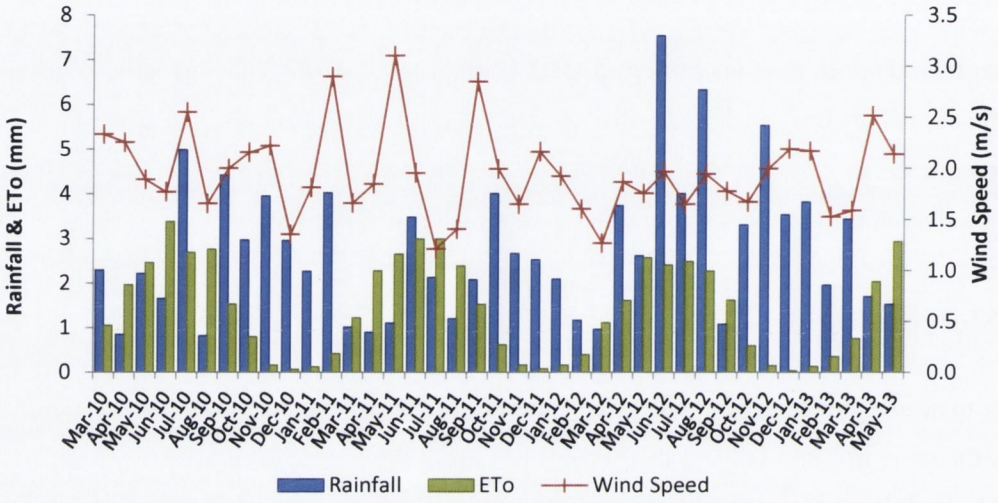


Figure 4.1 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Sites A & B

Mean ET_o was measured at 1.44 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.55 mm/day. The effects of seasonality can be seen, with mean daily values much higher in the summer months (April to September) than in the cooler winter months. As shown by the wind rose graphic in Figure 4.3, the predominant wind is a south westerly, with the willow systems situated on the northwest/south east axis.

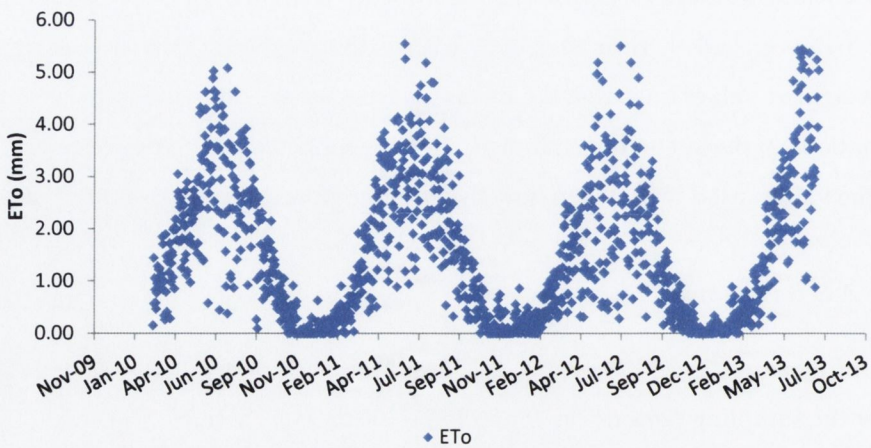


Figure 4.2 Daily Penman-Monteith reference evapotranspiration rates (ET_o) for Sites A & B

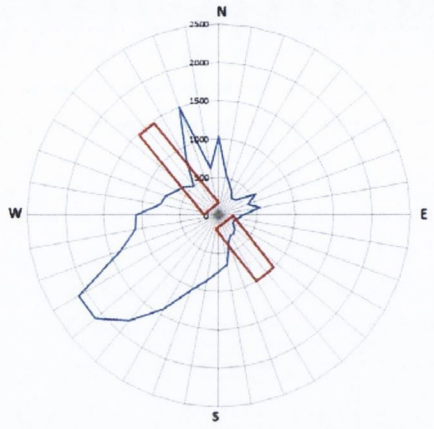


Figure 4.3 Orientation of willow systems with respect to wind speed and direction distribution for Sites A&B

4.2.2 *Site C Borehovel*

Measurement of meteorological data commenced in September 2010 for Site C. Total rainfall measured over the sampling period was found to be 2860.7 mm (September - December 2010: 357.8 mm; 2011: 910.3 mm; 2012: 1220 mm; January - May 2013: 372.6 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 2.19 m/s with daily means ranging from 0.41 m/s to 6.94 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site C are shown in Figure 4.4 with the daily reference evapotranspiration shown in Figure 4.5.

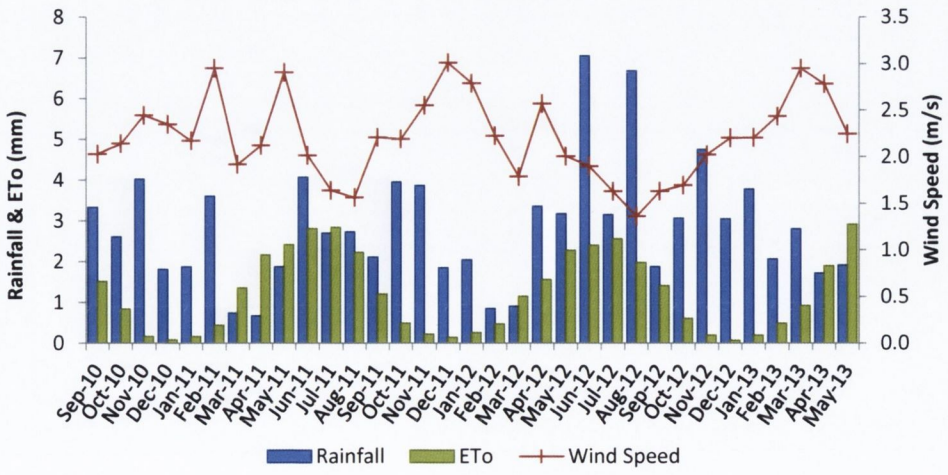


Figure 4.4 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site C

Mean ET_o was measured at 1.23 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.09 mm/day. As shown by the wind rose graphic in Figure 4.6, the predominant wind is a south westerly. The willow system points in a very similar direction meaning that most of the wind hits it along its narrow side.

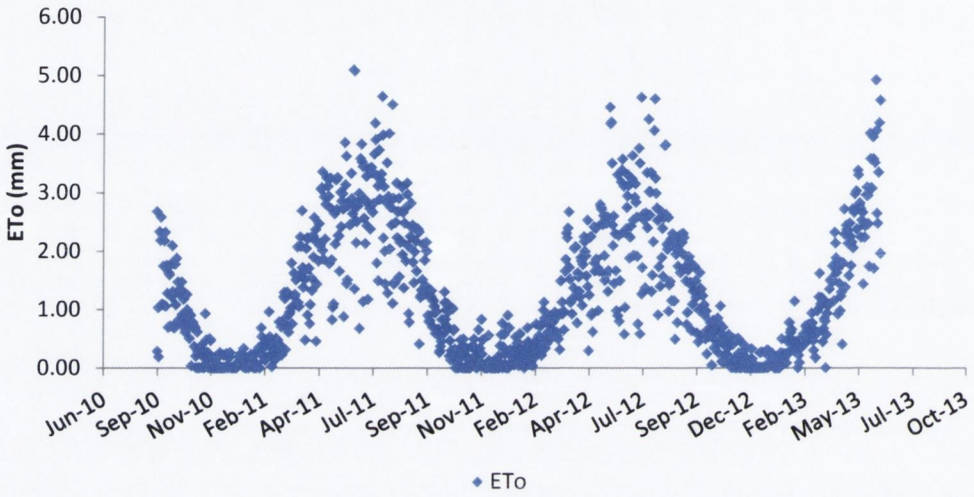


Figure 4.5 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site C

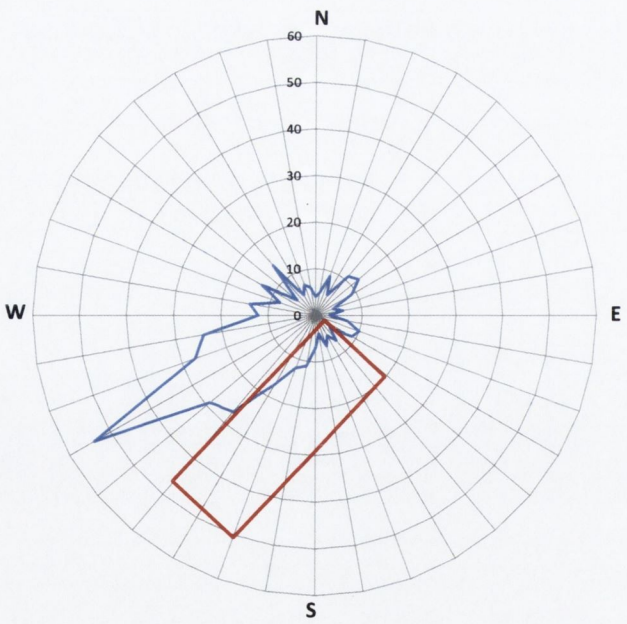


Figure 4.6 Orientation of willow systems with respect to wind speed and direction distribution for Site C

4.2.3 *Site D Ballask*

Measurement of meteorological data commenced in September 2010 for Site D. Total rainfall measured over the sampling period was found to be 2610.46 mm (September - December 2010: 444.2 mm; 2011: 740.5 mm; 2012: 1097.56 mm; January - May 2013: 328.2 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 1.84 m/s with means ranging from 0.37 m/s to 7.38 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site D are shown in Figure 4.7 with the daily reference evapotranspiration shown in Figure 4.8.

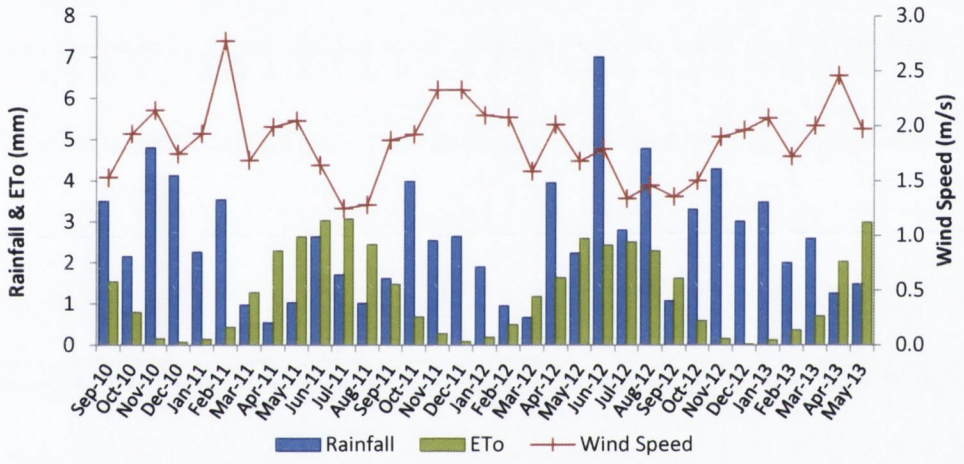


Figure 4.7 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site D

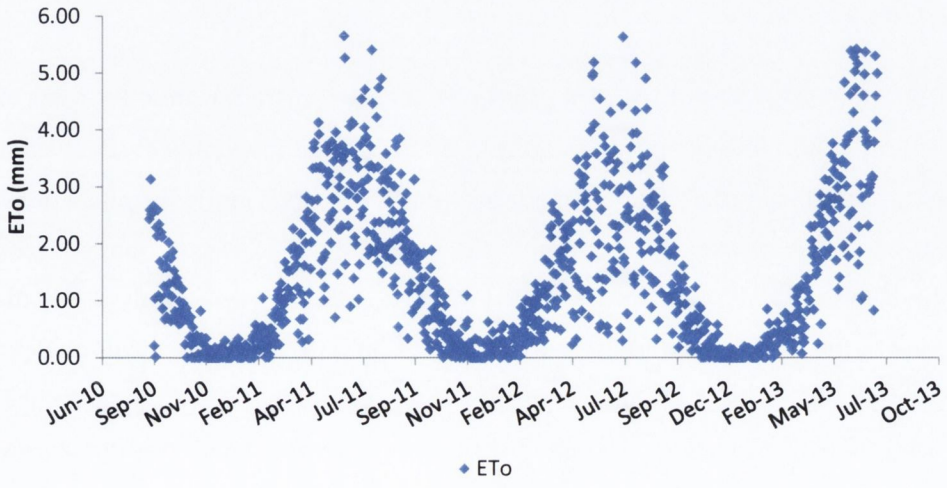


Figure 4.8 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site D

Mean ET_o was measured at 1.29 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.67 mm/day. The distribution of wind speed and direction at the site is illustrated in Figure 4.9. It can be seen that the predominant wind is south westerly in direction.

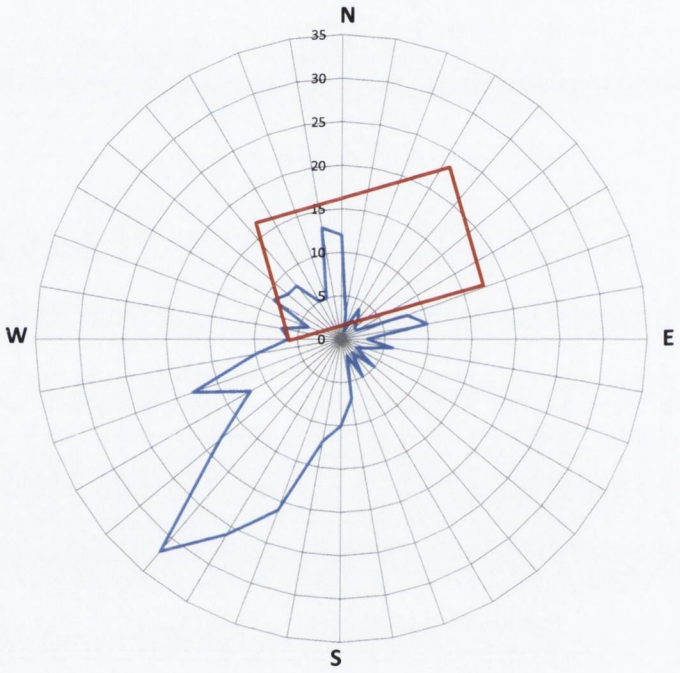


Figure 4.9 Orientation of willow systems with respect to wind speed and direction distribution for Site D

4.2.4 *Site E Jamestown*

Measurement of meteorological data began in September 2010 for Site E. Total rainfall measured over the sampling period was found to be 2393.0 mm (September - December 2010: 324 mm; 2011: 652.4 mm; 2012: 1102 mm; January - May 2013: 314.7 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 0.75 m/s with speeds ranging from 0.18 m/s to 2.94 m/s. As detailed in 4.2.11.3 this is significantly lower than the other sites due to the sheltered nature of the site. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site E are shown in Figure 4.10 with the daily reference evapotranspiration shown in Figure 4.11. The reference evapotranspiration was only determined until March 2013 at which point the wind anemometer was moved to Site C.

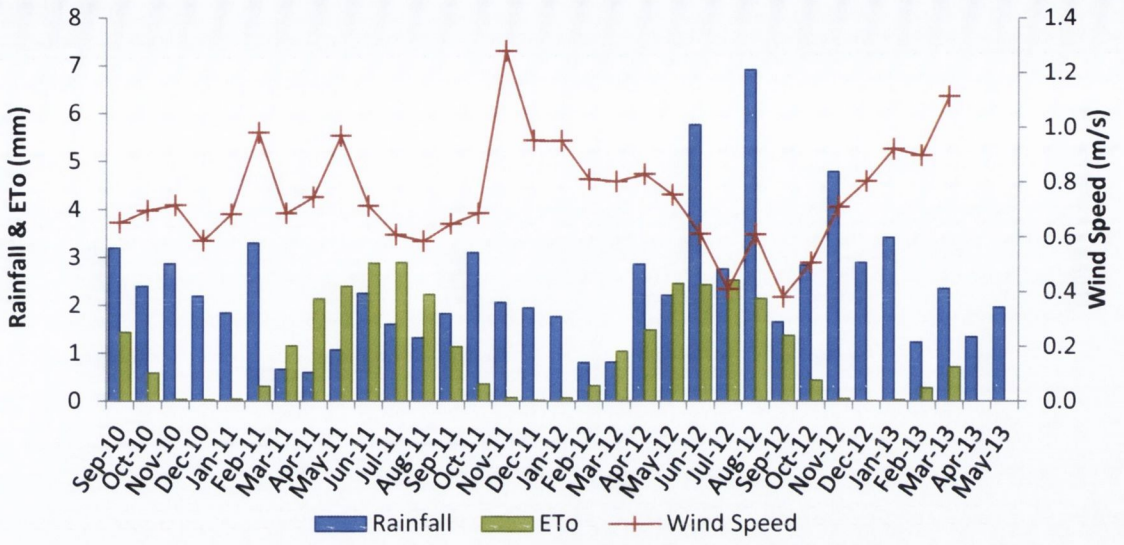


Figure 4.10 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site E

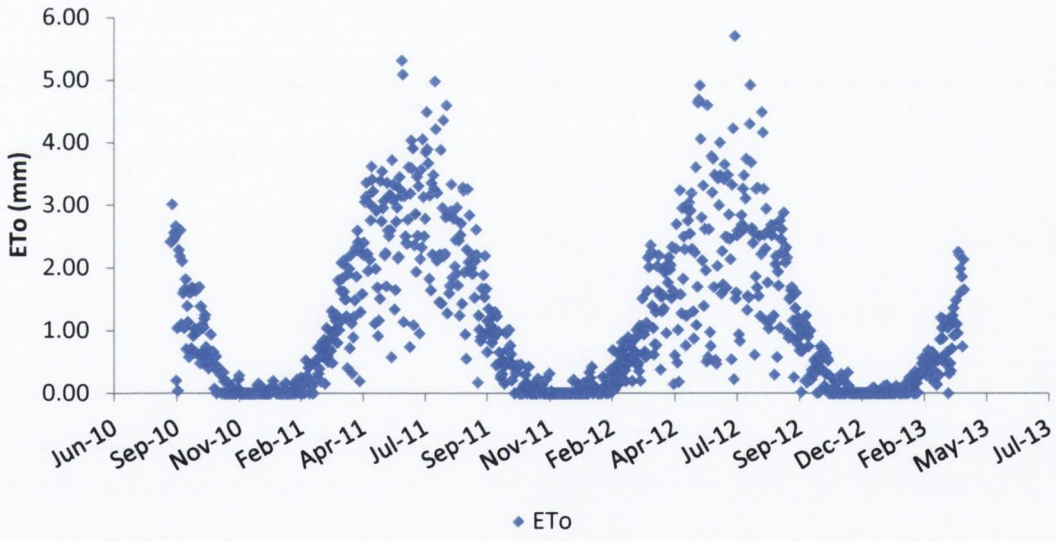


Figure 4.11 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site E

Mean ET_o was measured at 1.08 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.70 mm/day. As can be seen from the wind rose in Figure 4.12, the distribution of the wind speed and direction at the site is quite mixed. This is probably due to the nature of the site itself. The willow systems (and associated wind anemometer) was located

in a very sheltered area and had a lot of surrounding woodland, which more than likely affected the wind speed and direction at the site.

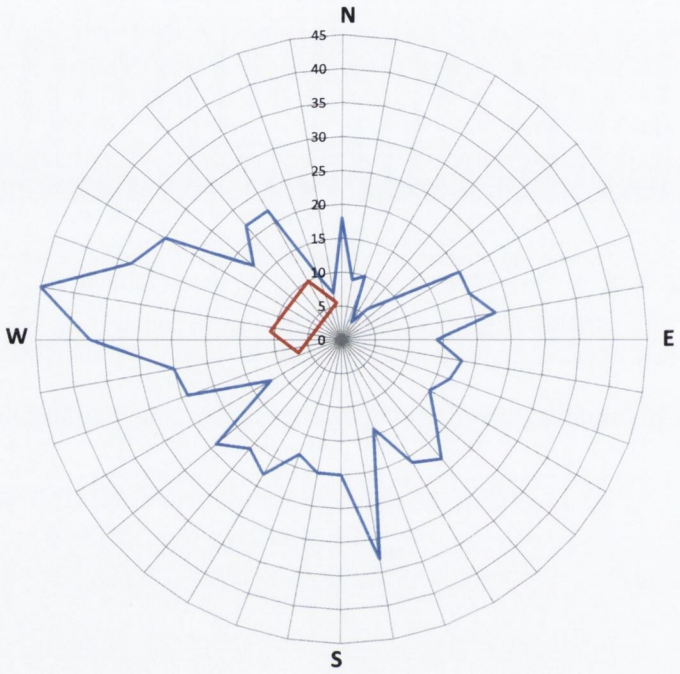


Figure 4.12 Orientation of willow systems with respect to wind speed and direction distribution for Site E

4.2.5 *Site F Ballywilliam*

Measurement of meteorological data commenced in April 2011 for Site F. Total rainfall measured over the sampling period was found to be 2252.3 mm (April - December 2011: 686.8; 2012: 1178.2 mm; January - May 2013: 386.9 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 2.28 m/s with daily means ranging from 1.03 m/s to 5.34 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Sites F are shown in Figure 4.13with the daily reference evapotranspiration shown in Figure 4.14.

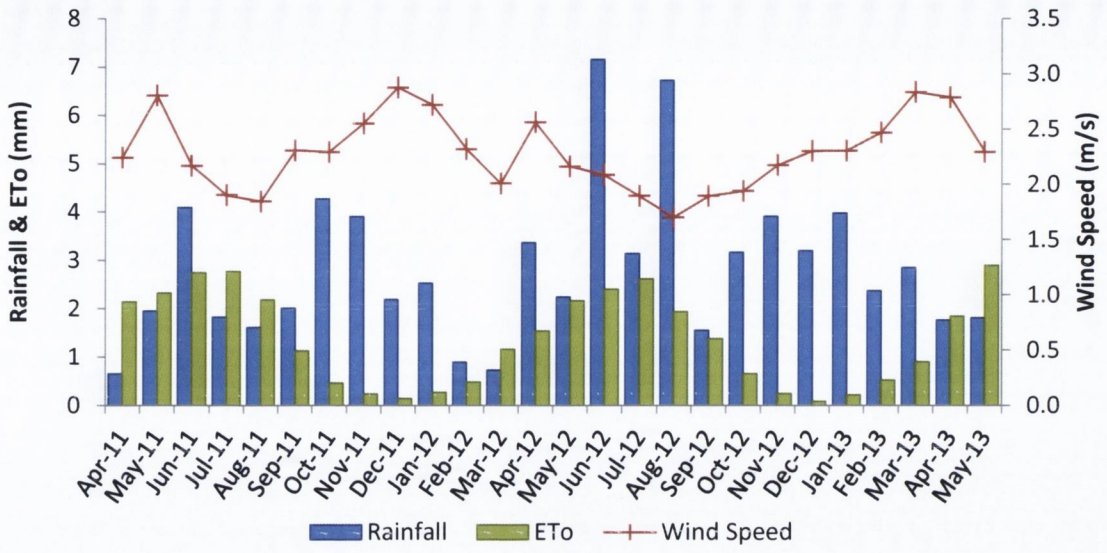


Figure 4.13 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site F

Mean ET_o was measured at 1.37 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.06 mm/day. As illustrated in Figure 4.15, the predominant wind comes from the west and south west on the site. The willow systems lie on the southwest/northeast axis.

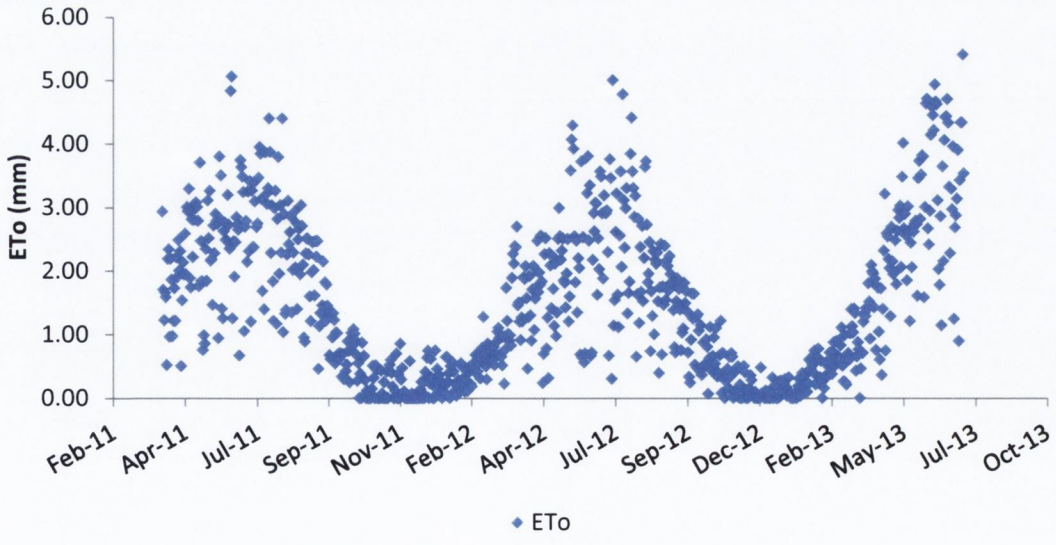


Figure 4.14 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site F

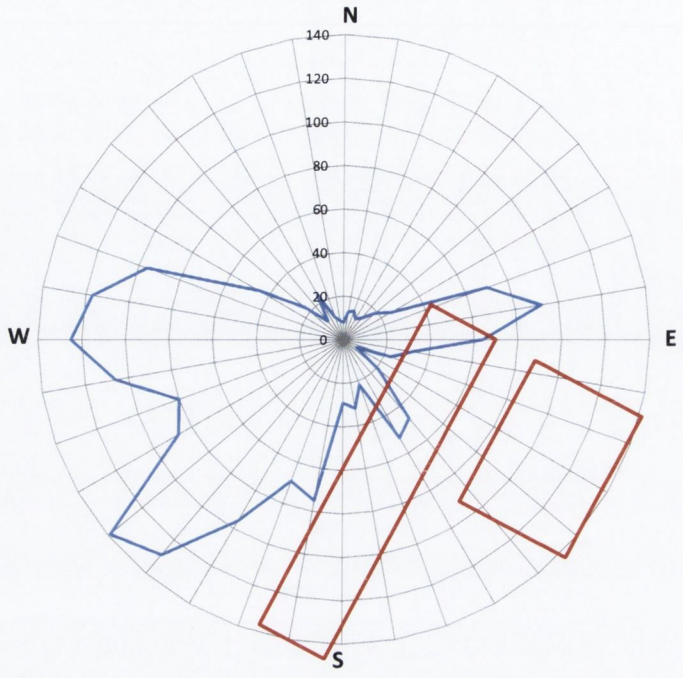


Figure 4.15 Orientation of willow systems with respect to wind speed and direction distribution for Site F

4.2.6 *Site G Ardcavan*

Measurement of meteorological data commenced in April 2011 for Site G. Total rainfall measured over the sampling period was found to be 2100.8 mm (April - December 2011: 572.6 mm; 2012: 1149.4 mm; January - May 2013: 378.8 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 2.68 m/s with mean speeds ranging from 0.78 m/s to 8.18 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site G are shown in Figure 4.16 and the daily reference evapotranspiration shown in Figure 4.17.

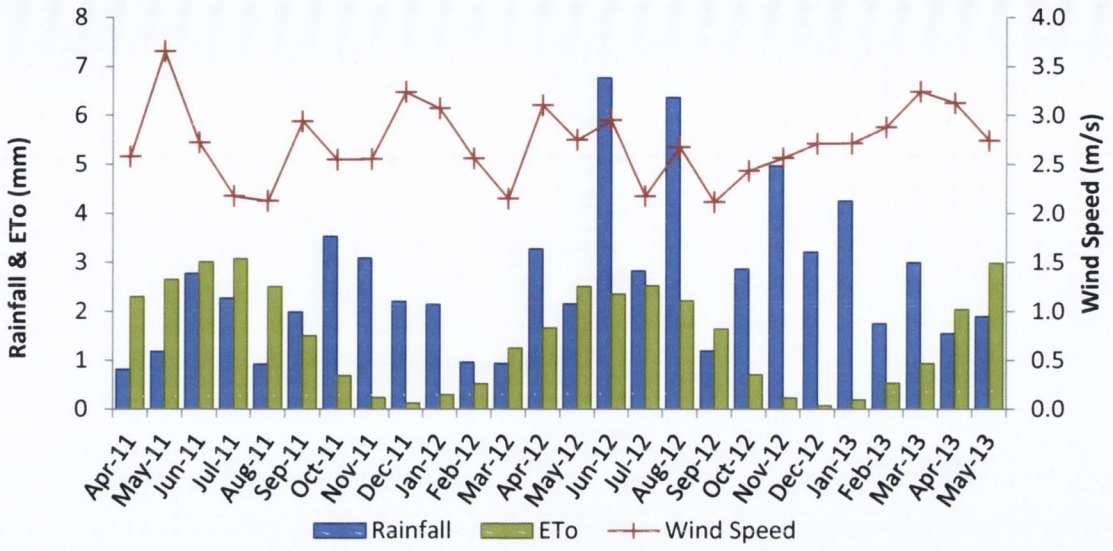


Figure 4.16 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site G

Mean ET_o was measured at 1.50 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.66 mm/day. As shown in Figure 4.18 the prevalent wind comes from a west southwest direction with the willow system lying just off the northwest/south east axis.

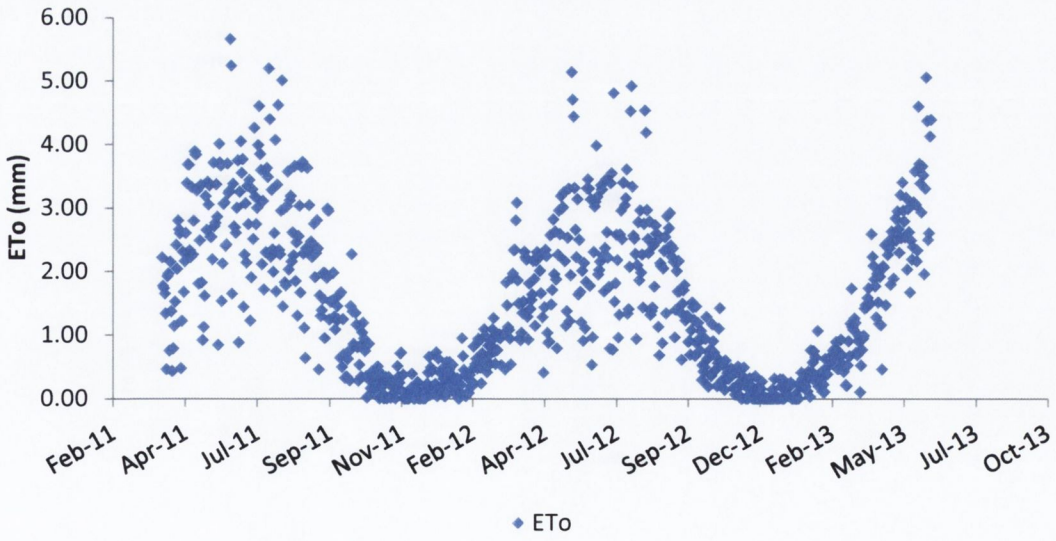


Figure 4.17 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site G

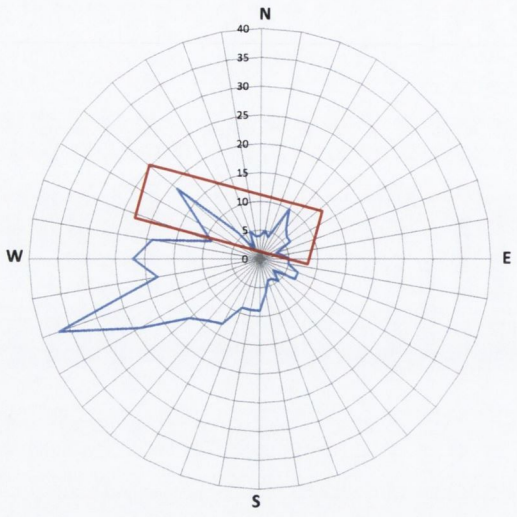


Figure 4.18 Orientation of willow systems with respect to wind speed and direction distribution for Site G

4.2.7 *Site H Duncormick*

Measurement of meteorological data started in April 2012 for Site H. Total rainfall measured over the sampling period was found to be 914.4 mm (April - December 2012: 586.4 mm; January - May 2013: 328.0 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 2.48 m/s with speeds ranging from 0.52 m/s to 7.22 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Sites H are shown in Figure 4.19 with the daily reference evapotranspiration shown in Figure 4.20.

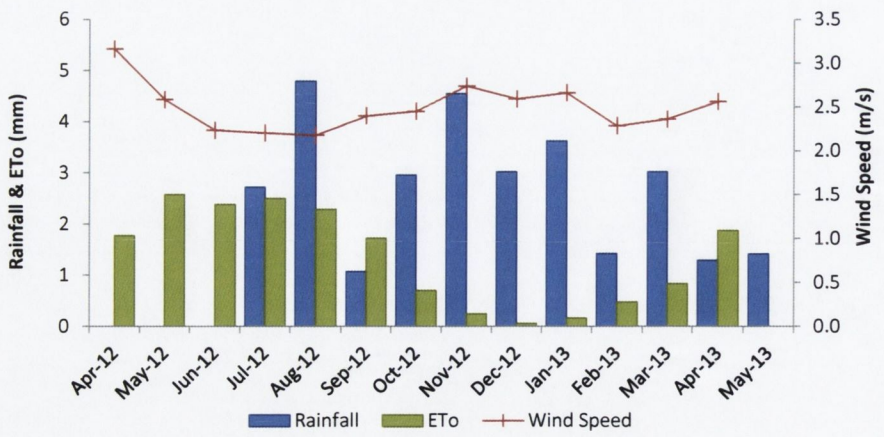


Figure 4.19 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site H

Mean ET_o was measured at 1.32 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.46 mm/day. As shown in Figure 4.21, the prevalent wind comes from a south westerly direction. The two willow systems on the site point in a very similar direction, meaning that the wind would hit them on the narrow end.

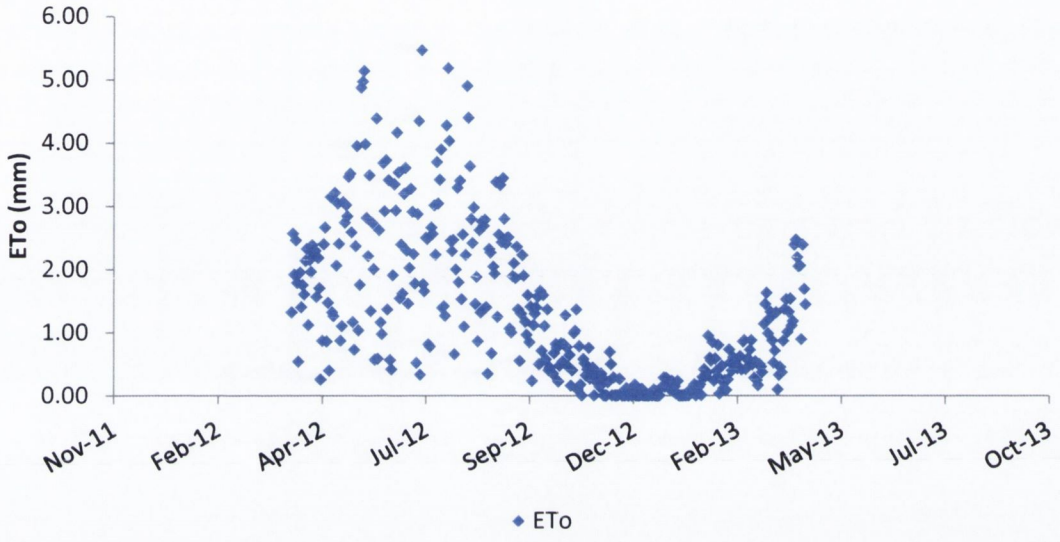


Figure 4.20 Daily Penman-Monteith reference evapotranspiration rates (ETo) for Site H

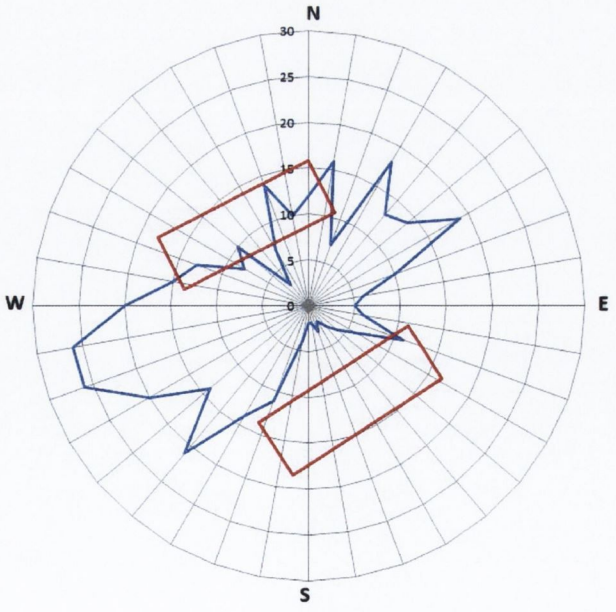


Figure 4.21 Orientation of willow systems with respect to wind speed and direction distribution for Site H

4.2.8 *Site I Carrigallen (Co. Leitrim)*

Measurement of meteorological data commenced in April 2012 for Site I. Total rainfall measured over the sampling period was found to be 1457.7 mm (April - December 2012: 979.5 mm; January - May 2013: 478.2 mm). The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site I are shown in Figure 4.22 with the daily reference evapotranspiration shown in Figure 4.23.

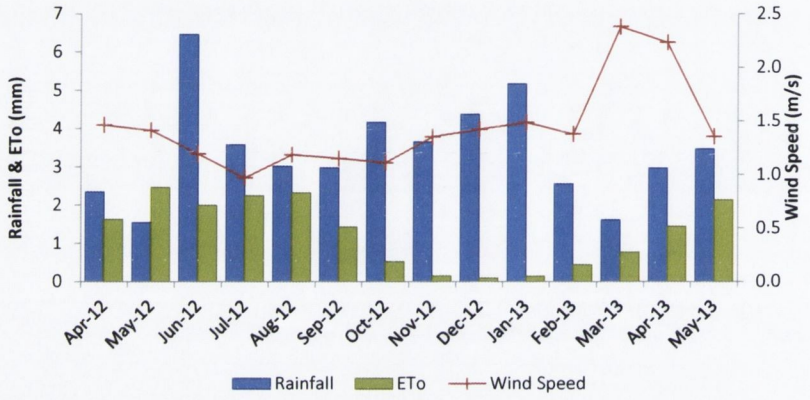


Figure 4.22 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site I

Mean ET_o was measured at 1.27 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 5.81 mm/day. There are two predominant wind directions on Site I (Figure 4.24). The westerly is almost perpendicular to the long side of the willow systems, while the second main wind comes from the north east.

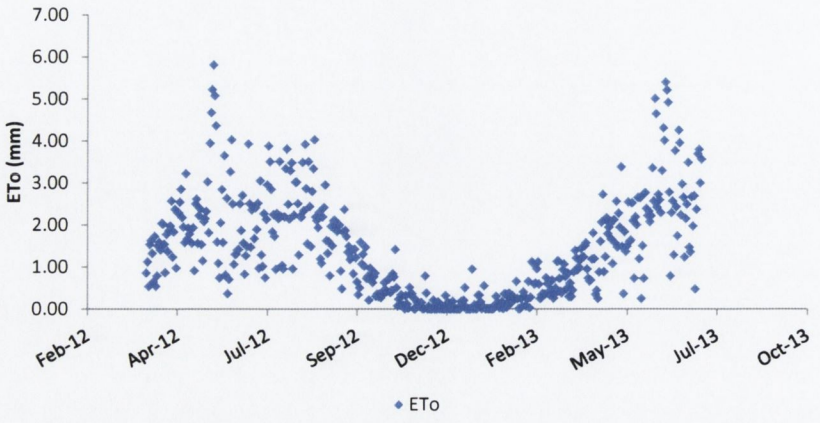


Figure 4.23 Penman-Monteith reference evapotranspiration rates (ETo) for Site I

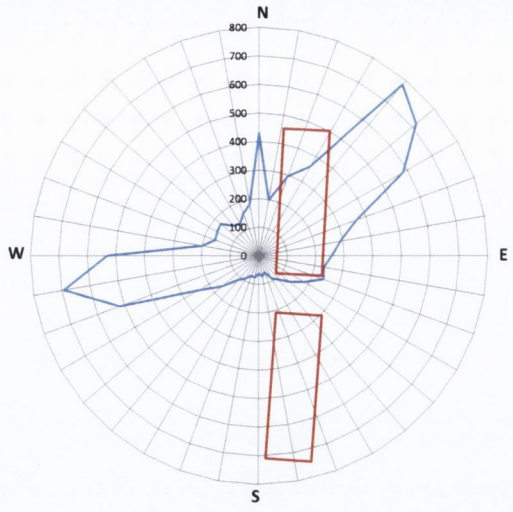


Figure 4.24 Orientation of willow systems with respect to wind speed and direction distribution for Site I

4.2.9 *Site J Ballylanders (Co. Limerick)*

Measurement of meteorological data commenced in December 2012 for Site J. Total rainfall measured over the sampling period was found to be 498.9 mm (December 2012: 125.5 mm; January - May 2013: 373.3 mm). The mean daily wind speed measured at the site over the duration of the sampling period was 1.88 m/s with speeds ranging from 0.4 m/s to 5.71 m/s. The mean daily reference evapotranspiration, rainfall and wind speed for each month on Site J are shown in Figure 4.25 with the daily reference evapotranspiration shown in Figure 4.26.

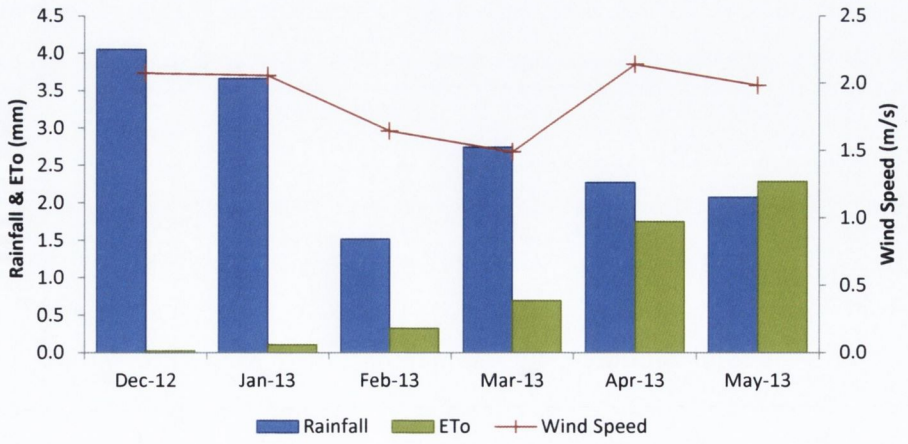


Figure 4.25 Mean Daily rainfall, reference evapotranspiration and wind speed for each month on Site J

Mean ET_o was measured at 0.84 mm/day over the duration of the sampling period with rates ranging from 0 mm/day to 4.93 mm/day. The weather station on Site J had no instrument for recording wind direction and as a result there is no wind rose graphic for the site. However, it was assumed that the prevalent wind comes from a south westerly direction due to the location and the nature of shelter at the site.

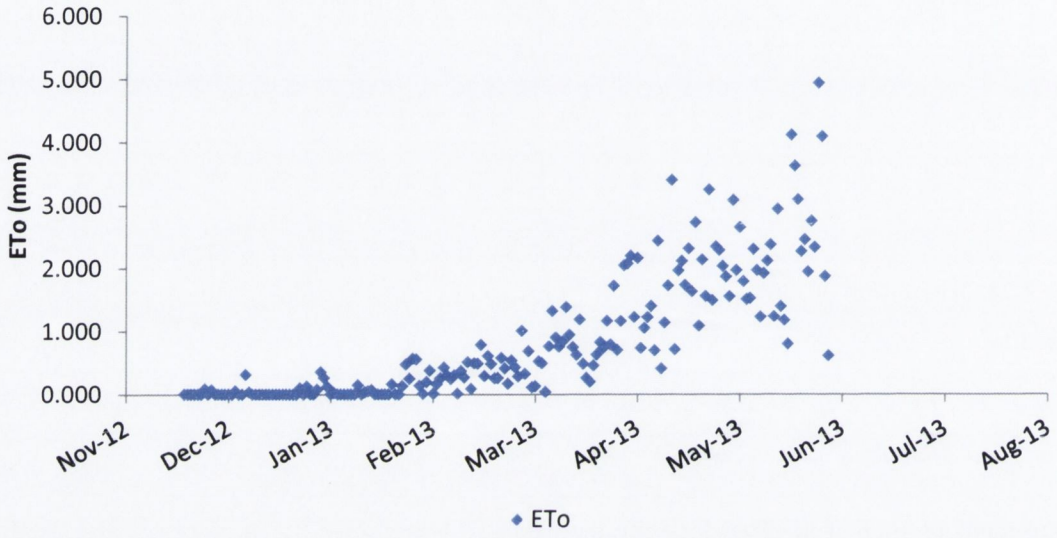


Figure 4.26 Penman-Monteith reference evapotranspiration rates (ETo) for Site J

4.2.10 *Sensitivity Analysis of Reference Evapotranspiration*

Before carrying out variance analysis on the meteorological data collected on the different sites a sensitivity analysis was implemented to determine the relative impact of the different meteorological parameters on the daily reference evapotranspiration rates. The analysis was carried out for the reference evapotranspiration on Site A&B and used the data collected between February 2010 and July 2013 to form the input distributions.

The sensitivity analysis was implemented in the risk analysis software package @Risk (version 6.0, Palisade Corp.), which is an add-on programme for Microsoft Excel. The inputs to the model were daily net radiation, daily mean temperature, daily mean humidity and daily mean wind speed. The input distributions for these parameters were first defined using the distribution tool in @Risk, which fitted a specific distribution for parameters based on the sampled dataset of each. The fitted distribution was selected according to which was ranked the highest, statistically.

The statistical tests carried out for each type of distribution included the Akaike information criterion (AIC), Bayesian information criterion (BIC), Chi- squared, Kolmogorov-Smirnov, and the Anderson- Darling statistics, all upon which the appropriate probability distribution was determined. The probability distributions for each parameter are shown in Table 4.1.

Table 4.1 The type of distributions assigned to each of the meteorological parameters.

Parameter	Type of Distribution	AIC	Distribution μ	Distribution σ	Input μ	Input σ
Max. Humidity	Uniform	8102.4	86.50	7.79	97.84	3.35
Min. Humidity	Beta-General	9507.2	72.30	11.83	72.31	11.92
Max. Temperature	Beta-General	7183.7	13.39	4.53	13.39	4.54
Min. Temperature	Beta-General	7093.3	6.48	4.42	6.46	4.42
Net Radiation	Triang	13791.0	65.24	73.9	63.24	72.41
Wind speed	Expon	4100.1	1.95	1.95	1.95	1.43
Atmos. Pressure	Beta-General	-3433.1	1008.84	0.06	1008.84	0.06

The model used was the Penman Monteith daily reference evapotranspiration equation (Eqn. 4.1), which employs all of the detailed input parameters to simulate daily ET_o rates. The model was set up in the following manner: the simulation was run just once and the number of iterations was set to 10,000.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T} + 273\right)u_2(e_s - e)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Eqn. 4.1}$$

Where,

ET_o = Penman Monteith reference evapotranspiration

R_n = net radiation (MJ/m²/day)

G = soil heat flux density (MJ/m²/day)

Δ = slope of the saturation vapour pressure curve (kPa/K)

γ = psychrometric constant (kPa/K)

T = mean daily air temperature (°C)

u_s = mean daily wind speed at height of 2 m (m/s)

e_s = saturation vapour pressure at mean daily temperature (kPa)

e = mean daily actual vapour pressure (kPa)

The sampling type used was Latin hypercube and the random number generator was carried out in @Risk using a Mersenne twister, which is a pseudorandom number generator developed in 1997 by Matsumoto and Nishimura that is based on a matrix linear recurrence over a finite binary field F_2. It was designed specifically to rectify many of the flaws found in older algorithms, and provides fast generation of high-quality pseudorandom numbers.

As you would expect a correlation exists between different meteorological parameters, by nature. For example, high net radiation values are generally going to be associated with high temperature values. The correlation between each parameter had to be determined, so as to ensure the model would predict accurate reference evapotranspiration rates. Correlation coefficients between all the individual input distributions were determined, thus allowing a matrix (see Table 4.2) to be defined in the @Risk software. A positive value indicates a generally (but not always) positive correlation between two variables - i.e. when the value sampled for one input is high, the second will also be high. A negative value in the matrix generally (but not always) indicates an inverse correlation between parameters - i.e. when the value sampled for one input is high, the value sampled for the second will be low.

Table 4.2 Correlation Coefficients between meteorological parameters

Parameter	Max Temp	Min Temp	Max Humidity	Min Humidity	Net Rad	Wind	Pressure
Max Temp	1	0.76	0.074	-0.239	0.7	-0.017	0.932
Min Temp	0.76	1	0.167	0.204	0.435	0.27	0.923
Max Humidity	0.074	0.167	1	0.5	-0.138	0.11	0.147
Min Humidity	-0.239	0.204	0.5	1	-0.496	0.247	0
Net Rad	0.7	0.435	-0.138	-0.496	1	-0.044	0.608
Wind	-0.017	0.27	0.11	0.247	-0.044	1	0.172
Pressure	0.932	0.923	0.147	0	0.608	0.172	1

The simulated daily reference evapotranspiration rates are compared graphically to the observed rates in Figure 4.27. As can be seen in the figure, the simulated evapotranspiration rates closely follow the experimentally determined rates.

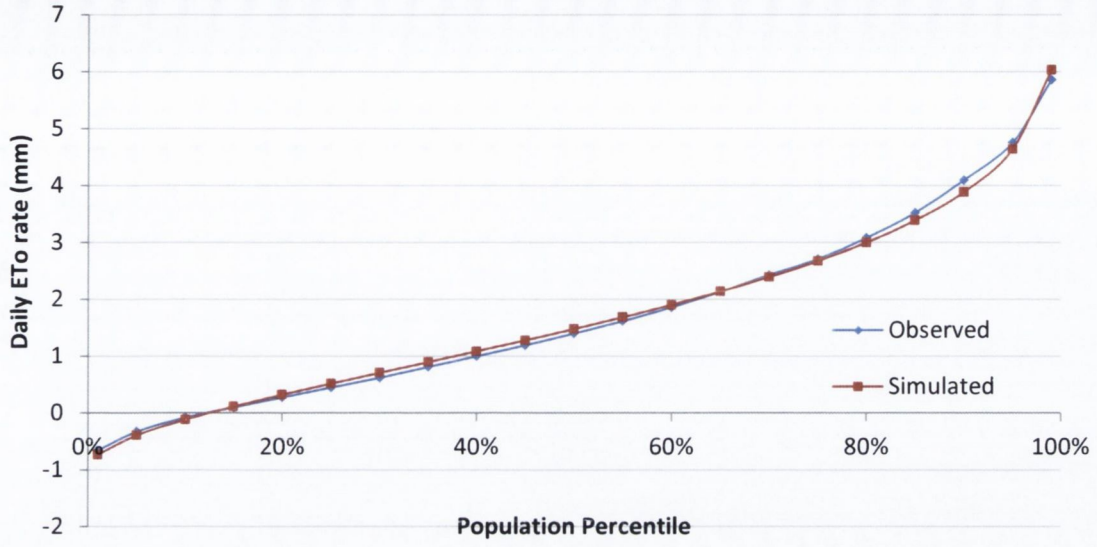


Figure 4.27 Comparison of observed and Latin Hypercube simulated ET_o simulations.

The Spearman's rank correlation coefficients of the daily reference evapotranspiration output versus each of the inputs are shown in Figure 4.28. This illustrates that the daily net radiation is the most highly correlated (ρ = 0.98) with the daily reference evapotranspiration. This is followed by the maximum daily temperature and atmospheric pressure, which also have a relatively high correlation of ρ = 0.72 and ρ = 0.63, respectively. Minimum daily humidity (ρ = -0.52) and minimum daily temperature (ρ = 0.47) both have moderate correlation, while maximum daily humidity (ρ = -0.19) and wind speed (ρ = 0.06) have relatively low correlation.

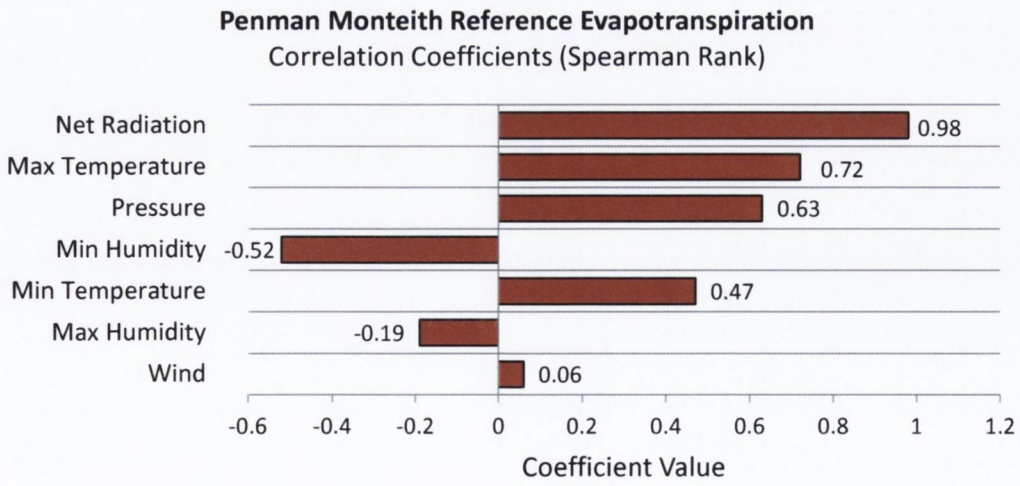


Figure 4.28 Correlation coefficients for simulated Penman Monteith reference evapotranspiration inputs of meteorological parameters.

The extent to which each of the meteorological input variables could influence the daily reference evapotranspiration output is shown in Figure 4.29. The figure shows the amount of change in daily reference evapotranspiration due to a one standard deviation change in input, while holding the other inputs constant. Thus, a one standard deviation increase in the net radiation would result in a reference evapotranspiration rate increase of over 1.37 mm/day.

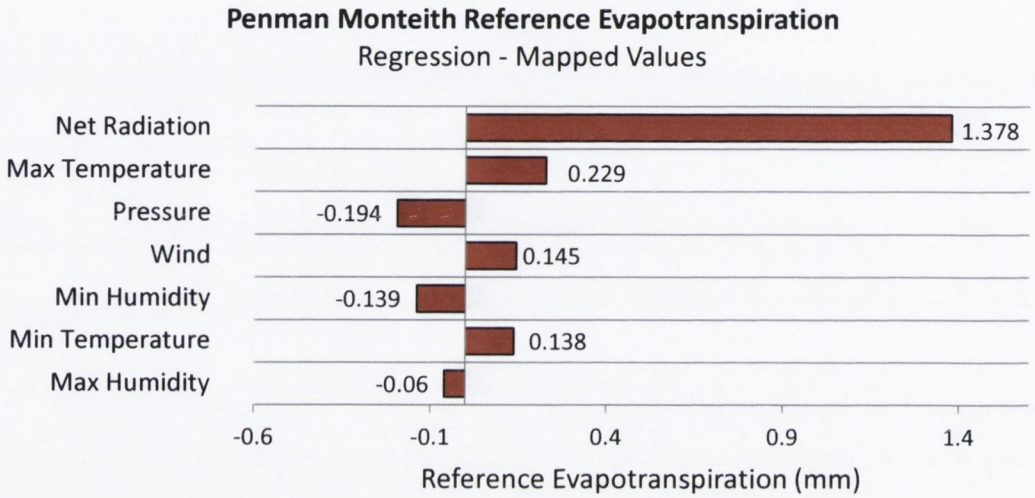


Figure 4.29 Tornado graph of the regression mapped values of the simulation model inputs. Each value represents the change in daily reference evapotranspiration with a one standard deviation change in a particular input, with all others held constant.

4.2.11 *Variance Analysis*

The variance analysis was implemented in the data analysis and modelling software package StatTools (version 6.0, Palisade Corp.), which is an add-on programme for Microsoft Excel. Daily means were used in the analysis as the statistical software found it difficult to highlight any variance when monthly data was used, even when it seemed obvious that there was a statistical significant difference between datasets. The parameters examined were reference evapotranspiration, rainfall, wind speed and net radiation.

Normality tests carried out on the daily means for these meteorological parameters showed that the data was not normally distributed meaning that parametric statistical tests could not be carried out. An example of this is shown in Figure 4.30, which shows that the daily reference evapotranspiration for Site A&B follows a beta general distribution and is skewed to the right. Non-normal distribution was confirmed with p-value < 0.05 for the Anderson Darling Test.

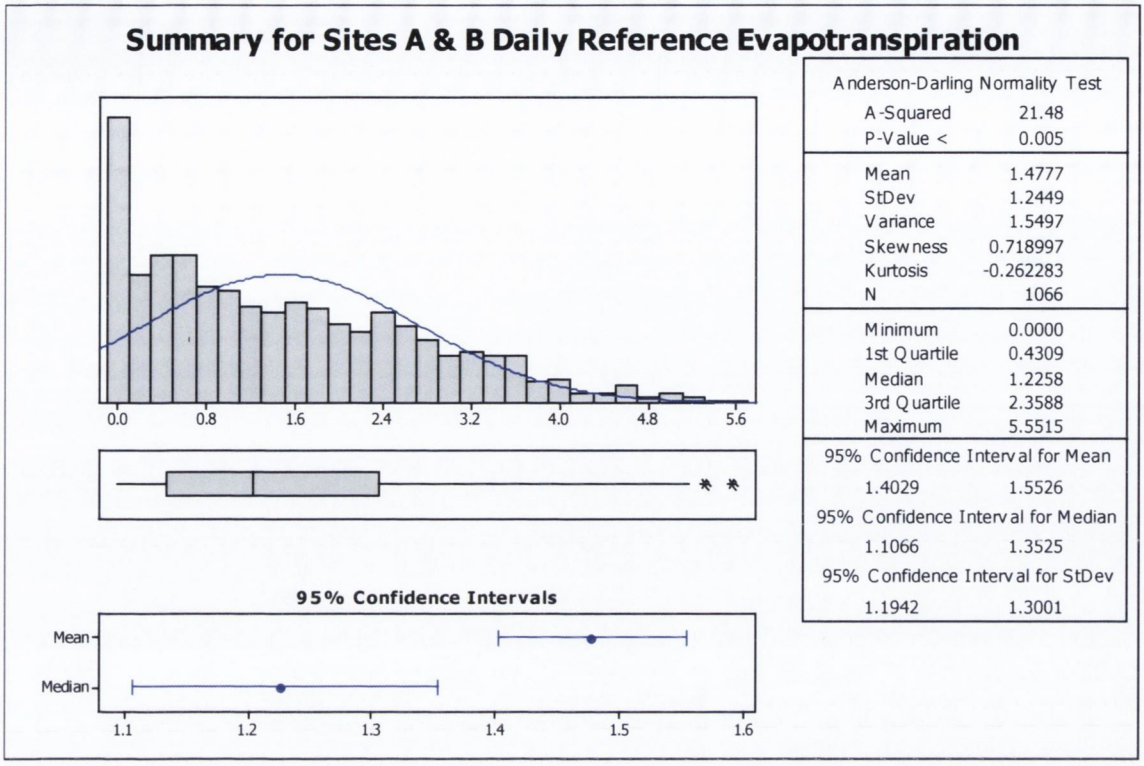


Figure 4.30 A summary for the daily reference evapotranspiration rates on Sites A & B

The distributions for the four different parameters, which were established using the distribution fitting tool in the software package @Risk, are detailed in Table 4.3. It can be seen that none of them are normally distributed. Because of this the datasets were assessed using non-parametric tests to determine if the values for a particular meteorological parameter were significantly different from site to site.

Table 4.3 Distribution type for meteorological parameters

Parameter	Type of Distribution	AIC
Net Radiation	Triang	13791.03
Wind Speed	Weibull	3957.60
Rainfall	Exponential	4940.71
ET_o	Exponential	3458.48

The Mann-Whitney U test (also known as the Wilcoxon Rank-Sum test) was used to test the datasets. However, this test can only be used to perform a hypothesis test on two samples at a time. A matrix was established to allow the comparison of p-values between results from the different sites. The matrix for each parameter is detailed in the following, relevant subsections.

The hypothesis for the median version of the Mann-Whitney U test states that the medians of the two datasets are identical. Before applying the test to the data, the assumption of the median version of the test meant that each pair of data sets had to be examined to check that the distributions were similar. The check was carried out in StatTools and the results for each parameter are detailed in the relevant subsection.

4.2.11.1 Comparison of Rainfall Levels

The distributions for the daily rainfall are shown in Figure 4.31. It can be seen that all the datasets generally follow the same distribution - exponential distribution in this case. Once this assumption was proven valid, the median version of the Mann-Whitney U test could be carried out on StatTools.

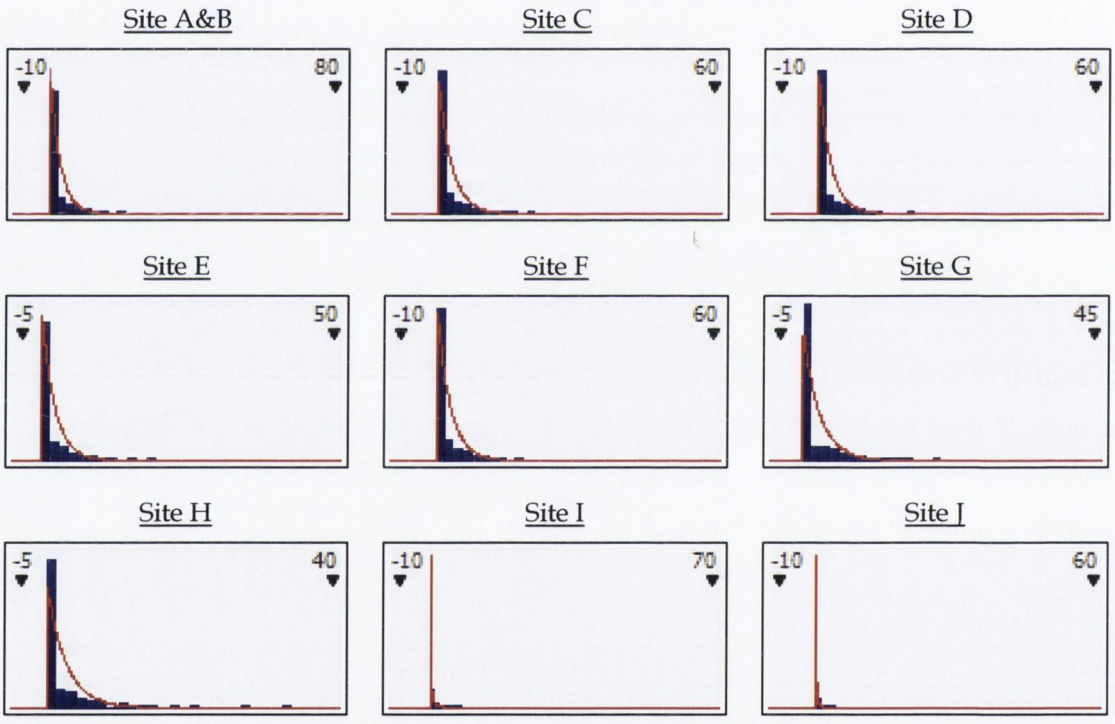


Figure 4.31 Distributions of rainfall for each site (mm)

Each pair of datasets compared had the same sample size and each pair of daily values was from the same day. As the time periods from which the data was collected was different for every site there was no merit in stating and comparing means or medians, as a site with, for example, an extra winter's worth of data is generally going to have a lower mean/median compared to a dataset from a site where the winter values are included.

The p-values which show whether there is a statistically significant difference between pairs of datasets are shown in the matrix in Table 4.4.

Table 4.4 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between rainfall for the different sites

Site	A&B	C	D	E	F	G	H	I	J
A&B	X	0.007	0.001	0.009	0.577	0.026	0.053	0.271	0.474
C	0.007	X	0.595	0.097	0.964	0.479	0.750	0.048	0.273
D	0.001	0.595	X	0.781	0.089	0.594	0.813	0.010	0.051
E	0.009	0.097	0.781	X	0.315	0.315	0.909	0.002	0.128
F	0.577	0.964	0.089	0.315	X	0.523	0.903	0.003	0.290
G	0.026	0.479	0.594	0.315	0.523	X	0.554	0.063	0.209
H	0.053	0.750	0.813	0.909	0.903	0.554	X	0.003	0.150
I	0.271	0.048	0.010	0.002	0.003	0.063	0.003	X	0.527
J	0.474	0.273	0.051	0.128	0.290	0.209	0.150	0.527	X

p-value < 0.05 indicates significant difference

The p-values which indicate statistically significant differences are highlighted in red. It can be seen that the main difference in medians occurred between Site A&B, which had statistically significantly greater daily rainfall, and Sites C, D, E. There was also a difference in medians between Site I (in Leitrim), which had statistically significantly greater daily rainfall, and Sites C, D, E, F and H (in Wexford).

Table 4.5 Comparison of rainfall at sites to 30 year average

Year	Sites A&B	Site C	Site D	Site E	Site F	Site G	Site H	Met
2010	94%	82%	102%	74%	-	-	-	90%
2011	78%	86%	70%	62%	86%	71%	-	77%
2012	121%	115%	104%	104%	111%	108%	99%	111%
2013	95%	94%	83%	79%	98%	96%	83%	82%

The rainfall on each site in Wexford was also compared to the 30 year (1981 - 2010) average rainfall recorded at Met Éireann's Johnstown Castle weather station in the south of the county. For any site in which there was not a full complement of annual data, the data was compared to the relevant time period. The results (see Table 4.5) show that, in general rainfall levels were

below average at all monitored sites in 2011, while they were above average (apart from Site H) in 2012. So far in 2013, rainfall is close to or a little below the 30 year average.

4.2.11.2 Comparison of Wind speed

The distributions for the wind speeds on the different sites are illustrated in Figure 4.32. It can be seen that all the datasets have a similar shape generally conform to Weibull shaped of distributions. Once this assumption was proven valid the median version of the Mann-Whitney U test was carried out.

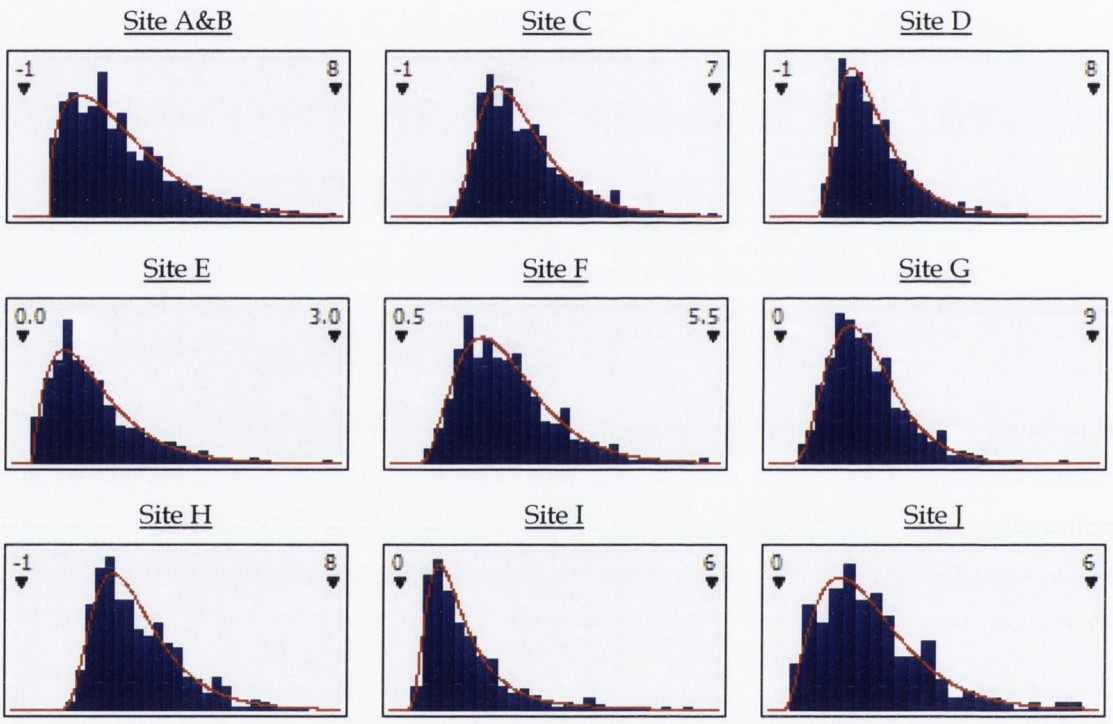


Figure 4.32 Distributions of wind speeds for each site (m/s)

As with the rainfall data, each pair of datasets compared had the same sample size and each pair of daily values was from the same day. Again, mean or median values were not stated, due to the data from all the sites spanning different time periods.

The p-values for the different pairs of datasets are shown in the matrix in Table 4.6. Statistically significant differences are highlighted in red. It can be seen that a significant difference in medians occurs between almost all datasets. These results are not surprising given that high

variability in wind speeds from one location to another is expected and they also justify the decision to erect a wind anemometer at all sites.

Table 4.6 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between wind speed for the different sites

Site	A&B	C	D	E	F	G	H	I	J
A&B	X	0.000	0.027	0.000	0.000	0.000	0.00	0.000	0.420
C	0.000	X	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D	0.027	0.000	X	0.000	0.000	0.000	0.000	0.000	0.103
E	0.000	0.000	0.000	X	0.000	0.000	0.000	0.000	0.000
F	0.000	0.000	0.000	0.000	X	0.000	0.056	0.000	0.000
G	0.000	0.000	0.000	0.000	0.000	X	0.000	0.000	0.000
H	0.000	0.000	0.000	0.000	0.056	0.000	X	0.000	0.000
I	0.000	0.000	0.000	0.000	0.000	0.000	0.000	X	0.007
J	0.420	0.000	0.103	0.000	0.000	0.000	0.000	0.007	X

p-value < 0.05 indicates significant difference; value of 0.000 indicates <0.0001

4.2.11.3 Comparison of Net Radiation

As with the previous detailed datasets, the distributions for the net radiation data sets were carried out using the distribution fitting tool in @Risk and are illustrated in Figure 4.33. It can be seen that datasets from the four different sites had varying distributions. Site A&B and Site I had a Triang distribution while Site F and Site J had Beta general and Gamma distributions respectively. As a result, the median version of the Mann-Whitney U test could not be carried out as the assumption of similar distributions between datasets was not fulfilled. Hence, the general version of the test was carried out, where this assumption is not made and the test hypothesis denies that either probability distribution tends to yield smaller values than the other.

As discussed previously, the net radiation was measured on only two sites in Co. Wexford, due to financial restrictions. The full weather stations on Site I and Site J were erected later in the research project when additional funding became available. The datasets compared had the same sample sizes and each pair of data points compared was from the same day.

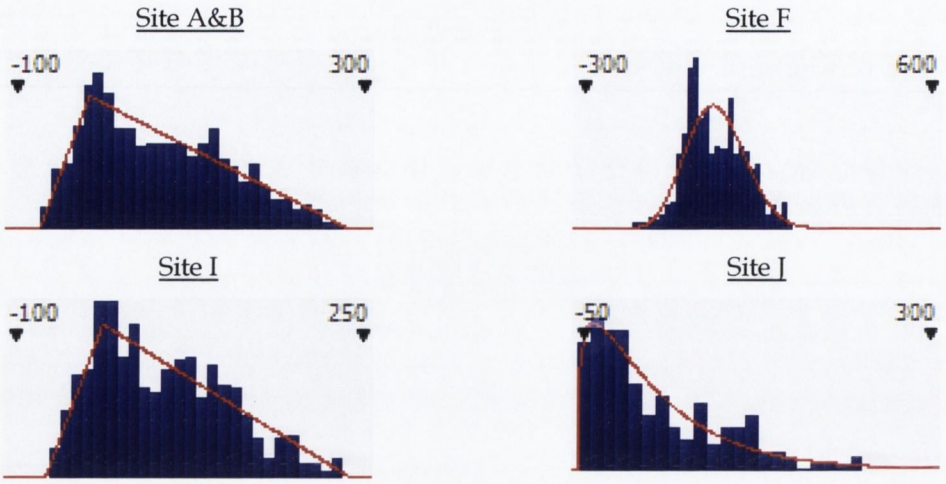


Figure 4.33 Distributions of net radiation for each site (MJ/m²/day)

The test results including the p-values are shown in Table 4.7. It can be seen that of the sites with complete weather stations there is a statistically significant difference in net radiation between Site A&B and Site F, and also between Site A&B and Site I.

Table 4.7 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between net radiation for the different sites

Ranks					**Test Statistics**	
	Site	N	Mean	Median		
Test 1	Site A&B	836	66.10	54.45	df	1
	Site F	836	48.40	37.69	Sig.	<0.0001
Test 2	Site A&B	443	72.09	58.38	df	1
	Site I	443	51.15	45.11	Sig.	0.0005
Test 3	Site A&B	189	40.94	13.27	df	1
	Site J	189	29.75	8.41	Sig.	0.279
Test 4	Site F	443	58.13	47.39	df	1
	Site I	443	51.15	45.11	Sig.	0.3072
Test 5	Site F	189	31.65	8.13	df	1
	Site J	189	29.75	8.41	Sig.	0.925
Test 6	Site I	169	21.48	3.85	df	1
	Site J	169	25.87	0.35	Sig.	0.860

p-value < 0.05 indicates significant difference

The difference existing between Site A&B and Site I was somewhat unsurprising given the respective locations of the sites in the country. However, the difference between the two Co. Wexford sites is surprising given that they are located relatively close to each other within the same county.

A time series with a 3 week moving average of the net radiation at the four sites is shown in Figure 4.34. The difference between Site A&B and Site F is clear to see and it can also be seen how summer 2013 values are notably higher than summer 2012 values.

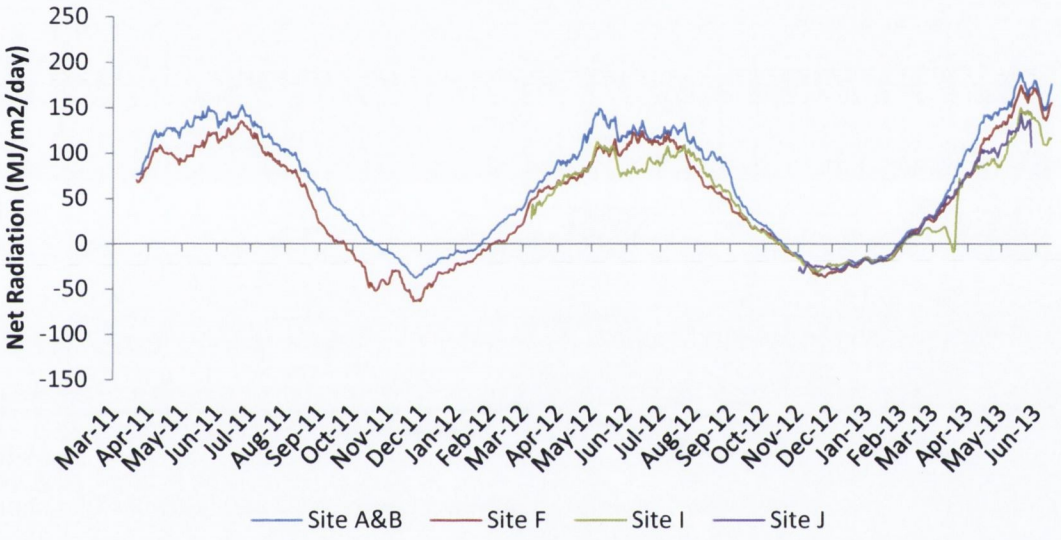


Figure 4.34 Times series comparison of net radiation (with a 3 week moving average trend line) between Sites A&B, Site F, Site I and Site J

4.2.11.4 Comparison of ET_o Rates

The distributions for the ET_o are illustrated in Figure 4.35. It can be seen that all the datasets have a similar shape generally conform to exponential shaped of distributions. Once this assumption was proven valid the median version of the Mann-Whitney U test was carried out.

As with the rainfall and wind speed data, each pair of datasets compared had the same sample size and each pair of daily values was from the same day. Again, mean or median values were not stated, due to the data from all the sites spanning different time periods.

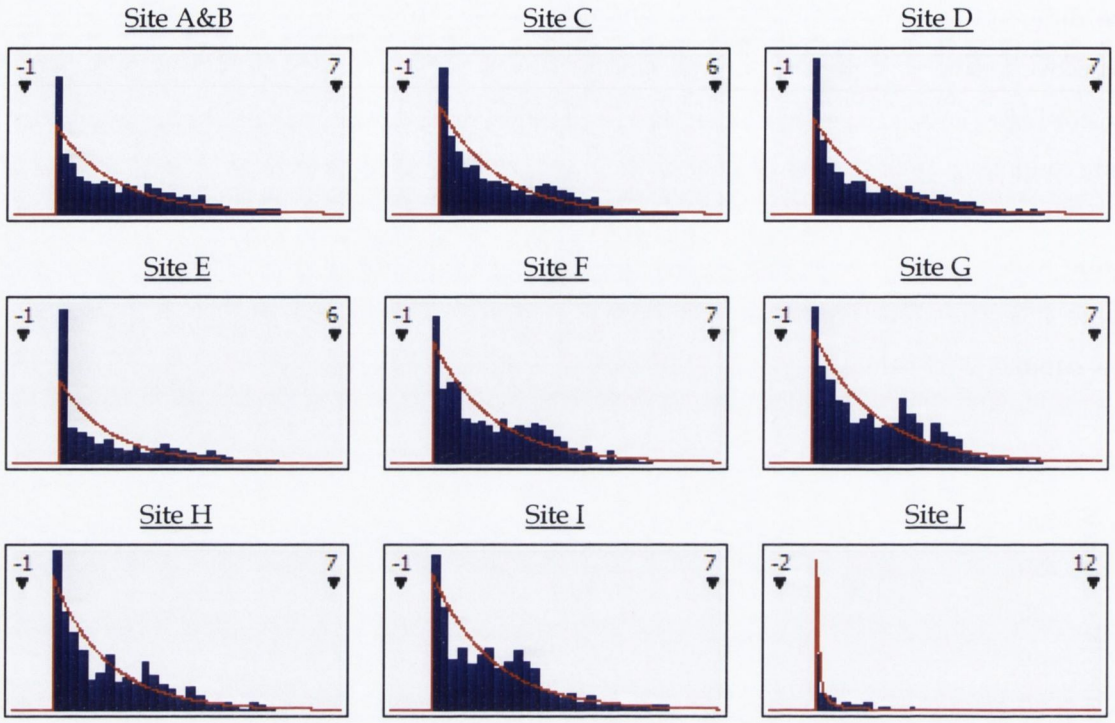


Figure 4.35 Distributions of reference evapotranspiration for each site (mm)

The p-values for the different pairs of datasets are shown in the matrix in Table 4.7. The sites which produced significantly different results are highlighted in red. The main sites that stand out as having statistically different values are Site E and Site J. Site E had a median value that were significantly lower than all of the other sites, bar Site J. The median for Site J was significantly lower than that for Site C, Site F, Site G and Site H.

Table 4.8 Results matrix of p-values from Mann-Whitney U test to assess if there was a significant difference between reference evapotranspiration for the different sites

Site	A&B	C	D	E	F	G	H	I	J
A&B	X	0.54	0.610	0.003	0.921	0.090	0.354	0.111	0.286
C	0.542	X	0.896	0.000	0.820	0.108	0.714	0.071	0.023
D	0.610	0.896	X	0.000	0.608	0.208	0.319	0.103	0.293
E	0.003	0.000	0.000	X	0.012	0.000	0.016	0.239	0.225
F	0.921	0.820	0.608	0.012	X	0.064	0.734	0.061	0.011
G	0.090	0.108	0.208	0.000	0.064	X	0.660	0.006	0.008
H	0.354	0.714	0.319	0.016	0.734	0.660	X	0.160	0.046
I	0.111	0.071	0.103	0.239	0.061	0.006	0.160	X	0.617
J	0.286	0.023	0.293	0.225	0.011	0.008	0.046	0.617	X

p-value < 0.05 indicates significant difference

As detailed in Section 4.2.10, of the weather parameters, net radiation has the greatest impact on daily reference evapotranspiration, so the lower median value for Site E is not surprising given the sheltered nature of the site. This could also be the reason for the lower evapotranspiration rates on Site J. Although, not significantly different it can be seen (Table 4.7) that both the median and mean net radiation are lower in comparison to the other sites where net radiation was measured.

4.3 Effluent Loading

For all of the willow system trial sites, the hydraulic loadings from the respective septic tank / pre-treatment unit were continually measured. From this, the treatment capacity, both in terms of hydraulic and pollutant removal can be accurately assessed. Along with the rainfall data assessed in Section 4.2, the hydraulic loading will constitute a key factor in the water mass balance carried out to determine evapotranspiration from each willow system.

As with the meteorological data, the hydraulic loadings will be presented on a site by site basis. Apart from a few brief periods where data had been lost on some sites as a result of malfunction of the respective datalogger, a continuous record of flow to the willow system was acquired.

Each section of the following sections compares the hydraulic loading from the wastewater flow to that from rainfall for each site. This will highlight whether or not the proportion from wastewater is significant and allow its relative importance to be assessed when it comes to designing willow systems.

4.3.1 Sites A Fardystown

Effluent loading to the willow system on Site A commenced in October 2010. Monitoring began in April 2011 and continued until August 2013 for this project. As outlined in Section 3.4.1, the accurate measurement of wastewater flow to the willow system was achieved using an OTT Thalimedes level meter situated within the pump sump. The daily on-site flow rate at the pump sump on Site A is shown in Figure 4.36.

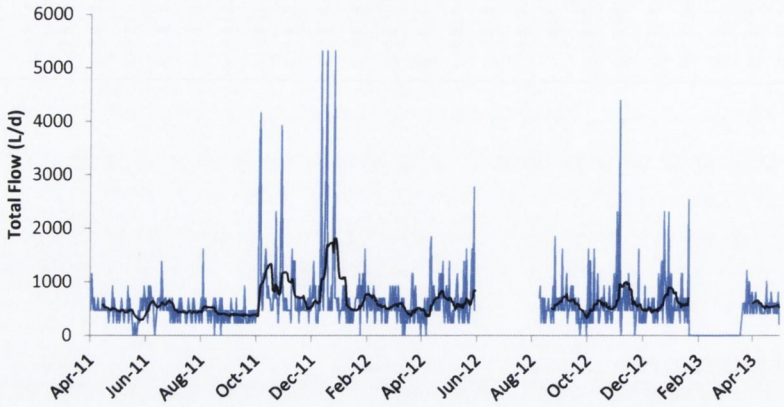


Figure 4.36 Daily flows to Site A (with 2 week moving average trend line)

It can be seen that the flow rate remained relatively constant over the monitoring period with the exception of some intermittent high loading. This high loading most likely occurred as a result of an increased number of visitors to the house over a short time period (e.g. party or Christmas) or from heavy rainfall. The mean flow measured on Site A was 628.4 L/day (Std. Dev. = 584.9). This figure equates to a mean effluent production per person of 157.1 litres per capita per day (L/c/day) [median value = 115.6 L/c/day]. This flow rate is slightly more than the 150 L/c/day assumed in the EPA Code of Practice (EPA, 2009a). However, from analysis of the data it would appear that the flow rate from the sump is enhanced by water from rainfall making its way into the system. This infiltration is illustrated in Figure 4.37 where it can be seen that large rainfall events are generally followed by spikes in flow rate. This is backed up by the scatterplot in Figure 4.38 which shows a strong correlation between the pair (Pearson r-value of 0.80).

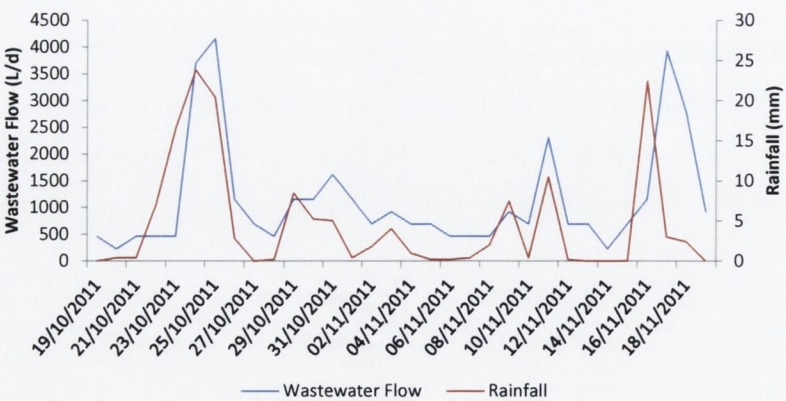


Figure 4.37 Comparison of daily wastewater flow with daily rainfall over a 1 month period on Site A

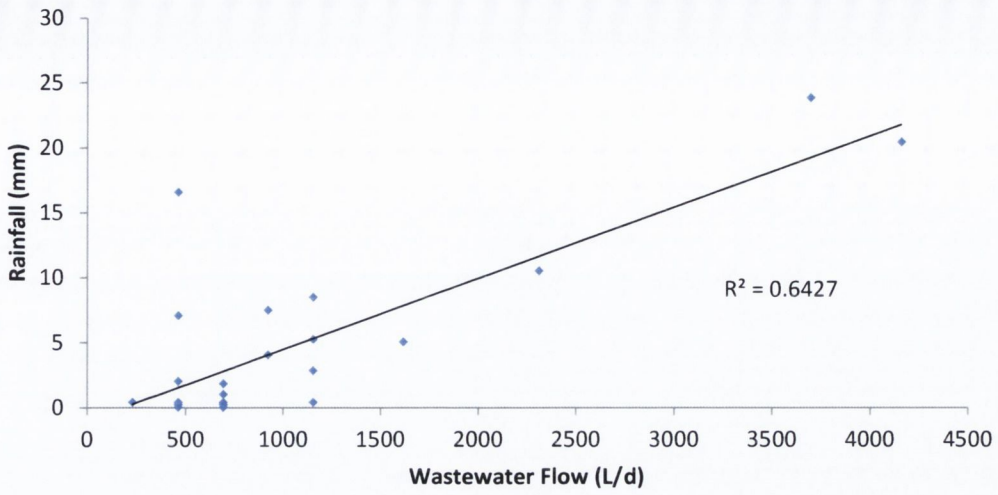


Figure 4.38 Correlation between daily wastewater flow and daily rainfall over a 1 month period on Site A

The hydraulic loading (mm) received by the willow system on Site A from rainfall and effluent loading for the period April 2011 - April 2013 is shown in Figure 4.39. It can be seen that the effluent loading constitutes a relatively large proportion of the overall hydraulic loading in many of the months. When broken down for the period monitored, rainfall accounted for 58.06% of the total loading, with effluent production accounting for 41.94%. However, it must be noted that the figure for effluent is probably inflated due to the rain infiltration that occurred at the site.

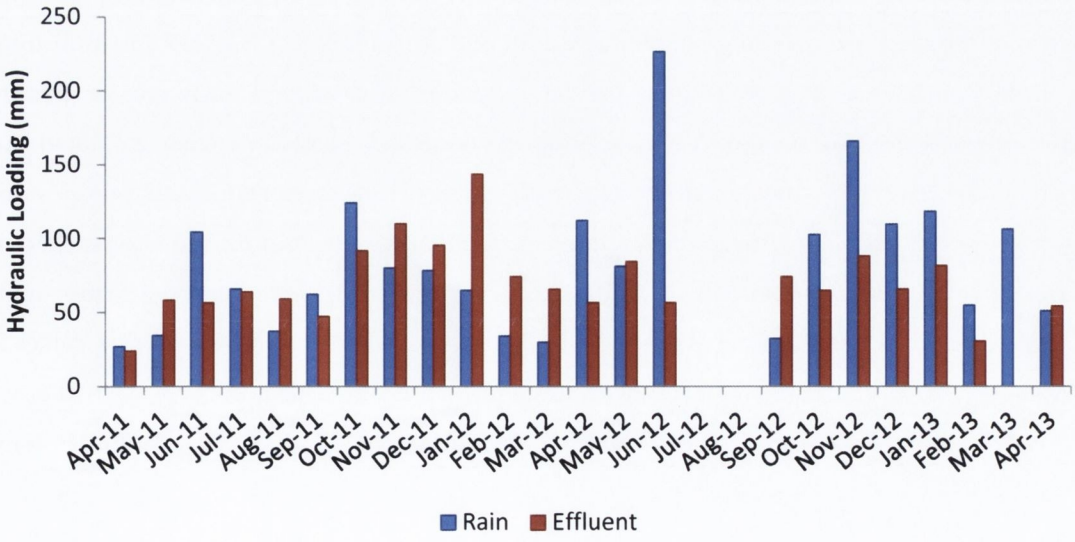


Figure 4.39 Hydraulic loading to willow system from rainfall and effluent (Site A)

4.3.2 *Site B Fardystown*

The dwelling on Site B remained vacant for almost three years after completion due the owner being unable to sell it. It eventually became occupied in January 2012 upon when loading of effluent to the willow system began. Monitoring of the wastewater flow began in April 2012 and continued until August 2013. As with Site A, measurement of the wastewater flow was achieved using an OTT Thalimedes level meter situated in the pump sump. The daily on-site flow rate at the pump sump on Site B is shown in Figure 4.40

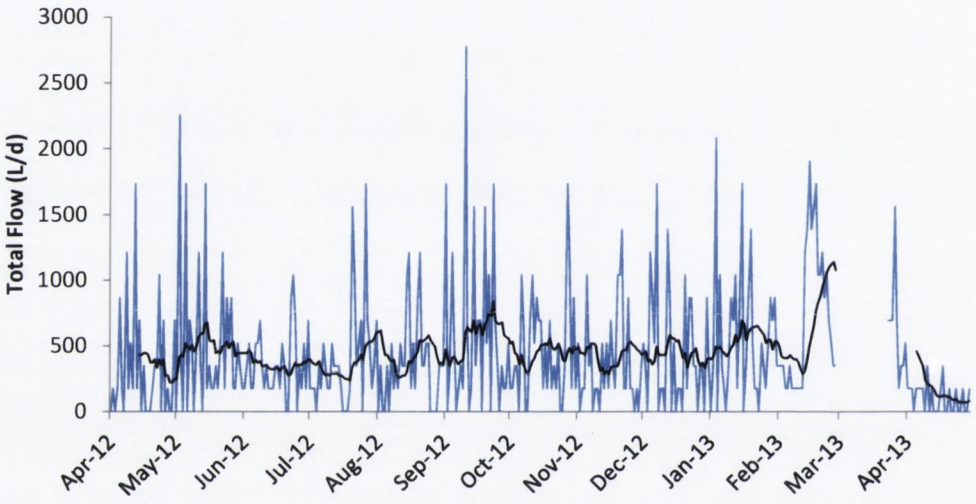


Figure 4.40 Daily flows to Site B (with 2 week moving average trend line)

Although the willow system on Site B was designed for a wastewater production of 4 PE, the majority of the time the dwelling was occupied by one person only. It became apparent upon examination of the flow data that the volume being produced was significantly greater than the amount expected for one person. After querying the issue with the homeowner, he noted that he had noticed surface water congregating in the area of the septic tank and pump sump following heavy rainfall. Further investigation revealed that after soil saturation was reached on the back lawn area during a rainfall event, the excess surface water flowed into the pump sump. This is illustrated in the two time series plots in Figure 4.41 where it can be seen that spikes in wastewater flow rate generally coincide with large rainfall levels. This is backed up by the two corresponding scatterplots (Figure 4.42) which shows a reasonably strong correlation (Pearson r-values of 0.46 and 0.47 respectively).

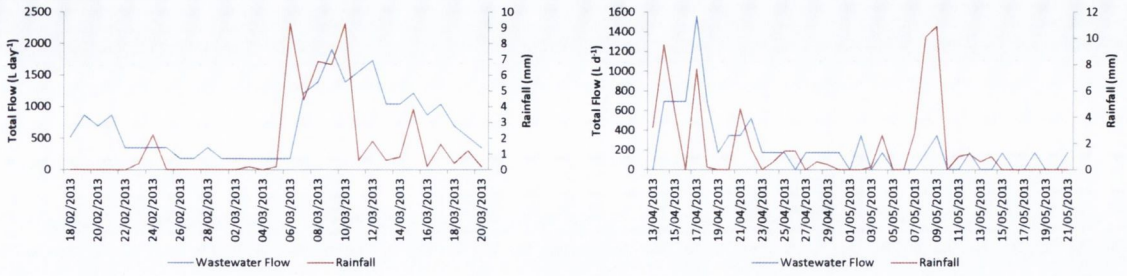


Figure 4.41 Comparison of daily wastewater flow with daily rainfall over two different time periods on Site B

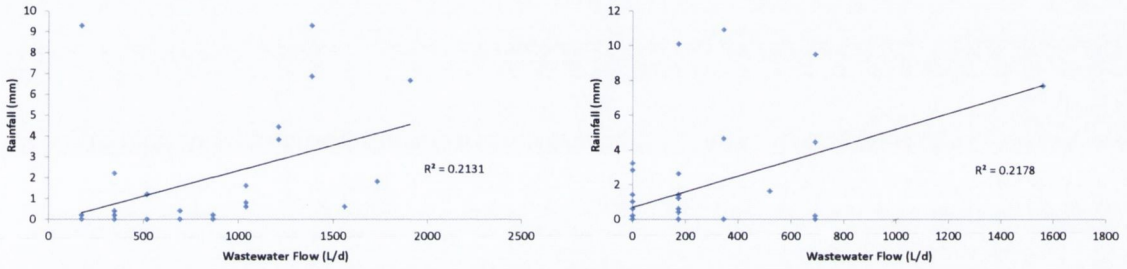


Figure 4.42 Correlation between daily wastewater flow and daily rainfall over 2 different time periods on Site B

As a result, this section will detail the total hydraulic loading from the pump sump rather than try and estimate the actual wastewater produced by the household. The mean flow measured on Site B was 443.1 L/day (Std. Dev. = 465.6). As there is only one person in the house this figure is also the mean effluent production per person (L/c/day) and is significantly greater than the value of 150 L/c/day assumed in the EPA Code of Practice (EPA, 2009a) for reasons previously discussed.

The hydraulic loading (mm) received by the willow system from April 2012 - May 2013 is shown in Figure 4.43. Effluent accounted for 16.63% of the total loading, with rainfall accounting for 83.37%. The lower loading from effluent compared to Site A would be expected given that there was only one person living in the dwelling. The volume from effluent is also probably overestimated given that rain infiltration occurred.

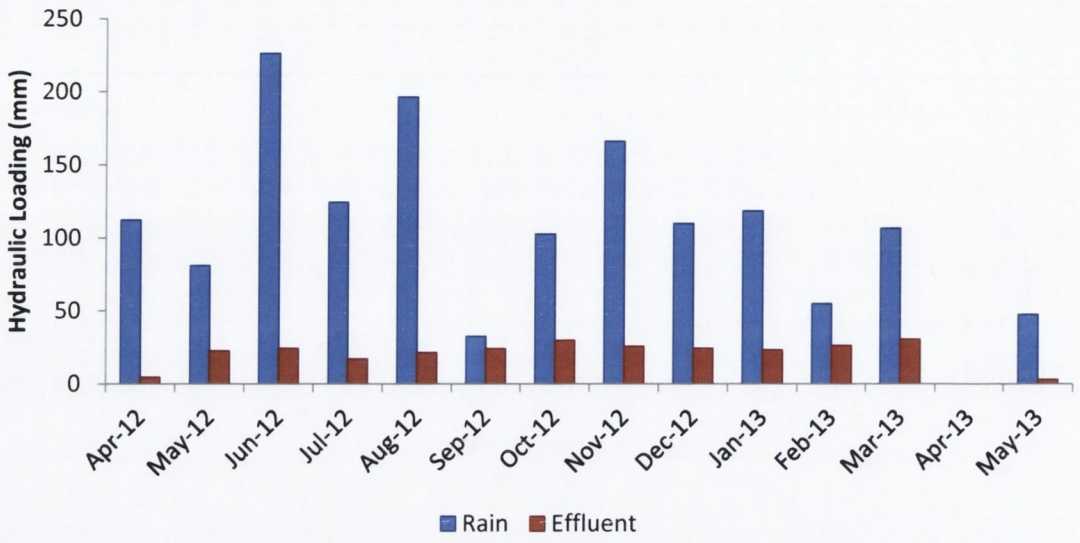


Figure 4.43 Hydraulic loading to willow system from rainfall and effluent (Site B)

4.3.3 *Site C Borehovel*

Loading of effluent to the willow system on Site C started on December 20th 2010. Monitoring of the effluent flow began in February 2011 and continued until May 2013. As detailed in Section 3.4.2, measurement of the wastewater flow to the willow system was achieved using an OTT Thalimedes level meter situated in the pump sump. The daily flow rate at the site is shown in Figure 4.44.

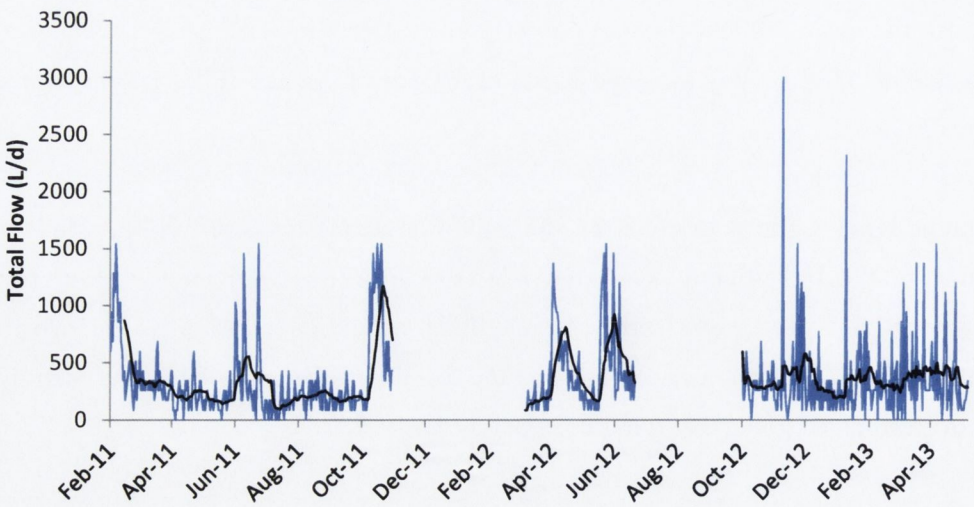


Figure 4.44 Daily flows to Site C (with 2 week moving average trend line)

A similar problem to the one encountered on Sites A and B occurred on Site C, with rain infiltration into the septic tank/pump sump during periods of heavy rainfall. It became apparent upon examination of the wastewater flow data that the volume being produced was significantly greater than the amount that would be expected from two people occupying the dwelling. The occurrence was not as obvious and scatter plots with wastewater flow against rainfall yielded low Pearson r-values. However, the two time series plots (Figure 4.45) with do show some correlation, with significant amounts of daily rainfall resulting in spikes in the wastewater flow rate.

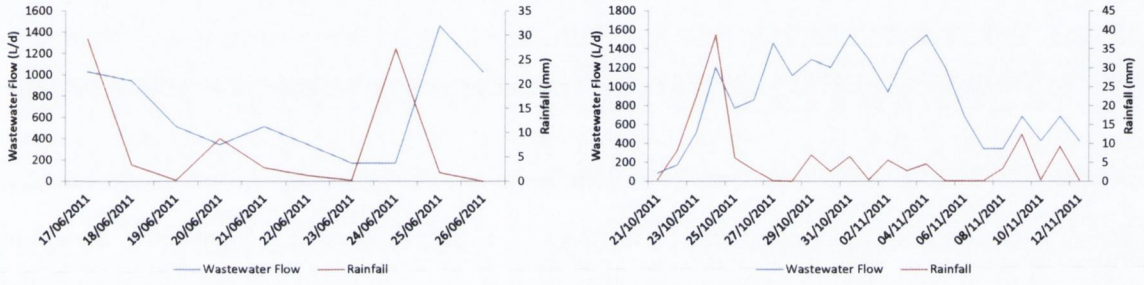


Figure 4.45 Comparison of daily wastewater flow with daily rainfall over two different time periods on Site C

The mean flow measured on Site B was 356.7 L/day (Std. Dev. = 345.9). This figure equates to a mean effluent production per person of 178.4 litres per capita per day (L/c/day) [median value = 128.7 L/c/day]. The true figure is probably lower than value for the reasons detailed.

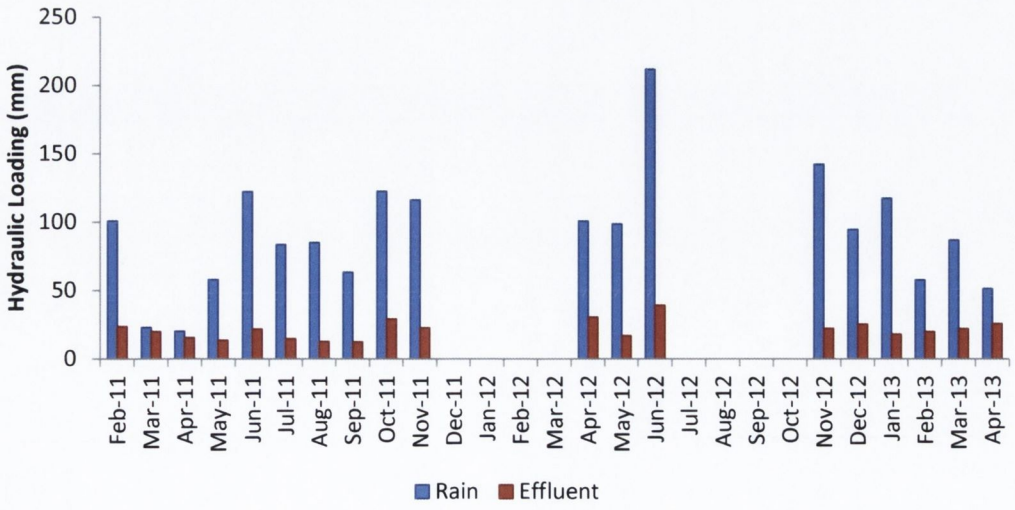


Figure 4.46 Hydraulic loading to willow system from rainfall and effluent (Site C)

A breakdown of the hydraulic loading received by the willow system from February 2011 - April 2013 is shown in Figure 4.46. It can be seen that rainfall provided the largest proportion (84.25%) of total loading, compared to 15.75% from effluent production. The monthly effluent volume was also relatively consistent throughout the monitored period. The figure for effluent loading may also be somewhat inflated, given that infiltration into the primary treatment system seemingly occurred.

4.3.4 *Site D Ballask*

Effluent production on Site D commenced immediately after construction of the willow system in May 2010. However, following the initial flooding in the willow system it was decided to divert the effluent to the old soil treatment unit so as not to waterlog the willow cuttings. Hence, loading to the willow system did not start until September 2012 (apart from a one 2 week period in June 2012). The effluent was distributed along the surface of the willow system in an attempt to help the willow growth on the site. Monitoring of the effluent flow started in August 2010 and continued until August 2013. As detailed in Section 3.4.3, measurement of the wastewater flow to the willow system was achieved using an OTT Thalimedes level meter situated in the pump sump. The daily on-site flow rate to the willow system is shown in Figure 4.47.

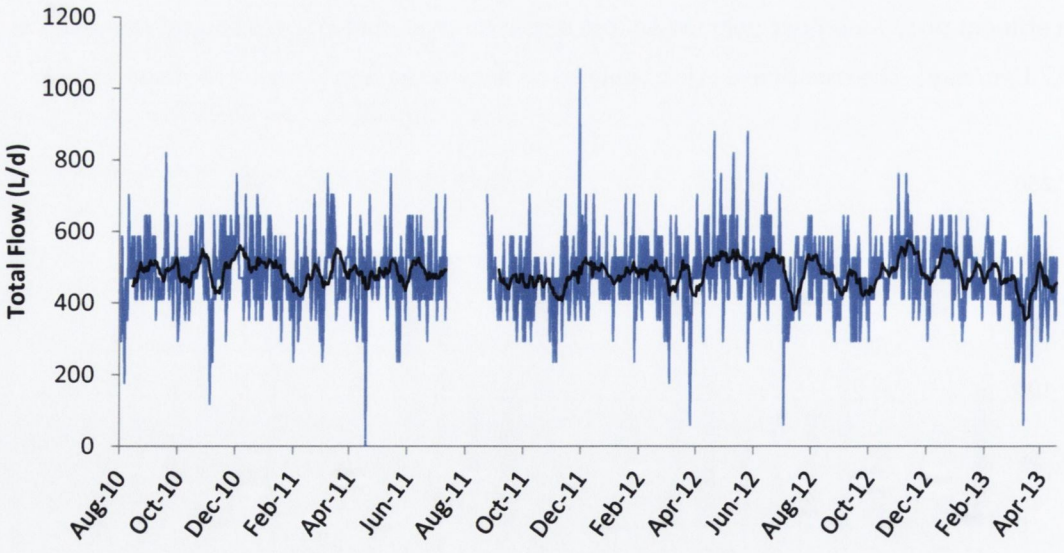


Figure 4.47 Daily flows to Site D (with 2 week moving average trend line)

It can be seen that the daily flow rate remained relatively constant over the monitoring period with the off exception of some intermittent high flow (most likely as a result of a party or event which resulted in an increased number of visitors to the house). The mean flow measured on Site D was 483.3 L/day (Std. Dev. = 110.2). This figure equates to a mean effluent production per person of 120.8 litres per capita per day (L/c/day) [median value = 117.2 L/c/day]. This is considerably lower than the figure of 150 L/c/day assumed in the EPA Code of Practice (EPA, 2009a) for single dwellings but is similar to results obtained by Gill et al. (2009a) and Gill et al. (2009b). It should also be noted that there was no evidence of rainwater infiltration into the system.

The hydraulic loading (mm) received by the willow system is shown in Figure 4.48. It can be seen that rainfall at the site accounted for most of the total loading (73.31%), with wastewater production accounting for 26.69%. The monthly effluent loading was relatively constant throughout the monitored period.

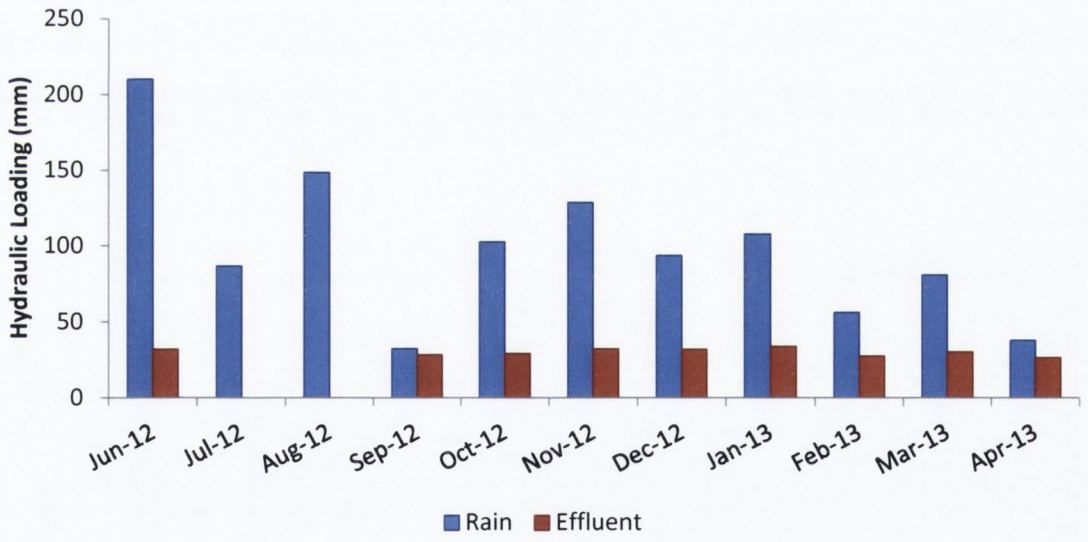


Figure 4.48 Hydraulic loading to willow system from rainfall and effluent (Site D)

4.3.5 *Site E Jamestown*

Wastewater loading from the two standalone toilets situated in an outhouse on Site E occurred between April and October during 2011 and 2012. As outlined in Section 3.4.4, the accurate measurement of wastewater flow to the willow system was achieved using a tipping bucket flow measuring device. Each tip corresponded to a volume of 900 ml of effluent.

The effluent flow rate from the outhouse was very low due to a lack of uptake in tours from local schools and REPS groups on the farm. In fact, the water supply to the toilets was shut off for long periods (especially during winter months) due to lack of use. Due to an issue with the datalogger which was counting the tips, the time and date on which a tip occurred was not stored. As a result of this an average daily flow is estimated by dividing the overall amount of tips by the total time period over which they took place. The results for different time periods are shown in Table 4.9

Table 4.9 Average daily flows to Site E

Time Period	No. of Days	Flow per day (L/day)
1st April - 5th July 2011	95	3.2
6th July - 19th October 2011	105	2.9
3rd April - 16th July 2012	104	2.0
16th July - 16th October 2012	92	3.3

It can be seen that effluent production provided a very small proportion of the total hydraulic loading to the willow system at Site E (see Figure 4.49). This was expected given the intermittent use of the toilet facilities at the site. Effluent accounted for just 4.39% of the total hydraulic loading during the periods when the toilets were in use, with rainfall providing 95.61%.

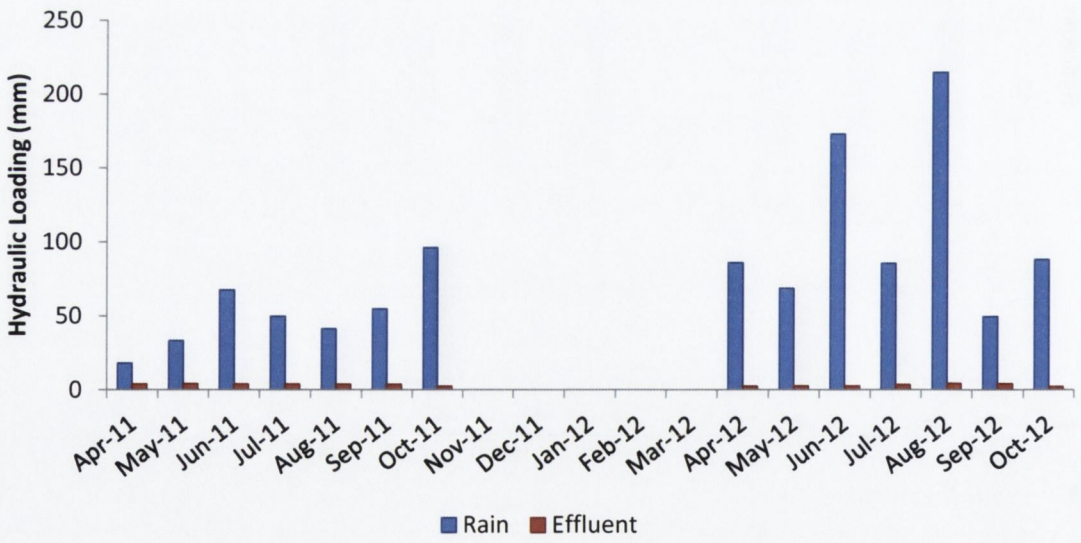


Figure 4.49 Hydraulic loading to willow system from rainfall and effluent (Site E)

4.3.6 Site F Ballywilliam

Effluent loading to the willow system on Site F commenced immediately after construction. As detailed in Section 3.4.5 the willow systems were designed for a 25 PE loading from five dwellings. However, for the majority of this research project only two of the dwellings were occupied with a third one occupied from June 2013. Due to various persistent problems on the site, including long term malfunctioning of the secondary treatment system (Enviropak Biological Aerated Filter (BAF) System), a faulty pump and a leak in the manhole which feeds the tipping bucket, the system did not receive the full amount of effluent being produced by the two occupied houses. As such, the estimated volume of wastewater entering the willow systems is not representative of the volume being produced by the dwellings.

Hence, this section will detail the estimated volume of wastewater that entered the willow systems on-site rather than estimate the total volume of wastewater that was produced. The original faulty pump was replaced in January 2013 and the daily flow was monitored from then until July 2013. However, as can be seen in Figure 4.50 the flow rate was still quite sporadic and was well below the volume expected for two occupied dwellings (4PE and 2PE respectively).

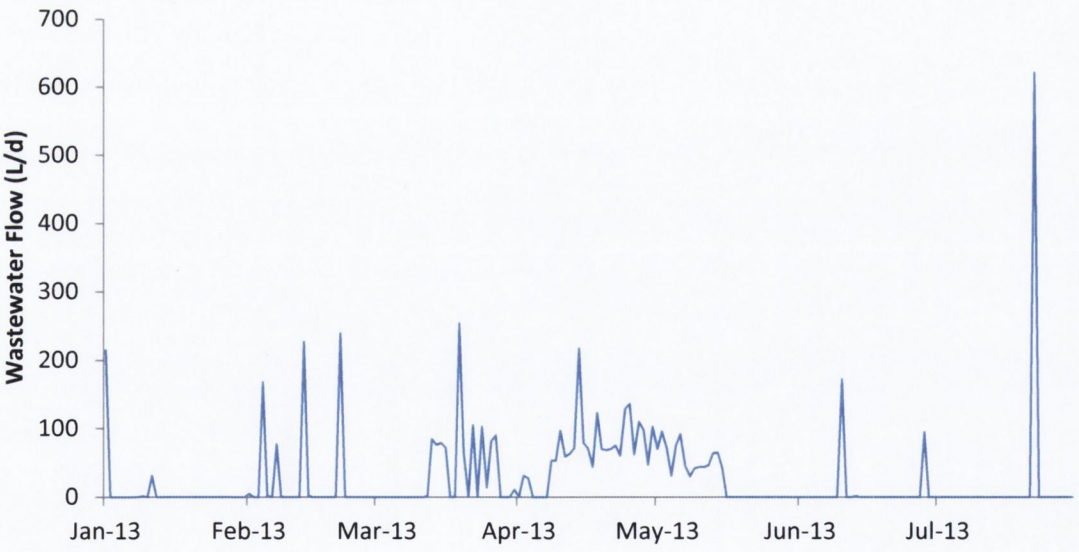


Figure 4.50 Daily flows to Site F (with 2 week moving average trend line)

As expected, given the problems that occurred at Site F, effluent production accounted for a tiny fraction of total hydraulic loading. For the period January 2013 - June 2013, effluent constituted just 0.7% of total loading to each willow system, with rainfall accounting for 99.3% (Figure 4.51).

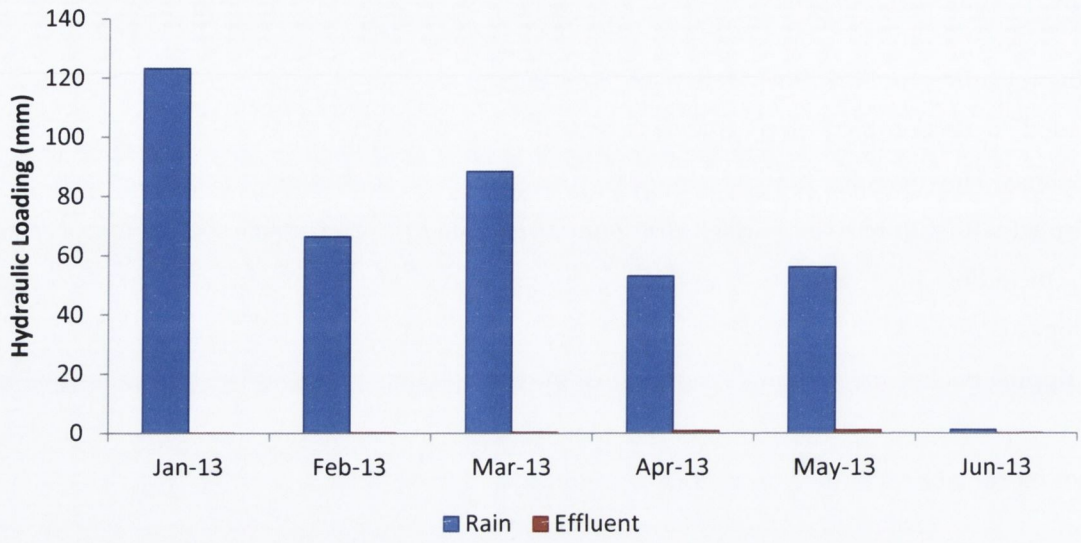


Figure 4.51 Hydraulic loading to willow system from rainfall and effluent (Site F)

4.3.7 *Site G Ardcavan*

The dwelling on Site G remained unoccupied throughout the entire monitoring period of this research. As a result, the effluent flow rate to the willow system was negligible. This was confirmed by level measurements recorded by an OTT Thalimedes level meter situated within the pump sump and is illustrated in Figure 4.52, where it can be seen that rainfall accounted for ~100% of loading to the willow system.

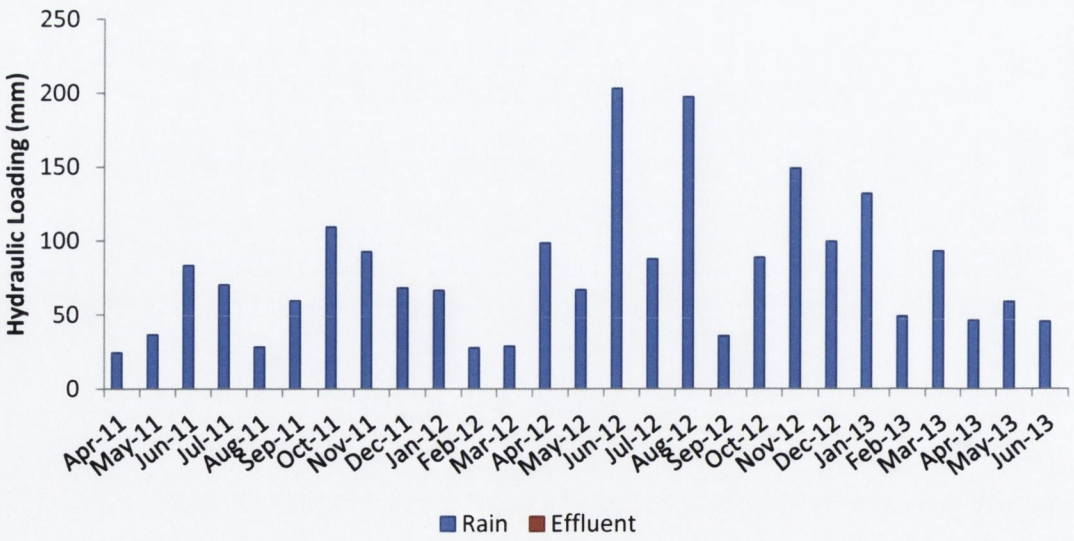


Figure 4.52 Hydraulic loading to willow system from rainfall and effluent (Site G)

4.3.8 Site H Duncormick

Monitoring of the effluent loading to the willow system on Site H commenced in March 2012 and was monitored until August 2013 for this project. As outlined in Section 3.4.7, the accurate measurement of wastewater flow to the willow system was achieved using an OTT Thalimedes level meter situated in the pump sump and the effluent was split between willow systems using a T-junction splitter valve. Initially there was a greater proportion of wastewater going to willow system 1 on the site. However, this error was rectified in May 2013 and both willow systems received equal volumes. The daily on-site flow rate at the pump sump on Site H is shown in Figure 4.53.

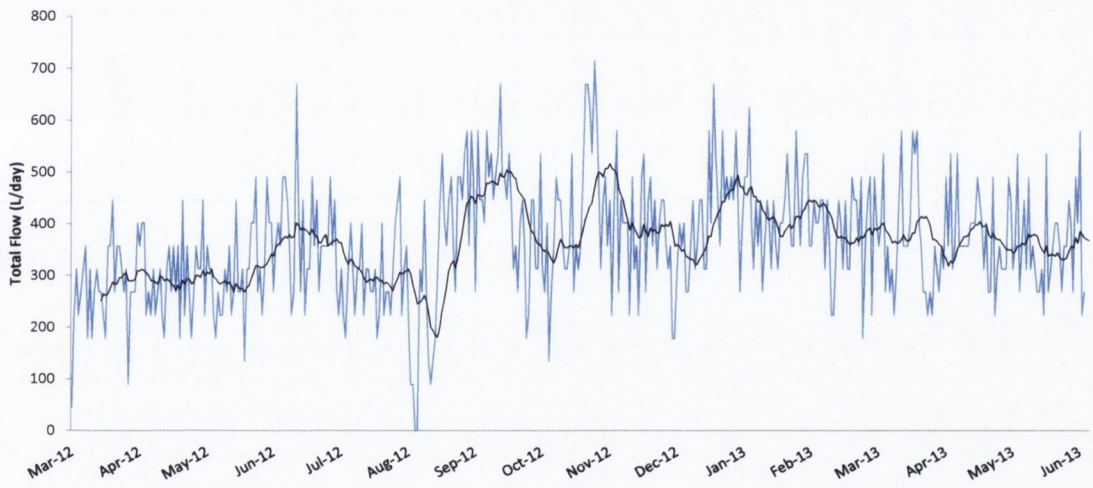


Figure 4.53 Daily wastewater flows to Site H (with 2 week moving average trendline)

It can be seen that the flow rate remained relatively constant over the monitoring period with the exception of some periodic high loading. This high loading most likely occurred as a result of an increased number of visitors to the house over a short time period (e.g. party or Christmas). The mean flow measured on Site H was 362.5 L/day (Std. Dev. = 114.9). This figure equates to a mean effluent production per person of 90.6 litres per capita per day (L/c/day) [median value = 89.32 L/c/day]. This is well below the daily wastewater consumption figure of 150 L/c/day assumed in the EPA Code of Practice (EPA, 2009a) for single dwellings and similarly to Site D, is quite close to values recorded by Gill et al. (2009a)

The breakdown of total hydraulic loading to each system into rainfall loading and effluent loading is shown in Figure 4.54 and Figure 4.55. It can be seen that the monthly loading from

effluent was relatively constant for both systems across the monitored period (July 2012 - June 2013). Rainfall accounted for 75.65% of total loading to system 1, with effluent accounting for 24.35%. For system 2, rainfall accounted for 83.66% of the total loading, with effluent making up 16.34%. The discrepancy between the two systems occurred as a result of the T-junction splitter valve being incorrectly set up.

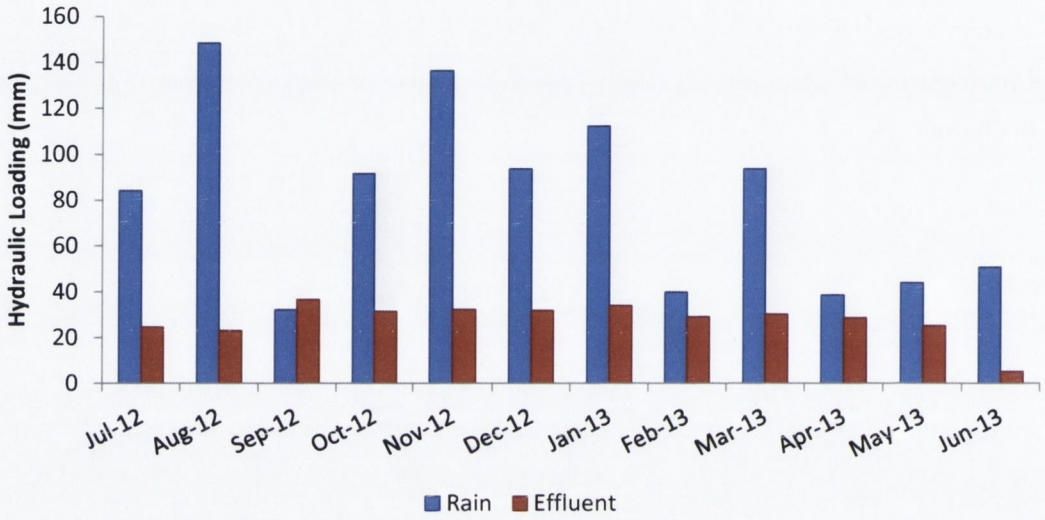


Figure 4.54 Hydraulic loading to willow system from rainfall and effluent (Site H - System 1)

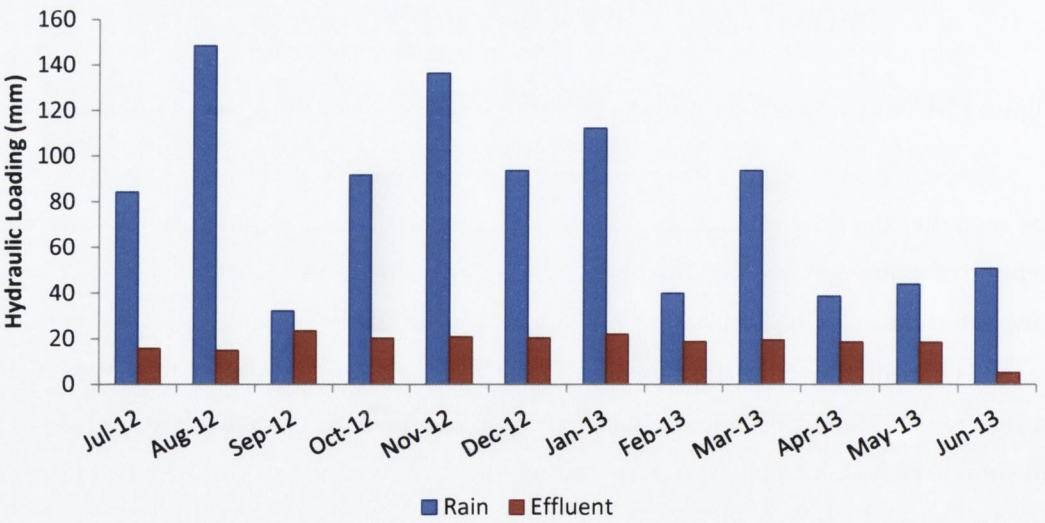


Figure 4.55 Hydraulic loading to willow system from rainfall and effluent (Site H - System 2)

4.3.9 *Site I Carrigallen (Co. Leitrim)*

Effluent loading to the willow systems on Site I began in November 2012. Monitoring began in January 2013 and continued until June 2013 for this project. As outlined in Section 3.4.8, the accurate measurement of wastewater flow to the willow system was achieved using a tipping bucket flow measuring device. The ratio between the left and right tip was 1: 0.92, with the greater amount going to willow system 1. The total daily flow rate measured by the tipping bucket is shown in Figure 4.56.

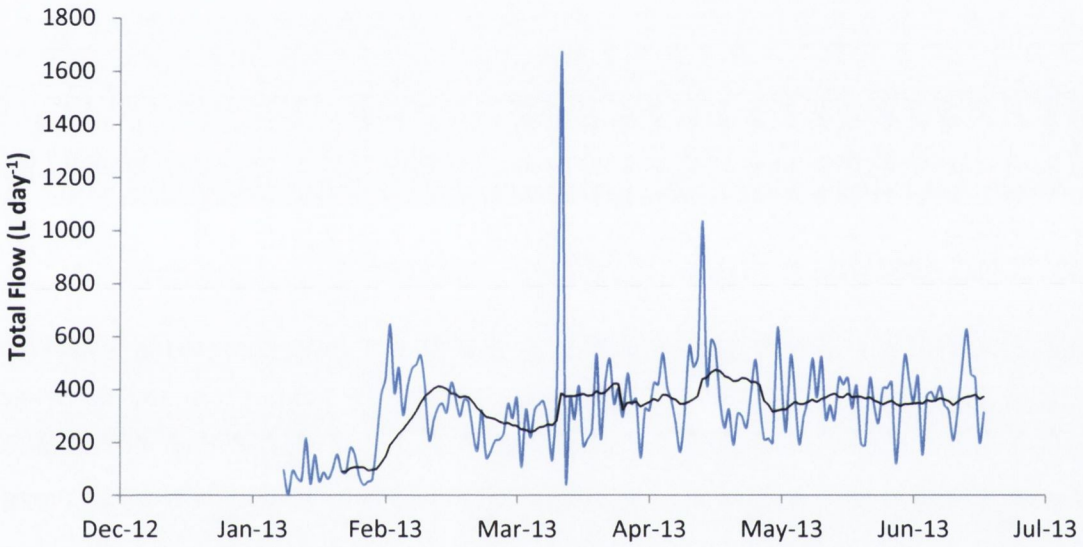


Figure 4.56 Daily wastewater flows to Site I (with 2 week moving average trendline)

It can be seen that the flow rate is relatively constant apart from two intermittent spikes. The mean flow rate measured on Site I was 326.7 L/day (Std. Dev. = 186.7). This figure equates to a mean effluent production per person of 81.7 litres per capita per day (L/c/day) [median value = 81.5 L/c/day]. This is almost half of the wastewater consumption assumed in the EPA Code of Practice (EPA, 2009a) for single dwellings. The deduction in per capita consumption (PCC) was probably aided in part by the installation of water saving devices in the dwelling.

The rainfall and effluent loading received by both willow systems on Site I is illustrated in Figure 4.57. It can be seen that effluent accounted for a small fraction of the total loading (6.42%) with rainfall accounting for the majority of it (93.58%).

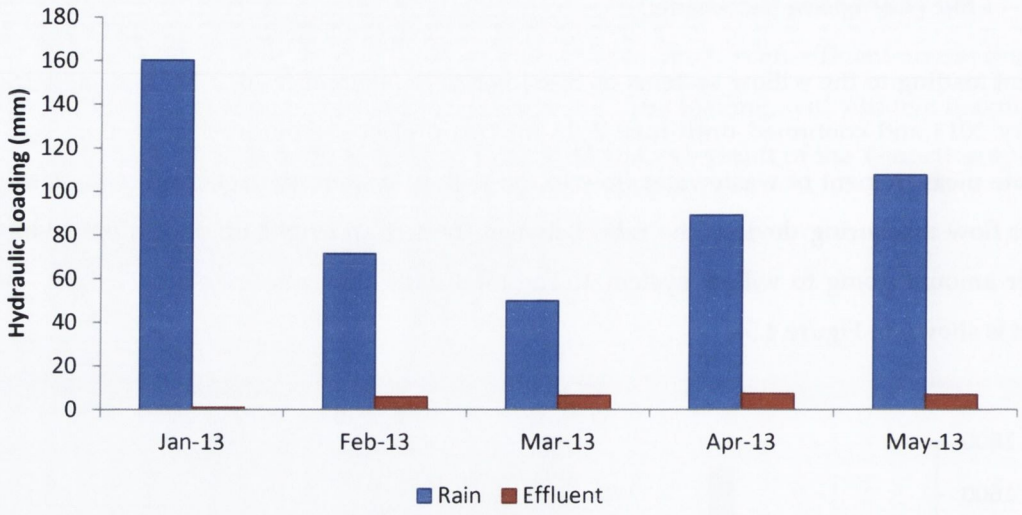


Figure 4.57 Hydraulic loading to willow system from rainfall and effluent (Site I - System 1 & 2)

4.3.10 Site J Ballylanders (Co. Limerick)

Although the willow system was constructed in early 2012, wastewater flow to the system only started in April 2013. This was due to problems with both the pump sump and the willow system. As a result of this issue there was no flow monitoring device installed on the site and an estimated daily volume for 3PE (based on PE values from other sites in this research project) was used for evapotranspiration calculations.

4.4 Comparison of Hydraulic Loading due to Rainfall and Effluent

The proportion of total hydraulic loading coming from rainfall and effluent loading (where applicable) were detailed on a site by site basis in Section 4.3. As the hydraulic loading is a critical factor in accurately designing the willow systems, it is important to understand the nature of the loading and its source. The results from each site are compared in Table 4.10. The figures in the table are based on the time period for which effluent flow was measured at that particular site. They are also representative of total effluent production, rather than the volume the willow system receives (e.g. the system at Site D went periods without receiving effluent).

It can be seen that rainfall constitutes the majority of hydraulic loading at all sites in comparison to the volume coming from wastewater production. The fraction varies from a minimum of 58.06% on Site A to a maximum of 100% on Site G (which had no occupants). As would be expected, the sites with a higher PE resulted in wastewater flow constituting a higher

proportion of total hydraulic loading to the system. It should also be noted that Sites A, B and C had rainfall infiltration into the wastewater, which would have resulted in an inflated representative proportion.

Table 4.10 Proportion of hydraulic loading from rainfall and effluent

System	Area receiving rainfall (m^2)	PE*	Time Period	Rainfall (mm)	Effluent (mm)	Rainfall (%)	Effluent (%)
A	250	4	May '11 - May '13	2206.44	1593.55	58.1	41.9
B	570	1	May '12 - May '13	1445.51	288.39	83.4	16.6
C	486	2	Feb '11 - May '13	2344.08	438.18	84.3	15.8
D	483.5	4	Sept '10 - May '13	2611.06	950.79	73.3	26.7
E	24	NA	Apr - Oct ('11&'12)	1015.44	46.67	95.6	4.4
F(1)	935	6	Jan '13 - Jun '13	376.97	2.65	99.3	0.7
F(2)	935	6	Jan '13 - Jun '13	376.97	2.73	99.3	0.7
G	432	0	Apr '11 - Aug '13	2206.20	0.00	100.0	0.0
H(1)	300	4	Mar '12 - May '13	1306.75	420.71	75.7	24.4
H(2)	300	4	Mar '12 - May '13	1306.75	255.19	83.7	16.3
I(1)	200.5	4	Jan '13 - May '13	474.83	32.58	93.6	6.4
I(2)	200.5	4	Jan '13 - May '13	474.83	32.58	93.6	6.4

* The volume of effluent produced may not be representative of the effluent loading produced as rain infiltration and pump malfunctioning occurred on some sites (as detailed on a site by site basis in Section 4.3)

The importance of ensuring that there is no rainfall infiltration into the septic tank/pump sump is also highlighted in Table 4.10. By comparing the percentage of loading attributed to wastewater production between Site A and Site D (both of which had a PE of 4), the significant increase caused by rainfall being directed into the sump on Site A is apparent. Thus, for closed evapotranspiration willow systems, which are designed with specific rainfall and wastewater loading in mind, it is imperative that additional rainfall infiltration into the system is avoided.

4.5 Soil Porosity

One of the key issues in the water balance calculations is the accurate determination of the available pore space in the soil within the zero discharge willow system. There are three main categories of pores in soils:

- Macro-pore: These are defined as cavities that a diameter greater than 75 µm. These significantly influence the hydraulic conductivity of the soil, allowing water to infiltrate and drain quickly.

- Meso-pore: These are defined as cavities with diameters between 75 µm – 30 µm.
- Micro-pore: The diameter of a micro-pore is < 30 µm.

(Soil Science Society of America, 1997)

While all three pores provide water storage, macro-pores and meso-pores are of greater importance with respect to this research. Both store water that is readily available to plants, whereas plants cannot exert enough force via transpiration to remove the water retained in micro-pores (Osman, 2012, Plaster, 2013). When soil saturation takes place the space in all three pores is filled with water. Following drainage of the soil via gravitational forces, it will reach the state of field capacity. At this stage water is still available in the meso-pores for plant adsorption. Eventually, following further water removal via evapotranspiration, the soil will reach the state of permanent wilting point. All remaining water is held in the micro-pores, which are small enough so that the adhesive and cohesive forces holding the water to the pore are greater than the transpiration force trying to drain it. So, from the perspective of creating a water balance based on soil porosity, it is the volume difference between permanent wilting point and saturation that needs to be determined. This is expressed in the following equation:

$$V_u = V_s - V_{wp} \qquad \text{Eqn. 4.2}$$

Where,

V_u = usable water volume storage within soil (m^3)

V_s = volume of water in soil at saturation point (m^3)

V_{wp} = volume of water in soil at permanent wilting point (m^3)

Permanent wilting point is defined as the largest water content of soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber (Soil Science Society of America, 1997). The main challenge in calculating the usable water volume storage using Eqn. 4.1 was determining the permanent wilting point of the soil. The permanent wilting point is generally estimated as the soil water content head in the soil at 1.5 MPa matric potential (Soil Science Society of America, 1997). In this method, a sieved soil sample is placed on a porous ceramic plate in a chamber and saturated with water. A pressure of 1.5 MPa is applied until equilibrium in water content between the plate or membrane and soil sample is reached (Cassel and Nielsen, 1986) at which time the soil water content is determined. However, Ritchie

(1981) state that field measurement of permanent wilting point may be the most preferable method, as it provides a more realistic assessment about how a plant grows in a particular soil.

This is particularly relevant to zero discharge willow systems in Ireland, as it is highly unlikely given the wet, mild climate, that even when empty, soil within the system reaches the true permanent wilting point. As such this research calculated the volume difference between saturation and drained volume (i.e. the lowest volume of water reached in the soil within the willow system when empty). The drained volume in this instance is not to be confused with the field capacity of the soil which takes account of water loss via gravity from the soil. The drained volume being described here refers to the lowest volume of water reached in the soil after water absorption by the willow trees (as drainage cannot occur from the sealed basin). Accurately determining the volume difference between the drained volume and saturation is a critical aspect for establishing willow system design guidelines as it is vital to know the volume of water and wastewater a basin of a certain size can store over the winter (when evapotranspiration rates are low). Also, given that it only the water level was being measured within the willow system, the usable water volume storage within the soil (along with the area and depth) was needed in order to determine evapotranspiration rates from the system. Thus, a revised version of Eqn. 4.2 is preferred:

$$V_u = V_s - V_d \qquad \text{Eqn. 4.3}$$

Where, V_u = usable water volume storage within soil (m^3)
V_s = volume of water in soil at saturation point (m^3)
V_d = volume of water in soil when drained under willow adsorption (m^3)

Three different methods, which are detailed below, were attempted in order to determine the volume at the fully drained point and from this the usable pore volume using Eqn. 4.3.

4.5.1 Method 1

The principle behind this method was drying soil samples outside, in climatic conditions similar to which they are under on site, rather the normal method of oven drying at 105 °C. In this manner, the volume of water in the soil when it reaches the 'drained volume point' should be comparable to the volume at the same point on the site. This method includes water loss

from both evaporation and drainage due to gravity from the soil. The process by which this is done is outlined below, followed by the results obtained.

The soil samples were collected in 100 mm diameter steel cores from within the willow systems on each site. It was ensured that any scrub on top of the ground was removed first so as to acquire a clean soil sample. Sample lengths were kept less than 200 mm as compression of the sample within the core would occur if longer samples were taken. Once removed from the ground, the metal cores were sealed with cling film and transported back to the soils laboratory at Trinity College Dublin.

Once back at the soils laboratory the soil sample was extruded from the steel core. The sample was then wrapped tightly in cling film and its length was accurately measured. It was then submerged under water for a number of days until saturation point was reached. Upon removal, the excess surface water on the core sample was allowed to drain away and the soil sample was then weighed. This weight represented the saturated soil weight.

After weighing of the saturated soil sample, it was then left on the roof of the soil lab to dry out. It was weighed periodically from then on, until the weight plateaued and remained relatively constant. This weight represented the 'drained volume' under these climatic conditions. The difference between the dried weight and the saturated weight represents the usable water volume storage in a soil sample of that volume.

$$V_u = \frac{(V_s - V_d)}{V_C} \qquad \text{Eqn. 4.4}$$

Where, V_u = usable water volume storage within soil (%)

V_s = volume of water in soil at saturation point (m^3)

V_d = volume of water in soil when drained (m^3)

V_c = volume of soil core

Three different core samples were taken from each willow system and the average of these was taken to give the final calculated usable storage volume. The results of this method for the different systems are shown in Table 4.11

Table 4.11 Results for usable water volume storage within soil (Method 1)

Site	System	Usable water volume storage (%)
A	1	34.6
B	1	23.5
C	1	34.6
D	1	23.8
E	1	34.8
F	1	38.1
	2	40.0
G	1	28.4
H	1	31.7
	2	29.7
I	1	27.5
	2	28.1
J	1	26.6

4.5.2 Method 2

The second method implemented was quite similar to the first one. However, samples for this method were taken at the end of the growing season when the water level within the willow system was relatively low. Water loss from the soil in this method is just as a result of willow evapotranspiration. There was no water loss due to gravity as the samples were taken in-situ from the sealed willow system basin. The process is outlined below followed by results.

The soil samples were collected from the willow systems in the same manner as described for Method 1. It was ensured that the cores were tightly sealed so that the water content would not drop before being weighed. After being transported back to the soils laboratory in Trinity College Dublin the soil sample was extruded from the steel cores and weighed immediately. It was assumed that the water content at this weight corresponds to the weight of water at the point of being fully drained (W_d).

The sample length was measured and then submerged in water until saturation point was reached. Upon removal, the excess water was allowed to drain away and the soil sample was then weighed. The water content at this weight corresponds to the weight of water at the saturation point (W_s).

The water volumes corresponding to W_d and W_s were calculated and the difference between them represented the usable water volume storage (V_u). The values calculated for V_u are shown in Table 4.12.

Table 4.12 Usable water volume storage within soil for each willow system (Method 2)

Site	System	Usable Water Volume Storage (V_u)
Site A	1	15.1%
Site B	1	15.6%
Site C	1	11.0%
Site D	1	11.0%
Site E	1	21.0%
Site F	1	18.0%
Site F	2	19.0%
Site G	1	9.6%
Site H	1	9.5%
Site H	2	9.5%
Site I	1	16.0%
Site I	2	20.0%
Site J	1	19.0%

4.5.3 Method 3

The third method of soil porosity estimation did not involve any physical analysis of the soil. Instead it focused on measured rain events and the change in water level within the willow system resulting from a particular event. In order to produce relevant results using this technique only large rainfall events over a short period of time were considered. This was to minimise the effect any evapotranspiration would have on the water level. It also had to be ensured that water level within the willow system at the start and end of the rain even was below the soil surface (i.e. all the water from the rainfall event was stored in the soil and not over the soil) and that the overflow point had not been breached. The results from this method of analysis are shown in Table 4.13.

It can be seen that volume storage could not be calculated for some sites. This was due to a number of reasons; lack of a large rainfall event, an event not occurring on a standalone basis (i.e. rainfall taking place over too long a time period), or the water level going above the overflow during the rain event, making it impossible to determine the exact height that the water level reached.

There is a certain level of inaccuracy associated with this method of soil porosity calculation. The main one being that it assumes all the rainfall during an event enters the system. If the event occurred during the growing season this would almost certainly not be the case, as leaf

interception can reduce the amount of water reaching the ground/basin by as much as 7% (Martin & Stephens, 2006). As a result, it was decided to weight the final porosity in favour of the results obtained by using method 2.

Table 4.13 Usable water volume storage within soil for each willow system (Method 3)

Site	System	Usable Water Volume Storage (V_u)
Site A	1	17.3
Site B	1	-
Site C	1	13.0
Site D	1	-
Site E	1	8.3
Site F	1	13.4
Site F	2	10.9
Site G	1	6.2
Site H	1	6.4
Site H	2	-
Site I	1	-
Site I	2	-
Site J	1	-

4.5.4 *Final Porosities*

After analysing results from the three different methods it became apparent that the results from the first method were considerably higher than those from the second and third methods (see Table 4.14). After comparing the dried soil samples from the first method to the site dried samples from the third method, it was obvious that they had dried to a much greater degree. For this reason, it was decided to ignore these results when it came to calculating the final usable storage volume in the soil.

The final usable storage volume for each site was determined by calculating the average of the three values obtained from the second method and the value obtained using the third method. In the case of not being able to determine a value using the third method, the mean of the three values from method 2 was used. The final mean values are weighted in favour of method 2 as it was deemed that this method provided the most consistently accurate representation of the actual usable water volume storage in the soil. As the samples were taken in-situ from empty willow systems, the degree of water loss that was measured should be close to reality. The final values are shown in Table 4.14.

Table 4.14 Comparison of usable water volume storage results and final value used

Site	System	Method 1 (not used)	Method 2	Method 3	Final
Site A	1	34.6	14.4	17.3	15.1
Site B	1	23.5	15.6	-	15.6
Site C	1	34.6	10.3	13.0	11.0
Site D	1	23.8	11.0	-	11.0
Site E	1	34.8	25.2	8.3	21.0
Site F	1	38.1	19.5	13.4	18.0
Site F	2	40.0	21.7	10.9	19.0
Site G	1	28.4	10.7	6.2	9.6
Site H	1	31.7	10.5	6.4	9.5
Site H	2	29.7	9.5	-	9.5
Site I	1	27.5	16.0	-	16.0
Site I	2	28.1	20.0	-	20.0
Site J	1	26.6	19.0	-	19.0

A comparison of the results from the three methods is illustrated in Figure 4.58. It can be seen that there appears to be some correlation between the three different methods, especially between methods 1 and 2. When compared statistically against each other it was determined that there was somewhat of a correlation between method 1 and method 2 (Pearson r-value of 0.36) and also between method 1 and method 3 (Pearson r-value of 0.54). However, there was little correlation between method 2 and method 3 (Pearson r-value of 0.08).



Figure 4.58 A comparison of the three different methods

4.6 Summary

4.6.1 Meteorological Data

The analysis on the collected meteorological data followed the general expected pattern:

- There was a high degree of variability in wind speed between all the sites. AS previously mentioned, this justified the decision at the start of the research project to install a wind anemometer on every site.
- There was much less variability in net radiation, rainfall and reference evapotranspiration between the sites in Co. Wexford. However, the Co. Leitrim and Co. Limerick sites did have significantly different values to the Co. Wexford sites for some of the parameters measured. This would be expected given the relatively large difference in geographical location.

4.6.2 Effluent Loading

There was a lot of variability in effluent production between the different sites. This was largely due to the fact that rainfall infiltration into the treatment system resulted in inflated flow measurements. However, on the sites where it was determined that rainfall infiltration did not occur, the wastewater production rate was well below the assumption of 150 L/c/day for a one off house made in the Code of Practice (EPA, 2009a).

4.6.3 Soil Porosity

As would be expected, the soil porosity results varied quite a lot between the different sites. However, more unexpectedly, there was also some variability between the porosity of soil samples collected on the same site. This highlights the difficulty faced in attempting to determine the usable porosity of a soil when the specific upper and lower boundaries in question are not accounted for in recognised laboratory techniques. For example, normally the lower boundary in porosity calculations would be the volume of water in the soil that defines the permanent wilting point. However, in the case of this research, the permanent wilting point is never reached and thus the lower boundary is the volume of water in the soil when the system is empty at the end of the growing season.

As a result, the uncertainties involved in accurately determining the usable water volume storage in the soil follow through to the evapotranspiration results as the soil porosity forms a key part of the water balance applied. However, given that there was a number of samples taken on each site, it is assumed that the final result is close to them true value. Thus, the uncertainty in the evapotranspiration results are minimised as best as possible.

Chapter 5

Evapotranspiration Results from Willow Systems

5 Evapotranspiration Results from Willow Systems

5.1 Introduction

This chapter examines the evapotranspiration performance of the willow systems on each site. The evapotranspiration rates achieved varied by system and by year and so, as with the previous chapter, the performance of each site will be assessed on an individual basis. The operational period of the willow systems provided valuable insight into the different factors affecting evapotranspiration. The performance of each system will be compared and these factors will be assessed to determine which had the greatest influence.

5.2 Method or Analysis/Water Balance

As detailed in Chapter 3 each site was monitored in the following manner throughout the trial period:

- The water level within the willow system was continuously monitored.
- The wastewater flow to the system (if any) was continuously monitored.
- The wind speed and rainfall were recorded at each site, with two of the site recording a full complement of meteorological parameters (humidity, net radiation, temperature, wind speed).

The evapotranspiration was determined on a daily basis. A daily water balance was carried out for each system taking into account the accurate hydraulic loading from rainfall and wastewater (see Eqn. 5.1):

$$ET_{willow} = R + I + \Delta H\,(V_u)(A) \qquad \text{Eqn. 5.1}$$

Where, ET_{willow} = evapotranspiration from willow system

R = rainfall

I = influent (wastewater)

ΔH = change in water level within system

V_u = usable water volume storage within soil/gravel

A = surface area

Once the evapotranspiration from the willow system was calculated the corresponding crop coefficient (K_c) could be determined using Eqn. 5.2:

$$K_c = \frac{ET_{willow}}{ET_o} \qquad \text{Eqn. 5.2}$$

Where, K_c = crop coefficient

ET_{willow} = evapotranspiration from willow system

ET_o = Penman Monteith Reference Evapotranspiration

5.3 Willow System Evapotranspiration

This section examines the evapotranspiration performance of the willow system on each site. Sites with two operational willow systems were examined on an individual basis. Initially it had been planned to present the evapotranspiration rates attained by the willow systems on a daily basis. However, upon preliminary analysis it became apparent that the calculations yielded large fluctuations sometimes when computed across such a timescale.

Such fluctuations generally arose from the occurrence of rainfall events. When calculated on a daily basis such events appeared to cause an artificially high evapotranspiration rate for the day of the event while making the following day's evapotranspiration appear artificially low. Hypothetically, a water balance should incorporate such hydraulic loading. However, in reality the time lag between the event and the time it takes for the additional water to find its 'true' level skews the evapotranspiration result from the water balance for that particular day. This effect is illustrated in Figure 5.1 over an 11 day summer period on Site A.

The rainfall event on 1st July results in a relatively high ET_{willow} rate being determined for that day. However, the determined ET_{willow} rate for the following day is actually a negative value. This is obviously not possible, and comes about as a result of the full increase in the water level due to the rainfall event not being reached within the day of it occurring. So, the water level on the following day (2nd July) has increased even though there was no rainfall on that particular day. Hence, a negative ET_{willow} rate is determined from the water balance for that day. A similar occurrence can be seen on for the 10th and 11th July.

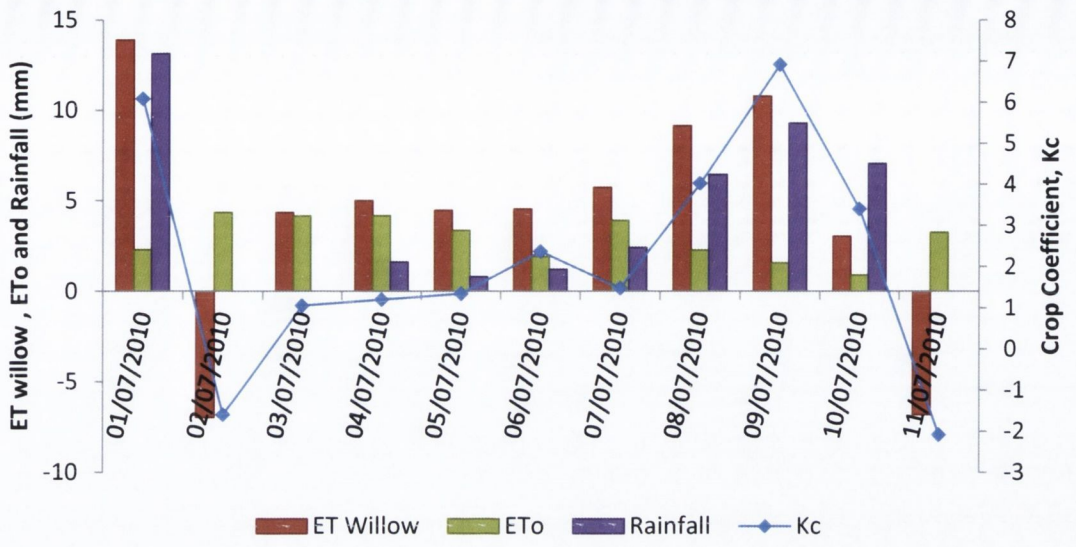


Figure 5.1 Daily fluctuation in ET_{willow} rates and crop coefficient (K_c) values

Presentation of evapotranspiration results on a weekly and fortnightly basis also produced inconsistent results (see Figure 5.2 and Figure 5.3). It was found that large rainfall events at the end of a particular week could result in false low evapotranspiration results for the following week; similar to that described for daily evapotranspiration calculation. It can also be seen that fortnightly ET_{willow} rates and the corresponding crop coefficients were very inconsistent.

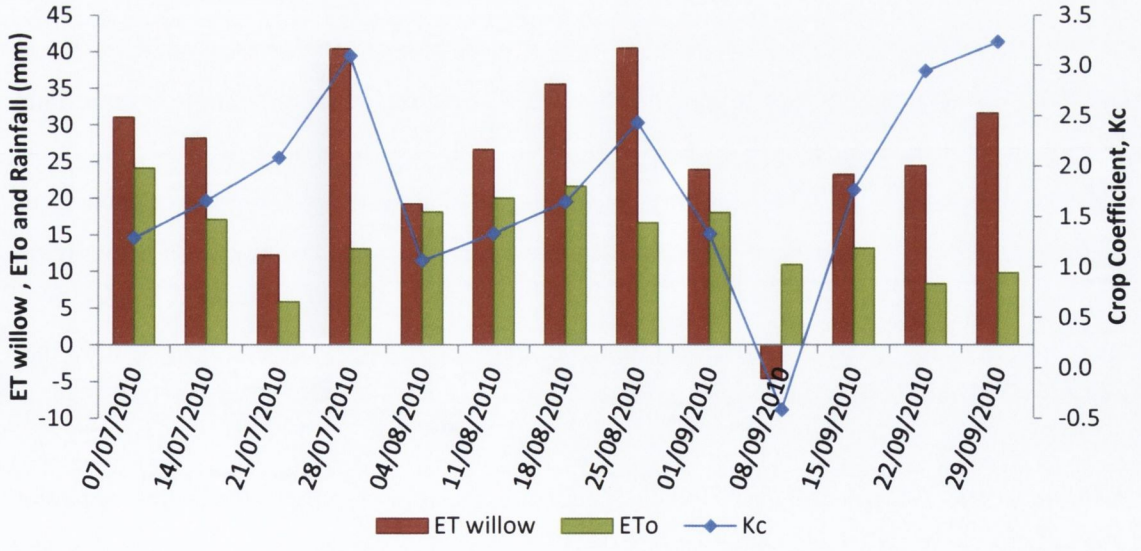


Figure 5.2 Weekly fluctuations in ET_{willow} rates and crop coefficient (K_c) values

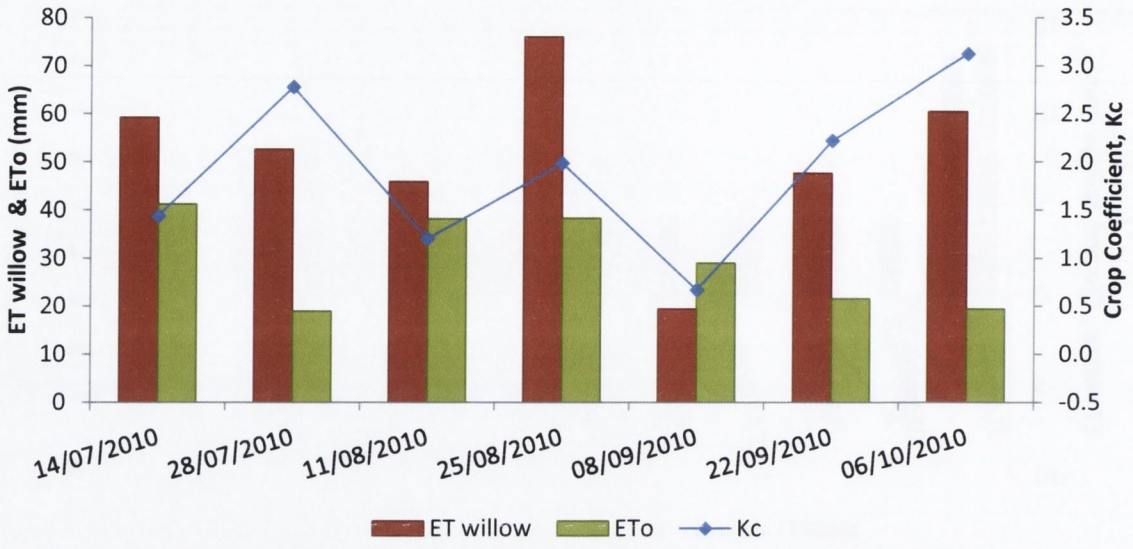


Figure 5.3 Fortnightly fluctuations in ET_{willow} rates and crop coefficient (K_c) values

Incorrect evapotranspiration rates could also have resulted from inconsistency in the soil porosity within the willow system. The soil porosities detailed in Section 4.5 have been used as an average for each willow system. However, as the backfilled soil was heterogeneous in nature, the soil porosity fluctuated slightly about the average for different depths and locations within the willow system and hence resulted in slightly varied evapotranspiration rates depending on the water level.

As a result of these fluctuations it was decided to calculate the evapotranspiration on a daily basis but present the results averaged on a monthly basis, as this format produced the most intuitively consistent results. The monthly results are detailed annually using the calendar year to allow for monthly comparisons between different years and sites. Usually studies involving water balances would align analysis and results with the hydrological year (October 1st - September 30th). However, given that this research involved closed systems it was decided that there was no benefit to be gained by doing this.

Although all the willow systems were designed to have zero discharge it became apparent through analysis of the water level data and also from observations at the site itself that this was not the case for many of the systems. The discharge from overflow resulted for different reasons which are detailed on a site by site basis later in this chapter. The overflow generally occurred during the winter (which would be expected as rainfall amounts are greater and

evapotranspiration is low) although it did also occur to a certain extent during the summer of 2012 when precipitation levels were exceptionally high.

It was impossible to accurately determine evapotranspiration from the willow systems when the water level was above the overflow point, as the volume of water leaving the system from evapotranspiration couldn't be distinguished from the volume of water leaving due to overflow. So, for the growing season mean daily evapotranspiration rates were determined from the actual amount of days when evapotranspiration could be calculated rather than the total days in the month. In the winter months when the trees were dormant, it was assumed that ET_{willow} was equal to ET_o (reference evapotranspiration for a hypothetical grass crop on days where the water level was above the overflow level and the actual evapotranspiration from the system couldn't be accurately calculated. In the winter months, the mean daily evapotranspiration was based on the assumed evapotranspiration. So, in the periods when the assumed evapotranspiration is higher than the measured evapotranspiration, this indicated that overflow from the system occurred during that month or that the water level in the willow system bottomed out during the month. Each monthly crop coefficient was calculated by dividing the assumed monthly ET_{willow} by the ET_o for the month.

Overflow from the willow systems did not always occur above the soil surface in the systems. This is highlighted in the water level graphs for each site in Section 5.3.1 to Section 5.3.11. Having a water level above the overflow level appears confusing but is as a result of the rate of water escape being less than the rate of hydraulic input (primarily from rainfall). The slower rate of escape is due to overflow occurring below the soil surface meaning the water has to pass through this medium. On sites where overflow occurred above the soil surface (e.g. Site D) it can be seen that the water level measured within the willow system doesn't rise very much above the determined overflow level at any time. This is due to the quick rate of escape of the water as it doesn't have to pass through a soil medium.

5.3.1 Site A Fardystown

Measurement of water levels within the willow system on Site A commenced on the 25th February 2010. As detailed in Section 3.4.1 the willow system was designed and constructed by an external designer. The specification in the design stated that the depth was to be 1.5 m (excluding additional height of berm). However, upon analysing the data it became apparent that the system was not built to the specification. The depth from soil surface to the bottom of the basin was 1.35 m; however, the height of sealed basin was just 0.92 m. Overflow from the

system occurred once the water level went above this level. After heavy rainfall in the winter months the water level consistently dropped back to this level and as such it has been taken to represent the physical overflow point from the system. This was confirmed by going to the site on a day of heavy rainfall, where the willow system could be seen to be overflowing on its lowest side. Unless the water level rose above the soil surface (and the rate of water loss from the system was quite rapid), water loss from the system was not always instantaneous. This was due to the low point of the liner being below ground level meaning that the escaping water had to pass through soil rather than being out in the open.

As mentioned earlier, it was impossible to distinguish evapotranspiration from water loss due to physical overflow when the water level was above this point. The annual analysis of evapotranspiration from the willow system demonstrates this, where winter time values were generally conservatively low. The system received septic tank effluent from October 2010 onward. As detailed in Section 4.5, the usable water volume storage in the soil on Site A was 15.1%.

5.3.1.1 2010 Evapotranspiration

The water level within the willow system along with daily rainfall at the site for 2010 (February to December) is shown in Figure 5.4. The calculated overflow level is also included. It can be seen that any significant rise in water level in the winter months was generally followed by a similar decrease. Such decreases would not be expected in winter months as evapotranspiration rates are low. The effect of large rainfall events on the water level can be seen when 71 mm of rainfall on the 6th September resulted in an increase in level in excess of 0.55 m within the willow system.

The monthly evapotranspiration rates for the willow system, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Figure 5.5 and Table 5.1. The ET_{willow} rate for the months of November and December could not be calculated due to an inability to distinguish between water leaving the system due to the overflow from water leaving as a result of evapotranspiration, as described at the start of this section. Hence, the reference ET_o values only are given for these months.

The mean daily ET_{willow} rates were determined from the actual number of days in which the willow evapotranspiration could be confidently determined (i.e. when the water level was below the overflow point). The mean daily ET_{willow} rates ranged from 2.2 mm/day (May) to 4.8

mm/day (July) for the growing season. The crop coefficient was 1.0 for the month of March rising steadily to a peak of 4.1 in October.

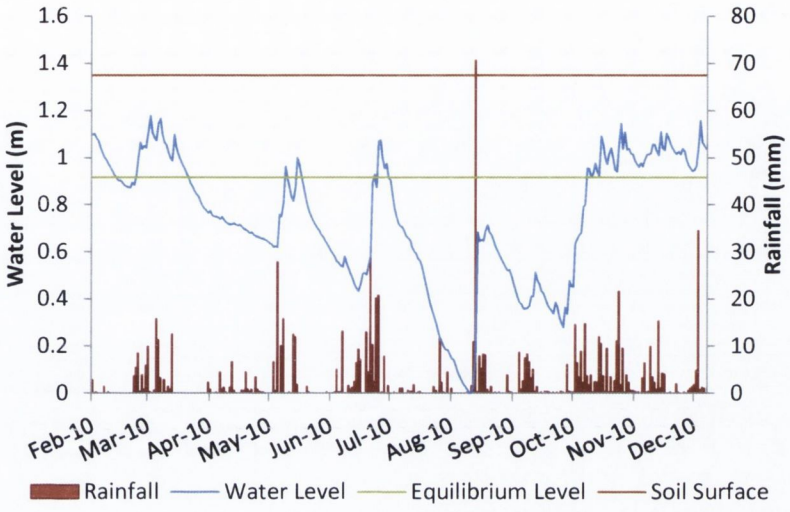


Figure 5.4 Water level and daily rainfall for February to December 2010 (Site A)

The May value of 0.9 did not follow the expected seasonal pattern and was lower than the April K_c value of 1.1. This could have been as a result of water not being readily available for the willows at the surface of the willow system. Closer examination of the water level in Figure 5.4 shows that following a relatively quick decline in April, the water level began to taper off and decreases in the level for May were less sudden. This tapering off effect did not appear to happen again during the year, possibly because the root systems on the willows were more developed by that point and had access to water at a lower level.

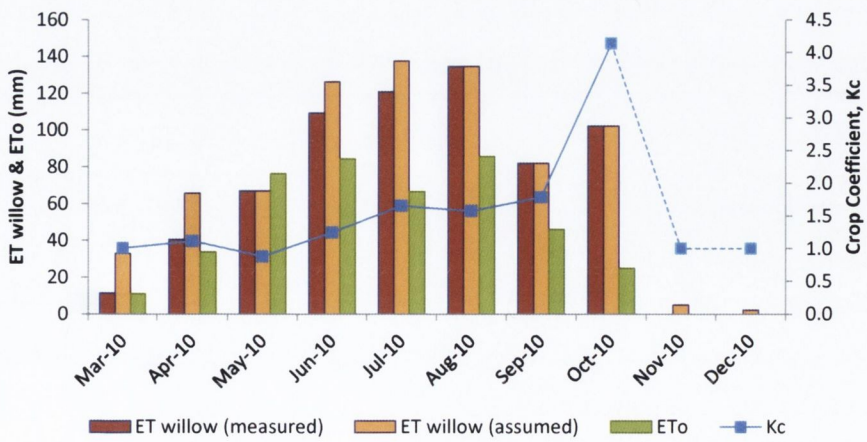


Figure 5.5 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010)

Table 5.1 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
March	11.2	32.8	32.6	10	1.1	1.0
April	40.5	65.8	59.0	17	2.4	1.1
May	66.9	66.9	76.2	31	2.2	0.9
June	109.3	126.3	101.3	26	4.2	1.3
July	120.9	137.6	83.3	25	4.8	1.7
August	134.6	134.6	85.6	31	4.3	1.6
September	81.9	81.9	45.9	30	2.7	1.8
October	102.3	102.3	24.7	31	3.3	4.1
November	0.0	4.9	4.9	0	0.2	1.0
December	0.0	2.0	2.0	0	0.1	1.0
Total	667.6	755.0 (TR = 829)[1]	515.5	202	3.3 (2.5)[2]	1.5

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The measured total ET_{willow} over the 9 months of monitoring in 2010 was 667.6 mm, based on 202 days of evapotranspiration values. The corresponding reference evapotranspiration for these days was 428 mm. This corresponded to an overall crop coefficient of 1.6 for the days measured. However, the overall assumed ET_{willow} for the year was 755 mm (corresponding to an annual average crop coefficient of 1.5). As explained at the start of this section, this calculation assumed reference evapotranspiration for days in which the water level was above the overflow level.

5.3.1.2 2011 Evapotranspiration

The water level within the willow system and the rainfall at the site for 2011 are shown in Figure 5.6. There was 15 days of lost water level data in August due to equipment malfunction. The water level decreased to zero at some point in this time period as the inspection well was noted to be empty when the equipment was fixed on the 18th August. The willow system continued to stay empty until 23rd October despite 118 mm of precipitation during this period. It can thus be assumed that the determined evapotranspiration values from the willow system

are conservative and would most likely be higher had more water being readily available within the system.

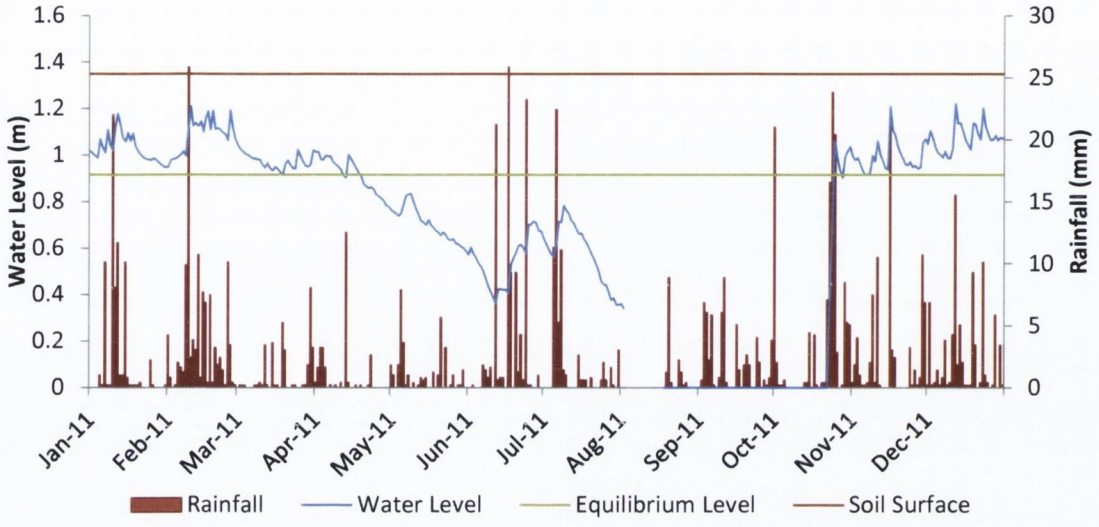


Figure 5.6 Water level and daily rainfall for 2011 (Site A)

The monthly evapotranspiration rates for the willow system, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Figure 5.7 and Table 5.2. The mean daily ET_{willow} rates ranged from 3.7 mm/day (August) to 6.2 mm/day (July) for the growing season. As previously detailed the relatively low August evapotranspiration values were due to the water level reaching the bottom of the willow system in the middle of the month.

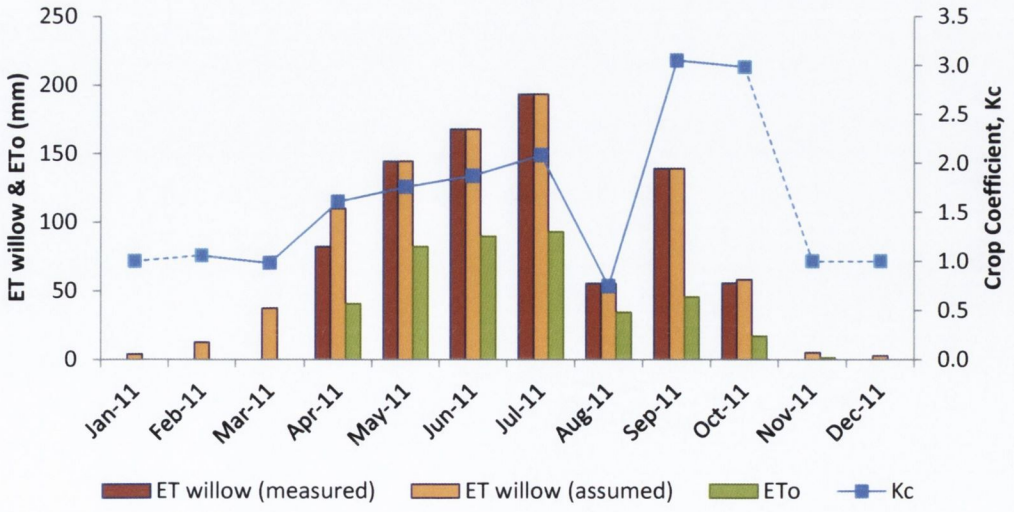


Figure 5.7 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011)

This graph clearly shows the extra evapotranspiration potential that the system had at this time of year had there been more storage capacity available. The crop coefficient ranged from 1.6 (April) to 3.1 (October) although, as with the daily evapotranspiration rate, the August K_c value did not follow the expected seasonal trend and was quite low at 0.7. This low crop coefficient was probably as a result of data loss from the water level meter coupled with the willow system being empty.

The total ET_{willow} for the monitoring period was 837.5 mm and was based on 176 days of evapotranspiration data from April to November. The corresponding reference evapotranspiration was 402.9 mm resulting in an overall crop coefficient of 2.1 for the days measured. When reference evapotranspiration rates for days on which the willow system was flooded was taken into account, the total assumed ET_{willow} increases to 928.7 mm for the year (corresponding to an a annual crop coefficient of 1.7).

Table 5.2 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	3.8	3.8	0	0.1	1.0
February	0.0	11.6	11.6	0	0.4	1.1
March	0.0	37.1	37.8	0	1.2	1.0
April	82.1	109.9	68.3	14	3.7	1.6
May	144.5	144.5	82.2	31	4.7	1.8
June	167.9	167.9	89.6	30	5.6	1.9
July	193.3	193.3	92.9	31	6.2	2.1
August	55.3	55.3	74.2	15	3.7	0.7
September	139.0	139.0	45.6	30	4.6	3.1
October	55.4	57.9	19.4	25	2.2	3.0
November	0.0	11.3	5.0	0	0.2	1.0
December	0.0	2.6	2.6	0	0.1	1.0
Annual	837.5	928.7 (TR = 828)[1]	533.0	176	4.8 (2.5)[2]	1.7

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.1.3 2012 Evapotranspiration

The water level within the willow system and the rainfall at the site for 2012 are shown in Figure 5.8. The year was characterised by a wet summer (875 mm of rain at the site between April and October, which is 83% of the mean annual rainfall for Co. Wexford) which resulted in the water level rising above the overflow level on many days. Hence, the ET_{willow} results for the year were quite inconsistent. The willow system never emptied out fully during the year as a result of the heavy summer rainfall.

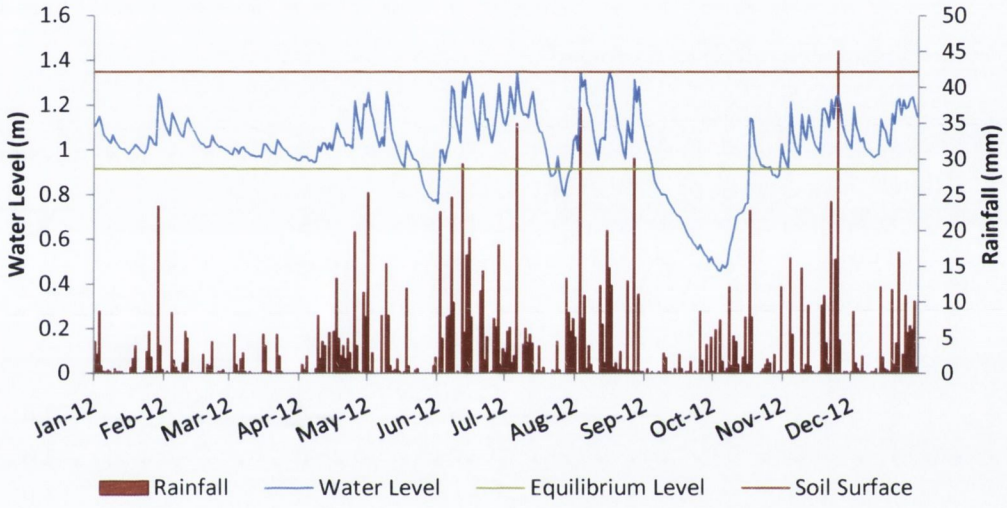


Figure 5.8 Water level and daily rainfall for 2012 (Site A)

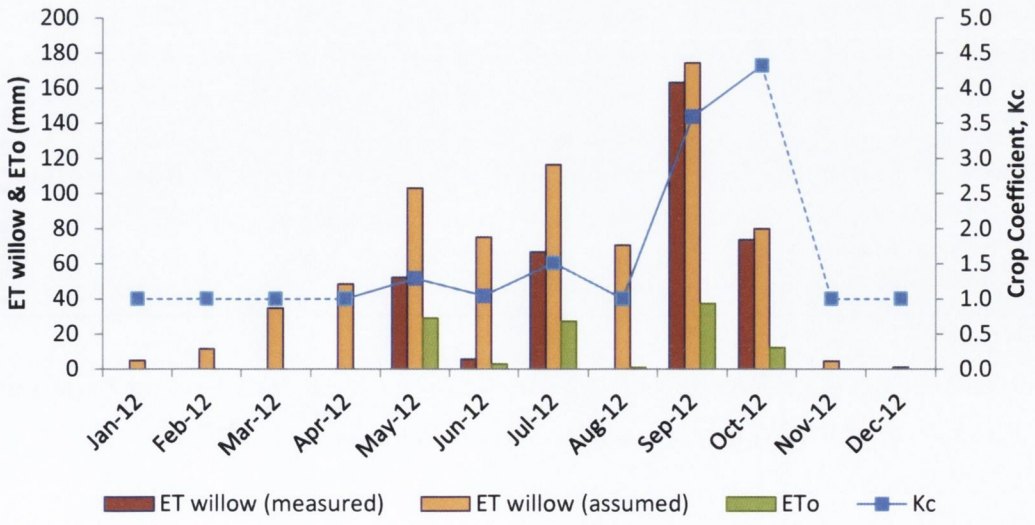


Figure 5.9 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2012)

The monthly ET_{willow} rates, ET_o rates and crop coefficients are shown in Table 5.3. The mean daily ET_{willow} rates ranged from 1.6 mm/day (April) to 7.4 mm/day (July). It should be noted that there were no evapotranspiration values determined for 7 months of the year (included April and August) due to the water level breaching the overflow level and so evapotranspiration was assumed to be equal to reference evapotranspiration for the winter months and average measured ET_{willow} for those days where it was possible for April and August. For the months in which the evapotranspiration was determined the K_c values followed the expected pattern throughout most of the growing season, rising from 1.3 in May to 3.6 in September (Figure 5.9). While the total ET_{willow} for October was not significantly high in itself, it did produce a noticeably high crop coefficient of 4.3.

Table 5.3 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	5.0	5.0	0	0.2	1.0
February	0.0	11.5	11.5	0	0.4	1.0
March	0.0	34.6	34.6	0	1.1	1.0
April	0.0	48.4	48.4	0	1.6	1.0
May	52.2	103.0	79.9	8	6.5	1.3
June	5.7	75.2	72.3	1	5.7	1.0
July	66.7	116.5	77.1	9	7.4	1.5
August	0.0	70.5	70.5	0	2.3	1.0
September	163.1	174.3	48.5	26	6.3	3.6
October	73.6	79.8	18.5	20	3.7	4.3
November	0.0	4.7	4.7	0	0.2	1.0
December	0.0	1.2	1.2	0	0.04	1.0
Annual	361.3	724.7 (TR = 1279)[1]	472.1	64	5.6 (2.0)[2]	1.5

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total ET_{willow} amount determined for the year was 361.3 mm and was based on just 64 days of data. The corresponding reference ET_o was 109.7 mm resulting in a crop coefficient of 3.3.

This value incorporated none of the winter months, however. The total assumed ET_{willow} was 724.7 mm for the year (corresponding to an annual average K_c of 1.5)

5.3.1.4 2013 Evapotranspiration

The water level in the willow system and the daily rainfall on the site for 2013 are shown in Figure 5.10. The monitoring period for the year was January - August. The year was characterised by a dry, warm summer. The effect of this can be seen on the water level within the willow system, as it reached the bottom at the start of July and remained there until monitoring ended.

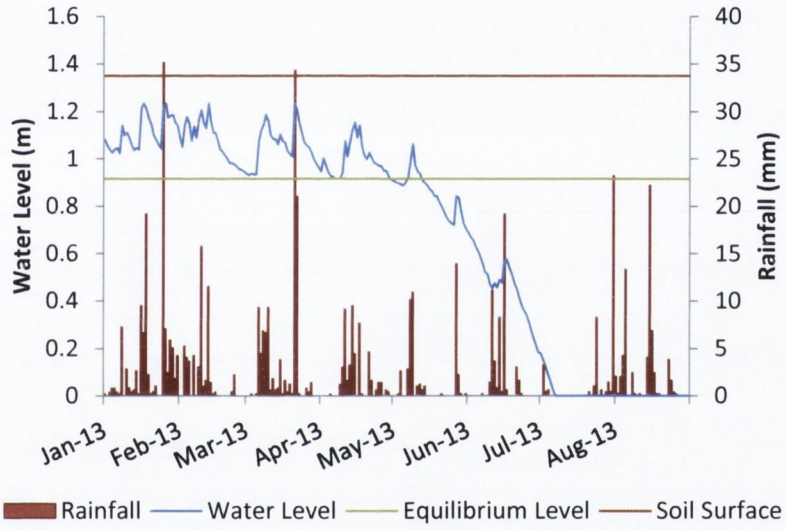


Figure 5.10 Water level and daily rainfall for 2013

The monthly ET_{willow} rates, ET_o rates and crop coefficients are shown in Table 5.4. It should be noted that the evapotranspiration rates are conservatively low for the months of July and August, as the water level had emptied out and hence, water was not as readily available to the willow trees. The mean daily ET_{willow} rates ranged from 2.1 mm/day (April) to 6.8 mm/day (June). The K_c values were relatively consistent throughout the growing season (Figure 5.11), ranging from 1.0 (April) to 2.0 (June). There were no ET_{willow} rates determined for the first three months of the year, as the water level was above the point of overflow, so ET from the systems was assumed to be equal to ET_o at the least.

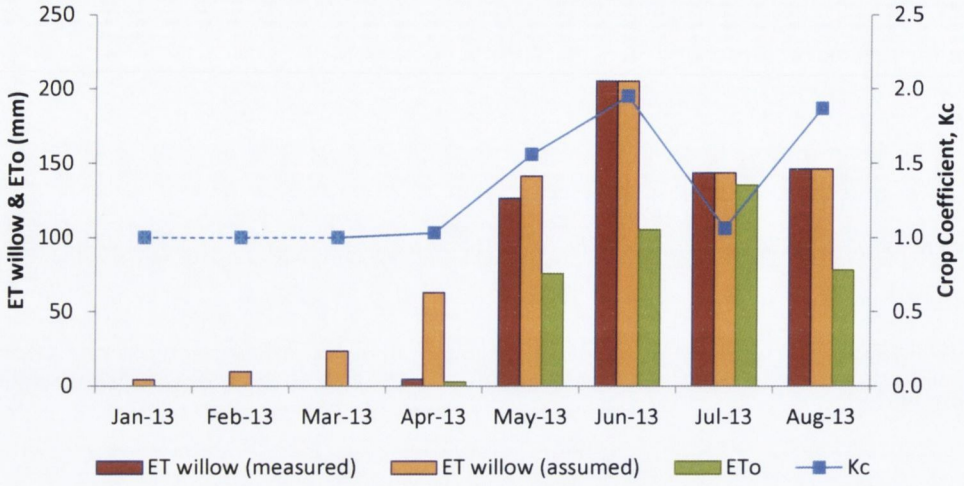


Figure 5.11 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2013)

The total measured ET_{willow} for the monitored period was 625.9 mm and was based on 120 days of evapotranspiration. This resulted in a K_c value of 1.6, which was based on an ET_o of 397.3 mm. The total assumed ET_{willow} for the period was 736.9 mm giving an equivalent overall annual K_c value of 1.4.

Table 5.4 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	4.4	4.4	0	0.1	1.0
February	0.0	9.9	9.9	0	0.4	1.0
March	0.0	23.5	23.5	0	0.8	1.0
April	4.6	63.0	61.1	3	2.1	1.0
May	126.5	141.4	90.7	25	5.1	1.6
June	205.3	205.3	105.3	30	6.8	2.0
July	143.5	143.5	135.3	31	4.6	1.1
August	146.0	146.0	78.2	31	4.7	1.9
Total	625.9	736.9 (TR = 535)[1]	508.31	120	5.2 (3.0)[2]	1.4

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.1.5 Yearly Comparison

It would be expected that evapotranspiration rates would increase year on year, as the willow trees develop and become larger and more established. However, it can be seen (Figure 5.12) that this is not always the case. While the mean daily ET_{willow} did increase year on year from 2010 - 2012 for the months May, June, July and September, it decreased for all these months (except June) in 2013. This is probably as a result of water availability within the system. For example, in Section 5.3.1.4, it was detailed how evapotranspiration rates calculated from the willow system would have been conservatively low for the months of July and August as the water level had reached the bottom. A similar occurrence can be seen for August 2012.

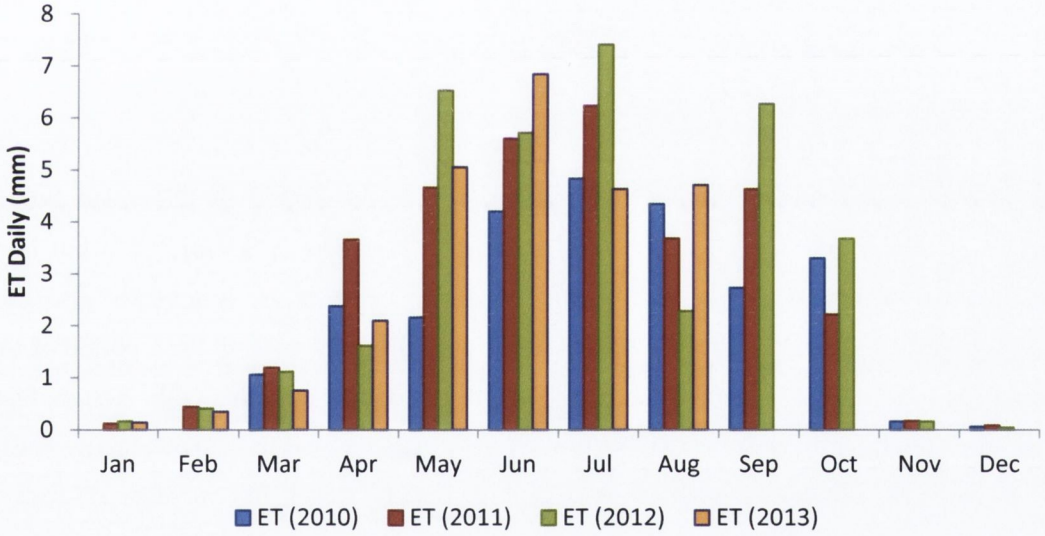


Figure 5.12 Yearly comparison of mean daily ET_{willow} rates for Site A

The comparison of the K_c values shows a similar result (see Figure 5.13). The monthly crop coefficients appear to be generally higher for the last three seasons compared to the first season (2010), but there is still some degree of variance and the effect of water availability (or lack thereof) within the system is again apparent.

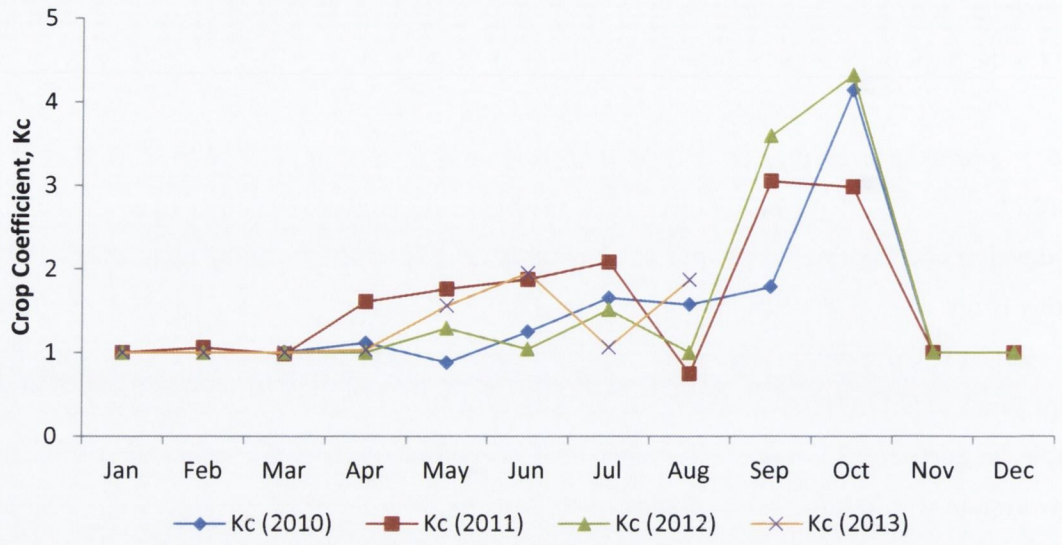


Figure 5.13 Yearly comparison of monthly K_c values for Site A

5.3.2 *Site B Fardystown*

Measurement of the water levels within the willow system on Site B started on the 25th May 2010. The willow system on the site was designed and constructed by the same external consultant as Site A and was constructed adjacent to it (detailed in Section 3.4.1) but had a larger plan area (570 m^2 compared to 296 m^2). The design depth of the system was also 1.5 m (excluding additional berm height). However, after monitoring the system for a period of time it became apparent that overflow was occurring at a depth significantly below the design depth. After analysis of water level data the overflow level was determined to be 0.66 m. Any rises in water level at a range above this point could not be used to calculate ET_{willow} as evapotranspiration couldn't be distinguished from water loss due to physical overflow. As such ET_{willow} was assumed to be at a minimum of ET_o for these periods. The system received septic tank effluent from January 2012 onward. The usable water volume storage in the soil on Site B was 15.6%.

5.3.2.1 *2010 Evapotranspiration*

The water level, daily rainfall levels and the overflow level from May to December 2010 on Site B are shown in Figure 5.14). The willow system was empty for two periods during the year (28th August to 5th September and 23rd to 30th October). The significant effect of the 70 mm rainfall event on 6th September is evident, which resulted in a 0.65 m rise in water level, indicating that the porosity of the soil in both systems was quite similar. This was quite similar to the increase

of 0.68 m in System A from the same rainfall event. It can be seen that the water level did drop below the overflow level in December. However, these false readings resulted from the severe cold weather which was occurring at this time. It is not certain why this occurred, but it probably due to ice forming at the top of the inspection well, which resulted in a drop in the water pressure to which the monitoring probe is subjected.

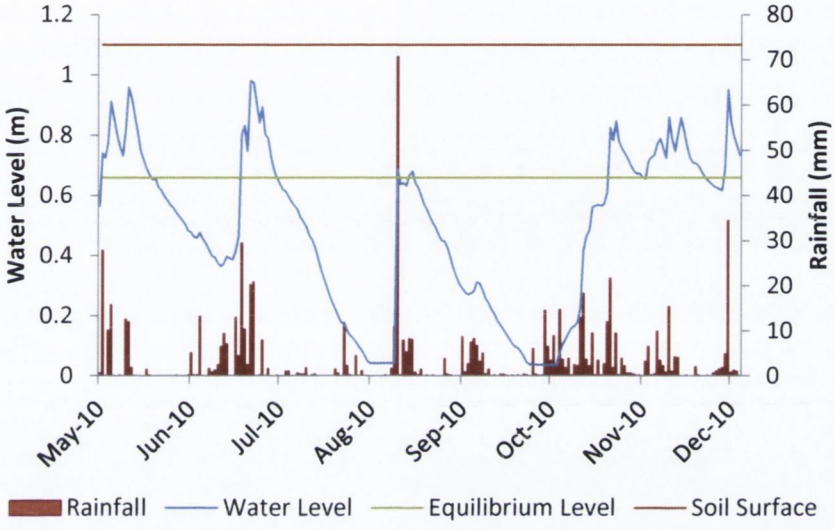


Figure 5.14 Water level and daily rainfall for 2010 (Site B)

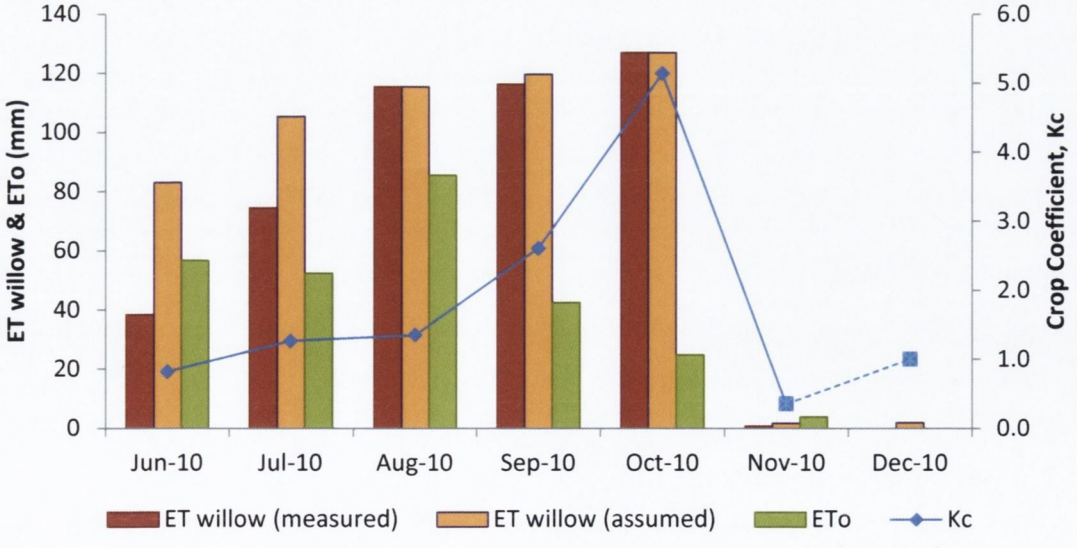


Figure 5.15 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2010)

The monthly evapotranspiration rates, the Penman-Monteith reference evapotranspiration and the monthly crop coefficients for 2010 are shown in Figure 5.15 and Table 5.5. The mean daily ET_{willow} rates ranged from 2.6 mm/day (June) to 4.3 mm/day (September) for the growing season. The monthly crop coefficients ranged from 0.8 (June) to 5.1 (October).

The total ET_{willow} over the monitored period was 472.5 mm, which was based on 132 days of data. The total ET_o for the same days was 265.8 corresponding to a K_c value of 1.8 over the period. The total assumed ET_{willow}, which assumed reference evapotranspiration on days when the water level was above the overflow point, was 554.3 mm for the period (which corresponded to an overall K_c of 1.4). As previously detailed, this calculation assumed reference evapotranspiration for days in which the water level was above the overflow level. It should also be highlighted that no effluent was discharged into the system in 2010.

Table 5.5 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2010)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
June	38.4	83.0	101.3	15	2.6	0.8
July	74.5	105.4	83.3	19	3.9	1.3
August	115.5	115.5	85.6	31	3.7	1.4
September	116.3	119.7	45.9	27	4.0	2.6
October	127.0	127.0	24.7	31	4.1	5.1
November	0.8	1.7	4.9	2	0.1	0.4
December	0.0	2.0	2.0	7	0.1	1.0
Total	472.5	554.3 (TR = 664)[1]	347.6	132	3.6 (2.6)[2]	1.4

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.2.2 2011 Evapotranspiration

As can be seen in Figure 5.16 the willow system on Site B performed particularly well throughout 2011. It was empty for almost the entire growing season (24th May to 11th November). However, the long period of being empty resulted in a conservatively low ET_{willow} rates being determined throughout the summer period. This was due to no significant decreases

in water level, which are an integral part of determining evapotranspiration using the water balance. Hence, the ET_{willow} rates determined while the system was empty equates to the volume of rain and effluent that entered the system during that time period exclusively. Again, it needs to be highlighted that no effluent was discharged into the system in 2011.

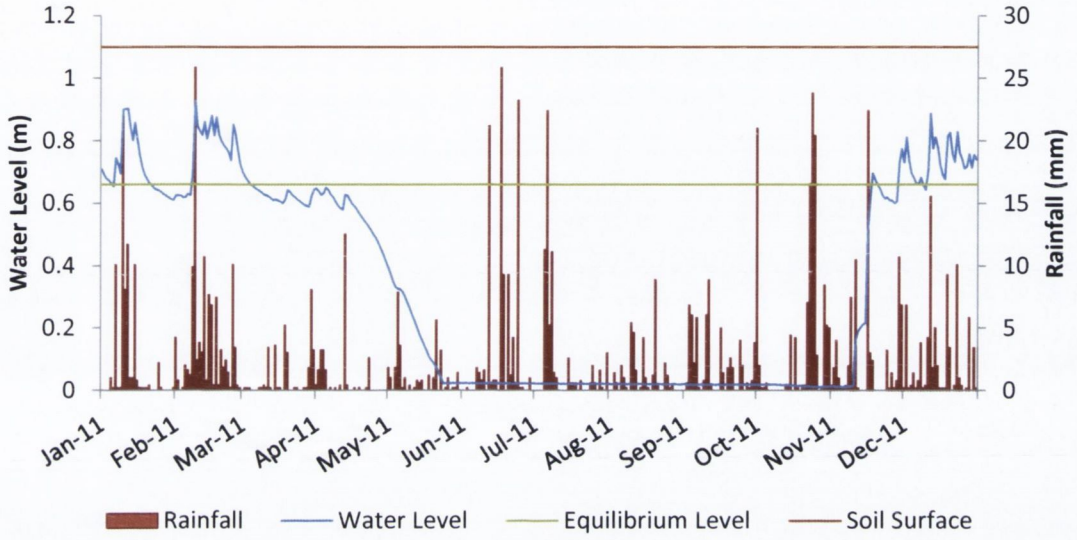


Figure 5.16 Water level and daily rainfall for 2011 (Site B)

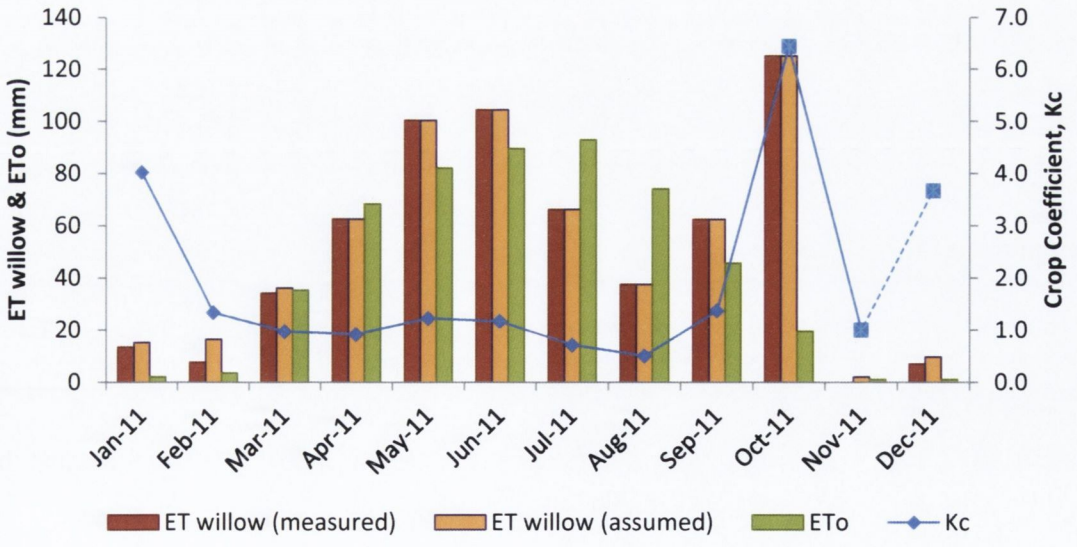


Figure 5.17 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2011)

The monthly evapotranspiration rates, the Penman-Monteith reference evapotranspiration and the monthly crop coefficients for 2011 are shown in Figure 5.17 and Table 5.6. The mean daily ET_{willow} rates ranged from 2.1 mm/day (April) to 4.0 (October) for the growing season (although the August dropped to 1.2 mm/day primarily due to lack of available water for the willows with correspondingly low K_c values). The values followed the expected pattern for April and May but then dropped off significantly. The values ranged from 0.5 (August) to 6.4 (October). The low value from August is as a result of the water level bottoming out, resulting in conservatively low ET_{willow} rates being determined. While not totalling high evapotranspiration rates, some of the winter K_c values were unusually high for that time of year. January and December had values of 4.0 and 3.7 respectively.

Table 5.6 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	13.5	15.2	3.8	12	0.5	4.0
February	7.6	16.4	12.3	8	0.6	1.3
March	34.1	36.0	37.1	27	1.2	1.0
April	62.6	62.6	68.3	30	2.1	0.9
May	100.4	100.4	82.2	31	3.2	1.2
June	104.4	104.4	89.6	30	3.5	1.2
July	66.2	66.2	92.9	31	2.1	0.7
August	37.4	37.4	74.2	31	1.2	0.5
September	62.4	62.4	45.6	30	2.1	1.4
October	125.2	125.2	19.4	31	4.0	6.4
November	0.0	1.0	2.0	2	0.1	1.0
December	7.0	9.6	2.6	4	0.3	3.7
Annual	620.7	637.8 (TR = 828)[1]	529.9	267	2.3 (1.7)[2]	1.2

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total ET_{willow} for the days monitored was 620.7 mm and was based on 267 days of data. The corresponding total reference evapotranspiration for these days is 514.9 mm resulting in a crop

coefficient of 1.2 for the monitored days. The total assumed ET_{willow} for the year was 637.8 mm (corresponding to an annual K_c of 1.2).

5.3.2.3 *2012 Evapotranspiration*

The recorded water levels for Site B were above the overflow level of 0.66 m for many periods during 2012 (see Figure 5.18). The high rainfall levels during the summer made it difficult to determine evapotranspiration results for these months. An abatement in rainfall towards the end of the summer meant that the system did empty out for the period between 22nd September and 16th October. So the ET_{willow} rates shown for this period would be conservative values.

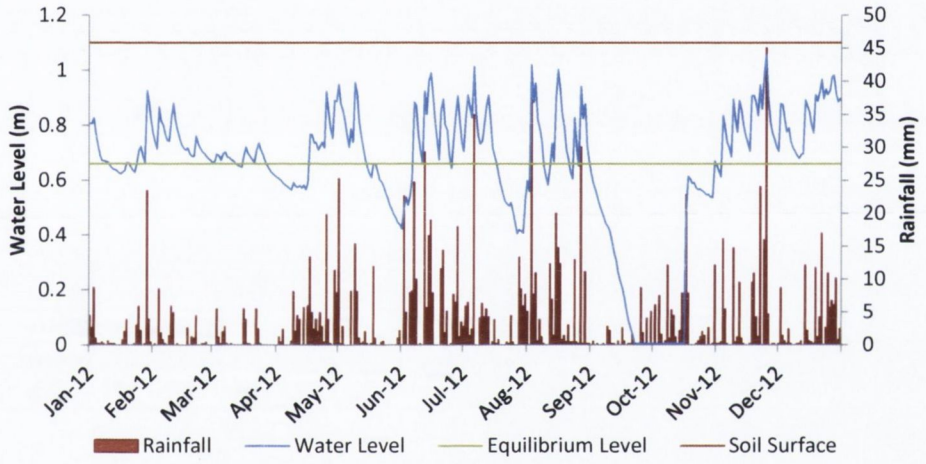


Figure 5.18 Water level and daily rainfall for 2012 (Site B)

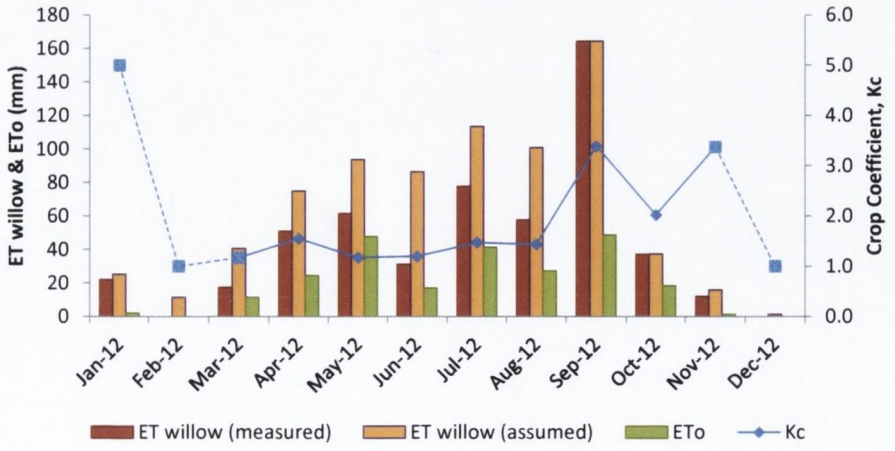


Figure 5.19 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2012)

The mean daily ET_{willow} rates during the growing season ranged from 3.2 mm/day (April) to 7.2 mm/day (August) and followed the expected seasonal pattern (see Figure 5.19 and Table 5.7). The K_c values followed the same pattern rising from 1.2 in May to 3.4 in September. Of the winter months, January and November both produced significantly high crop coefficient values (5.0 and 3.4 respectively). However, the high November value is heavily dependent on just three days of data at the very start of the month and may have come about as a result of some final evapotranspiration from the willows before they became fully dormant. Hence, it could be assumed that these values are not representative of the entire month. There were no evapotranspiration results determined for February or December for the same reason.

The total ET_{willow} amount for this period was 531.7mm and was determined from 149 days of data. The corresponding total ET_o for these days was 239.1 mm which gave an crop coefficient of 2.2. The total assumed ET_{willow} was 765.0 mm for the year (corresponding to an annual K_c of 1.6).

Table 5.7 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	22.1	25.2	5.0	17	0.8	5.0
February	0.0	11.5	11.5	0	0.4	1.0
March	17.3	40.4	34.6	8	1.3	1.2
April	50.9	74.9	48.4	16	3.2	1.6
May	61.5	93.7	79.9	15	4.1	1.2
June	31.2	86.5	72.3	8	3.9	1.2
July	77.7	113.4	77.1	13	6.0	1.5
August	57.5	100.8	70.5	8	7.2	1.4
September	164.3	164.3	48.5	30	5.5	3.4
October	37.3	37.3	18.5	31	1.2	2.0
November	12.0	15.8	4.7	3	0.5	3.4
December	0.00	1.2	1.2	0	0.1	1.0
Annual	531.7	765.0 (TR = 1279)	472.1	149	3.6 (2.1)[2]	1.6

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.2.4 2013 Evapotranspiration

The monitored period for 2013 ran from January to August. As detailed in Section 5.3.1.4, the summer of 2013 was dry and warm. The effect of this is apparent on the water level within the willow system and it can be seen (Figure 5.20) that it reached the base of system at the start of June and remained there for the rest of the monitoring period.

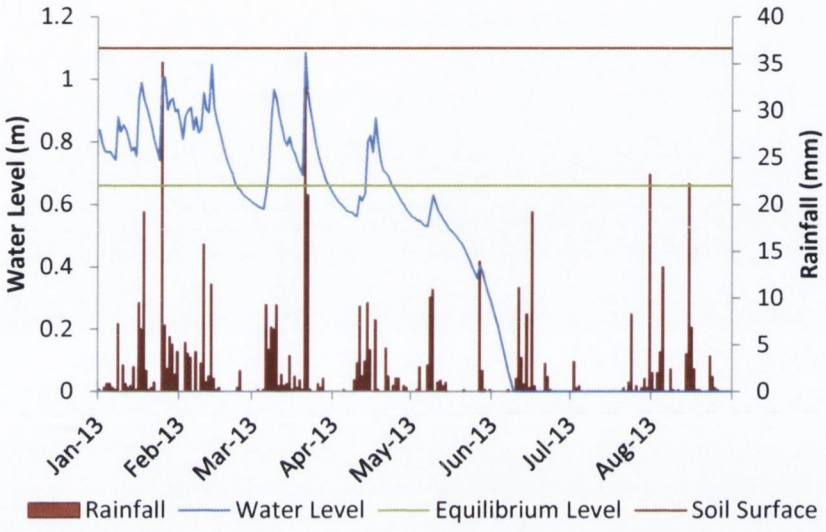


Figure 5.20 Water level and daily rainfall for 2013 (Site B)

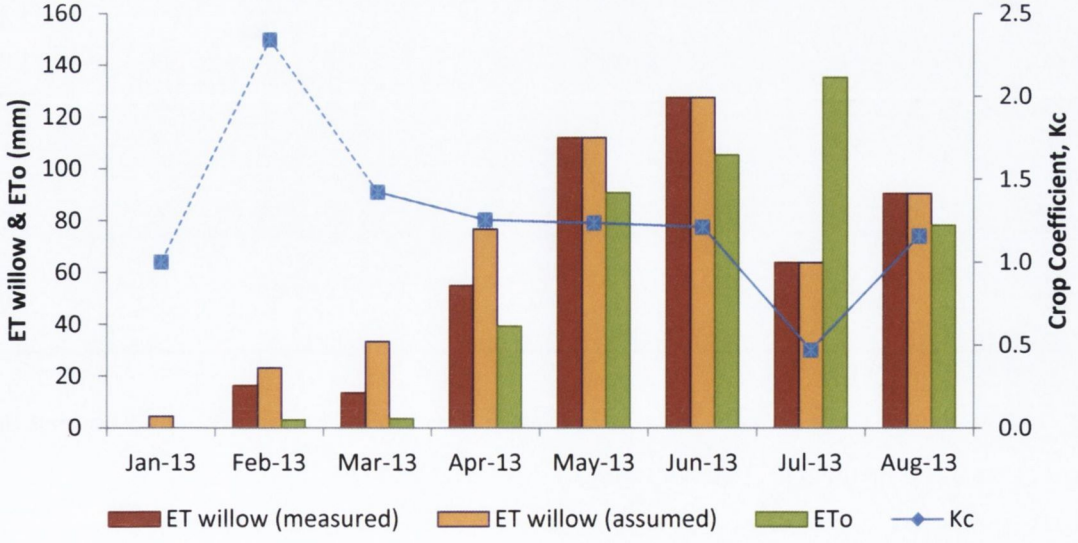


Figure 5.21 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2013)

The mean daily ET_{willow} rates are quite low for the year (see Table 5.8) ranging from 3.9 mm/day (April) to a high of 4.2 mm day (June) for the growing season. It then dropped off for the months of July and August. Similarly to Site A, this is probably as a result of lack of available water within the system for the willow trees to access. The K_c values for the growing season were also quite low and relatively constant (Figure 5.21) ranging from 0.5 (July) to 1.4 (April). The higher early season values seem to be correlated to high water levels in the system. The assumed ET_{willow} rates for the dormant months ranged from 0.1 mm/day (January) to 1.7 mm/day (March), with a crop coefficient high of 2.3 being reached in February.

The total ET_{willow} for this period totalled 478.4 mm and was based on 150 days of evapotranspiration. This corresponded to a total reference evapotranspiration of 445.5 mm for the same days and an overall crop coefficient of 1.1 for the monitoring period. The total assumed ET_{willow} was 531.2 mm, corresponding to an annual crop coefficient of only 1.0, which shows the impact of the system being too shallow to provide adequate storage.

Table 5.8 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site B (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.00	4.4	4.4	0	0.1	1.0
February	16.3	23.1	9.9	5	0.8	2.3
March	13.5	33.4	23.5	8	1.7	1.4
April	54.9	76.7	61.1	14	3.9	1.3
May	112.1	112.1	90.7	31	3.6	1.2
June	127.5	127.5	105.3	30	4.2	1.2
July	63.8	63.8	135.3	31	2.1	0.5
August	90.4	90.4	78.2	31	2.9	1.2
Total	478.4	531.2 (TR = 535)	508.3	150	3.2	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.2.5 Yearly Comparison

It can be seen (Figure 5.22) that there was quite a bit of variation in monthly ET_{willow} rates from year to year. It would be expected that the daily evapotranspiration would increase year on

year. While this did occur generally, for the months April, May and June, it was not the case for the remaining months of the growing season on Site B. As per Site A, this is more than likely because of the lack of available water within the system during the latter summer months in 2011, 2012, and 2013, which resulted in conservatively low ET_{willow} rates for those months.

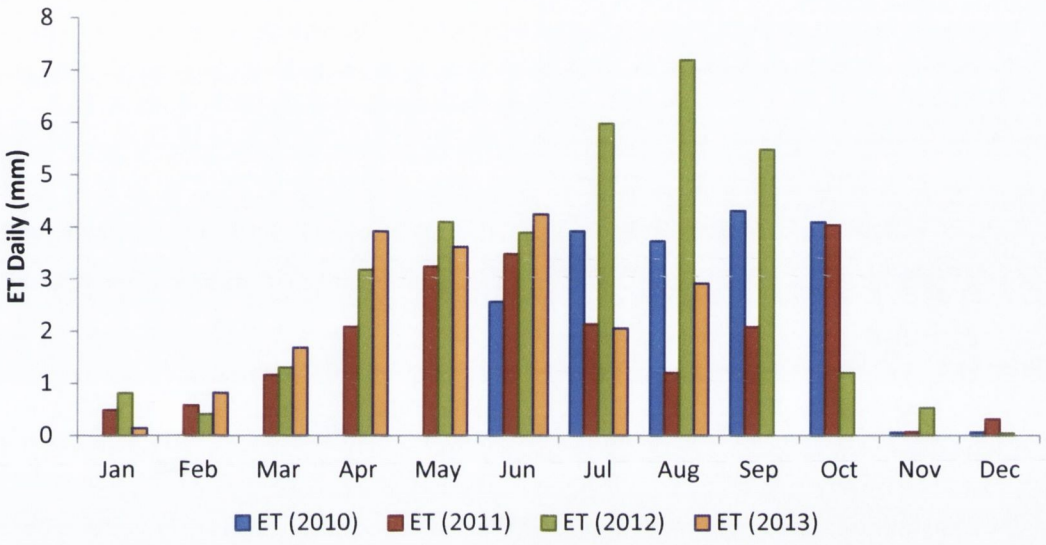


Figure 5.22 Yearly comparison of mean daily ET_{willow} rates for Site B

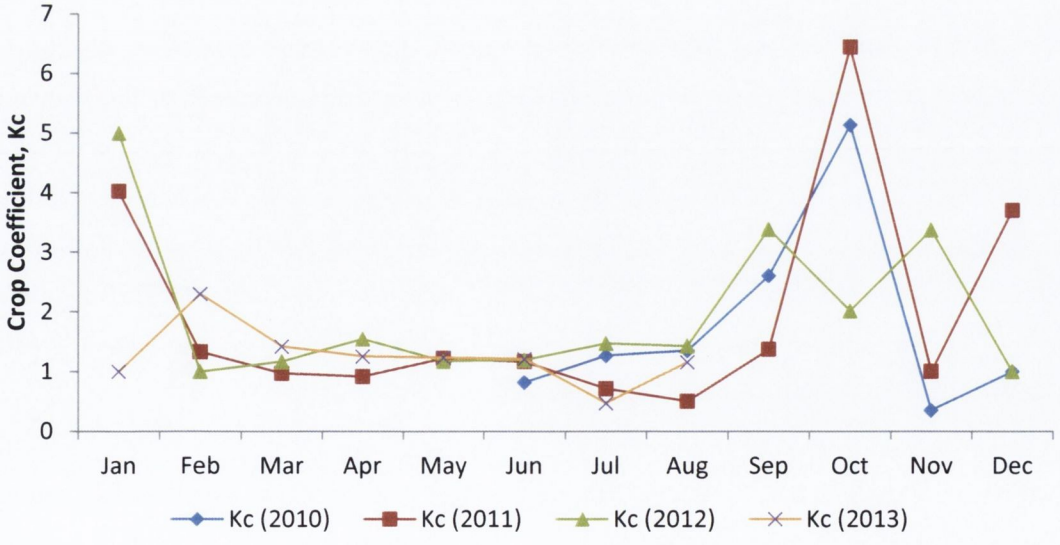


Figure 5.23 Yearly comparison of monthly K_c values for Site B

Again, the same can be said of the monthly crop coefficients from year to year (Figure 5.23). It would seem that, in general, water availability was the dominant factor in determining the evapotranspiration rates and not willow tree development. As was the case on Site A, the crop coefficients were relatively high for the month of October.

5.3.3 Site C Borehovel

Measurement of water levels within the willow system on Site C commenced on the 19th September 2010. As detailed in Section 3.3.3 the willow system was designed to a specification height of 1.8 m (excluding the 0.2 m berm). However, upon analysing the data it became apparent that water was escaping from the system once the level went above approximately 1.73 m. The rate of escape was quite low in comparison to that occurring on Sites A and B, which suggests that it wasn't a surface water type overflow from the system but a slow release through soil in the constructed berm.

As detailed previously any loss of water above the overflow level had to be ignored with respect to calculating the true rate of evapotranspiration and during such periods the reference evapotranspiration was used as a conservative value. The system on Site C received septic tank effluent from November 2010 onward. The usable water volume storage in the soil on Site C was 11% (see Section 4.5.4).

5.3.3.1 2010 Evapotranspiration

The water level and rainfall for the monitoring period September to December 2010 is shown in Figure 5.24. The graph also highlights the estimated overflow level of 1.73 m. The decreases in the level were quite gradual compared to the sudden drops seen on Site A when the overflow point was breached. It can be seen that increases in water level due to large rainfall events throughout the winter months were quite gradual. This was due to the water level rising above the willow system surface whereupon the effective storage volume of the system greatly increased (i.e. the storage volume above ground level is 100%).

As detailed for Sites A and B, December 2010 was subject to a severe cold spell which resulted in some false water level readings (most probably due to ice forming in the inspection well and thus affecting the water pressure on the probe).

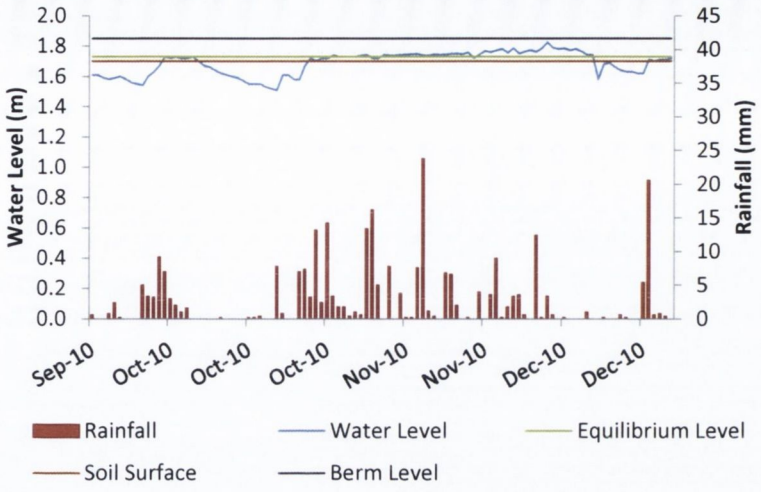


Figure 5.24 Water level and daily rainfall for September to December 2010 (Site C)

The monthly evapotranspiration rates for the willow system, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Figure 5.25 and Table 5.9. The mean daily ET_{willow} rates for the growing season were determined from the actual number of days in which the willow evapotranspiration could be confidently determined (i.e. when the water level was below the overflow point). The mean daily ET_{willow} rate was relatively low for September, only amounting to 1.1 mm/day (although this was just for the last 11 days of the month) which corresponded to a K_c value of 0.8. This increased to 1.8 mm/day (increase in K_c value to 2) for the month of October. There was no evapotranspiration determined for the months of November or December, so ET_{willow} was assumed to be equal to ET_o.

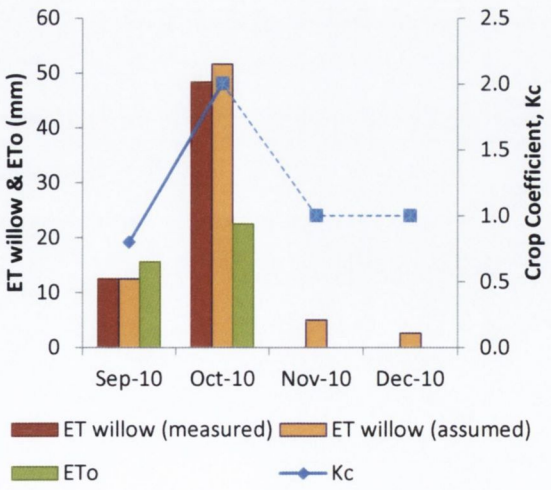


Figure 5.25 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2010)

The ET_{willow} for this period totalled 60.9 mm and was based on 38 days of evapotranspiration. This corresponded to a total reference evapotranspiration of 38.18 mm for the same days and an overall crop coefficient of 1.6 for the monitoring period. The total assumed ET_{willow} for the four months was 71.9 mm (corresponding to a total K_c of 1.5).

Table 5.9 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (September to December 2010)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
September	12.5	12.5	15.7	11	1.1	0.8
October	48.4	51.7	25.8	27	1.8	2.0
November	0.00	5.1	5.1	0	0.2	1.0
December	0.00	2.6	2.6	0	0.1	1.0
Annual	60.9	71.9 (TR = 358)	49.1	38	1.6 (0.6)	1.5

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.3.2 2011 Evapotranspiration

The water level and rainfall for 2011 are shown in Figure 5.26. The overflow level of 1.73 m is also included on the graph. The water level throughout November and December provide further evidence of a slow escape rate once the water goes above the overflow level. In contrast with Site A and Site B there were no sudden decreases in level.

As with the previous winter at Site C, water level increases from large rainfall events were quite gradual once the water level was above the estimated overflow level. This contrasts greatly with the summer months where any rainfall event resulted in a significant rise in water level, due to the change in level occurring entirely within the soil medium.

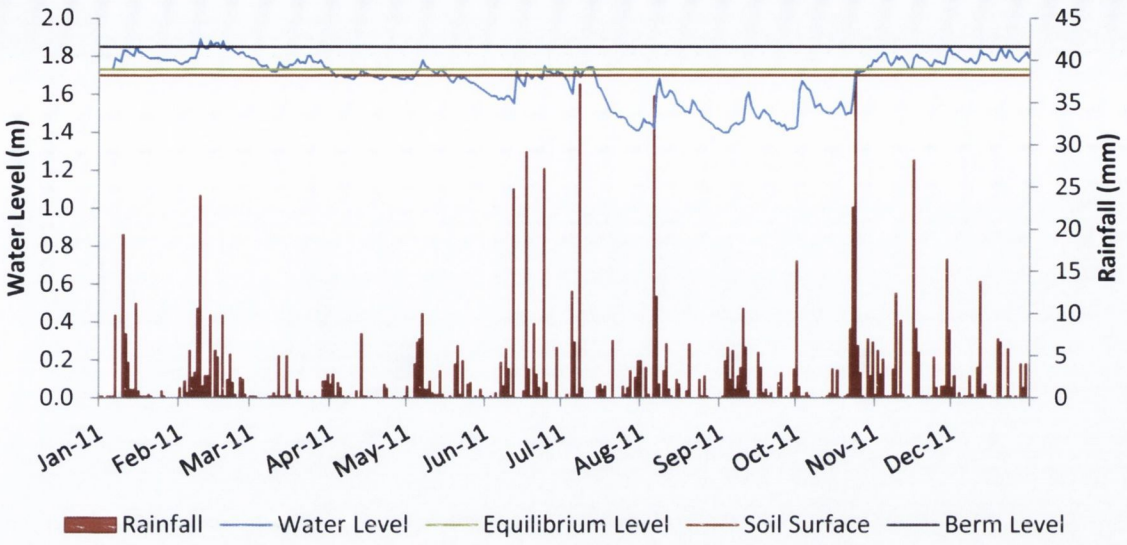


Figure 5.26 Water level and daily rainfall for 2011 (Site C)

The monthly willow system evapotranspiration rates, the reference evapotranspiration and the monthly crop coefficient are shown in Figure 5.27 and Table 5.10. The mean daily ET_{willow} rates ranged from 1.8 mm/day (April) to 5.8 mm/day (July) for the growing season. There was no recorded evapotranspiration for January, February, November or December in 2011 so ET_{willow} was assumed to be equal to ET_o at a minimum. Of the remaining dormant months, March had an assumed mean daily ET_{willow} rate of 1.4 mm/day. As expected this resulted in a crop coefficient of 1.1 for the month. The crop coefficients ranged from 0.8 (April) to 4.6 (October) for the growing season. The August value of 1.5 is lower than the July value of 1.9, which does not follow the expected seasonal pattern. This could be as a result of a decrease in the water level, which resulted in a slower uptake by the willow trees. However, it increases again for September to 2.4. This may have come about as a result of the rainfall at the start of the month, which would have made water more readily available to the willow trees for absorption near the surface.

The total willow evapotranspiration for 2011 was 619.3 mm which was based on 199 days of evapotranspiration. The corresponding total reference evapotranspiration was 405.9 mm which produced a crop coefficient of 1.5. The total assumed ET_{willow} for the year (which assumed reference evapotranspiration rates on days when the water level was above the determined overflow point) was 717.2 mm (which resulted in an overall assumed K_c of 1.4)

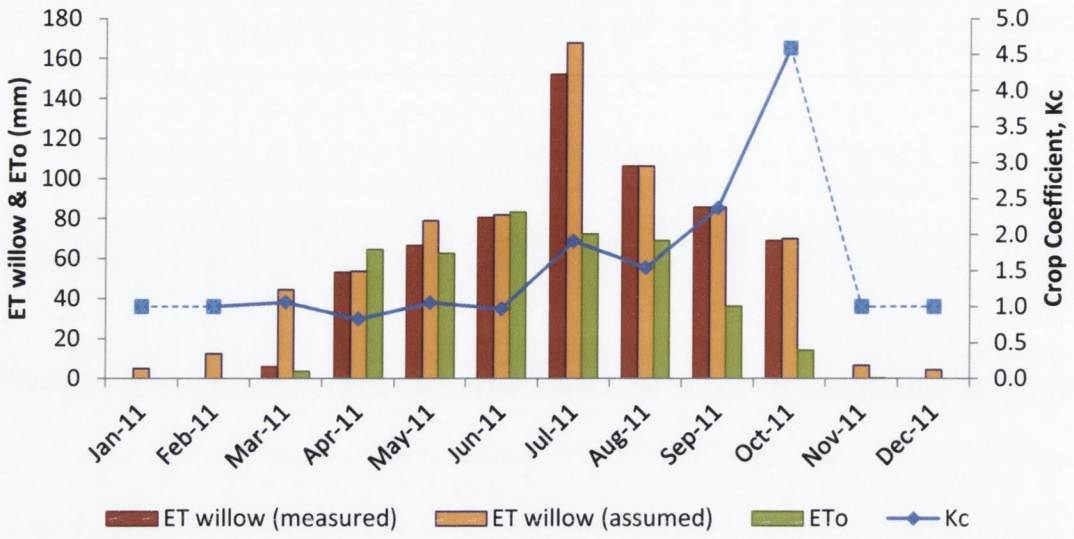


Figure 5.27 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site A (2011)

Table 5.10 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	5.1	5.11	0	0.2	1.0
February	0.0	12.5	12.47	0	0.4	1.0
March	6.1	44.5	41.98	3	1.4	1.0
April	53.2	53.6	65.05	29	1.8	1.1
May	66.5	78.9	74.93	25	2.7	0.8
June	80.6	81.7	84.41	29	2.8	1.1
July	152.0	167.9	88.01	26	5.8	1.0
August	106.3	106.3	69.07	31	3.4	1.9
September	85.8	85.8	36.19	30	2.9	1.5
October	68.9	69.9	15.25	26	2.7	2.4
November	0.0	6.7	6.73	0	0.2	4.6
December	0.0	4.3	4.27	0	0.1	1.0
Annual	619.3	717.2 (TR = 910)	503.5	199	3.1 (3.6)[2]	1.4

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.3.3 2012 Evapotranspiration

The water level and rainfall for 2012 is shown in Figure 5.28. There was some loss of water level data in October and November due to a faulty data logger. The year was characterised by an extremely wet summer. This resulted in flooding on the surface of the willow system, some of which it leaked out of the system through berm which made it difficult to accurately determine evapotranspiration from the system in June and July.

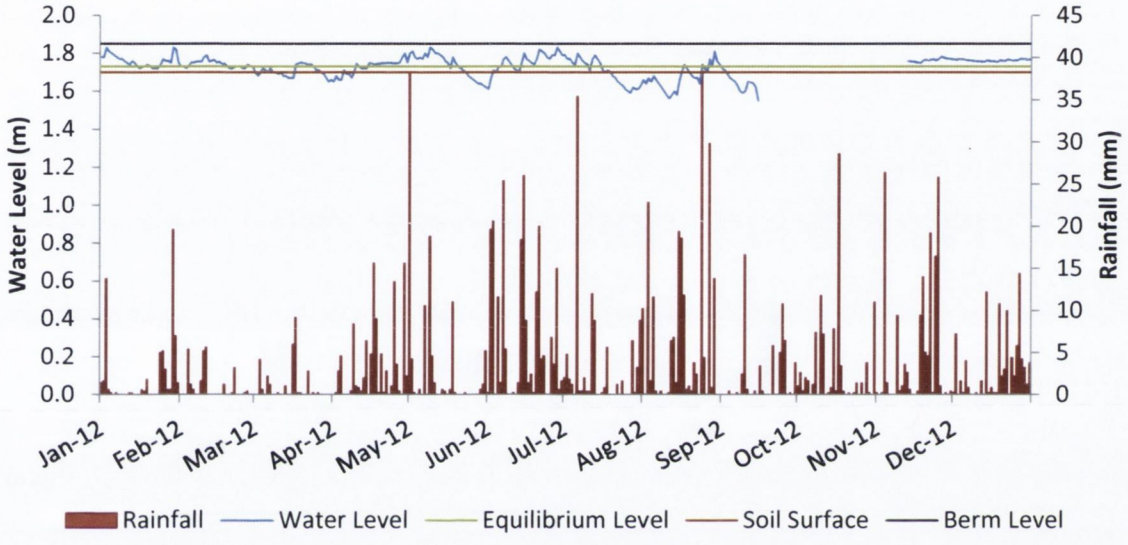


Figure 5.28 Water level and daily rainfall for 2012 (Site C)

The monthly evapotranspiration rates for the willow system, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Figure 5.29 and Table 5.11. The mean daily ET_{willow} rates ranged from 2 mm/day (April) to 6.1 mm/day (August) for the growing season. The ET_{willow} could only be determined on a relatively small number of days for much of the dormant months. The mean daily ET_{willow} was 0.5 mm/day for January, rising to 1.8 mm/day for March. This was either due to the water levels being above the overflow level or loss of data due to a faulty datalogger. The crop coefficients for the growing season ranged from 1.1 (April) to a high of 2.5 (August). The July crop coefficient of 1.3 did not increase from the June value and is possibly as a result of water not being readily available at the surface for absorption by the willow trees.

The total ET_{willow} for the year is 449.7 mm and was based on 119 days of evapotranspiration data. The reference evapotranspiration for the same period was 220.2 mm resulting in an overall crop coefficient of 2.04 for the monitoring period. The total assumed evapotranspiration from the willow system was 669.9 mm (which gave an overall annual K_c of 1.5).

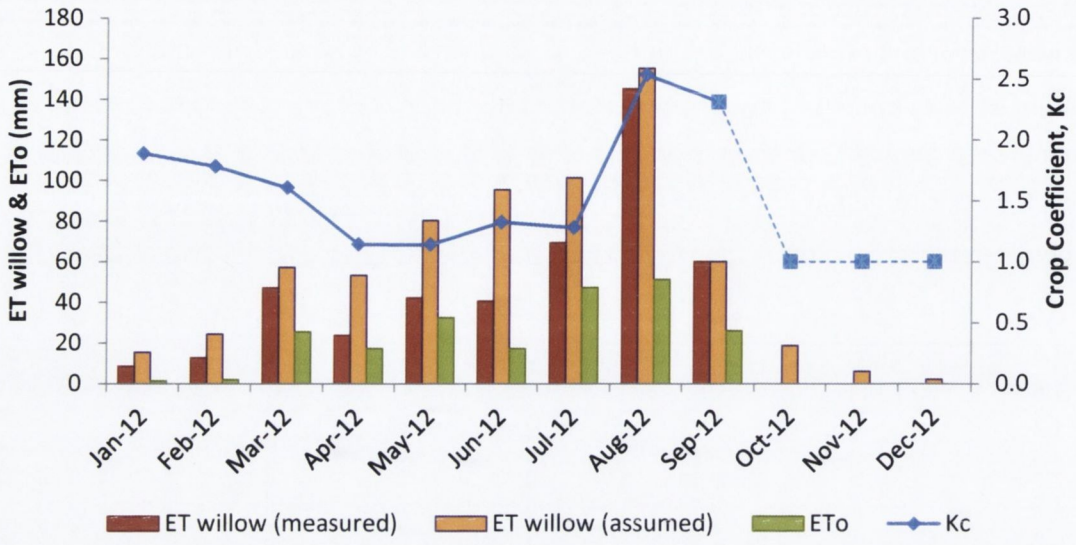


Figure 5.29 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2012)

Table 5.11 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	8.7	15.4	8.2	4	0.5	1.9
February	12.7	24.3	13.7	5	0.9	1.8
March	47.1	57.3	35.7	23	1.8	1.6
April	23.8	53.4	46.7	12	2.0	1.1
May	42.2	80.3	70.5	12	3.5	1.1
June	40.6	95.4	72.1	7	5.8	1.3
July	69.3	101.3	79.3	17	4.1	1.3
August	145.2	155.3	61.3	23	6.1	2.5
September	60.0	60.0	26.0	15	4.0	2.3
October	0.0	18.7	18.7	0	0.6	1.0
November	0.0	6.1	6.1	0	0.2	1.0
December	0.0	2.2	2.2	0	0.1	1.0
Annual	449.7	669.9 (TR = 1220)	440.4	119	3.8 (1.8)[2]	1.5

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.3.4 2013 Evapotranspiration

The water level within the willow system and the daily rainfall for Site C is shown in Figure 5.30. The effect of the dry, warm summer can be seen on the water level, reaching its lowest point over the entire course of the monitoring period at the site. However, a slowing down in the rate of decrease can be seen as the level gets lower within the system. This could be as a result of the very clayey soil which was used to backfill the system.

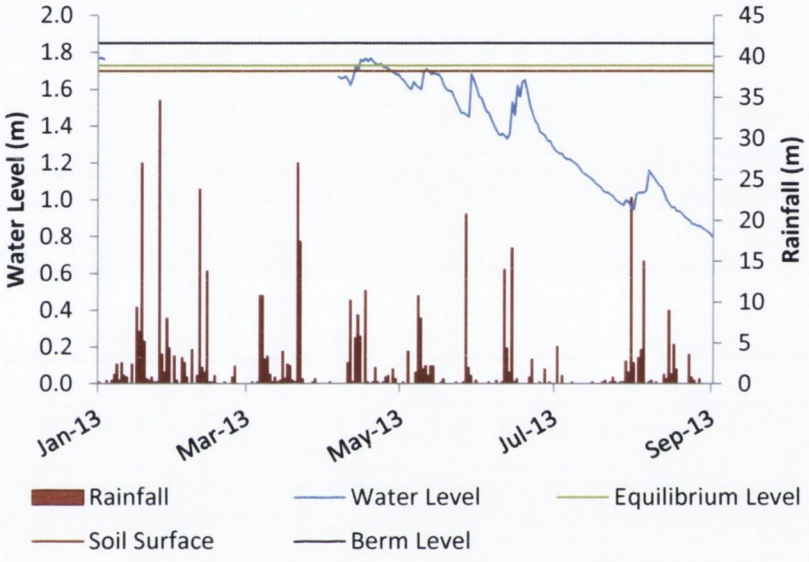


Figure 5.30 Water level and daily rainfall for 2013 (Site C)

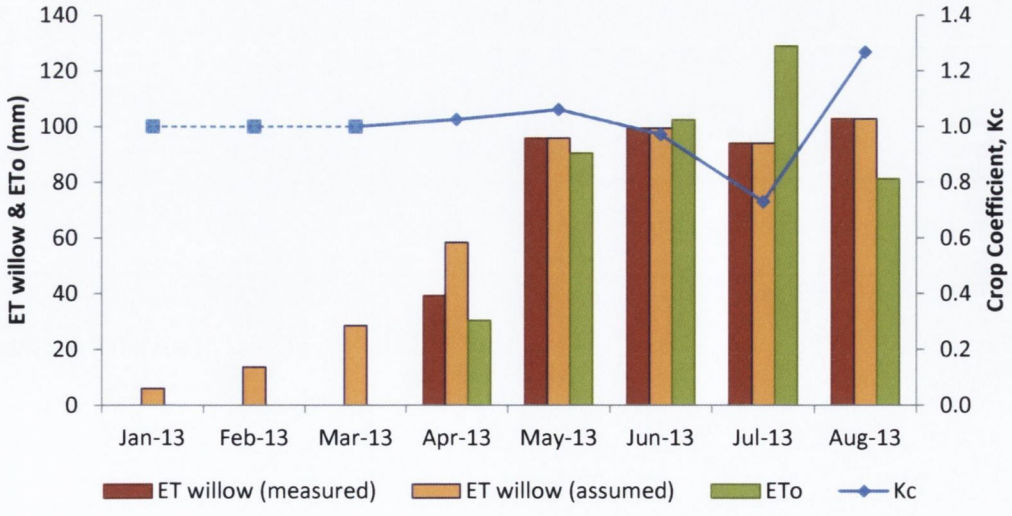


Figure 5.31 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2013)

The mean daily ET_{willow} rates were surprisingly low during the growing season given the warm summer. As mentioned already this appears to be the case because of the willow trees' inability to access water at their optimum rate due to low permeability clay within the system. The daily rates ranged from 1.5 mm/day (April) to 3.3 mm/day (July and August) for the growing season, hovering just above 3 mm/day from May to August (see Table 5.12). The corresponding K_c values ranged from 1.0 (April) to 1.3 (August). There were no ET_{willow} rates determined for January, February or March, so the ET_{willow} was assumed to be at least equal to ET_o.

The total ET_{willow} for this 8 month monitoring period was 431.1 mm and was based on 149 days of evapotranspiration. This corresponded to a total reference evapotranspiration of 433 mm for the same days and an overall crop coefficient of 0.99 for the monitoring period. The total assumed ET_{willow} was 498.4 mm for the 8 month period (resulting in a K_c value of 1.0 for the entire period).

Table 5.12 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site C (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	6.0	6.0	0	0.2	1.0
February	0.0	13.7	13.7	0	0.5	1.0
March	0.0	28.6	28.6	0	0.9	1.0
April	39.3	58.3	56.9	26	1.5	1.0
May	95.8	95.8	90.3	31	3.1	1.1
June	99.3	99.3	102.4	30	3.3	1.0
July	93.9	93.9	128.8	31	3.0	0.7
August	102.8	102.8	81.2	31	3.3	1.3
Annual	431.1	498.4 (TR = 502)	507.9	149	2.9 (2.1)	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.3.5 Yearly Comparison

As with Site A and Site B, it appears that water availability to the willow trees was the dominating factor on the ET_{willow} rates determined, rather than the meteorological conditions or willow tree development (see Figure 5.32). Most of the monthly highs (April, May, June, August

and September) throughout the growing season occurred in 2012, when water availability was at its highest due to the high rainfall levels.

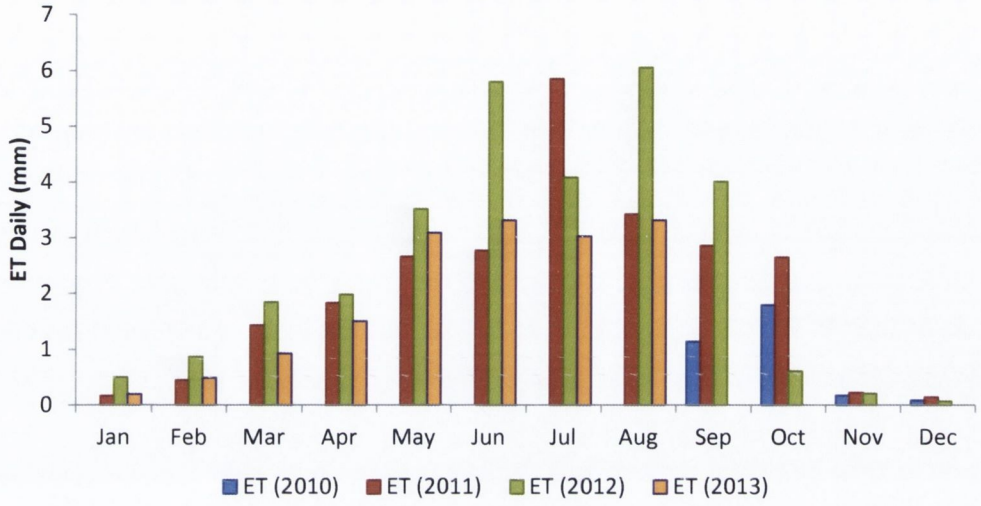


Figure 5.32 Yearly comparison of mean daily ET_{willow} rates for Site C

Similarly, water availability appeared to have the greatest bearing on the monthly crop coefficients from year to year. Most of the highest values during the growing season occurred in 2012 (see Figure 5.33), when rainfall levels were high and not in 2013 when the willow trees were more developed and reference evapotranspiration rates were higher.

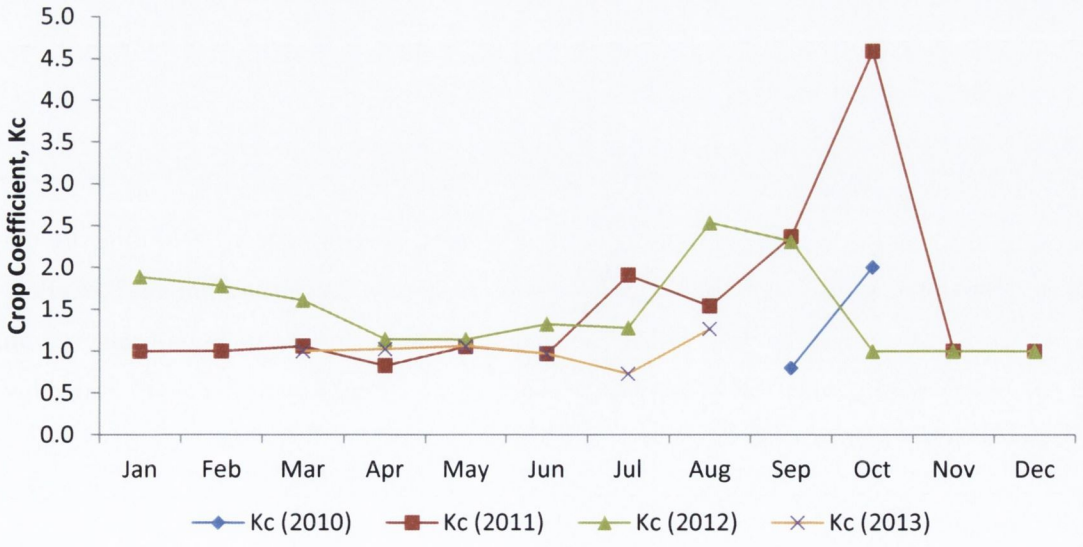


Figure 5.33 Yearly comparison of monthly K_c values for Site C

5.3.4 *Site D Ballask*

Measurement of water levels within the willow system on Site D started on the 27th July 2010. As detailed in Section 3.4.3 the system was designed and constructed by Trinity College Dublin to a specified depth of 1.8 m (excluding the 300 mm berm). The willow system was originally planted with willow in June 2010. It became apparent within a month after planting that establishment of the cuttings was quite poor. This was attributed to the lack of topsoil at the surface of the system and the soil being extremely dry at the time of planting. Replanting of new cuttings was carried out every season since establishment in an effort to attain as a high an evapotranspiration rate for the willow system as possible. While the overall willow establishment and growth has improved on the first season, it is still not performing as might be expected for a willow system that has been in operation for over three years.

As a result of very low porosity clay (as detailed in Section 4.5.4 the usable water volume storage was determined to be 11%) combined with the poor willow growth, the willow system quickly became waterlogged and surface water gathered on the surface. Because of this it was decided to divert the wastewater coming from the dwelling back to the old, existing soil treatment unit on the site while also creating an overflow channel through the berm on one side of the willow system to allow surface water to escape. This was to prevent water logging and aid in the establishment of newly planted willow cuttings. The overflow channel meant that the maximum depth of water within the willow system at any time was limited to 1.65 m. As with the previous sites that had overflows, the evapotranspiration for this system could not be confidently determined above this level and so ET_o rates were assumed for these periods. The system on Site D received septic tank effluent from September 2012 (and also a once-off two week period in June 2012) onwards.

5.3.4.1 *2010 Evapotranspiration*

There were no willow system evapotranspiration values determined in 2010 due to the overflow channel being installed. The water level was constantly above the estimated overflow point of 1.65 m throughout the year which meant that the water loss from evapotranspiration could not be separated from the water loss due to the overflow. The water level and daily rainfall are shown in Figure 5.34.

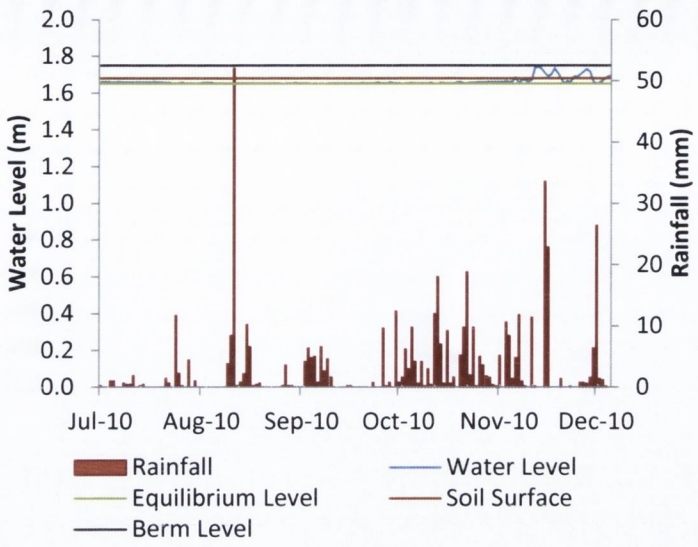


Figure 5.34 Water level and daily rainfall for 2010 (Site D)

5.3.4.2 2011 Evapotranspiration

The water level and daily rainfall for 2011 are shown in Figure 5.35. It can be seen that the inspection well was pumped out twice at the beginning of the year (January and February) in an attempt to assess whether the water level in the inspection well represented the true level throughout the entire system. Initially it had been thought that perhaps the low porosity soil at the top levels of the willow system were preventing rainwater and effluent percolating downwards towards the base. However, this was shown not to be the case as the inspection well level rose back up to the overflow point within a day on both occasions. The overflow channel became partially blocked in November of 2011. This was as a result of grass growth and build-up of soil at the channel. The slower release of water was not seen to have a detrimental effect on willow development so the channel was left this way.

As a result of the poor willow establishment, evapotranspiration rates for the system were relatively low for 2011. The monthly willow system evapotranspiration rates, the reference evapotranspiration and the monthly crop coefficient for the year are shown in Figure 5.36 and Table 5.13. The mean daily ET_{willow} rates were relatively constant throughout the growing season ranged from 2.3 mm/day (April) to 3.1 mm/day (July). The K_c values ranged from 0.8 (June) to 1.8 (September) for the growing season, fluctuating slightly about 1.00 for most of the period. There was no recorded evapotranspiration for December due to the water level being constantly above the overflow level for the month. The mean daily ET_{willow} rates during the

dormant months ranged between 0.1 mm/day (December) to 1.4 mm/day (March). Some notably high K_c values were 1.4 (January) and 1.9 (February).

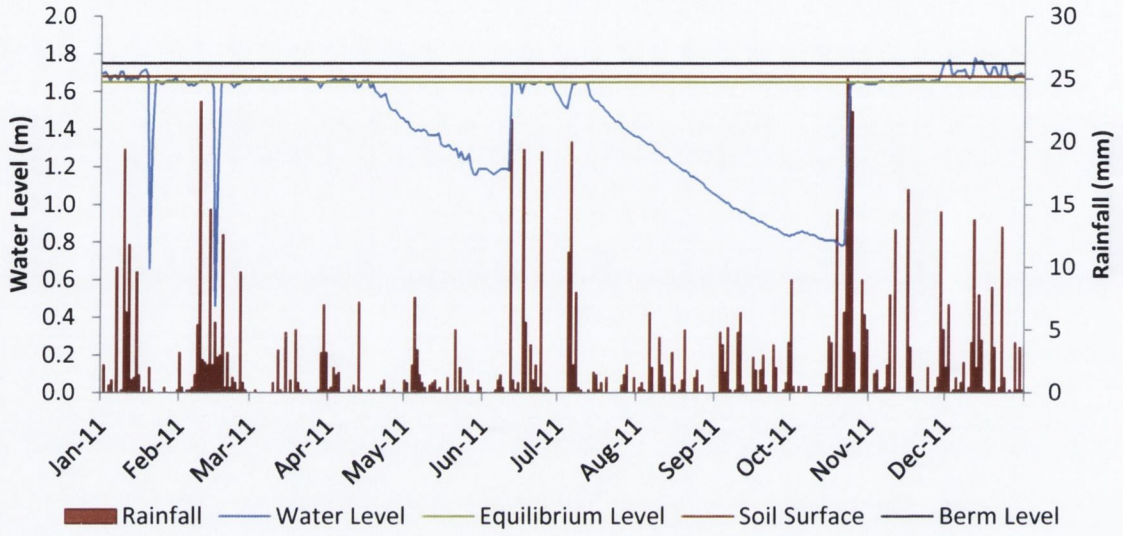


Figure 5.35 Water level and daily rainfall for 2011 (Site D)

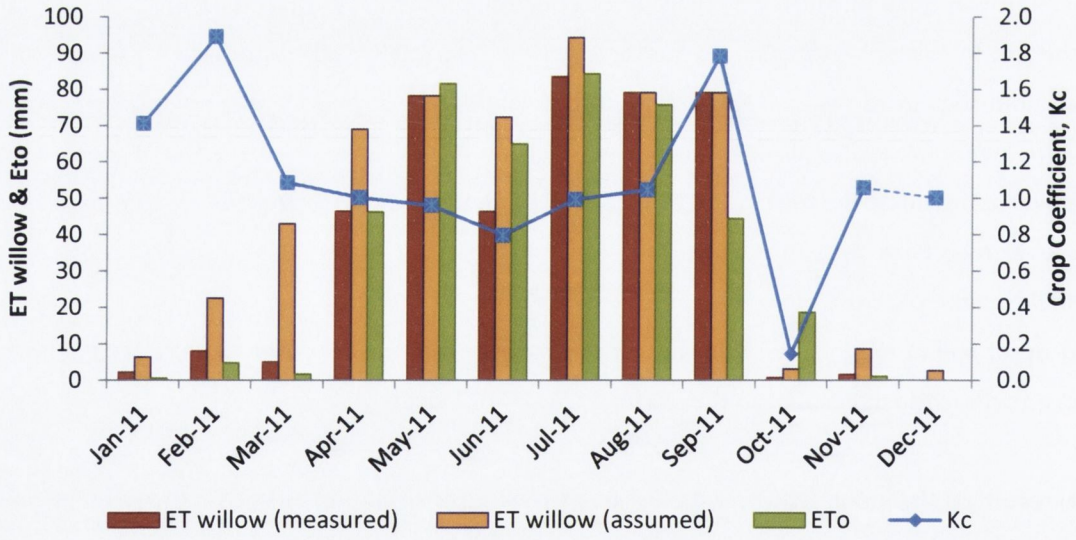


Figure 5.36 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2011)

The total ET_{willow} for the monitored period was 429.9 mm and was determined from 202 days of evapotranspiration data. This corresponded to a total reference evapotranspiration of 423.6 mm giving an overall K_c value of 1.0. The total assumed ET_{willow} was 558 mm for the year (resulting

in an annual K_c of 1.0). Again, it should be highlighted that no effluent was being discharged into the system during this period.

Table 5.13 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	2.2	6.3	4.4	4	0.2	1.4
February	8.0	22.5	11.9	11	0.8	1.9
March	5.0	42.9	39.6	2	1.4	1.1
April	46.4	69.0	68.8	16	2.3	1.0
May	78.2	78.2	81.6	31	2.5	1.0
June	46.3	72.3	90.9	20	2.3	0.8
July	83.5	94.3	95.1	27	3.1	1.0
August	79.1	79.1	75.8	31	2.6	1.0
September	79.1	79.1	44.3	30	2.6	1.8
October	0.7	3.0	21.0	27	0.6	0.1
November	1.5	8.7	8.2	3	0.3	1.1
December	0.0	2.6	2.6	0	0.1	1.0
Annual	429.9	558.0 (TR = 741)	544.2	202	2.1 (1.5)[2]	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.4.3 2012 Evapotranspiration

As with the previous sites, evapotranspiration data for the willow system on Site D was relatively low in 2012. Effluent loading on the site took place for 3 weeks in June and then continuously from 19th September until the end of the monitoring period. This was largely due to the heavy rainfall during the summer months. It can be seen in Figure 5.37 that the main decreases in water level within the system occurred during periods were there was a reduction in rainfall amounts.

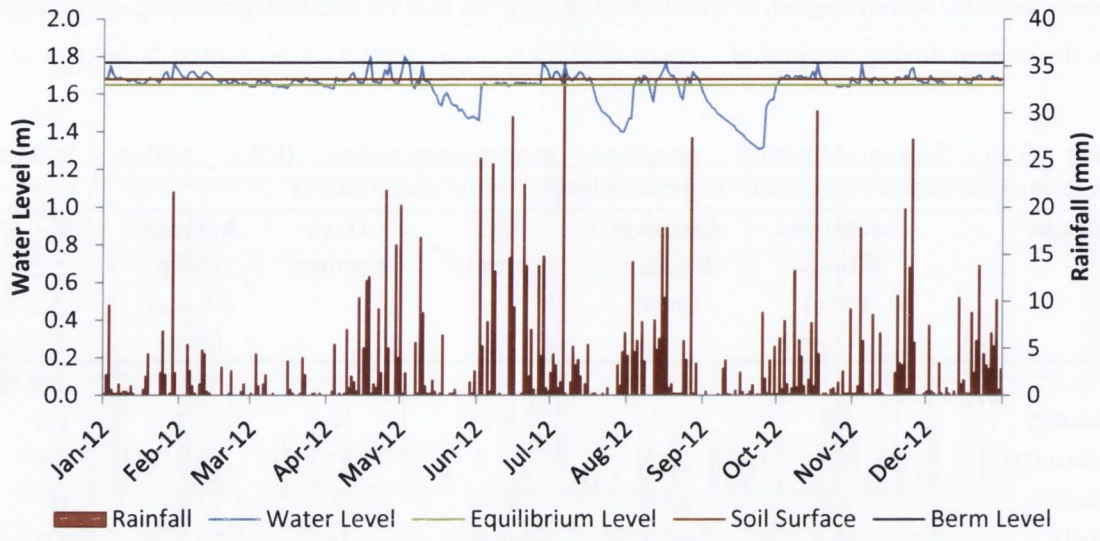


Figure 5.37 Water level and daily rainfall for 2012 (Site D)

The mean daily ET_{willow} rates ranged from 1.6 mm/day (April) to 3.8 mm/day (July) for the growing season. As can be seen in Figure 5.38 the total amounts were relatively low for June and August, due to the heavy rainfall and the water level being above the overflow level for many days. The K_c values were again quite low, most likely as a result of the poor willow development. They ranged from 0.9 (May) to 1.2 (July), rising to 1.4 in October.

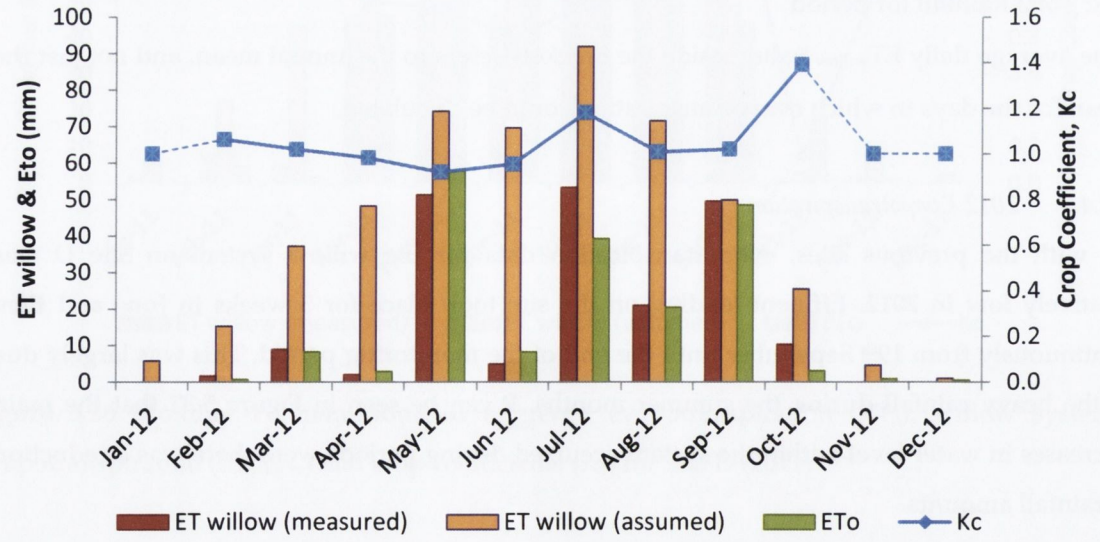


Figure 5.38 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2012)

The total ET_{willow} for the 94 days examined was 220.7 mm (Table 5.14). The corresponding ET_o is 191.3 mm, resulting in an overall crop coefficient of 1.1. The total assumed ET_{willow} was 494.7 mm for the year (giving an annual K_c of 1.0).

Table 5.14 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	5.7	5.7	0	0.2	1.0
February	1.6	15.3	14.4	2	0.5	1.1
March	8.9	37.3	36.6	10	1.2	1.0
April	2.0	48.2	49.1	3	1.6	1.0
May	51.3	74.2	80.7	20	2.6	0.9
June	4.9	69.6	72.9	3	1.6	1.0
July	53.3	91.9	77.9	14	3.8	1.2
August	21.0	71.6	71.0	7	3.0	1.0
September	49.5	49.8	48.8	29	1.7	1.0
October	10.2	25.5	18.3	5	2.0	1.4
November	0.0	4.5	4.5	0	0.2	1.0
December	0.0	0.9	0.9	1	0.1	1.0
Annual	220.7	494.7 (TR = 1098)	481.0	94	2.3 (1.4)	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.4.4 2013 Evapotranspiration

The water level and rainfall for the monitoring period January to August 2013 is shown in Figure 5.39. The drop in level throughout the summer is not as significant as might be expected, especially when compared to 2011, which saw a greater decrease. This may have been as a result of the higher loading rate due to continuous effluent loading to the willow system which started in September 2012.

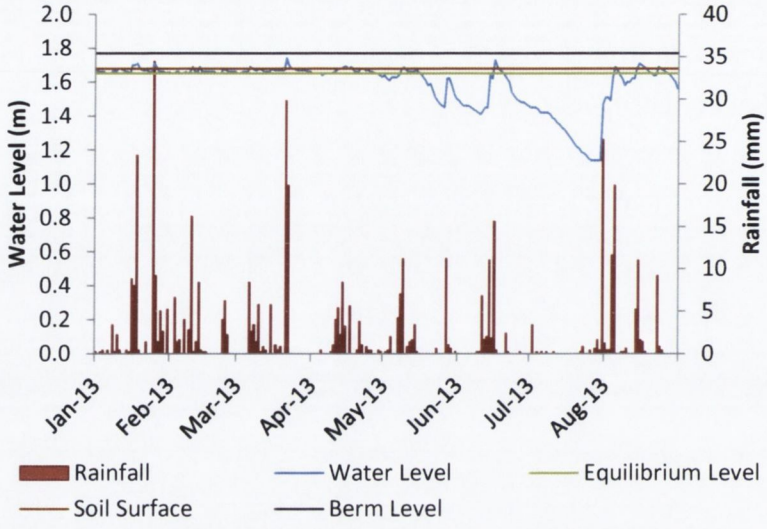


Figure 5.39 Water level and daily rainfall for 2013 (Site D)

The mean daily ET_{willow} rate ranged from 2-3 mm/day for the months April to July, dropping back slightly to 1.8 mm/day in August (Table 5.15). The corresponding K_c values were relatively low (Figure 5.40), ranging from a surprising low of 0.5 in July to a high of 1.0 which occurred early in the season (April). The low evapotranspiration values throughout the summer may have come about from the drop in water level, which meant that water was not as readily available to the willow trees. There were no evapotranspiration values determined for the first 3 months of the year, so the ET_{willow} was assumed to be equal to ET_o.

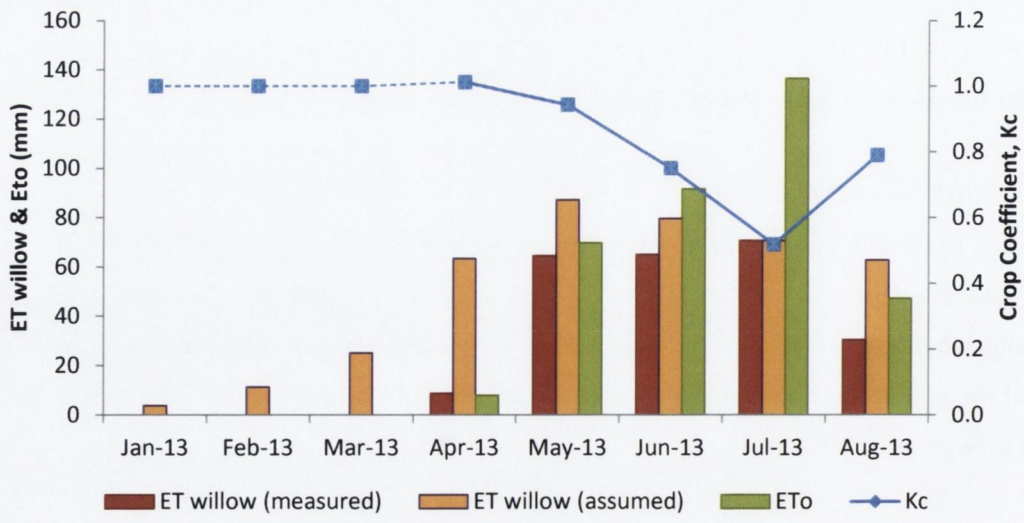


Figure 5.40 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2013)

The total measured ET_{willow} for 2013 up to August was 239.5 mm. The ET_o for the corresponding days was 353.21 mm, which resulted in a relatively low overall K_c of 0.4. The total assumed ET_{willow} was 403.9 mm (giving a K_c of 0.8 for the 8 months).

Table 5.15 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site D (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	3.8	3.8	0	0.1	1.0
February	0.0	11.4	11.4	2	0.4	1.0
March	0.0	25.1	25.1	0	0.8	1.0
April	8.8	63.3	62.6	3	2.1	1.0
May	64.5	87.2	92.4	22	2.9	0.9
June	65.1	79.7	106.3	26	2.5	0.7
July	70.6	70.6	136.4	31	2.3	0.5
August	30.5	62.8	79.5	17	1.8	0.8
Total	239.5	403.9 (TR = 468)	517.6	101	2.4 (1.7)[2]	0.8

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.4.5 Yearly Comparison

Again, the expected increase in evapotranspiration rates year on year was not measured for the willow system on Site D (see Figure 5.41). While there was a general increase for some of the months in the growing season (April, May and June), the trend did not transfer across the entire summer. The lack of a noticeably increase year on year may have been as a result of the poor development of the trees on the site.

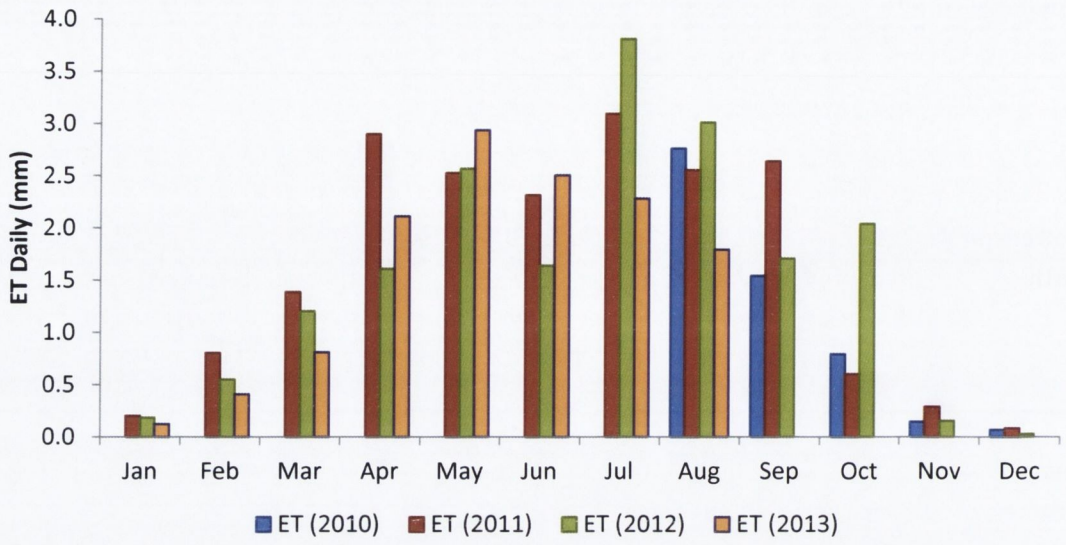


Figure 5.41 Yearly comparison of mean daily ET_{willow} rates for Site D

The same pattern transferred across to the determined K_c values for the site (see Figure 5.42) where no discernible difference between the four years monitored can be identified. One noticeable aspect is the relatively high crop coefficients attained in the early months of the year in between 2011.

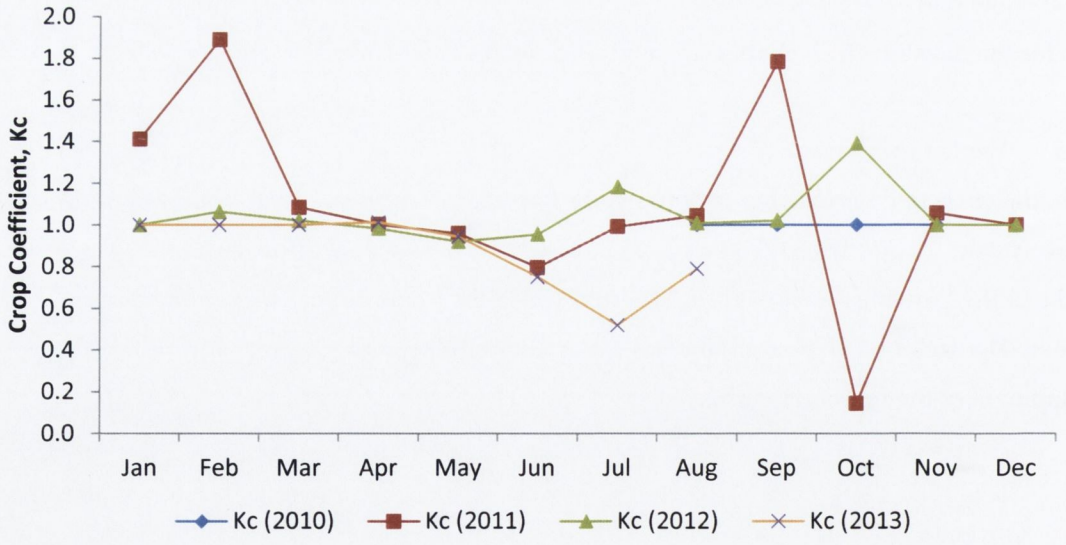


Figure 5.42 Yearly comparison of monthly K_c values for Site D

5.3.5 *Site E Jamestown*

Measurement of evapotranspiration rates for the willow system on Site E commenced on the 28th May 2010. The depth of the system was originally supposed to be 1.80 m, however a tear in the butyl rubber meant that actual depth was 1.12 m. So, evapotranspiration rates were only determined at water levels below this. In contrary to all of the other sites, the willow varieties used in this system were native to Ireland, about one third of which failed to take root, resulting in relatively mediocre evapotranspiration rates for the first two seasons. However, the planting of additional cuttings in 2011 resulted in improved results the following year. Septic tank effluent loading was very low and sporadic on the site, average approximately 3 L/day for the period April - October in 2011 and 2012. As detailed in Section 4.5.4 the usable water volume storage in the soil on Site E was 21%.

5.3.5.1 *2010 Evapotranspiration*

As can be seen from Figure 5.43, which shows the water level and daily rainfall, there were not many significant drops in the level for the months monitored in 2010. This would be expected given that the cuttings were planted at the start of June and so did not have a full season to develop. As detailed for previous sites, the drop in water level in December was caused by the cold weather, which affected the water pressure on the sensor and hence the water level within the inspection well.

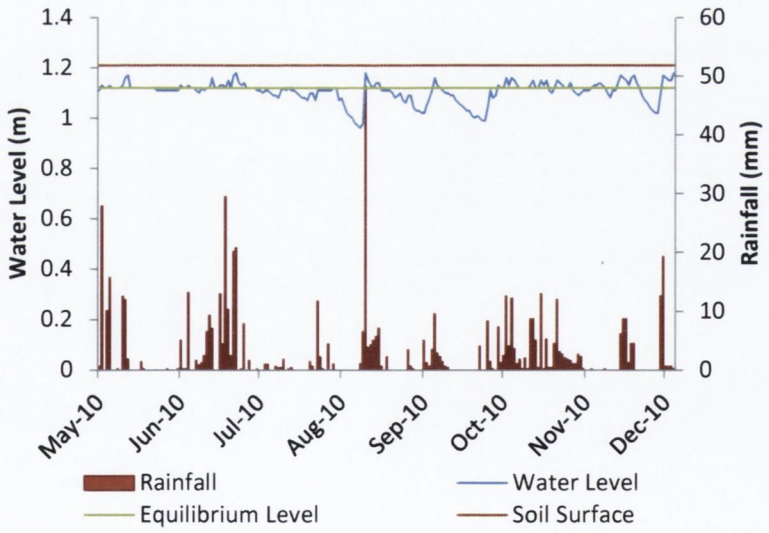


Figure 5.43 Water level and daily rainfall for 2010 (Site E)

The monthly willow system evapotranspiration rates, the reference evapotranspiration and the monthly crop coefficient are shown in Figure 5.44 and Table 5.16. The daily mean ET_{willow} rates

decreased steadily 2.4 mm/day in the first month of monitoring (June) to 0.9 mm/day in October. The crop coefficients for the growing season ranged from 0.7 (June) to 1.3 (October). There were no ET_{willow} or K_c values determined for either November or December due to the water level being above the overflow level, so evapotranspiration was assumed to be ET_o.

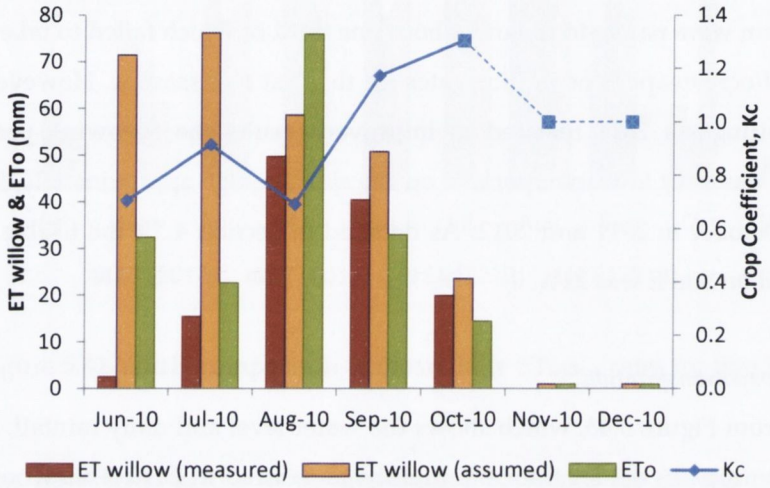


Figure 5.44 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2010)

Table 5.16 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2010)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
June	2.5	71.4	101.3	9	2.4	0.7
July	15.5	76.2	83.3	8	1.9	0.9
August	49.7	58.6	84.7	27	1.8	0.7
September	40.4	50.7	43.3	24	1.7	1.2
October	19.9	23.5	18.0	22	0.9	1.3
November	0.0	0.9	0.9	9	0.1	1.0
December	0.0	0.9	0.9	12	0.1	1.0
Total	128.0	282.2 (TR = 592)	332.4	111	1.2 (1.3)[2]	0.9

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total ET_{willow} for the monitoring period was 128 mm and was based on 111 days of data. The corresponding total ET_o was 178.2 mm resulting in a K_c of 0.7. The total assumed ET_{willow} was 280.4 mm for the period monitored in 2010 (resulting in a K_c of 0.9).

5.3.5.2 2011 Evapotranspiration

As can be seen from Figure 5.45 which shows the water level and daily rainfall, evapotranspiration performance improved in 2011 with a significant decrease in water level during the summer months. The effect of rainfall events on the water level can be seen with the 21 mm of precipitation on 1st October causing an increase of 0.5 m within the system.

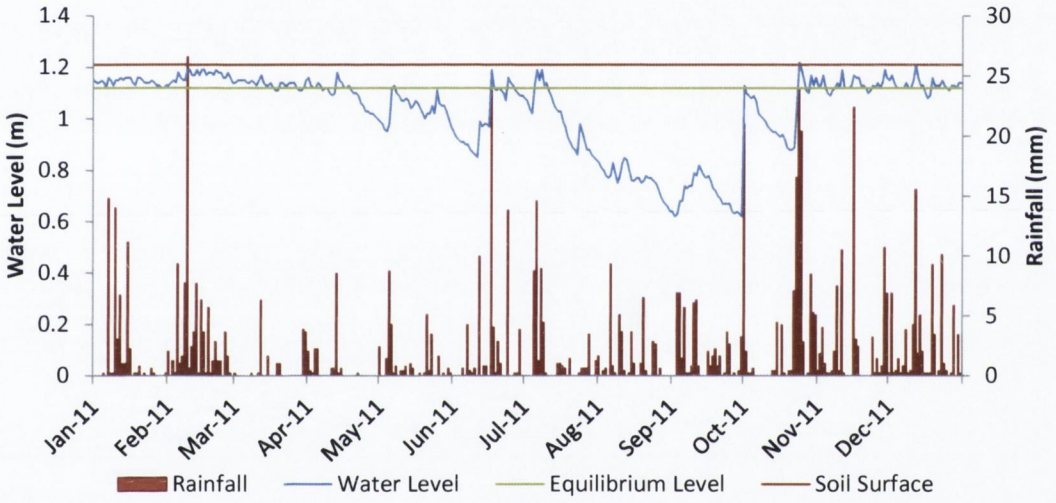


Figure 5.45 Water level and daily rainfall for 2011 (Site E)

As can be seen from Table 5.17, the mean daily ET_{willow} rates ranged from 2.0 mm/day (June) to 3.7 mm/day (July) during the growing season. Apart from June (which had a K_c of 0.7), the crop coefficient increased steadily during the growing season from 1.0 (April) to 1.8 (September), before increasing markedly to 6.2 in October. The mean daily ET_{willow} rates for the dormant season ranged from 0.1 mm/day (December) to 1.2 mm/day (March) and there was no evapotranspiration results for January or February. The corresponding dormant season K_c values were high, varying from 1.0 (January and February) to 4.2 (December).

The total ET_{willow} for the year was 476.9 mm which was for 195 days of evapotranspiration data. The overall mean daily ET_{willow} was 2.4 mm/day. The ET_o for the measured days was 382.96 mm resulting in an overall K_c of 1.3. The total assumed ET_{willow} for the year was 573.1 mm (corresponding to an annual K_c of 1.2).

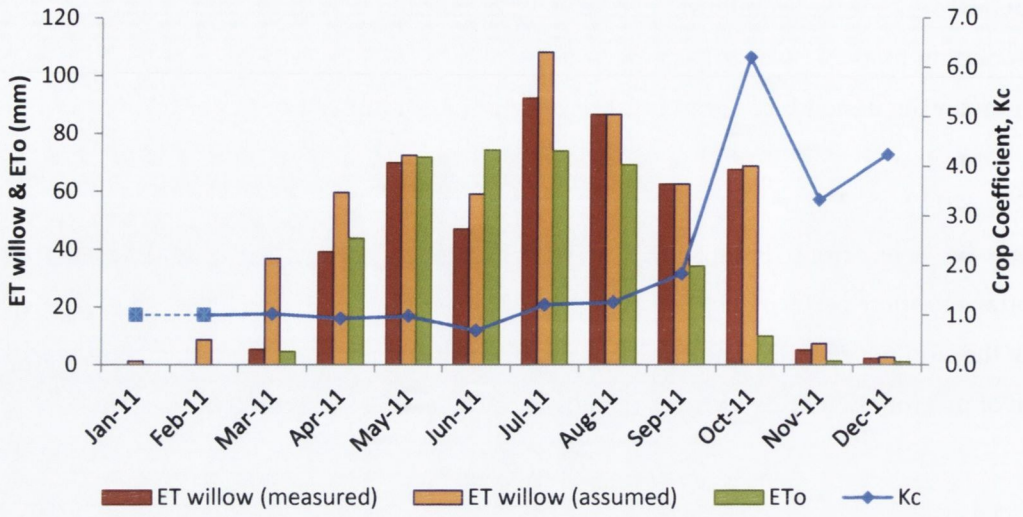


Figure 5.46 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2011)

Table 5.17 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	Actual ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	1.2	1.2	0	0.0	1.0
February	0.0	8.6	8.6	0	0.3	1.0
March	5.2	36.7	35.9	4	1.2	1.0
April	39.0	59.5	64.1	16	2.4	0.9
May	69.8	72.5	74.4	29	2.4	1.0
June	46.9	59.0	86.3	24	2.0	0.7
July	92.2	108.0	89.7	25	3.7	1.2
August	86.6	86.6	69.1	31	2.8	1.3
September	62.5	62.5	34.1	30	2.1	1.8
October	67.5	68.7	11.1	24	2.8	6.2
November	5.0	7.2	2.2	8	0.2	3.3
December	2.1	2.5	0.6	4	0.1	4.2
Annual	476.9	573.1 (TR = 652)	477.4	195	2.4 (1.6)[2]	1.2

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.5.3 2012 Evapotranspiration

Measurable evapotranspiration from the willow system was affected by the heavy rainfall (especially during the summer months) in 2012. It can be seen in Figure 5.47 that the willow system struggled to maintain consistent decreases in water level during the growing season.

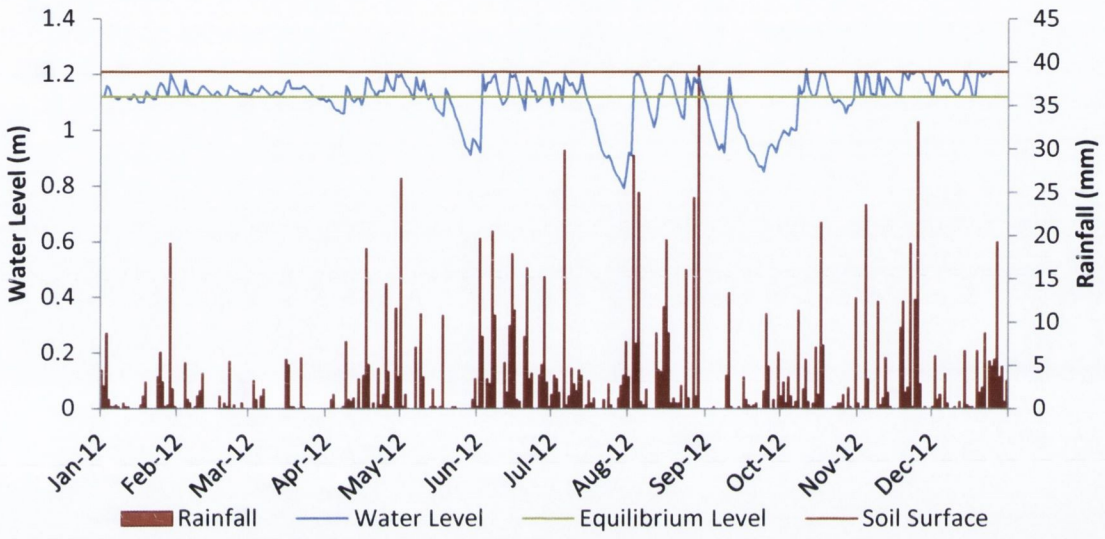


Figure 5.47 Water level and daily rainfall for 2012 (Site E)

The monthly ET_{willow} and ET_o rates along with the monthly K_c values are shown in Figure 5.48 and Table 5.18. The mean daily ET_{willow} ranged from 2.4 mm/day (April) to a high of 8.7 mm/day (July), eventually dropping off to 0.8 mm/day in October. The monthly crop coefficient values were somewhat erratic during the growing season. August had the lowest K_c value (1.2), while September had the highest (2.5). The low value in August may have been as a result of a drop in the water level away from the surface, which meant water was not as readily available for the willow trees to absorb. Evapotranspiration from the system was only determined for a low number of days throughout the winter months, with K_c values varying from a low of 0.9 in March to a high of 3.9 in January.

The total ET_{willow} for the 127 days with evapotranspiration results was 458.3 mm. The ET_o for those days was 229.4 mm resulting in an overall K_c of 2.0. The overall assumed ET_{willow} was 668.7 mm for the year (giving an annual K_c of 1.5)

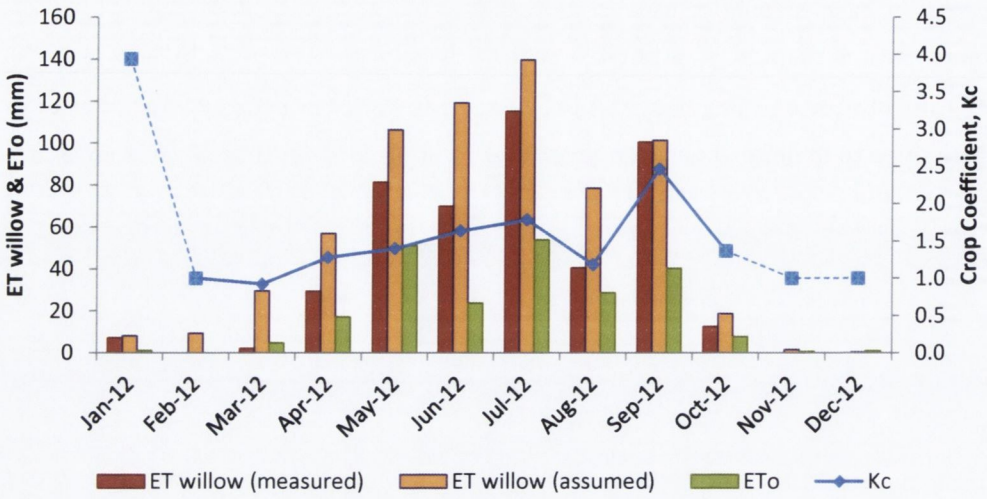


Figure 5.48 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2012)

Table 5.18 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	Actual ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	7.1	8.0	2.0	9	0.3	1.0
February	0.0	9.3	9.3	1	0.3	1.0
March	2.1	29.6	32.1	3	1.0	0.9
April	29.4	56.9	44.5	12	2.4	1.3
May	81.3	106.3	76.1	18	4.5	1.4
June	69.8	119.1	73.0	8	8.7	1.6
July	115.1	139.6	78.3	19	6.1	1.8
August	40.5	78.4	66.5	10	4.1	1.2
September	100.4	101.3	41.1	29	3.5	2.5
October	12.6	18.5	13.6	16	0.8	1.4
November	0.0	1.5	1.5	1	0.1	1.0
December	0.0	0.2	0.2	1	0.0	1.0
Annual	458.3	668.7 (TR = 1102)	438.2	127	3.6 (1.8)	1.5

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.5.4 2013 Evapotranspiration

Monitoring of the willow system on Site E lasted only four months (January to April) in 2013 because of malfunction of the water level meter. As these months are primarily in the dormant season, evapotranspiration results were sporadic given that the water level was above the overflow point for much of the time period. The water level within the willow system along with the daily rainfall at the site is shown in Figure 5.49. It can be seen that the drop in water level following overflow was quite slow. This is probably as a result of having to escape through surrounding soil (as the leak was below ground level) rather than being able to flow over ground.

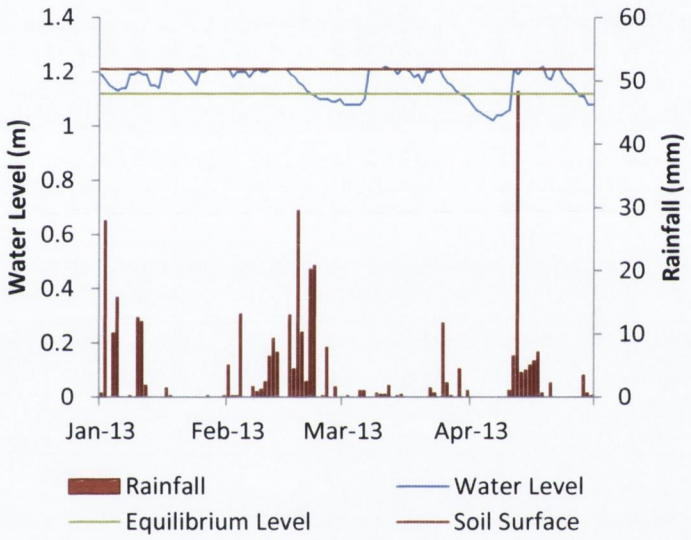


Figure 5.49 Water level and daily rainfall for 2013 (Site E)

The mean daily ET_{willow} rates for the monitored period ranged from 0.3 mm/day (February) to 1.9 mm/day (April). There was no evapotranspiration determined for January. The corresponding K_c values ranged from 1.0 for January and April to 1.8 for February (Figure 5.50).

The measured ET_{willow} for the 4 month period totalled 42.1 mm (Table 5.19). The corresponding ET_o was 30.34 mm, which gave an overall K_c of 1.4. The total assumed ET_{willow} was 89.9 mm (resulting in an overall K_c of 1.2).

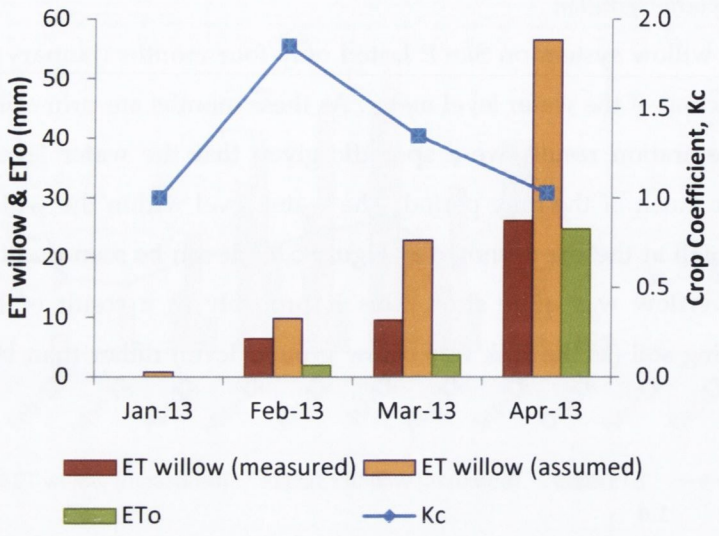


Figure 5.50 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2013)

Table 5.19 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site E (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	0.8	0.8	0	0.0	1.0
February	6.4	9.8	5.3	7	0.3	1.9
March	9.5	22.9	17.0	8	0.7	1.4
April	26.2	56.5	55.1	14	1.9	1.0
Total	42.1	89.93 (TR = 252)	78.2	29	1.5 (0.7)[2]	1.2

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.5.5 Yearly Comparison

The evapotranspiration rates from the willow system on Site E did generally follow the expected pattern of increasing year on year as the willow trees develop and grow larger (see Figure 5.51). This increase was quite significant in 2012, possibly aided by the higher availability of water near the surface due to the unseasonal heavy rainfall as effluent loading was relatively

consistent between years and only made up a very small proportion of overall hydraulic loading to the system. There was not much difference between the different years for the earlier months of the growing season, but there was a significant year on year increase for all remaining months of the season.

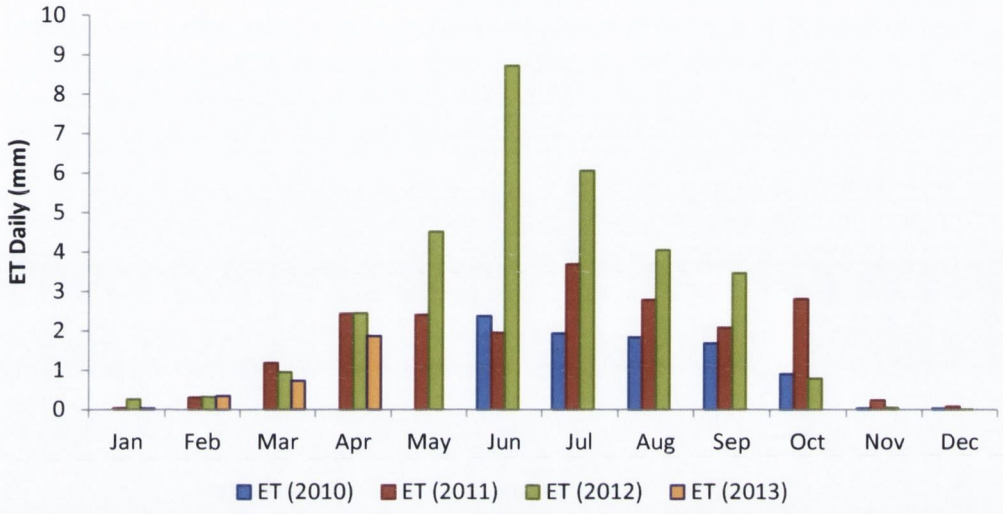


Figure 5.51 Yearly comparison of mean daily ET_{willow} rates for Site E

The crop coefficients follow a similar pattern, increasing year on year for almost all the months analysed (Figure 5.52). The high crop coefficients attained in some of the dormant months in different years is also quite noteworthy.

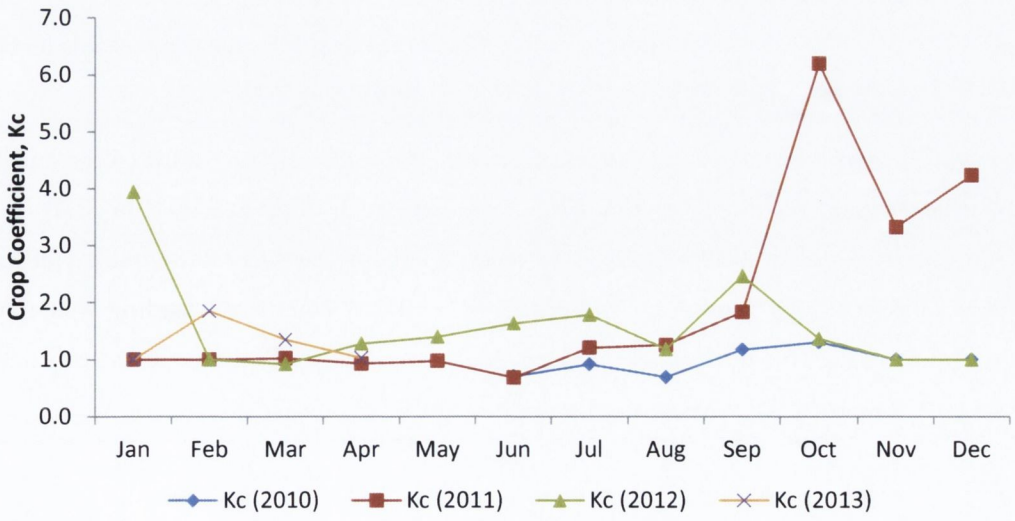


Figure 5.52 Yearly comparison of monthly K_c values for Site E

5.3.6 Site F Ballywilliam - System 1

Monitoring of water levels within willow system 1 on Site F commenced on 15th February 2011. The specified depth for the system was 1.8 m (excluding berm). However, a leak in the liner meant that the true depth was 0.65 m. The effect of this is illustrated in the figures showing the water level within the system (e.g. Figure 5.54) where increases in water level due to rainfall events are quickly negated from water leaving through the hole in the liner. The hole was due to a pipe running through the system at this level. Although it was attempted to correctly seal the piping during installation of the liner, it is apparent that this was not properly done. The piping is shown in Figure 5.53.



Figure 5.53 Piping running through System 1 on Site F that resulted in leakage at this level

Willow establishment was mixed on the system, with approximately one third of the cuttings dying off after original planting. New cuttings were planted in their place at the start of the second season. The system was supposed to receive half of the secondary treated effluent produced from 5 dwellings. However, as outlined in Section 4.3.6 effluent loading was almost non-existent during the monitoring period. The usable water volume storage in the soil within System 1 on Site F was determined to be 18% (see Section 4.5.4)

5.3.6.1 2011 Evapotranspiration

The water level within the willow system, the daily rainfall at the site and the determined overflow level are shown in Figure 5.54. The rapid decrease in water level after an initial rise due to heavy rainfall is very evident.

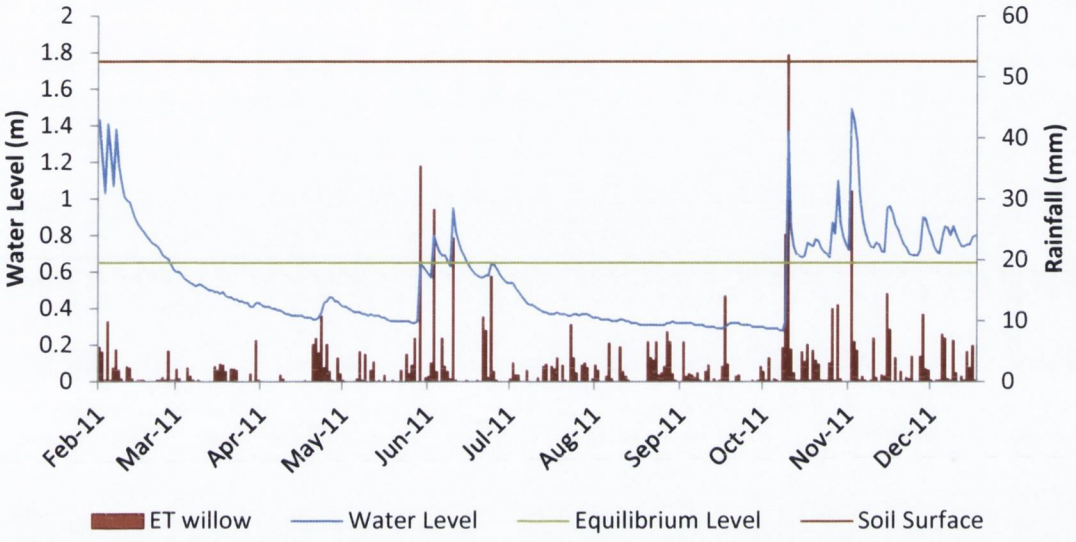


Figure 5.54 Water level and daily rainfall for 2011 (Site F - System 1)

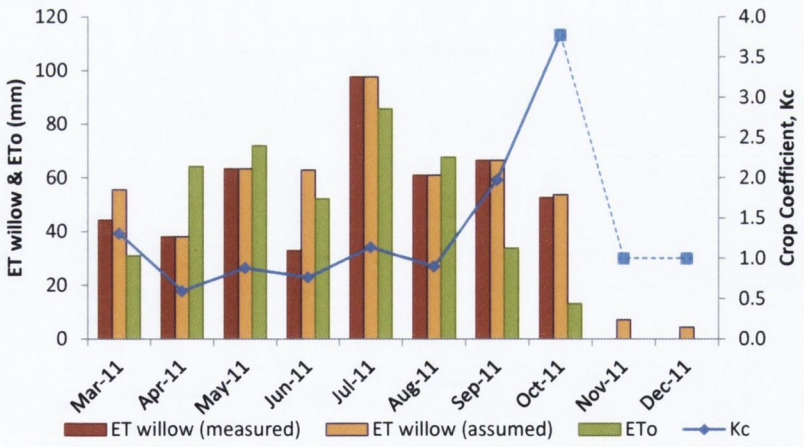


Figure 5.55 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2011)

The mean daily ET_{willow} rate (see Table 5.20) ranges from 1.8 mm/day (April) to 3.1 mm/day (July) for the growing season in 2011. The K_c values for the growing season ranged from 0.6 in

April to 2.0 September before increasing markedly to 3.8 for October (illustrated in Figure 5.55). There were no evapotranspiration rates determined for November or December due to the water level being above the overflow point for the entire duration of those two months.

The total ET_{willow} was 456.5 for 2011 which comes from 212 days of results. This gives a mean daily ET_{willow} rate of 2.2 for all the days monitored. The total ET_o for those days was 419.84 mm resulting in an overall K_c of 1.1. The total assumed ET_{willow} for the monitored period was 510.6 mm (resulting in an overall K_c of 1.0).

Table 5.20 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
March	44.2	55.7	42.5	19	1.8	1.3
April	38.1	38.1	64.3	30	2.1	0.6
May	63.5	63.5	72.0	31	2.0	0.9
June	32.9	62.9	82.2	17	1.9	0.8
July	97.6	97.6	85.8	31	3.1	1.1
August	61.0	61.0	67.7	31	2.0	0.9
September	66.5	66.5	33.7	30	2.2	2.0
October	52.6	53.7	14.2	23	2.3	3.8
November	0.0	7.1	7.1	0	0.2	1.0
December	0.0	4.4	4.4	0	0.1	1.0
Total	456.5	510.6 (TR = 710)	473.9	212	2.2 (1.7)[2]	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.6.2 2012 Evapotranspiration

The evapotranspiration rates for the willow system could only be calculated for a relatively low number of days during the 2012 growing season. This was as a result of heavy rainfall which meant that the water level was consistently above the overflow level. This is clearly illustrated in Figure 5.56 which shows the water level and daily rainfall at the site.

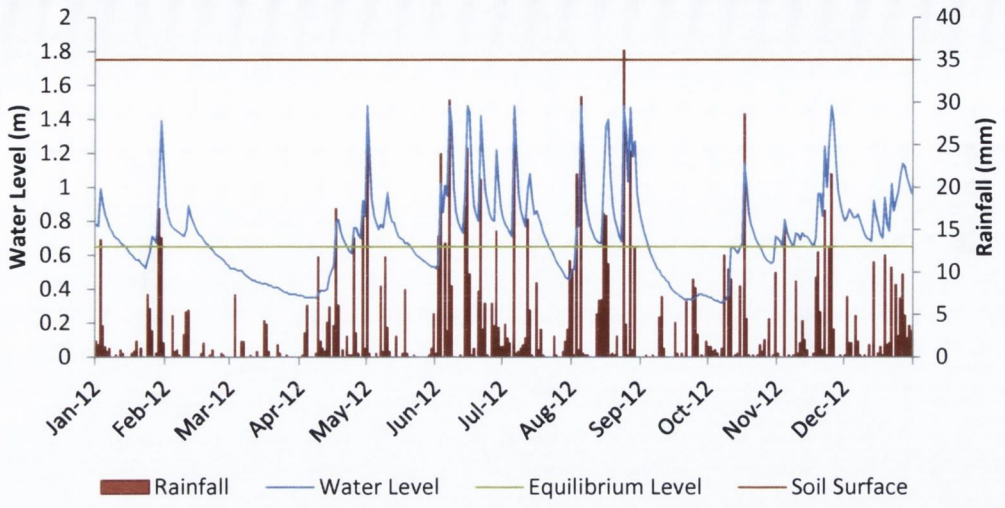


Figure 5.56 Water level and daily rainfall for 2012 (Site F - System 1)

Calculated ET_{willow} rates were quite erratic for the growing season. This was due to the low number of days for which ET_{willow} could be determined and large fluctuations in the water level over relatively short time frames. The mean daily ET_{willow} rate ranged from 1.2 mm/day (April) to 7.2 mm/day (June), decreasing steadily from then until the end of the season (apart from a sudden drop to 0.4 mm/day in August). The K_c values were also quite erratic (see Figure 5.57) with a maximum value of 2.4 attained in September. The early months of the year resulted in relatively high evapotranspiration from the willow system considering it was the dormant season. The K_c values peaked at 3.1 (January) for the winter months.

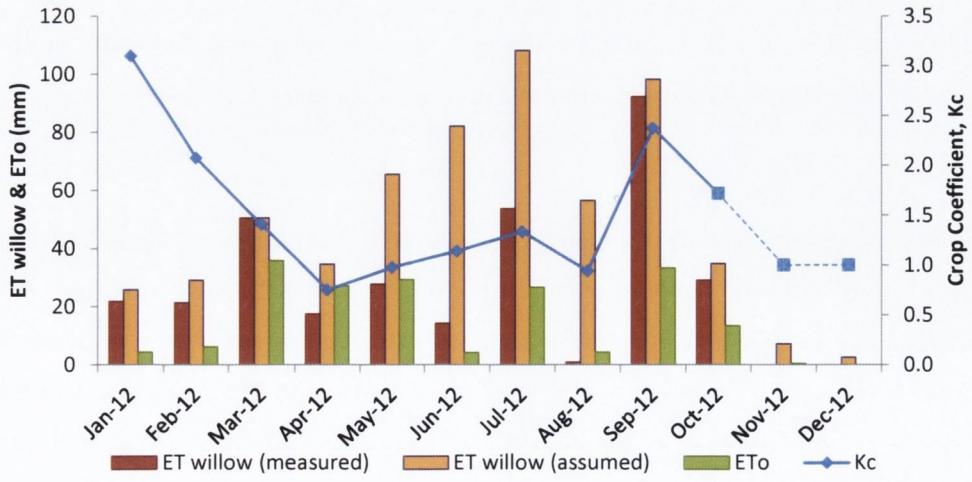


Figure 5.57 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2012)

The total ET_{willow} for the 140 days on which evapotranspiration could be determined was 329.3 mm (Table 5.21). This resulted in a mean daily ET_{willow} rate of 2.4 mm/day. The corresponding ET_o was 185.3 mm resulting in an overall K_c of 1.8. The overall assumed ET_{willow} for the year was 595.1 mm (which resulted in an annual K_c value of 1.3).

Table 5.21 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	21.8	25.8	8.3	11	0.8	3.1
February	21.3	29.1	14.0	9	1.0	2.1
March	50.5	50.5	35.9	31	1.6	1.4
April	17.4	34.6	46.1	18	1.2	0.8
May	27.8	65.6	67.1	11	2.5	1.0
June	14.3	82.0	72.0	2	7.2	1.1
July	53.7	108.2	81.0	10	5.4	1.3
August	0.9	56.4	60.0	2	0.4	0.9
September	92.3	98.2	41.4	26	3.6	2.4
October	29.2	34.8	20.3	20	1.5	1.7
November	0.0	7.2	7.2	0	0.2	1.0
December	0.0	2.6	2.6	0	0.1	1.0
Annual	329.3	595.1 (TR = 1178)	456.0	140	2.4 (1.6)	1.3

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.6.3 2013 Evapotranspiration

The water level within the system along with the daily rainfall is shown in Figure 5.58. It can be seen that the water level was above the overflow point for much of the early months of the year. An initial quick decrease in May was followed by an almost continuous slow decrease for the rest of the summer until the spike in water level from the rainfall at the start of August. This suggests that the willow trees were having difficulty in taking up the water at such distance away from the surface.

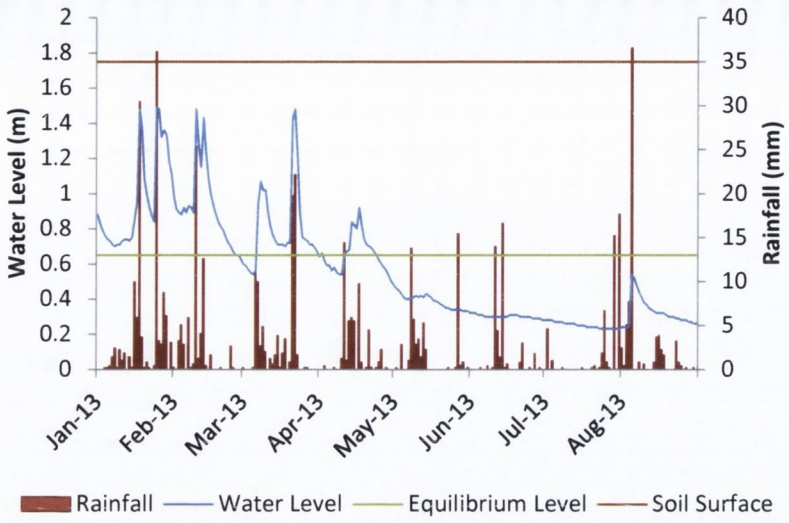


Figure 5.58 Water level and daily rainfall for 2013 (Site F - System 1)

The evapotranspiration rates were relatively low considering the high reference evapotranspiration rates that were a feature of the summer period (see Table 5.22). The mean daily ET_{willow} ranged from 1.9 mm/day (June) to 3.8 mm/day (April). There was a steady decrease in K_c values from the start of the season (1.1 in April) to a K_c of 0.5 in July, before increasing somewhat to 0.9 in August. As already detailed, the low values in the summer can probably be attributed to the almost consistently low water level within the willow system. The evapotranspiration rates ranged from 0.2 mm/day (January) to 1.2 mm/day (March) for the dormant months. The March rate resulted in a K_c value of 1.4.

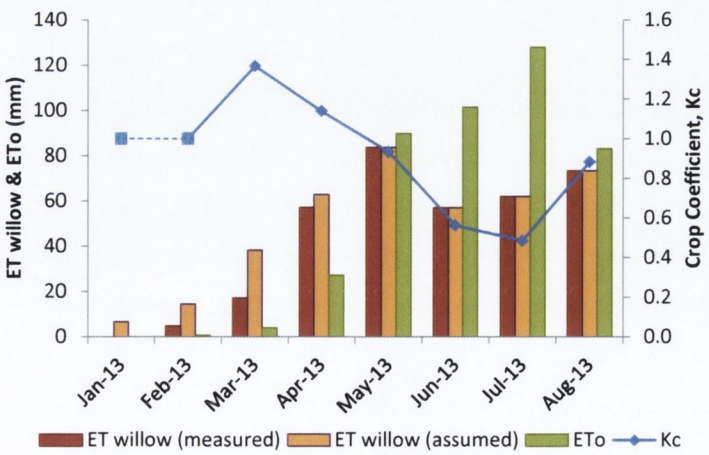


Figure 5.59 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2013)

The total ET_{willow} was 355 mm for the 8 month monitored period in 2013. This was based on 145 days of data, which had a corresponding total ET_o of 434.0 mm. Hence, the overall K_c value for the period was 0.7. The total assumed ET_{willow} for the time period was 398.3 mm, which gave an overall K_c value of just 0.78.

Table 5.22 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 1 (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	Measured ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	6.7	6.7	0	0.2	1.0
February	4.8	14.5	14.5	1	0.5	1.0
March	17.1	38.3	28.0	6	1.2	1.4
April	57.1	62.9	55.2	15	3.8	1.1
May	83.7	83.7	89.7	31	2.7	0.9
June	57.0	57.0	101.4	30	1.9	0.6
July	62.0	62.0	128.0	31	2.0	0.5
August	73.3	73.3	83.1	31	2.4	0.9
Annual	355.0	398.3 (TR = 551)	506.6	145	2.4 (1.6)[2]	0.78

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.6.4 Yearly Comparison

A year on year increase in ET_{willow} did occur to some degree on Site F (System 1). It can be seen in Figure 5.60 that there was a general increasing trend in mean daily ET_{willow} across the 3 years for the months March, April and May. For the rest of the months in the growing season, there was a general increase between 2011 and 2012 (August being the exception). The increase was quite significant in some cases, which could be as a result of the heavy rainfall that fell during the growing season. However, this increase did not follow through from 2012 to 2013. The reasoning behind the low ET_{willow} rates in 2013 (as detailed in previous sections) was attributed to water being more readily available (i.e. more frequent rainfall) in 2012; hence, it could be reasonably assumed that the ET_{willow} rates in 2013 would have been much improved.

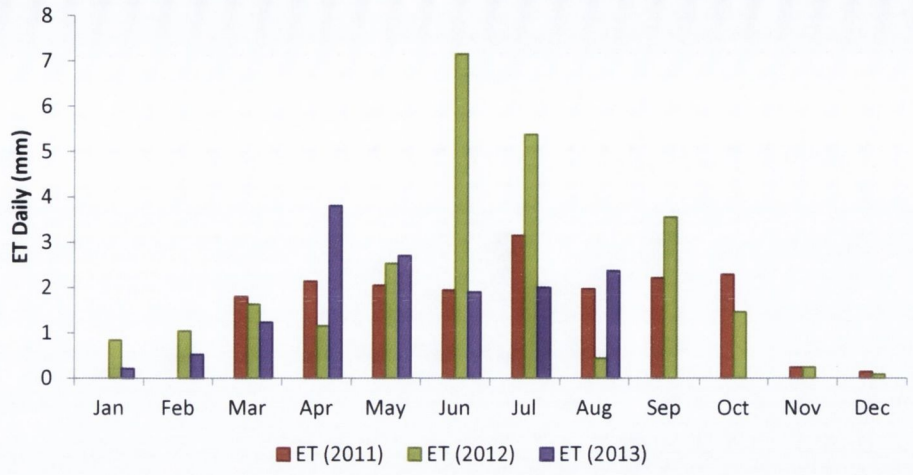


Figure 5.60 Yearly comparison of mean daily ET_{willow} rates for System 1 on Site F

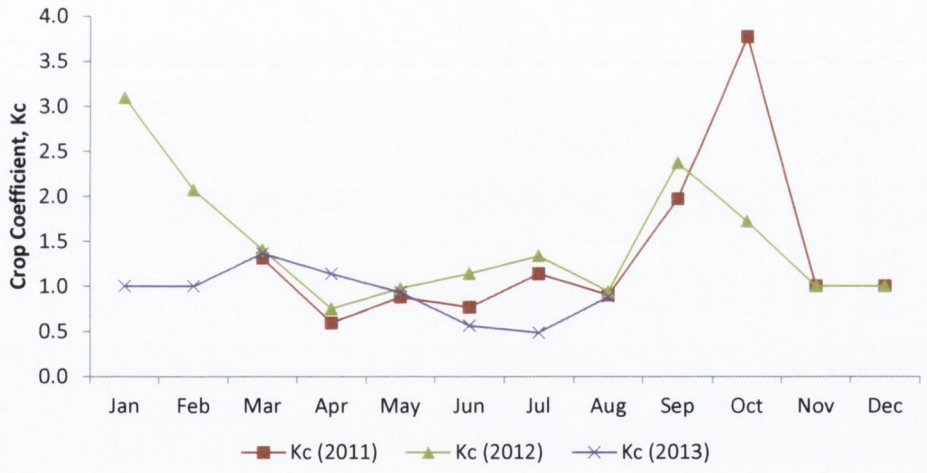


Figure 5.61 Yearly comparison of monthly K_c values for System 1 on Site F

The crop coefficients follow a similar pattern (see Figure 5.61) with the 2012 monthly values higher (or at least the same as their 2011 counterparts). Apart from the early months of the year, in which they produced the highest crop coefficients, the 2013 crop coefficients were lower than the 2011 and 2012 values for much of the growing season. The high K_c values attained in the early dormant months of 2012 are also noteworthy.

5.3.7 Site F Ballywilliam - System 2

Monitoring of the water levels within willow system 2 started on the 15th February 2011. The system was designed with a specified depth of 1.8 m (excluding berm). However, overflow

from the system occurs at a depth of 1.45 m over the berm on one side at the low point of the system.

Willow development of the initial cuttings planted in 2011 was quite poor due to heavy weed growth on the system, which crowded out the cuttings, preventing adequate light reaching them. To help remedy this, replanting was carried out in 2012 and 2013. The system is still behind where it should be in terms of development but has improved as a result of the replanting. The system was supposed to receive half of the secondary treated effluent produced from 5 dwellings. However, as outlined in Section 4.3.6 effluent loading was almost non-existent during most of the monitoring period. The usable water volume storage in the soil within System 2 on Site F was 19% (see Section 4.5.4).

5.3.7.1 2011 Evapotranspiration

The water level and daily rainfall for the site is shown in Figure 5.62. It can be seen that the water level decreased significantly over the summer period. The rainfall event on the 23rd/24th October caused an increase in level of 1.15, with negligible decreases occurring from then until the end of the year. The mean daily ET_{willow} rates increased steadily from 1.4 mm/day in March to a high of 4.5 mm/day in July (apart from a decrease to 1.4 mm/day in June), before decreasing again, to 0.5 mm/day in October (Table 5.23). There isn't an obvious reason for the drop in June, and may be as a result of the low water level in the willow system. The K_c values for the growing season followed the expected pattern (apart from a similar drop in June). The seasonal high of 2.7 occurred in September. There was no evapotranspiration determined for November or December in 2011 (see Figure 5.63).

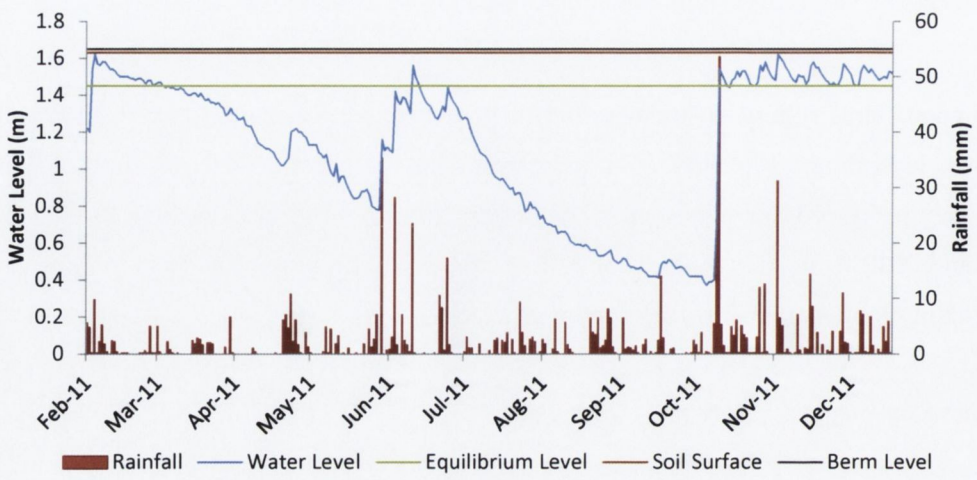


Figure 5.62 Water level and daily rainfall for 2011 (Site F - System 2)

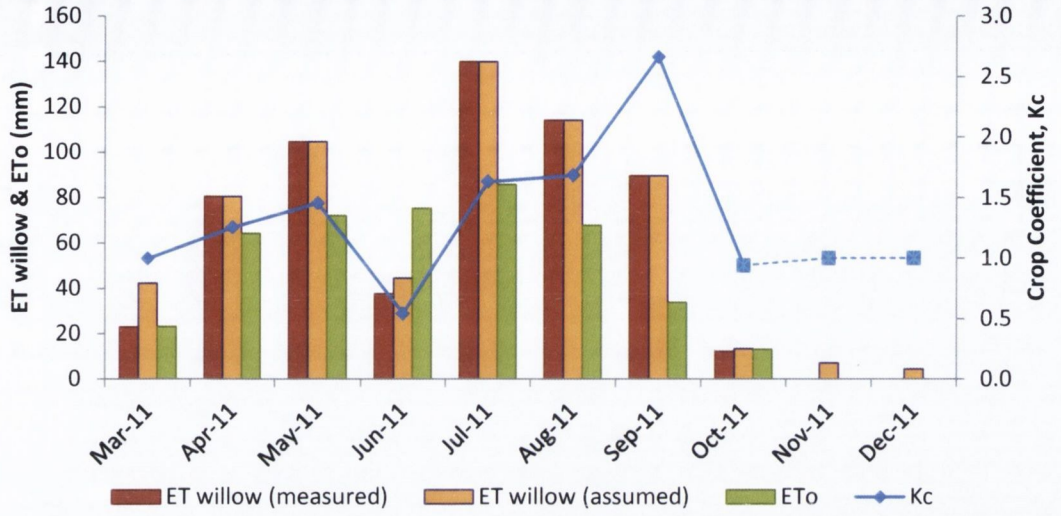


Figure 5.63 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2011)

Table 5.23 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
March	23.0	42.3	42.5	13	1.4	1.0
April	80.6	80.6	64.3	30	2.7	1.3
May	104.6	104.6	72.0	31	3.4	1.5
June	37.7	44.5	82.2	27	1.4	0.5
July	139.9	139.9	85.8	31	4.5	1.6
August	114.0	114.0	67.7	31	3.7	1.7
September	89.7	89.7	33.7	30	3.0	2.7
October	12.3	13.4	14.2	24	0.5	0.9
November	0.0	7.1	7.1	0	0.2	1.0
December	0.0	4.4	4.4	0	0.1	1.0
Total	601.9	640.6 (TR = 710)	473.9	217	2.8 (2.1)[2]	1.4

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total evapotranspiration for 2011 on willow system 2 was 601.9 mm which was for 217 days of data. The resulting mean daily ET_{willow} for the period was 2.8 mm. The corresponding ET_o was 435.2 mm giving an overall K_c of 1.4 for the monitored period. The overall assumed ET_{willow} was 640.6 mm, which when divided by the annual ET_o resulted in a K_c of 1.4.

5.3.7.2 2012 Evapotranspiration

As with system 1, the evapotranspiration rates could only be calculated for a relatively low number of days in the summer period due to the heavy rainfall on system 2. Figure 5.64 shows that the water level was above the overflow level for large periods of the growing season.

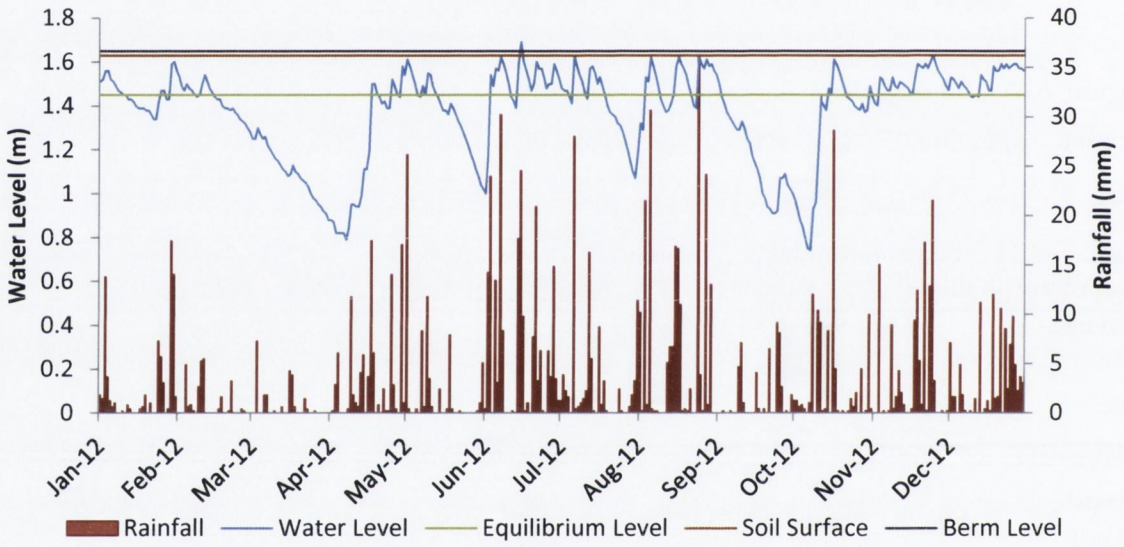


Figure 5.64 Water level and daily rainfall for 2012 (Site F - System 2)

The total monthly ET_{willow}, the monthly ET_o and the crop coefficients are shown in Figure 5.65. Total evapotranspiration amounts were relatively poor in June and August due to the low number of days in which results could be obtained. However, the daily mean ET_{willow} rates were relatively high (Table 5.24) ranging from 1.2 mm/day (April) to a high of 6.4 mm/day (July) for the growing season. The April rate was actually lower than that of the preceding month, which is quite surprising. This may have been as a result of a low water level towards the start of the month, followed by high rainfall levels for much of the second half of the month, which made it quite difficult to accurately determine the evapotranspiration from the system.

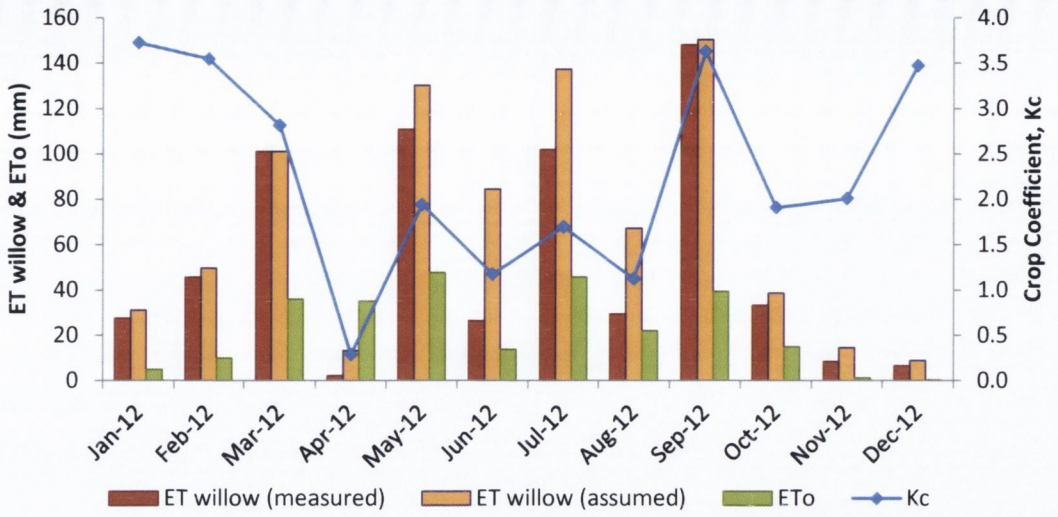


Figure 5.65 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F – System 2 (2012)

Table 5.24 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F – System 2 (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	Measured ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	27.6	31.0	8.3	15	1.0	3.7
February	45.7	49.8	14.0	16	1.8	3.5
March	101.0	101.0	35.9	31	3.3	2.8
April	2.2	13.2	46.1	22	1.2	0.3
May	110.9	130.3	67.1	20	5.5	1.9
June	26.4	84.5	72.0	5	5.3	1.2
July	102.0	137.4	81.0	16	6.4	1.7
August	29.4	67.2	60.0	7	4.2	1.1
September	148.1	150.3	41.4	29	5.1	3.6
October	33.2	38.6	20.3	22	1.5	1.9
November	8.6	14.5	7.2	4	0.5	2.0
December	6.6	8.9	2.6	-	0.3	3.5
Annual	641.8	826.9 (TR = 1178)	456.0	187	3.4 (2.3)[2]	1.8

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The monthly crop coefficients for the growing season were somewhat erratic in nature due to the difficulty in accurately determining evapotranspiration because of large fluctuations in water level. They varied from a low of 0.3 (April) to a high of 3.6 (September). The dormant season produced some relatively high evapotranspiration rates. The corresponding crop coefficients were also high, with January, February and November all having values greater than 3.

The total ET_{willow} for the 187 days with evapotranspiration results for the year was 641.8 mm. This resulted in a mean daily ET_{willow} rate of 3.4 mm/day. The corresponding ET_o was 270.66 mm resulting in an overall crop coefficient of 2.4. The overall assumed ET_{willow} was 826.9 mm for the monitored period, which resulted in an annual crop coefficient of 1.8.

5.3.7.3 2013 Evapotranspiration

It can be seen that the water level was above the overflow point for much of the early part of the year (Figure 5.66). This was followed by an almost constant decrease in water level from the end of April until a spike in mid-June (when significant rainfall occurred). The drop in water level from this point onwards is very gradual considering the relatively warm, dry conditions. So, as with system 1 on the same site, it appears that after a certain point, it was water availability to the plants rather than meteorological conditions or willow tree size that had the greatest bearing on evapotranspiration from the willow system.

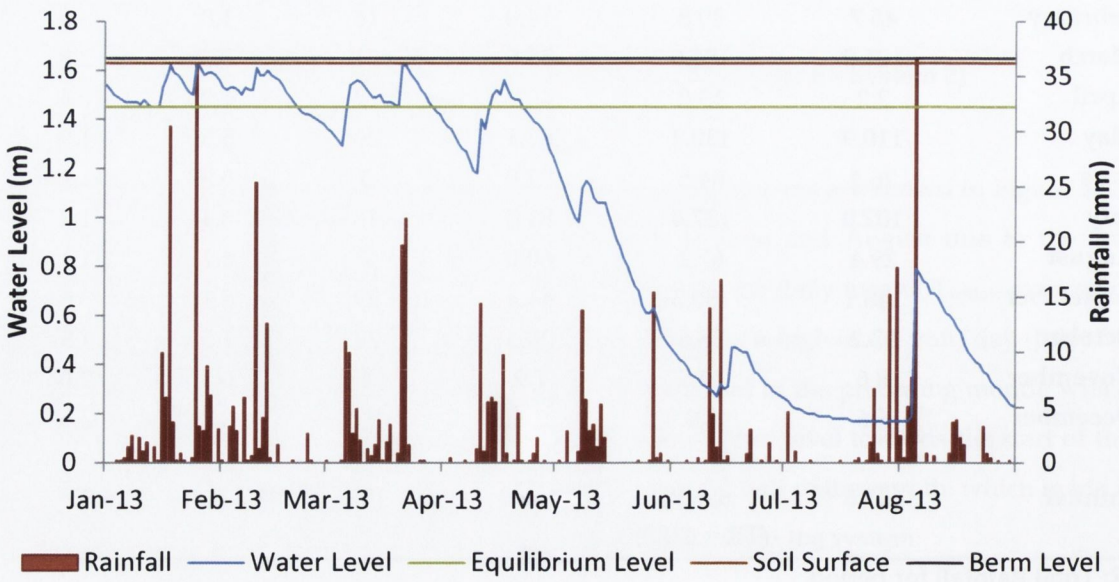


Figure 5.66 Water level and daily rainfall for 2013 (Site F - System 2)

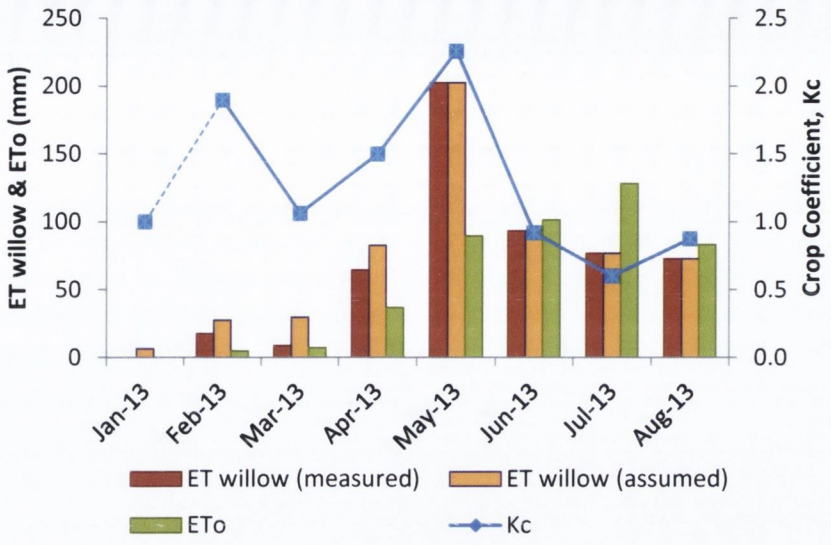


Figure 5.67 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2013)

Table 5.25 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site F - System 2 (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	6.7	6.7	0	0.2	
February	17.8	27.6	14.5	7	1.0	1.9
March	9.0	29.8	28.0	8	1.0	1.1
April	64.5	82.8	55.2	21	3.1	1.5
May	202.7	202.7	89.7	31	6.5	2.3
June	93.4	93.4	101.4	30	3.1	0.9
July	76.9	76.9	128.0	31	2.5	0.6
August	72.8	72.8	83.1	31	2.3	0.9
Total	537.0	592.5 (TR = 551)	506.6	159	3.4 (2.4)[2]	1.17

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The ET_{willow} rates started out high in the growing season with mean daily rates of 3.1 mm/day and 6.5 mm/day for April and May respectively. Evapotranspiration rates started to decrease

after this, despite the warm, dry weather conditions in June and July. The crop coefficients for the growing season followed a similar pattern, peaking at 2.3 in May, before dropping back to below 1 for June, July and August. As detailed already this appears to be as a result of low water levels in the willow system. The ET_{willow} rates for the dormant months ranged from 0.2 mm/day for January to 1.0 mm/day for February and March. The February rate resulted in a crop coefficient value of 1.9 for the month.

The total measured ET_{willow} for the monitored period was 537 mm, which was determined from 159 days of evapotranspiration data. The corresponding ET_o was 451.1 mm, resulting in an overall crop coefficient of 1.2. The total assumed evapotranspiration from the willow system was 592.5 mm, which resulted in an overall K_c of 1.17 for the period.

5.3.7.4 Yearly Comparison

The ET_{willow} rates for system 2 on Site F followed the expected pattern of increasing year on year, as the willow trees developed, for 2011 to 2012, but the trend did not continue on for 2013 (Figure 5.68). The increase from 2011 to 2012 occurred for all months except April. As discussed previously, the decrease in evapotranspiration for most of the growing season in 2013 was probably as a result of the low water level within the system, reducing the water availability to the willows.

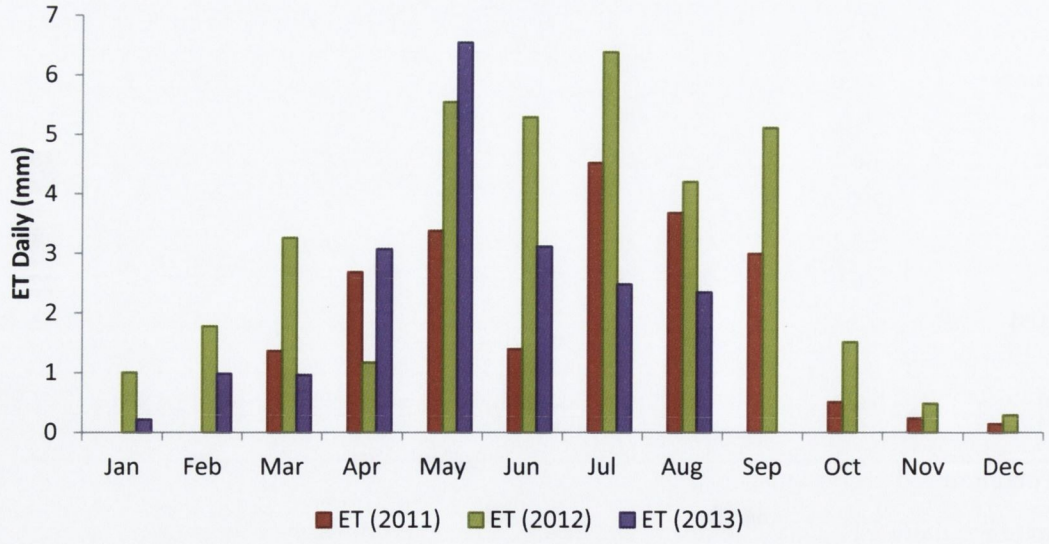


Figure 5.68 Yearly comparison of mean daily ET_{willow} rates for System 2 on Site F

The same pattern applied to the crop coefficients (Figure 5.69). The values were generally higher in 2012 compared to 2011 with the exception of April and August. Similarly, the 2013 K_c values started off higher for the first two months of the growing season, before dropping off for the remainder of the summer.

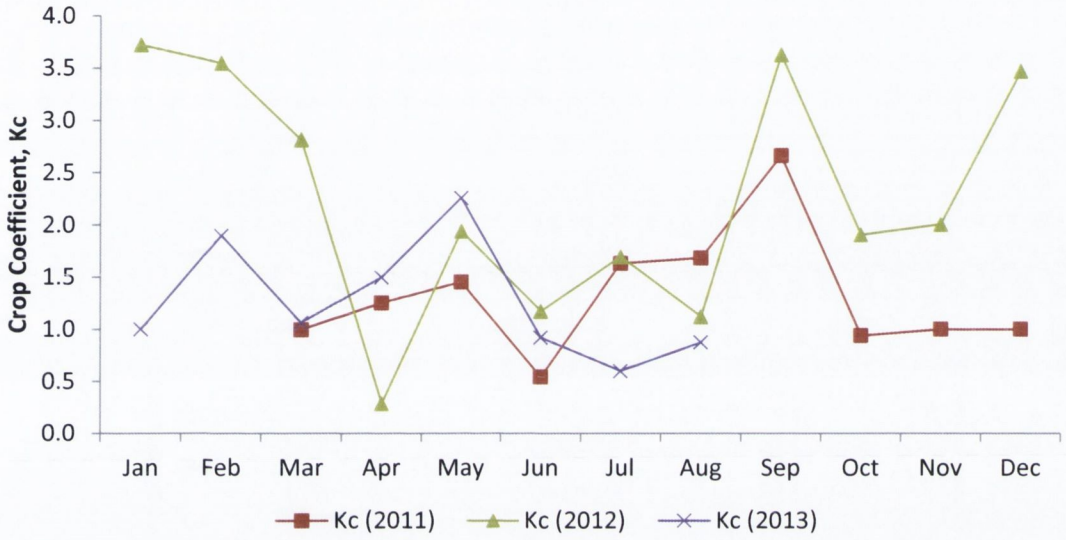


Figure 5.69 Yearly comparison of monthly K_c values for System 2 on Site F

5.3.8 Site G Ardcavan

Monitoring of water levels within the willow system on Site G commenced on 13th May 2011. The system employed a clay liner and was designed with a specified depth of 1.8 m. However, it was discovered that there was an overflow point at 1.71 m where upon any further increase in level resulted in water escaping through one of the sides of the system.

Willow growth was quite poor on the site with approximately two thirds of the planted cuttings failing to become established. Replanting was carried out in 2012 and 2013 with new cuttings in an effort to attain the desirable planting density on the system. There was a noticeable lack of topsoil at the surface of the willow system after construction, which may have been a factor in the poor willow development. The lack of suitable soil in which to plant the willow cuttings was compounded by the absence of effluent flow on the site, meaning that there were likely very little nutrients available to the willow trees to aid establishment and development. The willow system on Site G was supposed to receive secondary treated effluent, but as detailed in Section 4.3.6 no one moved into the house on the site, so effluent loading has been negligible to

date. The usable water volume storage in the soil on Site G was 9.6% (as detailed in Section 4.5.4).

5.3.8.1 2011 Evapotranspiration

The water level within the system and the daily rainfall at the site is shown in Figure 5.70. It can be seen from the water level in November and December that the water left the system via the overflow at a slow rate, as it appeared that it was percolating through the less compacted clay sides at the top of the willow system rather than having a quick escape route over the top like some of the other systems.

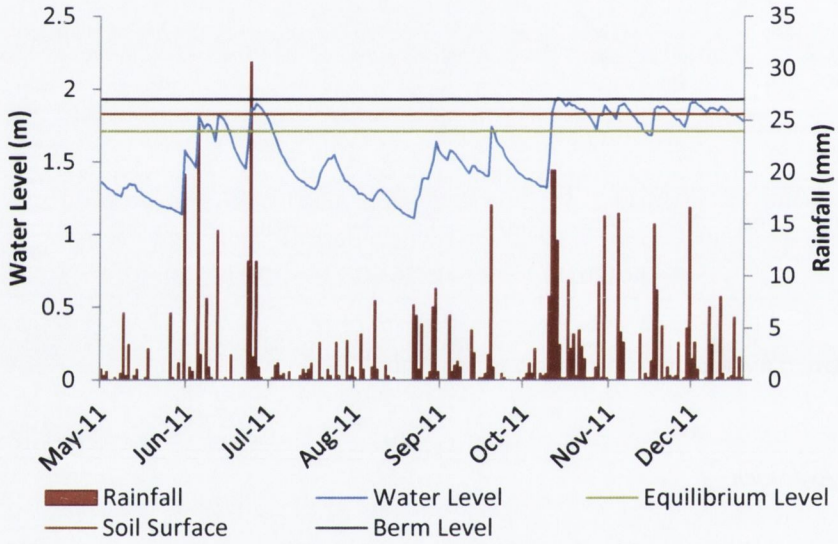


Figure 5.70 Water level and daily rainfall for 2011 (Site G)

The total monthly ET_{willow} and the corresponding ET_o are shown in Figure 5.71. The mean daily ET_{willow} rates were relatively consistent during the growing season, ranging between 1.4 mm/day (September) to 3.0 mm/day (July). The K_c values ranged from 0.7 (June) to just under 1.00 (0.97, 0.9, 0.95) for the months up until and including September before increasing notably to 2.6 for October (Table 5.26). This dropped down to 0.4 for November and 0.1 for December.

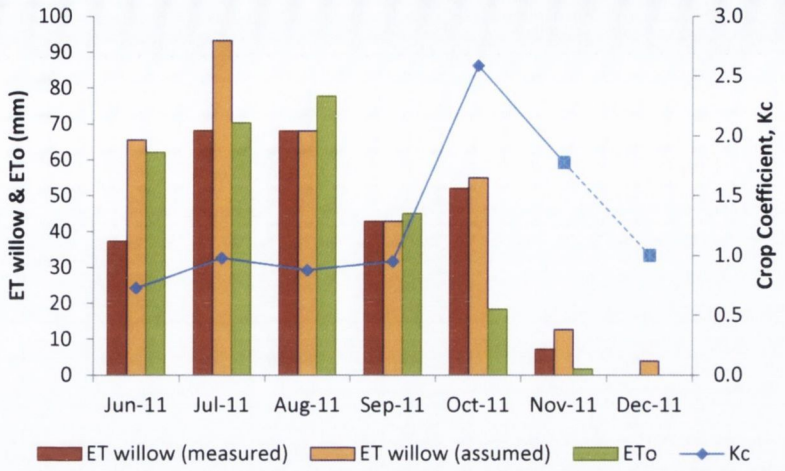


Figure 5.71 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2011)

Table 5.26 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2011)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
June	37.3	65.5	90.2	19	2.0	0.7
July	68.1	93.2	95.4	23	3.0	1.0
August	68.0	68.0	77.7	31	2.2	0.9
September	42.8	42.8	45.0	30	1.4	1.0
October	52.0	54.9	21.2	21	2.5	2.6
November	7.2	12.6	7.1	3	0.4	1.8
December	0.0	3.9	3.9	0	0.1	1.0
Total	275.5	341.1 (TR = 512)	340.5	127	2.2 (1.6)	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total ET_{willow} for the months June to December was 275.5 mm which was from 127 days of data. This resulted in a mean daily ET_{willow} of 2.2 for the days monitored. The corresponding ET_o for those days was 274.9 mm, which gave an overall K_c of just over 1.0. The total assumed measured ET_{willow} for the monitored period was 341.1 mm, which resulted in a crop coefficient of 1.0 for the entire period.

5.3.8.2 2012 Evapotranspiration

As can be seen in Figure 5.72 the water level remained above the overflow level for large periods of the growing season. This resulted in relatively low ET_{willow} totals being determined.

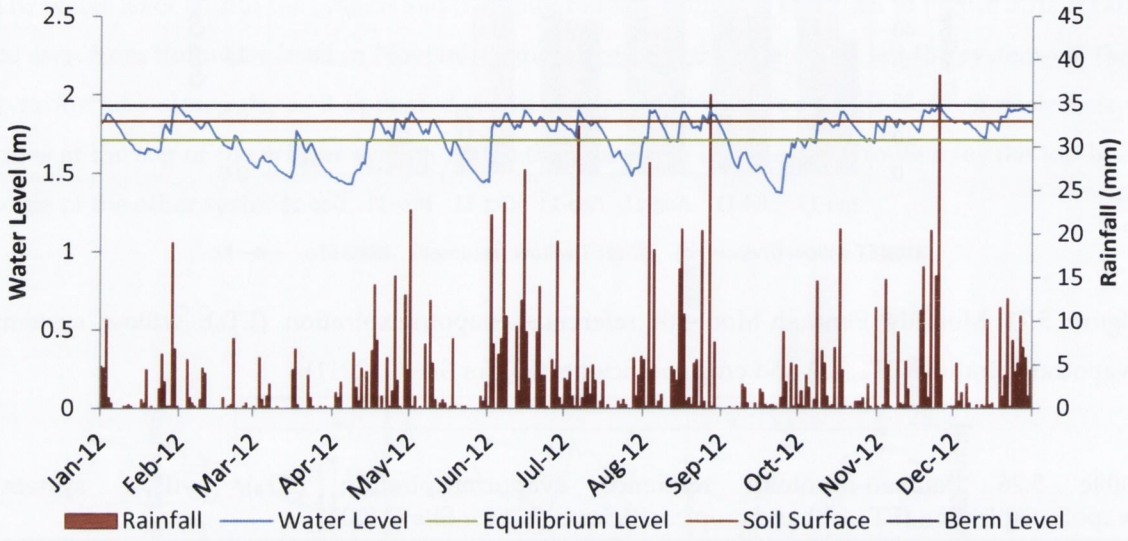


Figure 5.72 Water level and daily rainfall for 2012 (Site G)

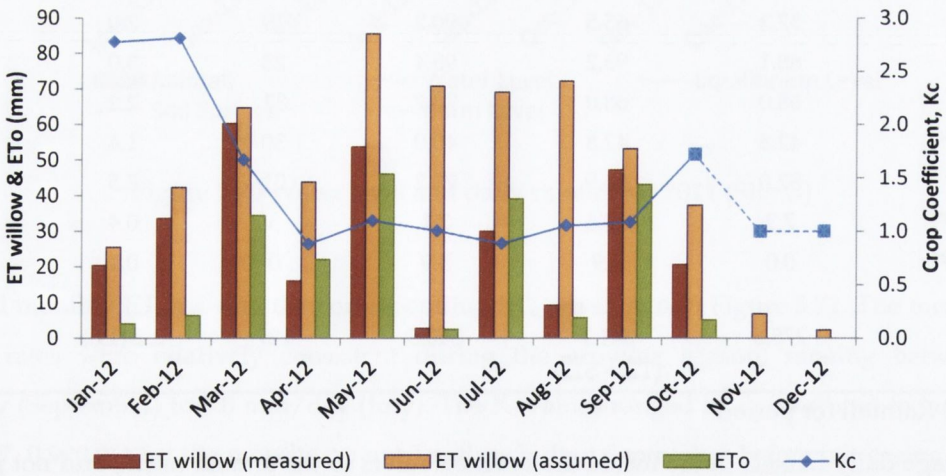


Figure 5.73 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2012)

As can be seen in Table 5.27 the mean daily ET_{willow} rates ranged from 1.1 mm/day (April) to 4.7 mm/day (August) for the growing season. The K_c values for the growing season varied from 0.9 (April) to 1.7 (October). The non-growing season produced surprisingly high willow

evapotranspiration results. The mean daily ET_{willow} varied from 0.1 mm/day (December) to a high of 1.5 mm/day (February). These rates resulted in K_c values of 1.0 and 2.8 for the 2 months, respectively.

The total ET_{willow} for the days 132 days of evapotranspiration data was 294.0 mm. This resulted in a mean daily ET_{willow} of 2.2 mm/day for those days. The ET_o was 208.6 resulting in a K_c value of 1.4. The total assumed ET_{willow} for the year was 573.7 mm, which gave an annual K_c of 1.2.

Table 5.27 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2012)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	20.4	25.5	9.2	13	0.8	2.8
February	33.6	42.2	15.0	10	1.5	2.8
March	60.3	64.7	38.8	28	2.1	1.7
April	16.1	43.9	49.9	14	1.1	0.9
May	53.7	85.6	77.9	16	3.4	1.1
June	2.7	70.8	70.5	1	2.7	1.0
July	30.0	69.1	78.2	14	2.1	0.9
August	9.3	72.2	68.6	2	4.7	1.1
September	47.3	53.2	49.1	27	1.8	1.1
October	20.7	37.3	21.7	7	3.0	1.7
November	0.0	6.9	6.9	0	0.2	1.0
December	0.0	2.3	2.3	0	0.1	1.0
Annual	294.0	573.7 (TR = 1149)	488.2	132	2.2 (1.6)[2]	1.2

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.8.3 2013 Evapotranspiration

The 2013 growing season resulted in a considerable drop in the water level within the willow system (see Figure 5.74). However, the slowdown in the rate of the decrease as the level gets lower is also evident, especially towards the end of July. The significant increase in water level in response to rainfall events is also very apparent, highlighting the low usable water volume storage in the soil on the site.

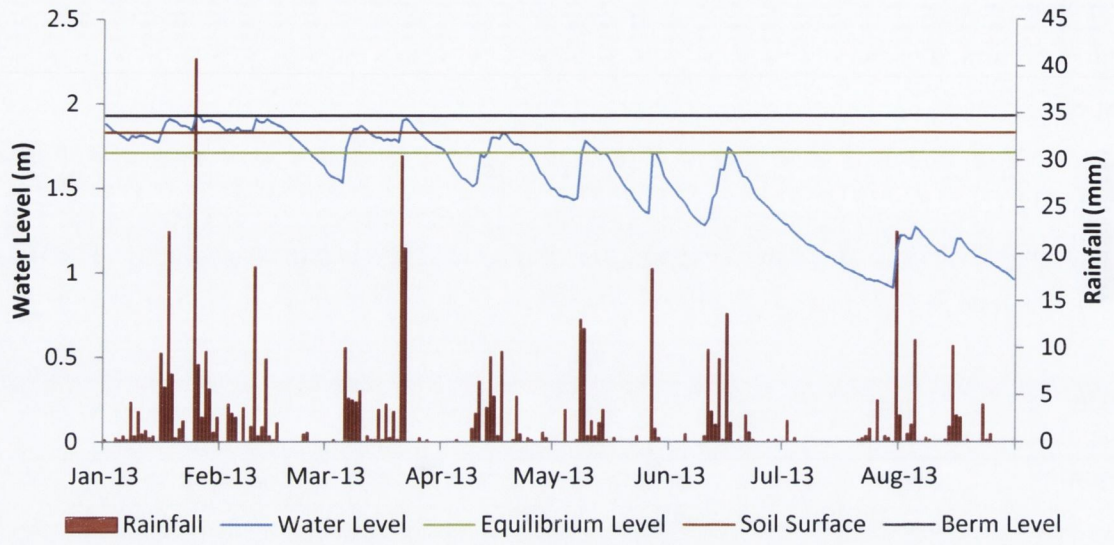


Figure 5.74 Water level and daily rainfall for 2013 (Site G)

There was a steady decline in evapotranspiration from the willow system during the growing season. The mean daily ET_{willow} was 1.7 mm/day for April, and increased steadily to 2.7 mm/day in July, before dropping off again to 2.2 mm/day in August. The crop coefficients decreased from 1.2 in April to 0.5 in July, before increasing slightly to 0.8 in August (Figure 5.75). The highest crop coefficient of the dormant season occurred in February with a value of 1.6.

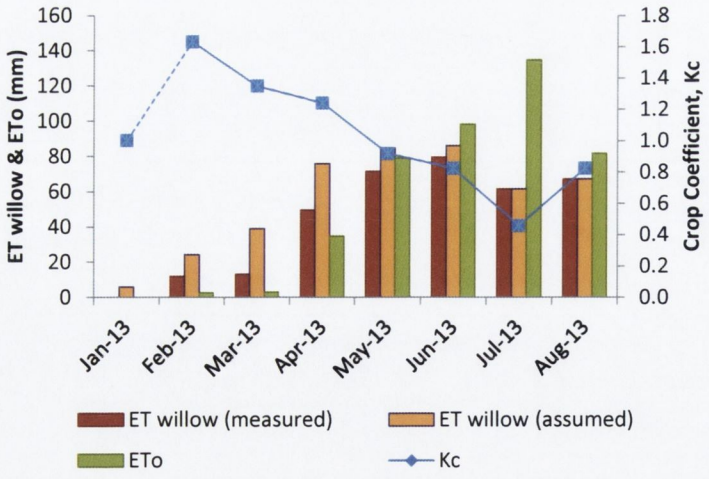


Figure 5.75 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2013)

The total measured ET_{willow} for the monitored period was 354.4 mm. The corresponding ET_o, which was based on 137 days of data was 431.37 mm resulting in an overall K_c of 0.82 (Table 5.28) The total assumed ET_{willow} for the period was 417.88 mm resulted in a crop coefficient of 0.8 for the period.

Table 5.28 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site G (2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
January	0.0	5.9	5.9	0	0.2	1.0
February	12.0	24.3	14.9	4	0.9	1.6
March	13.2	39.0	28.9	5	1.3	1.3
April	49.5	75.9	61.3	17	1.7	1.2
May	71.4	84.8	92.3	25	2.3	0.9
June	79.7	86.1	104.7	28	2.7	0.8
July	61.5	61.5	134.6	31	2.0	0.5
August	67.2	67.2	81.7	31	2.2	0.8
Total	354.4	444.8 (TR = 497)	524.4	141	2.5 (1.8)[2]	0.8

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.8.4 Yearly Comparison

There was no clear trend of a year on year increase in evapotranspiration rates on Site G (see Figure 5.76). The most noticeable examples were the increase in daily mean ET_{willow} for June, August, September and October between 2011 and 2012.

The crop coefficients followed a very similar pattern with 2012 values higher in general than 2011 values, and then a decrease in 2013 values (Figure 5.77). It is noticeable that the growing period was bookended by high crop coefficients during the dormant winter months in many instances across the three years. This may have been as a result of water escaping via infiltration through the clay liner, and is analysed in more detail in Section 8.11.

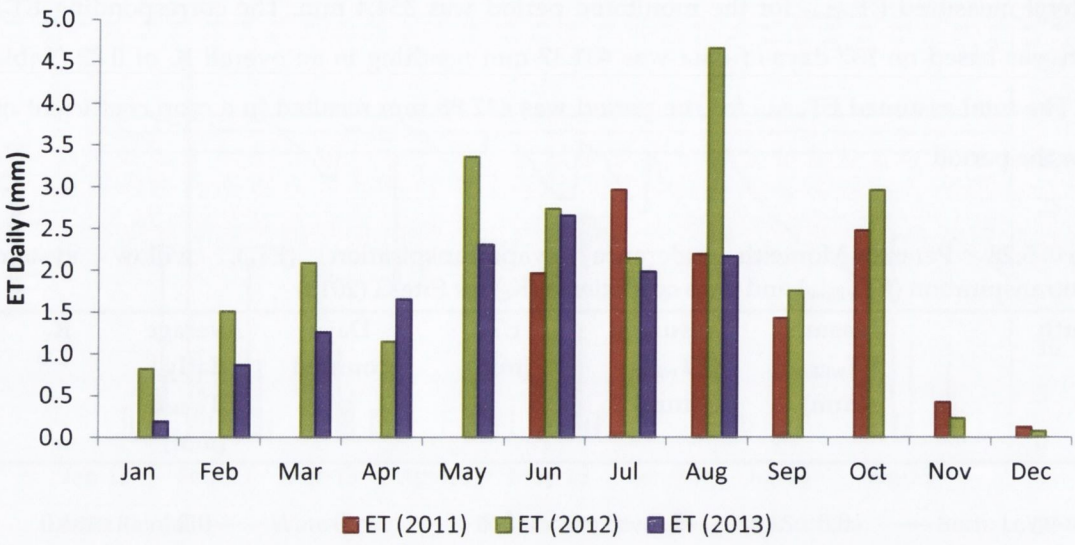


Figure 5.76 Yearly comparison of mean daily ET_{willow} rates for Site G

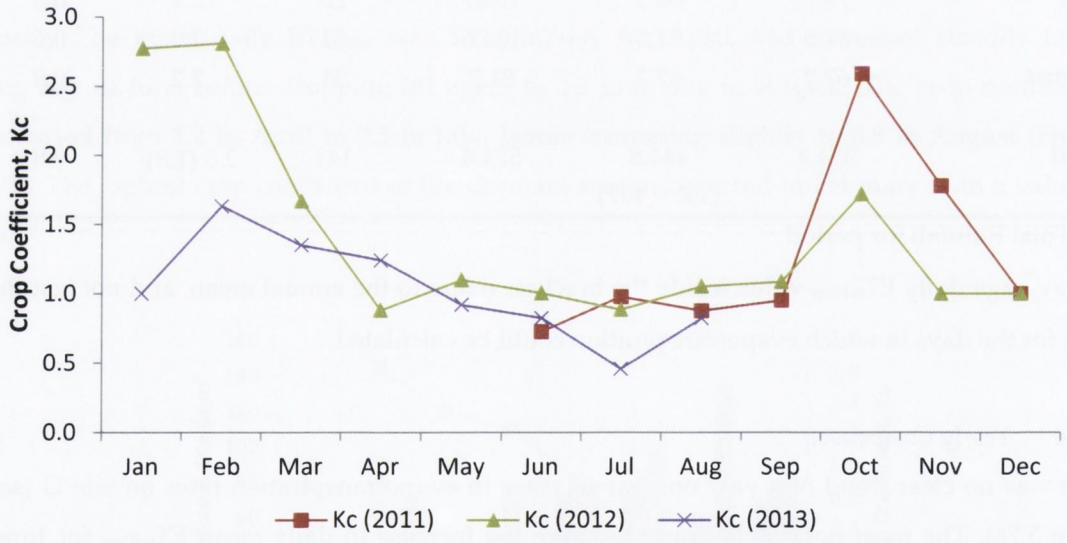


Figure 5.77 Yearly comparison of monthly K_c values for Site G

5.3.9 Site H Duncormick

Measurement of water within the two willow systems on Site H started on 13th March 2013 and continued until August 31st 2013. Because the total monitoring period was quite short (approximately 18 months), it was decided to present the results from 2012 and 2013 from each system together, rather than do an individual set of results for each year. There was no overflow from either system given that the top surface of both systems was at least one metre below

finished ground level on the site. Both systems were pumped out at the beginning of the monitoring period to minimise any surface flooding that might occur. The willow cuttings were planted in August 2011 on both systems.

However, there was data loss of water levels on both systems due to significant flooding on the surface over the winter period, which resulted in part of the water level meters becoming submerged and hence causing malfunction. Both systems were pumped out over an extended period between January and March 2013 to help aid against possible rotting of the newly planted willow cuttings. The willow systems on Site H received septic tank effluent from March 2012 onwards. The usable water volume storage was determined to be 9.5% for both systems (see section 4.5.4).

5.3.9.1 Willow System 1 – 2012/2013 Evapotranspiration

Although the design height of the willow system (excluding the berm) was 1.8 m, it can be seen in Figure 5.78 that it is somewhat short of this at 1.6 m. It seems probably that this occurred due to compaction of the refilled soil in the system. Despite being pumped out before monitoring, the water level climbed back up to the surface within two months due to the hydraulic loading from rainfall and effluent production. There was a decrease in water level in May/June but the surface of the system was flooded for much of the remainder of the summer. There was a significant period of data loss from November to April, although evapotranspiration rates could not have been determined for much of the start of 2013 anyway, as continuous pumping out of the system was taking place.

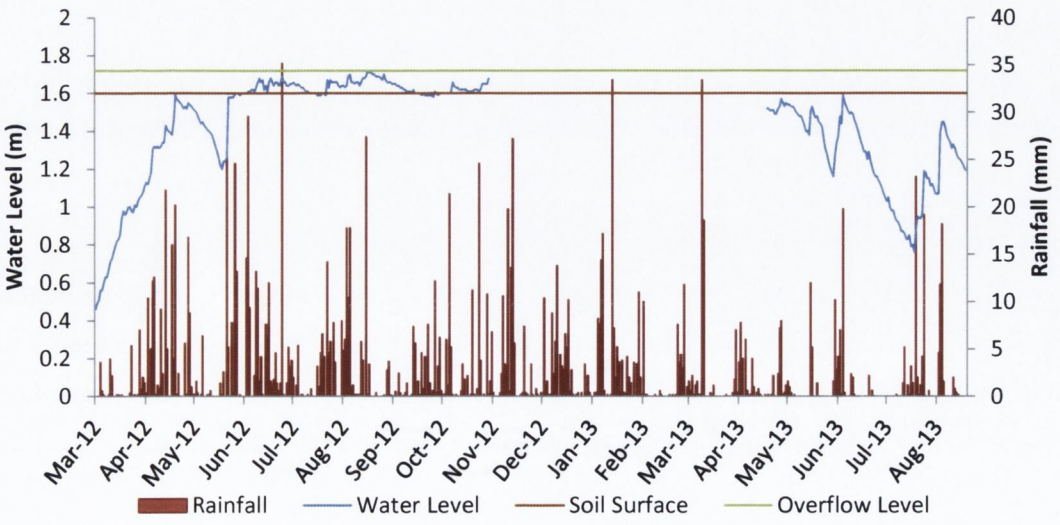


Figure 5.78 Water level and daily rainfall for System 1 on Site H (March 2012 – August 2013)

The mean daily ET_{willow} rates ranged from 2.5 mm/day (April) to 4.92 (September) for the 2012 growing season (Table 5.29). The corresponding crop coefficients followed the expected trend of increasing throughout the season until August/September (1.5 in April; 2.9 in September) but then increased markedly again to 5.5 in October. The mean daily ET_{willow} dropped to 0.2 mm/day (K_c = 0.9) for November before malfunction (and resultant data loss) of the water level meter occurred.

The evapotranspiration rates from the system decreased for 2013. The mean daily ET_{willow} was 2.3 mm/day for May, increasing to 3.4 mm/day in July, before dropping off again in August. The K_c values were also considerably lower compared to 2012, remaining below 1 for all months monitored.

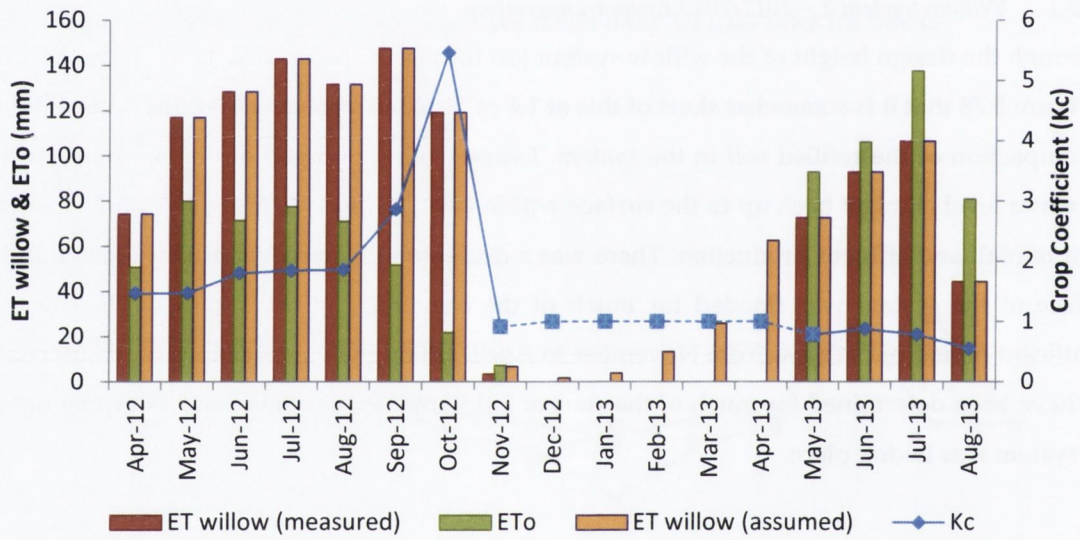


Figure 5.79 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site H (April 2012 - August 2013)

The total measured ET_{willow} for the months monitored in 2012 was 864.2 mm. The corresponding ET_o was 430.9 mm, resulting in a K_c of 2.0. The total assumed ET_{willow} (which assumed a rate equal to reference evapotranspiration occurring on the days in which there were no water levels recorded) was 869.1 mm, which also gave an overall crop coefficient of 2.0.

The total measured ET_{willow} for the monitored period in 2013 was 316.1 mm, which when divided by the ET_o of 417.1 mm resulted in a comparatively low K_c of 0.76. The total assumed ET_{willow} was 421.5 mm, which gave an overall crop coefficient of 0.8.

Table 5.29 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site H (April 2012 - August 2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
2012						
April	74.1	74.1	50.7	30	2.5	1.5
May	117.0	117.0	79.8	31	3.8	1.5
June	128.4	128.4	71.3	30	4.3	1.8
July	142.8	142.8	77.4	31	4.6	1.8
August	131.6	131.6	70.9	31	4.2	1.9
September	147.6	147.6	51.6	30	4.9	2.9
October	119.2	119.2	21.8	31	3.8	5.5
November	3.4	6.7	7.3	10	0.2	0.9
December	0.0	1.7	1.7	0	0.1	1.0
2013						
January	0.0	3.7	3.7	0	0.1	1.0
February	0.0	13.4	13.4	0	0.5	1.0
March	0.0	25.8	25.8	0	0.8	1.0
April	0.0	62.5	62.5	1	2.1	1.0
May	72.5	72.5	92.7	31	2.3	0.8
June	92.8	92.8	106.2	30	3.1	0.9
July	106.5	106.5	137.4	31	3.4	0.8
August	44.3	44.3	80.9	31	1.4	0.5
Total	1180.2	1290.7 (TR = 1450)	955.2	518	3.0 (2.5)[2]	1.4

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.9.2 Willow System 1 - Yearly Comparison

The expected increase in evapotranspiration from the willow system in 2013 (compared to 2012) did not materialise (see Figure 5.79). This was despite a relatively warm and dry growing season. The reason for this would seem to be due to a decrease in water available to the willow

trees. Much of the surface of the willow system was flooded for large periods of the 2012 summer compared to the 2013 summer, which saw water levels dropping to close to 0.8 m from the surface. The evaporation from the open water combined with the evapotranspiration from the willows and soil surface resulted in higher overall evapotranspiration from the system in 2012 even though the trees would have been smaller and not as developed compared to 2013.

5.3.9.3 Willow System 2 – 2012/2013 Evapotranspiration

As illustrated in Figure 5.80 the depth of the willow system (excluding the berm) was at the specified design height of 1.8 m. Similarly to system 1 it can be seen that the water level rebounded back up pretty quickly following the initial pumping out before monitoring began. There was also a drop in water level in May/June, although the soil surface was flooded for much of the remainder of the year. There was some data loss from November to January, with pumping out of the system carried out from January until the end of March.

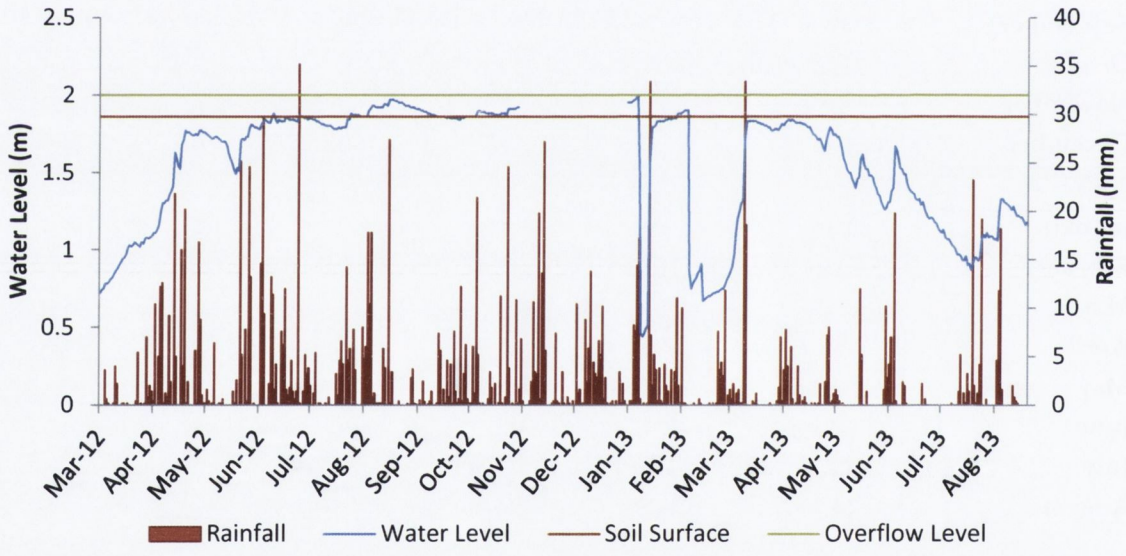


Figure 5.80 Water level and daily rainfall for System 2 on Site H (March 2012 – August 2013)

The mean daily ET_{willow} rates ranged from 0.99 mm/day in April to a high of 5.83 mm/day in June, before dropping off to 3.54 mm/day in October (Table 5.30). The corresponding crop coefficients (see Figure 5.81) ranged from 0.59 (April) to a significant high of 5.03 (October). The daily mean for the first 10 days of November was 1.46 mm/day which produced a correspondingly high crop coefficient of 2.01.

Similarly to system 1, there was a drop in evapotranspiration rates in 2013. The daily mean ET_{willow} ranged from 1.06 mm/day in March to a high of 3.37 mm/day in July. The K_c values were also low, starting just above 1 before dropping off continuously to 0.64 in August.

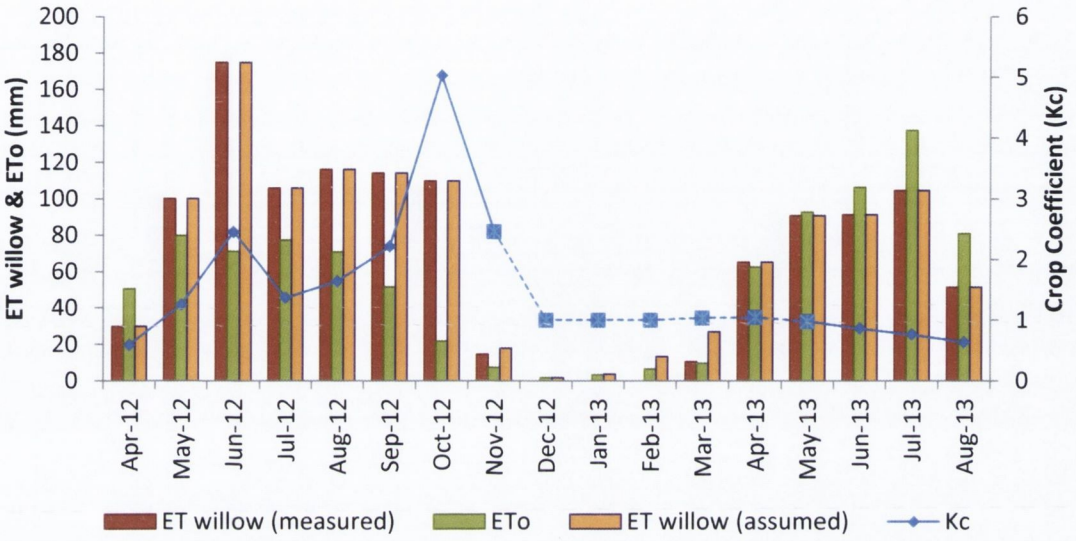


Figure 5.81 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site H (April 2012 - August 2013)

The total measured ET_{willow} for the months monitored in 2012 was 765.5 mm. The corresponding ET_o was 432.6, resulting in a K_c of 1.8. The total assumed ET_{willow} (which assumed a rate equal to reference evapotranspiration occurring on the days in which there were no water levels recorded) was 770.5 mm, which also gave an overall crop coefficient of 1.8.

The total measured ET_{willow} for the monitored period in 2013 was 414.0 mm, which when divided by the ET_o of 499.1 mm resulted in a comparatively low K_c of 0.8. The total assumed ET_{willow} was 447.4 mm, which gave an overall crop coefficient of 0.9.

Table 5.30 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site H (April 2012 - August 2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
2012						
April	29.8	29.8	50.7	30	0.99	0.6
May	100.0	100.0	79.8	31	3.23	1.3
June	174.9	174.9	71.3	30	5.83	2.5
July	105.9	105.9	77.4	31	3.41	1.4
August	116.2	116.2	70.9	31	3.75	1.6
September	114.3	114.3	51.6	30	3.81	2.2
October	109.8	109.8	21.8	31	3.54	5.0
November	14.6	17.9	7.3	10	0.60	2.5
December	0.0	1.7	1.7	0	0.05	1.0
2013						
January	0.0	3.7	3.7	0	0.12	1.0
February	0.0	13.4	13.4	0	0.48	1.0
March	10.6	26.8	25.8	10	0.87	1.0
April	65.3	65.3	62.5	30	2.18	1.0
May	90.7	90.7	92.7	31	2.93	1.0
June	91.4	91.4	106.2	30	3.05	0.9
July	104.5	104.5	137.4	31	3.37	0.8
August	51.5	51.5	80.9	31	1.66	0.6
Total	1179.5	1217.8 (TR = 1450)	955.2	387	3.0 (2.4)[2]	1.3

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.9.4 Willow System 2 – Yearly Comparison

As with System 1, there was no increase in evapotranspiration from system 2 in the second year of monitoring probably due to the same reason. The open water on the surface of the willow system in the 2012 growing season was removed at a quicker rate by evapotranspiration compared to the water in 2013 which dropped well below the surface for much of the growing season.

5.3.10 Site I Carrigallen (Co. Leitrim)

Measurement of water levels within the willow systems on Site I commenced on the 31st March 2012. The evapotranspiration rates calculated for the system are detailed from the start date to the end of the monitoring period in August 2013. The two willow systems were designed to a specification height of 1.8 m (as detailed in Section 3.3.3). An overflow channel was constructed on both systems in May 2012 to allow surface water that had collected over the previous winter to escape. This was carried out to help prevent rotting of the newly planted willow cuttings. The overflow levels will be detailed for each system individually further on in this section.

As with the other willow systems with an overflow level, the evapotranspiration could not be confidently determined once the water level went above the point of overflow. The willow systems were also drained throughout the 2012/2013 winter period. This was done with the intention of making more storage available within each system to cater for the effluent from the dwelling which was discharged into the systems from November 2012 onwards (when the family moved into the house). It was thought that removing hydraulic load from the system at an early stage would have a negligible effect on the surrounding environment as it would be consist almost entirely of rainfall.

Poor establishment and growth of the willow clones was a major problem on the two willow systems. The cause of this appeared to be due to lack of topsoil near the surface of the willow systems for the cuttings to root in. This reasoning is backed up by the favourable establishment and growth rate of cuttings along one side of willow system 1 where there was topsoil at the surface. The effect of this issue on the evapotranspiration rates attained is detailed for each system. Both systems received secondary treated effluent from November 2012 onwards. The usable water volume in the soil was 16% for system 1 and 20% for system 2 (as detailed in Section 4.5.4), suggesting that more of the topsoil from the site was refilled into system 2.

5.3.10.1 Willow System 1

The water level and rainfall for the monitoring period April 2012 to July 2013 is shown in Figure 5.82. The graph also includes the constructed overflow point of 1.63 m. The drainage of the willow system throughout the winter period can be seen. These efforts showed a somewhat limited result, with the water level requiring just 20 days in February 2013 to reach the overflow point after being drained to a depth of 0.56 m. This suggests that while the level within the inspection well was being lowered, perhaps this level was not representative of the true overall

level within the system (i.e. the rate of infiltration from soil to inspection well was less than the rate of removal of water from the system).

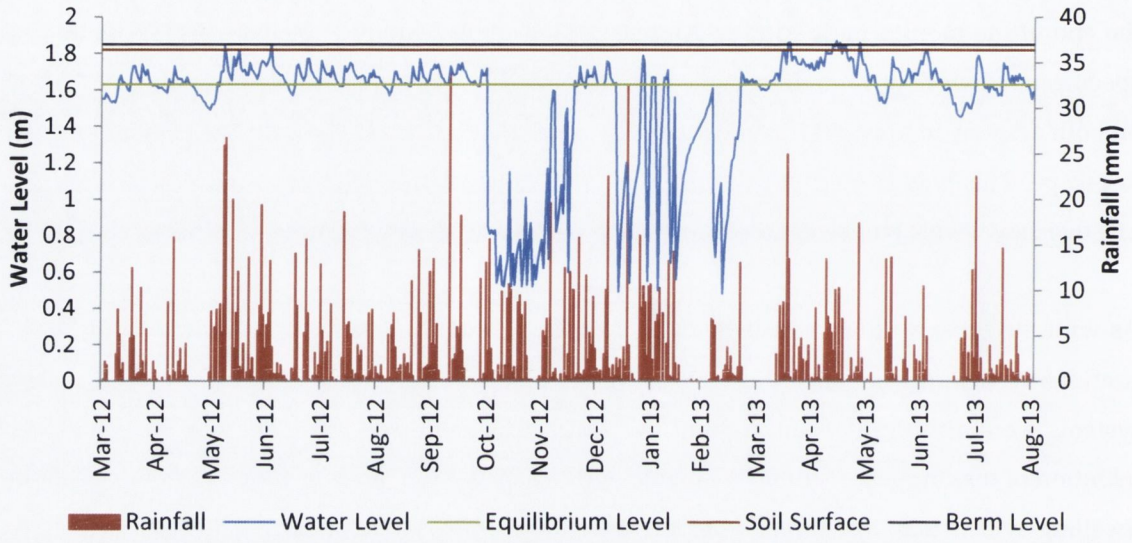


Figure 5.82 Water level and daily rainfall for System 1 on Site I (April 2012 - August 2013)

The monthly evapotranspiration rates for willow system 1, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Figure 5.83 and Table 5.31. The evapotranspiration rates were quite low overall due to the poor willow establishment detailed at the start of this section. The mean daily ET_{willow} rates ranged from 1.5 mm/day (October) to 3.3 mm/day (September) for the 2012 growing season. The calculated crop coefficients ranged from 0.91 (June) to 1.25 (September). Neither the mean daily evapotranspiration nor the crop coefficient followed any discernible pattern, as illustrated in Figure 5.83. Also, both were determined from a low number of days for many of the months due to the water level being over the overflow point.

The evapotranspiration rates did increase somewhat in 2013. The mean daily ET_{willow} ranged from 1.6 mm/day in April to 5.9 mm/day in August. The crop coefficients ranged from 1.0 in July to 1.6 in August. Neither the ET_{willow} nor the crop coefficient followed any recognisable pattern throughout the growing season.

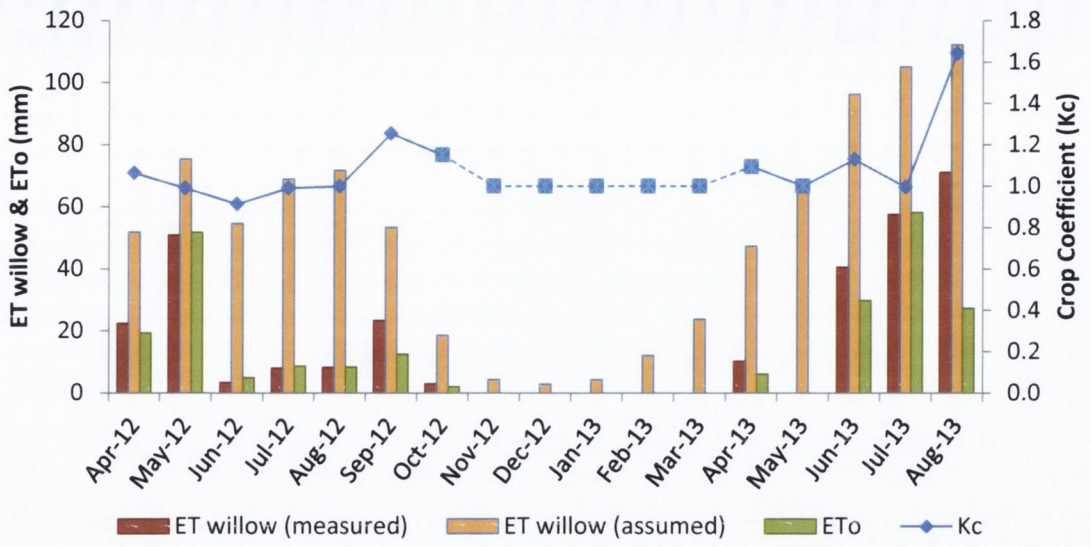


Figure 5.83 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site I (April 2012 - August 2013)

The total measured ET_{willow} for the months monitored in 2012 totalled 119.0 mm and was based on 49 days of evapotranspiration. This corresponded to a total reference evapotranspiration of 107.4 mm for the same days and an overall crop coefficient of 1.1 for the monitoring period. The total assumed ET_{willow} was 401.48 mm, which resulted in an overall crop coefficient of 1.0 for the period.

The total measured ET_{willow} for the monitored period in 2013 was 179.3 mm, which when divided by the ET_o of 121.2 mm resulted in a K_c of 1.5. The total assumed ET_{willow} was 467.1 mm, which resulted in an overall crop coefficient of 1.1 for the period.

Table 5.31 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 1 on Site I (April 2012 - August 2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
2012						
April	22.4	51.9	48.8	13	1.7	1.1
May	50.9	75.3	76.2	18	2.8	1.0
June	3.4	54.7	59.8	2	1.7	0.9
July	8.0	68.9	69.6	4	2.0	1.0
August	8.1	71.7	71.9	3	2.7	1.0
September	23.3	53.4	42.6	7	3.3	1.3
October	3.0	18.5	16.1	2	1.5	1.2
November	0.0	4.3	4.3	0	0.1	1.0
December	0.0	2.8	2.8	0	0.1	1.0
2013						
January	0.0	4.3	4.3	0	0.1	1.0
February	0.0	12.1	12.1	0	0.4	1.0
March	0.0	23.8	23.8	0	0.8	1.0
April	10.2	47.3	43.3	6	1.6	1.1
May	0.0	66.1	66.1	0	2.1	1.0
June	40.6	96.2	85.2	8	3.2	1.1
July	57.5	105.0	105.7	18	3.2	1.0
August	71.1	112.2	68.4	21	5.9	1.6
Total	298.38	868.6 (TR = 1643)	801.0	93	3.2 (1.7)[2]	1.1

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.10.2 Willow System 1 – Yearly Comparison

A general increase in evapotranspiration from system 2 did occur between corresponding months in 2012 and 2013. While the April mean daily ET_{willow} rate did remain quite similar, June, July, and August all saw significant increases (see Table 5.31).

5.3.10.3 Willow System 2

The water level and rainfall for the monitoring period, as well as the overflow level of 1.64 m is shown in Figure 5.84. As with system 1, the pumped drainage carried out during the winter

period can be seen. Again, its effects were quite limited with the water level requiring just 30 days in February/March 2013 to reach the overflow level subsequent to being drained to a level of 0.19 m.

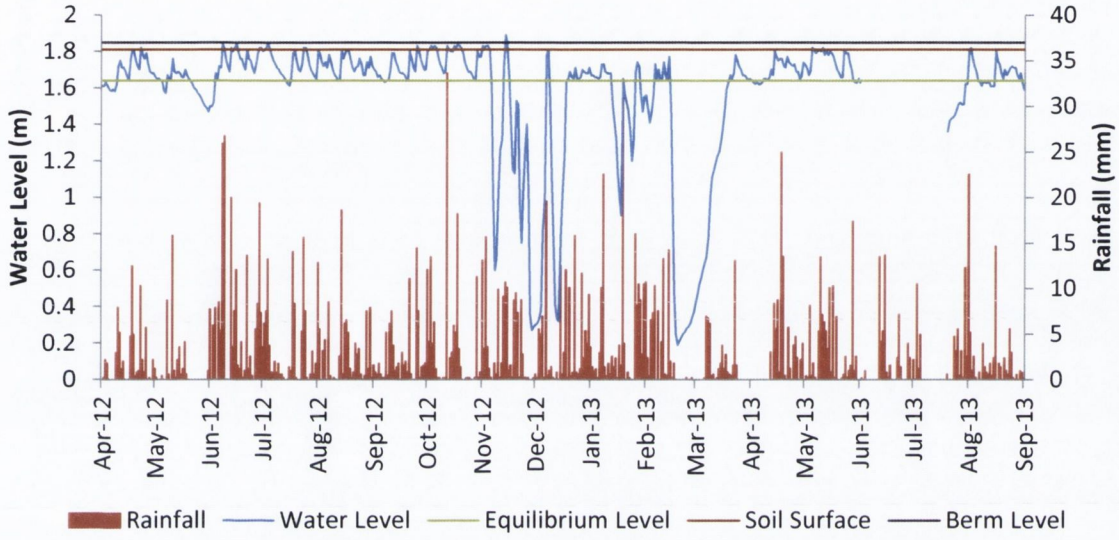


Figure 5.84 Water level and daily rainfall for System 2 on Site I (April 2012 - August 2013)

The monthly evapotranspiration rates for willow system 2, along with the Penman-Monteith reference evapotranspiration and the monthly crop coefficients are shown in Table 5.32. Similarly to willow system 1, the evapotranspiration results in 2012 are quite poor due to poor establishment of the willow clones at the site. The mean daily ET_{willow} rates ranged from 1.5 mm/day (April) to 4 mm/day (May) for the growing season. The calculated crop coefficients ranged from 0.9 (April) to 1.2 (May). Once again, neither the mean daily evapotranspiration nor the crop coefficient followed any discernible pattern throughout the season, as illustrated in Figure 5.85. The number of days in which the water level was below the overflow point was also very low, meaning that the determined evapotranspiration values were based on only a few days' data for many of the months.

The ET_{willow} rates for the 2013 growing season ranged from 1.2 mm/day in April to 5.1 mm/day in August. The crop coefficients were quite low at the start of the growing season, hovering just above 1 for most of the summer, before increasing to 1.4 in August.

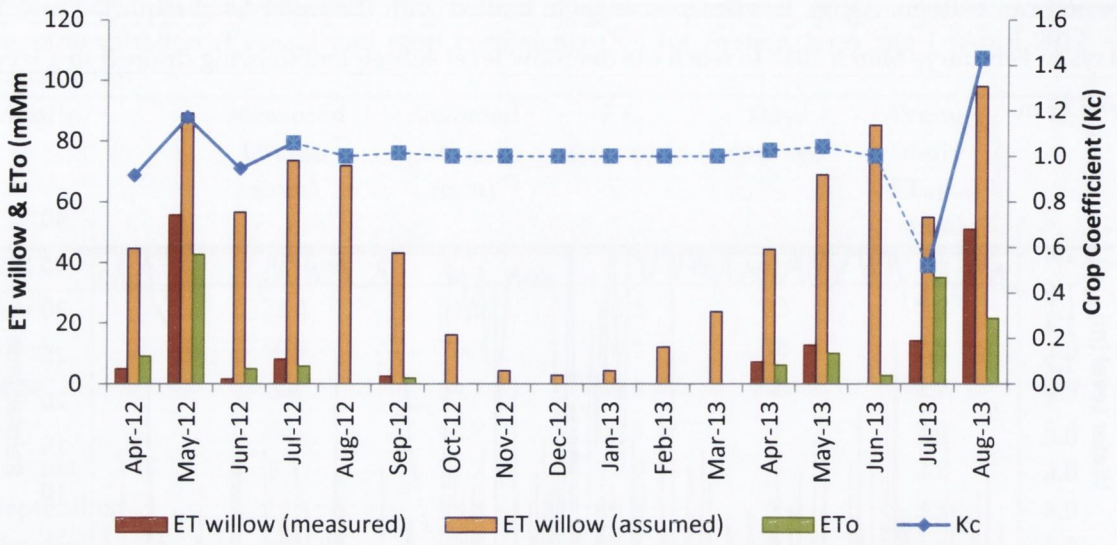


Figure 5.85 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site I (April 2012 - August 2013)

The total measured ET_{willow} for the months monitored in 2012 totalled 72.7 mm and was based on just 28 days of evapotranspiration. This corresponded to a total reference evapotranspiration of 64.2 mm for the same days and an overall crop coefficient of 1.1 for the monitoring period. The total assumed ET_{willow} was 402.3 mm resulted in an overall crop coefficient 1.0.

The total measured ET_{willow} for the monitored period in 2013 was 85.2 mm, which when divided by the ET_o of 75.37 mm resulted in a K_c of 1.13. The total assumed ET_{willow} was 391.6 mm gave an overall crop coefficient of 0.96.

5.3.10.4 Willow System 2 – Yearly Comparison

A general increase in mean daily ET_{willow} rates occurred between 2012 and 2013. The months of April, May, June all recorded increases in the mean evapotranspiration. The same months also registered increases in the crop coefficient.

Table 5.32 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for System 2 on Site I (April 2012 - August 2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
2012						
April	4.9	44.7	48.8	8	1.5	0.9
May	55.7	89.2	76.2	14	4.0	1.2
June	1.6	56.5	59.8	2	1.9	0.9
July	8.1	73.6	69.6	3	2.7	1.1
August	0.0	71.9	71.9	0	2.3	1.0
September	2.4	43.2	42.6	1	2.4	1.0
October	0.0	16.1	16.1	0	0.5	1.0
November	0.0	4.3	4.3	0	0.1	1.0
December	0.0	2.8	2.8	0	0.1	1.0
2013						
January	0.0	4.3	4.3	0	0.1	1.0
February	0.0	12.1	12.1	0	0.4	1.0
March	0.0	23.8	23.8	0	0.8	1.0
April	7.2	44.4	43.3	6	1.2	1.0
May	12.8	68.9	66.1	3	4.3	1.0
June	0.0	85.2	85.2	0	2.8	1.0
July	14.2	54.9	105.7	12	1.2	0.5
August	51.0	97.9	68.4	10	5.1	1.4
Total	157.9	773.8 (TR = 1643)	801.0	59	2.7 (1.5)[2]	1.0

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

5.3.11 Site J Ballylanders (Co. Limerick)

As monitoring of the site started late in 2012 (23rd November) the 2012 evapotranspiration results from the site will be presented together with the 2013 results. As detailed in Section 3.4.9 the willow system was designed by an external designer and had a specified depth of 1.5 m (excluding berm). An unforeseen complication occurred during construction when the ditch adjacent to one end of the willow system fell inwards, pulling the liner down. Unfavourable weather meant that this could not be remedied by the contractor until March 2013 (when the system was also partially pumped out). Failure to fully rectify this problem, coupled with a

non-completed berm on the other end of the system meant that there was an overflow at a height of 1.4 m, which coincided in height with the surface of the soil at the top of the system. The system received septic tank effluent from April 2013 onwards. The usable water volume in the backfilled soil in the willow system was 19% (see Section 4.5.4).

5.3.11.1 2012/2013 Evapotranspiration

There were no evapotranspiration data results obtained for over 3 months from the start of monitoring due to the water level being above the point of overflow (illustrated in Figure 5.86). There was a significant drop in water level during the warm, dry weather in June and July, however heavy rainfall at the end of July/start of August saw the water level rebound rapidly over the overflow point.

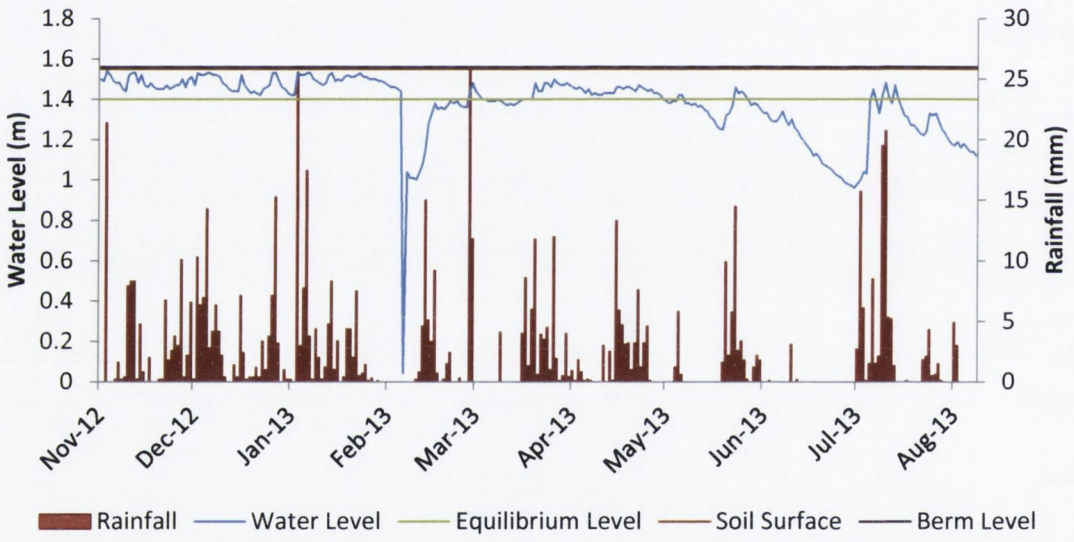


Figure 5.86 Water level and daily rainfall on Site J (November 2012 – August 2013)

The mean daily ET_{willow} rates ranged from 2 mm/day (April) to 6.5 mm (August) during the growing season. There was a general increasing trend as the season progressed, apart from July, which saw a slight drop from June's rate. This could be as a result of lack of water close to the surface for the root system of the willow trees to absorb easily, an occurrence that seems to have affected the evapotranspiration on many of the systems in 2013. The crop coefficients ranged from 1.1 in April to 3.8 in August for the growing season. They also followed a general increasing trend with the exception of July which saw a decrease on June's figure. The evapotranspiration rates ranged from 0.12 mm/day (January) to 1.9 mm/day (March) for the dormant season.

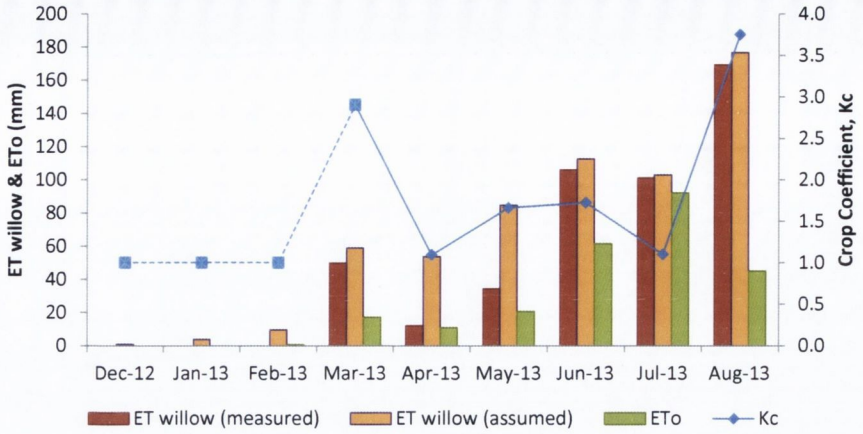


Figure 5.87 Monthly Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for Site J (November 2012 - August 2013)

Table 5.33 Penman-Monteith reference evapotranspiration (ET_o), willow system evapotranspiration (ET_{willow}) and crop coefficients (K_c) for on Site J (November 2012 - August 2013)

Month	Measured ET_{willow} (mm)	Assumed ET_{willow} (mm)	ET_o (mm)	Days counted	Average daily ET_{willow} (mm)	K_c
December	0.0	0.9	0.9	0	0.03	
January	0.0	3.7	3.7	0	0.12	
February	0.0	9.6	9.6	0	0.34	
March	50.0	58.8	21.9	14	1.90	2.9
April	12.0	53.9	52.8	6	2.00	1.1
May	34.4	84.7	71.0	7	4.92	1.7
June	106.0	112.5	68.0	25	4.24	1.7
July	101.3	102.9	93.7	29	3.49	1.1
August	169.5	176.8	52.5	26	6.52	3.8
Annual	473.3	603.8 (TR = 658)	374.0	107	4.4 (2.2)[2]	1.3

[1]TR: Total Rainfall for period

[2]The average daily ET_{willow} value inside the brackets refers to the annual mean, and not just the mean for the days in which evapotranspiration could be calculated.

The total measured ET_{willow} for the period monitored in 2013 was 473.3 mm. This was from 107 days of data, which had a corresponding ET_o of 248.2, resulting in an K_c of 1.91. The total

assumed ET_{willow} was 603.8mm which resulted in an overall crop coefficient of 1.3 for the monitored period.

5.4 Summary

5.4.1 Overview of Evapotranspiration Performance

The total assumed ET_{willow} for the monitored period in each calendar year for each willow system is shown in Table 5.34. It can be seen that there is quite an amount of variance between willow systems (even those in which the willow cuttings were planted in the same year). There are a multiple reasons for this including different amounts of overflow between systems (which meant varying amount of days in which the ET_{willow} could be actually determined), different effluent loadings, different soil porosities and different rates of establishment/development of the willow trees. Each of these factors will be analysed in more detail in Chapter 8. The highest ET_{willow} rates appear to be from Sites A, B and C, which would be expected as these sites undoubtedly had better willow tree development (also aided by effluent loading in the case of Sites A & C). The benefit of having no overflow from a system in terms of being able to determine ET_{willow} is also apparent; both systems on Site H had significantly high evapotranspiration totals in 2012 (864 mm and 771 mm respectively), especially considering it was the first full growing season.

Table 5.34 Total assumed ET_{willow} for each willow system

System	2010		2011		2012		2013	
	ET*	Months	ET*	Months	ET*	Months	ET*	Months
A	755	10	929	12	725	12	737	8
B	554	7	638	12	765	12	531	8
C	358	4	717	12	670	12	498	8
D	-	-	558	12	495	12	404	8
E	282	7	573	12	669	12	90	4
F (1)	-	-	511	10	595	12	398	8
F (2)	-	-	641	10	827	12	593	8
G	-	-	341	7	574	12	445	8
H (1)	-	-	-	-	864	9	422	8
H (2)	-	-	-	-	771	9	447	8
I (1)	-	-	-	-	402	9	467	8
I (2)	-	-	-	-	402	9	392	8
J	-	-	-	-	-	-	603	8

*Total assumed ET_{willow} for the monitored period in that year

5.4.2 *Overflow from the Willow Systems*

The number of days in which overflow from the system was deemed to have occurred out of the total monitored days is shown for each year in Table 5.35. It can be seen that overflow occurred on a significant amount of days for many of the sites across the four years. Most of the overflow would have occurred during the dormant season; however, a significant amount also occurred during the unseasonably wet summer in 2012. It is worth noting that there was no overflow from either of the systems on Site H. This was due to the manner in which both systems were constructed. The surface of the willow system was approximately one metre below the finished ground level on the site, which translated to having the equivalent of a one metre berm. However, both systems did require pumping out, as it was thought that a flooded surface could have a detrimental effect on the development of the willows. Generally, however, it can be seen that the willow systems were undersized in terms of capacity. The systems' apparent inability to cope with the heavy rainfall during summer 2012 was also noteworthy.

Table 5.35 Number of days that each willow system was overflowing per year

System	2010	2011	2012	2013
A	104/306	189/365	301/365	123/243
B	82/214	98/365	216/365	93/243
C	84/122	166/365	246/365	94/243
D	153/153	163/365	272/365	144/243
E	103/214	170/365	238/365	91/120
F (1)	-	94/306	225/365	98/243
F (2)	-	89/306	178/365	84/243
G	-	87/214	233/365	102/243
H (1)	-	-	0/365	0/365
H (2)	-	-	0/365	0/365
I (1)	-	-	226/275	199/243
I (2)	-	-	247/375	212/365
J	-	-	31/31	136/243

5.4.3 *Crop Coefficients*

It is interesting to note the high K_c values measured in October for the first three seasons, which are much higher than those reported in literature for the same month (Guidi et al., 2008 and Pistocchi et al., 2009). There are a number of reasons as to why this may be the case. There may have been some physical removal of water from leaf interception and by the wind, whereas normal evapotranspiration would not take this phenomenon into account. There may also have been some overflow of rainfall from the system, overflow which may not have been taken into account by the water balance equation. This would probably only have occurred during a large

rainfall event, where the soil within the system could not absorb the water quick enough, resulting in some loss over the side. It must also be remembered that all evapotranspiration results are subject to uncertainty due to soil porosity calculations. While every effort was made to ensure that porosity values were as accurate as possible, soil is heterogeneous by nature and porosity can vary from sample to sample.

The high crop coefficients may also be as a result of the relatively low reference evapotranspiration rates measured for October. The daily ET_o rates measured on Site A for the month of October ranged between 0.71 - 0.97 mm/day. This is significantly lower than the values recorded by Guidi et al. (2008) for the same month (1.58 - 1.75 mm/day). Lower reference evapotranspiration rates are obviously going to have the knock on effect of producing higher crop coefficients. An example in literature of a similar occurrence (although not as severe in effect) is shown by Pistocchi et al. (2009), in reporting ET_{willow} rates and crop coefficients for willows in a lysimeter experiment in Italy (Figure 5.88). It can be seen that there is a steady and relatively steep decline in ET_{willow} rates from September onwards. However, this does not translate to an equivalent decline in crop coefficients. The decrease in the K_c values from the end of September until the middle of November is much slower and there is even an increase for the final third of October compared to the middle third. This highlights the fact that late in the growing season when reference evapotranspiration rates are relatively low, it is the willows themselves rather than the meteorological conditions that influence ET_{willow} the most.

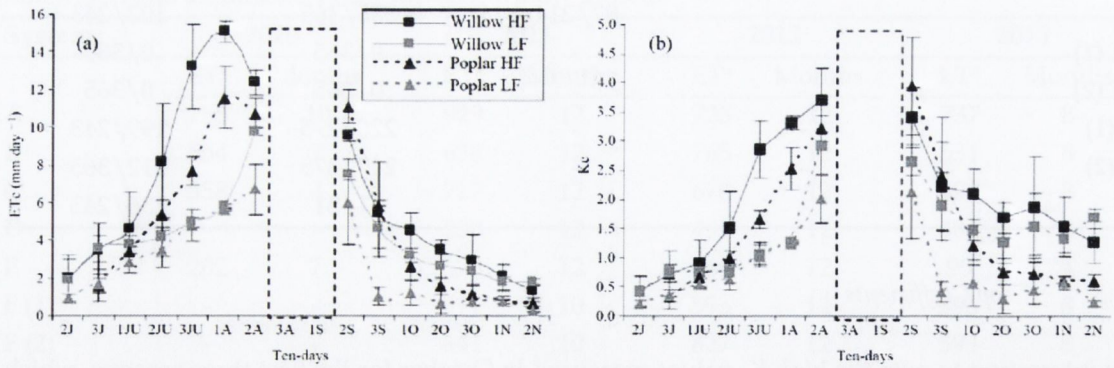


Figure 5.88 Ten-day average ET_{willow} rates (a) and crop coefficients (b) (adapted from Pistocchi et al,. 2009)

5.4.4 *Conclusions*

As expected, it was determined that the willow systems provide a much greater evapotranspiration potential in comparison to the reference evapotranspiration. However, it appears that zero discharge will be very difficult to achieve in an Irish climate. This is primarily due to the relatively high rainfall levels that occur.

As it appears that there will be some amount of overflow occurring from the systems, the next chapter will look to analyse the treatment performance of the systems with regards to the main pollutant mechanisms. Thus it can determined whether or not the overflow from the systems is a pollutant threat to the surrounding environment.

Chapter 6

Nutrients and Water Quality

6 Nutrients and Water Quality

6.1 Introduction

The design of willow systems for the treatment of on-site wastewater primarily focuses on the hydraulic aspects of the process. Although this is the most important factor, the treatment performance of the willow system in terms of nutrient uptake, organic uptake and salt accumulation also needs to be assessed. As shown in Chapter 7 (Mesocosm Chapter) as well as in multiple other studies (Martin and Stephens, 2006, Guidi et al., 2008, Pistocchi et al., 2009), there exists a strong correlation between nutrient availability growth rate, size of willow trees and most importantly, evapotranspiration.

As such this chapter examines the treatment efficiency of the willow systems on each site. Each willow system was assessed for the removal efficiency of organics, nitrogen, phosphorus, salts, and pathogenic bacteria. Reporting on parameter concentration alone is somewhat meaningless in the case of a closed system with a varying hydraulic capacity like a willow system. For example, there will be a greater amount of a particular nutrient in the willow system for any given concentration when the system is hydraulically full compared to when it is empty. So, in an effort to assess the removal efficiency by the willow trees, the cumulative pollutant loading in addition to the parameter concentrations are also reported on. The pollutant loading between two dates from the septic tank/secondary treatment unit are calculated in accordance with Eqn. 6.1:

$$P_L = C_m \times F_m \times N \qquad \text{Eqn. 6.1}$$

Where, P_L = pollutant loading

C_m = mean concentration of parameter

F_m = mean daily effluent flow over period

N = number of days between sampling days

The pollutant stored within the willow system at each sampling visit was determined from Eqn. 6.2:

$$P_L = C_m \times H_L \times V_u \qquad \text{Eqn. 6.2}$$

Where, P_L = mass of pollutant in system

C_m = mean concentration of parameter

H_L = total flooded volume within willow system

V_u = usable water volume storage within soil/gravel

A comparison between the cumulative loading from the septic tank/secondary treatment unit and the loading within the willow system throughout the monitoring period has been carried out for each site in order to ascertain the removal efficiency of the willow trees.

As detailed in Section 3.8.3 it was necessary to dilute some samples during bacteriological analysis. In such cases, the minimum detection level of the bacterial concentrations was affected and therefore expressed in the form < x MPN/100 ml. For example, if a sample was analysed for *E. coli* and found to contain <10 MPN/100ml, this means that the original sample was diluted by a factor of 1 in 10 with distilled water. Even though the presence of *E. coli* was not detected, the dilution step had to be accounted for.

Some of the systems were completely empty on sampling days (mainly on Site A and Site B during summer periods) and so water samples could not be obtained from within the inspection well.

6.2 Background Concentrations

As detailed in Section 4.3, there were a number of systems that didn't receive any (or negligible amounts of) effluent during the monitoring period of this research for reasons detailed previously on a case by case basis. This section will look at the concentrations of the different pollutants from samples collected from those willow systems (Systems E, F(1), F(2) and G) as they provide an interesting comparison against the samples from the willow systems which were receiving effluent. The willow system on Site E was included in this category because although it was receiving some effluent, as detailed in Section 4.3.5, the amounts were negligible. The temporal patterns of the different parameter concentrations on Site F (System 2) are also plotted to assess for any seasonal trends that are occurring.

The mean concentrations for the different nitrogen components from the four sites are shown in Table 6.1. It can be seen that the concentrations are relatively consistent between all the sites. The mean total N ranged from 6.3 mg/l (System F2) to 11.5 mg/l (System E) with organic

nitrogen comprised a large proportion of this. As would be expected, NO_3-N made up the majority of the inorganic-N measured, with organic-N making up a large proportion of the total nitrogen.

Table 6.1 Mean concentration of Total N, NH_4-N, NO_3-N, and NO_2-N for sites not receiving effluent

System	Total N (mg/l)	Organic-N	NH_4-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)
E	11.5	9.9	0.2	1.3	<0.1
F(1)	7.3	4.1	0.4	2.7	<0.1
F(2)	6.3	3.3	0.8	2.1	<0.1
G	7.1	3.6	0.1	3.3	<0.1

The temporal patterns for the different forms of nitrogen concentrations throughout the sampling period are shown in Figure 6.1. It can be seen that there was a tendency for the total-N concentration to increase during the growing season. This would be expected to a certain extent, due to the natural concentration of chemical in the basin as the volume of water stored drops due to evapotranspiration. A similar pattern, although not as pronounced, emerged for NH_4-N concentrations. This was not the case for NO_3-N, with increases in concentration tending to occur during the dormant season. With heavier rainfall occurring during these months, which would providing oxygenated conditions, it was not surprising that this was the case. It could also be the case that the lower NO_3-N concentrations in the summer are as a result of the willow trees absorbing this form of nitrogen as they grown.

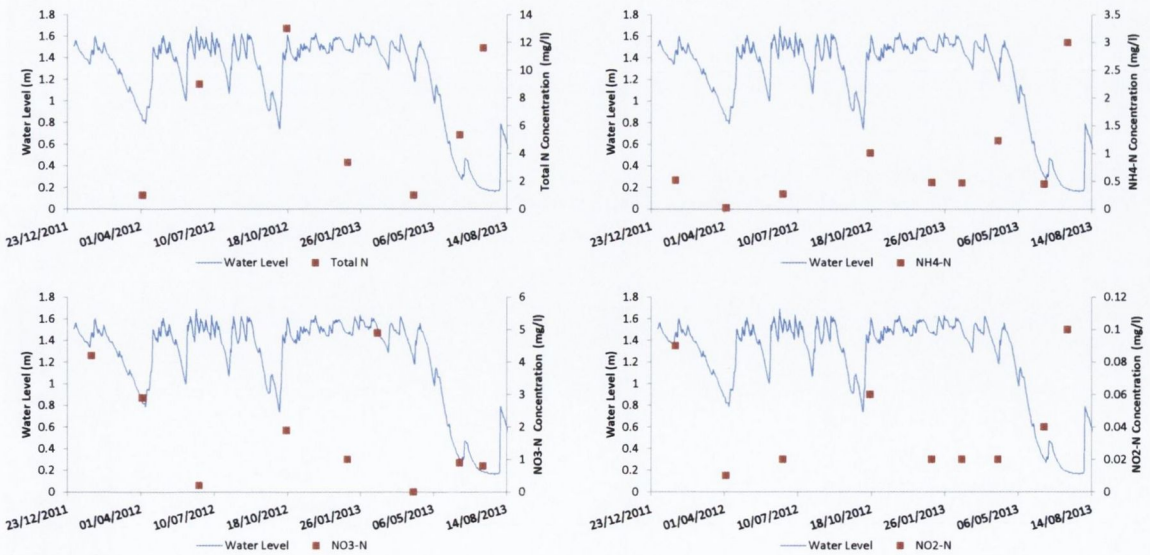


Figure 6.1 Temporal concentrations (Total N, NH_4-N, NO_3-N, and NO_2-N) during sampling period (Site F - System 2)

The mean concentrations for COD, phosphorus, chloride and sulphate are shown in Table 6.2. As with the nitrogen parameters, the concentrations for all four parameters are relatively consistent. The mean COD ranges from 26.1 mg/l (Site E) to 43.7 mg/l (Site G). The mean chloride concentration ranges from 13.2 mg/l (Site E) to 21.1 mg/l (Site G), while mean sulphate concentrations ranged from 6.3 mg/l to 15 mg/l.

Table 6.2 Mean concentrations of COD, PO_4-P, Cl^-, and SO_4^{2-} for sites not receiving effluent

System	COD (mg/l)	PO_4-P (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)
E	26.1	0.2	13.2	6.3
F(1)	31.0	0.8	15.8	15.0
F(2)	30.7	0.1	15.1	14.4
G	43.7	0.1	21.1	12.2

The temporal patterns for COD, PO_4-P, Cl and SO_4 concentrations throughout the sampling period on Site F are shown in Figure 6.2. The COD shows some tendency towards higher concentrations during periods of low water levels within the willow system but it was not always the case with the highest concentration (58 mg/l) occurring in January 2012. After an initial spike in January 2012, the PO_4-P concentration decreased rapidly and remaining low for the rest of the sampling period. The chloride concentration spiked to 24 mg/l when the water level was relatively low in April 2012, but then decreased and hovered between 11.6 - 16 mg/l for the rest of the sampling period.

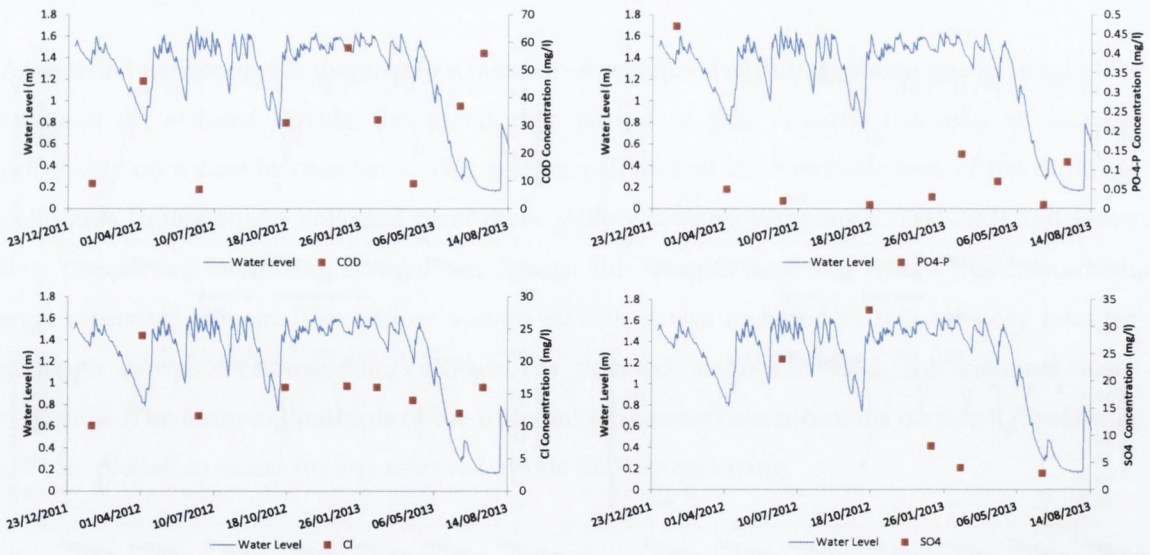


Figure 6.2 Temporal concentrations (COD, PO_4-P, Cl, and SO_4) during sampling period (Site F - System 2)

6.3 Site A Fardystown

6.3.1 Organics

The results from the COD analysis are presented in Table 6.3. It can be seen that there was a significant reduction of COD between the discharged effluent and samples from the monitoring well, both in terms of concentration and total cumulative load. Although there was effluent flow to the willow system from October 2010 onwards, sampling did not commence until January 2012. For the purpose of clarity the starting date of net effluent loading was assumed to be on the first day of sampling.

Table 6.3 COD concentrations and cumulative loading for STE and willow system on Site A

Date	COD Concentration (mg/l)		Cumulative COD (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	93.0	9.0	0.1	0.4
03/04/2012	781.0	17.0	16.1	0.6
19/06/2012	215.0	11.0	33.9	0.4
07/08/2012	315.0	18.0	45.2	0.8
16/10/2012	634.0	51.0	61.4	1.4
08/01/2013	299.0	37.0	80.8	1.6
18/02/2013	126.0	25.0	90.3	1.0
08/04/2013	287.0	8.0	101.7	0.1
10/06/2013	566.0	10.0	116.2	0.2

The extent of COD removal within the willow system is illustrated in Figure 6.3. Both the COD concentration and total mass within the willow system increased during the monitored winter period. This was expected given that the willows are in the dormant season and hence uptake would be expected to be lower. However, the increase was still low with respect to the corresponding increase in effluent loading. This could be as a result of two factors; further treatment taking place by a different means within the system and/or effluent is escaping from the system due to overflow. The relatively low concentrations for the dormant season are probably as a result of dilution by rainfall. Further microbial anaerobic treatment could also have taken place in the soil within the system.

The mean COD concentration (from the willow system sample) of 18.8 mg/l was lower than the mean concentrations from the systems not receiving effluent; the concentrations for those four systems ranged from 26.1 mg/l to 43.7 mg/l. This is hence an indication of the high level of removal taking place within the system.

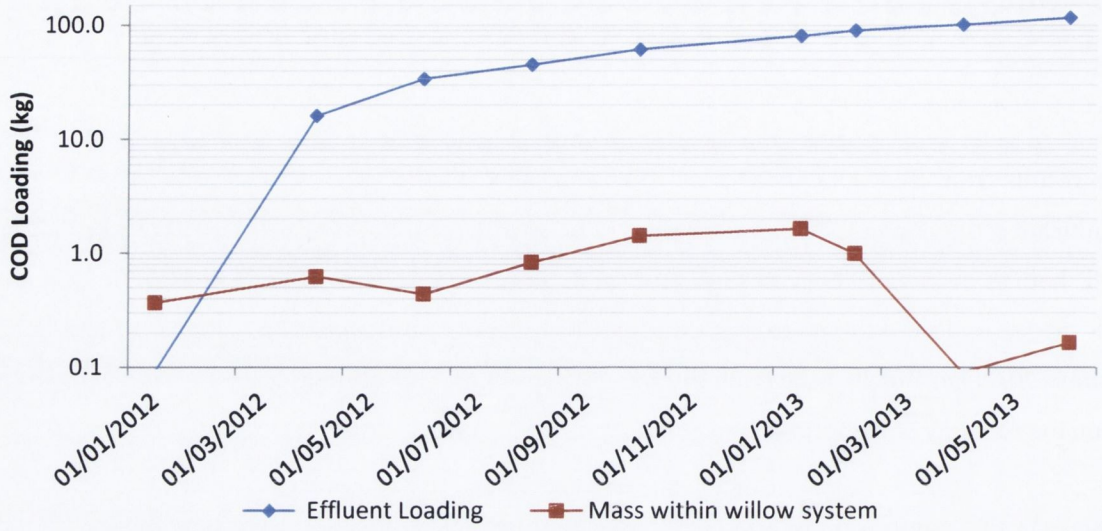


Figure 6.3 COD removal on Site A throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

6.3.2 *Nitrogen*

The extent of total inorganic-N removal within the willow system is illustrated in Figure 6.4. The concentration and the total mass of inorganic-N was relatively consistent within the willow system except for one spike on the sampling date 16/10/2012. It can be seen that there was a very significant reduction (> 99%) in total inorganic-N throughout the sampling period.

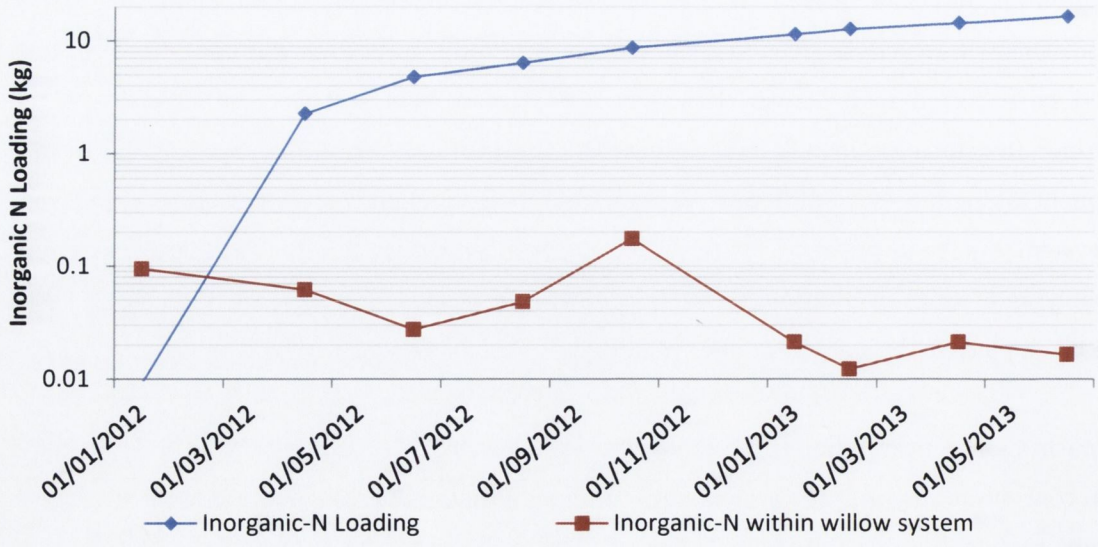


Figure 6.4 Inorganic-N removal on Site A throughout monitoring period (note log scale)

The high removal rate continues during the winter months, which is somewhat surprising given that the willow trees are dormant and hence it would be expected that there would be negligible uptake of nutrients. This suggests that there is a percentage of total inorganic-N being lost in the system, which could have resulted from overflow of effluent from the system when it was flooded in the winter months (coupled with rainfall diluting the effluent) or also from denitrification taking place. The breakdown of the nitrogen is shown in Table 6.4. As would be expected, NH_4-N comprises the majority of inorganic-N in the STE (mean, 98.4%). It can also be seen that organic-N comprises the majority of nitrogen within the willow system. This may have come directly from the effluent and/or may a result of nutrient recycling by the willow trees (i.e. it is from the breakdown of plant matter that had previously being taken up by the tree as nitrogen from the effluent). A similar occurrence with horizontal subsurface flow reed beds was reported on by O'luanaigh et al. (2010).

The majority of the inorganic-N stored within the willow system was in the form of NO_3-N, showing that some nitrification of NH_4-N in the effluent has occurred. It can be seen from Figure 6.5 that although the percentage of NO_3-N increases from 1.3% in the STE to 83.5% in the willow system, the total mass in the willow system was still significantly lower than that in the effluent.

Table 6.4 Concentrations of different forms of nitrogen in STE and willow system on Site A

Date	**STE**					**Willow System**				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	86.0	10.6	75.0	0.2	0.2	5.0	2.7	0.0	2.3	0.0
03/04/2012	92.0	10.6	81.0	0.2	0.2	4.0	2.3	0.1	1.6	0.0
19/06/2012	52.0	32.6	19.0	0.3	0.1	8.0	7.3	0.2	0.5	0.0
07/08/2012	72.0	16.7	54.0	1.2	0.1	11.0	10.0	0.1	0.9	0.1
16/10/2012	78.0	58.0	19.0	0.9	0.1	26.0	19.7	5.0	1.2	0.1
08/01/2013	61.0	29.4	31.0	0.5	0.1	2.5	2.0	0.1	0.4	0.0
18/02/2013	55.0	11.9	43.0	0.0	0.1	11.0	10.7	0.0	0.3	0.0
08/04/2013	72.0	4.6	67.0	0.3	0.2	12.0	11.4	0.0	0.6	0.0
10/06/2013	84.4	10.7	72.0	1.6	0.1	4.9	3.9	0.0	1.0	0.0
Mean	72.5	10.7	51.2	0.6	0.1	9.4	3.9	0.6	1.0	0.0
% *	-	-	98.4%	1.3%	0.3%	-	-	15.4%	83.5%	1.1%

* Percentage of inorganic-N

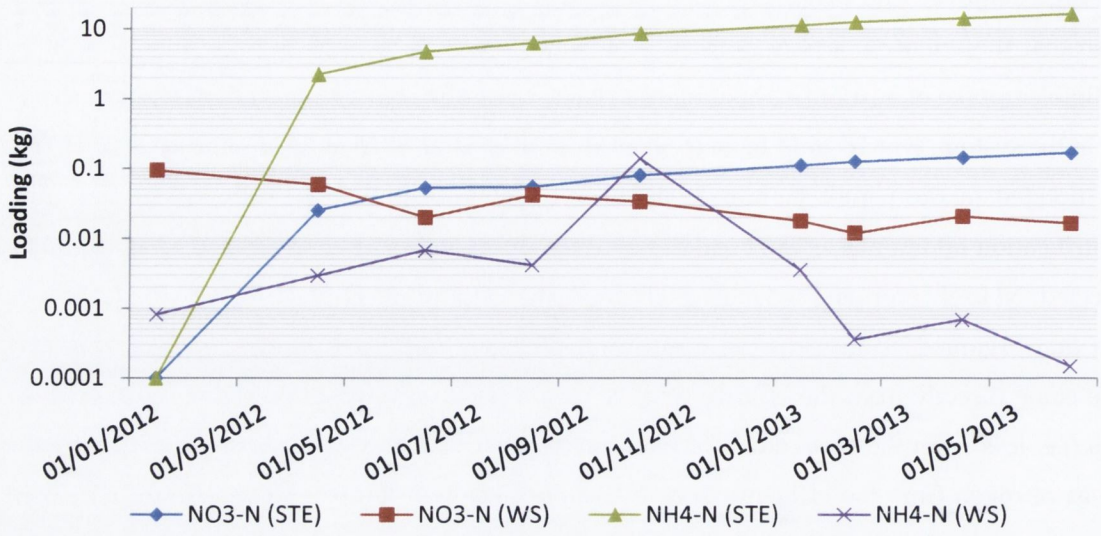


Figure 6.5 NH_4-N and NO_3-N loading in the STE and corresponding mass in the willow system (note log scale)

The mean concentrations of the different nitrogen forms measured in samples from the willow system were similar to the corresponding samples taken from the systems not receiving effluent. The mean total N of the samples from willow System A was 8.5 mg/l, with the mean concentrations ranging from 6.3 mg/l to 11.5 mg/l on the four systems not receiving effluent. The mean NH_4-N and NO_3-N concentrations of 0.6 mg/l and 1 mg/l also compared very favourably with the results of the four systems not receiving effluent, which had NH_4-N concentrations ranging from 0.1-0.8 mg/l and NO_3-N concentrations ranging from 1.3-3.3 mg/l. This provides further indication of the high removal rate of inorganic-N from the effluent provided by the willow system.

6.3.3 *Phosphorus*

The removal of PO_4-P within the willow system on Site A is highlighted in Figure 6.6. The PO_4-P mass within the willow system was relatively consistent with the exception of a single spike which occurred on the sampling on the 08/04/2013. It can be seen that there was a high rate of removal (99-100%) throughout the sampling period. As with the previously discussed pollutants, the PO_4-P stored in the willow system remains low throughout the winter period. This suggests that treatment/reduction is taking place by a different means, as uptake by the willow trees in the dormant season would be negligible. The main removal mechanism is probably due to precipitation and/or adsorption in the soil. In addition, some of the

phosphorus loss could be from the overflow when the willow system is flooded in the winter months.

Removal of phosphorus from the effluent in the soil is typically due to adsorption and mineral precipitation processes. The P-fixation capacity of a soil is dependent on a number of factors, one of which is the clay content of the soil. The P-sorption capacity of fine grained subsoils can persist for ten years at least (Jenssen, 2001).

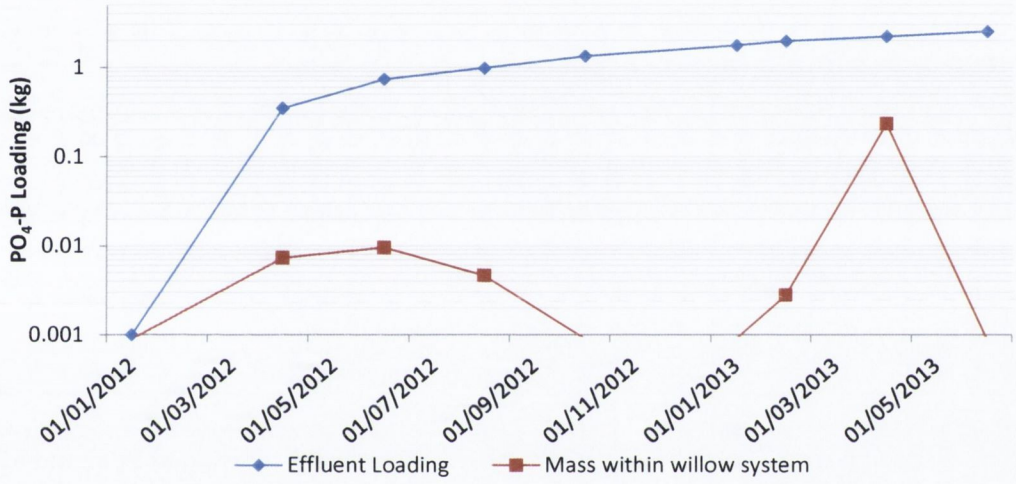


Figure 6.6 PO_4-P removal on Site A throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

The mean PO_4-P concentration of 0.8 mg/l which was determined from the willow system samples is in a similar to the background concentration measured in the four willow systems not receiving effluent. This provides further evidence of the high removal rate achieved by the willow system.

6.3.4 Salinity

As discussed in Section 2.4.3.5, salinity is a key parameter which can regulate the growth of the willow and hence the sustainability of its use as part of a zero discharge evapotranspiration system. The chemical analysis carried out on the wastewater and willow system samples including testing for chloride (Cl) and sulphate (SO_4) as these are the predominant non-carbonate salts found in wastewater.

The mean Cl concentration in the effluent was 268 mg/l, which is quite high in comparison to findings from other studies carried out in Ireland (Larsson, 2003, Gill et al., 2009a). The mean SO_4 concentration in the effluent was 51 mg/l. The cumulative loading rates for the monitoring period are shown in Table 6.5. It can be seen that the amount of chloride in the willow system remained relatively constant throughout the year. Apart from an initial spike, the same can be said of the amount of sulphate.

Table 6.5 Cumulative chloride and sulphate loading in STE and willow system on Site A.

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.00	1.29	0.10	-
03/04/2012	11.71	2.11	2.32	-
19/06/2012	24.66	1.04	4.81	2.99
07/08/2012	32.91	1.89	6.39	0.83
16/10/2012	44.68	3.15	8.64	0.36
08/01/2013	58.81	1.38	11.35	0.71
18/02/2013	65.71	1.47	12.67	0.32
08/04/2013	73.95	1.10	14.25	-
10/06/2013	84.55	0.49	16.28	0.10

The extent of the removal of Cl and SO_4 within the willow system is illustrated in Figure 6.7. It can be seen that there is no apparent significant cumulative increase for either salts over the monitoring period. As detailed with the previous pollutants, there could be loss of chloride due to overflow from the system in the winter months.

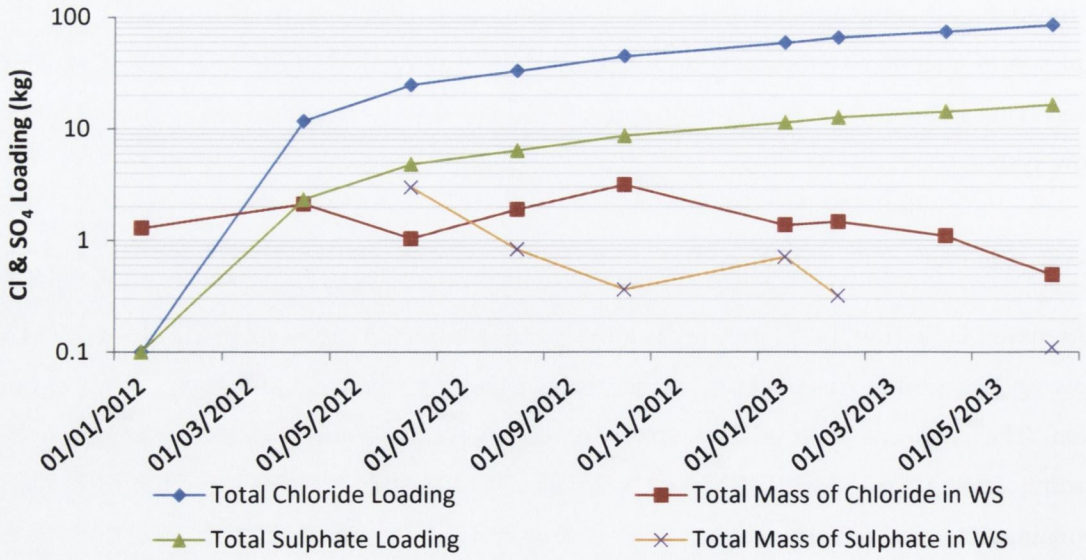


Figure 6.7 Cl & SO_4 removal on Site A throughout monitoring period (log scale)

It is interesting to note, however, that the mean concentrations of Cl and SO_4 determined from samples taken from the willow system are noticeably higher than the corresponding concentrations measured at the systems not receiving effluent. The mean Cl concentration for System A was 44.4 mg/l compared to a range of 13.2-21.1 mg/l for the other 4 sites. The mean SO_4 concentration for the samples from this system was 22.7 mg/l, which similarly was noticeably higher than the range of 6.3-15 mg/l from the 4 sites not receiving effluent. This indicates the impact of the extra loading in the wastewater effluent and suggests that a build-up of salts is occurring within the system.

6.3.5 Bacteriological Analysis

The TC concentrations ranged from $8.16 \times 10^5 - 4.88 \times 10^6$ MPN/100 ml for the STE and $2 \times 10^1 - 9.33 \times 10^2$ MPN/100 ml for the willow system samples. The high purification capability of the willow system is shown in Table 6.6, with a 4 log-unit removal in TC (equivalent to a 99.99% reduction) taking place.

Table 6.6 Reduction in total coliform concentrations with respect to STE in the willow system on Site A

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	7	$8.16 \times 10^5 - 4.88 \times 10^6$	1.76×10^6	-
Willow System	6	$2 \times 10^1 - 9.33 \times 10^2$	1.61×10^2	4

The geometric mean *E. coli* concentrations of the STE and willow system samples were 9.84×10^4 MPN/100 ml and 1.95×10^1 MPN/ 100ml respectively. This represented a log-unit removal rate of 3.7 (equivalent to an overall reduction of 99.99%). However, when the individual samples from the willow system are examined it can be seen that half of them contained significant numbers of enteric bacteria (see Table 6.7).

Table 6.7 Concentrations of *E. coli* measured on 6 different occasions on Site A

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	6	-	-	-	6
Willow System	6	3	1	2	-

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site A are shown in Figure 6.8. There may be evidence for the *E. coli* to be much higher during the

summer, with winter concentrations all below 50 MPN/100ml, although with such low numbers of samples it is not possible to be definitive. However, if this this pattern is valid, it is interesting to note that pathogen concentrations would be relatively low during the dormant season when overflow is most likely to occur.

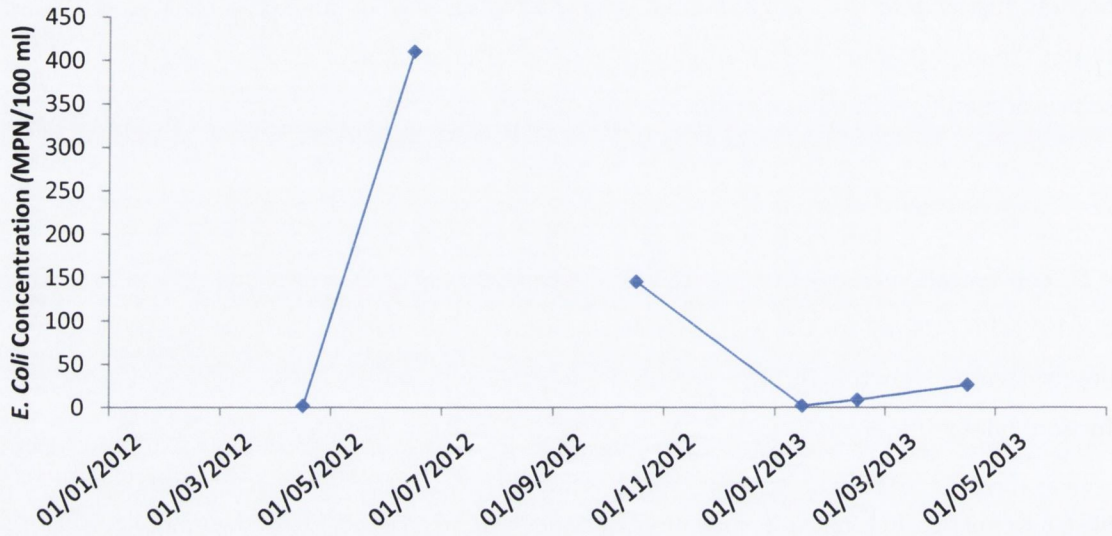


Figure 6.8 Temporal *E. coli* concentrations during sampling period on Site A

6.4 Site B Fardystown

6.4.1 Organics

As shown in Table 6.8, there was a significant reduction in COD both in terms of concentration and mass between the discharged effluent loading and levels within the willow system. Although there was effluent flow to the willow system from the start of January 2012 onwards, sampling did not commence until the 25th January 2012. Again, for the purpose of presenting the results with clarity the starting date of net effluent loading was assumed to be on the first day of sampling.

A comparison of the mass within the willow system with the effluent loading between each sampling date is shown in Figure 6.9. Both the COD concentration and the total mass within the willow system increased over the winter period, before dropping off again towards the summer. Even though there was no sample obtained on the 16th October 2012, it appears as though there was little cumulative increase in the stored COD within the willow system over

the winter. It is also noticeable that the cumulative mass in the system began to decrease in February 2013, still the dormant season. This suggests that effluent may have escaped from the system or further treatment occurred within the soil medium.

Table 6.8 COD concentrations and cumulative loading for STE and willow system on Site B

Date	COD Concentration (mg/l)		Cumulative COD (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	130.0	5.0	0.6	0.0
03/04/2012	125.0	18.0	1.2	0.9
19/06/2012	43.0	31.0	3.2	1.7
07/08/2012	91.0	27.0	4.2	1.8
16/10/2012	154.0	-	7.1	-
08/01/2013	72.0	40.0	8.1	2.9
18/02/2013	13.0	26.0	8.1	1.6
08/04/2013	80.0	8.0	9.3	0.4
10/06/2013	101.0	-	12.3	-

The mean COD concentration (from the willow system sample) of 21.4 mg/l compares positively to the mean concentrations from the systems not receiving effluent. The concentrations for those four systems ranged from 26.1 mg/l to 43.7 mg/l. This is further indication of the high removal rate of organics carried out by the willow system.

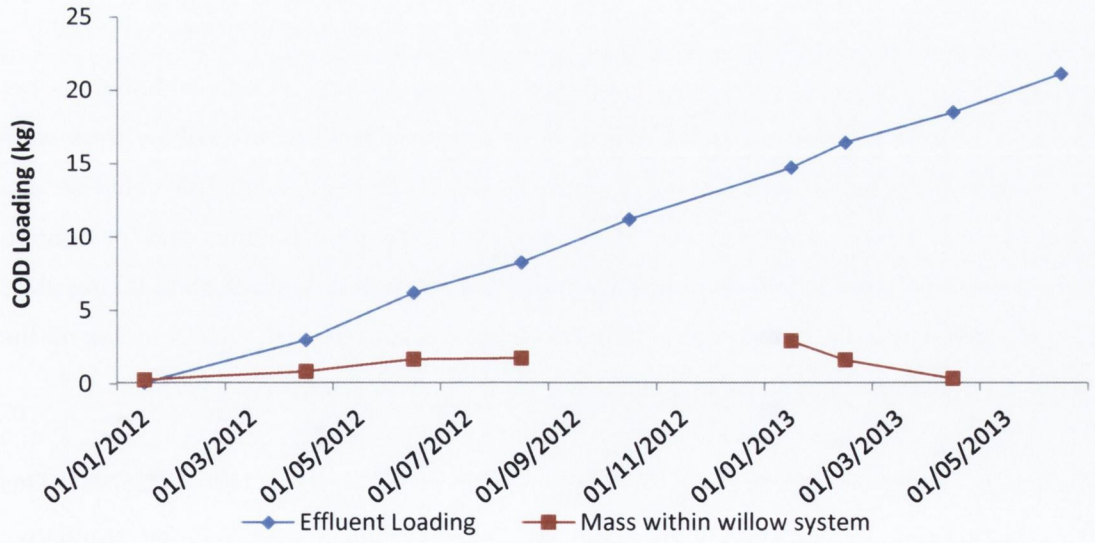


Figure 6.9 COD removal on Site B throughout monitoring period

6.4.2 *Nitrogen*

A comparison between inorganic-N mass in the willow system to the mass added via STE loading is illustrated on a log scale graph in Figure 6.10. Although there are some missing sampling points on the graph, it can be seen that there was a very significant reduction in total inorganic-N throughout the sampling period.

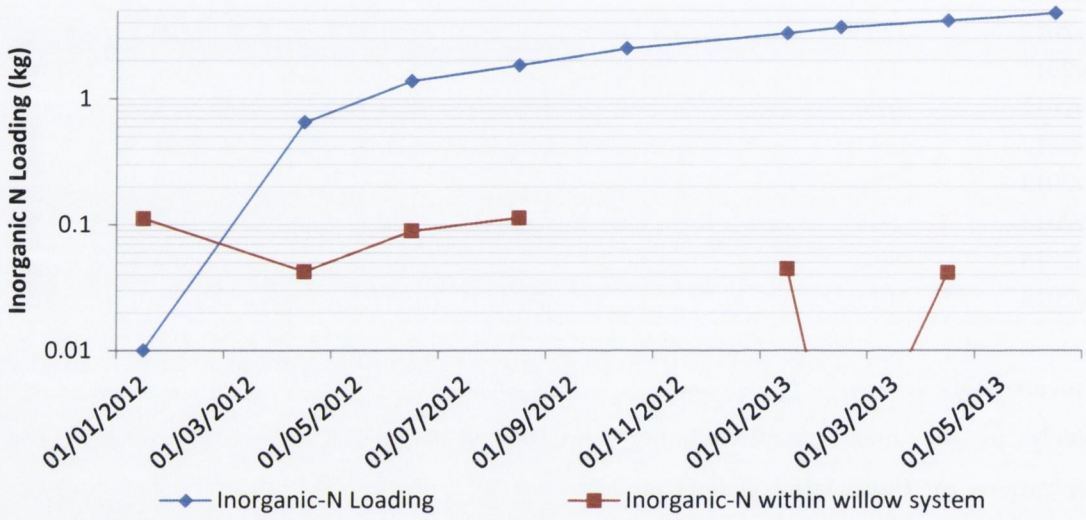


Figure 6.10 Inorganic-N removal on Site B throughout monitoring period (note log scale)

Similarly to Site A, the high removal rate continued during the winter months (although it does appear that a slight increase occurred), which is surprising given that the willow trees were dormant during this period (and uptake of nutrients should be negligible). This could be as a result of overflow from the system when it became flooded during the winter and/or dilution due to rainfall. The reduction is also more than likely as a result of denitrification taking place in the soil. The breakdown of nitrogen is shown in Table 6.9. As expected, NH_4-N makes up the majority of the inorganic-N in the STE (mean, 89.8%), with NO_3-N comprising 9.6%.

The majority of inorganic-N in the willow system was in the form on NO_3-N (96.7%). This translated to a higher overall mass of NO_3-N in the willow system compared to the cumulative effluent loading for the first half of the monitoring period (although there was significant overall inorganic-N removal throughout the monitoring period [see Figure 6.10]). However, it did drop below the cumulative loading in January 2013 and remained lower for the rest of

monitoring (Figure 6.11); showing that a reduction of NO_3-N was taking place. It can also be seen that there was a significant reduction in NH_4-N throughout the sampling period.

Table 6.9 Concentrations of different forms of nitrogen in STE and willow system on Site B

Date	STE					Willow System				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	21.0	3.0	17.0	0.9	0.1	2.0	0.1	0.0	1.9	0.0
03/04/2012	26.0	4.9	21.0	0.1	0.0	1.0	0.1	0.1	0.8	0.0
19/06/2012	6.0	3.6	2.1	0.3	0.1	15.0	13.4	0.0	1.6	0.0
07/08/2012	28.0	6.1	21.0	0.8	0.0	5.0	3.3	0.0	1.7	0.0
16/10/2012	19.0	4.8	13.0	1.2	0.0	-	-	-	-	-
08/01/2013	5.4	0.5	4.2	0.6	0.1	2.5	1.9	0.0	0.6	0.0
18/02/2013	3.0	0.9	1.4	0.7	0.0	6.0	6.0	0.0	0.0	0.0
08/04/2013	82.0	19.5	62.0	0.5	0.1	13.0	12.1	0.0	0.9	0.0
10/06/2013	40.7	6.3	33.0	1.4	0.0	-	-	-	-	-
Mean	25.7	5.5	19.4	0.7	0.0	6.4	4.1	0.0	1.1	0.0
% *	-	-	89.8%	9.6%	0.6%	-	-	2.9%	96.7%	0.4%

* Percentage of inorganic-N

The mean concentration of total N measured in the willow system samples of 6.4 mg/l compared very favourably with the corresponding mean concentration from the 4 sites not receiving any effluent. The concentration for these sites ranged from 6.3 - 11.5 mg/l. The same applied to the mean NH_4-N and NO_3-N concentrations of the samples taken from the willow system, with both being lower than the mean concentrations measured at any of those four sites.

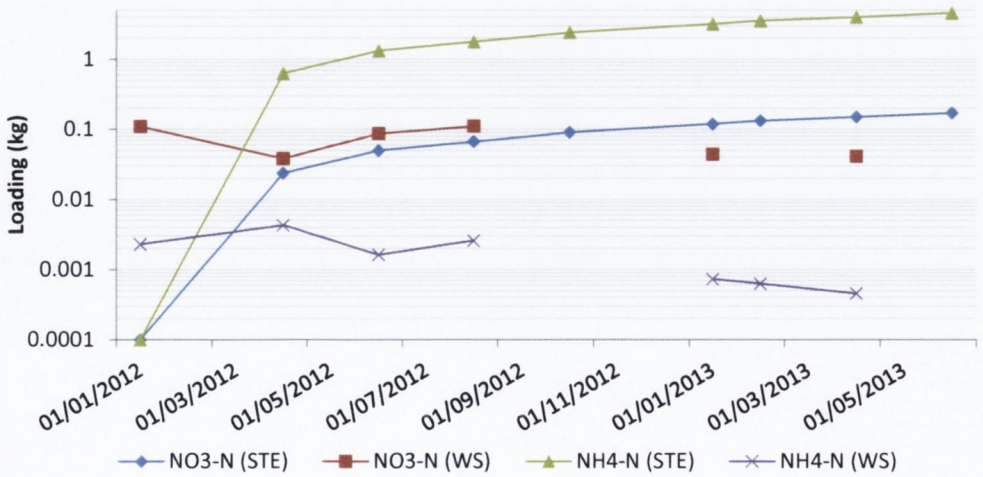


Figure 6.11 NH_4-N and NO_3-N loading in the STE and corresponding mass in the willow system on Site B (note log scale)

6.4.3 *Phosphorus*

The rate of removal of PO_4-P within the willow system on Site B is illustrated in Figure 6.12. It can be seen that the cumulative PO_4-P mass in the willow system was relatively consistent throughout the sampling period. There was a high rate of removal, with cumulative PO_4-P decreasing to negligible amounts in August 2012 and remained close to zero for the winter period. The low winter amounts suggest that treatment/reduction was taking place by a different means, as uptake by the willow trees in the dormant season would be non-existent. This could have been as a result of PO_4-P loss due to overflow from the system or from adsorption and/or precipitation in the soil medium (which can be particularly high for soil with high clay content).

The mean PO_4-P concentration of 0.1 mg/l determined from the willow system samples was on a par with the lowest mean concentration measured at the four sites, which were not receiving effluent loading.

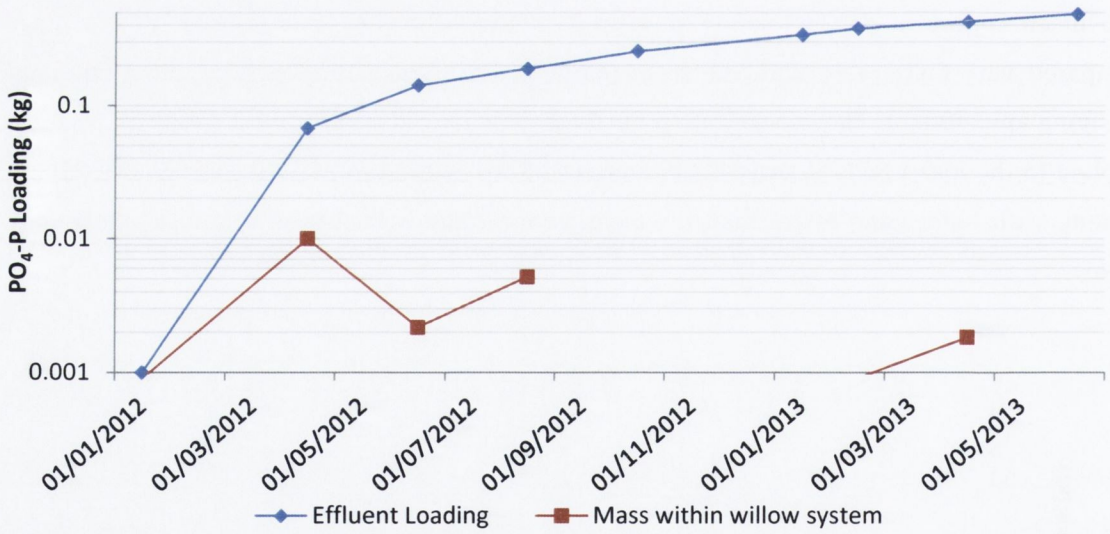


Figure 6.12 PO_4-P removal on Site B throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

6.4.4 *Salinity*

The mean Cl concentration in the effluent was 90 mg/l, which is similar to the concentrations reported by Gill et al. (2009a) for STE produced by a number of Irish dwellings. The mean SO_4 concentration in the effluent was 35 mg/l. The cumulative loading rate and the cumulative

mass within the willow system for both non-carbonate salts are shown in Table 6.10. Despite continuous loading of the STE, there seemed to be no noticeable build-up of either Cl or SO_4 in the willow system over the sampling period.

Table 6.10 Cumulative chloride and sulphate loading in STE and willow system on Site B

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.10	1.11	0.10	-
03/04/2012	3.75	2.03	0.64	-
19/06/2012	7.82	1.41	1.25	1.79
07/08/2012	10.41	2.26	1.63	0.71
16/10/2012	14.12	-	2.18	0
08/01/2013	18.56	2.99	2.84	0.73
18/02/2013	20.73	1.95	3.16	-
08/04/2013	23.32	1.37	3.54	-
10/06/2013	26.65	-	4.04	-

The extent of Cl and SO_4 removal within the willow system is illustrated in Figure 6.13. After a slight increase in accordance with the increase in STE loading, the amount of chloride in the system levelled out, remaining relatively constant for the rest of the sampling period. Although there were only four sulphate samples from within the willow system, it appeared a similar pattern had developed. The amount in the willow system was initially higher than the amount added via the effluent (probably the background concentration of the system), before decreasing to almost zero in July 2012. The increase that followed still resulted in a lower amount than the cumulative amount added via the effluent loading up to that date.

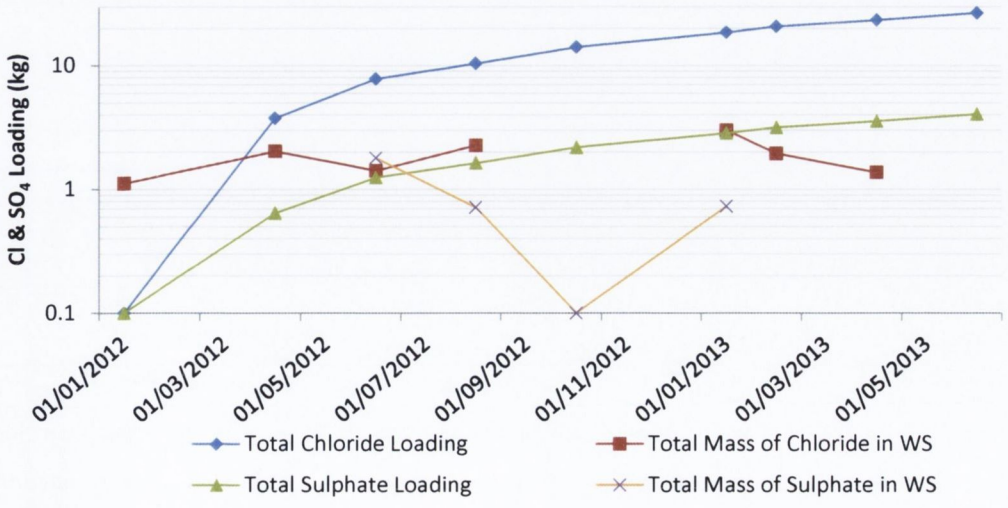


Figure 6.13 Cl & SO_4 removal on Site B throughout monitoring period (note log scale)

The mean concentration of Cl and SO_4 from this willow system was significantly higher than the levels measured on the systems not receiving effluent which possibly indicates a slight build-up of salts occurring. The mean Cl concentration for System B was 32.1 mg/l, which was considerably higher than any of the mean concentrations measured from the systems not receiving effluent (range: 13.2 - 21.1 mg/l). Equally, the mean SO_4 concentration of 19.3 mg/l measured from the system on Site B was higher than any of the mean concentrations from the 4 systems not receiving effluent (range 6.3 - 15 mg/l).

6.4.5 Bacteriological Analysis

The total coliforms ranged from $2.2 \times 10^4 - 8.3 \times 10^5$ MPN/100 ml for the STE and $5.2 \times 10^1 - 3.77 \times 10^2$ MPN/100 ml for the willow system samples. The willow system had a 3 log-unit removal rate in TC (equivalent to a 99.9% reduction), which was less than that achieved by the willow system on Site A (see Table 6.11).

Table 6.11 Reduction in total coliform concentrations with respect to STE in the willow system on Site B

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	7	$2.2 \times 10^4 - 8.3 \times 10^5$	1.37×10^5	-
Willow System	6	$5.2 \times 10^1 - 3.77 \times 10^2$	1.35×10^2	3

The geometric mean *E. coli* concentrations of the STE and willow system samples were 5.64×10^3 MPN/100 and 1.08×10^1 MPN/100 ml respectively. This represented a log-unit removal of 2.7 (equivalent to an overall reduction of 99.81%). When the individual samples from the willow system are examined, however, it can be seen that three out of the five contained significant enteric bacteria (see Table 6.12).

Table 6.12 Concentrations of *E. coli* measured on 5 different occasions on Site B

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	5	-	-	-	5
Willow System	5	2	3	-	-

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site B are shown in Figure 6.14. Similarly to System A, the measured concentrations were higher in the growing season (although still relatively low). As overflow from a willow system is most likely

to occur in winter, these results highlight the fact that the levels of pathogens in such an overflow would be quite low and not represent a high risk to human health.

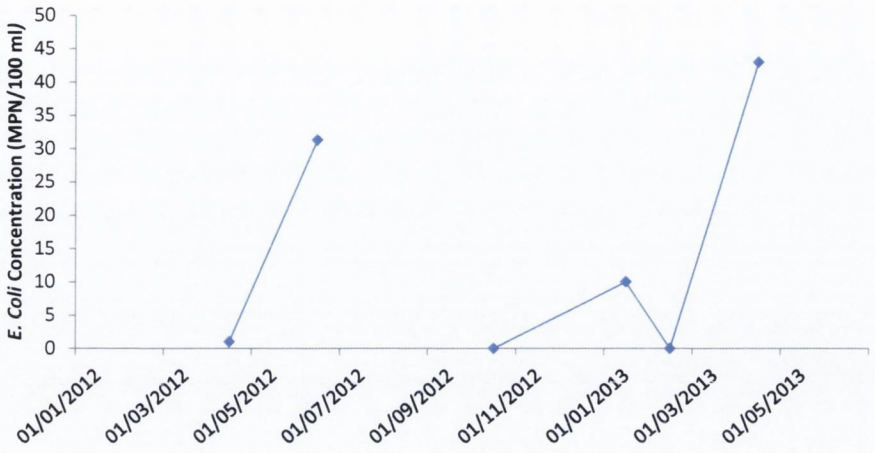


Figure 6.14 Temporal *E. coli* concentrations during sampling period on Site B

6.5 Site C Borehovel

6.5.1 Organics

The COD concentrations and corresponding loads are shown in Table 6.13. It can be seen that there was a significant reduction of COD both in terms of concentration and total mass. While there was effluent flow to the willow system from December 2010 onwards, sampling did not commence until January 2012, so for the purpose of clarity the starting date of net effluent loading was assumed to be on the first day of sampling.

Table 6.13 COD concentrations and cumulative loading for STE and willow system on Site C

Date	COD Concentration (mg/l)		Cumulative COD (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	72	13	1	1.7
03/04/2012	477	27	10.8	3.2
19/06/2012	75	49	21.8	6.1
07/08/2012	385	31	28.8	3.6
16/10/2012	265	17	38.8	2.1
08/01/2013	517	56	50.8	7.2
18/02/2013	232	51	56.6	6.2
08/04/2013	578	14	63.6	1.6
10/06/2013	658	39	72.6	3.6
12/07/2013	736	10	77.2	0.8

The degree of COD removal within the willow system is illustrated using a log scale in Figure 6.15. While effluent loading increased relatively consistently, as would be expected, this was not the case for net COD mass within the willow system. In 2012, the COD within the willow system increased from January until June, before decreasing consistently until October, at which point it began to increase again. This suggests that the reduction throughout the summer was due to uptake by the willow trees. However, it should be noted that the net COD mass within the willow system was still significantly lower than the cumulative COD loading from the effluent throughout the entire monitoring period. Some of the reduction may also have resulted from effluent escaping from the system due to overflow. This effect was probably not as significant, however, compared to Sites A&B, as the rate of escape on Site C was much lower compared to those two systems.

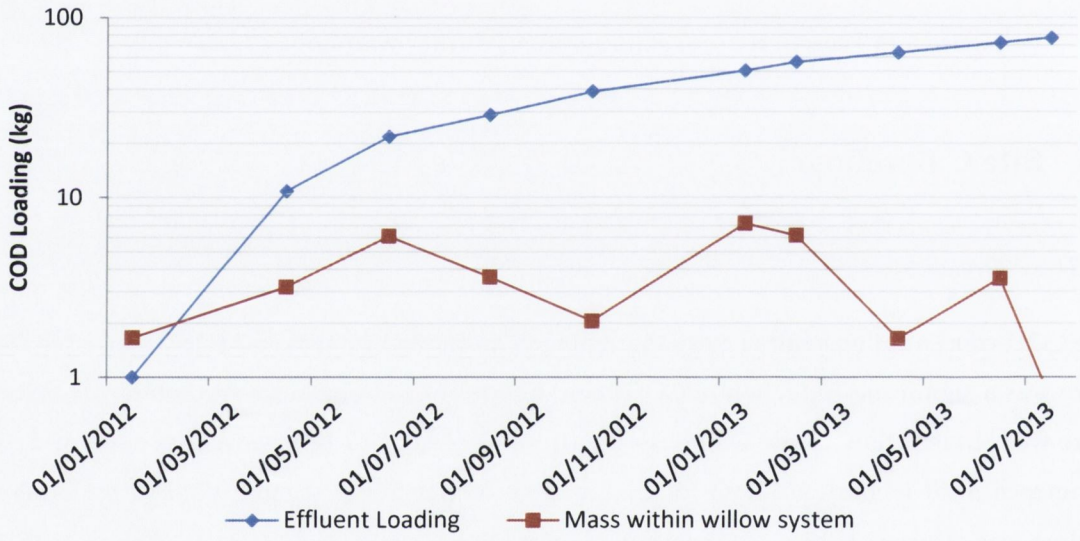


Figure 6.15 COD removal on Site C throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

The mean COD concentration (from the willow system sample) of 30.7 mg/l can be compared positively to the mean concentrations from the systems not receiving effluent (which ranged from 26.1 mg/l to 43.7 mg/l), which indicates some level of removal taking place within the system.

6.5.2 Nitrogen

The range of total inorganic-N removal within the willow system is shown on a log scale in Figure 6.16. The concentration and the total load of inorganic-N was relatively consistent within

the willow system apart from one spike on the 18/02/2013, as a result of a relatively high concentration measurement in comparison to the other sampling dates. Overall, it can be seen that there is a significant reduction in total inorganic-N throughout the monitoring period.

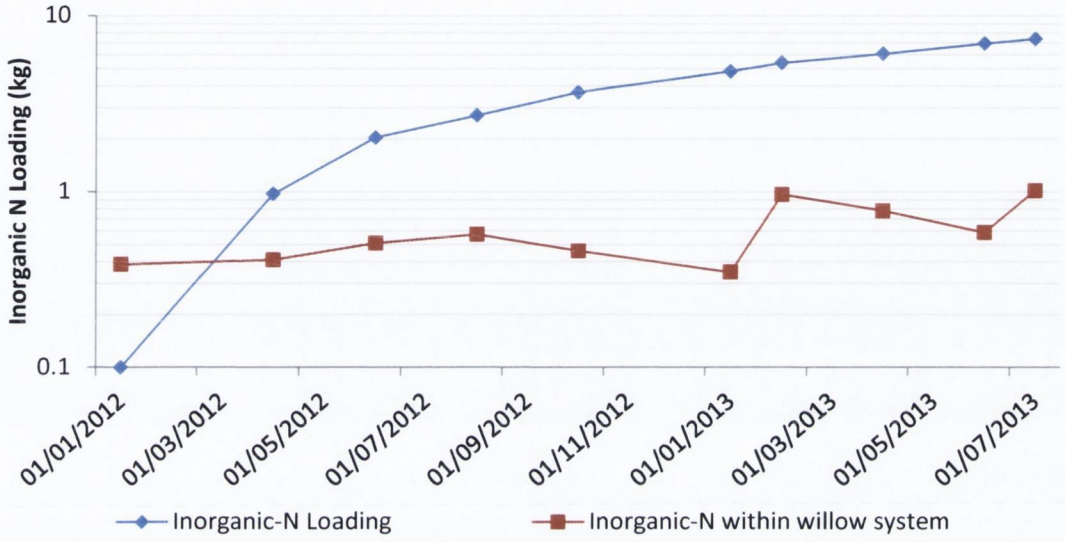


Figure 6.16 Inorganic-N removal on Site C throughout monitoring period (note log)

The removal rate was relatively consistent throughout the year, which is somewhat surprising during the winter time given that the willow trees are dormant and not absorbing nutrients. However, on closer inspection of Figure 6.16, it can be seen that there was a general increasing trend for the total inorganic-N mass within the willow system, which matches the general increasing trend of total inorganic-N loading from the effluent. So, while some nitrogen may be lost from the system via overflow, there does appear to be a slight build-up occurring over time (although it is a very small amount compared to the amount entering the system via effluent loading). However, the sampling period was relatively short, so further monitoring over an extended period of time may be required to determine conclusively if there is a long term build-up over time.

The breakdown of the total inorganic-N in the effluent and willow system is shown in Table 6.14. Again, as expected the majority in the STE comprised of NH_4-N (mean 86.5%). Surprisingly, however, NH_4-N also comprises a large proportion (78.6%) of the mass within the willow system, suggesting that conditions within the system are somewhat anaerobic, hindering the nitrification process. Even though the decrease in the proportion of NH_4-N between STE and willow system is apparently small, the total mass within the willow system is

still significantly lower than in the STE (see Figure 6.17). The same applied to NO_3-N; although there was an increase in proportion between STE and willow system (11.9% to 22.4%), apart from on one occasion the total stored NO_3-N within the system was lower than the cumulative amount entering via effluent loading.

Table 6.14 Concentrations of different forms of nitrogen in STE and willow system on Site C

Date	STE					Willow System				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	5	3.7	0.1	1	0.2	3.5	0.4	2.8	0.2	0
03/04/2012	78	16.1	61	0.7	0.2	5.1	1.6	3.1	0.3	0
19/06/2012	58	6.7	51	0.3	0	8	3.9	0.1	4	0
07/08/2012	42	14.3	26	1.5	0.2	6	1.1	4	0.9	0
16/10/2012	14	4.2	9	0.8	0	8	4.2	3	0.8	0
08/01/2013	52	11.8	40	0.1	0.1	6.5	3.8	2.5	0.2	0
18/02/2013	37	13.9	21	1.9	0.2	22	14	7	0.6	0.4
08/04/2013	71	10.8	59	1	0.2	8	1.4	6.5	0.1	0.1
10/06/2013	40.6	6.5	33	0.9	0.2	15.6	9.2	5.5	0.9	0
12/07/2013	80.5	4.8	65	10.5	0.2	16.3	2.9	7.7	5.6	0.1
Mean	47.8	9.3	36.5	1.9	0.1	9.9	4.3	4.2	1.4	0.1
% *	-	-	86.4%	11.9%	1.7%	-	-	76.5%	22.4%	1.0%

* Percentage of inorganic-N

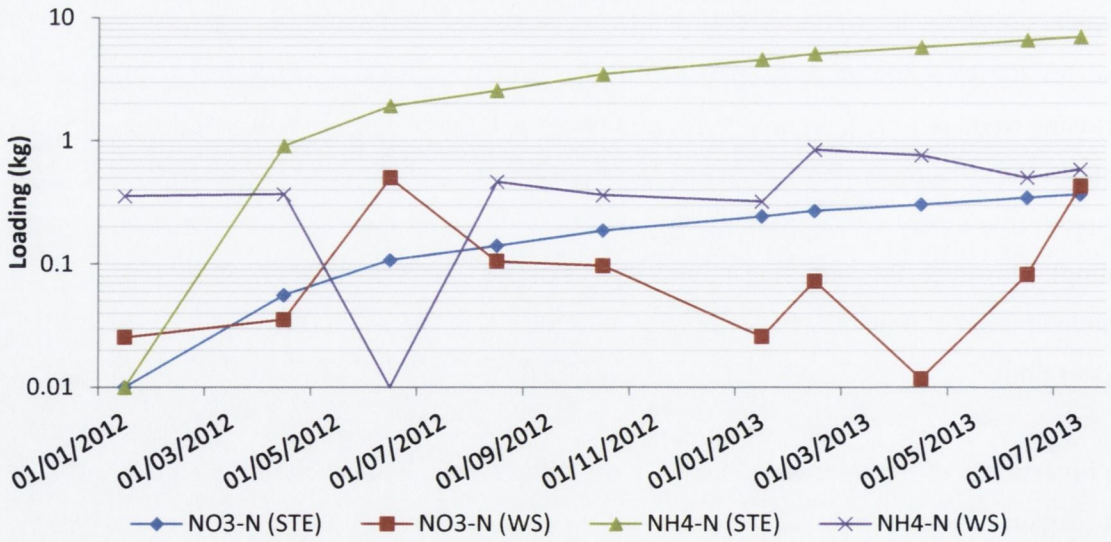


Figure 6.17 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site C (note log scale; a value below the minimum value on the y-axis represents zero)

The mean concentrations of the different nitrogen forms measured in samples from the willow system compared quite similarly with the corresponding samples taken from the systems not receiving effluent. The mean total N of the samples from willow System C was 9.3 mg/l, with the mean concentrations ranging from 6.3 mg/l to 11.5 mg/l on the four systems not receiving effluent. The mean NO_3-N concentration of 1.4 mg/l also compared very favourably with the results of the four systems not receiving effluent, which had NO_3-N concentrations ranging from 1.3-3.3 mg/l. The NH_4-N concentration did not, however, compare as favourably. The mean concentration of the samples from the willow system on Site C was 4.2 mg/l, which was considerably higher than any of the mean concentrations from the 4 sites not receiving any effluent (all of them had concentrations < 1 mg/l). This suggests that there may be some build-up of inorganic nitrogen in the form of NH_4-N occurring on the system. However, the relatively high mean NH_4-N concentration was probably influenced by the drop in water level within the willow system. This decrease in overall hydraulic load would naturally result in an increase in relative concentration. However, it is worth noting that the total amount of NH_4-N was decreasing over the same period.

6.5.3 Phosphorus

The extent of PO_4-P removal within the willow system is illustrated in Figure 6.18. The PO_4-P mass within the system appears quite fragmented, however, this is just as a result of the concentration being measured as almost zero on three occasions, and hence these dates could not be plotted on a log scale. It can be seen that there was a high rate of removal (91-100%) throughout the sampling period. The apparent continued removal up until mid-winter 2013/13 suggests that treatment may be taking place by a different means, as the willow trees would be dormant and absorbing no nutrients. This could as a result of overflow from the system or by removal via adsorption and mineral precipitation in the soil medium, as described in Section 6.3.3.

Although there was an increase in PO_4-P within the willow system from January 2013 onwards (although on a very small scale) the total mass does start to decease again with the onset of the 2013 growing season, suggesting that uptake by the willow trees had re-commenced.

The mean PO_4-P concentration of 0.4 mg/l determined from the willow system samples was within the range of 0.1 - 0.8 mg/l, which represents the mean PO_4-P concentrations of the willow system samples that were not receiving effluent. This provides further evidence of the high removal rate achieved by the willow system on Site C.

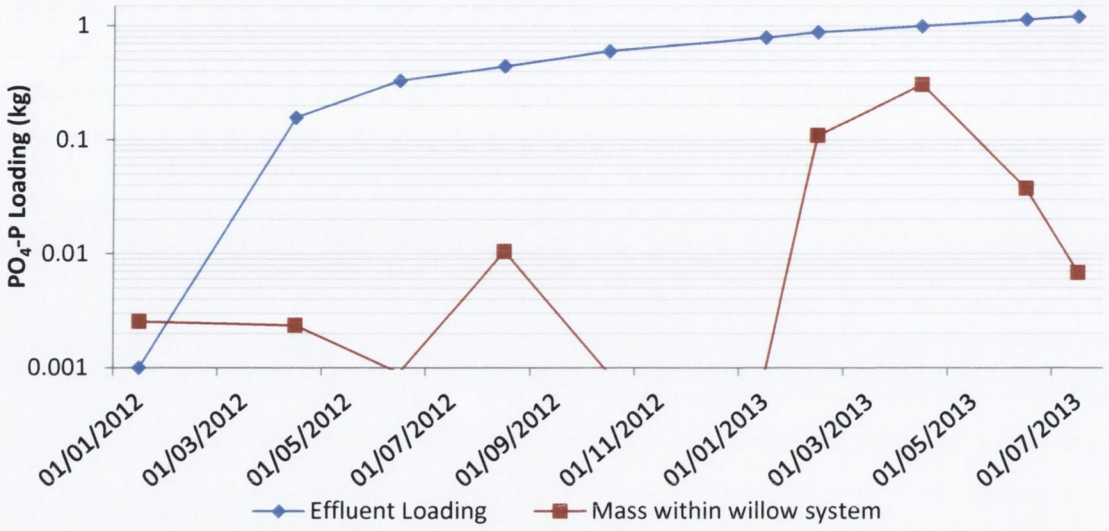


Figure 6.18 PO_4-P removal on Site C throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

6.5.4 Salinity

The mean Cl concentration in the effluent was 400 mg/l, which was quite high, especially when compared to the concentrations reported by Gill et al. (2009a) for STE at a number dwellings in Ireland. The mean SO_4 concentration was 73 mg/l. The cumulative loading rate and the amounts stored within the willow system for both non-carbonate salts are shown in Table 6.15. Despite continuous loading of the STE, there is no noticeable build-up of either Cl or SO_4 in the willow system over the sampling period.

Table 6.15 Cumulative chloride and sulphate loading in STE and willow system on Site C

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.1	1.6	0.1	-
03/04/2012	1.4	3.7	1.9	-
19/06/2012	2.9	4.1	3.9	0.1
07/08/2012	3.8	4.3	5.2	0.2
16/10/2012	5.1	3.5	7.0	0.4
08/01/2013	6.7	4.9	9.2	0.1
18/02/2013	7.5	4.3	10.2	0.4
08/04/2013	8.4	5.5	11.5	-
10/06/2013	9.6	3.5	13.1	0.1
12/07/2013	10.2	3.1	14.0	-

The extent of Cl and SO_4 removal within the willow system is illustrated in Figure 6.19. After briefly increasing in line with the STE loading, the total amount of Cl remained quite constant throughout the remainder of the sampling period. Although the total amount of SO_4 varies quite a bit throughout the monitoring period, it remained relatively low for all sampling dates, representing a high removal rate.

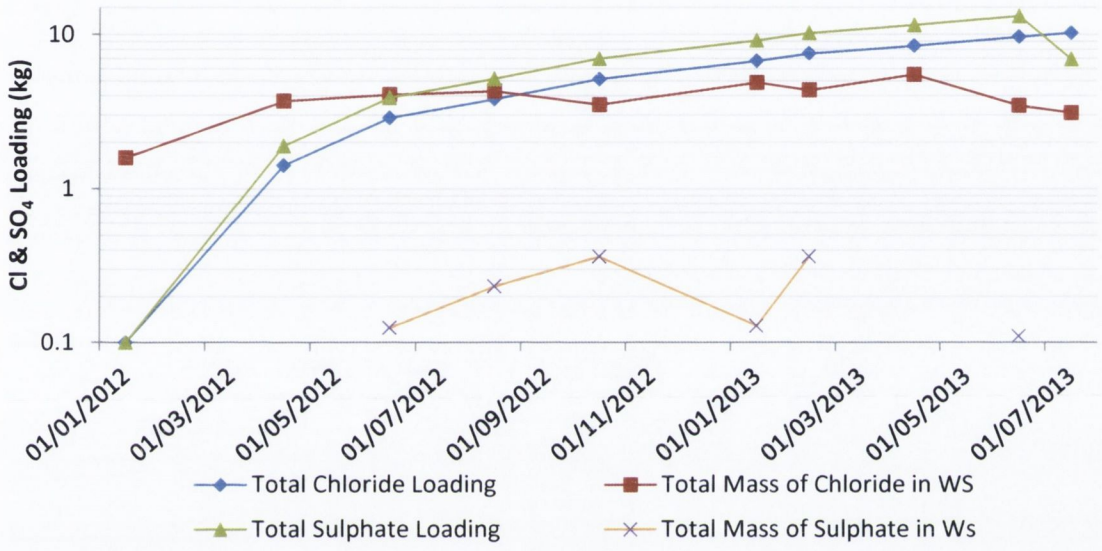


Figure 6.19 Cl & SO_4 removal on Site C throughout monitoring period (note log scale)

By comparing the mean concentration of Cl and SO_4 from willow system samples, it can be seen that there appeared to be a slight build-up of chloride occurring over time. The mean Cl concentration for System B was 34.3 mg/l, which was considerably higher than any of the mean concentrations measured from the systems not receiving effluent (range: 13.2 - 21.1 mg/l). However, a similar difference was not evident with the mean sulphate concentration of 1.8 mg/l from willow System C, which was surprisingly lower than the mean concentrations determined for the four systems receiving no effluent (6.3 - 15 mg/l).

6.5.5 *Bacteriological Analysis*

The TC concentrations ranged from 9.8×10^4 - 6.49×10^6 MPN/100 ml for the STE and 1.99×10^2 - 7.77×10^3 MPN/100 ml for the willow system samples. The willow system had a 2.9 log-unit removal rate in TC (equivalent to a 99.9% reduction), which was slightly less than that achieved by the willow systems on Site A&B (see Table 6.16).

Table 6.16 Reduction in total coliform concentrations with respect to STE in the willow system on Site C

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	6	$9.8 \times 10^4 - 6.49 \times 10^6$	1.64×10^6	-
Willow System	5	$1.99 \times 10^2 - 7.77 \times 10^3$	1.91×10^3	2.9

The geometric mean *E. coli* concentrations of the STE and willow system samples were 1.91×10^5 MPN/100 ml and 1.7×10^2 MPN/100 ml respectively. This represented a log-unit removal rate of 3.1 (equivalent to an overall reduction of 99.91%). However, when the individual samples from the willow system are examined it can be observed that most of them contained significant numbers of enteric bacteria (Table 6.17). This suggests that an overflow from the willow system could pose a pathogen risk to the local environment.

Table 6.17 Concentrations of *E. coli* measured on 6 different occasions on Site C

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	6	-	-	-	6
Willow System	6	1	3	1	1

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site C are shown in Figure 6.20. It can be seen that most of the samples, regardless of the time of year contained significant enteric bacteria. This contrasts with the findings from Sites A&B, which showed winter concentrations to be much lower.

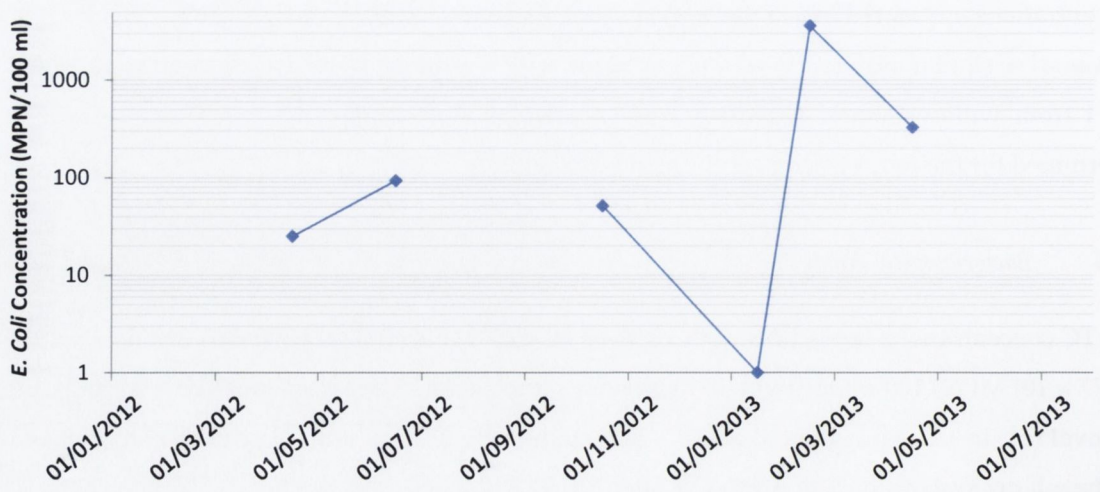


Figure 6.20 Temporal *E. Coli* concentrations during sampling period on Site C

6.6 Site D Ballask

6.6.1 Organics

The results from the COD analysis are presented in Table 6.18. The mean COD concentration of the STE was 193 mg/l. It can be seen that initially the amount of COD within the willow system appeared to be greater than the amount which had been added via the STE up until that point. This is probably just comprised mainly of the background concentration of COD within the system. The mean COD concentration in the willow system up until full time loading commenced was 54 mg/l, which is only marginally higher than the concentrations measured in the sites which were not receiving effluent. Apart from a two week period in June 2012, full time loading of effluent to the willow system started in September 2012. There was an apparent increase in the COD stored within the system that coincided with the brief loading period in June 2012. This decreased quickly as soon as loading ceased. The stored level within the system remained low during the winter period, relative to the loading rate, probably as a result of overflow, which took place quite rapidly from this system. Escape was also probably aided by the fact that effluent distribution was on the surface of the willow system, which meant it had quick, easy access to the constructed overflow channel.

Table 6.18 COD concentrations and cumulative loading for STE and willow system on Site D

Date	COD Concentration (mg/l)		Cumulative COD (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	30	18	0.00	2.7
03/04/2012	383	47	0.00	6.5
19/06/2012	80	100	2.67	14.2
07/08/2012	232	49	2.67	7.1
16/10/2012	330	57	4.00	8.3
08/01/2013	253	63	4.61	9.0
18/02/2013	31	49	4.61	7.0
08/04/2013	139	43	4.73	6.1
10/06/2013	234	70	8.86	8.1
12/07/2013	220	69	12.25	7.7

The degree of COD removal from the willow system is illustrated in Figure 6.21, with the periods of effluent loading to the system highlighted in blue. The amount within the system remained relatively low for the full duration of the sampling period. As mentioned already, it is also interesting to note the apparent spike in the amount of COD within the willow system which followed the brief period in June 2012 in which the system was receiving STE. The

increase was quite high compared to the corresponding loading of effluent which suggests that the effluent was accumulating near the inspection well as a result of being distributed on the surface. This may have given an artificially high COD concentration that wasn't representative of the entire system.

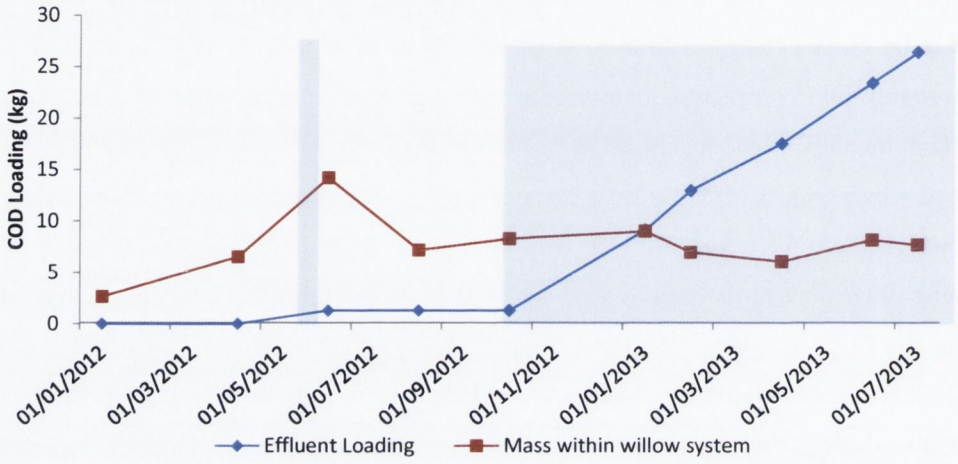


Figure 6.21 COD removal on Site D throughout monitoring period

By comparing the mean COD concentration of the willow system samples with the means from the four systems not receiving effluent, it can be seen that the organic removal rate was not as high on System D compared to the systems on Sites A, B and C, which were also receiving STE. While those systems all had a mean COD within the range measured on the systems not receiving effluent (26.1 - 43.7 mg/l), it was marginally higher (56.5 mg/l) for this system.

6.6.2 Nitrogen

The extent of inorganic-N removal within the willow system is illustrated in Figure 6.22. The concentration and total mass of inorganic-N was relatively consistent within the system, with the exception of the last sampling date (12/07/2013) which saw a spike in the NO_3-N concentration. It can be seen that there as a significant reduction over the sampling period.

It can be seen in Figure 6.22 that reduction in total inorganic-N continued throughout the winter months. This could be as a result of the effluent escaping via overflow. As detailed for the COD, the effluent was distributed on the surface so this was more likely to occur on this particular system. Denitrification may also have accounted for some of the loss from the system. The

proportion of each of the nitrogen forms in the STE loading and the mass within the willow system is shown Table 6.19.

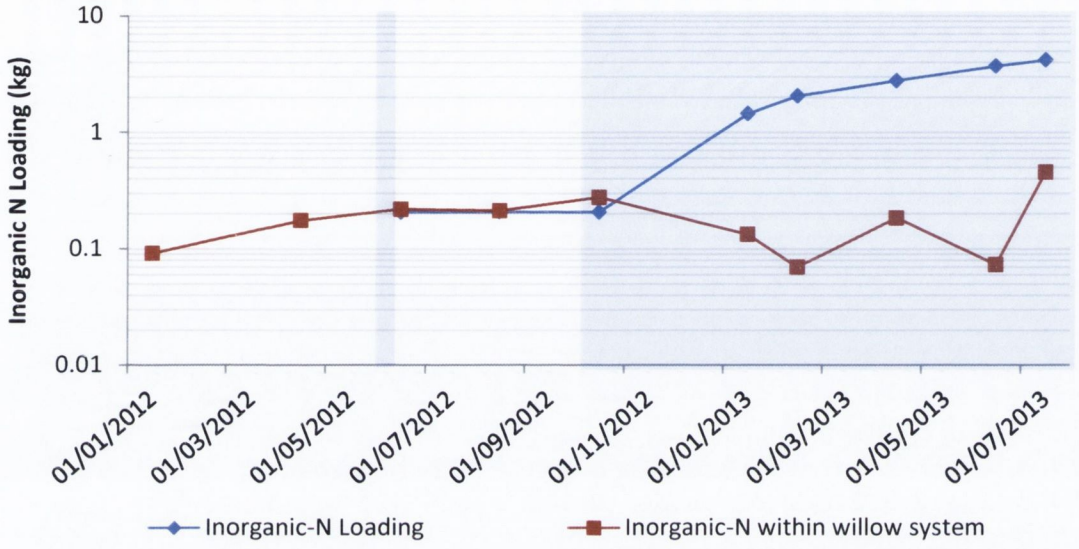


Figure 6.22 Inorganic-N removal on Site D throughout monitoring period (note log scale)

Table 6.19 Concentrations of different forms of nitrogen in STE and willow system on Site D

Date	STE					Willow System				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	6.0	1.1	2.9	2.0	0.1	1.0	0.4	0.1	0.5	0.1
03/04/2012	58.0	9.5	48.0	0.4	0.1	3.0	1.7	0.3	0.9	0.0
19/06/2012	26.0	24.4	1.3	0.3	0.0	7.0	5.5	0.2	1.3	0.1
07/08/2012	43.0	10.2	32.0	0.8	0.0	6.0	4.6	0.5	0.9	0.1
16/10/2012	31.0	5.4	25.0	0.6	0.0	10.0	8.1	0.8	0.9	0.3
08/01/2013	15.5	5.3	10.2	0.0	0.0	3.9	3.0	0.2	0.7	0.0
18/02/2013	6.2	3.0	3.2	0.0	0.0	1.1	0.6	0.5	0.0	0.0
08/04/2013	63.0	9.0	54.0	0.0	0.1	2.0	0.7	0.4	0.8	0.1
10/06/2013	87.5	15.6	71.0	0.9	0.1	5.0	4.4	0.2	0.4	0.0
12/07/2013	60.0	7.1	52.0	0.9	0.1	5.1	1.0	0.0	4.0	0.1
Mean	39.6	9.0	30.0	0.6	0.0	4.4	3.0	0.3	1.0	0.1
% *	-	-	92.2%	7.2%	0.6%	-	-	30.3%	64.3%	5.3%

* Percentage of inorganic-N

As expected NH_4-N makes up the majority of the STE (mean, 92.2%). The majority of the inorganic-N in the willow system was in the form of NO_3-N (mean, 64.3%) showing that

nitrification has taken place, although the concentrations of NO_3-N are very low and NH_4-N still makes up a significant proportion (mean, 30.3%). This increase in the proportion of NO_3-N also translates across to the overall mass in the willow system. As illustrated in Figure 6.23 the amount of NO_3-N within the willow system was greater than that added via effluent loading up to that point for almost the entire sampling period. However, the amount was still quite small and was probably representative of the amount within the system due to background concentrations. This was negated somewhat by the significant reduction in NH_4-N between STE and willow system.

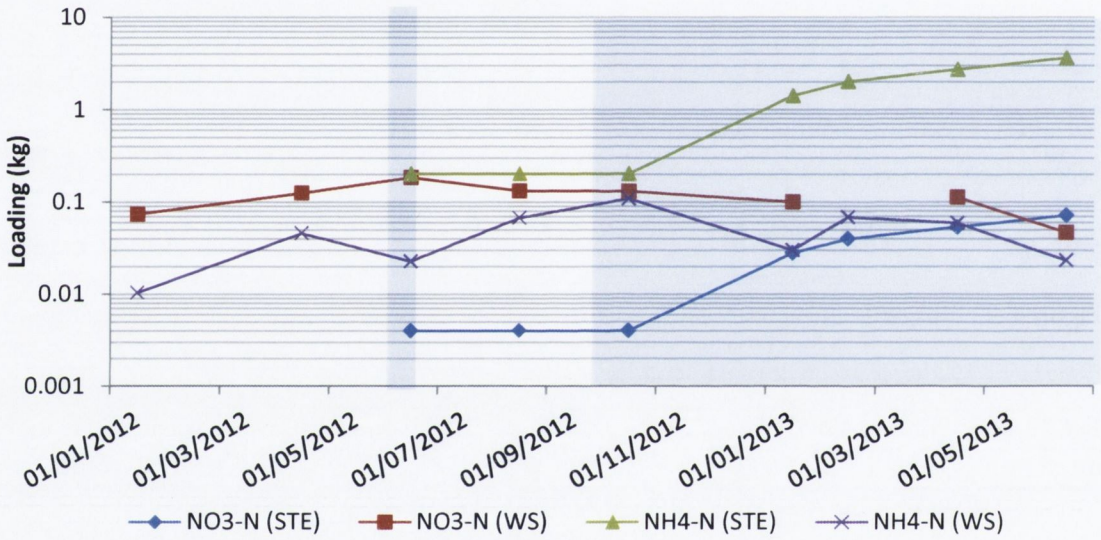


Figure 6.23 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site D (log scale; a value below the minimum value on the y-axis represents zero)

The mean concentrations of the different nitrogen forms measured in samples from the willow system compared positively with the corresponding samples taken from the systems not receiving effluent. The mean total N of the samples from willow System A was 4.4 mg/l, with the mean concentrations ranging from 6.3 mg/l to 11.5 mg/l on the four systems not receiving effluent. The mean NH_4-N and NO_3-N concentrations of 0.3 mg/l and 1 mg/l also compared very favourably with the results of the four systems not receiving effluent, which had NH_4-N concentrations ranging from 0.1-0.8 mg/l and NO_3-N concentrations ranging from 1.3-3.3 mg/l.

6.6.3 *Phosphorus*

The rate of removal of PO_4-P within the willow system on Site D is illustrated in Figure 6.24. Similarly to the organics, there was a spike in the apparent stored mass within the system that coincides with the two weeks of loading that took place in June 2012. It quickly decreases after this period of loading was finished and does not increase again until January 2013, approximately 4 months after permanent loading had commenced. It is noticeable that the amount of phosphorus drops off in the winter period, which may be a result of overflow from the system. As with the previously discussed systems, there is likely to have been some removal of phosphorus within the soil due to absorption and mineral precipitation.

The mean PO_4-P concentration of 0.2 mg/l, which was determined from the willow system samples, was within the range (0.1 - 0.8 mg/l) determined for the samples on the four willow systems that were not receiving effluent, indicating the relatively good removal rate of PO_4-P by the system.

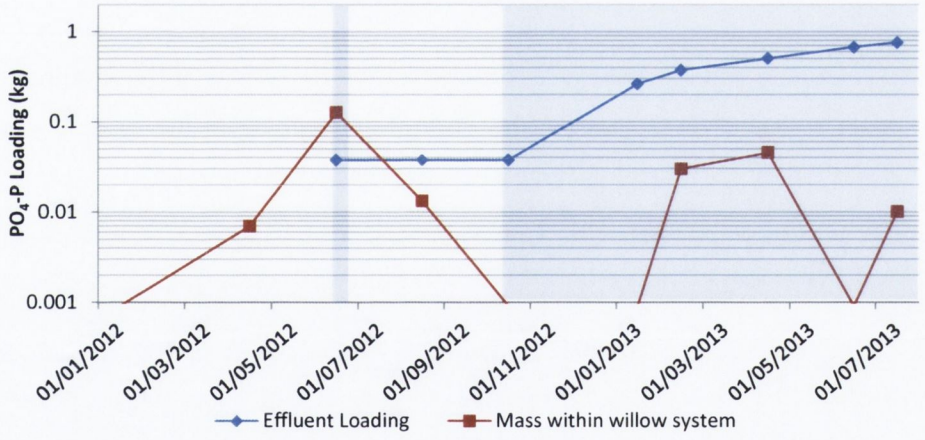


Figure 6.24 PO_4-P removal on Site D throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

6.6.4 *Salinity*

The mean Cl concentration in the effluent was 193 mg/l, which is towards the higher end of the range reported by Gill et al. (2009a) for STE from a number of Irish dwellings. The mean SO_4 concentration in the STE was 79 mg/l. The cumulative loading from the STE along with the cumulative mass within the willow system is shown for both salts in Table 6.20. The amount of chloride within the willow system is higher than the apparent amount received up until that

point by effluent loading. The background levels in the soil may have contributed towards some of this, and some may be remaining from the initial effluent loading to the system shortly after it had been completed in the summer of 2010.

Table 6.20 Cumulative chloride and sulphate loading in STE and willow system on Site D

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.00	4.86	0.00	-
03/04/2012	7.10	10.01	2.62	-
19/06/2012	15.02	10.08	5.54	0.71
07/08/2012	20.06	6.58	7.40	0.00
16/10/2012	27.26	9.43	10.06	0.87
08/01/2013	35.90	5.45	13.25	0.14
18/02/2013	40.12	5.54	14.81	0.57
08/04/2013	45.16	8.45	16.67	-
10/06/2013	51.65	7.91	19.06	0.47
12/07/2013	54.94	8.90	20.27	-

The extent of Cl and SO_4 removal within the willow system is shown in Figure 6.25. It can be seen that the amount of chloride entering the system quickly surpassed the measured amount within the system which remains relatively constant for the remainder of the sampling period, even after almost a year of STE loading. The amount of sulphate in the system was not as constant; however, it remains much lower than the cumulative loading rate.

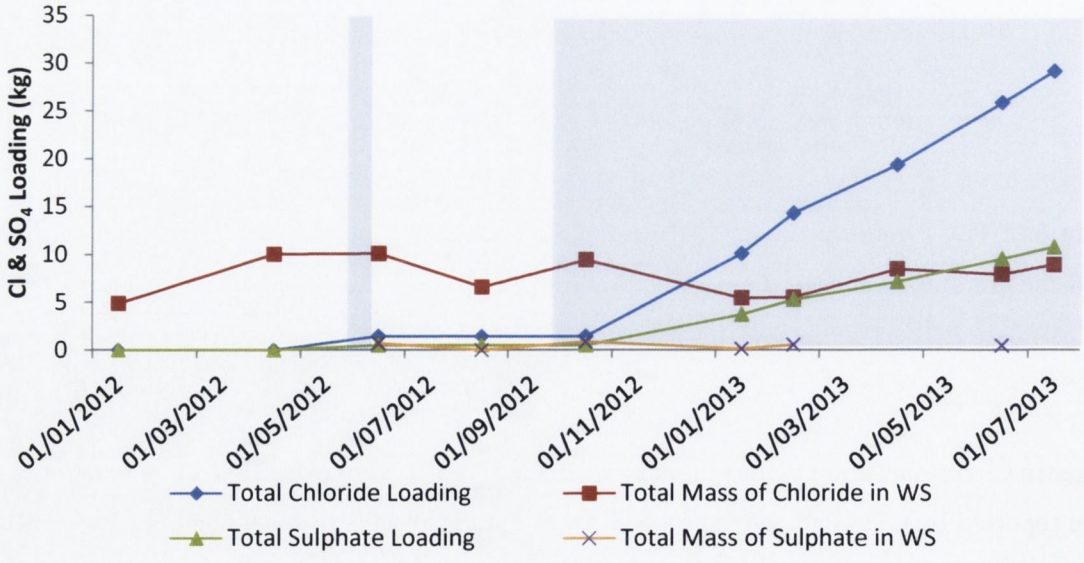


Figure 6.25 Cl & SO_4 removal on Site D throughout monitoring period

By comparing the mean concentration of Cl and SO_4 from willow system samples, it can be seen that there appears to be a build-up of chloride occurring over time. The mean Cl concentration for System D was 57.1 mg/l, which was considerably higher than any of the mean concentrations measured from the systems not receiving effluent (range: 13.2 - 21.1 mg/l). However again, this was not the case with the mean sulphate concentration. The mean concentration was 4 mg/l for the samples from willow System D. This was surprisingly lower than the mean concentrations determined for the four systems receiving no effluent, which ranged 6.3 - 15 mg/l.

6.6.5 *Bacteriological Analysis*

The TC concentrations ranged from 1.22×10^5 - 1.98×10^6 MPN/100 ml for the STE and 5.2×10^1 - 6.13×10^3 MPN/100 ml for the willow system samples. The willow system had a 3.2 log-unit removal rate in TC (equivalent to a 99.9% reduction), which was slightly less than that achieved by the willow system on Site A, but better than on Sites B&C (see Table 6.21).

Table 6.21 Reduction in total coliform concentrations with respect to STE in the willow system on Site D

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	7	1.22×10^5 - 1.98×10^6	6.99×10^5	-
Willow System	6	5.2×10^1 - 6.13×10^3	3.96×10^2	3.2

The geometric mean *E. coli* concentrations of the STE and willow system samples were 6.14×10^4 MPN/100 ml and 1.97×10^2 MPN/100 ml respectively. This represented a log-unit removal rate of 2.5 (equivalent to an overall reduction of 99.7%). However, when the individual samples from the willow system are examined it can be observed that some of them contained significant numbers of enteric bacteria (Table 6.22). This suggests that an overflow from the willow system could pose a possible risk to human health if the effluent were to reach groundwater drinking supplies.

Table 6.22 Concentrations of *E. coli* measured on 6 different occasions on Site D

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	6	-	-	-	6
Willow System	6	4	1	-	1

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site D are shown in Figure 6.26. It can be seen that there is a tendency for it to be much higher during the summer, with winter concentrations all below 50 MPN/100ml. The spike (3900 MPN/100 ml) in June 2012 coincides with the brief loading of STE that took place at that time. As was the case for Sites A&B, this pattern is significant in that it shows that pathogen concentrations were relatively low during the dormant season when overflow from a fully developed willow system is most likely to occur.

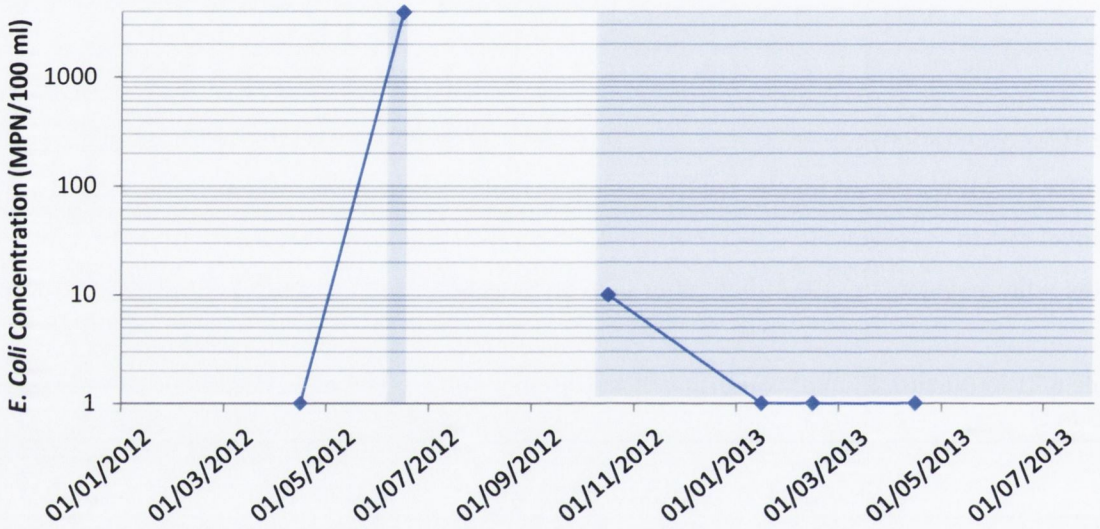


Figure 6.26 Temporal *E. coli* concentrations during sampling period on Site D (note log scale)

6.7 Site H Duncormick - System 1

6.7.1 Organics

The results from the COD analysis are shown in Table 6.23. It can be seen that there was a significant reduction of COD both in terms of the concentration and the cumulative amount within the willow system. Effluent flow to the site did not start until March 2012, which explains the zero COD loading at the beginning of the sampling period. It should be noted that this willow system was receiving approximately 75% of the total amount of STE produced on the site (mean daily total of 362.5 L/day).

Table 6.23 COD concentrations and cumulative loading for STE and willow system on Site H (System 1)

Date	COD Concentration (mg/l)		Cumulative COD (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	-	20	0.0	0.3
03/04/2012	406	5	7.0	0.2
19/06/2012	385	81	22.8	6.4
07/08/2012	854	-	32.9	4.6
16/10/2012	-	81	47.2	6.3
18/02/2013	352	48	72.9	-
08/04/2013	842	37	83.0	-
10/06/2013	1274	28	95.9	1.8
12/07/2013	1172	55	102.5	3.1

The extent of COD removal within the willow system is illustrated in Figure 6.27. There are some data points missing from the cumulative amount within the willow system at the start of 2013 as a result of the pumping out of the system which took place during that period. It can be seen that there was a noticeable increase in the amount of organics within the system coinciding with the start of effluent loading. This appears to have dropped off again towards the end of the sampling period probably as a result of the willow trees being more developed and thus requiring more carbon.

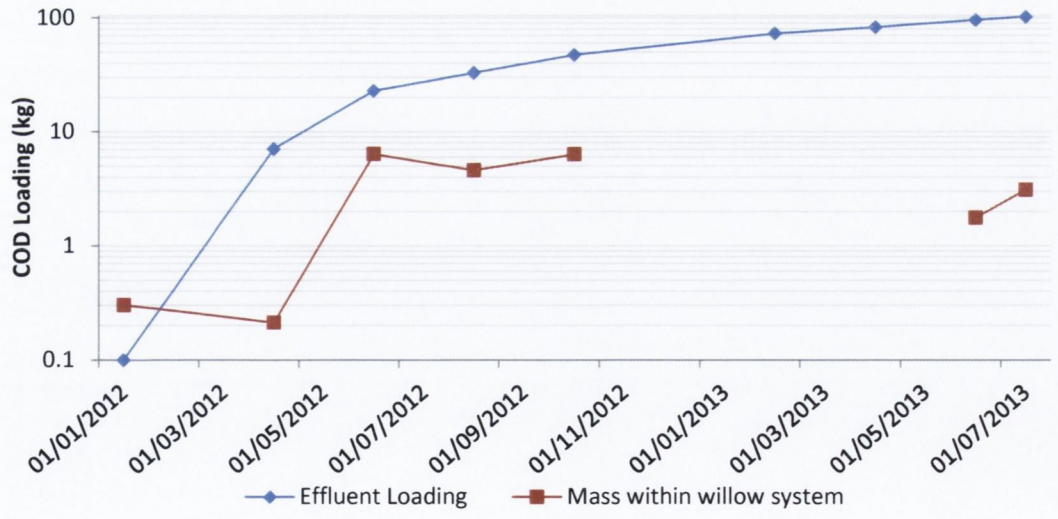


Figure 6.27 COD removal on Site H (System 1) throughout monitoring period (note log scale)

The mean COD concentration (from the willow system sample) of 45.7 mg/l, although slightly higher, still compared quite positively to the range of mean COD concentrations determined for the willow systems that were not receiving effluent which ranged from 26.1 mg/l to 43.7 mg/l).

6.7.2 Nitrogen

The extent of total inorganic-N removal within the willow system is shown in Figure 6.28. The concentration of NO_3-N in the willow system was relatively constant throughout the sampling period; however, there did appear to be an increase occurring for the NH_4-N concentration as the sampling period progressed. This may be because of anaerobic conditions within the system, as it was almost constantly at full capacity (apart for a brief period after being pumped out), which meant there would have been a lack of oxygen for nitrification to take place. However, it can be seen that there was a still a significant reduction in total inorganic-N taking place during the sampling period.

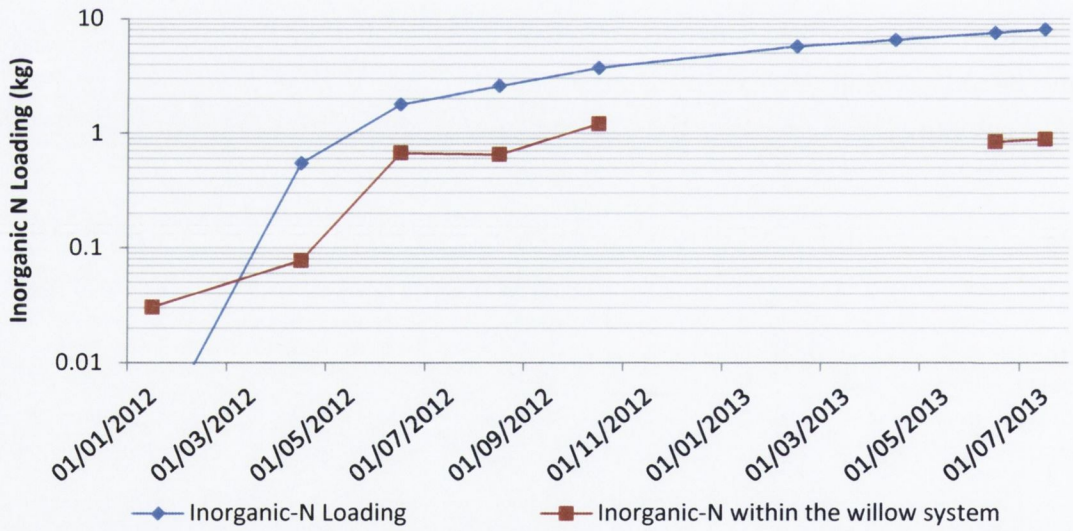


Figure 6.28 Inorganic-N removal on Site H (System 1) throughout monitoring period (note log scale)

Unfortunately, due to the pumping out taking place, it is difficult to ascertain whether or not there was a build-up of inorganic-N over the winter months. The breakdown of the different forms of nitrogen is shown in Table 6.24. The majority of the STE was comprised of NH_4-N (96.5%), with NO_3-N making up most of the rest.

Table 6.24 Concentrations of different forms of nitrogen in STE and willow system on Site H (System 1)

Date	STE					Willow System				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	-	-	-	-	-	-	-	0.1	1.9	0.0
03/04/2012	33.0	10.7	22.0	0.2	0.1	5.0	3.2	0.2	1.6	0.0
19/06/2012	76.0	12.2	63.0	0.6	0.2	15.0	6.5	8	0.5	0.0
07/08/2012	74.0	11.6	61.0	1.2	0.2	21.0	13.1	6.8	1.1	0.0
16/10/2012	-	-	-	-	-	33.0	17.5	15	0.5	0.0
18/02/2013	45.0	10.1	34.0	0.7	0.2	14.0	9.2	4.7	0.1	0.0
08/04/2013	98.0	10.9	86.0	0.8	0.3	9.0	1.6	7.2	0.2	0.0
10/06/2013	95.0	33.8	59.6	1.4	0.2	17.4	4.0	12.5	0.9	0.0
12/07/2013	85.0	3.5	71.0	10.3	0.2	16.0	0.3	14.1	1.6	0.0
Mean	72.3	13.3	56.7	2.2	0.2	16.3	6.9	7.6	0.9	0.0
% *			96.5%	3.1%	0.4%			64.6%	34.7%	0.6%

* Percentage of inorganic-N

It can be seen that there is some nitrification occurring within the willow system (NO_3-N comprises 34.7 % of the total inorganic-N in the samples), but NH_4-N still makes up a significant proportion of the total inorganic-N (64.6%) that wasn't taken up by the willow trees. When the mean NO_3-N concentrations are compared it can be seen that the mean concentration in the willow system (0.9 mg/l) was only slightly less than that in the STE (2.2 mg/l). This suggests that while there is some nitrification occurring in the system, a substantial amount of N-removal may be as a result of the anammox process, which allows the conversion of NH_4-N directly to nitrogen gas bypassing the NO_3-N phase in the process.

When the total amounts are examined it can be seen that there was a significant reduction in the total amount of NH_4-N (see Figure 6.29). While there was an increase in the proportion of NO_3-N in the willow system compared to the STE, it can be seen that there was a reduction in the overall amount.

The mean concentration of total N measured in the willow system samples of 16.3 mg/l which was somewhat higher than the background concentrations measured at the four systems not receiving effluent. The mean NH_4-N concentration of 7.6 mg/l was significantly higher that measured in the four systems (which ranged 0.1 - 0.8 mg/l). This is probably as a result of the relatively slow development of the willow trees, as the mean concentrations in the willow systems with more developed trees were much lower.

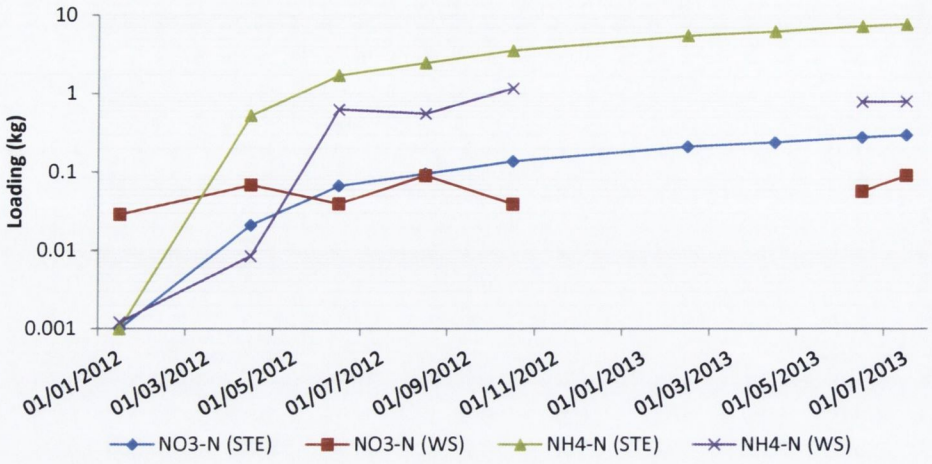


Figure 6.29 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site H (System 1) (note log scale)

6.7.3 *Phosphorus*

The degree of removal of PO_4-P within the willow system is illustrated in Figure 6.30. The PO_4-P mass within the willow system was quite erratic. There was a spike shortly after STE loading began in March 2012, before the apparent amount dropped off to negligible amounts, before increasing again at the end of the sampling period. It should be noted that some data points are missing for the time period when pumping out of the system was taking place. Apart from one spike, the cumulative amount within the willow system remained significantly lower than the cumulative amount entering the system from the STE.

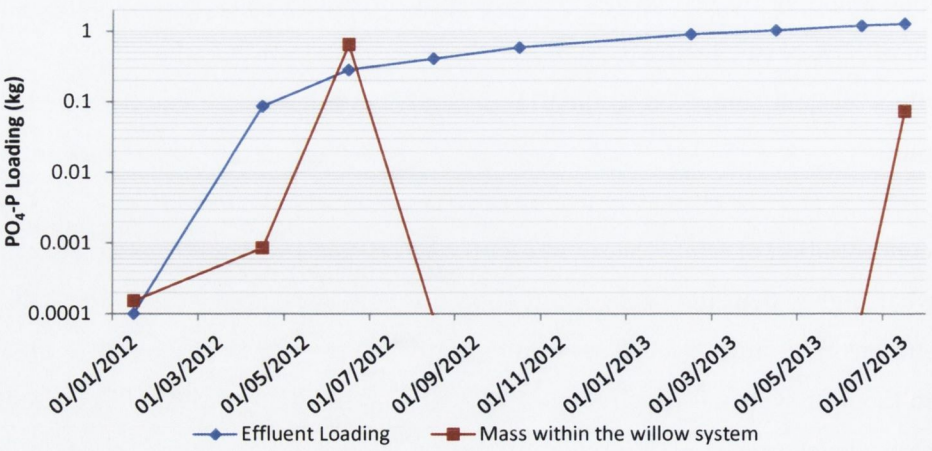


Figure 6.30 PO_4-P removal on Site H (System 1) throughout monitoring period (note log scale; a value below the minimum value on the y-axis represents zero)

The mean PO_4-P concentration of 1.3 mg/l determined from the willow system samples was somewhat higher than the background concentrations measured within the willow system not receiving effluent (which ranged 0.1 - 0.8 mg/l). This suggests that not all of the phosphorus was being taken up by the willow trees, which is not that surprising giving their somewhat stunted development.

6.7.4 Salinity

The mean Cl concentration in the STE was 105.3 mg/l, which is in line with previously reported concentrations from an Irish context (Gill et al., 2009a). The mean SO_4 concentration in the STE was 76.3 mg/l. The cumulative loading rate and the cumulative mass within the willow system for both non-carbonate salts are shown in Table 6.25.

Table 6.25 Cumulative chloride and sulphate loading in STE and willow system on Site H (System 1)

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.00	0.13	0.00	-
03/04/2012	0.97	1.26	0.71	-
19/06/2012	3.18	3.18	2.30	0.79
07/08/2012	4.58	0.00	3.32	0.00
16/10/2012	6.59	3.74	4.77	0.62
08/01/2013	10.17	0.00	7.36	0.00
18/02/2013	11.57	0.00	8.38	-
08/04/2013	13.38	3.27	9.69	0.57
10/06/2013	14.29	3.15	10.35	-

The extent of reduction of Cl and SO_4 within the willow system is shown in Figure 6.31. It can be seen that the amount of chloride within the system increases almost simultaneously with the corresponding amount entering the system via STE up until midway through 2012. By the end of the sampling period the amount of chloride has stayed at approximately the same level. This may have been aided by the pumping out process, which may have removed some chloride. The amount of sulphate within the system appears quite erratic, but remains at a much lower amount that the cumulative amount entering the system.

By comparing the mean concentration of Cl and SO_4 from willow system samples, it can be seen that there appears to have been a build-up of chloride occurring over time in comparison to the willow systems that were not receiving any effluent. The mean Cl concentration for System 1 was 40.3 mg/l, which was considerably higher than any of the mean concentrations measured

from the systems not receiving effluent (range: 13.2 - 21.1 mg/l). The mean sulphate concentration of 19.8 mg/l was also higher than the mean background concentrations. Although the difference was not as significant, as the background concentrations on the systems not receiving effluent ranged from 6.3 - 15 mg/l.

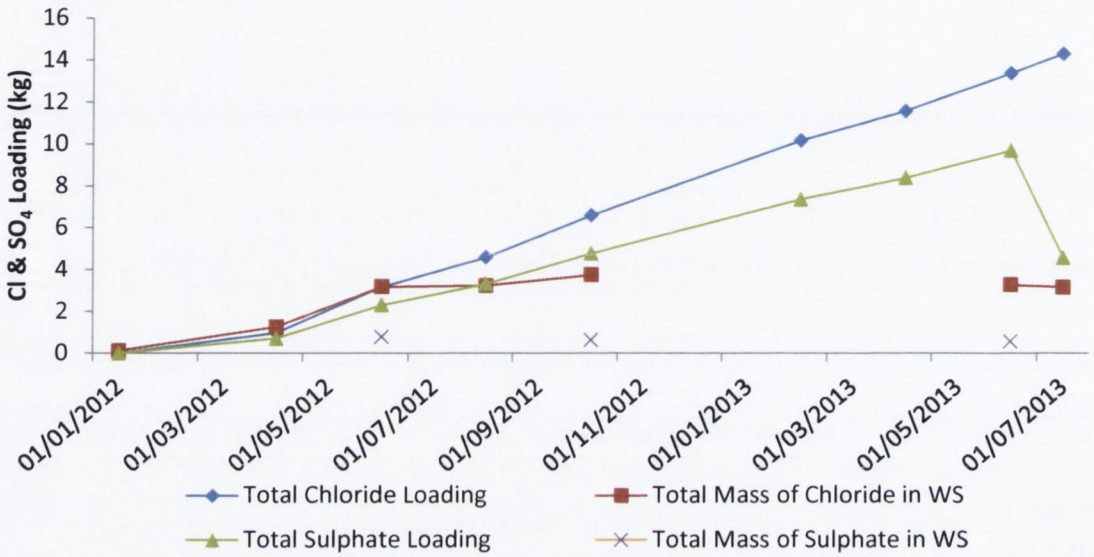


Figure 6.31 Cl & SO_4 removal on Site H (System 1) throughout monitoring period

6.7.5 *Bacteriological Analysis*

The TC concentrations ranged from 1.98×10^6 – 6.13×10^6 MPN/100 ml for the STE and 6.2×10^2 – 1.99×10^5 MPN/100 ml for the willow system samples. The willow system had a 2.5 log-unit removal rate in TC (equivalent to a 99.7% reduction), which was lower than that achieved by all the previous systems (see Table 6.26)

Table 6.26 Reduction in total coliform concentrations with respect to STE in the willow system on Site H (System 1)

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	4	1.98×10^6 – 6.13×10^6	3.17×10^6	-
Willow System	4	6.2×10^2 – 1.99×10^5	1.01×10^4	2.5

The geometric mean *E. coli* concentrations of the STE and willow system samples were 1.42×10^5 MPN/100 ml and 7.69×10^1 MPN/100 ml respectively. This represented a log-unit removal rate of 5 (equivalent to an overall reduction of > 99.9%). However, when the individual samples

from the willow system are examined it can be observed that two out of the four samples contained significant numbers of enteric bacteria (Table 6.27). This suggests that an overflow from the willow system could pose a risk if it made its way to groundwater supplies.

Table 6.27 Concentrations of *E. coli* measured on 6 different occasions on Site H (System 1)

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	4	-	-	-	4
Willow System	4	2	-	-	2

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site H (System 1) are shown in Figure 6.32. Although there are relatively few samples, it can be seen that there was a spike in concentration (16070 MPN/100 ml) during the winter, with concentrations that were measured during the summer period dropping back to zero. This is in great contrast to the trend on Sites A&B, which had low concentrations in the winter.

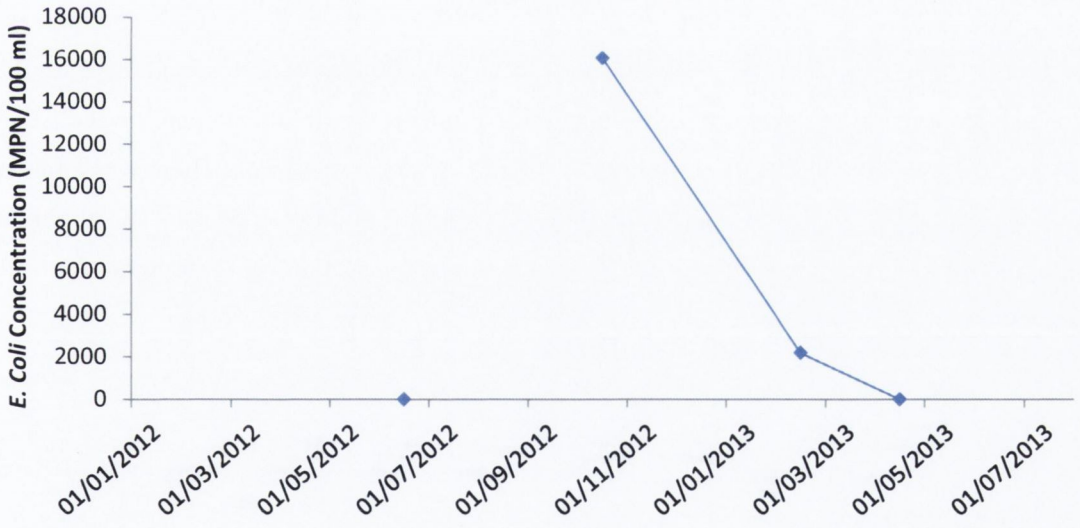


Figure 6.32 Temporal *E. Coli* concentrations during sampling period on Site H (System 1)

6.8 Site H Duncormick - System 2

6.8.1 Organics

The results of the COD analysis for System 2 on Site H are presented in Table 6.28. It can be seen that there was a significant reduction of COD both in terms of the concentration and the

cumulative amount. Effluent flow to the site did not start until March 2012, which explains the zero COD loading at the beginning of the sampling period. It should be noted that this willow system was receiving approximately 25% of the total amount of STE produced on the site (mean daily total of 362.5 L/day).

Table 6.28 COD concentrations and cumulative loading for STE and willow system on Site H (System 2)

Date	COD Concentration (mg/l)		Cumulative COD storage (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	-	2	0.00	0.1
03/04/2012	406	16	2.3	0.7
19/06/2012	385	68	7.6	6.3
07/08/2012	854	95	11.0	9.2
16/10/2012	-	36	15.8	3.5
18/02/2013	352	100	24.4	3.0
08/04/2013	842	129	27.8	11.6
10/06/2013	1274	114	32.1	6.5
12/07/2013	1172	130	34.3	6.4

The extent of COD removal within the willow system is illustrated in Figure 6.33. The increase in the amount of COD within the willow at the start of the sampling period coinciding with the start of STE loading at the site is apparent. It continued to increase simultaneously until the end of the 2012 growing season, before dropping off during the dormant season. There was another increase at the start of 2013, before a continual decline until the end of the season. The apparent decrease over the dormant season is probably as a result of the system being pumped out over that period.

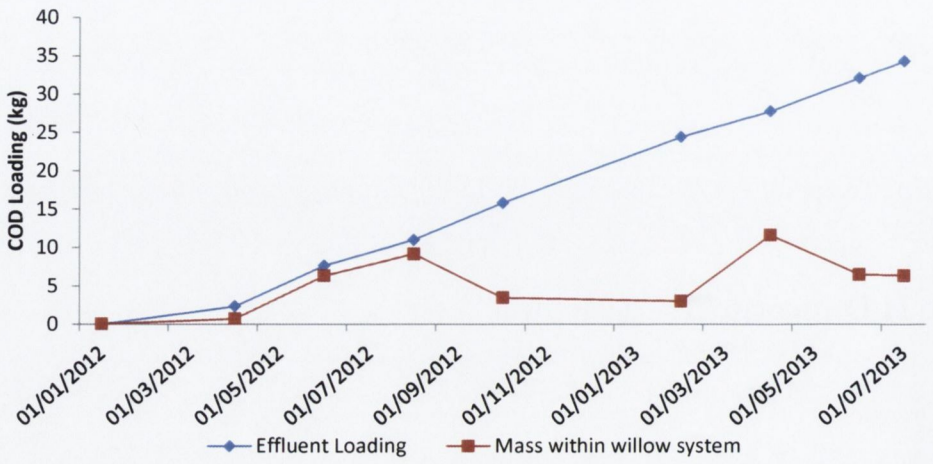


Figure 6.33 COD removal on Site H (System 2) throughout monitoring period

The mean COD concentration (from the willow system sample) of 76.7 mg/l was significantly higher than the background concentrations measured within the willow systems that were not receiving effluent (26.1 mg/l to 43.7 mg/l). This highlights the fact that this willow system was not performing as well as the other discussed systems with more developed willow trees.

6.8.2 Nitrogen

The extent of total inorganic-N removal within the willow system is shown in Figure 6.34. The concentration of NO_3-N in the willow system was relatively constant throughout the sampling period; however, there was a steady increase noted in the NH_4-N concentration. As pointed out for System 1 on this site (H), this may have been as a result of anaerobic conditions within the system.

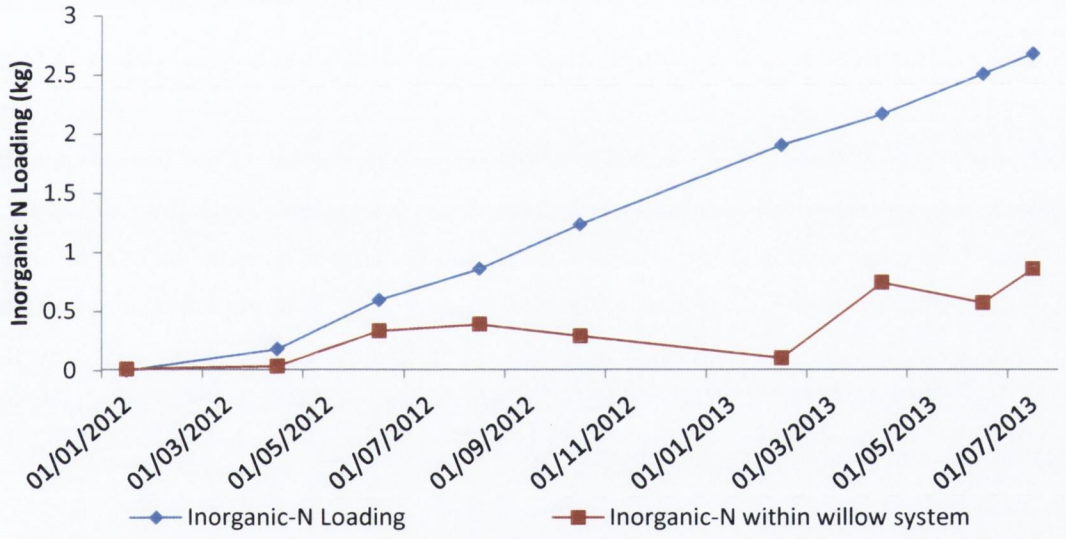


Figure 6.34 Inorganic-N removal on Site H (System 2) throughout monitoring period

It is difficult to ascertain the removal rate throughout the dormant season due to the pumping out that took place during the winter months. There was a slight decrease noted in the total amount of organics within the system towards the end of the 2012 growing season. The total amount can be seen to increase rapidly as the system fills up after being pumped out at from March to April 2013. As detailed for System A, the majority of the STE was comprised of NH_4-N (96.5%), with NO_3-N making up most of the remainder.

Table 6.29 Concentrations of different forms of nitrogen in STE and willow system on Site H (System 2)

Date	STE					Willow System				
	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N	Total N	Org-N	NH_4-N	NO_3-N	NO_2-N
25/01/2012	-	-	-	-	-	1.5	0.91	0.08	0.8	0.03
03/04/2012	33.0	10.7	22.0	0.2	0.1	4	0.91	0.03	0.8	0.08
19/06/2012	76.0	12.2	63.0	0.6	0.2	5	3.63	0.49	3.1	0.04
07/08/2012	74.0	11.6	61.0	1.2	0.2	13	4.06	2.75	1.2	0.11
16/10/2012	-	-	-	-	-	15	3.07	2.66	0.4	0.01
18/02/2013	45.0	10.1	34.0	0.7	0.2	13	3.6	2.8	0.6	0.2
08/04/2013	98.0	10.9	86.0	0.8	0.3	28	8.26	7.6	0.5	0.16
10/06/2013	95.0	33.8	59.6	1.4	0.2	12.9	10.12	9.1	0.9	0.12
12/07/2013	85.0	3.5	71.0	10.3	0.2	22.5	17.6	15.2	2.3	0.1
Mean	72.3	13.3	56.7	2.2	0.2	12.8	7.0	4.5	1.2	0.1
% *	-	-	96.5%	3.1%	0.4%	-	-	58.4	38.7	2.8

* Percentage of inorganic-N

It can be seen that there was some nitrification occurring within the willow system (NO_3-N comprises 38.7% of the total inorganic-N in the samples), but NH_4-N still makes up a significant proportion of the total inorganic-N (58.4%) that wasn't taken up by the willow trees. When the total amounts are examined it can be seen that there was a significant reduction in the total amount of NH_4-N (see Figure 6.35). After an initial spike, the total amount of NO_3-N in the system then declines and remains less than the cumulative amount entering the system until the end of the sampling period. The decline over the winter period was probably aided by the system being pumped out, as it can also be seen that there was an increasing trend towards the end of the sampling period after pumping has ceased.

The mean concentration of total N measured in the willow system samples of 12.6 mg/l which was only marginally higher than the background concentrations measured at the four systems not receiving effluent. The mean NH_4-N concentration of 4.5 mg/l was significantly higher than that measured in the four systems (which ranged 0.1 - 0.8 mg/l). This is probably as a result of the relatively slow development of the willow trees, as the mean concentrations in the willow systems with more developed trees were much lower.

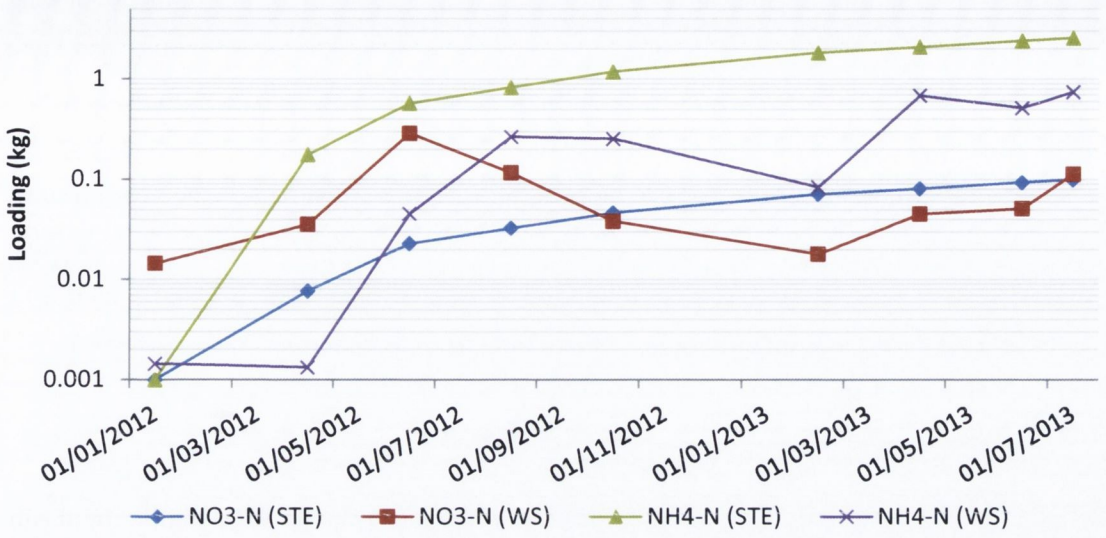


Figure 6.35 NH_4-N and NO_3-N loading in the STE and corresponding mass within the willow system on Site H (System 2) (note log scale)

6.8.3 Phosphorus

The extent of removal of PO_4-P within the willow system is illustrated in Figure 6.36. It can be seen that the PO_4-P mass within the willow system was quite erratic. There was a spike shortly after STE loading began in March 2012, before the apparent amount dropped off to negligible amounts. Apart from one sharp increase, the amount within the willow system remained significantly lower than the cumulative amount entering the system from the STE.

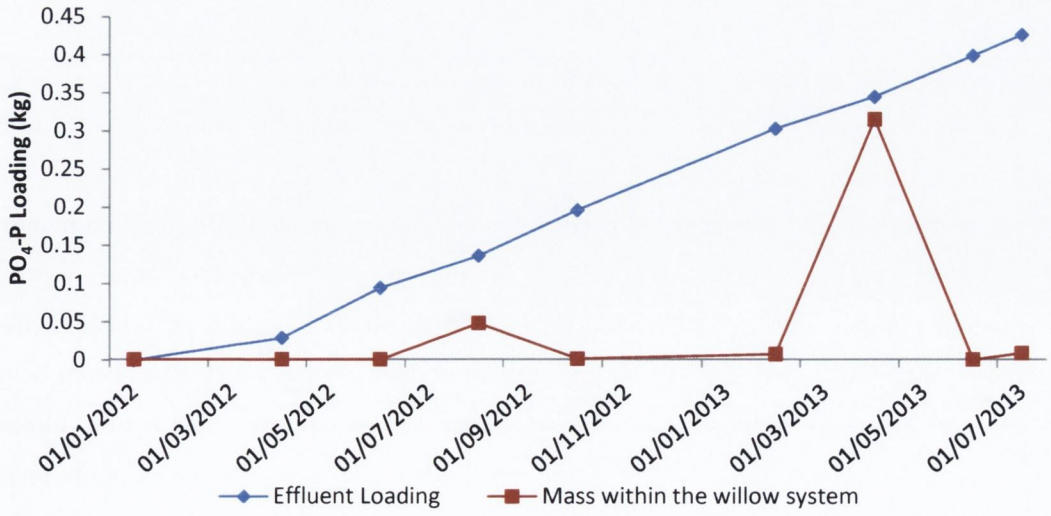


Figure 6.36 PO_4-P removal on Site H (System 2) throughout monitoring period

The apparent low amounts during the dormant season suggests that there was reduction taking place in the soil within the system (although the low level at the start of 2013 would also have been as a result of the system getting pumped out) via adsorption and precipitation processes.

The mean PO_4-P concentration of 0.5 mg/l compared positively to the background concentrations measured on the systems that weren't receiving effluent. It was also considerably lower than the mean concentration measured on System 1 on this site, which isn't surprised given the load was much smaller (25% of total STE compared to 75% on System 1).

6.8.4 Salinity

As detailed for System 1, the mean Cl concentration in the effluent was 105.3 mg/l. The mean SO_4 concentration in the effluent was 76.3 mg/l. The cumulative loading rate and the mass stored within the willow system for both non-carbonate salts are shown in Table 6.30.

Table 6.30 Cumulative chloride and sulphate loading in STE and willow system on Site H (System 2)

Date	Chloride Loading (kg)		Sulphate Loading (kg)	
	STE	Willow System	STE	Willow System
25/01/2012	0.00	0.29	0.00	
03/04/2012	0.33	2.25	0.24	
19/06/2012	1.06	3.52	0.77	2.23
07/08/2012	1.53	4.34	1.11	0.00
16/10/2012	2.20	3.64	1.60	0.19
18/02/2013	3.40	1.32	2.46	0.39
08/04/2013	3.87	4.78	2.80	
10/06/2013	4.47	2.67	3.24	0.68
12/07/2013	4.78	3.08	3.46	

It can be seen (Figure 6.37) that the total amount of chloride within the system appears to be greater than the cumulative amount that would have entered via STE loading. Obviously this should not be the case, and the recorded concentrations may be inflated due to effluent short-circuiting to the inspection well before dispersing through the soil. Thus, these values may not be representative of the entire willow system. The total amount of chloride does appear to drop off at the end of the 2012 growing season, before a large decrease caused by the system being pumped out in early 2013. However, it rebounds back up shortly after this before another decline coinciding with the start of the 2013 growing season. Readings for the sulphate levels within the willow system are quite sparse, but apart from a spike at the start of the sampling

period coinciding with the effluent loading to the system, the total amount remains significantly less than the cumulative amount that would have entered via loading.

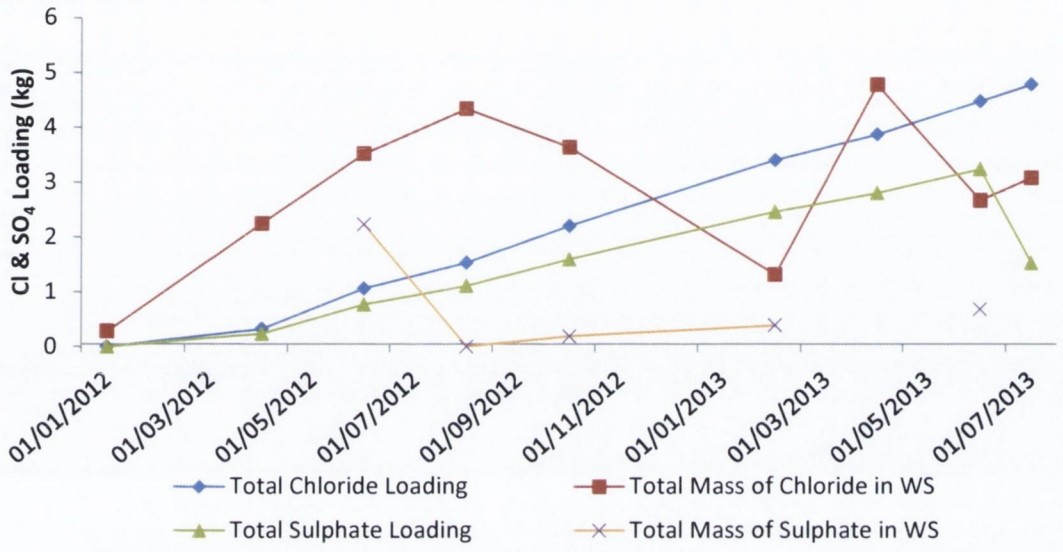


Figure 6.37 Cl & SO_4 removal on Site H (System 2) throughout monitoring period

A comparison of the mean concentration of Cl of the samples taken from the willow system with the background concentrations measured on the willow system that were not receiving effluent reveals that it was significantly higher. The relative high concentration (43.8 mg/l) shows that there may be a slight build-up of salinity in the system. This difference does not exist when comparing the sulphate concentrations, however, with the mean sulphate concentration 12.8 mg/l lying within the range of those 4 systems not receiving effluent.

6.8.5 Bacteriological Analysis

The TC concentrations ranged from 1.98×10^6 - 6.13×10^6 MPN/100 ml for the STE and 6.2×10^2 - 3.44×10^3 MPN/100 ml for the willow system samples. The willow system had a 2.7 log-unit removal rate in TC (equivalent to a 99.8% reduction), which was quite similar to that achieved by System 1 on the same site (Table 6.31).

Table 6.31 Reduction in total coliform concentrations with respect to STE in the willow system on Site H (System 2)

	No. of Samples	Range (MPN/100 ml)	Geometric Mean (MPN 100 m/L)	Log-unit Removal
STE	4	1.98×10^6 - 6.13×10^6	3.17×10^6	-
Willow System	4	3.44×10^3 - 9.08×10^3	6.1×10^3	2.7

The geometric mean *E. coli* concentrations of the STE and willow system samples were 1.42×10^5 MPN/100 ml and 2.41×10^1 MPN/100 ml respectively. This represented a log-unit removal rate of 3.8 (equivalent to an overall reduction of 99.9%). However, when the individual samples from the willow system are examined it can be observed that three out of the four samples contained significant enteric bacteria (Table 6.32). This suggests that an overflow from the willow system could pose a risk to human health if it made its way into groundwater drinking supplies.

Table 6.32 Concentrations of *E. coli* measured on 4 different occasions on Site H (System 2)

	No. of Samples	Number of samples with concentration (MPN/100 ml)			
		<10	10-100	101-1000	>1000
STE	4	-	-	-	4
Willow System	4	1	1	2	-

The temporal patterns for the *E. coli* concentrations throughout the sampling period on Site H (System 2) are shown in Figure 6.38. Although there are relatively few samples, it can be seen that two spikes in concentration occur; one measured on the 16th October 2012 (109 MPN/100 ml) and the other measured on the 8th April 2013 (100 MPN/100 ml). However, these concentrations are low compared to high concentrations measured on System 2 probably because of the lower loading rate to this system. With such a low number of results it was not possible to determine whether or not there was a seasonal trend.

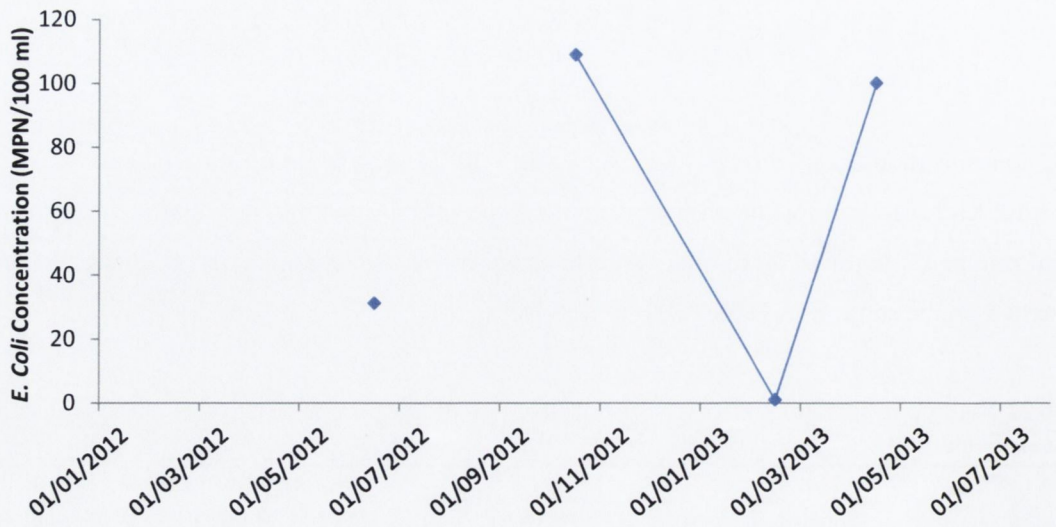


Figure 6.38 Temporal *E. coli* concentrations during sampling period on Site H (System 2)

6.9 Summary

6.9.1 Organics and Nutrients

There was a very high removal rate of organics noted on Sites A, B and C which were the sites with the most developed trees. By the end of the sampling period the removal rate was > 95% for the 3 systems on these sites. This was achieved for loading rates of 3,920 kg/ha, 216 kg/ha, and 1,838 kg/ha for Sites A, B and C respectively. The removal rates equal or better those reported by Dimitriou and Aronsson (2010) for TOC removal rates by willows in lysimeters. The removal rates are also higher than those reported by Rastas Amofah et al. (2012) for a novel willow system, although the loading was much less than the 18,250 kg/ha loading to that system on an annual basis. Removal was not as high on Site D and Systems 1 & 2 on Site H (loading rates of 569 kg/ha, 3946 kg/ha [System 1] and 1319 kg/ha [System 2] respectively), which was probably due to the willow trees on the system being less developed.

The total-N loading rates and removal for the different systems over the duration of the sampling period are shown in Table 6.33. The removal rate was determined with respect to the amounts added via the effluent and the amount within the willow system at the end of the sampling period.

Table 6.33 Total-N removal rates for willow systems by the end of the sampling period

Site	Input Loading (kg-N/ha)	Removal Rate
A	770	99%
B	105	86%
C	217	86%
D	234	95%
H(1)	377	91%
H(2)	126	67%

It can be seen that the removal rates were over 85% for the first five systems but dropped back to 67% for System 2 on Site H, which was probably due to poorly developed willow trees on that site. The removal rates for the first five systems are all similar to those reported by Dimitriou and Aronsson (2010) and Dimitriou and Aronsson (2011) for willows receiving loading in lysimeters but was much higher than the 43% removal rates reported by Rastas Amofah et al. (2012) for a novel willow system in trialled in Sweden. This may have been because of the relatively high loading rate of 4400 kg-N/ha applied to this system over the same period coupled with the small area of the system (32m^2).

The total PO_4-P loading rates and removal for the different systems over the duration of the sampling period are shown in Table 6.34. It can be seen that the removal rates were almost 100% for the systems on Sites A, B, C, D and decreased marginally to 94% and 98% for Systems 1&2 on Site H respectively. High removal rates by willow receiving effluent load are well documented in lysimeter experiments (Dimitriou and Aronsson, 2010, Dimitriou and Aronsson, 2011) so the high removal rates are not surprising. This contrasts greatly with the findings of Rastas Amofah et al. (2012) who reported a removal rate of just 23% for a willow system. This low figure can probably be attributed to the small area of the system (32 m^2) coupled with a higher loading rate (600 kg-P/ha) over a similar time period.

Table 6.34 Total PO_4-P removal rates for willow systems

Site	Input Loading (kg-PO_4-P/ha)	Removal Rate
A	85.5	> 99%
B	8.4	> 99%
C	29	> 99%
D	33	> 99%
H(1)	49	94%
H(2)	16.5	98%

6.9.2 Bacteria

As shown in Table 6.35 the bacteriological removal rate was varied between the systems. The highest log-unit removal rates were generally on the sites with better willow development, although Site D was an exception to this. This may have been as a result of the relative fast overflow that may have occurred at times due to the fact that the effluent was distributed on the surface of the system, meaning it had a short pathway to the constructed overflow channel. Log-unit removal of *E. coli* was more varied with no discernible pattern between sites, with respect to tree development.

Table 6.35 Bacteriological removal rates for the systems receiving STE

	Total Coliforms Reduction		***E. coli* Reduction**	
Site	Log-Unit	Total	Log-Unit	Total
A	4	99.99%	3.7	99.99%
B	3	99.9%	2.7	99.81%
C	2.9	99.9%	3.1	99.91%
D	3.2	99.9%	2.5	99.7%
H (1)	2.5	99.7%	5.0	99.99%
H (2)	2.7	99.8%	3.8	99.9%

6.9.3 Salinity

As detailed in Section 2.4.3.5 the build-up of salts over time is seen as an issue which may affect the functionality of a willow system in the long term. However thus far, almost over ten years since being established there have been no reports of salt build-up having a detrimental effect on willow systems in Denmark (Gregersen and Brix, 2001, Brix and Arias, 2011) with monitoring on-going. The oldest systems in this research project are over four years old (constructed in 2009) and there have been no detrimental effects which would have been caused by high salinity levels noticed on any of the systems receiving effluent.

A comparison of the mean concentrations between the sites receiving effluent and those not receiving effluent is shown in Table 6.36. It can be seen that the mean Cl concentration for the sites receiving STE loading are all considerably higher compared to the background Cl concentrations measured on the sites not receiving effluent. There is not as much of a difference for the SO_4 concentrations, with the systems on Sites C & D having quite low values, although systems A, B, and H(1) were slightly above the range of that measured on the sites not receiving effluent.

Table 6.36 Mean concentration of Cl and SO_4 for the willow system samples

Background Site	**Mean Concentration(mg/l)**		**Site**	**Mean Concentration(mg/l)**	
	Cl	SO_4		Cl	SO_4
E	13.2	6.3	**A**	44.4	22.7
F(1)	15.8	15.0	**B**	32.1	19.3
F(2)	15.1	14.4	**C**	34.3	1.8
G	21.1	12.2	**D**	57.1	4.0
			H(1)	40.3	19.8
			H(2)	43.8	12.8

The measured Cl concentrations in the systems receiving effluent are well below any concentrations that have been shown to have a detrimental effect on willow development in various studies. Mirck and Volk (2010) applied five different dilutions (1%, 2%, 5%, 10% and 50%) of leachate with a Cl concentration of 16,423 mg/l and found that the 1% (164 mg/l) dilution had no negative effect on the willow. This is nearly three times the highest concentration measured on any of the willow systems in the project. In a study carried out over two years, Dimitriou and Aronsson (2010) applied up to 9153 kg-Cl/ha per season to willow trees in lysimeters, with no negative effects reported. This was nearly five times the loading rate

applied to the most intensely loaded system in the project (Site A - 1914 kg-Cl/ha per year) showing that salinity levels within the systems are not anywhere near toxic concentrations.

6.9.4 Accuracy of Results

It should be noted that there was a certain degree of uncertainty in the various parameter concentrations determined from laboratory analysis. In field research projects such as this one there are some obstacles to accuracy that are difficult or impossible to overcome. The main issues which would have led to uncertainty in results are the following:

- Single sampling location: The willow system water quality samples were all taken from within the inspection well on each system. This was due to both practical and financial constraints in the project. Such sampling could have led to biased results as the water quality in the inspection well might not be representative of the entire system.
- Time delay: The test kit manuals instruct that sample analysis take place immediately after the sample is collected. This was obviously not possibly in this project as there were over 10 sites, all of which were at least a 1.5 hour drive from the Environmental Lab in Dublin. In order to preserve the samples as much as possible, they were kept in a cooled container while in transit.
- Test kit inaccuracy: The parameter concentration confidence intervals listed with the test kit documentation are generally very small. However, those quality assurance tests are carried out in near perfect laboratory conditions. These conditions would be very difficult to replicate which could lead to further inaccuracies in the analysis results.
- Final removal percentages calculated in terms of final measured values
    - May not be a very accurate representation as there was overflow from a lot of the systems and some of the removal was probably as a result of this.
    - However in a supposedly closed system this is the only way in which a removal rate can be determined.
    - So, the figures provide an idea of the level of removal rates than can be achieved but large confidence intervals should be applied.

So, while individual test results may have some degree of uncertainty associated with it, the analysis results should still present a relatively accurate and useful overview of the treatment performance of the willow systems.

6.9.5 *Conclusion*

Willow systems, when designed correctly, can provide high removal rates with regards to the main pollutant mechanisms in wastewater. As determined in Chapter 5, it is highly unlikely that there will zero discharge from the systems over an extended period of time. However, the results from this chapter show that the willows have the potential to absorb a large percentage of the nutrients and organics from the wastewater. As such, overflow from a system should not represent a major threat to the surrounding environment, due to it consisting primarily of rainfall.

Chapter 7

Mesocosm

7 Mesocosm

7.1 Introduction

As part of this research, a series of mesocosm lysimeter experiments was carried out in Dartry, Dublin 6 on four different willow varieties in order to assess the evapotranspiration rate between each variety under Irish meteorological conditions. The effect on growth response and evapotranspiration from applying different strength effluents to the willow clones was also examined. The monitoring period of the experiment was from January 2010 to December 2012.

7.2 Materials and Methodology

7.2.1 Experimental Setup

Cylindrical containers of height 1000 mm and diameter 540 mm were placed at an open site, and filled with layers of gravel (75 mm), sand (440 mm) and topsoil (460 mm). A 30 mm plastic inspection pipe was inserted into each container to allow for measurement of the water level. Each pipe had 10 mm diameter holes drilled at the bottom to allow for the ingress of water from the gravel layer (see Figure 7.1).

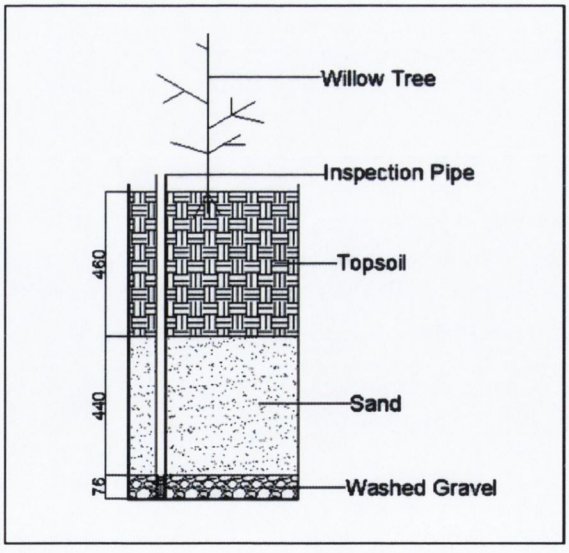


Figure 7.1 Cross sectional detail of container

Before planting the willow trees, each container was calibrated in order to show the volume of water in the barrel with respect to increasing water depth. An example of this is illustrated in

Figure 7.2, which shows the calibration curve for container 1. There appears to be little difference between the storage capacity of the sand and the soil inside the container.

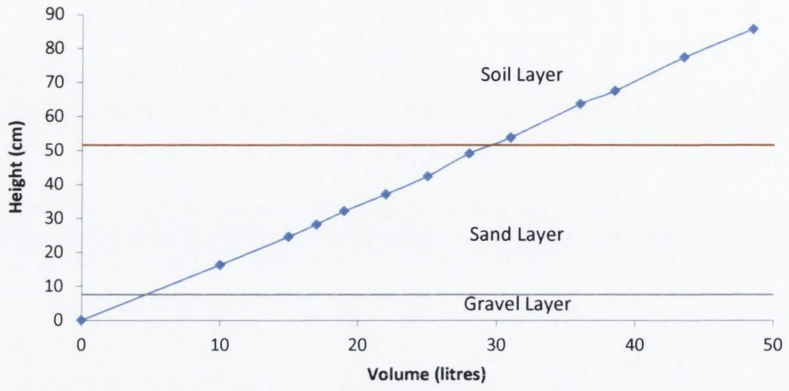
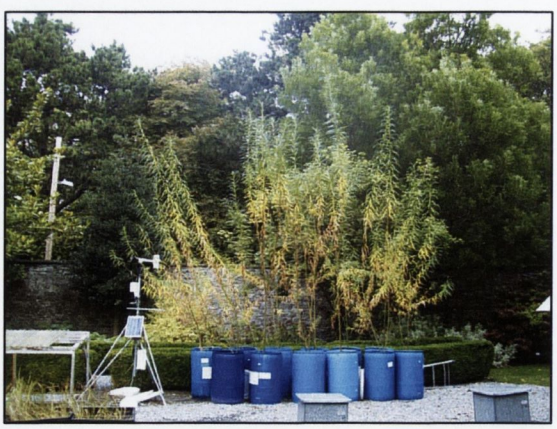


Figure 7.2 Calibration curve for barrel 1

A plant from each variety was given an application of primary (septic tank) effluent (P), secondary treated effluent (S) and rain water (W) (as a control) (see Section 7.2.3). The dosage for all containers (including the control containers) was 2.2 litres per week (i.e. 9.6 mm per week) which equated to the approximate areal hydraulic loading rate that one willow tree would receive in a full-scale willow system, on the basis of assumed on-site wastewater production in Ireland of 150 L per capita per day (EPA, 2009a). All containers were open and in an exposed area and so also received the local natural rainfall (see Figure 7.3 for pictures of experiment).



(A)



(B)

Figure 7.3 (A) Willow trees in the middle of the first growing season (2009); (B) Willow trees at the end of the second growing season (2010), with weather station also in view

7.2.2 *Water Balance*

The evapotranspiration from each lysimeter was calculated by using a water balance equation, in a similar manner to the full scale willow systems (as detailed in Chapter 5). An accurate mass balance of elements entering and leaving the systems required a rigorous assessment of the water budget throughout the monitoring period on the basis of treatment inflows combined with local meteorological effects (rainfall, evapotranspiration rates) as detailed in Eqn. 5.1 and Eqn. 7.2.

$$ET_{willow} = R + I + \Delta V - E \qquad \text{Eqn. 7.1}$$

Where, ET_{willow} = evapotranspiration from willow container

R = rainfall

I = influent / water applied

ΔV = change in water volume within the lysimeter

E = Drainage occurring (mm) [assumed to be zero in these experiments since the mesocosms are in sealed containers]

A weather station (Campbell Scientific) which measured rainfall, temperature, air humidity, net radiation and wind speed was erected in close proximity to the containers. The instruments used to measure the different meteorological parameters are the same as those used on Site A&B and Site F in Co. Wexford (see Section 3.7.5 for details) and were connected to a Campbell Scientific® CR800 datalogger. The potential evapotranspiration (ET_o) was calculated from the collected meteorological data using the modified Penman-Monteith equation (Allen et al., 1998). There were no automatic level loggers as with the full scale willow systems due to financial constraints, so the water level in each container was manually measured at regular time intervals over three growing seasons, from which the corresponding volume was obtained. The actual evapotranspiration from each container for any particular time interval was then calculated using a water balance equation (Eqn. 5.1), taking into account the additional volume of rainfall onto each surface area. The values obtained for actual evapotranspiration were then compared with the potential evapotranspiration to calculate a crop coefficient. Suitable season-dependent crop coefficients (K_c) were established in order to estimate the evapotranspiration related to the willow system (ET_{willow}), as per Eqn. 7.2

The values for each variety and treatment were compared in order to determine the most efficient variety and the optimum treatment type.

$$K_c = \frac{ET_{willow}}{ET_o} \quad \text{Eqn. 7.2}$$

where, K_c = crop coefficient

ET_{willow} = reference evapotranspiration

ET_o = reference evapotranspiration

7.2.3 *Water Sampling and Analysis*

The recipes for the synthetic effluent were based upon recipes by Peeples and Mancl (1998) but then adjusted so the effluent reflected the concentrations more usually found in Irish septic tank (i.e. primary treated) and secondary treated on-site effluent (Gill, 2011). Each ingredient was weighed on a scale, mixed together and then effluent was made up to a total volume of 30 litres. 2.2 litres of the specific effluent treatments were then applied every week to all the willow varieties (i.e. 9.6 mm per week). The treatments were added 20 times over the course of the 2010 growing season, totalling 192 mm, 18 times over the 2011 season totalling 173 mm and 16 times over the 2012 season totalling 144 mm. The rain water for the control containers was collected from runoff from a glass-house roof adjacent to where the mesocosm trials were located. During periods of high evapotranspiration it was occasionally necessary to add some extra water to some of the containers to prevent them drying out and so ensure that there was always available water in the containers for the willows to continue at their maximum evapotranspiration rate. The concentrations of the main parameters along with total amount of each added over the three seasons can be seen in Table 7.1.

Table 7.1 Effluent concentrations and quantities

Parameter	Primary Treatment			Secondary Treatment		
	Average Value (mg/l)	StDev (mg/l)	Total Added[a] (g)	Average Value (mg/l)	StDev (mg/l)	Total Added[a] (g)
COD	849.50	104.50	100.90	261.40	140.80	31.10
Nitrate (as N)	1.00	0.10	0.12	38.90	6.10	4.62
Chloride	159.90	24.80	19.00	81.40	19.43	9.67
Ammonia (as N)	59.10	8.30	7.02	19.90	10.70	2.36
Total Nitrogen (as N)	163.20	49.70	19.40	80.50	18.60	9.56
Ortho-phosphate (as P)	13.90	6.90	1.65	9.52	5.22	1.13
Total-phosphate (as P)	13.24	0.11	1.57	8.93	0.35	1.06
Potassium (as K)	22.60	0.13	2.68	17.61	1.03	2.09

[a] Total amount of each parameter added to each barrel over three seasons

7.2.4 *Plant Biomass Analysis*

At end of the second growing season all trees were coppiced in order to quantify the level of nutrient and organic uptake by the trees. The height, diameter of the main stem and the dried biomass weight were measured. The main stem, side shoots and leaves for each plant were then separated and cut into 2 cm segment samples. All parts were then thoroughly washed in distilled water to remove any sediment or biofilm which may have compromised the sample. The respective stems, side shoots and leaves for each experiment were then labelled and dried in a forced air oven for 3 days at 105°C (until the weight remained constant). Once dry, the respective biomass samples were then weighed. Each sample was then ground down to a fine dust using a mill (Retsch Planetary Ball Mill PM 100).

The phosphorus and potassium extraction was carried out using the acid digestion method as per Standard Methods (Apha, 1998). Firstly, 0.3 g of sample was added to 10 ml of nitric acid and 2 ml of sulphuric acid. The mixture was placed in a vessel and then microwaved for 2 hours in a microwave (Multiwave PRO microwaved reaction system). The mixture was then allowed to cool overnight, before being made up to 50 ml with distilled water. The total phosphorus and potassium concentrations were subsequently measured in an ICP (Inductively Coupled Plasma) machine (Varian, Liberty AX Series II ICP-AES) following calibration against standards over 0.5 to 100 mg/L range.

The Total Nitrogen and Total Organic Carbon values were determined by weighing samples of 5 mg on a micro balance and then wrapping them in foil. The samples were then placed in the Elementar vario EL Cube (which had been calibrated against fixed standards) where they were subjected to high temperature combustion, with detection carried out using thermal conductivity.

Soil samples from each of the containers were taken and analysed in the same manner as the biomass, so that the Total Nitrogen, Total Organic Carbon, Total Phosphorus and Potassium available to the plants from the outset could be determined.

7.2.5 *Statistical Analysis*

The experiment consisted of a 4 x 3 factorial design using the 2 factors, willow variety and treatment type. All parameters measured were expressed as a mean and referred to the individual container. All data was subjected to a two-way analysis of variance (ANOVA) to

statistically test the effects of variety and treatment type on evapotranspiration and nutrient absorption. If it was determined that there was a significant effect due to either factor, further post-hoc tests were carried out. These tests were one-way analysis of variance tests to determine the groups between which the significant effect occurred. The analysis was carried out on the Minitab statistical software package (Minitab Inc., USA). LSD (Least Significant Difference) test ($p \leq 0.05$ by convention, (Agresti, 1996)) was used to identify significant differences.

7.3 Results

7.3.1 Meteorological

The average monthly weather data along with the monthly ET_o at the site location for 2010, 2011 and 2012 are shown in Figure 7.4. In general, the climatic data over the three growing seasons were similar with a few notable exceptions. Although not significantly different (p = 0.235), the average temperature during June and July of 2010 was noticeably higher than the following two years which also promoted higher evapotranspiration, especially in the month of June. It should also be noticed that the 2012 growing season was unseasonably wet and cool with almost twice the normal precipitation falling during this period.

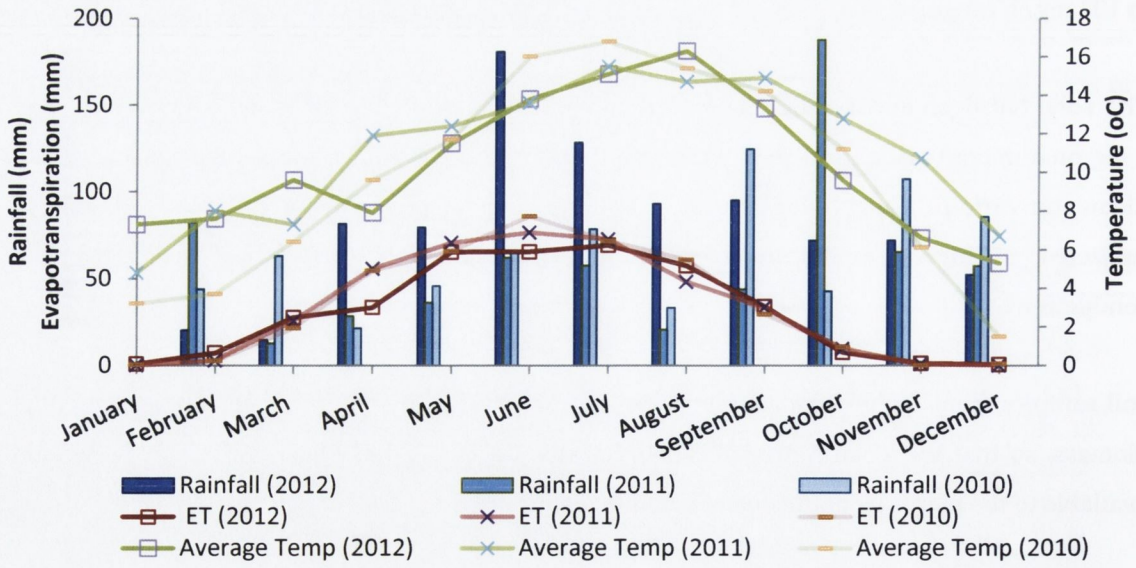


Figure 7.4 Monthly meteorological data for 2010 / 2011 / 2012

The total rainfall for each year was 788 mm (2010), 685 mm (2011) and 839 mm (2012); average temperature was 9.7°C (2010), 11.1°C (2011) and 11.2°C (2012) and total reference

evapotranspiration was 405 mm (2010), 396 mm (2011) and 368 mm (2012). There was a strong correlation (Pearson r-value of 0.77) between the air temperature and the reference evapotranspiration, as shown in Figure 7.5.

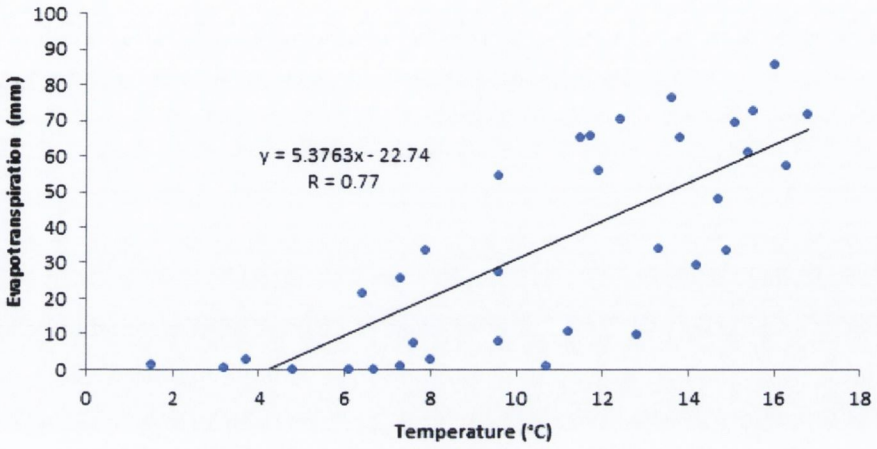


Figure 7.5 Correlation between monthly evapotranspiration and temperature

The correlation between mean wind speed and reference evapotranspiration was somewhat lower (Pearson r-value of 0.41), as shown in Figure 7.6, indicating the independence of wind speed with respect to different seasons in such a maritime temperate climate. It can also be seen that the mean wind speed of 0.85 m/s is relatively low when compared to the mean wind speeds measured on the sites in Co. Wexford, with the exception of Site E (0.75 m/s). This is not surprising given that both sites were similarly sheltered by large trees. The mean wind speeds ranged from 1.43 - 2.68 m/s for sites in Co. Wexford (excluding Site E).

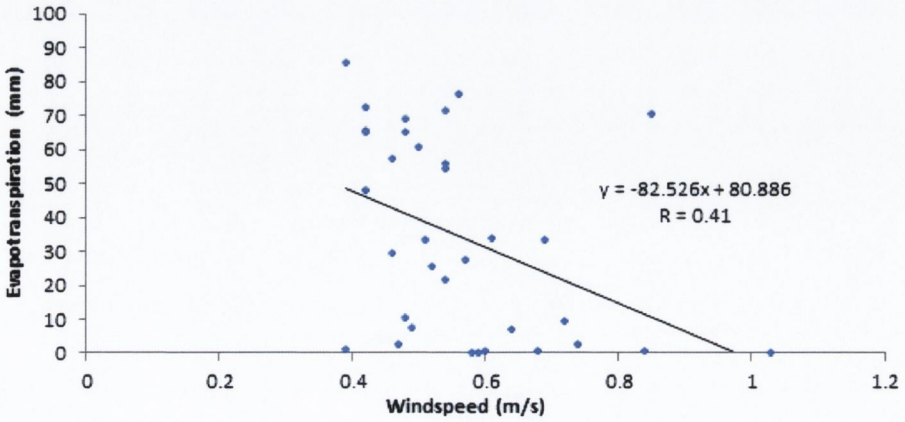


Figure 7.6 Correlation between monthly evapotranspiration and wind speed

7.3.2 *Evapotranspiration and Crop Coefficients*

The general pattern for all seasons was similar, with the clones receiving primary effluent having the highest evapotranspiration, followed by the clones receiving secondary effluent with the clones receiving water having the lowest evapotranspiration (although there was only a significant difference between the trees receiving primary treated effluent and those receiving rain water; (p = *0.001*) but the actual evapotranspiration values in 2011 and 2012 were much lower (p = *0.0*) than those obtained in 2010. The results from each year are analysed on an individual basis.

7.3.2.1 *2010 Growing Season*

The total evapotranspiration along with the ET_o baseline for each lysimeter throughout 2010 is shown in Figure 7.7. The daily evapotranspiration rate along with both the growing and dormant seasons' crop coefficients are shown in Table 7.2. Over the growing season it was observed that the trees applied with primary treated effluent had slightly higher evapotranspiration (mean = 7.21 mm/day) compared to the trees receiving secondary treated effluent (mean = 5.61 mm/day) and both of these outperformed the trees receiving just rain water (mean = 4.32 mm/day) (i.e. neither primary nor secondary effluent). Results from the two-way analysis of variance showed that there was a significant difference between treatment type (p = 0.046). There was no such significant difference between variety type (p = 0.397).

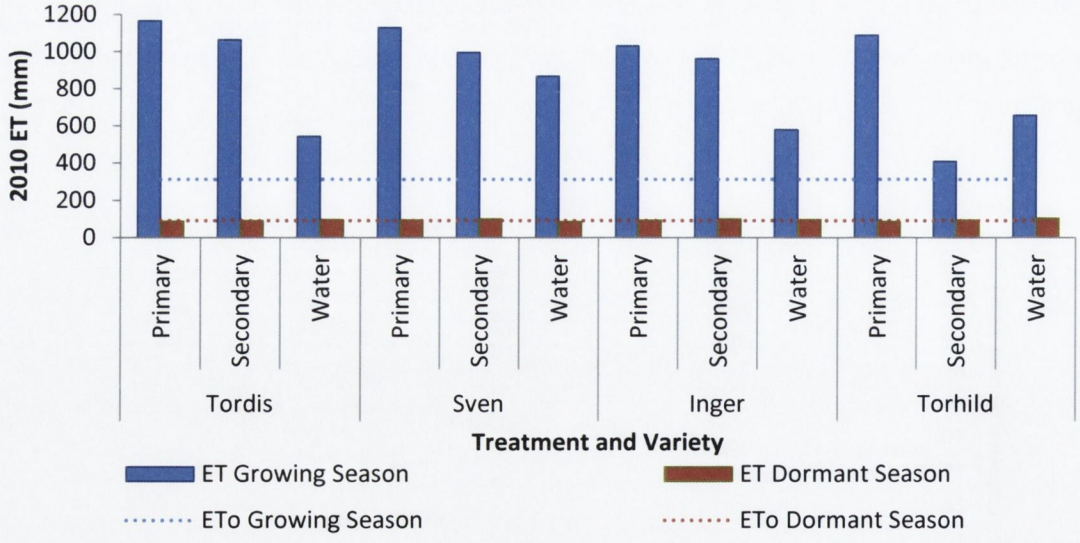


Figure 7.7 Willow evapotranspiration and reference evapotranspiration for 2010

Further analysis (one-way analysis of variance) of the mean evapotranspiration from the different treatment groups showed that there was no statistical difference (p = 0.162) between the trees receiving primary effluent and secondary treated effluent or between the trees receiving secondary treated effluent and rain water (p = 0.286). However, there was a significant difference (p = 0.001) between trees receiving primary effluent and rain water. However, one variety, *Torhild*, revealed a different trend with very low evapotranspiration measured from the containers receiving secondary treated effluent. During the dormant season there was no significant difference (p = 0.089) between the actual evapotranspiration and the reference evapotranspiration for all varieties, regardless of treatment type.

The crop coefficients, K_c followed the same pattern as the ET rates (see Table 7.2). The 2010 growing season provided the highest K_c values, varying from 4.5 to 5.1 (mean: 4.82) for the cultivars receiving primary treated effluent. This decreased to 1.79 to 4.64 (mean: 3.74) for the cultivars receiving secondary treated effluent. The values dropped further for the cultivars receiving water treatment; 2.38 - 3.78 (mean: 2.89).

Table 7.2 Willow evapotranspiration rates (mm/day) and crop coefficients for different effluent treatments and varieties during the 2010 season.

		Variety			
Parameter	Treatment	Tordis	Sven	Inger	Torhild
Daily ET	Primary	7.61 ± 0.39	7.38 ± 0.93	6.73 ± 0.60	7.10 ± 0.30
	Secondary	6.95 ± 0.39	6.50 ± 0.50	6.29 ± 0.73	2.68 ± 0.07
	Water	3.56 ± 0.42	5.67 ± 0.37	3.78 ± 0.45	4.29 ± 0.29
Growing K_c [a]	Primary	5.1 ± 0.26	4.93 ± 0.62	4.5 ± 0.40	4.75 ± 0.20
	Secondary	4.64 ± 0.26	4.34 ± 0.34	4.2 ± 0.49	1.79 ± 0.04
	Water	2.38 ± 0.28	3.78 ± 0.25	2.53 ± 0.30	2.86 ± 0.19
Dormant K_c [b]	Primary	0.96 ± 0.10	1.04 ± 0.14	1.02 ± 0.08	0.94 ± 0.11
	Secondary	1.01 ± 0.05	1.09 ± 0.10	1.09 ± 0.06	1.15 ± 0.12
	Water	1.06 ± 0.12	0.95 ± 0.12	1.11 ± 0.12	1.13 ± 0.07

[a] Growing K_c, Crop coefficient for growing season

[b] Dormant K_c, Crop coefficient for dormant season

7.3.2.2 2011 Growing Season

The total evapotranspiration along with the ET_o baseline for each lysimeter throughout 2011 can be seen in Figure 7.8. The daily evapotranspiration rate along with both the growing and dormant seasons' crop coefficients are shown in Table 7.3. The growing season resulted in much

lower (p = 0.001) evapotranspiration values but the pattern of the fertilised trees outperforming the controls remained. Again, the trees under primary treated effluent had slightly higher ET values (mean = 4.56 mm/day) compared to the trees receiving secondary treated effluent (mean = 3.38 mm/day) and both these outperformed the trees receiving water treatment (mean = 2.83 mm/day) with the exception again of the *Torhild* variety receiving secondary treated effluent.

Results from the two-way analysis of variance showed that there was a significant difference between treatment type (p = 0.048). There was no such significant difference between variety type (p = 0.571).While there was no statistical difference between trees receiving primary and secondary treated effluent (p = 0.104) or trees receiving secondary treated effluent and rain water (p = 0.37), there was a statistical difference between trees receiving primary treated effluent and those receiving rain water (p = 0.002). As per the previous year, there was no significant difference (0.089) between the actual evapotranspiration and the reference evapotranspiration for all varieties and treatment types during the dormant season.

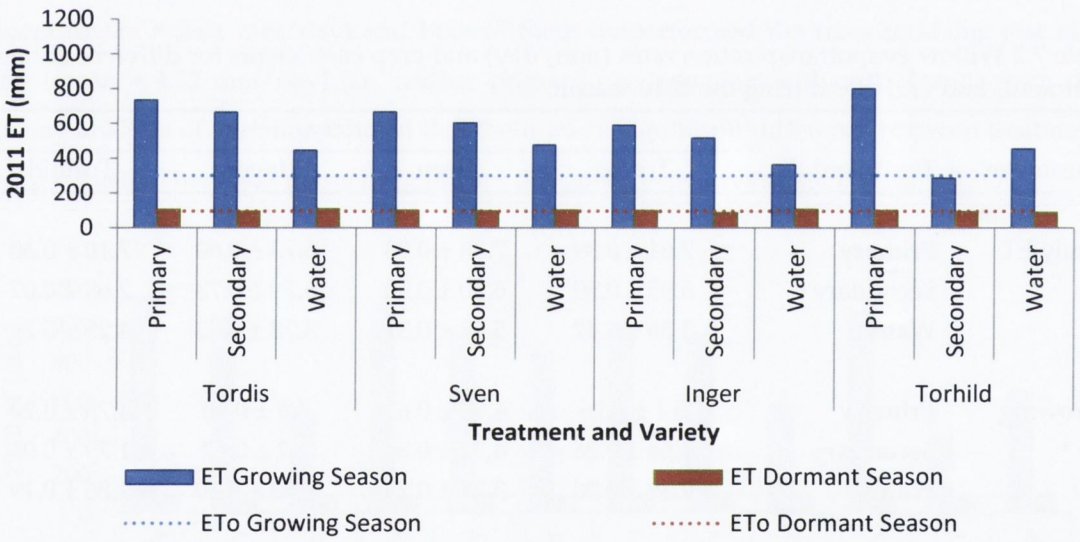


Figure 7.8 Willow evapotranspiration and reference evapotranspiration for 2011

The crop coefficient values for the 2011 growing season (see Table 7.3) were as follows; cultivars receiving primary treated effluent: 2.84 to 3.85 (mean: 3.36), cultivars receiving secondary treated effluent: 1.38 to 3.1 (mean: 2.47) and cultivars receiving water treatment: 1.74 to 2.14 (mean: 2.09)

Table 7.3 Willow evapotranspiration rates (mm/day) for different treatments and varieties during the 2011 growing season

Year	Treatment	Variety			
		Tordis	Sven	Inger	Torhild
Daily ET	Primary	4.80 ± 0.39	4.36 ± 0.27	3.86 ± 0.36	5.23 ± 0.59
	Secondary	4.35 ± 0.24	3.93 ± 0.38	3.38 ± 0.37	1.87 ± 0.11
	Water	2.91 ± 0.39	3.11 ± 0.29	2.37 ± 0.14	2.96 ± 0.31
Growing K_c [a]	Primary	3.53 ± 0.29	3.2 ± 0.20	2.84 ± 0.26	3.85 ± 0.43
	Secondary	3.10 ± 0.17	2.90 ± 0.28	2.49 ± 0.27	1.38 ± 0.08
	Water	2.14 ± 0.28	2.29 ± 0.22	1.74 ± 0.10	2.18 ± 0.22
Dormant K_c [b]	Primary	1.10 ± 0.12	1.07 ± 0.11	1.04 ± 0.06	1.04 ± 0.10
	Secondary	1.01 ± 0.08	1.02 ± 0.13	0.91 ± 0.10	1.00 ± 0.11
	Water	1.13 ± 0.13	1.07 ± 0.07	1.12 ± 0.07	0.93 ± 0.12

[a] Growing K_c, Crop coefficient for growing season

[b] Dormant K_c, Crop coefficient for dormant season

7.3.2.3 2012 Growing Season

The total evapotranspiration along with the ET_o baseline for each lysimeter throughout 2012 can be seen in Figure 7.9. The daily evapotranspiration rate along with both the growing and dormant seasons' crop coefficients are shown in Table 7.4. The evapotranspiration rates remained low for the 2012 growing season, with similar values (p = 0.34) to the 2011 season. The fertilised trees outperformed their water receiving counterparts again. The values were slightly lower for varieties receiving secondary treated effluent (mean = 3.98 mm/day) than the varieties receiving primary treated effluent (mean = 4.45 mm/day), but both were higher than the ET rates for the varieties receiving only water (mean = 3.36 mm/d).

Results from the two-way analysis of variance showed that there was a significant difference between treatment type (p = 0.011). There was no such significant difference between variety type (p = 0.096). While there was no statistical difference between trees receiving primary and secondary treated effluent (p = 0.296) or trees receiving secondary treated effluent and rain water (p = 0.843), there was a statistical difference between trees receiving primary treated effluent and those receiving rain water (p = 0.012). It should be noted that the poorly performing *Torhild* cultivars receiving secondary effluent, while still having a lower ET rate compared to the other cultivars under the same effluent applications, did improve in 2012 relative the other *Torhild* willows receiving primary effluent and water applications.

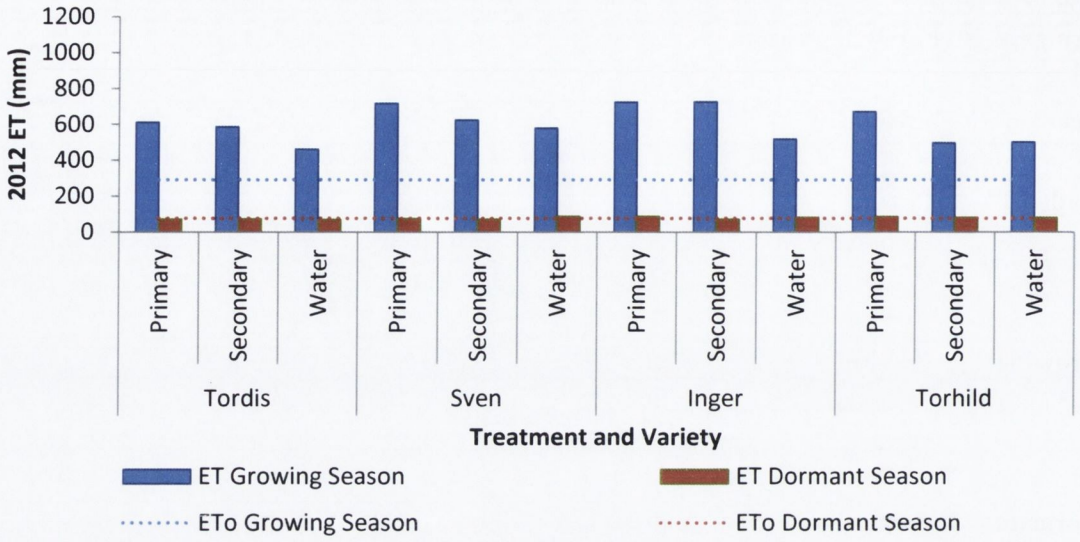


Figure 7.9 Willow evapotranspiration and reference evapotranspiration for 2012

The crop coefficient values for the 2012 growing season (see Table 7.4) were as follows; cultivars receiving primary treated effluent: 2.54 to 3.01 (mean: 2.83), cultivars receiving secondary treated effluent: 2.43 to 3.02 (mean: 2.53) and cultivars receiving water treatment: 1.91 to 2.41 (mean: 2.14).

Table 7.4 Willow evapotranspiration rates (mm/day) for different treatments and varieties during the 2012 growing season

Year	Treatment	Variety			
		Tordis	Sven	Inger	Torhild
Daily ET	Primary	3.99 ± 0.38	4.69 ± 0.31	4.74 ± 0.44	4.39 ± 0.27
	Secondary	3.82 ± 0.18	4.07 ± 0.42	4.75 ± 0.42	3.26 ± 0.18
	Water	3.01 ± 0.20	3.78 ± 0.46	3.38 ± 0.38	3.26 ± 0.25
Growing K_c [a]	Primary	2.54 ± 0.24	2.98 ± 0.19	3.01 ± 0.28	2.79 ± 0.17
	Secondary	2.43 ± 0.12	2.59 ± 0.27	3.02 ± 0.27	2.06 ± 0.11
	Water	1.91 ± 0.13	2.41 ± 0.29	2.15 ± 0.24	2.07 ± 0.16
Dormant K_c [b]	Primary	0.94 ± 0.11	0.98 ± 0.08	1.15 ± 0.09	1.11 ± 0.10
	Secondary	0.95 ± 0.07	0.93 ± 0.11	0.92 ± 0.09	1.06 ± 0.08
	Water	0.91 ± 0.09	1.14 ± 0.07	1.07 ± 0.12	1.04 ± 0.07

[a] Growing K_c, Crop coefficient for growing season

[b] Dormant K_c, Crop coefficient for dormant season

7.3.3 *Biomass*

The physical properties of the willow plants after the first and third growing seasons can be seen in Figure 7.10 and Figure 7.11. In the first growing season the heights of the main stem of each plant varied from 3.0 m to 4.7 m with the irrigated effluent type not having any significant effect on the height (p = 0.196). The heights of the stems varied between 3.1 m to 4.7 m at the end of the 3rd growing season with treatment type again having no effect on the heights (p = 0.660). The variety type did have a significant effect on stem height in the first season (p = 0.003) but not in the third season (p = 0.922). A post-hoc comparison test of the means from the first season illustrates the varieties in which a significant difference occurs (see Table 7.5).

Table 7.5 Tukey post-hoc test for stem heights after the first season

Clone	Mean (m)	Grouping
Inger	4.47	A
Sven	4.40	A
Tordis	3.83	A B
Torhild	3.27	B

The diameter of the main stems ranged from 24 mm to 36.5 mm for the first season and again, although effluent quality did show some correlation, it was not significant at the 95% level (p = 0.060). In the 3rd growing season the stem diameters ranged from 16 mm to 29 mm, with treatment type have no significant effect on values (p = 0.395). The variety type had no significant effect on stem diameters in either the first or third seasons (p = 0.056, p = 0.778 respectively).

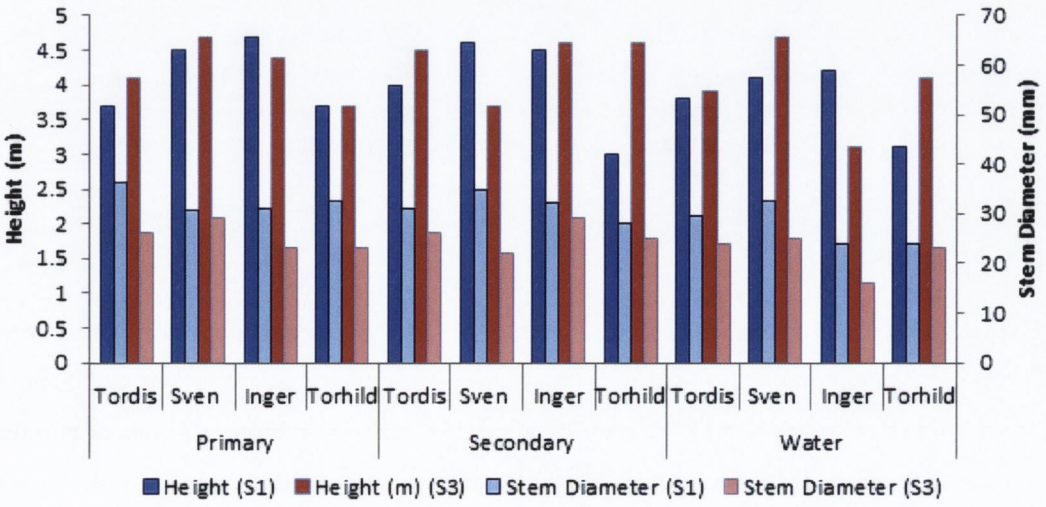


Figure 7.10 Height and stem diameter of willow clones at end of Season 1 and Season 3

The dry weight of the biomass recovered from each lysimeter at the end of the first season ranged from 228 g to 863 g and the effluent quality did have a significant effect on these values (p = 0.019). The average biomass dry weight for the trees receiving primary treated effluent was 728 g which decreased to 544 g for the trees receiving secondary treated effluent and 372 g for the trees receiving water. Although the treatment type did not have a significant effect (p = 0.233) on the dry weight of the biomass recovered from the willows at the end of the third growing season, there still remained a pattern quite similar to that of the first growing season, with greater biomass produced for the more concentrated effluent received. The dry weight of the biomass for the willows coppiced at the end of the third season ranged from 250 g to 1599 g. The average biomass dry weight of trees receiving primary effluent was 1243g, decreasing to 875 g for trees receiving secondary effluent and decreasing again to 802 g for trees receiving water. As with the stem diameter, the variety type had no significant effect on the dry weight of the willow biomass in either the first or third season (p = 0.119, p = 0.928).

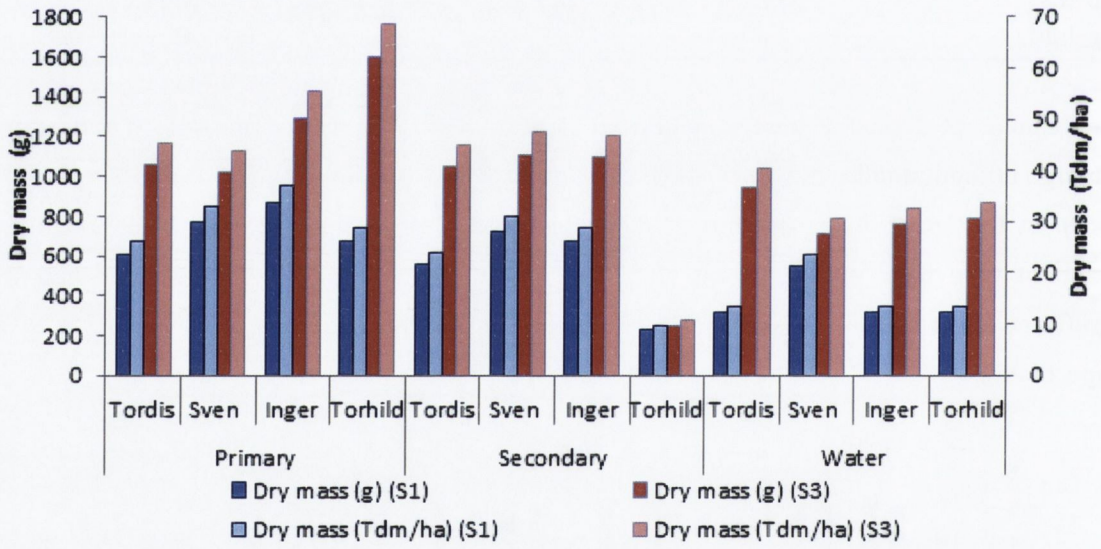


Figure 7.11 Dry biomass of willow clones at end of Season 1 and Season 3

7.3.4 *Nutrients*

The tree biomass was analysed for nutrient (nitrogen, phosphorus and potassium) and organic (total organic carbon) uptake at the end of the first season which was compared to the amount available to the trees throughout the season. It should be noted that there were small variations in the amount of compounds added to each plant due to the extra water that was added to some containers which were low in available water due to high evapotranspiration at that particular time.

7.3.4.1 Nitrogen

The total nitrogen available to the different willow clones (from the original soil in the lysimeter as well as from the irrigated treatment) and the uptake of nitrogen from the willow clones is shown in Table 7.6 and Figure 7.12. It can be seen that at the outset of the experiment the majority of nitrogen available comes from the soil rather than from the effluent applied.

Table 7.6 Nitrogen availability and uptake throughout the first season

Variety	Nitrogen Available (kg/ha)					
	Source		Source		Source	
	Primary[1]	Soil	Secondary[2]	Soil	Water[3]	Soil
Tordis	293.5	6242	146.7	6337	1.75	6810
Sven	293.1	6337	146.2	6432	4.98	5770
Inger	292.1	6337	146.2	6243	2.16	7094
Torhild	292.4	6621	141.9	6810	2.74	5864

	Nitrogen Uptake (kg/ha)		
Tordis	177.6	158.1	97.6
Sven	213.0	262.4	101.4
Inger	228.4	232.7	97.2
Torhild	158.7	83.6	82.0

[1]Primary = primary effluent and water that was added to container
[2]Secondary = secondary treated effluent and water that was added to container
[3]Water = rain water that was added to container

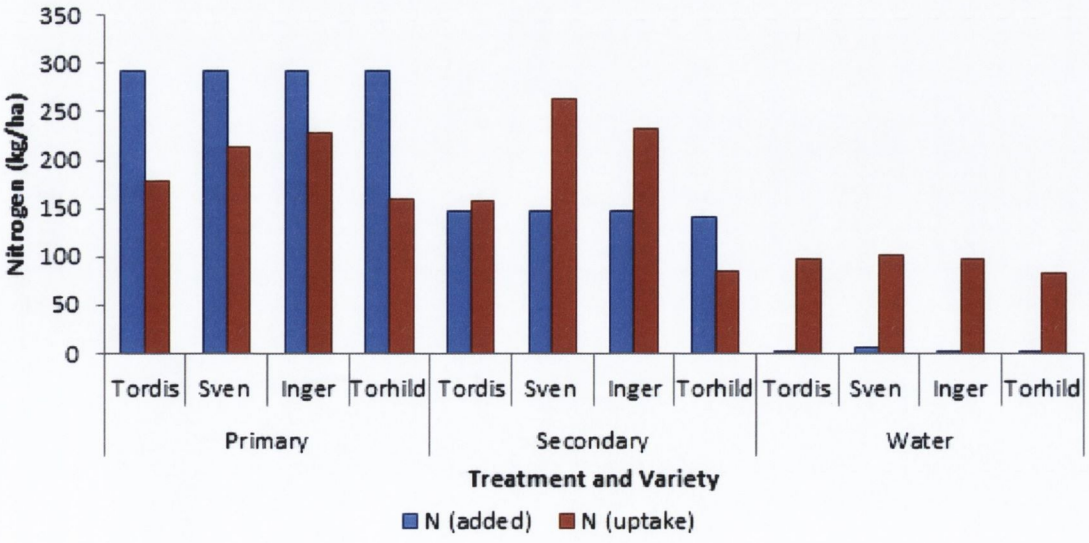


Figure 7.12 Nitrogen uptake by different willow clones

7.3.4.2 Phosphorus

The total phosphorus available to the different willow clones (from the original soil in the lysimeter as well as from the irrigated treatment) and the uptake of phosphorus from the willow clones is shown in Table 7.7 and Figure 7.13.

Table 7.7 Phosphorus availability and uptake throughout the first season

Variety	Phosphorus Available (kg/ha)					
	Source		Source		Source	
	Primary[1]	Soil	Secondary[2]	Soil	Water[3]	Soil
Tordis	23.3	1950	15.7	1979	NA[a]	2127
Sven	23.3	1979	15.7	2009	NA	1802
Inger	23.3	1979	15.7	1950	NA	2216
Torhild	23.3	2068	15.7	2127	NA	1832
	Phosphorus Uptake (kg/ha)					
Tordis	27.8		25.2		13.3	
Sven	33.6		38.6		17.8	
Inger	34.7		32.8		12.5	
Torhild	30.7		12.3		13.6	

[a] NA = Values are negligible

[1]Primary = primary effluent and water that was added to container

[2]Secondary = secondary treated effluent and water that was added to container

[3]Water = rain water that was added to container

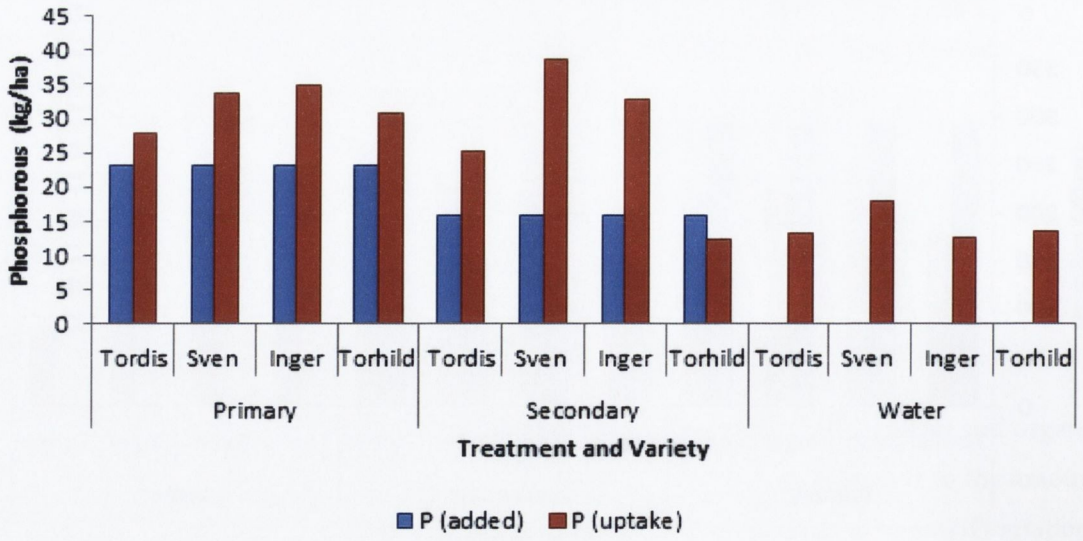


Figure 7.13 Phosphorus uptake by different willow clones

7.3.4.3 Potassium

The total potassium available to the different willow clones (from the original soil in the lysimeter as well as from the irrigated treatment) and the uptake of potassium from the willow clones is shown in Table 7.8 and Figure 7.14.

Table 7.8 Potassium availability and uptake throughout the first season

Variety	Potassium Available (kg/ha)					
	Source		Source		Source	
	Primary[1]	Soil	Secondary[2]	Soil	Water[3]	Soil
Tordis	45.0	482	35.2	489	1.5	526
Sven	44.7	489	34.8	497	4.2	445
Inger	43.8	489	34.8	482	1.8	548
Torhild	44.1	511	31.2	526	2.3	453
	Potassium Uptake (kg/ha)					
Tordis	20.6		18.3		10.4	
Sven	25.8		24.3		18.4	
Inger	28.6		22.2		10.4	
Torhild	22.1		7.6		10.3	

[1]Primary = primary effluent and water that was added to container
[2]Secondary = secondary treated effluent and water that was added to container
[3]Water = rain water that was added to container

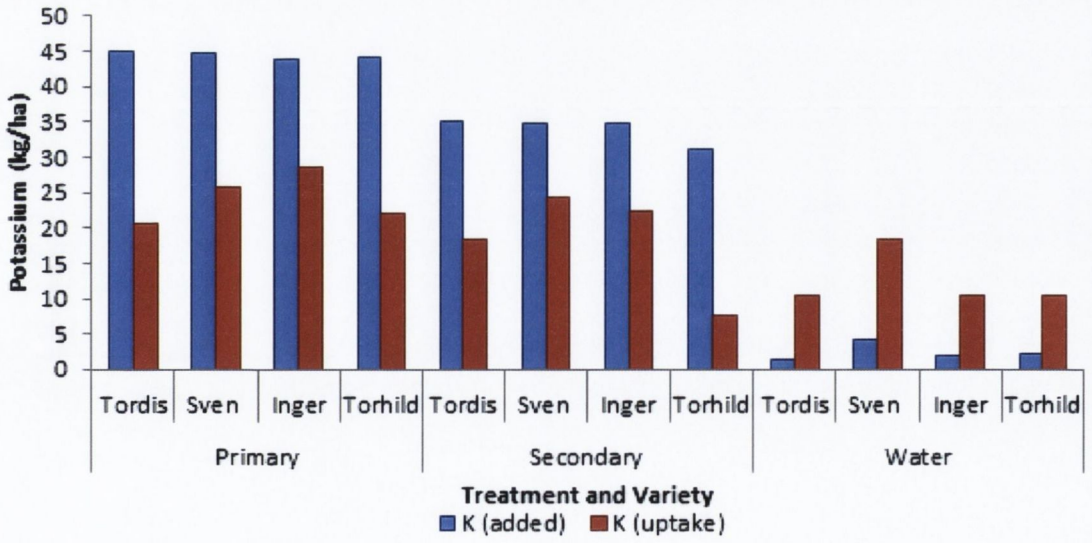


Figure 7.14 Potassium uptake by different willow clones

7.3.4.4 Total Organic Carbon

The total organic carbon available to the different willow clones (from the original soil in the lysimeter as well as from the irrigated treatment) and the uptake of total organic carbon from the willow clones is shown in Table 7.9 and Figure 7.15.

Table 7.9 Total organic carbon availability and uptake throughout the first season

Variety	Total Organic Carbon Available (kg/ha)					
	Source		Source		Source	
	Primary[1]	Soil	Secondary[2]	Soil	Water[3]	Soil
Tordis	675.4	50,508	261.6	51,283	5.3	55,100
Sven	674.3	51,294	263.8	52,039	15.1	46,682
Inger	671.1	51,273	260.2	50,508	6.5	57,396
Torhild	672.1	53,569	247.1	55,100	8.3	47,447
	Total Organic Carbon Uptake (kg/ha)					
Tordis	11,298		10,275		5,889	
Sven	14,227		13,244		10,272	
Inger	16,003		12,518		5,844	
Torhild	12,644		4,275		5,916	

[1]Primary = primary effluent and water that was added to container

[2]Secondary = secondary treated effluent and water that was added to container

[3]Water = rain water that was added to container

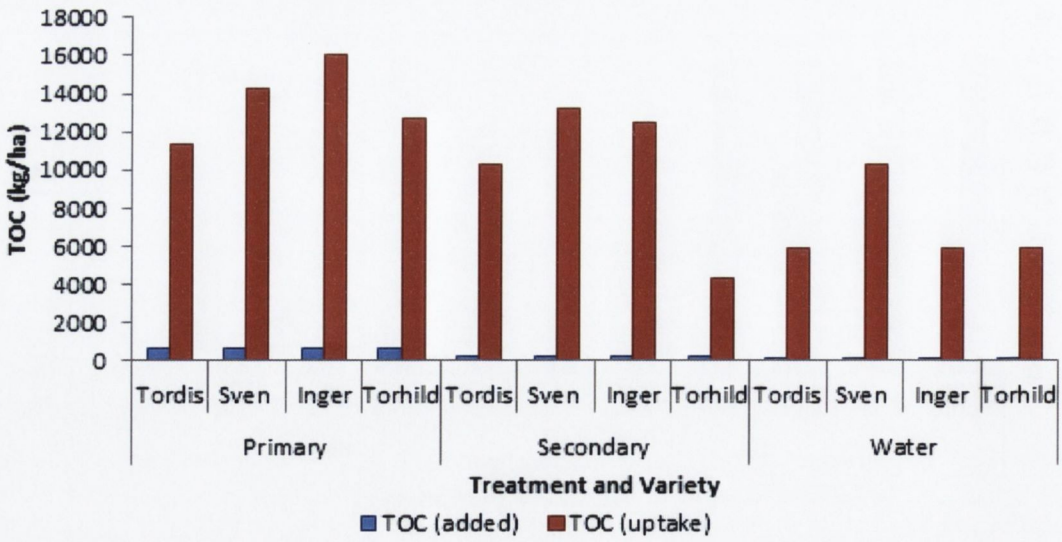


Figure 7.15 Total organic carbon uptake by different willow clones

7.4 Discussion

7.4.1 *Evapotranspiration and Crop Coefficients*

As can be seen from Figure 7.7, Figure 7.8 and Figure 7.9 there was no discernible difference in the ET_{willow} rates between the four willow varieties, with the exception of the *Torhild* being applied with secondary treated effluent. These *Torhild* cultivars in question had visually obvious growth and development defects for the first two years of growth, which had a knock-on effect on the ET_{willow} rate and compound uptake for these trees. It is suspected that the initial cuttings must have been taken from the same original defective willow plant. Total ET_{willow} and K_c for all three growing seasons appeared to be affected by the strength of effluent received (see Table 7.10) with the varieties receiving primary treated effluent outperforming those receiving secondary treated effluent which in turn outperformed those receiving water.

Table 7.10 Effect of different treatments and varieties on ET

Parameter	Means							Significance [a]	
	Treatment [b]			Variety				*P*-value	
	P	S	W	Tordis	Sven	Inger	Torhild	T [c]	V [d]
2012									
ET (mm)	681	607	514	552	639	656	555	0.011	0.096
2011									
ET (mm)	698	518	434	615	582	490	513	0.048	0.571
2010									
ET (mm)	1103	858	661	924	997	857	718	0.046	0.397

[a] *P*-value <0.05 denotes a statistically significant relationship

[b] P: Primary effluent; S: Secondary treated effluent; W:water.

[c] T: Treatment

[d] V: Variety

ET_{willow} rates for the varieties receiving primary effluent in the first season in this experiment ranged between 1030 mm and 1165 mm (average 6.73-7.61 mm/day). This compares similarly to the ET_{willow} obtained with fertilised willow (seasonal ET_{willow} of 1190 mm) in Italy by Guidi et al. (2008). The ET_{willow} for the varieties receiving secondary effluent in this experiment were slightly less (410 mm to 1064 mm). These values also compared favourably with those determined by Guidi et al. (2008) for fertilised willow. Equally, the varieties receiving water in this experiment (ET_{willow} rate ranging from 544 mm to 867 mm) responded similarly to the willow in the Guidi et al. (2008) trials, which noted a seasonal ET_{willow} of 620 mm for the non-

fertilised plants. It should be noted that this mesocosm experiment was carried out in a temperate, maritime climate - this is in contrast to the arid, Mediterranean climate in which the study conducted by Guidi et al. (2008) was located. The ET_{willow} rates for the varieties receiving both primary and secondary treated effluent were slightly higher than the 870 mm obtained by Martin and Stephens (2006) during the first season after coppice in research in a similar climate (UK) to Ireland's.

There was a noticeable decrease in ET_{willow} rates for all varieties under all three treatments in the second and third years. This contrasted to the findings of Guidi et al. (2008) which showed an ET_{willow} rate increase of 50% for fertilised willow and 44% for unfertilised willow over the second growing season. It also differs from Gregersen and Brix (2001) which saw similar increases in ET_{willow} rates from the first season to the second season. The reason for the measured decreases in the second and third years may have been due to cooler temperatures during the second and third growing seasons (on average 0.54 °C less) compared to the first growing season. From visual observation, the trees also appeared to be woodier and not have as much an abundance of leaves in the second and third growing seasons compared to the first season. As leaf area index is a critical factor in evapotranspiration (Running et al., 1989, Persson, 1995) this could have been an additional reason for the lower ET rates. It is also possible that the trees may have been inhibited due to the build-up of some contaminant in the containers over time, such as chloride.

The average crop coefficient, K_c for the willow varieties receiving primary effluent in 2010 (K_c = 4.82) is significantly higher than the values obtained by Guidi et al. (2008) (season 1 K_c of 1.61 and season 2 K_c of 2.97) and Pistocchi et al. (2009) (seasonal K_c of 1.71) for willow cultivars under similar conditions. However, the varieties receiving secondary treated effluent performed similarly, with a mean K_c of 3.74 for the season. The varieties receiving water treatment achieved a mean K_c of 2.89 which is also much greater than the seasonal average K_c obtained by Guidi et al. (2008) for non-fertilised willow cultivars (first season K_c of 0.84 and second season K_c of 1.47) which might be a result of the significant nutrient in the original soil in the experiments presented here. The K_c values for the 2011 and 2012 were lower but still compared very favourably with results obtained by Guidi et al. (2008) and Pistocchi et al. (2009) for willows under similar treatment conditions. It should also be noted when comparing coefficients determined from different climatic areas that the calculation of the crop coefficient is strongly determined by the reference evapotranspiration at any site.

7.4.2 *Nutrient and Organic Uptake*

The uptake of organics and nutrients by the cultivars was affected by treatment type but not variety type. The cultivars receiving primary treated effluent were supplied with a relatively high amount of nitrogen (although similar to the amount applied by Dimitriou and Aronsson (2011) compared to the recommended fertilisation rates for short rotation coppicing (SRC) willow in both Ireland (83kg-N/ha) (Caslin et al., 2010) and Sweden (80kg-N/ha) (Gustafsson and Larsson, 2007). The uptake of total nitrogen from these cultivars varied from 54% to 78% of the total nitrogen added (Figure 7.12). This is lower than the results obtained by Dimitriou and Aronsson (2011) where approximately 95% of the total nitrogen applied was retained by the tree biomass. However, the uptake value of 194.4 kg-N/ha from the cultivars receiving primary effluent is more comparable to that obtained by Aronsson and Bergström (2001) where willows supplied with 244 kg-N/ha, showed a nitrogen uptake of 172 kg-N/ha by the third growing season. For the plants receiving secondary treated effluent the retention increased to over 100% of total nitrogen added for three of the plants cultivars (although only 59% for the apparently struggling *Torhild*). The total amount absorbed (184.3 kg-N/ha) was only slightly lower than that for primary treated effluent. The uptake for the plants receiving water treatment is well over 100% in all cases, however, the overall amount absorbed is substantially lower (94.6 kg-N/ha) than that for the willows receiving effluent. Again, it is assumed that the excess nitrogen was being taken from the soil, as discussed earlier.

The retention of phosphorus was over 100% of total phosphorus added for all plants (Figure 7.13) except the *Torhild* receiving secondary effluent due to reasons explained previously. The retention values of ≥100% are in line with results obtained by Dimitriou and Aronsson (2011) and Sugiura et al. (2008) in which all of the applied phosphorus was retained by the willow plants. Hence, it might be surmised that phosphorus may well be the limiting nutrient for the growth and performance of such willow varieties receiving on-site effluent, although this cannot be confirmed from these experiments.

The uptake of total potassium from the plants receiving primary treated effluent varied from 46% - 65% of the total potassium added (Figure 7.14). The 44 kg-K/ha added via the primary treated effluent was almost exactly that recommended by Caslin et al. (2010). The uptake varies from 24% - 69% for the plants receiving secondary treated effluent and was over 100% for the plants receiving water treatment. The retention was slightly higher than that obtained by Larsson (2003) in which SRC willows receiving between 45-135 kg-K/ha achieved a maximum retention of 36%.

The retention of TOC was emphatically greater than 100% of the TOC added via the treatments for all willow plants (Figure 7.15). The 673.2 kg-TOC/ha added through the primary treated effluent is similar to two levels (609 & 707 kg-TOC/kg) of treatment used by Dimitriou and Aronsson (2010). However, the results of this study were markedly better (compared to 84% retention in that investigation), with the TOC added only providing a small percentage of that taken up into the willow tree biomass (the rest assumed to have come from the soil). The 258.2 kg-TOC/ha added through the secondary treated effluent is similar to the one of the levels (203 kg-TOC/ha) of treatment added to willows in the same experiment by Dimitriou and Aronsson (2010). Again, while a good retention rate of 85% was achieved in that study, the uptake in this study was significantly greater.

As detailed in Section 7.3.3, the addition of effluent during the first season can be seen to have had a significant effect on the dry weight of the biomass (see also Figure 7.11). Although not statistically significant, this pattern continues for the third season results (see Figure 7.11). This compares similarly to the results of multiple examples of previous research (Martin and Stephens, 2006, Guidi et al., 2008, Pistocchi et al., 2009).

As can be seen from Figure 7.16, the 2010 and 2011/2012 growing seasons showed a strong correlation between biomass weight and evapotranspiration performance (Pearson's R values of 0.89 and 0.85 respectively). This result matches with the findings of Martin and Stephens (2006). Hence, it can be deduced that there is a strong link between the strength of effluent added, to an increase of biomass and corresponding increase in the evapotranspiration rate in willows.

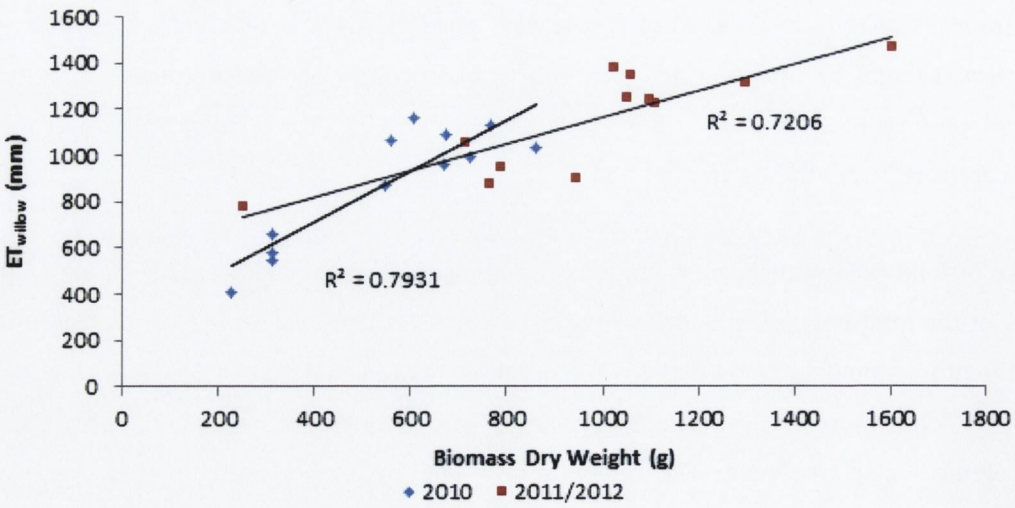


Figure 7.16 Correlation between ET_{willow} and dry weight of biomass

Finally, as can be seen from Table 7.6, Table 7.7, Table 7.8 and Table 7.9 the nutrients from the added effluents only made up a small proportion of the overall nutrients potentially available to the plants, with the soil providing the majority of the compounds. Yet, as discussed above, the addition of the effluent had a significant effect on the development and ET rates of the willows. It is therefore hypothesized that the apparent sensitivity of the willows to the strength of the effluent being applied was probably due to the nutrients in the effluent being in a soluble form which could be more preferentially taken up by the willow trees as opposed to the nutrients in the soil, most of which would be in a more particulate form.

7.4.3 Comparison with Full Scale Systems (Loading Rate)

The loading rate to the barrels in this mesocosm experiment were based on a 4 PE producing 150 l/c/day as assumed in the On-Site wastewater treatment Code of Practice for Ireland (EPA, 2009a) and also by assuming a willow system area of 110 m^2 per person. This worked out at 1.4 mm of effluent being applied to each barrel per day (see Table 7.11). This assumption compared relatively well to the actual loading rates applied to the full scale systems that were receiving effluent. The equivalent rates for sites with 4 PE ranged from 0.7 mm/day (Site H) to 2.1 mm/day (Site A).

Table 7.11 Comparison of effluent loading rates between mesocosm and the full scale systems that were receiving effluent

	Daily Effluent Loading (mm/day)					
Mesocosm	**Site A**	**Site B**	**Site C**	**Site D**	**Site H (2 Systems)**	**Site I (2 Systems)**
1.4	2.1 (4 PE)	0.8 (2 PE)	0.8 (2 PE)	1.1 (4 PE)	0.7 (4 PE)	0.8 (4 PE)

7.4.4 Comparison with Full Scale Systems (Evapotranspiration)

This section will compare the evapotranspiration rates attained by the willow trees in the barrels receiving the different effluent types to the rates attained on the full scale sites. The comparison will only take into account Systems A - E as these were constructed in the same year as the mesocosm experiment was set up and also only takes into account the same time period (i.e. May to September). It should be noted that one of the key differences between the mesocosm experiment and the full scale systems was the porosity of the soil. The full scale systems all contain clayey, low porosity subsoil, whereas the barrels in the mesocosm all

contained top soil, laid on top of a sand layer which in turn was laid on top of a gravel layer (see Figure 7.1). The usable pore space in the top soil would have been significantly more than that in the clayey subsoils, which would probably promote higher evapotranspiration.

It would be expected that the willow trees in the mesocosm experiment would have overall higher ET_{willow} rates as water availability would have been much higher due to the barrels being kept topped up.

The total evapotranspiration amount for each of the three years is shown in Table 7.12. It can be seen that the mesocosm results could only be compared to Sites A & B in 2010, as monitoring on the other systems did not commence until late in the summer. It can be seen that the willows in the mesocosm had higher ET_{willow} rates for all treatments compared to the two full scale systems.

All five of the full scale systems were fully functional in 2011. It can be seen that the total ET_{willow} for the trees under the different treatments in the mesocosm all decreased compared to 2010. The total amount for Site A increased to 700 mm which surpassed the mesocosm willows and the total amount for Site C was higher than the willows receiving secondary treated effluent and water in the mesocosm.

The ET_{willow} totals for the period in 2012 decreased on Site A, C and D, which was mainly due to flooding on the systems, meaning evapotranspiration couldn't be determined for many days. The totals ET_{willow} also decreased slightly for the willow trees receiving primary effluent, but increased somewhat for those receiving secondary treated effluent and water. The total ET_{willow} was quite comparable across the mesocosm and all the full scale systems with the exception of System D, which was somewhat lower.

Table 7.12 Total ET_{willow} (mm) for period May - September

Year	Mesocosm			Site A	Site B	Site C	Site D	Site E
	Primary	Secondary	Water					
2010	1102	858	662	547	424*	-	-	-
2011	698	518	434	700	371	521	403	389
2012	681	608	514	539	559	492	357	545

*Monitoring period of June - September

When the total ET_{willow} amounts for the period are broken down into daily means, the pattern remains quite similar (see Table 7.13). The willow trees in the mesocosm all produced higher

daily means compared to the full scale systems (significantly higher in the case of those receiving primary and secondary treated effluent).

Of the full scale systems, only Site A had a higher daily mean compared to the willows in the mesocosm experiment in 2011. The willow system on Site C receiving septic tank effluent also outperformed the mesocosm willows that were receiving secondary treated effluent and water. The systems on Sites B, D and E all had lower daily means compared to the willows in the mesocosm, irrespective of whether they were receiving effluent or not.

The mean daily ET_{willow} of four of the full scale systems (Sites A, B, C, E) were all higher than any of the willow trees in the mesocosm experiment in 2012. This may have been as a result of the heavy rainfall during the summer period, which meant water was more accessible to the trees on the full scales systems.

Table 7.13 Mean daily ET_{willow} (mm/day) for period May to September

Year	Mesocosm			Site A	Site B	Site C	Site D	Site E
	Primary	Secondary	Water					
2010	7.2	5.6	4.3	3.6	3.7*	-	-	-
2011	4.6	3.4	2.8	5.1	2.4	3.5	2.6	2.6
2012	4.5	4.0	3.4	6.5	5.3	4.8	2.5	4.8

*Monitoring period of June - September

Chapter 8

Analysis and Discussion of Results

8 Analysis and Discussion of Results

8.1 Introduction

The primary objective at the outset of the research project was to evaluate the applicability and effectiveness of using zero-discharge willow systems for the treatment of on-site wastewater effluent, particularly on sites with low permeability clay subsoils and produce guidelines for the design of such willow systems in Co. Wexford based on the results.

The main aspect of the project involved determining the evapotranspiration rates that can be attained by willow trees in the system throughout the year. As part of this, it was intended to vary and then compare the following parameters between each willow system and determine the effect (if any) on the evapotranspiration performance:

- Area of willow system per PE
- Aspect ratio
- Effluent type
- Willow clone variety

This chapter will address each of the parameters and also includes a section on the effect the water level within the willow system at different times of the year has on evapotranspiration.

8.2 Effluent Loading Analysis

The hydraulic loading on each system throughout the monitoring period was quantified by measuring rainfall as well as the effluent production at each site. Although there were issues with some of the sites (e.g. no one living in the dwelling to produce effluent, problems with equipment, etc.) the effluent loading was successfully monitored at six sites for varying periods of time throughout this research. The total daily on-site flow rates as well as the mean daily effluent production per person are shown in Table 8.1.

The loading rates varied quite an amount from site to site and the effect of rainfall infiltration on the loading rates is also apparent. It can be seen that the mean daily flow per person for Sites A, B and C, where rainfall infiltration was deemed to have occurred (see Section 4.3.1 - Section 4.3.3), was significantly higher than that determined for Sites D, H and I, where there was no

evidence of rainfall infiltration. For example, effluent loading on Site D contributed just 27% of overall hydraulic loading to the willow system compared to 42% on Site A (both had PE of 4). As the design of willow systems is centred on hydraulic loading, the importance of ensuring that rainfall infiltration does not occur is obvious.

Table 8.1 Effluent loading rate at different sites.

Site	PE	Total Daily Flow (L/day)	Mean Daily Flow per Person (L/c/day)
A	4	628.4*	157.1*
B	1	443.1*	443.1*
C	2	356.7*	178.4*
D	4	483.3	120.8
E	NA	-	-
F	6	-	-
G	6	-	-
H	4	362.5	89.32
I	4	326.7	81.70
J	4	-	-

*Rainfall infiltration into the wastewater system occurred

As the rainfall on Site A and Site B was identical, an attempt was made to estimate the true mean daily flow rate per person. For example, when the total daily flow from Site B is deducted from the Site A figure, the difference between the two should approximately equal the flow rate generated by the extra people in the dwelling on Site A. The difference between the two dwellings is 185.3 L/day. There are three extra people living in the house on Site A, which gives a daily flow rate per person for that house of 61.7 L/c/day (185.3 / 3). The real figure may be higher than this due to economies of scale, so the figure could actually be closer to 92.7 L/c/day (185.3 / 2). While being a crude method of deduction, it does help give an approximation of the actual flow rate per person from Site A.

Results from the sites in which there was no rainfall infiltration show that, although lowered from 180 L/c/day (EPA, 2000) the assumption of 150 L/c/day in the Irish EPA Code of Practice (EPA, 2009a) appears to over-predict the mean wastewater production in such one-off dwellings with typical sized family units. This concurs with data recorded in previous studies carried out in Ireland (O' Súilleabháin, 2004, Gill et al., 2009c).

The original design figure of 180 L/c/day was a value typically used for urban wastewater statistics, which includes significant sewer infiltration (should not be applicable to on-site

treatment systems). Also, in towns and cities it is usual for people to live and work within the same drainage network. For one-off houses, however, a number of the occupants will generally spend a significant proportion of the day outside the on-site treatment "catchment" and hence some of their daily effluent production will be directed to other systems.

8.3 Willow System Evapotranspiration Comparisons

This section will compare the evapotranspiration results for all systems across the sites. It also includes details of the statistical analysis carried out to highlight any correlation that may exist between the evapotranspiration rates from a system and the corresponding meteorological parameters on the site.

8.3.1 2010 Evapotranspiration Rates

There were evapotranspiration results from four willow systems (Sites A, B, C & E) for varying periods in 2010. The mean daily ET_{willow} rates for each month are shown in Table 8.2, where the cells have been coloured to reflect magnitude from green being the lowest up to red being the highest. It can be seen that the highest ET_{willow} rates were from the systems on Sites A & B. The system on Site B was also fully empty for brief periods in the months of August and October, which means that the daily means are probably conservative for those months. The ET_{willow} rates for Sites C & E are somewhat lower, most likely as a result of the willow trees been less developed.

Table 8.2 Comparison of the mean daily ET_{willow} (mm/day) in 2010

Month	Site A	Site B	Site C	Site E
January	-	-	-	-
February	-	-	-	-
March	1.1	-	-	-
April	2.4	-	-	-
May	2.2	-	-	-
June	4.2	2.6	-	2.4
July	4.8	3.9	-	1.9
August	4.3	3.7*	-	1.8
September	2.7	4	1.1	1.7
October	3.3	4.1*	1.8	0.9
November	0.2	0.1	0.2	0.1
December	0.1	0.1	0.1	0.1

*Willow system was empty for part/all of month

The daily ET_{willow} rates were also analysed for a measure of the correlation that exists between them and the different meteorological parameters measured at the site. The method of correlation used was the Spearman Rank-Order. The results of the correlation of each parameter with the ET_{willow} are shown in Table 8.3. A low correlation ($0 < \rho < 0.25$) is highlighted in red; a moderate correlation ($0.25 \leq \rho < 0.5$) is highlighted in yellow; and a relatively high correlation ($0.5 \leq \rho \leq 1.0$) is highlighted in green.

When the results in the table are examined it can be seen that there is very low correlation between ET_{willow} and most of the meteorological parameters for all four of the sites. It would appear that rainfall is the most highly correlated parameter with ET_{willow}. This seems to have had the effect of skewing a lot of the remaining parameters. For example, the net radiation shows up as having a negative correlation with ET_{willow} which makes little sense. However, the reasoning for this is probably that as the highest ET_{willow} rates are occurring on days with rainfall, the net radiation for those days would naturally be lower. The same reasoning is also valid for instances of temperature having a negative correlation and humidity having a positive correlation. It is interesting to note that wind speed has a moderate correlation with the ET_{willow} on Site C.

Table 8.3 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2010)

Site	ET_o	Rainfall	Max. Temp	Min. Temp	Max. Humidity	Min. Humidity	Net Radiation	Wind Speed
A	-0.03	0.37	0.12	0.11	0.08	0.09	-0.06	0.17
B	-0.21	0.45	-0.14	0.21	0.09	0.02	-0.25	0.2
C	0.09	0.11	0.16	0.19	-0.15	0.06	-0.21	0.48
E	-0.26	0.24	-0.33	-0.24	-0.37	-0.02	-0.29	0.22

$0 < \rho < 0.25$ $0.25 \leq \rho < 0.5$ $0.5 \leq \rho \leq 1.0$

8.3.2 2011 Evapotranspiration Rates

The mean daily ET_{willow} rates for the willow systems monitored in 2011 are shown in Table 8.4. It can be see that in general the higher values occurred on Sites A, B & C. This would be expected given that the willow trees on these systems would be in their second year of growth. It also worth noting that the systems of Sites A & B were empty for extended periods throughout the summer, which probably means that the evapotranspiration rates are somewhat conservative for those months. Site C had a relatively high mean ET_{willow} rate of 5.8 mm/day in July, but then decreased in August. This is probably as a result of the drop in water level

reducing water availability to the trees (discussed further in Section 8.8). The remaining systems had broadly similar ET_{willow} rates during the growing season, although they were slightly higher for system 2 on Site F.

Table 8.4 Comparison of the mean daily ET_{willow} (mm/day) in 2011

Month	Site A	Site B	Site C	Site D	Site E	Site F (1)	Site F (2)	Site G
January	0.1	0.5	0.2	0.2	0	-	-	-
February	0.4	0.6	0.4	0.8	0.3	-	-	-
March	1.2	1.2	1.4	1.4	1.2	1.8	1.4	-
April	3.7	2.1	1.8	2.3	2.4	2.1	2.7	-
May	4.7	3.2*	2.7	2.5	2.4	2	3.4	-
June	5.6	3.5*	2.8	2.3	2	1.9	1.4	2
July	6.2	2.1*	5.8	3.1	3.7	3.1	4.5	3
August	3.7*	1.2*	3.4	2.6	2.8	2	3.7	2.2
September	4.6*	2.1*	2.9	2.6	2.1	2.2	3	1.4
October	2.2*	4	2.7	0.6	2.8	2.3	0.5	2.5
November	0.2	0.1	0.2	0.3	0.2	0.2	0.2	0.4
December	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1

*Willow system was empty for part/all of month

Table 8.5 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2011)

Site	ET_o	Rainfall	Max. Temp	Min. Temp	Max. Humidity	Min. Humidity	Net Radiation	Wind Speed
A	-0.2	0.35	-0.1	0	-0.04	0.06	-0.21	-0.12
B	-0.25	0.67	-0.34	0.06	0.03	0.09	-0.3	0.43
C	-0.39	0.64	-0.31	0.1	0.12	0.22	-0.38	0.16
D	0.1	0.67	-0.01	-0.04	0.02	-0.08	0.15	0.05
E	0.03	0.15	-0.03	-0.18	-0.22	-0.18	0.02	-0.02
F (1)	-0.01	0.67	-0.2	0.11	0.16	0.14	0.06	0.01
F (2)	0.02	0.43	0.03	0.32	0.22	0.15	0.05	-0.06
G	-0.11	0.38	-0.39	-0.02	-0.04	0.17	-0.09	0.31

$0 < \rho < 0.25$ $0.25 \leq \rho < 0.5$ $0.5 \leq \rho \leq 1.0$

The determined ET_{willow} rates from the systems in 2011 were again checked for Spearman Rank-Order correlation with the meteorological parameters. The coefficients for each parameter are shown in Table 8.5. It can be seen that, in general, rainfall had the highest correlation with ET_{willow}. The correlation ranged from being relative strong for Sites B, C, D & F(1) to moderate for Sites A, F(2) & G. Once again, this seems to have had the effect of skewing the coefficients of

the other meteorological parameters. There was a moderate positive correlation with the ET_{willow} and the wind speed on Sites B & G.

8.3.3 2012 Evapotranspiration Rates

The mean daily ET_{willow} rates for the systems in 2012 are shown in Table 8.6. When examined, it can be seen that, in general, the evapotranspiration rates are relatively high compared to the previous year. As would be expected, there is a tendency for the earlier constructed willow systems to have higher values as the trees would be larger and hence have a higher water demand. The highest recorded mean daily ET_{willow} was 8.7 mm/day in June on System E. The relatively low value for August on Site A is as a result of the heavy rainfall in that month, which meant that the ET_{willow} could only be determined on a very small number of days due to a lot of overflow from the system. It is also worth noting the relatively high ET_{willow} rates that extend into October for many of the systems.

Table 8.6 Comparison of the mean daily ET_{willow} (mm/day) in 2012

	A	B	C	D	E	F (1)	F (2)	G	H (1)	H (2)	I (1)	I (2)
January	0.2	0.8	0.5	0.2	0.3	0.8	1	0.8	-	-	-	-
February	0.4	0.4	0.9	0.5	0.3	1	1.8	1.5	-	-	-	-
March	1.1	1.3	1.8	1.2	1	1.6	3.3	2.1	-	-	-	-
April	1.6	3.2	2	1.6	2.4	1.2	1.2	1.1	2.5	1.0	1.7	1.5
May	6.5	4.1	3.5	2.6	4.5	2.5	5.5	3.4	3.8	3.2	2.8	4
June	5.7	3.9	5.8	1.6	8.7	7.2	5.3	2.7	4.3	5.8	1.7	1.9
July	7.4	6	4.1	3.8	6.1	5.4	6.4	2.1	4.6	3.4	2	2.7
August	2.3	7.2	6.1	3	4.1	0.4	4.2	4.7	4.2	3.8	2.7	2.3
September	6.3	5.5	4	1.7	3.5	3.6	5.1	1.8	4.9	3.8	3.3	2.4
October	3.7	1.2	0.6	2	0.8	1.5	1.5	3	3.8	3.5	1.5	0.5
November	0.2	0.5	0.2	0.2	0.1	0.2	0.5	0.2	0.2	0.6	0.1	0.1
December	0.04	0.1	0.1	0.1	0	0.1	0.3	0.1	0.1	0.1	0.1	0.1

* Willow system was empty for part/all of month

The Spearman Rank-Order correlation coefficients between ET_{willow} and the different meteorological parameters are shown in Table 8.7. It can be seen that there is no discernible pattern to the coefficients. In general rainfall had the highest correlation with ET_{willow} from the meteorological parameters. The coefficients ranged from relatively high on Sites C, D & F (1) to moderate values on Sites A & G. As with 2010 and 2011, the high coefficients for rainfall seem to have the effect of distorting the coefficients from the other meteorological parameters. It is only System 2 on Site H that follows the pattern that would be expected for evapotranspiration from

a willow system. The temperature and net radiation coefficients with ET_{willow} were positive and moderately strong, while the humidity coefficients were negative.

Table 8.7 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2012)

Site	ET_o	Rainfall	Max. Temp	Min. Temp	Max. Humidity	Min. Humidity	Net Radiation	Wind Speed
A	0.02	0.35	-0.12	-0.18	0.05	-0.29	-0.03	-0.05
B	-0.02	0.2	0.2	0.31	0.12	0.2	-0.37	-0.34
C	-0.62	0.86	-0.03	-0.06	0.44	0.52	-0.58	-0.18
D	-0.22	0.56	0.08	0.13	-0.01	0.11	-0.18	0.33
E	0.13	-0.03	-0.31	-0.42	-0.45	-0.37	0.1	-0.54
F (1)	-0.05	0.51	0.33	0.37	0.37	0.3	-0.09	-0.17
F (2)	-0.09	0.12	-0.63	-0.44	-0.57	-0.41	-0.07	-0.01
G	0.06	0.46	0.25	0.31	-0.1	-0.34	0.04	0.45
H (1)	0.03	0.17	0.19	0.34	-0.45	-0.09	-0.1	0.12
H (2)	0.4	0.18	0.54	0.45	-0.3	-0.37	0.28	-0.09

$0 < \rho < 0.25$ $0.25 \leq \rho < 0.5$ $0.5 \leq \rho \leq 1.0$

The relatively high ET_{willow} rates during the growing season were probably aided by the high rainfall throughout the summer. This would have ensured that there was high water availability to the willow trees, so they could reach evapotranspiration rates a lot closer to their maximum potential evapotranspiration in contrast to 2011 when water levels dropped quite low on many of the systems.

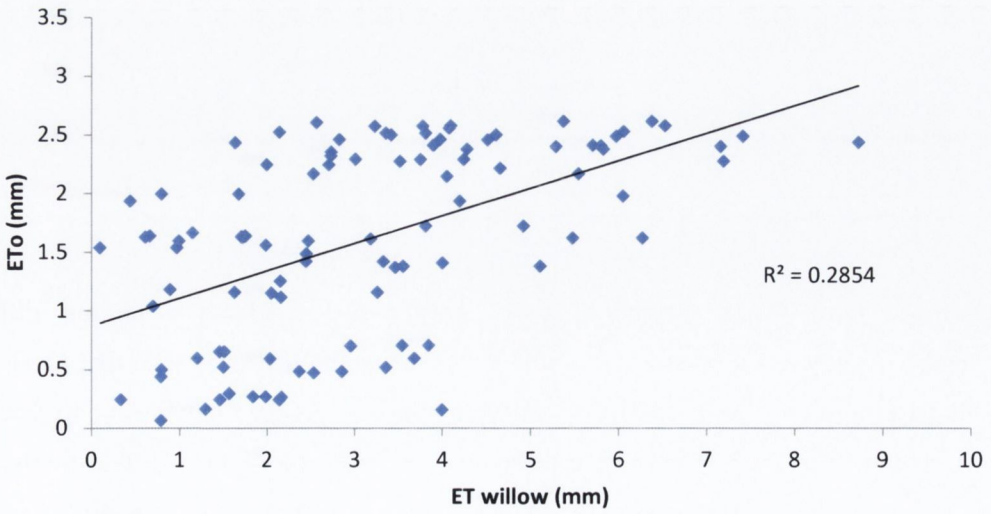


Figure 8.1 Correlation between mean daily ET_{willow} rates and mean daily ET_o rates during the 2012 growing season

It can also be seen (Figure 8.1) that there was a relatively good correlation (Pearson r-value of 0.534) between the mean daily ET_{willow} rate for each month and the corresponding mean daily ET_o. This highlights the fact that ET_o had a significant effect on the evapotranspiration rates from the systems and factors arising from issues such as soil porosity/compaction and water availability were not as significant.

8.3.4 2013 Evapotranspiration Rates

The mean daily ET_{willow} rates from the systems in 2013 are shown in Table 8.8. In general there seems to be somewhat of a decrease in rates from the 2012 season. Once more, the systems on Sites A & B appear to have higher rates in comparison to the later established systems. However, the evapotranspiration for these two systems are also probably conservative due to the water level reaching the bottom of the basin for extended periods throughout the summer. While the relatively warm, dry weather did appear to have a positive effect on evapotranspiration at the start of the summer (at least on the systems with good plant development), the knock on effect of this was to reduce ET_{willow} rates later in the summer. This seemed to occur as a result of lack of water availability, which meant the willows could not reach their potential evapotranspiration due to water stress.

Table 8.8 Comparison of the mean daily ET_{willow} (mm/day) in 2013

Month	A	B	C	D	E	F (1)	F (2)	G	H (1)	H (2)	I (1)	I (2)	J
Jan	0.1	0.1	0.2	0.1	0	0.2	0.2	0.2	0.1	0.1	0.1	0.1	-
Feb	0.4	0.8	0.5	0.4	0.3	0.5	1	0.9	0.5	0.5	0.4	0.4	-
Mar	0.8	1.7	0.9	0.8	0.7	1.2	1	1.3	0.8	0.9	0.8	0.8	2.9
Apr	2.1	3.9	1.5	2.1	1.9	3.8	3.1	1.7	2.1	2.2	1.6	1.2	1.1
May	5.1	3.6	3.1	2.9	-	2.7	6.5	2.3	2.3	2.9	2.1	4.3	1.7
June	6.8	4.2*	3.3	2.5	-	1.9	3.1	2.7	3.1	3.1	3.2	2.8	1.7
July	4.6*	2.1*	3	2.3	-	2	2.5	2	3.4	3.7	3.2	1.2	1.1
Aug	4.7*	2.9*	3.3	1.8	-	2.4	2.3	2.2	1.4	1.7	5.9	5.1	3.8

*Willow system was empty for part/all of month

The Spearman Rank-Order correlation coefficients between ET_{willow} and the different meteorological parameters are shown in Table 8.9. Once again, it can be seen that there is no discernible pattern to the coefficients. Rainfall again appears to have the highest correlation to ET_{willow} rates with Sites C, F(1), G & I(1) all having moderate coefficients. Interestingly, only Sites A & B seem to follow the expected pattern for evapotranspiration from a willow system. Both have a moderate to relatively strong ($\rho = 0.29$, $\rho = 0.54$) correlations with ET_o. Both also

have a relatively strong, positive correlation for temperature and net radiation, and negative correlations with humidity as would be expected for evapotranspiration.

Table 8.9 Spearman Rank coefficients between ET_{willow} and the individual meteorological parameters (2013)

Site	ET_o	Rainfall	Max. Temp	Min. Temp	Max. Humidity	Min. Humidity	Net Radiation	Wind Speed
A	0.29	0.2	0.5	0.49	0.05	-0.12	0.17	0.19
B	0.54	0.17	0.55	0.66	0.04	-0.34	0.53	0.05
C	-0.18	0.37	-0.26	-	0.01	0.02	-0.02	0.12
D	0.13	0.09	0.06	0.13	-0.11	-0.31	0.09	0.09
E	-	-	-	-	-	-	-	-
F (1)	-0.36	0.45	-0.2	-0.1	0.08	-0.01	-0.33	0.12
F (2)	-0.34	0.05	-0.46	-0.35	0.01	0.32	-0.24	0.31
G	-0.47	0.43	-0.65	-0.58	0.19	0.3	-0.27	0.33
H (1)	-0.22	-0.06	-0.16	-0.22	0.02	0.06	-0.09	-0.01
H (2)	-0.21	0.13	-0.26	-0.21	0.01	0.02	-0.1	0.16
I (1)	0.46	0.41	0.51	0.09	-0.2	-0.36	0.49	0.06
I (2)	0.09	0.01	0.06	-0.2	-0.23	-0.01	0.13	0.35
J	0.03	0.12	-0.09	-0.26	-0.09	0.01	0.07	0.14

$0 < \rho < 0.25$ $0.25 \leq \rho < 0.5$ $0.5 \leq \rho \leq 1.0$

The correlation between mean daily ET_{willow} and mean daily ET_o at the different sites is illustrated in Figure 8.2 It can be seen that the correlation is quite poor with a Pearson r-value of 0.118. This suggests that other issues such as soil porosity and water availability were quite important factors in determining the ET_{willow}.

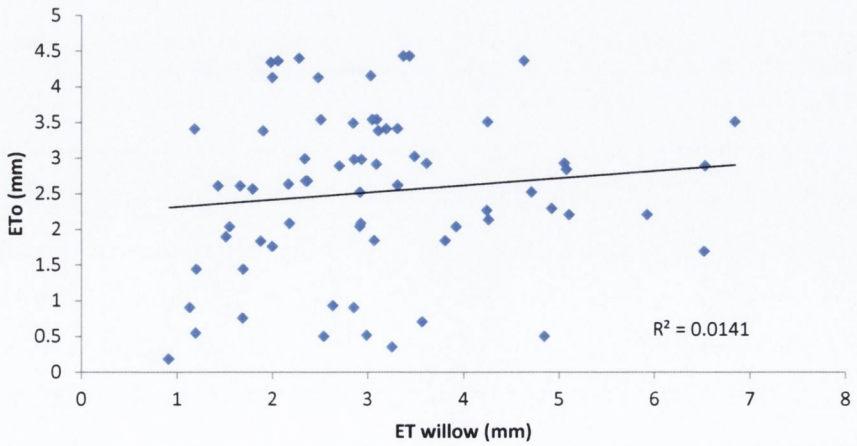


Figure 8.2 Correlation between mean daily ET_{willow} rates and mean daily ET_o rates during the 2013 growing season

8.3.5 Summary of Evapotranspiration

The correlation between ET_{willow} and the different weather parameters produced mixed results for all the systems. It appears that rainfall has a large bearing on the evapotranspiration rate attained, which makes sense as water availability is a key issue in terms of the willow reaching their potential evapotranspiration rates (Allen et al., 1998). The results from 2013 provided perhaps the most useful correlation results. The warm, dry spell mean that ET_{willow} could be compared more accurately to meteorological parameters such as temperature, net radiation and humidity without rainfall skewing the results. It was also shown how the soil conditions appeared to affect the ET_{willow} from the willow system on Site C.

The effect of the different meteorological parameters along with water level and soil conditions are examined in more depth through regression analysis in Section 8.9.

8.4 Crop Coefficient Comparison

The only study of note that has been carried out to assess the crop coefficient of willow throughout the growing season was conducted in northern Italy by Guidi et al. (2008), and Pistocchi et al. (2009). The experiment involved measuring the water use of willow clones, which were planted in lysimeters where a readily available supply of water was provided at all times. This section will compare the crop coefficients obtained from the three willow systems that were deemed to have reached the expected stages of development. The comparison involves the results from the systems on Sites A, B & C during the first and second growing seasons, which corresponds to the growing seasons monitored in the aforementioned experiments.

The results of the first growing season comparison are illustrated in Figure 8.3. It can be seen that the crop coefficients for all of the systems followed a similar trend from April to July. The values for Sites A & B were slightly higher than those found by Guidi et al. (2008), while the values for Site C were slightly lower. However, in August the crop coefficients for all of the full scale systems decreased somewhat (to between 1.35 - 1.57), while the crop coefficient in the lysimeter experiment increased to 2.59. The decrease for the full scale systems was probably as a result of lack of readily available water, as the system on Site B emptied out completely over this period and the ET_{willow} on Site C appeared to be affected by soil porosity (detailed in Section

8.8). It is also interesting to note that the crop coefficients are higher (significantly so) in September (except for Site A) and October compared to the lysimeter experiment.

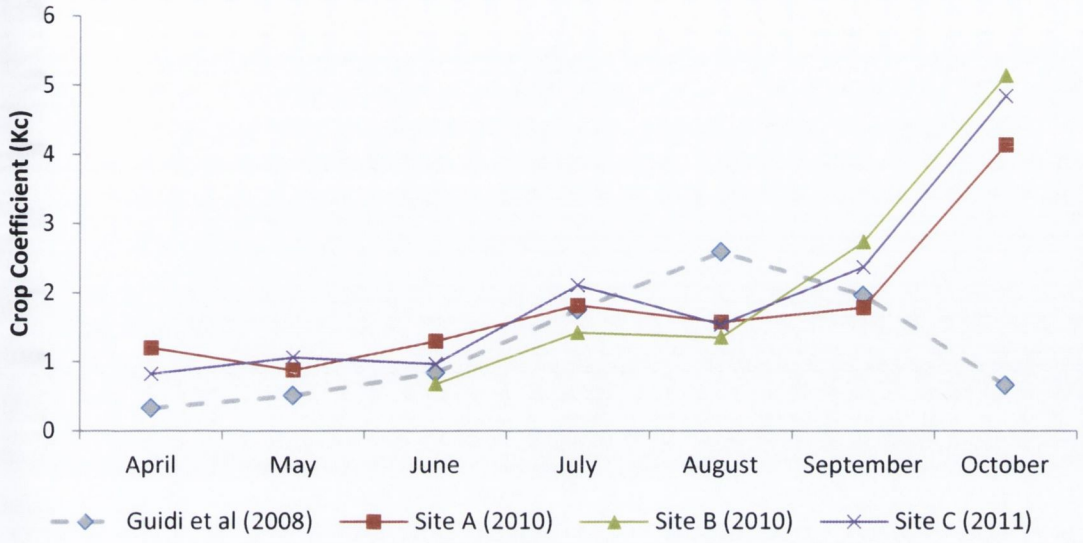


Figure 8.3 Comparison of monthly crop coefficients with those reported by Guidi et al. (2008) for willows in the first growing season

The results of the second growing season comparison are shown in Figure 8.4. It can be seen that the crop coefficients were a lot more varied for this season. Again, the Irish full scale systems performed relatively well in the early stages of the growing season having higher crop coefficients than the those reported from the lysimeter experiment for May and June (except for Site B, which was slightly lower). However, from July to September the crop coefficients for the full scale systems were significantly lower than those reported by Guidi et al. (2008) for the lysimeter experiment. This appears to be primarily as a result of lack of available water on the full scale systems. As detailed in Sections 5.3.1.2 and 5.3.2.2, the willow system on Site A was completely empty from the start of August onwards, while the system on Site B was empty from the start of June onwards. The lack of available water in contrast to the lysimeter experiment, which supplied the trees with a constant, measured amount of water, was almost certainly going to result in reduced crop coefficients.

Once again, however, it is interesting to note that the crop coefficients for October are higher for the full scale systems compared to the lysimeter experiment. This may be as a result of the higher reference evapotranspiration rates that were measured as part of the lysimeter experiment conducted in Italy. For example, the mean daily ET_o rates for the October period

during that experiment ranged from 1.58 - 1.75 mm/day. Whereas the mean daily ET_o rates measured in October (on Sites A & B) as part of this research ranged from just 0.71 - 0.97 mm/day. Further possible reasons for this occurrence are detailed in more depth in Section 5.4.3.

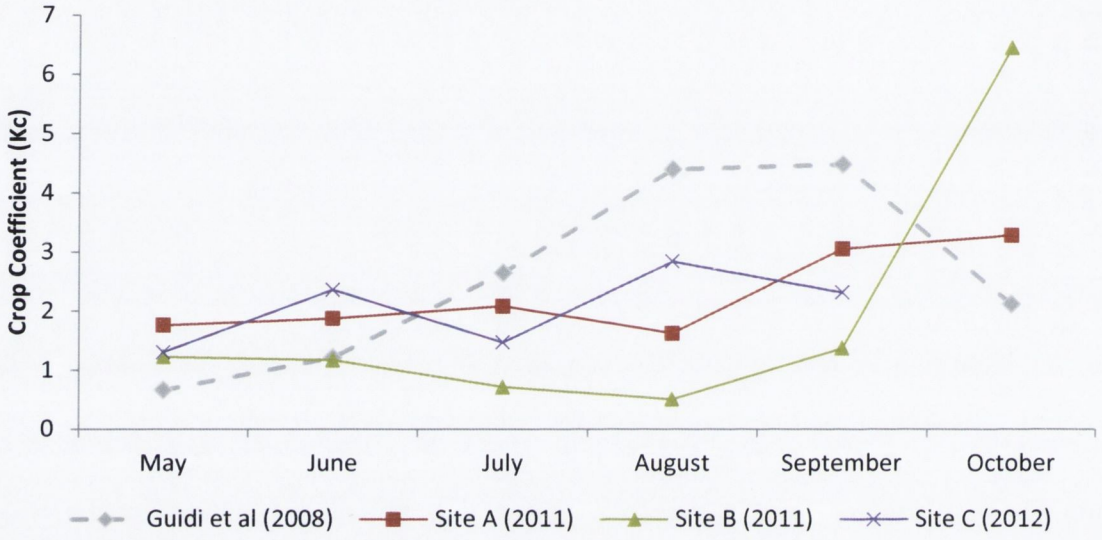


Figure 8.4 Comparison of monthly crop coefficients with those reported by Guidi et al. (2008) for willows in the second growing season

8.5 Effluent Type

As detailed at the start of this chapter, one of the objectives of this research was to determine the effect that effluent type had on evapotranspiration from a willow system. Initially, the plan was to establish willow systems at different existing dwellings that would then receive different effluent types (septic tank effluent and secondary treated effluent). This would have allowed for comparison of similar willow systems at similar stages of plant development. However, due to lack of interest from homeowners with existing dwellings, construction of the willow systems took place on a staggered time frame over two years. Also, growth and development of the willow clones varied between the different sites, meaning that it would be difficult to assign a significant difference in ET_{willow} to a change in effluent type, rather than to the size of the willow plants. As a result, it was impossible to conduct a comprehensive cross county comparison.

As part of the research project a mesocosm experiment, which is dealt with in Chapter 4, was established. The objective of the experiment was to determine the effect that three different

treatment types (STE, SE and water) had on four different varieties of willow clones. As the effect of effluent type on ET_{willow} could not be comprehensively examined across the full scale systems, it was the outcome of this experiment which provided the most insight into the effect of effluents on evapotranspiration. It concluded that evapotranspiration was highest from those clones receiving STE, followed by those receiving SE, with the clones receiving water having the lowest ET rate. These results were reinforced to some degree by the findings of a comparison carried out between the full scale systems on Site A and Site B.

As detailed in Section 3.4 the willow systems on Site A and Site B were both constructed and planted at the same time (May 2009). However, Site A had effluent production of 4PE from October 2010 onwards, whereas Site B only had effluent production of 1PE which commenced in January 2012. This meant that evapotranspiration from a system receiving septic tank effluent (Site A) could be compared to the evapotranspiration from a willow system receiving no effluent (Site B) to determine if there was a significant difference between the two.

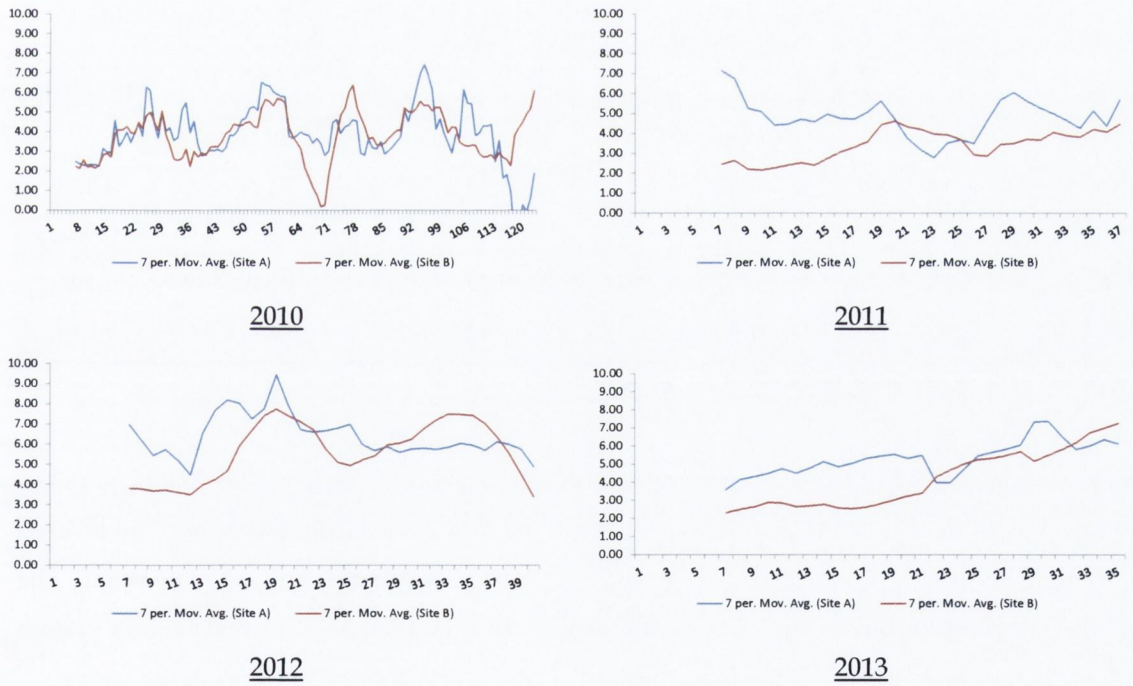


Figure 8.5 Comparison of daily ET_{willow} rate on Site A and Site B (2 week moving average trend line)

In order to carry out an unbiased comparison between the systems, evapotranspiration values were only included from days in which neither system was overflowing (which meant that the

evapotranspiration from the system would have been assumed to be equal to the reference evapotranspiration for that day, rather than the actual evapotranspiration) nor empty (an empty system would have less water available to the willow plants to access, meaning that evapotranspiration would almost certainly be lower for that system). A 7 day moving-average graph was plotted for each system and for each growing season (Figure 8.5). The growing season of 2010 had the largest number of ET_{willow} rates for comparison as it was a relatively dry summer (little overflow) and neither willow system bottomed out for extended periods.

The results of the Mann-Whitney U test carried out to determine whether or not there was a statistically significant difference between the daily ET_{willow} from each site is shown in Table 8.10. It can be seen that the daily ET_{willow} was higher on Site A for all four of the growing seasons. However, the difference between the systems was only significantly different for 2011 and 2013. While there was a still a difference in 2010 and 2012, the test did not deem it to be a significant one (at the 95% confidence level) for either year.

Table 8.10 Results from Mann-Whitney U test to assess if there was a significant difference between ET_{willow} for the different growing seasons

Year	Site A		Site B		p-value
	Mean (mm)	Median (mm)	Mean (mm)	Median (mm)	
2010	3.80	3.95	3.78	3.42	0.139
2011	5.16	4.95	3.52	3.21	0.001
2012	6.29	5.82	5.29	4.48	0.106
2013	5.30	5.47	4.34	3.71	0.019

p-value < 0.05 indicates significant difference

As the systems on both sites were practically identical in terms of design, willow clone varieties used, and plant development, any difference between ET_{willow} rates from the system can be used to assess the effect of STE loading to a system compared to a system receiving just rainfall. The lack of significant difference (p-value of 0.139) in 2010 is expected, given that neither system was receiving any effluent loading from the start of the year to the end of the growing season.

In 2011, however, the willow system on Site A (which had being receiving STE loading from October 2010 onwards) had considerably higher evapotranspiration (see Table 8.10) compared to the willow system on Site B. STE loading contributed 40.4% of total hydraulic loading to the system on Site A in 2011 compared to 0% on Site B, suggesting that this could have been the determining factor.

There was no significant difference (p-value of 0.106) noted between the systems in 2012. While wastewater loading did commence on Site B at the start of the year, it can be seen from Table 8.11 that it only accounted for a relatively low percentage of total hydraulic loading to the system. This coupled with the heavy rainfall in the summer, which resulted in significant overflow from the systems and probably loss of effluent as a result, meant that the overall effect of effluent loading was probably quite diluted in 2012.

It can be seen from Table 8.11 that septic tank effluent contributed a significant amount of the total hydraulic loading to both systems in 2013 (66% for Site A, 59% for Site B). The daily ET_{willow} rate was again higher on Site A compared to Site B, and the Mann-Whitney U test determined that the difference was statistically significant, with a p-value of 0.019 (Table 8.10). The difference between the values, however, was not as large compared to 2010 when there was no effluent loading to Site B. So, while there was still a higher percentage of effluent loading to Site A in 2012, the fact that the willow system on Site B was also receiving effluent at this stage helped narrow the gap between the evapotranspiration rates attained by both systems.

Table 8.11 Proportion of rainfall and wastewater on Site A and Site B (April - October)

Year	Site A		Site B	
	Rainfall (%)	Wastewater (%)	Rain (%)	Wastewater (%)
2010	100.0	0.0	100.0	0.0
2011	59.6	40.4	100.0	0.0
2012	85.8	14.2	89.1	10.9
2013	34.0	66.0	41.1	58.9

Overall, this comparison has indicated that the addition of effluent (STE in this case) is beneficial to the willow trees in terms of the evapotranspiration rates they can attain. This reaffirms the findings of the mesocosm experiment, which is detailed in Chapter 4.

8.6 Aspect Ratio

In Denmark, the only European country where there exist guidelines pertaining to the design, construction, and maintenance of zero discharge willow systems, there is a strong emphasis put on the shape of such systems. It is outlined in numerous reports (Gregersen and Brix, 2001, Brix and Arias, 2011) that a higher aspect ratio is desirable (i.e. long and narrow as opposed to square shaped). The main reasoning behind this idea is based on higher wind speed resulting in higher evapotranspiration.

(Brix and Arias, 2011) describe how a long, narrow willow system can take maximum benefits from the 'oasis' and 'clothesline' effects. The 'oasis' effect is the phenomenon where warmer and dry air in equilibrium with dry areas flows across a vegetation of plants with a high water availability. The 'clothesline' effect is when the vegetation height (the willow plants in this case) is greater than that of the surroundings. (Allen et al., 1998) has suggested that this occurrence may also increase evaporative water loss. This occurs where turbulent transport of sensible heat into the canopy and transport of vapour away from the canopy is increased by the 'broadsiding' of wind horizontally into the taller vegetation. An example is illustrated in Figure 8.6, whereby a row of trees planted perpendicular to the prevailing wind direction will increase evaporative water loss because plants use sensible heat from the air to evaporate water and furthermore, the wind transports water vapour quickly away from the plants.

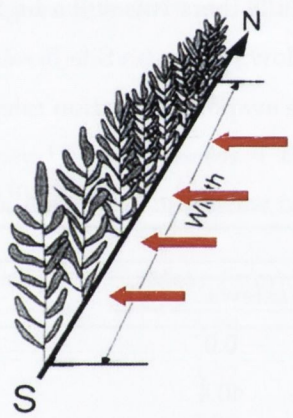


Figure 8.6 The 'clothesline' effect illustrated by a row of trees planted perpendicular to the prevailing wind direction ((adapted from Brix and Arias, 2011))

In order to analyse this effect of aspect ratio on evapotranspiration from a willow system, it had been planned to construct two willow systems on the same site with highly contrasting aspect ratios and compare the ET_{willow} rates attained from each. Site F was chosen as the preferred site and the willow systems (both had an area of 800 m^2) were designed with aspect ratios of 8 (System 1: 80m x 10 m) and 1.3 (System 2: 32 m x 25 m) respectively.

The ET_{willow} rates were just compared on days during the three growing seasons (2011, 2012, 2013) in which there was deemed to have been no overflow from either system. This was to ensure there was no bias shown to either system. The results from the Mann-Whitney U test (as the data was not normally distributed, hence required a non-parametric test) are shown in Table

8.12. It can be seen that the mean ET_{willow} for System 2 (mean = 5.2 mm/day) was significantly higher (at the 95% confidence level) than that determined for System 1 (mean = 3.0 mm/day). Initially, this would appear to suggest that the aspect ratio had no bearing on evapotranspiration performance, as System 1 (aspect ratio = 8) had much lower evapotranspiration rates on average compared to System 2 (aspect ratio = 1.3). All variables being equal (except the aspect ratio) this is a surprising result and so the validity of the comparison must be assessed.

Table 8.12 Comparison of daily ET_{willow} between systems on Site F

System	Aspect Ratio	Mean daily ET_{willow} (mm/day)	Median daily ET_{willow} (mm/day)	p-value
F (1)	8	3.0	2.4	<0.0001
F (2)	1.3	5.2	4.6	

When the different variables from both willow systems are examined it becomes apparent that aspect ratio probably had very little to do with the difference in ET_{willow} rates for the two systems. For example, the willow tree establishment and development on System 1 was much better than that on System 2. Also, the overflow point in System 1 was at a very low level (0.66 m from the base) and was a result of a suspected hole/tear in the liner, whereas the overflow on System 2 was above the surface level at a depth of 1.45 m from the base.

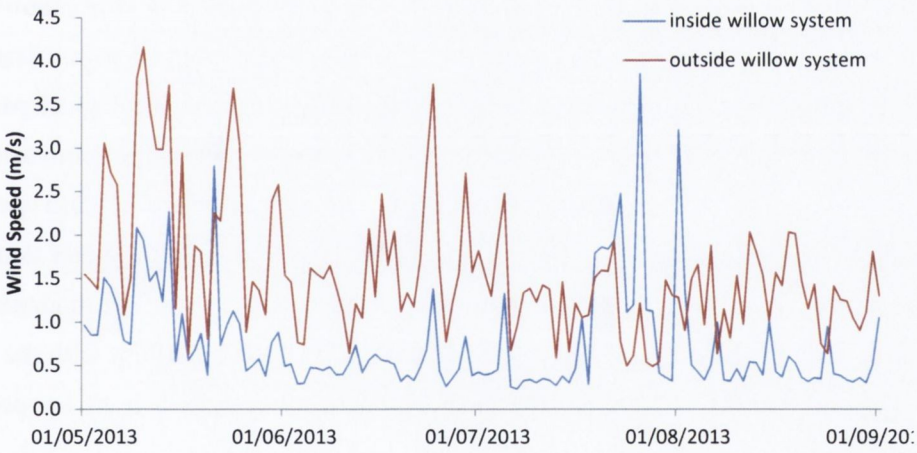


Figure 8.7 Comparison of the mean daily wind speeds inside and outside the willow system on Site C (May - August)

Hence, an additional study was set up in order to quantify the difference in wind speed between the outside of the system to that inside. This was done by erecting a second

anemometer at the end of April 2013 along the centre line approximately 15 m from one end of the system (40 m x 10.5 m). A time-series of the mean daily wind speeds measured by the existing anemometer outside the willow system and those measured by the anemometer inside the system is shown in Figure 8.7

It is quite apparent that the wind speed inside the willow system is significantly lower than that measured outside the system. This was confirmed by carrying out a Mann-Whitney U test (as the data was not normally distributed, hence required a non-parametric test), which showed that there was a significant difference between the wind speed outside [mean = 1.58 m/s] the willow system and that measured inside the willow system [mean = 0.76 m/s] (see Table 8.13).

Table 8.13 Results from Mann-Whitney U test to assess if there was a significant difference between the wind speeds inside and outside the willow system on Site C

Location	Mean (m/s)	Median (m/s)	p-value
Inside	0.76	0.51	<0.0001
Outside	1.58	1.46	

This demonstrates that there is a significant reduction in wind speed across a relatively short distance of the willow system. However, it was shown in the sensitivity analysis carried out in Section 4.2.10 that in Irish meteorological conditions wind speed has a relatively low impact on reference evapotranspiration. This was quite similar to the findings from the correlation analysis conducted on ET_{willow} rates in Section 8.3. There was a very low correlation between wind speed and ET_o (Spearman's rank coefficient, ρ of 0.06) and a mapped regression showed that a one standard deviation increase in wind speed (while other meteorological parameters are held constant) would result in an increase in reference evapotranspiration of just 0.14 mm/day. This suggests that in a temperature, moist climate such as Ireland's, wind speed is not as great a factor in determining evapotranspiration. This could be due to the fact that there is not as large a contrast in the moisture content between the willow leaves and the surrounding atmosphere as there might exist in drier, more arid climates. This is consistent with the findings of (Skidmore et al., 1969) who reported that a change in wind speed when air temperature is low or humidity is high only slightly affects the evapotranspiration rate.

8.7 Willow Clone Variety

As detailed at the start of this chapter, one of the objectives of this research was to determine if certain willow clones produced higher evapotranspiration rates compared to others, this making them better suited to being used in a zero discharge willow system. It had been

planned, at the start of the project, to plant varying willow clones at the different willow systems in such a manner that would allow for close comparison between varieties. The final clone layout for the different sites and systems is highlighted in Section 3.4.

However, as with the analysis on the effect of effluent type and the effect of aspect ratio on evapotranspiration from a willow system, the potential clarity of this investigation was also hampered by other overriding factors; the main one being the difference in willow plant establishment and development on the different sites.

As a result of this, there were no definitive results determined regarding better performing willow clones from the full scale willow systems in Co. Wexford. From a qualitative point of view, there was no marked difference observed between any of the different varieties on the different sites. The most conclusive results in this regard, came from the mesocosm experiment, which is detailed in Chapter 4. It showed in its comparison of four different willow clones, each receiving three different effluent types, which the clone used did not result in any statistically significant evapotranspiration rate being attained. The four clones examined were Tordis, Sven, Inger and Torhild, are all cultivars of *Salix Viminalis*.

8.8 Soil Porosity

As detailed for some of the sites in Chapter 5, the depth of the water level within the willow system appeared to be having an effect on the evapotranspiration rates attained. This especially appeared to be the case for the willow system on Site C and was most apparent during the 2013 growing season as illustrated in Figure 8.8. It can be seen that the time required for the water level to drop to a similar level to that in Systems A & B is much greater on Site C than for those two systems. While there is obviously going to be some variance between systems, this degree of time difference is surprising given that willow development on Systems A, B & C was quite similar.

When the different water levels are looked at, it can be seen that the slopes of the levels in Systems A & B are much more linear compared to that of System C. The slope of the water level line of on System C starts off quite linearly (mid-June), but the rate of decrease begins to drop off rapidly.

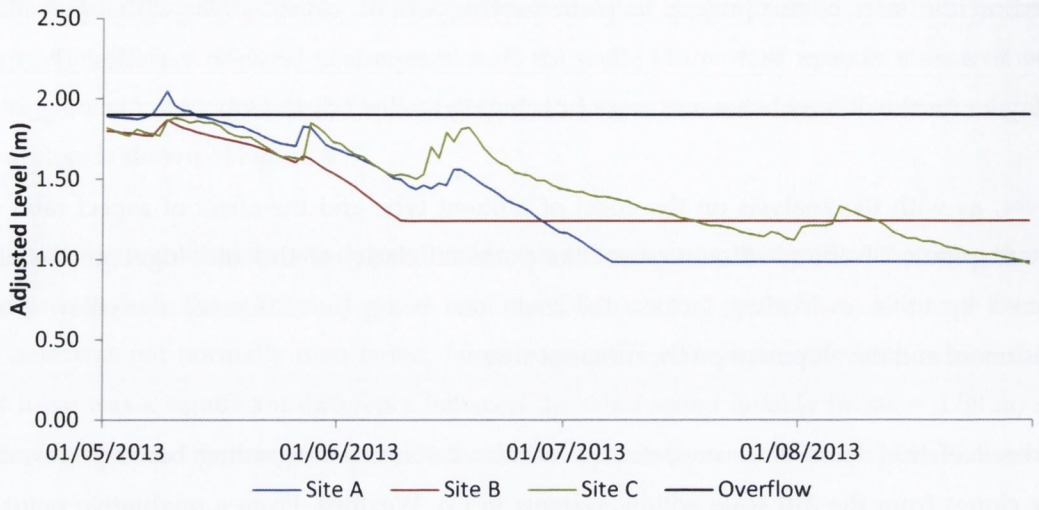


Figure 8.8 Water level within System A, B, C, and D with the overflow level set at 1.9 m (May – August 2013)

When the decrease in water level from 18th June – 26th July on Site C is examined (Figure 8.9) it can be seen that there is a strong linear correlation (Pearson r-value of 0.75) between the evapotranspiration rate attained on a particular day and the distance of the water level from the surface of the willow system on that day – as the level drops, so too does the evapotranspiration rate. This contradicts normal convention which predicts that evapotranspiration rates should increase from early to mid-summer as reported from multiple studies (Guidi et al., 2008, Pistocchi et al., 2009, Guidi and Labrecque, 2010).

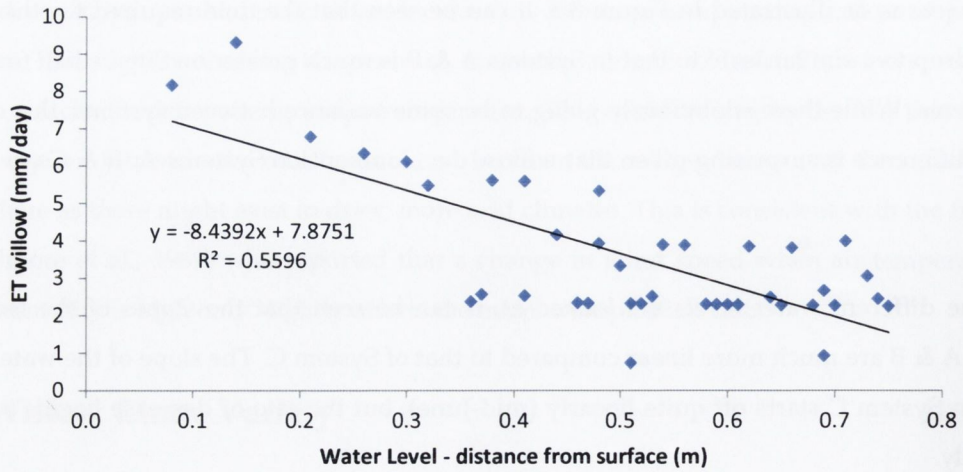


Figure 8.9 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site C, for the period 18th June – 26th July 2013)

When the water level on System A is examined (Figure 8.10) in the same manner it can be seen that there only exists a very weak correlation exists (Pearson r-value of 0.29) between the daily ET_{willow} and the distance of the water level from the surface on that day. Thus it can be assumed that the water level had little bearing on the evapotranspiration rate. While the evapotranspiration doesn't appear to follow the expected pattern of increasing as the growing season progresses (i.e. as the depth decreases), this may be as a result of having a small number of samples days (18).

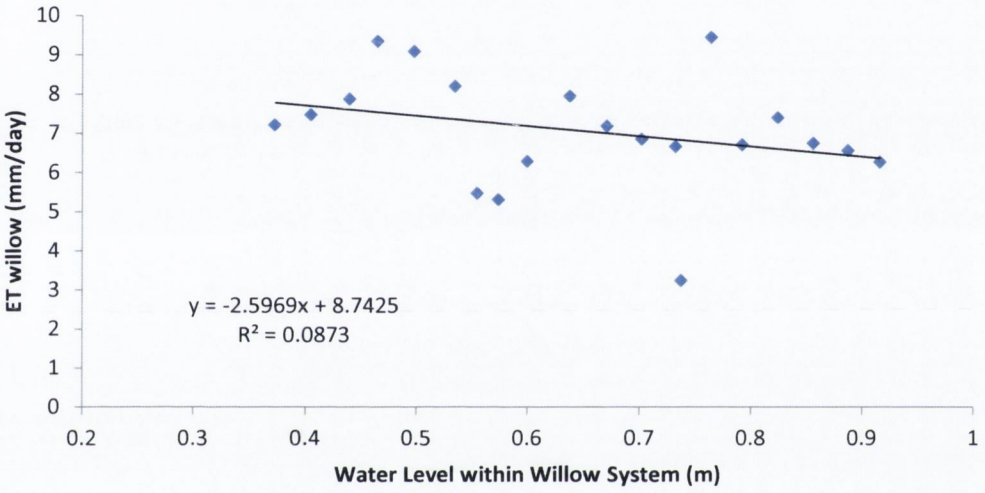


Figure 8.10 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site A, for the period 18th June - 7th July 2013)

When the water level on Site B is examined (Figure 8.11) it can be seen that there exists no correlation between a decrease in water level within the system and a decrease in evapotranspiration rate. In fact, the opposite pattern occurs in this case with an increase in evapotranspiration as the water level decreases (Pearson r-value of 0.69). This follows the trend reported by various studies which show an increase in ET_{willow} as the summer progresses (Guidi et al., 2008, Pistocchi et al., 2009).

The decrease in evapotranspiration coinciding with the decrease in water level on Site C would appear to be a function of the porosity of the soil within the system. It seems that the low hydraulic conductivity cannot sustain adequate water supply to the root system of the willow trees to keep up with the potential rate of evapotranspiration. This may be due to the inherent properties of clayey soil, however, it is also thought that the problem was made worse by compaction, when refilling of the soil was taking place during construction. The manner in

which the distribution drains were constructed within the soil medium in the willow system required the mechanical excavator to track in on top of the newly placed, relatively loose soil (see Figure 8.12). This would have had the effect of causing compaction in the soil.

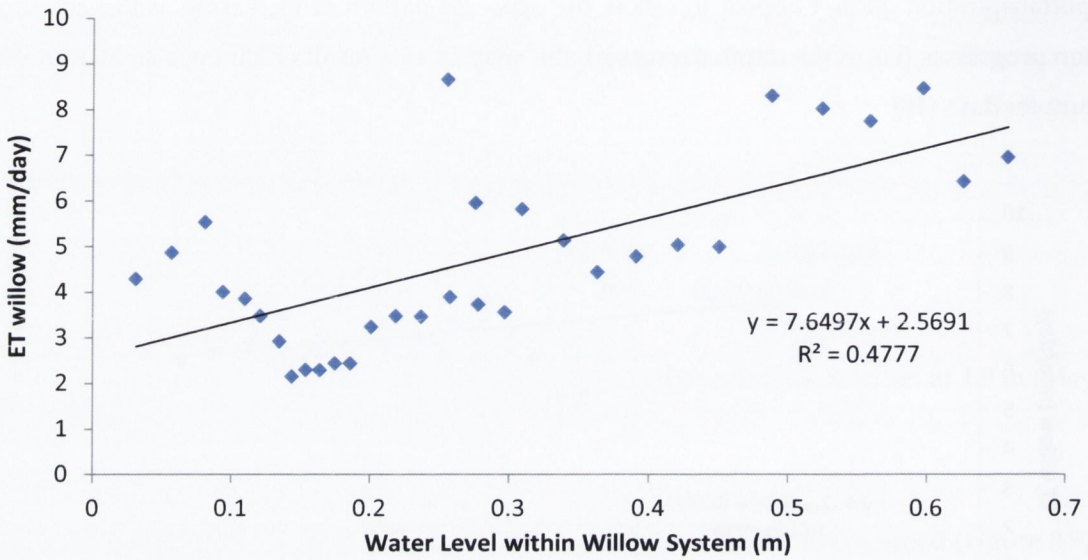


Figure 8.11 Correlation between daily ET_{willow} (mm/day) and water level within the willow system (Site B, for the period 9th May - 9th June 2013)



(A) (B)

Figure 8.12 (A) Refilling of relatively loose soil into basin; (B) Compaction of soil by excavator while constructing distribution drains

Soil compaction has been shown to have a negative effect from a number of aspects regarding plant growth. The main issue with regards to Site C is lowering of the porosity of the soil and reducing its permeability. Clay soils are known to have already low rates of permeability, with

coefficients of permeability ranging from 10^{-10} - 10^{-7} m/s (Bs 8004, 1986). As detailed in Section 4.5, the macro porosity of the soil is of most relevance when designing willow systems, as it is these voids which make free water available to the trees and ultimately dictates the storage capacity of the system. (Lowery and Schuler, 1994) reports on how compaction can significantly reduce the macro porosity of a soil, which has the knock on effect of reducing the hydraulic conductivity, as both are intrinsically linked (Childs and Collis-George, 1950, Vogel, 2000). So ultimately, in instances where the hydraulic conductivity of the soil is lower than the transpiration by the willow trees, it will be the hydraulic conductivity that will dictate the actual evapotranspiration rather than the potential ET of the willow trees.

It can be concluded from this, that it is imperative that compaction of soil be avoided during the willow system construction process.

8.9 Regression Analysis

The aim of this regression analysis was to gain some insight into the different factors which may affect the evapotranspiration performance of a willow system. Regression is often carried out with the purpose of creating a model on which an outcome can be predicted based on one or more inputs. This was not the intent with this analysis, as evapotranspiration from a willow system for any period of time cannot be accurately predicted primarily due to the high variance in seasonal meteorological conditions that can occur (especially in a temperate climate such as Ireland's that can see large fluctuations in rainfall from year to year). As such, this analysis was conducted in order to help assess the performance of the willow systems from a larger scope, which may aid the design and construction guidelines for the systems. It was decided to carry out the regression analysis on the three best performing willow systems (Sites A, B and C) as most of the other systems had complicating issues that may override any outcomes found with respect to meteorological or soil conditions at the site (e.g. poor establishment and development rate of the willow trees).

While there was correlation analysis conducted on the sites for the different growing seasons in Section 8.3, the results only gave an estimate as to the degree of association between ET_o and the different meteorological parameters. The regression analysis in this section will look to go one step further and describe the dependence of the ET_o on the different parameters. It assumes that there is a one-way causal effect from the explanatory variables (meteorological parameters) to the response variable (ET_o).

8.9.1 *Introduction to Regression*

Regression analysis is the fitting of equations to statistical data, and includes many techniques for modelling and analysing several variables, when the focus is on the relationship between a dependent variable (ET_{willow}) and one or more independent variables (e.g. ET_o, rainfall, water level). Regression analysis can aid the understanding of how a typical value of a dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed.

8.9.2 *Simple Linear Regression*

The simple linear regression model consists of a single regressor x that has a relationship with a response y that is a straight line, and can be seen in Eqn. 5.1.

$$y = \beta_0 + \beta_1 x + \varepsilon \qquad \text{Eqn. 8.1}$$

In the model, the intercept β_0 and the slope β_1 are unknown constants and ε is a random error component. The errors are assumed to have a mean zero and unknown variance σ^2. Additionally, errors are assumed to be uncorrelated; meaning that the value of one error does not depend on the value of any other error.

8.9.3 *Multiple Linear Regression*

An expansion of the simple linear regression model is one that involves more than one regressor variable and is referred to as a multiple linear regression model. This model (Eqn. 8.2) was used to assess the effect of multiple predictor variables on ET_{willow}. In general, the response y may be related to k regressor or predictor variables.

$$y = \beta_0 + \beta_1 x + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad \text{Eqn. 8.2}$$

The parameters β_j, $j = 0, 1, \ldots, k$, are called the regression coefficients. The parameter β_j represents the expected change in response y per unit change in x_j when all of the remaining variables x_i ($i \neq j$) are held constant. For this reason the parameters β_j, $j = 1, 2, \ldots, k$, are often called the partial regression coefficients. Multiple linear regression models are often used as empirical models for approximated functions. That is, the true functional relationship between y and $x_1, x_2, \ldots, x_k$ is unknown, but over certain ranges of the regressor variables the linear

regression model is an adequate approximation to the true unknown function (Montgomery et al., 2012).

8.9.4 Site C – Regression Analysis

8.9.4.1 ET_o as a predictor of ET_{willow}

The first analysis of the performance of the willow system on Site C was to compare the daily ET_{willow} measured from the system to the corresponding ET_o for the previous two growing seasons. The two summers provided a good contrast in meteorological conditions, which should allow for a relatively balanced analysis. The ET_o was chosen as the predictor in this case as it would appear to be the most obvious factor affecting evapotranspiration from the willow system. Thus, the correlation between the ET_{willow} and the ET_o was assessed by means of simple linear regression analysis, with the following model:

$$ET_w = \beta_o + \beta_1 ET_o \qquad \text{Eqn. 8.3}$$

Where ET_w is the evapotranspiration from the willow system on a particular day, β_o and β_1 are constants and ET_o is the reference evapotranspiration. Both the predictor and response variables for the 2012 growing season were analysed to test for normality and both passed the Anderson-Darling test with p-values of 0.631 and 0.212 respectively.

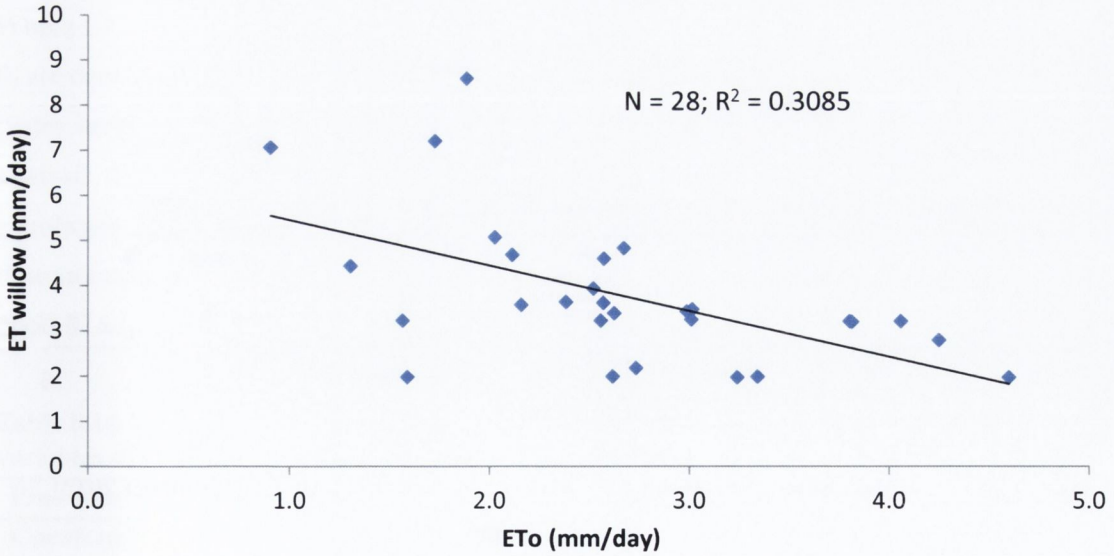


Figure 8.13 Linear regression plot of the daily ET_{willow} versus the daily ET_o (Summer 2012)

The results from the linear regression analysis are illustrated in Figure 8.13. It can be seen that there is a poor correlation between the ET_o and the ET_{willow} on the site for the 2012 season. While the correlation coefficient is relatively good (R = 0.56), the relationship is the inverse to what it should be - i.e. the ET_{willow} is decreasing with increasing ET_o. So as highlighted in Figure 8.7 (Section 8.3), of the meteorological parameters, it is rainfall that has the highest correlation with ET_{willow} in the 2012 growing season. As ET_o is logically going to be relatively low on days in which there is rainfall occurring, this is probably the reason for a low correlation between ET_o and ET_{willow}. The fitted linear regression model is shown in Eqn. 8.4.

$$ET_w = 6.467 - 1.011ET_o \qquad \text{Eqn. 8.4}$$

As detailed in Chapter 4, the 2012 growing season was exceptionally wet and thus water availability to the willows was relatively high, which would optimise the evapotranspiration rates attained. The 2013 summer, which will now be assessed, was in stark contrast to this and was characterised by relatively warm and dry weather. The same regression model was used again and both the predictor and response (ET_o and ET_w) passed the Anderson-Darling test for normality.

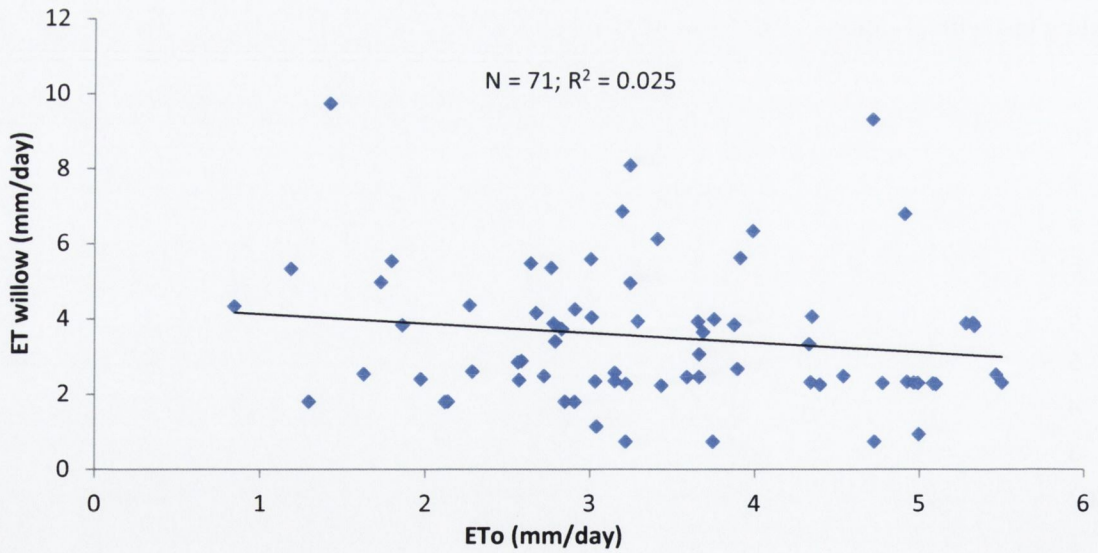


Figure 8.14 Linear regression plot of the daily ET_{willow} versus the daily ET_o (Summer 2013)

The results from the linear regression analysis are illustrated in Figure 8.14. It can be seen that there was a poor correlation (R = 0.158) between the ET_o and the ET_{willow} on the site for the 2013 season. Similarly to the 2013 growing season, the relationship was the inverse to what it should

have been, with an increase in ET_o corresponding to a decrease in ET_{willow}. The fitted linear regression model is shown in Eqn. 8.5.

$$ET_w = 4.381 - 0.254ET_o \quad \text{Eqn. 8.5}$$

It can be seen from the regression analysis carried for the two growing seasons that using ET_o as a predictor of ET_{willow} produced poor results for Site C. It would appear that other factors had a stronger influence on the ET_{willow} rates on the site, namely rainfall (2012) and water level within the willow system (2013). As such, the next section will examine the effect of these two factors using multiple linear regression techniques.

8.9.4.2 ET_o, Rainfall and Water Level as a predictor of ET_{willow}

As detailed in the previous section using ET_o as a predictor for ET_{willow} had varying levels of accuracy. This section will look to build on those results by adding the predictors of rainfall and water level within the willow system and analysing the effect that they had on the ET_{willow} rates in the 2013 growing season. Thus the correlation between ET_{willow} and the ET_o, daily rainfall and water level were assessed by means of multiple linear regression (MLR) analysis, with the following model:

$$ET_w = \beta_o + \beta_1 ET_o + \beta_2 R + \beta_3 W_L \quad \text{Eqn. 8.6}$$

Where ET_w is the evapotranspiration from the willow system on a particular day, β_o, β_1, β_2, and β_3 are constants and ET_o is the reference evapotranspiration; R is the daily rainfall; and W_L is the water level with the system. The results of the analysis are shown in Table 8.14. The MLR analysis found both the water level predictor and the rainfall predictor to be statistically significant ($p < 0.05$) when predicting ET_{willow} in summer 2013. The overall coefficient of determination was much improved from simple linear regression model with a considerable good R^2 adjusted value of 0.404.

Table 8.14 Model Summary for ET_{willow} on Site C (18th June - 30th August 2013) with predictor variables of rainfall (mm), ET_o, and water level within the system (m)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	-1.691	1.093	-1.547	0.127
Water Level	4.704	0.972	4.841	0.000
Rainfall	0.593	0.128	4.653	0.000
ET_o	-0.130	0.178	-0.733	0.466

S = 1.44 R-Sq = 42.9% R-Sq(adj) = 40.4%

The MLR model is shown in the following equation:

$$ET_w = -1.691 - 0.13ET_o + 0.593R + 4.704W_L \quad \text{Eqn. 8.7}$$

Where ET_w is the daily evapotranspiration from the willow system, ET_o is the reference evapotranspiration, R is the daily rainfall, and W_L is the water level. This analysis shows how the water level within the willow system and the daily rainfall had a much greater impact in determining the ET_o in 2013 compared to the reference evapotranspiration. This supports the findings in Section 8.8 which determined that a low water level combined with compaction in soil resulted in poor ET_{willow} rates from the system.

8.9.4.3 Meteorological Parameters as a predictor of ET_{willow}

Although it has been shown that ET_o had limited influence on the ET_{willow} rates from the willow system on Site C, the effect of the different meteorological parameters will still be assessed using multiple linear regression. The results of the MLR analysis, which analysed the importance of rainfall, temperature, humidity, net radiation and wind speed, are shown in Table 8.15.

Table 8.15 Model Summary for ET_{willow} on Site C (2012) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation (MJ/m²/day) and wind speed (m/s)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	-7.329	10.310	-0.711	0.485
Rainfall	0.362	0.046	7.914	0.000
Temperature	-0.075	0.108	-0.688	0.499
Max. Humidity	0.113	0.117	0.968	0.344
Min. Humidity	0.025	0.023	1.087	0.289
Net Radiation	-0.001	0.005	-0.202	0.842
Wind Speed	-0.764	0.295	-2.588	0.017

S = 0.7 R-Sq = 85.7% R-Sq(adj) = 81.7%

The MLR analysis showed just rainfall to be statistically significant ($p < 0.05$) when predicting ET_{willow} in the 2011 growing season. The model is shown in Eqn. 8.8.

$$ET_w = -7.329 + 0.362R - 0.075T + 0.113H_{max} + 0.025H_{min} - 0.001R_n - 0.764W \quad \text{Eqn. 8.8}$$

There were quite a few inconsistencies in the model, with temperature, humidity, net radiation and wind speed all having coefficients that suggest a relationship with ET_{willow} that is inverse to the one it should have. The MLR model had a relatively high coefficient of determination with an R^2 value of 0.857

8.9.5 Site A – Regression Analysis

Following on from the regression analysis carried out on the willow system on Site C, this section will now assess the different factors that may have had an impact on the evapotranspiration rate from the system on Site A.

8.9.5.1 ET_o, Rainfall and Water Level as a predictor of ET_{willow}

It was shown in Section 8.8 that there appeared to be no correlation between ET_{willow} and the depth of water in the system. This multiple linear regression analysis aims to verify this and also checks for the impact caused by rainfall and ET_o on a particular day. The results of the analysis are shown in Table 8.16.

Table 8.16 Model Summary for ET_{willow} on Site A (14th May - 6th July 2013) with predictor variables of rainfall (mm), ET_o, and water level within the system (m)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	5.277	1.198	4.407	0.000
Water Level	-1.542	1.111	-1.388	0.172
Rainfall	0.257	0.219	1.169	0.248
ET_o	0.501	0.252	1.986	0.053

S = 1.91 R-Sq = 12.3% R-Sq(adj) = 6.7%

The MLR analysis found none of the predictors (water level, rainfall, and ET_o) to be statistically significant ($p < 0.05$) when predicting ET_{willow} in the summer of 2013. However, it should be noted that the p-value for ET_o is just marginally above the 95% confidence threshold (0.053), and in fact drops below that threshold (p-value = 0.041) when the water level predictor is removed from the model. The MLR model is shown in the following equation:

$$ET_w = 5.277 + 0.501ET_o + 0.257R - 1.542W_L \quad \text{Eqn. 8.9}$$

Where ET_w is the daily evapotranspiration from the willow system, ET_o is the reference evapotranspiration, R is the daily rainfall, and W_L is the water level. The overall coefficient of determination for the MLR model was quite low with an R^2 value of 0.123. However, as detailed at the start of this section, creating a model to predict ET_{willow} was not the main reason for carrying out regression analysis. The primary objective was to analyse the relative effect different factors may have on evapotranspiration from the willow system. Thus, for the willow system on Site A, it was determined that ET_o did appear to play a significant part in determining ET_{willow} and that water level (and soil compaction by extension) had a relatively low bearing it.

8.9.5.2 Meteorological Parameters as a predictor of ET_{willow}

As it has been shown that ET_o can have a significant effect on the evapotranspiration from a willow system, further analysis was conducted in order to assess the impact that individual meteorological parameters may have on ET_{willow}. As shown in Section 8.3, there is a strong correlation between rainfall and ET_{willow} for almost all the sites in every season. This suggests that rainfall is by far the strongest factor when it comes to determining ET_{willow} rates on a given day. As a result it is difficult to determine the effects of other meteorological parameters have if water availability is assumed to be relatively consistent. On Site A, the summer of 2013 provided the best sample period to analyse the relative importance of the other meteorological parameters, as it was relatively dry with many days without rainfall. The results of the MLR analysis, which analysed the importance of rainfall, temperature, humidity, net radiation and wind speed, are shown in Table 8.17.

Table 8.17 Model Summary for ET_{willow} on Site A (14th May - 6th July 2013) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	3.201	9.607	0.333	0.741
Rainfall	0.046	0.240	0.193	0.848
Max. Temp.	0.230	0.159	1.443	0.156
Min. Temp.	0.151	0.163	0.924	0.361
Max. Humidity	0.057	0.124	0.464	0.645
Min. Humidity	-0.107	0.053	-2.000	0.052
Net Radiation	-0.010	0.007	-1.451	0.154
Wind Speed	0.594	0.345	1.722	0.092

S = 1.78 R-Sq = 30.5% R-Sq(adj) = 19.2%

The MLR analysis showed that rainfall is of no statistical significance in predicting ET_{willow} and only the minimum humidity on a certain day was shown to be close to having a statistically significant effect. The wind speed on a particular day also appeared to have an effect, but was just beyond the 95% confidence interval. The MLR model is shown in the following equation:

$$ET_w = 3.201 + 0.046R + 0.23T_{max} + 0.151T_{min} + 0.057H_{max} - 0.107H_{min} - 0.01R_n + 0.594W \quad \text{Eqn. 8.10}$$

Where, ET_{willow} is the evapotranspiration from the willow system, R is the rainfall, T_{max} is maximum temperature, T_{min} is the minimum temperature, H_{max} is the max humidity, H_{min} is the minimum humidity on a particular day, R_n is the net radiation, and W is the wind speed. Net radiation was determined to have negative coefficient which obviously shouldn't be the case and is probably just an inconsistency in the regression model. The MLR model had a moderate coefficient of determination with an R^2 value of 0.305.

8.9.6 Site B – Regression Analysis

8.9.6.1 Meteorological Parameters as a predictor of ET_{willow}

This section will conduct further analysis on the effect of the different meteorological parameters on ET_{willow}. The analysis will examine the 2011 and 2013 growing seasons on Site B. It was assumed, given the depth of the water had no effect on ET_{willow}, that apart from the impact by the willow trees themselves, only the meteorological effects were left as a factor. The results from the MLR model, which analysed the importance of rainfall, temperature, humidity, net radiation and wind speed for 2011, are shown in Table 8.18

Table 8.18 Model Summary for ET_{willow} on Site B (16th April – 24th May 2011) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	12.140	3.194	3.801	0.001
Rainfall	0.845	0.107	7.912	0.000
Max. Temp.	-0.052	0.094	-0.552	0.585
Min. Temp.	-0.081	0.078	-1.047	0.303
Max. Humidity	-0.068	0.034	-1.986	0.056
Min. Humidity	-0.029	0.018	-1.597	0.120
Net Radiation	-0.005	0.004	-1.083	0.287
Wind Speed	0.345	0.114	3.034	0.005

S = 0.73 R-Sq = 84.6% R-Sq(adj) = 81.1%

The MLR analysis showed rainfall and wind speed to be statistically significant ($p < 0.05$) when predicting ET_{willow} in the 2011 growing season. Maximum humidity was also deemed to be almost statistically significant ($p = 0.056$). The model is shown in Eqn. 8.11.

$$ET_w = 12.14 + 0.845R - 0.052T_{max} - 0.081T_{min} - 0.068H_{max} - 0.029H_{min} - 0.005R_n + 0.345W \quad \text{Eqn. 8.11}$$

Again, there were some inconsistencies in the model, with net radiation having a negative coefficient which doesn't make intuitive sense. This may be because rainfall was deemed to have the greatest bearing on ET_{willow} and net radiation, by nature, is going to be relatively low on days with rainfall occurring (see Figure 8.15 for confirmation). The MLR model had a relatively high coefficient of determination with an R^2 value of 0.846.

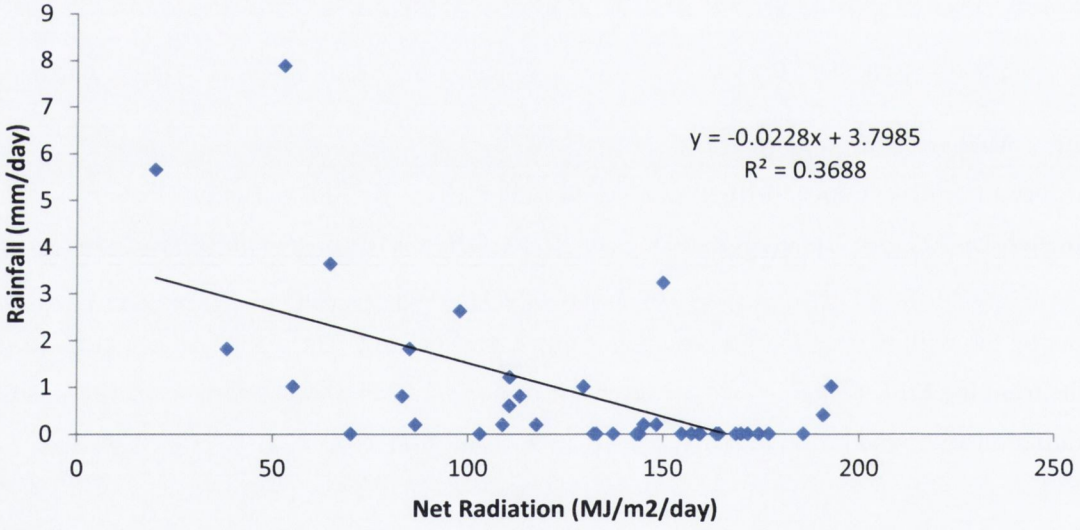


Figure 8.15 Relationship between rainfall and net radiation in Site B (2011)

As with Site A, it was thought that the summer of 2013 would provide the best insight into the impact by different meteorological parameters on ET_{willow} as there were long dry spells without rainfall which would skew the model. The results from the MLR model for that growing season are shown in Table 8.19.

Table 8.19 Model Summary for ET_{willow} on Site B (10th May - 9th June 2013) with predictor variables of rainfall (mm), max. and min. temperature (°C) max. and min. humidity (%), net radiation ($MJ/m^2/day$) and wind speed (m/s)

Predictor	Coefficient	Standard Error	t-value	p-value
Constant	-7.623	7.344	-1.038	0.311
Rainfall	1.635	0.538	3.039	0.006
Max. Temp.	-0.001	0.176	-0.004	0.997
Min. Temp.	0.467	0.184	2.540	0.019
Max. Humidity	0.086	0.108	0.801	0.432
Min. Humidity	-0.033	0.060	-0.552	0.587
Net Radiation	0.014	0.007	1.999	0.050
Wind Speed	0.066	0.285	0.232	0.819

S = 1.20 R-Sq = 68.7% R-Sq(adj) = 58.7%

The MLR analysis provided excellent insight into the effect that meteorological parameters have on ET_{willow} for the 2013 growing season. It deemed rainfall, minimum temperature and net radiation to be statistically significant ($p < 0.05$) in predicting ET_{willow}. Wind speed was shown to have no statistically significant effect on ET_{willow}, which contrasts with the findings in 2012. It is not obvious as to why this is the case, but perhaps the wind plays a bigger part in removing rainwater from the physical exterior of the trees (e.g. from the leaf and bark surfaces) during periods of rainfall. This effect may not be as relevant in drier weather when transpiration would account for the majority of the water loss from the system. The model is shown in Eqn. 8.12.

$$ET_w = -7.623 + 1.635R - 0.001T_{max} + 0.467T_{min} + 0.086H_{max} - 0.033H_{min} + 0.014R_n + 0.066W \quad \text{Eqn. 8.12}$$

The MLR model followed the general expected pattern in that parameters such as rainfall, minimum temperature, net radiation, and wind speed all had positive coefficients as would be expected. The MLR model had a relatively high coefficient of determination with an R^2 value of 0.687.

8.9.7 Regression Analysis Summary

The regression analysis provided some valuable insight into the factors which may affect the evapotranspiration rate from a willow system. The analysis conducted for the system on Site C provided support to the findings from Section 8.8, which showed that low soil porosity (most probably caused by soil compaction) had a large bearing on the ET_{willow} rates.

This was in contrast to the initial results from the regression analysis of the system on Site A during the 2013 summer, which showed that ET_o, not water level or rainfall, had the greatest bearing when predicting ET_{willow}. Further analysis of the effect of individual meteorological parameters provided some mixed results. The regression model for Site B using summer 2011 data showed rainfall and wind speed to have a significant effect ($p < 0.05$) when predicting ET_{willow}. However, additional analysis on the same system for the stable, warm and dry conditions in 2013 showed net radiation, rainfall and temperature to have the greatest bearing when determining ET_{willow}.

8.10 Comparison of willow systems on same site

Two identically designed willow systems were constructed on two of the sites (Sites H & I). This setup allowed for the close comparison of the systems in order to determine any difference in ET_{willow} that may have arose from issues such as willow establishment and development, construction techniques and soil conditions.

8.10.1 Site H Duncormick

Construction on Site H was completed in April 2011 and comprised of two willow systems, each with an area of 260 m^2. The systems were receiving STE from dwelling with 4 PE. System 1 was receiving most of the STE (~ 75%) for the majority of the monitoring period, with System 2 receiving the remaining ~ 25%.

Analysis of the daily ET_{willow} rates was conducted using the non-parametric Mann-Whitney U test (as data was not normally distributed) to check for differences in evapotranspiration performance between the two systems. The results from the analysis are shown in Table 8.20.

Table 8.20 Comparison of daily ET_{willow} between the System 1 and System 2 on Site H

System	Sample Size	Mean daily ET_{willow} (mm/day)	Median daily ET_{willow} (mm/day)	p-value
H (1)	317	3.5	3.1	0.145
H (2)	317	3.2	2.2	

It can be seen that the statistical analysis determined that there was no significant difference between the mean ET_{willow} rates between the two willow systems ($p > 0.05$). However, although it was not deemed significant, the mean daily ET_{willow} from System 1 was a little higher than that for System 2. There may have been a number of reasons for this. Establishment of the willow

clones was noted to have been better on System 1 compared to System 2. This coupled with the fact that willow System 1 was receiving more STE, meant that the trees on this system were probably more developed and thus larger, which would have resulted in higher ET_{willow} rates being attained. The willow systems were very similar in all other aspects regarding design and layout, so there are very few other reasons as to why the ET_{willow} rate was higher (albeit not significantly) on System 1.

8.10.2 Site I Carrigallen

Construction on Site I was completed in May 2011 and comprised of two willow systems, each with an area of 280 m^2. The systems were receiving secondary treated effluent from a dwelling with a PE of 4. Both systems were receiving the same amount of effluent. The results of the ANOVA which was conducted to check for a difference between the mean daily ET_{willow} between the two systems is shown in Table 8.21

Table 8.21 One way ANOVA test results for daily ET_{willow} between the System 1 and System 2 on Site I

System	Sample Size	Mean daily ET_{willow} (mm/day)	Median daily ET_{willow} (mm/day)	p-value
I (1)	56	2.5	2.8	0.980
I (2)	56	2.4	2.3	

It can be seen that analysis determined that there was no statistically significant difference between the evapotranspiration rates from the systems ($p > 0.05$). It did show up that the mean ET_{willow} for System 1 was slightly higher than that for System 2. This was not surprising, as the willow development in System 1 was much better than in System 2. In fact it is quite surprising that there is not a greater difference between the means. This result may have arisen from the manner in which the test was carried out. In order to conduct an unbiased test, the ET_{willow} rate was only taken used on days in which there was an ET_{willow} result determined for both systems. By referring to Section 5.3.10, the overall evapotranspiration performance was better on System 1. As mentioned this was expected given that the willow development was notable better on System 1.

The improved willow establishment and development on System 1 was suspected to have arisen from the manner in which the soil was back filled into the basin. It was noted that in the area where development was especially good on System 1, extra topsoil had placed at the surface by the contractor as the backfill had been depleted. This seemed to encourage

establishment and growth much better than the subsoil, which was located near the surface on the remainder of System 1 and all of System 2.

8.11 Assessment of Clay Liner

In order to examine the possibility of significantly reducing the cost involved in constructing a willow system, this research looked into the use of a clay liner to seal the basin of the system on Site G. The evapotranspiration rates (taken on days that none of the systems were overflowing) over the 2011/2012 dormant period were compared in order to determine if there was a noticeable difference between the lined systems and the unlined system (Site G). The results from the different Mann-Whitney U tests (which were conducted as the data was not normally distributed) are shown in Table 8.22.

Table 8.22 Results from Mann-Whitney U test to assess if there was a significant difference in ET_{willow} between different sites for the 2011/2012 dormant season

	Site G	Site C	Site D	Site E	Site F (1)	Site F (2)
Mean ET_{willow} (mm)	0.260	0.115	0.014	0.134	0.206	0.280
p-value	-	0.013	0.000	0.059	0.109	0.709

It can be seen that the mean winter ET_{willow} determined for the system on Site G was significantly higher than the ET_{willow} rates determined for Sites C & D over the same period. The p-value determined from the comparison between Site G and Site E was also just marginally over the 95% confidence threshold. Only system 2 on Site F had a higher mean ET_{willow} rate than the system on Site G. This analysis suggests that there may have been some leakage through the clay liner on the system on Site G.

Clay has been used as the secondary liner on landfills for a number of decades and it was originally thought that it was the clay liner rather than the plastic geomembrane that was the most important component of an impermeable layer in the long term (Simon and Müller, 2004 cites, Finsterwalder, 2003 and, Schmid and Schulz, 2004). This view has now changed and it has been shown that the functional engineering properties of certified high density polyethylene (HDPE) lasts hundreds of years and hence aging is no longer relevant for design considerations. Also, it has been reported that a conventional compacted clay liner can be destroyed by root penetration (which is especially relevant in the instance of willow systems) and crack formation (Melchior et al., 2001).

From the practical experiences of this research it has been noted that although in general the subsoils on the sites were clayey and of low permeability, there were instances of sand (or higher density subsoil) lens or layers occurring. Such layers could be quite difficult to seal sufficiently and as such use of a plastic/rubber impermeable liner may be the better option. It has also been reported that correct installation of a clay liner requires careful monitoring and execution and must be done when the clay has high water content (O' Sullivan and Quigley, 2002).

8.12 Establishment and Development of Clones

As detailed on a site by site basis in Chapter 5, a number of the willow systems saw poor establishment and development of the planted willow cuttings. As reported by (Gregersen and Brix, 2001), if the establishment rate and stem growth is poor in the first year, it will also generally be relatively poor in the second year, which ultimately effects biomass and this evapotranspiration.



(A) (B)

Figure 8.16 (A) Extensive weed growth on Site F (System 1) compared to (B) Site C which saw little weed growth as a result of using a weed proof membrane.

The poor willow development on the sites seems to have resulted for a number of different reasons. The two willow systems on Site F had extensive heavy weed growth in the initial year of planting. The extent of the weed growth is illustrated in Figure 8.16, in which System 1 (Site F) is compared to the willow system on Site C. Both pictures were taken shortly after first coppicing, and highlight the benefit of employing a weed proof membrane. As outlined by (Sage, 1999), tall weeds in competition with the willows for space and light are the primary factor in limiting willow stem numbers and length. All SRC and willow system guidelines

(including Defra, 2002, Miljøstyrelsen, 2003, Caslin et al., 2010) reiterate the importance of weed prevention in the first season.

The poor growth of willow cuttings on Site D appears to have been as a result of soil compaction and excessively dry soil when planting took place. The extent of this problem is illustrated in Figure 8.17. It can be seen that the establishment rate was very poor from picture (C). This was taken two years (2012) after original planting took place, with replanting having taken place in the interim year. Development had improved somewhat by the following year (2013) but was still quite poor, especially in comparison to some of the other systems that were planted around the same time (Figure 8.17 (D)).

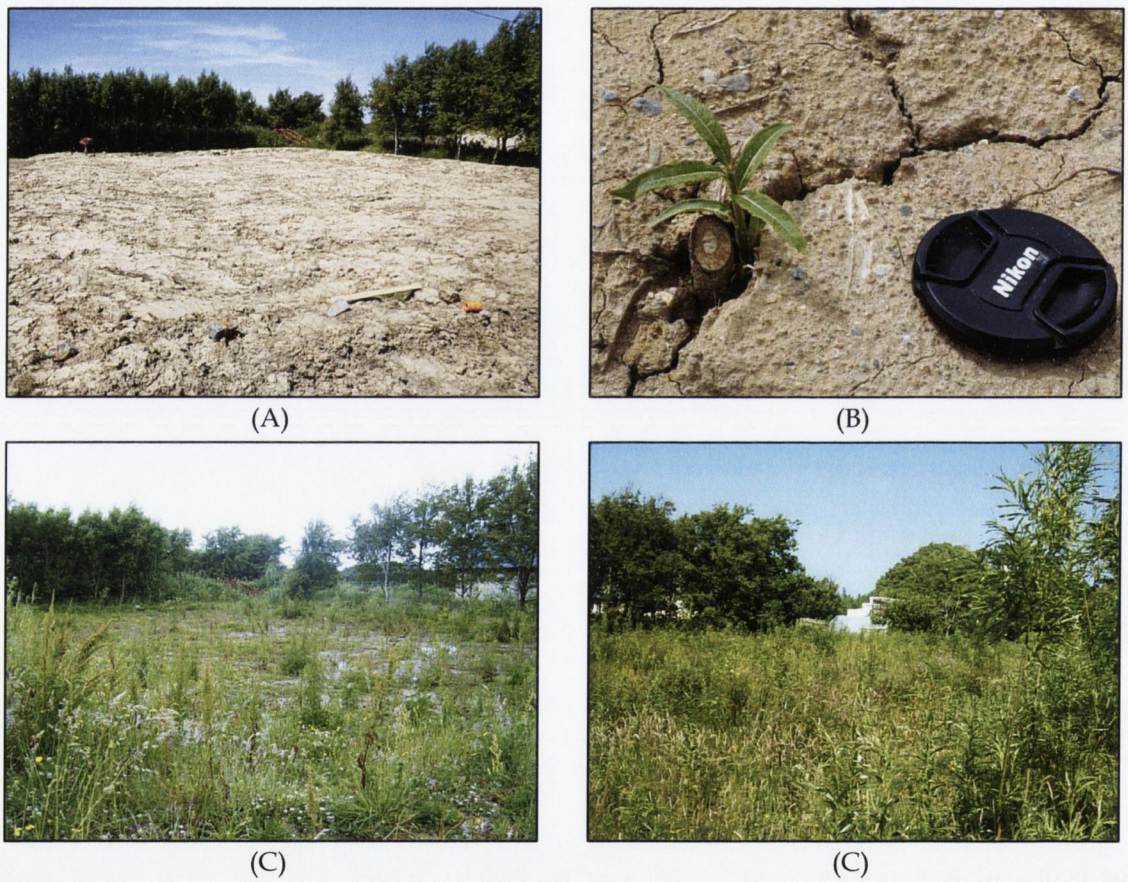


Figure 8.17 (A) Surface of the willow system prior to planting; (B) Poor willow establishment due to dry, compact soil; (C) Willow development on Site D two years after originally planting; (D) Three years after originally planting.

The cuttings were originally planted in June 2010, during a hot spell of weather. This had the effect of drying the surface of the bare soil in the willow system, which because it was very

clayey, resulted in a very hard planting medium. Also, compaction of the soil by the mechanical excavator would have compounded this problem. (Nixon et al., 2001) cited by (Dobson and Moffat, 1993) who reported that soil compaction is probably the biggest single factor responsible for poor tree growth (in regard to willow grown on landfill caps). It was also reported that compacted soils have a reduced water holding capacity, are more prone to waterlogging in winter, and inhibit root penetration and development. These findings were reinforced by (Ruark et al., 1982, and Kozlowski, 1999) who also determined that soil compaction significantly reduced base diameter, height and crown development in trees.

As detailed in Section 3.9.3 a trial was attempted in order to assess different remedial methods in the removal of weeds from an infested system. The trial was set up on three different 5 x 5 m plots on system 1 on Site F. The three different methods included covering with weed proof membrane, spraying of weeds with herbicide, and manual removal of weeds. The development of the willow trees in each plot was monitored to see if there was a visual difference. However, the results from the trial were inconclusive, as the relatively infrequent visits to the site meant some of the method (primarily the manual removal of weeds) was difficult to continuously implement.

Due to the timing of construction some of the systems were planted outside the recommended optimum period of March to May (June at the latest). The two systems on Site H, which were planted in July, were particularly late with respect to this timeframe. This seemed to have an effect on the plant development as the first growing season was particularly short (July - early October). As reported by (Dawson, 2007) earlier planting results in better establishment in the first season, which, as reported by (Gregersen and Brix, 2001) has the knock on effect of better development in the second season.

Chapter 9

Design Guidelines

9 Design Guidelines

9.1 Introduction

This research project included the design, construction and monitoring of willow evapotranspiration systems to evaluate their applicability and effectiveness in treating on-site wastewater in low permeability subsoils (with zero discharge) in an Irish climate. Hence, the reason that these systems would be considered for installation in Ireland is provide a solution to on-site wastewater treatment and disposal in low permeability subsoil where more conventional on-site systems based on percolation areas would not be suitable; this is in contrast to Denmark (where these systems have been trialled and are in operation for over a decade) where such systems are often considered as a more eco-friendly and/or cheaper alternative to standard on-site treatment systems.

Denmark was one of the first countries in the EU to introduce wastewater disposal charges for wastewater treatment plants, industry with direct discharge and dwellings not connected to a sewerage network in 1993 (Ecotec Research & Consulting et al., 2001). The standard rate was based on the amount of BOD, nitrogen and phosphorus produced. The use of zero discharge systems was seen as a ways of bypassing this tax, which led to trials of the systems being implemented in the late 1990s. The systems were deemed to be viable zero discharge units and guidelines for their design were produced.

There are no such charges in Ireland at present, with on-site treatment generally consisting of septic tank systems followed by discharge to groundwater via a soil treatment unit (with secondary treatment units treating the effluent before final discharge to groundwater in some cases). The Code of Practice for on-site wastewater treatment in Ireland (EPA, 2009a) has introduced a new a minimum field saturated hydraulic conductivity of T=90 (equivalent to $k_{fs} \approx$ 0.47 m/day), below which the discharge of on-site effluent to ground is not permitted. Zero discharge willow systems are seen as a possible alternative treatment system in areas of the country (estimated to be 40% - (EPA, 2012b)) which has inadequate percolation due to low permeability subsoils.

This chapter will outline the design guidelines for willow systems, which will be based on the results and practical experiences obtained from constructing and monitoring the willow

systems as part of this research. The sizing model will be based on meteorological conditions for Co. Wexford.

9.2 Design Model

The design model for sizing of a willow system was based on a water balance which incorporated hydraulic loading to the system via rainfall and effluent and removal of water from the system via evapotranspiration. The model used the daily rainfall and reference evapotranspiration measured on Sites A & B over the duration of the monitoring period. The water balance which determined the water level on a daily basis is shown in Eqn. 9.1. Each daily water level was then summed cumulatively to produce a profile over the monitored period (February 2010 - August 2013).

$$W_L = V_u(R + E - ET_{Willow}) \qquad \text{Eqn. 9.1}$$

Where,

W_L = Water level within the willow system

V_u = useable void ratio

R = rainfall (mm)

E = effluent (mm)

ET_{willow} = evapotranspiration from the willow system

The usable void ratio depended on the medium at any particular water level. If a change in water level occurred within the soil medium then a V_u value of 15% was assumed. If it was within the gravel layer a V_u of 33% was used and if the water level was above the surface of the soil the V_u was assumed to be 100% (see Figure 9.1 for an example).

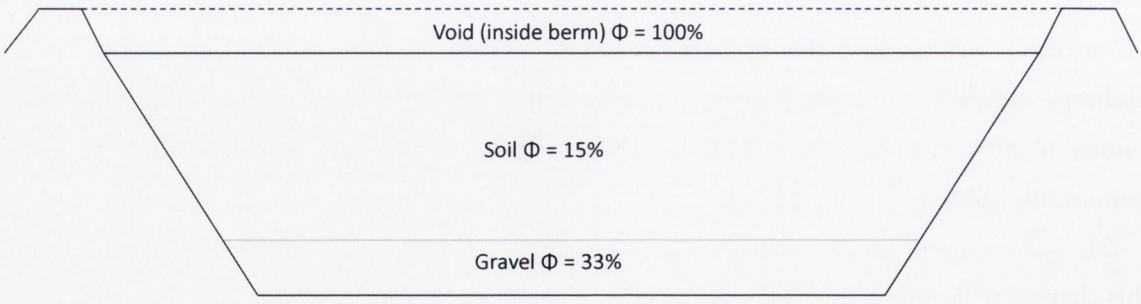


Figure 9.1 Sample cross sectional area of willow system with relevant porosities

The evapotranspiration rates used were based on the results found for Systems A & B as these were deemed to have been the only systems that performed to the expected standard over the duration of the research project. The ET_{willow} rates were determined on a monthly basis using the crop coefficient approach (Eqn. 9.2).

$$ET_{Willow} = ET_o \times K_c \qquad \text{Eqn. 9.2}$$

Where, ET_{willow} = evapotranspiration from the willow system

ET_o = reference evapotranspiration

K_c = crop coefficient

The growing season crop coefficients were based on those determined from Systems A & B. The main problem that arose from this, however, was the conservatively low crop coefficients that were calculated from some of the months on those particular systems. This was primarily due to the fact that the systems emptied out quite early in two of the monitored growing seasons and as a result there was no water readily available for evapotranspiration. This is illustrated in Figure 9.2 which shows a comparison between the crop coefficients for the two systems with those determined by Guidi et al. (2008) for willows in the second growing season. It can be seen that the crop coefficients on Sites 1 & 2 were equal to or higher than those in the lysimeter experiment for May and June but then dropped back for the rest of the summer months when the systems were empty. It should be noted that Site A was empty from the beginning of August until the end of October and Site B was empty from the end of May until the start of November.

As such it was deemed that these crop coefficients were not representative of the actual values that could be expected had water been more readily available. Hence the K_c values that would be used for the model were estimated based mainly upon early and late season crop coefficients but also influenced by the higher values determined by Guidi et al. (2008) as a guide. The dormant season crop coefficient were determined by taking the average from all the systems as it was assumed that willow development would have minimal bearing on these values.

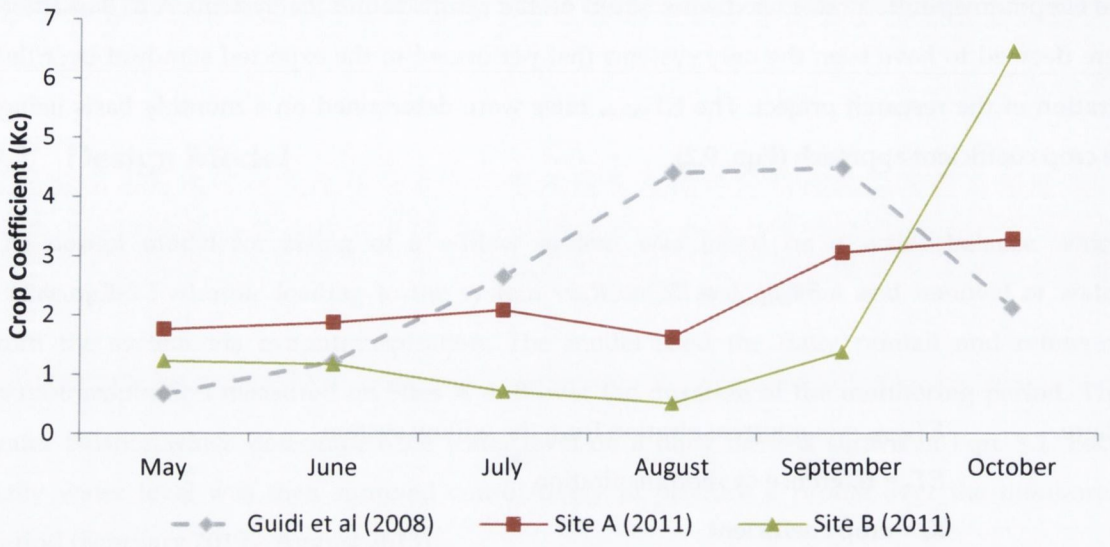


Figure 9.2 Second season crop coefficients for Sites A & B compared to those determined by Guidi et al. (2008).

Table 9.1 Mean Monthly K_c rates assumed for each month for use in the design model

Month	Assumed K_c	Mean ET_o (mm)	ET_{willow} (mm)
January	1.5	4.4	9.1
February	1.4	11.0	20.8
March	1.4	32.1	48.0
April	1.3	59.2	77.0
May	1.5	82.2	123.4
June	1.9	92.1	175.0
July	2.1	84.4	177.2
August	3.4	76.7	260.9
September	3.6	46.7	168.1
October	3.2	20.9	66.8
November	1.4	4.9	6.8
December	1.2	1.9	2.3
Annual Mean	2.2	516.6	1135.4

The final crop coefficients decided upon are shown in Table 9.1. It can be seen that the annual crop coefficient works out at 2.2. The mean annual ET_o on Sites A & B over the monitoring period was 517 mm, which gave an expected annual total of 1135 mm of evapotranspiration from the willow system.

9.2.1 *Model*

The monthly crop coefficients shown in Table 9.1 were then applied to the water balance described in Eqn. 9.1. Using the rainfall and reference evapotranspiration values determined over the monitoring period, a water level profile can then be modelled for any defined wastewater production, the water level profile being dependant on the following physical design factors:

- Area of system
- Porosity of the storage medium (soil and gravel)
- Depth of soil within the willow system basin
- Depth of gravel layer within the system
- Depth of free space available above soil surface (maintained by berm)

Various combinations (within practical constraints) of the above factors were used in order to determine the minimum area required to try and ensure zero discharge throughout the year. However, it became apparent that zero discharge could not always be achieved; primarily during/following years in which heavy rainfall occurred, as was the case in 2012. This mirrored the findings on most of the systems monitored. An example of a water level profile produced by the model for a dwelling with 4PE is shown in Figure 9.3 with parameters as shown in Table 9.2.

Table 9.2 Willow system parameters used for water profile model

Area (m^2)	Effluent (L/c/day)	Soil Porosity (%)	Gravel Porosity (%)	Depth of Gravel Layer (m)	Depth to soil surface (m)	Depth of Free Space (m)
500	100	15	35	0.3	1.8	0.3

The system was determined to have overflow for 105 days across a 3 and a half year period (which corresponds to the monitoring period of the full-scale systems). It was found that by increasing the area, the numbers of days in which overflow occurred was reduced. For example, if the area of this particular modelled system was increased to 750 m^2 the overflow days decreased to 65, while a further increase in area to 1000 m^2 resulted in just 13 overflow days. However, from both a practical and cost point of view there reaches a stage in which an increase in area is not feasible and thus a compromise must be reached. As such, the following

section will focus on optimising the specifications for the willow system while taking practical and cost aspects into account.

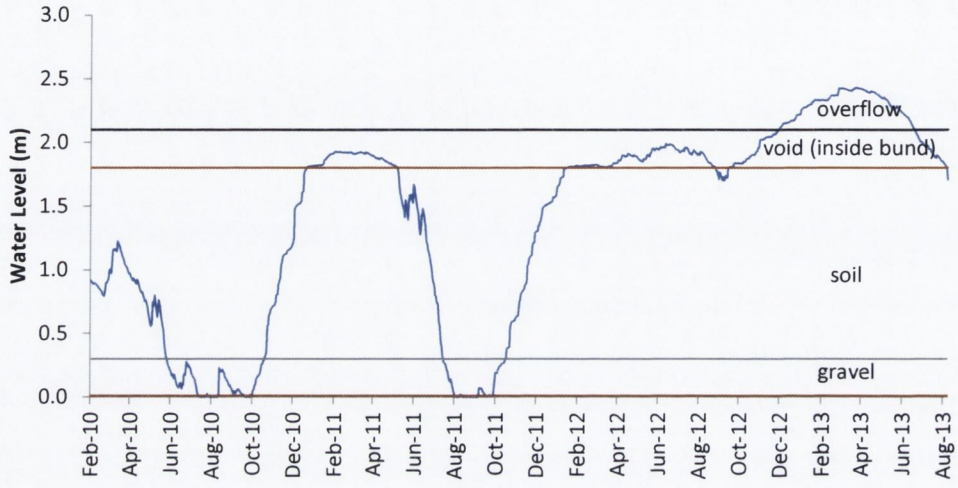


Figure 9.3 Water level profile determined by model (using rainfall and ET_o data collected on Sites A & B)

The modified water level profile, which assumes that any overflow is lost from the system, and does not need to be removed via evapotranspiration, is shown in Figure 9.4. It is worth noting that water level reaches the bottom of the system by the end of August in the 2013 growing season.

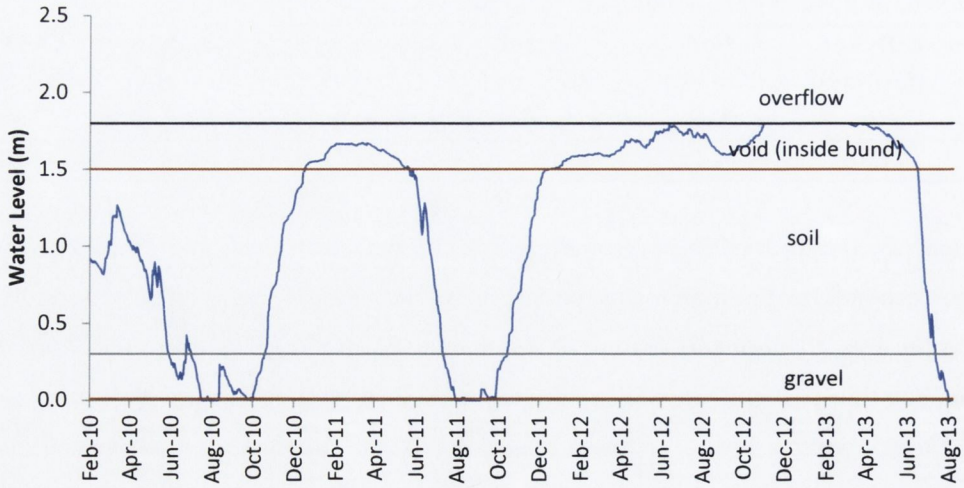


Figure 9.4 Water level profile determined by model (after overflow is assumed to be lost from the system)

9.2.2 *Overflow*

As detailed in the previous section it is apparent that the evapotranspiration that can be expected from a willow system in a given year may be lower than the corresponding hydraulic load (rainfall and effluent). If this situation were to arise it would result in overflow from the system occurring. This section will seek to optimise the system in terms of lowering the amount of overflow days that may occur, while also taking practical area and financial constraints into account.

The first aspect examined was implementing various area and depth combinations. It should be noted that this design was for a dwelling with a PE of 4, and the design parameters of the system with the exception of area and depth are the same as those in Table 9.2. The areas used in the model for this analysis ranged from 250 - 700 m^2 (50 m^2 increments), while the depths ranged from 1500 - 2200 mm (100 mm increments). The depths also included a 300 mm free space above the soil surface bounded by a berm. The effect of increasing the area on the number of overflow days is illustrated in Figure 9.5.

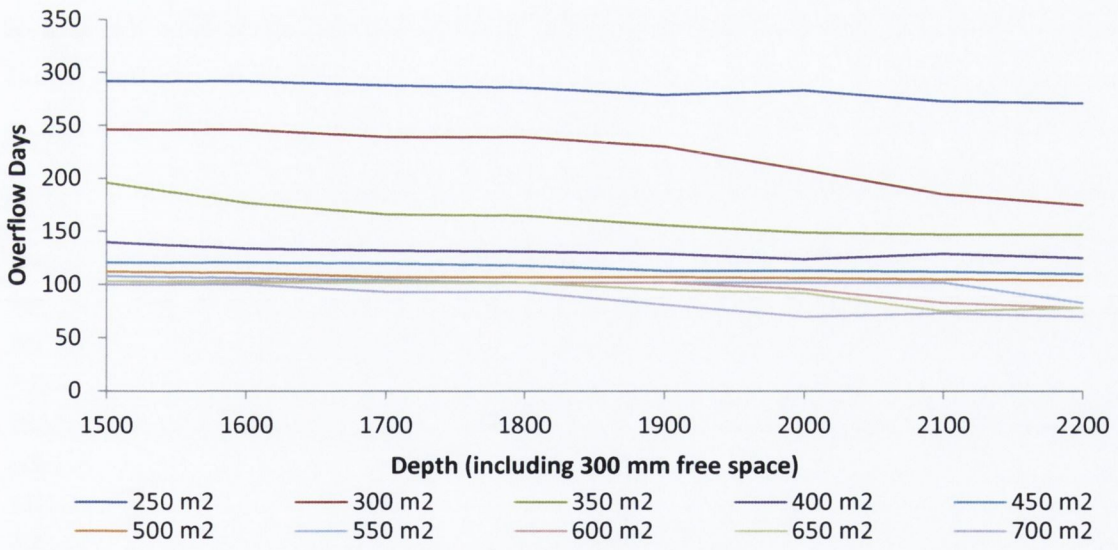


Figure 9.5 Effect of increasing the area on the number of overflow days

It can be seen that significant gains in terms of decreasing the amount of overflow days can be made by increasing the area from 250 m^2 up to 500 m^2. From this point onwards the gains made by increasing the surface area of the willow system are quite marginal and the expense that would be incurred trying to achieve less overflow would not be worth it. This is highlighted

again in Table 9.3. By increasing the area from 250 m^2 to 500 m^2 decreases the days in which overflow occurs from 283 to 107 (176 days), however, further a further increase in area to 700 m^2 only results in a further decrease of 22 days. Thus, it can be concluded that the optimum area for a willow system receiving effluent from a dwelling with 4PE is approximately 500 m^2.

Table 9.3 Mean number of days with overflow for different surface areas (across depths ranging from 1.5 - 2.2 m)

Area (m^2)	Overflow Days	Overflow Volume (m^3)	Δ Overflow Days
250	283	342	-
300	221	354	62
350	163	335	58
400	131	308	32
450	116	284	15
500	107	277	9
550	101	271	6
600	96	292	5
650	94	313	2
700	85	291	9

It should also be noted that while increasing the area reduces the amount of days in which overflow occurs, the actual volume of overflow starts to increase again once the area is increased beyond 550 m^2. However, at this large of an area, the majority of the overflow would be comprised of rainwater, while for the smaller areas, the effluent would make up a higher proportion of the overflow and would be more of a pollution risk.

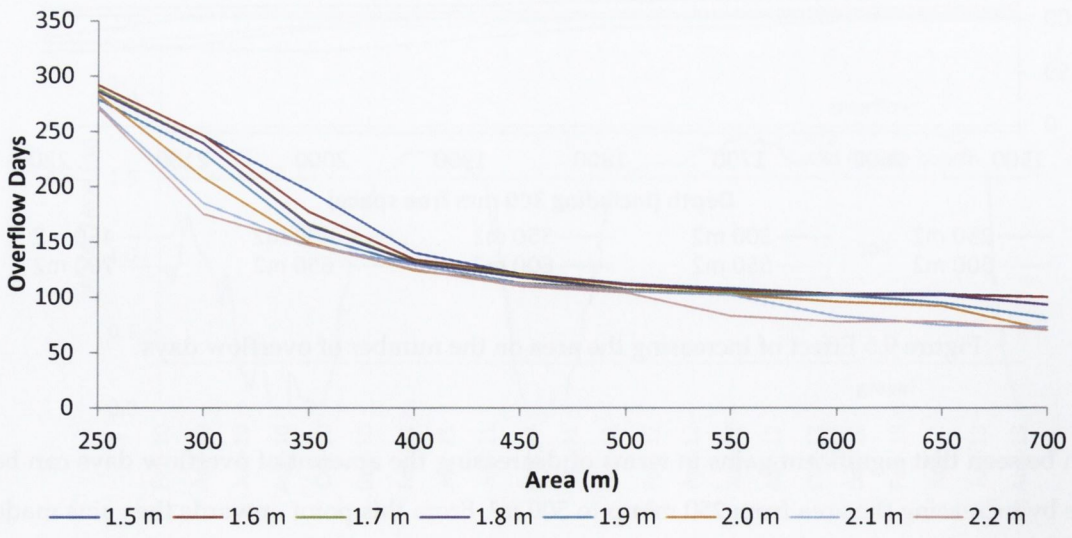


Figure 9.6 Effect of increasing the depth on the number of overflow days

The second aspect to be examined is the effect of increasing the overall depth on the amount of overflow from the willow system. The results for varying the depth, which are from the same model which was run to check for the benefit of increasing area is shown in Figure 9.6 It can be seen that an increase in area can be worthwhile for smaller areas (< 350 m^2) and then again for larger areas (> 550 m^2). For the range of areas in between, it appears that there is not much to be gained by increasing the depth of the system.

A matrix highlighting the overflows for different combinations of area and depth is illustrated in Table 9.4. As would be expected, the combinations of higher area and depth result in lower days with overflow. There are quite a few combinations that will result in approximately 100 - 110 days of overflow and this is probably the optimum range to aim at, taking practical and financial constraints into account. For example, it is shown that the overflow days can be reduced to as low as 70 for a 4PE dwelling, but this would require a significantly larger system of area 700 m^2 and overall depth of 2.2 m. Indeed, the overflow could be reduced even further, but again, the system required to do so would deem it not to be financially viable. As such, the depth will be limited to 2.1 m on the design model.

Table 9.4 Matrix showing the amount of overflow days from the willow system for different area and depth combinations

	Number of Overflow Days							
Area/Depth	**1.5 m**	**1.6 m**	**1.7 m**	**1.8 m**	**1.9 m**	**2.0 m**	**2.1 m**	**2.2 m**
250 m^2	292	292	288	286	279	283	273	271
300 m^2	246	246	239	239	230	208	185	175
350 m^2	196	177	166	165	156	149	147	147
400 m^2	140	134	132	131	129	124	129	125
450 m^2	121	121	120	118	113	113	112	110
500 m^2	112	111	107	107	107	106	105	104
550 m^2	108	106	104	102	102	102	102	83
600 m^2	103	103	102	102	102	96	83	78
650 m^2	103	102	102	102	95	92	75	78
700 m^2	100	100	93	93	81	70	73	70

This section compares the effect of different combinations of area and depth on the water level profile. It can be seen in Figure 9.7 that there are extended periods of overflow (246 days in total) from a 300m^2 willow system with an overall depth of 1.5 m. The benefit of increasing the area to 500 m^2 is clearly illustrated with the number of overflow days significantly reduced to 112. Further increase in area to 700 m^2 has limited benefit with the number of overflow days decreasing by just 12 to 100 days in total.

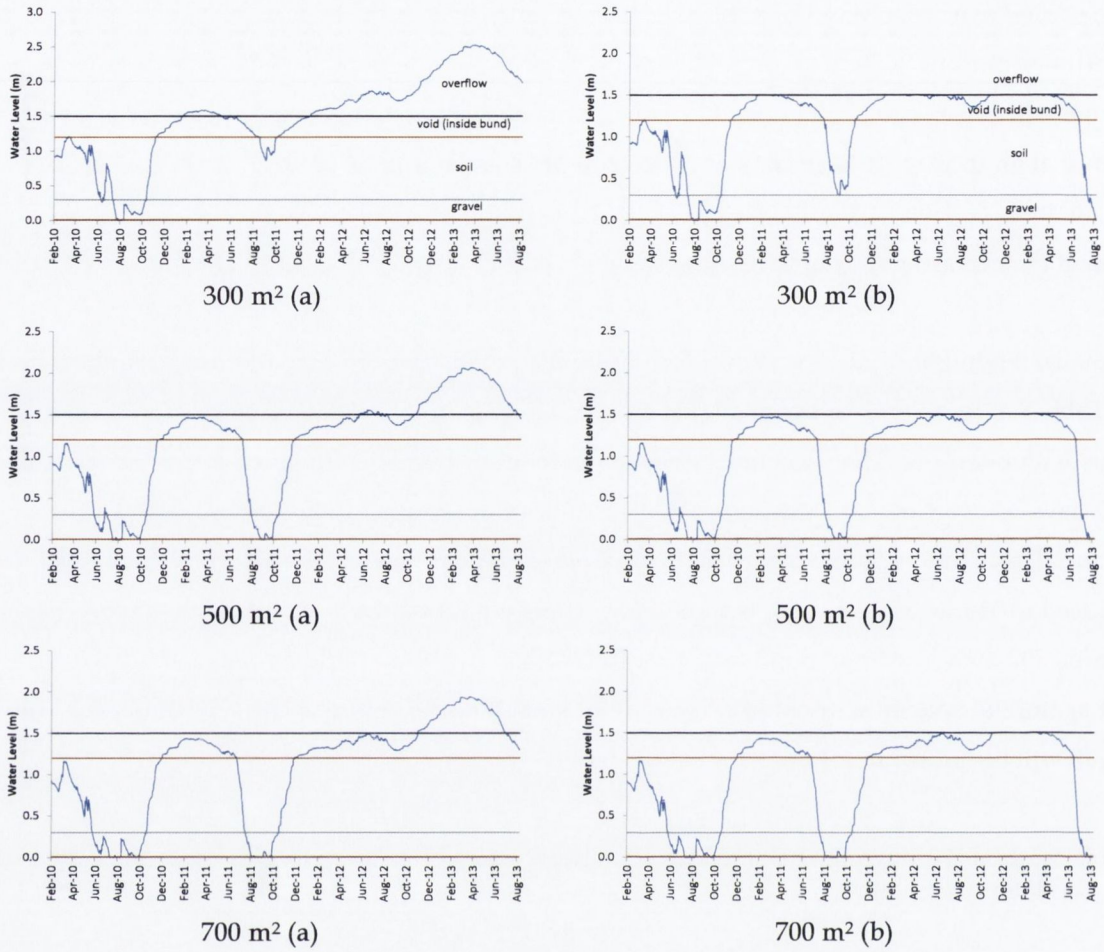


Figure 9.7 Water profile for willow system of and depth 1.5 m and areas area 300 m², 500 m², 700 m²; (a) overflow assumed to still be in system, (b) overflow assumed to have been lost from system

The effect on the water level profile of increasing the depth of a 500 m² willow system from 1.5 m to 1.8 metres is illustrated in Figure 9.8. The increase has limited effect and the number of overflow days decreased from 112 to 107. Further increase of depth of the 500 m² to 2.1 m again has limited effect, with decrease of just 2 overflow days over the duration of the modelled period.

The result of running the model again for four different effluent loadings is shown in Figure 9.9. The loading rates were 5PE, 6PE, 8PE, and 10PE, while assuming a daily effluent production of 100 L/c/day. While this loading rate is lower than that assumed in the Code of Practice (EPA, 2009a), it is based on the assumption that any dwelling using a willow treatment system should

have up to date water saving appliances (e.g. dual flush toilet, low-flow shower head, tap aerators). The effect of an increased loading rate is discussed further in Section 9.2.7.

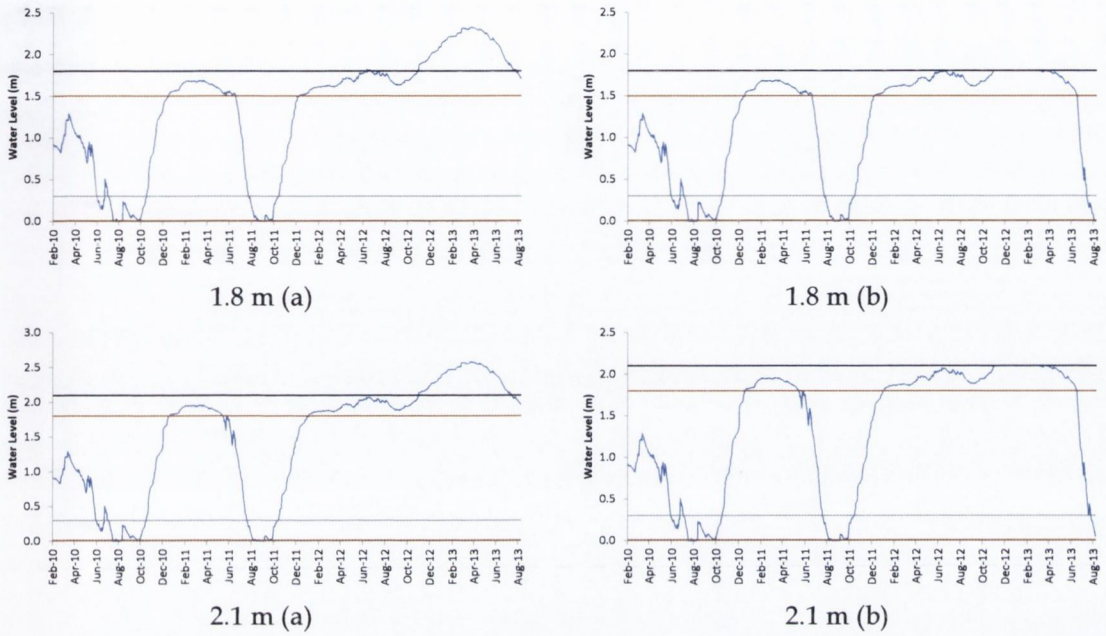


Figure 9.8 Water profile for willow system of area 500 m² and depths 1.8 m and 2.1 m; (a) overflow assumed to still be in system, (b) overflow assumed to have been lost from system

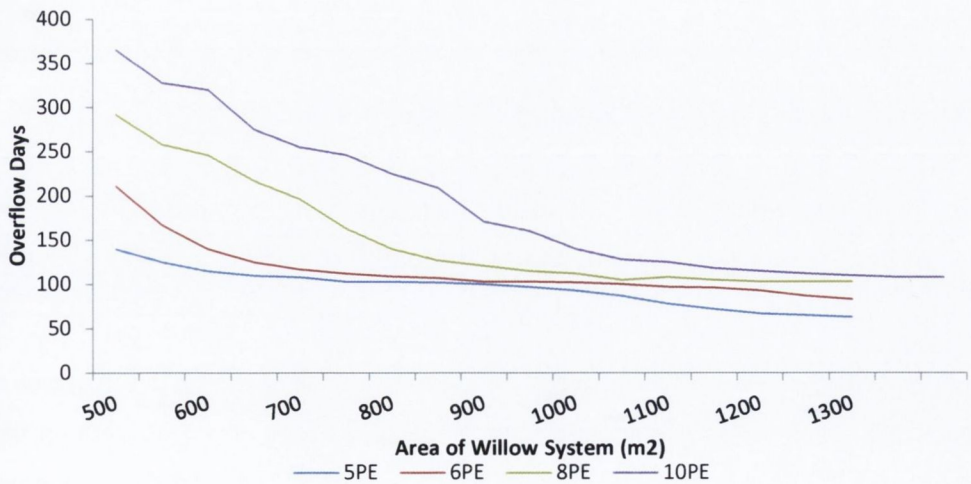


Figure 9.9 Effect of increasing area on the number of overflow days for a willow system receiving effluent from a dwelling with 5PE, 6PE, 8PE, and 10 PE

Similarly to the previous analysis, it can be seen that reductions in the number of overflow days plateaus off once a certain area is reached. Lowering the number of overflow below the 100 -

110 range requires a significant increase in area and would not be feasible from an financial point of view. This is highlighted in the area-overflow matrix for different PE in Table 9.5.

Table 9.5 Matrix showing the effect of varying the area on the amount of overflow generated by four different dwelling sizes

Area (m^2)	5PE	6PE	8PE	10PE
500	140	211	292	365
550	125	167	258	328
600	115	140	246	320
650	110	125	217	275
700	108	117	196	255
750	103	112	163	246
800	103	109	140	225
850	102	107	127	209
900	100	103	121	171
950	97	103	115	160
1000	93	102	112	140
1050	87	100	105	128
1100	78	97	108	125
1150	72	96	105	118
1200	67	93	103	115
1250	65	87	103	112
1300	63	83	103	110
1350	-	-	-	108
1400	-	-	-	108

The optimum area for the four different loading rates is shown in Table 9.6.

Table 9.6 Optimum area for loading from a dwelling with 5PE, 6PE, 8PE, and 10 PE

	2PE	**4PE**	**5PE**	**6PE**	**8PE**	**10PE**
Optimum Area (m^2)	250	500	650	750	1000	1200

The next aspect of the willow system design to be examined is the optimum depth of free space above the surface of the soil and bounded by the berm. It has been observed, both on the full scale systems and in the model itself, that the free space provides a significant amount of hydraulic storage and is thus an important aspect of the design. Ideally, long term ponding of a rainfall/effluent mix on top of the willow system is not desirable. However, the organic and nutrient analysis carried out on Site C (detailed in Section 6.5), which was subject to long periods of surface flooding showed that pollutant concentrations in the surface water were relatively low. Furthermore, there was no foul odour observed on any visits to the site either.

The effect of varying the depth of free space on the willow system design was conducted by entering a range of depths between 0 - 350 mm (50 mm increments) for 3 different overall willow system depths (1.5 m, 1.8 m, and 2.1 m). Overall depths greater than 2.1 m were not considered because of practical constraints during the excavation phase of construction. The area of the willow system was set at 500 m^2 for this particular analysis. The change in the number of overflow days by varying the depth of free space is illustrated in Figure 9.10 and Table 9.7.

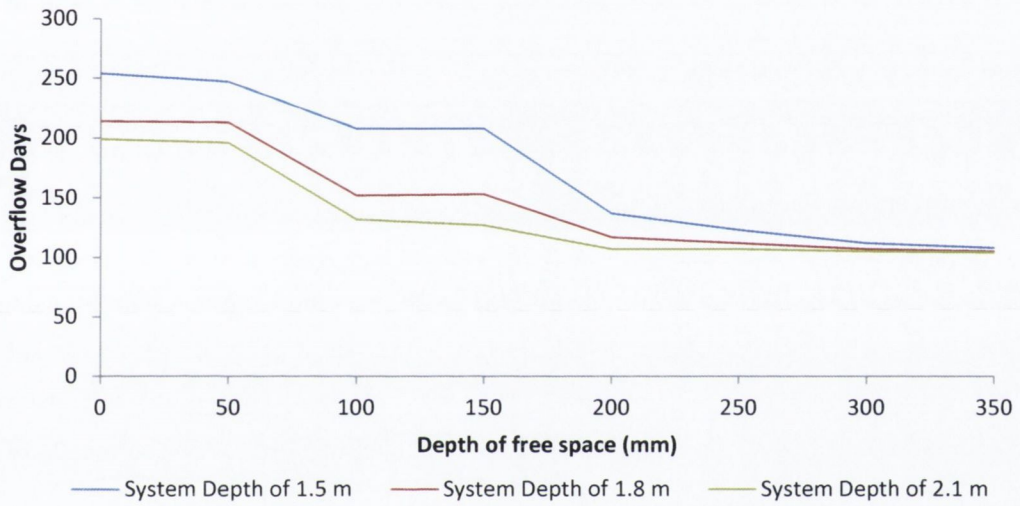


Figure 9.10 Number of days of overflow for different heights of free space for three different depth of willow system

Table 9.7 Effect of varying the depth of free space above the surface of the willow system for three different system depths

	Overall Depth of Willow System		
Depth of Free Space (mm)	1.5 m	1.8 m	2.1 m
0	254	214	199
50	247	213	196
100	208	152	132
150	208	153	127
200	137	117	107
250	123	112	107
300	112	107	105
350	108	105	104

Similarly to the increasing the area to lower the number of days with overflow, the gains made by increasing the free space appear to be less significant beyond a certain point. The optimum

depth of free space in systems with a total depth of 1.5 m and 1.8 m is approximately 250 mm (with 123 and 112 overflow days respectively). While the optimum depth for a system of depth 2.1 m is slightly less at 200 mm (107 overflow days). However, increasing the free space by small amounts is relatively inexpensive, so for the purpose of the final design the free space above the surface of the willow system, which is bounded by the berm will be set at 300 mm.

9.2.2.1 Decreasing Hydraulic Load

This section will assess the benefit of decreasing the hydraulic loading on the system by using an impermeable membrane on the surface of the willow system to direct a proportion of the rainfall away from the basin. The two main disadvantages with implementing such a measure would be that the system would lose its 100% void space within the berms and also, if overflow were still to occur, it may contain a higher concentration of pollutants as it would likely have a less proportion of rain water mixed through it.

As the proportion of rainfall that would be diverted away from the willow system by using an impermeable membrane at the surface is unknown, a hypothetical analysis will be carried out where the rainfall is assumed to be reduced by varying degrees. The model will assume a willow system area of 500 m^2 receiving effluent from a dwelling with 4PE. The results of the analysis are shown in the matrix in Table 9.8.

Table 9.8 Matrix showing the amount of overflow days from the willow system for different reduced rainfall and depth combinations

% Rainfall	Number of Overflow Days						
	1.5 m	1.6 m	1.7 m	1.8 m	1.9 m	2.0 m	2.1 m
100 %	254	250	226	214	210	208	199
90 %	222	208	203	201	189	166	148
80 %	183	172	160	123	111	106	100
70 %	133	97	88	85	80	74	57
60 %	62	49	41	35	26	23	13
50 %	25	18	10	6	4	3	0
40 %	6	4	0	0	0	0	0
30 %	0	0	0	0	0	0	0
20 %	0	0	0	0	0	0	0

It can be seen that the number of overflow days can be decreased to < 100 for nearly all depths if the rainfall can be reduced by 30%. This represents an improvement on the 100 - 110 overflow day range that was achieved using a willow system with a 300 mm storage void above the soil surface which was receiving 100% of the rain falling on the site. The number of overflow days

drops to zero or close to zero for nearly all depths when the rainfall is reduced by 50%. However, the amount that the hydraulic loading due to rainfall can be reduced by is difficult to define. As such, this is a very interesting aspect, and perhaps one that requires further research, especially in a climate such as Irelands that sees relatively high annual rainfall totals.

9.2.3 Optimum Design

This section seeks to further refine the willow system design by using different combinations of the following factors in order to minimise the number of overflow days using optimisation. The optimisation was conducted on the Excel add-on Solver. An optimisation model has three parts: the target parameter, the changing parameters, and the constraints. The target parameter in this analysis is the number of overflow days which is to be minimised. The changing parameters along with their constraints are as follows:

- Area (up to a maximum of the value detailed for the corresponding PE in Table 9.6
- Depth (up to a maximum overall depth of 2.1 m due to practical constraints during construction)
- Depth of gravel layer (up to a maximum of 350 mm due to cost constraints)
- Depth of free space at the surface (up to a maximum of 300 mm)

The Solver software works by searching over all feasible solutions and finds the feasible solution that has the optimum target parameter value (the smallest value in this case). The design details for the different PE are shown in Table 9.9.

Table 9.9 Design parameters for willow system determined from optimisation

PE	Area (m^2)	Overall Depth (mm)	Depth of gravel layer (mm)	Depth of free space (mm)	Overflow Days
2	250	2100	300	300	105
4	496	2100	300	278	106
5	650	2100	257	300	103
6	741	2100	257	287	106
8	1000	2100	269	300	105
10	1200	2100	269	300	106

As would be expected, the area required to give the lowest number of overflow days is approximately equal to the maximum area constraint for all cases. The overall optimum depth is equal to 2100 mm for all loading rates. There is some variance in the depths of the gravel

layer determined for each the different PE, ranging from 257 mm to the maximum of 300 mm. The optimal free space depth above the surface is close to the maximum of 300 mm in all cases.

9.2.4 *Final Design*

It can be seen from the optimisation analysis that the optimum overall depth of willow system is the maximum that the constraint in the model would allow (2.1 m). This was the expected result and follows the logic that a deeper system will obviously have less overflow. The optimum depth for the gravel layer and the free space has been determined to be approximately 300 mm, which are also the maximum constraints imposed on the model. Thus, the final design dimensions for a willow system under different PE loadings are shown in Table 9.10

Table 9.10 Willow system design dimensions for different PE loading

PE	Area (m^2)	Overall Depth (m)	Gravel Layer (m)	Free Space (m)
2	250	2.1	0.3	0.3
4	500	2.1	0.3	0.3
5	650	2.1	0.3	0.3
6	750	2.1	0.3	0.3
8	1000	2.1	0.3	0.3
10	1200	2.1	0.3	0.3

9.2.5 *Modelled Hydraulic Level*

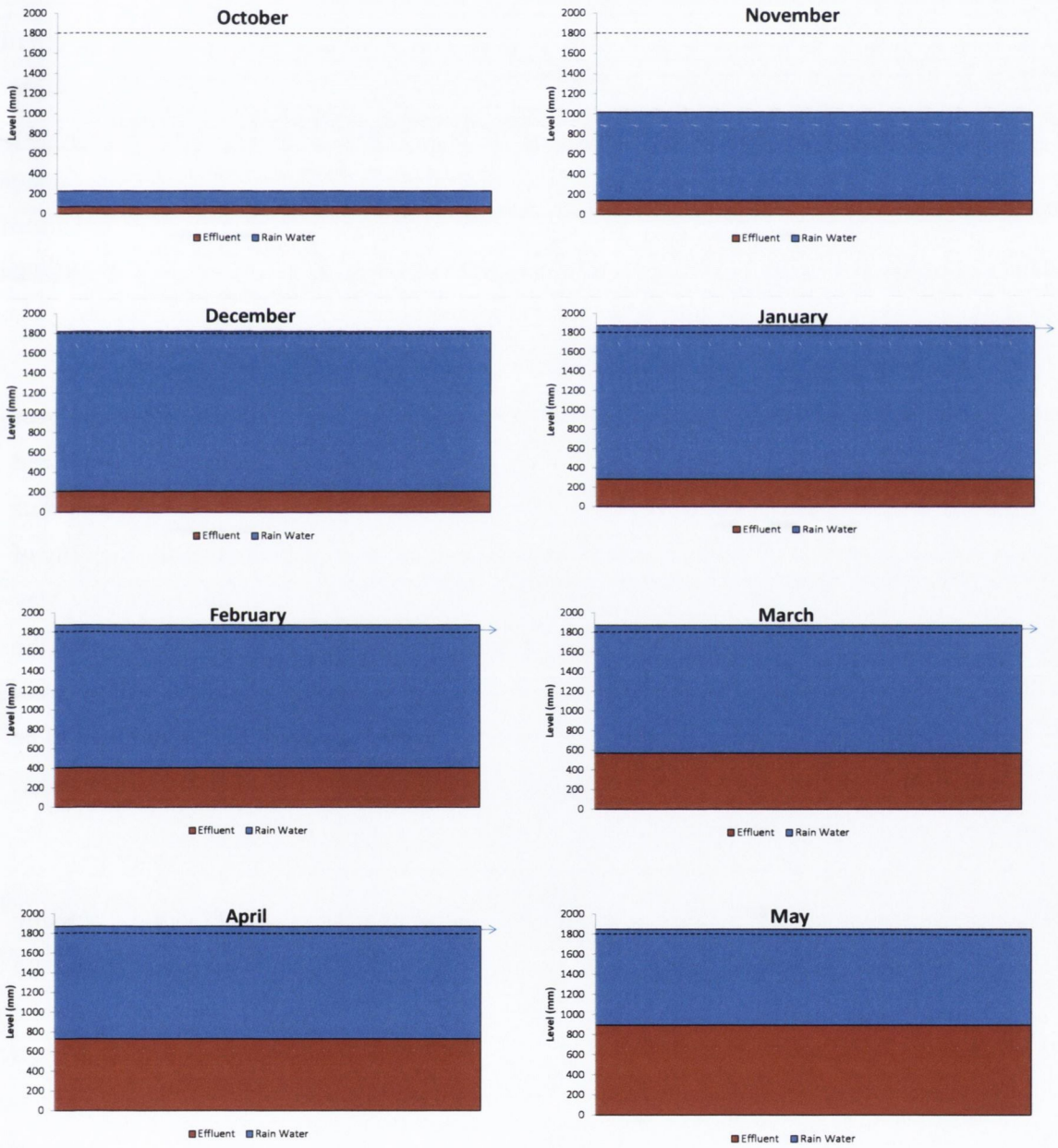
As outlined in the Code of Practice (EPA, 2009a), discharge of effluent to surface water is not permitted without first obtaining consent from the Local Authority (which is not granted in the majority of cases). However, this section will assess the nature of overflow from the system to determine whether or not it is likely to contain a significant amount of wastewater.

As previously discussed, it is apparent that hydraulic overflow from the system is likely to occur during most years due to the evapotranspiration been lower than the hydraulic loading. This analysis assesses the hydraulic levels in the system on a monthly basis to determine whether the overflow is primarily rainwater or wastewater.

The analysis assumed that no mixing of effluent and rainwater occurred in the soil within the willow system. The wastewater was assumed to accumulate from the bottom up (as this is where the distribution pipes are located) and the rainwater was assumed to accumulate from

the top down and 'sit' on top of the wastewater layer. The conservation assumption that water uptake by the willows occurred from the top down was also made.

The depth of the willow bed was set at 1.8 m with the overflow at 1.9 m. The wastewater input was set for a 4PE dwelling producing effluent at a rate of 100 L/c/day. The analysis applied a water balance equation (using mean annual rainfall for Met Éireann's Johnstown Castle weather station). The results are illustrated in Figure 9.11.



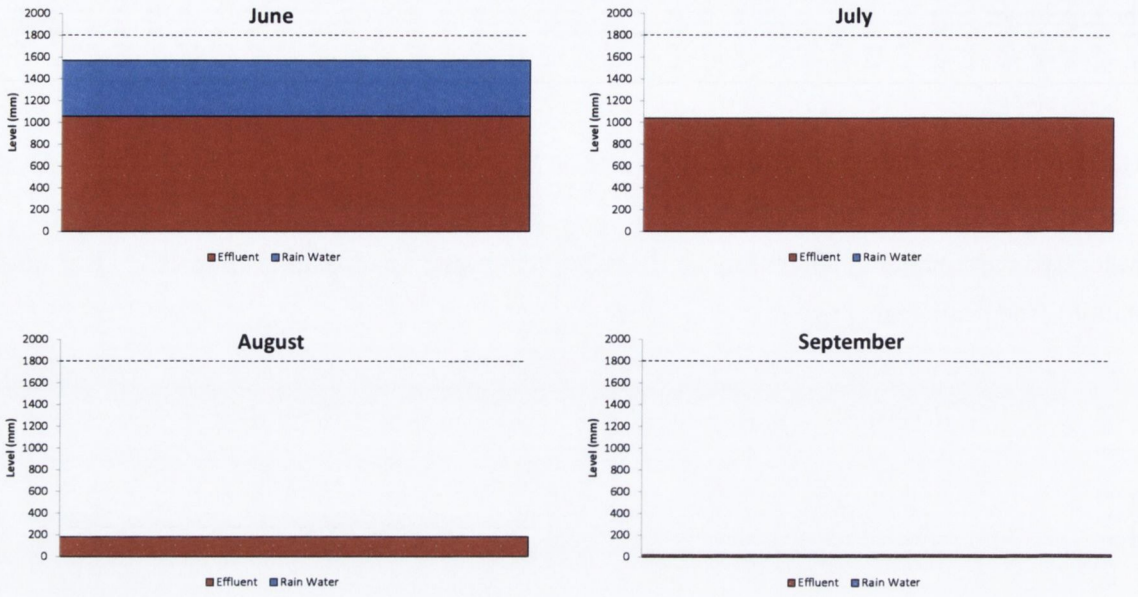


Figure 9.11 Expected hydraulic levels in willow evapotranspiration system designed according to the guidelines in County Wexford across an annual cycle.

The results show that overflow from the system occurs throughout four months of the year (January - April). However, going by the assumption that there was no mixing of rainwater and wastewater in the willow system, all of the overflow volume consisted of rainwater and thus would present very little pollution threat to the environment. It can be seen that the majority of the hydraulic loading is rainwater throughout the winter period. It is from approximately May onwards that the wastewater begins to make up the majority, but this is all contained within the willow system. This is the case due to the conservative assumption that the willow trees absorbed all the rainfall at the top before any wastewater was removed. This is unlikely to be the case in reality, as the willow trees would have a preference for the nutrient rich wastewater. However, it does provide useful insight into the worst case scenario that could occur.

From the viewpoint of this analysis, it could be assumed that the physical overflow actually reduces the overall hydraulic loading on the system by removing rainfall and meaning that the a much greater proportion of willow evapotranspiration goes towards removing the hydraulic loading resulting from wastewater input. Thus the system can operate effectively as a zero discharge systems with regards to effluent.

9.2.6 *Aspect Ratio*

As detailed in Section 8.9 this research could find no conclusive evidence to show if wind speed has a significant bearing on the evapotranspiration rate from a willow system. Regression analysis showed that it did have a significant effect (p-value < 0.05) on the 2011 ET_{willow} rate on Site B, but not on the 2013 rates. The analysis on the ET_{willow} rates from Site A showed that it was just outside the 95% confidence interval for having a significant effect on the 2013 rates (p-value = 0.092).

In the sensitivity analysis conducted in Section 4.2.10, in which the relative effect of the different meteorological parameters on the ET_o was assessed, it was shown that wind speed had a low Spearman Rank-order correlation coefficient with the ET_o. It was also determined that wind speed had a relatively low influence on the ET_o, with a one standard deviation increase resulting in an increase of just 0.15 mm for ET_o (for comparison, a one standard deviation increase for net radiation would be expected to result in an increase of 1.38 mm).

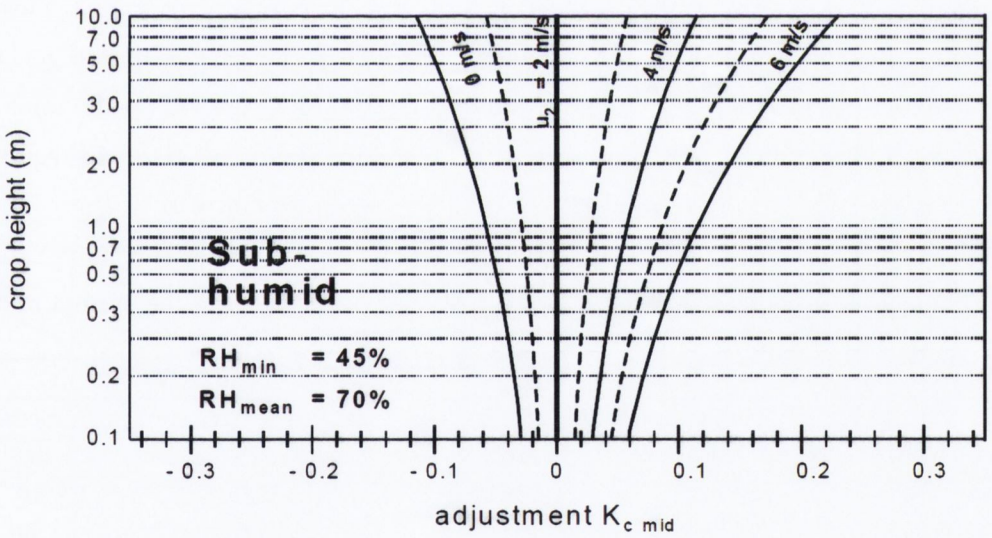


Figure 9.12 Effect of wind speed with increasing crop height for a relatively humid climate (modified from Allen et al., 1998)

While this analysis only applied to the reference evapotranspiration, it indicated that the relative effect of wind speed on willow evapotranspiration is going to be much lower in a temperate, relatively high humidity climate (such as Ireland's) compared to a warm, arid climate. The effect of wind speed has been reported to have a greater effect on ET_o for taller crops (Allen et al., 1998). However, as illustrated in Figure 9.12, a relatively high wind speed is

required to have any significant effect on the expected crop evapotranspiration. Given that the average wind speed at the sites monitored as part of this research project was between 2-3 m/s, the benefit of tailoring the willow system design to take advantage of wind speed via the oasis and clothesline effect is questionable.

If space is available on the site on which the willow system is to be constructed, then it is recommended to utilise the space in order to attain a high aspect ratio, as there is some benefit to be had from the wind. However, from the findings of this research, for a willow system in an Irish Climate it is not deemed a critical factor in the design.

9.2.7 Effluent Production

It is important to note that an effluent production rate of 100 l/c/day was assumed in the design model for determining the specifications of a willow system for different PE. This is quite similar to the loading rates that were measured on Sites H & I throughout the monitoring period (see Section 8.2). This is significantly lower than the 150 L/c/day assumed in the EPA Code of Practice (EPA, 2009a) for a typical one-off dwelling. The effect of increasing the loading rate to 150 L/c/day in the model is illustrated in Table 9.11. It can be seen that in general it approximately doubles the amount of overflow days that could be expected for the same area for any given PE. If the difference is to be negated by an increase in area it would require an increase of between 40 - 50%, which would result in a very significant increase in cost.

Table 9.11 Effect of an increased effluent loading rate on overflow from the system and the increased area required to negate this effect.

		Overflow Days		**Area**	
PE	Area (m^2)	100 l/c/day	150 l/c/day	Increased Area (m^2)	% increase
2	250	112	226	375	50
4	500	112	226	700	40
5	600	102	185	900	50
6	700	116	220	1050	50
8	950	111	212	1400	47
10	1150	117	221	1700	48

It is imperative that in an Irish climate, where the expected annual ET_{willow} is going to be marginally higher than the expected annual rainfall at best, the wastewater production is kept as low as possible. Reports have shown that on-site wastewater production in Ireland is generally close to 100 L/c/day in many existing houses (Gill et al., 2009a, Gill et al., 2009b), but a requirement to include water saving devices in the dwelling may still be highly beneficial. It is

also critical that that rainfall infiltration into the wastewater system does not occur. The increase in hydraulic loading from this occurring was demonstrated as part of this research project (see Section 4.3) and it is imperative that it be avoided.

9.3 Liner

As detailed in Section 8.11 there were some questions arising as to the level of impermeability provided by a clay liner. As such it is recommended that a purpose made impermeable membrane is used. The three different types of impermeable membrane used as part of this research and their properties are shown in Table 9.12. There was no obvious difference noted between any of the liners apart from a leak through liner 1 (*Wepelen*® Geosynthetic barrier FPP) on system 1 on Site F. This is thought to be as a result of a failure of a seal between two segments of the membrane, of which the welding took place on the site. It is in this regard that the butyl rubber, perhaps, provides the highest guarantee of no leakage, as welding of the seams between segments takes place in the factory rather than on site where conditions would not be as suitable. It should be ensured that excess is left along the top edge of the basin in order to maintain a seal along the berm.

Table 9.12 Impermeable membranes and their key properties

Liner [a]	**Property**				
	Thickness (mm)	Strength at break (MPa)	Elongation at break (%)	Tear Resistance (N/mm)	Puncture Resistance (N)
1	0.50	>18	>750	>45	>120
2	0.75	8	350	30	-
3	0.50	13	800	50	120

[a] 1, *Wepelen*® Geosynthetic barrier FPP;
2, Butyl Rubber;
3, *GSE Environmental* UltraFlex LDPE

Protection of the impermeable membrane is provided by a geosynthetic barrier which is placed underneath and on top of the membrane. This helps aid against punctures occurring as a result of sharp rocks coming in contact with the membrane.

The area of liner required for a 500 m^2 willow system with different aspect ratios is shown in Table 9.13. An extra 5 m is added onto both the length and width to cover the sides of the willow system as well as the berm around the perimeter at the top. It can be seen that a decreasing aspect ratio requires a smaller area of liner.

Table 9.13 Area of liner required for different aspect ratios

Length (m)	Width (m)	Aspect Ratio	Total Liner Area (m^2)
62.5	8	7.8	878
50	10	5	825
40	12.5	3.2	788
30	16.7	1.8	758
22.4	22.4	1	749

9.4 Distribution Layer

As detailed in Section 9.2.4, a gravel distribution layer of 300 mm is required as part of the willow system design. The gravel layer should be at the base of the willow system, so as to ensure compaction of the soil being refilled into the basin does not occur.

Distribution of the effluent takes place via 110 mm percolation pipes which are placed in the gravel layer. The percolation pipes should be laid with the holes facing downwards and then wrapped in a geosynthetic barrier so as to prevent ingress of soil particles and willow roots, which may block up the pipes. The percolation pipes are served by one inlet pipe entering the willow system.



(a) (b)

Figure 9.13 Connection between pipe from pump and inlet pipe; (a) before, (b) after

Effluent is supplied to the non-pressurised distribution system by gravity fall if the site allows for it, or else via a pump. In the case of a gravity feed, a 110 mm sewer pipe stretches from the effluent source to the willow system, connecting with the inlet pipe by means of a 100 mm

coupler fitting. If a pump feed is used, the semi-rigid piping should run from the pump sump to the willow system and connect to the inlet pipe using a connection, as shown in Figure 9.13.

9.5 Inspection Well, Berm and Refilling

The willow system design should include a vertical inspection well, which can be used to monitor the water level and also to pump out the system if required. The inspection well should be at least 300 mm diameter so as to for pumping equipment if needs be. Slots are cut into the inspection well and it is then wrapped in a geosynthetic barrier to prevent ingress of soil, while allowing water to infiltrate. The inspection well should be placed on top of a concrete tile so as not damage the impermeable liner. The willow system should also be accessible by tanker in case it is required to be pumped out.

When the soil is being backfilled into the basin, it is imperative that no compaction from machinery occurs. Also, the top soil should be set aside during excavation and then placed at the top during backfilling, to maximise the chances of establishment and development of the willow cuttings. The system should have a 300 mm impermeable berm erected around the perimeter at the top of the willow system. This will maintain the 100% void storage space above the soil surface in the system. Finally, the low point in the berm should be at the opposite end of the system in which the effluent enters. This is to maximise the level of treatment in the case of overflowing occurring.

9.6 Willow Planting and Maintenance

As reported in several instances in literature (Defra, 2002, Caslin et al., 2010, Brix and Arias, 2011) and also from the experiences of this research project it has been shown that it is important that the willow cuttings get off to a good start in the first year. If this does not occur, it has been shown that development in the following years can suffer as a result (Gregersen and Brix, 2001).

9.6.1 Planting

Planting of willow cuttings should take place in early spring from mid-March to May. It can be carried out later than this; however it is more beneficial to plant as early as possible to ensure

good first year tree development, which will have a knock-on effect on development in the second year.

Cuttings should be prepared from one-year old wood, which is supplied in rods of 1.5 - 2.5 m by specialist suppliers. A list of Irish suppliers is provided in the Short Rotation Coppice Willow Best Practice Guidelines (Caslin et al., 2010). At least three different varieties should be used to ensure good resistance to disease. Cuttings should be 20 - 30 cm in length (this ensures that they have an adequate reserve of carbohydrate to sustain until root establishment) and planted at a density of 3/m^2. The cutting should be planted with the buds facing upwards with approximately one quarter of the cutting sticking out above ground level. From the experience of this research it was also noted that longer cuttings generally had a better establishment and development rate. As detailed in Section 9.5, topsoil should be situated at the top of the willow system to maximise the chances of establishment and development of the willow cuttings.

9.6.1.1 Weed Control

As detailed in Section 8.12, weed control is a critical aspect of willow establishment. It should be ensured that there is no weed growth in the first year of the willow system. From the practical experience gained from this research it was deemed that the most effect means of ensuring this was to cover the surface of the willow system with a weed proof membrane before planting the cuttings. The membrane can then be removed when cutback is being carried out in the first winter. It was found that the willows were established well enough at this stage to out-compete the weeds in the second season. It was found that the use of pesticides had limited success and struggled to eradicate weeds such as thistles, broadleaf docks, and nettles. It was also noted that it had the effect of damaging weaker, less developed willows.

9.6.2 Coppicing

The willow stems are cutback in the first winter of growth to encourage an increase in stems per plant in the second growing season. The stems should be cut back close to the ground as shown in Figure 9.14. The establishment of multiple new stems on the willow stool is also illustrated.



Figure 9.14 An example of a cut back willow stool after the first season

Normal coppicing can then take place on a two or three year cycle, with an alternating half or third being coppiced every year. It is more preferable to implement a three year cycle as this will ensure that there is a higher proportion of large, more developed willow trees growing at any time (see Figure 9.15). The coppicing should take place after leaf fall and before bud-break, which usually ranges between mid-October and early March (Brix and Arias, 2011).

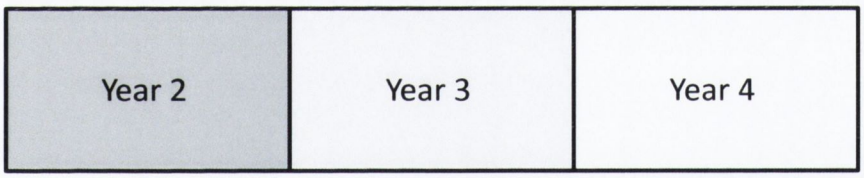


Figure 9.15 Coppicing of willow system on three year cycle

9.7 Summary

As previously detailed, it is apparent that the willow evapotranspiration is going to be less than the hydraulic loading applied to the systems over an extended period of time. With this in mind, the design model for the system aimed at minimising the overflow, while keeping within reasonable practical and financial constraints, rather than trying to achieve zero discharge.

The theoretical hydraulic model (Section 9.2.5) showed that if mixing of rainfall and wastewater is assumed to be minimal, the majority of the overflow will consist of rainfall, thus representing little threat to the local environment. To ensure that mixing is kept to a minimum, the effluent is distributed at the bottom of the basin.

Chapter 10

Conclusions and Recommendations

10 Conclusions and Recommendations

10.1 Conclusions

10.1.1 Overview

This research project assessed the performance of willow evapotranspiration systems for the treatment of on-site wastewater on low permeability subsoils in an Irish climate. On-site treatment of wastewater usually consists of a septic tank, or a secondary aerobic treatment unit, followed by discharge of effluent to the subsoil via a percolation area. However, in some regions of Ireland the subsoil has very low permeability (normally due to the presence of heavy clay soils) which can result in lack of percolation capacity. The inadequate percolation poses a risk to surface water and water courses around the site.

Eight systems (Co. Wexford) were constructed (with an additional system in Co. Leitrim and Co. Limerick), each comprising a sealed basin in which the hydraulic load was stored. The storage medium consisted of the re-instated excavated subsoil and a gravel layer within which the wastewater was distributed by means of either percolation or pressurised pipes. The wastewater being treated was either septic tank effluent or secondary treated effluent. The surfaces of the systems were planted with different varieties of willow clones at a density of 3 plants/m^2. The systems were initially designed on the basis of having zero discharge, as is the case with willow systems in Denmark. However, one of the main findings of this research is that willow evapotranspiration systems in prevailing Irish conditions cannot provide zero discharge consistently, on a long term basis. This is primarily due to the relatively high rainfall levels in the country.

As part of the research, guidelines on the design and construction of willow systems in Co. Wexford have been developed based upon the results of these trials. It was deemed that the design of a zero discharge system suitable for single house on-site wastewater treatment would be very difficult to achieve in an Irish climate. As such, the guidelines were designed on the premise of minimising the volume of overflow while keeping within reasonable practical and financial constraints. A hydraulic model (Section 9.2.5) was used to assess the likelihood of overflow occurring from a system. The hydraulic level within the system was predicted on a monthly basis. The model assumed that effluent entered the system from the bottom and

rainfall entered from the top and that there was minimal mixing between the two. In this manner, it was shown that although overflow will occur during the winter months, it consists largely of rainfall and not wastewater (as the rainfall is at the top of the system and the wastewater is at the bottom). So, although the willow systems may not provide overall zero discharge, they can maintain zero discharge of *effluent* and thus willow beds represent a robust wastewater treatment solution on sites with low permeability subsoils in Ireland.

10.1.2 Evapotranspiration

Evapotranspiration (ET) rates were determined by means of a mass balance equation and compared to a reference evapotranspiration, which is the evapotranspiration from a hypothetical grass reference crop. It was found that the usable storage capacity in the re-instated clay subsoil was quite low, ranging from 9.5 - 21% by volume. As a result, the basin did not have the capacity to store all the hydraulic loading, hence flooding of the systems occurred. The relatively high rainfall levels compounded this effect. The low porosity of the soil also had the effect of reducing ET from the system.

The ET rates from the willow systems varied greatly from system to system. A synopsis comparing the willow evapotranspiration to the reference evapotranspiration at the different sites is illustrated in Table 10.1. It can be seen that, in general, willow provides a significant improvement on the reference evapotranspiration (ET_o), with improvements of up to 400 mm recorded. The highest ET rates came from the three earliest established systems, and ranged from 358 mm to 929 mm (per year). However, these values were conservative due to the fact that ET could not be determined on days in which overflow from the system was deemed to have occurred. When compared to the reference ET for each site, it was determined that the expected annual ET from a system was approximately 2.2 times (the crop coefficient) the reference value. Tree development had the singular greatest impact on ET. The level of tree growth had the effect of greatly reducing the impact of other factors such as radiation, wind speed, rainfall, effluent loading, aspect ratio of the system, and geographical location in Ireland. The ET rates for systems with sub optimal tree development ranged from 341 mm to 827 mm (per year). The estimated annual ET from these systems was approximately 1.5 times greater than the reference ET. This was significantly lower than the value for the better performing willow systems. It is also shown that the willow could provide up to 628 mm additional water

removal (compared to the reference evapotranspiration) via evapotranspiration on a site in Co. Wexford.

Table 10.1 Difference between ET_o and ET_{willow} for different sites (mm)

Year	Site A	Site B	Site C	Site D	Site E	Site F(1)	Site F(2)	Hypothetical
2010	+240	+206	+23	-	-50	-	-	+600
2011	+396	+105	+213	+14	+96	+37	+167	+628
2012	+253	+293	+230	+14	+230	+139	+371	+554
2013	+229	+23	-10	-114	+12	+108	+86	+508

From a meteorological point of view, ET_{willow} was largely dependent on water availability rather than on weather conditions. Most of the highest mean daily rates during the growing season occurred in 2012, when rainfall levels were high rather than in 2013 when the willow trees would have been more developed and evapotranspiration conditions would have been better (given the relatively warm, dry summer). The addition of septic tank effluent (STE) appeared to have a positive effect on the development and evapotranspiration rates of the willow trees on the full scale system. This was also confirmed by the findings in the mesocosm experiment.

The aspect ratio of a willow system seemed to have little effect on the evapotranspiration rate from that system. This conclusion follows on from the determination of wind speed having little bearing on reference evapotranspiration. It is also in agreement with the FAO guidelines on crop evapotranspiration (Allen et al., 1998) which reported than even with an increase in plant height, crop evapotranspiration will not increase significantly with wind speed in a relatively humid, temperate climate.

Soil compaction was found to have a large bearing on ET_{willow} rates with the porosity of the soil apparently having a large influence on the evapotranspiration rates. Overflow of hydraulic loading occurred on almost all the willow systems with the average number of overflow days per system as follows:

- 2010 - 105 days
- 2011 - 133 days
- 2012 - 199 days
- 2013 - 103 days

10.1.3 *Nutrients and Water Quality*

- Total-N removal was determined to be > 90% on the systems with properly developed willow trees. The removal rate was somewhat less on the systems that had poor establishment and development of willows. Total PO_4-P removal was determined to be over 95% on all systems receiving effluent, and was above 99% on the 3 best performing systems. However, as detailed in Section 6.9.4 there was a large degree of uncertainty with regard to the parameter concentration measured within the willow systems and the removal rates achieved by the systems. However, it can be seen that the systems do provide a significant level of effluent treatment and any overflow from a system is likely to consist mainly of rainfall.

- There was no evidence of significant salt accumulation in any of the systems and no detrimental effects from salinity were observed on any of the willow trees.

- Removal rates for TC and *E. coli* were varied between systems. The highest removal rates (Site A) were 4.0 and 3.7 log-unit removal (>99.99%) respectively, while the lowest (Site H -System 1) were 2.7 and 3.8 log-unit removal (99.8% and 99.9%) respectively.

10.1.4 *Effluent Loading*

- Continuous flow measurement on the sites producing effluent revealed that the daily per capita wastewater generation assumption of 150 L/c/day in the Code of Practice (EPA, 2009a) would appear to be conservative with respect to the measured average wastewater production in such one-off dwellings, despite being lowered from 180 L/c/day in the previous Code of Practice (EPA, 2000). The results from this research indicate that average wastewater production for a single house is more in the range 90 to 120 L/c/day.

- Rainfall infiltration into the wastewater system arising from roof and driveway runoff was an issue on a number of the sites and appears still to be a relatively common occurrence in newly built houses despite the Code of Practice (EPA, 2009a) specifically prohibiting the practice.

10.1.5 Meteorological and Subsoil Conditions

- Net radiation was found to have the largest bearing on reference evapotranspiration, in an Irish climate, followed by temperature, with wind speed having relatively low effect. As would be expected, there was high variability between wind speeds on the different sites. It was found that there was generally no significant difference in rainfall levels between the sites in County Wexford and also with the site in Co. Limerick. There was, however, a significant difference between rainfall on the Co. Leitrim site and most of the Co. Wexford sites. The net radiation recorded on the Co. Wexford sites was generally higher than on the Co. Leitrim and Co. Limerick sites. However, the higher values were only deemed statistically significantly on Site A&B.

- Analysis of reference evapotranspiration showed little significant difference between the sites in Co. Wexford with the exception of Site E, which was notably in a hollow, in the shade.

- It was found that while the total water content in a clay soil is >50%, the usable pore volume in the low permeability soils is quite low (ranging between 9.5% - 21%). This is significantly lower than the >40% figure assumed in the Danish willow system design guidelines (Miljøstyrelsen, 2003). There was also considerable uncertainty in the porosity calculations for the soil samples due mainly to the heterogeneous nature of soil and also to the robust nature of the research (the willow systems were field scale, working treatment systems taking up extensive areas on site). Trying to determine representative results in such conditions is much more difficult than for a small scale, controlled experiment conducted under laboratory conditions.

10.1.6 Mesocosm

- The series of mesocosm experiments determined that the addition of STE resulted in the highest development and evapotranspiration rates. Secondary treated effluent had a lesser effect, while the addition of water had the least effect on ET_{willow} and development rates.

- The variety of willow clone was found to have no bearing on the evapotranspiration rate.

- There exists a strong positive correlation between willow biomass and evapotranspiration.

10.1.7 Design and Construction Guidelines

- The design model, which used the meteorological data from the monitoring period, determined that designing a zero discharge willow system for a single house, taking financial and practical constraints into account, does not seem to be possible in Irish conditions. As such, the willow systems should be designed on the basis of keeping overflow to a minimum.

- A suitable HDPE 'impermeable' liner should be used to seal the basin as there is likely to be difficulty in installing and maintaining the integrity of a clay liner.

- During establishment, it is imperative to keep the newly planted willow system free of weeds. Vigorous growth of weeds has been shown from the full-scale trials to significantly reduce the production and development of willow stems in the first year.

- Compaction of the soil during construction must be avoided as it was shown to have a negative effect on evapotranspiration and storage capacity.

10.2 Recommendations for Further Research

10.2.1 System Design Improvement

As discussed in the conclusions, the willow systems are unable to consistently attain zero discharge in a climate with relatively high rainfall levels, such as Ireland's. As a result it is recommended that further research be conducted which would consider altering the system design to try and reduce hydraulic loading and thus decrease the potential overflow from the systems. The following are some modifications that could be trialled:

- Examination of the effect of covering the surface of the willow system with an impermeable liner that would direct rainwater away from the system. The benefit of a reduced hydraulic load has been shown to be an important aspect when designing a

willow system (Section 9.2.2.1), so removal of a proportion of rainfall could see a smaller system being required.

- Assessment of varying the plant management on the system. This could include varying the planting density as well as the coppicing regime. For example, cutting half of the trees every second year or cutting a quarter of the trees every fourth year.

It is also recommended that water saving devices (dual flush toilets, push taps, low flow shower heads, etc.) are installed for houses using a willow system as they will significantly decrease the hydraulic loading and therefore result in smaller sized systems being required.

10.2.2 Future Research

- Long term monitoring (> 10 years) of the systems should assess the following:
    - The effect of more varied climatic conditions on the performance of the system.
    - Removal rates of pollutants such as organics, nitrogen, and phosphorus.
    - Salinity concentration within the system and its effect on willow growth and evapotranspiration rates.
- Rigorous monitoring and analysis of overflow from willow systems to determine the concentrations of pollutants and pathogenic bacteria escaping.
- Construction and monitoring of willow systems in different areas of the country to assess the effect of different rainfall/evapotranspiration conditions on the performance of the systems.
- Long term rigorous assessment of an *unlined* system.
- Combination of willow system with discharge to a final polishing filter during times of overflow. Examples of such tertiary polishing filters include a soil polishing filter or a sand polishing filter, as detailed in the Code of Practice (EPA, 2009a).

References

AASC 1985. Publication of the American Association of State Climatologists: Height and Exposure Standards for Sensors on Automated Weather Stations. *The State Climatologist,* 9.

Agresti, A. 1996. *Categorical Data Analysis,* Hoboken, NJ, John Wiley & Sons, Inc.

Allen, R. G., Environmental & Evapotranspiration, W. R. I. T. C. o. S. o. R. 2005. *The Asce Standardized Reference Evapotranspiration Equation,* Amer Society of Civil Engineers.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998. Crop Evapotranspiration. Guidelines for computing crop water requirements. *FAO irrigation and drainage paper.* , 55, 227.

Amatya, D. M., Skaggs, R. W. & Gregory, J. D. 1995. Comparison of methods for estimating Ref-ET. *Journal of Irrigation and Drainage Engineering,* 121, 427-435.

APHA 1998. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, 20th Edition.

Argus, G. W. 1997. Infrageneric classification of *Salix* (Saicaceae) in the New World. *Syst. Bot. Monogr.,* 52.

Arienzo, M., Christen, E. W., Quayle, W. & Kumar, A. 2009. A review of the fate of potassium in the soil-plant system after land application of wastewaters. *Journal of Hazardous Materials,* 164, 415-422.

Aronsson, P. & Perttu, K. 2001. Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. *The Forestry Chronicle,* 77, 293-299.

Aronsson, P. G. & Bergström, L. F. 2001. Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type. *Biomass and Bioenergy,* 21, 155-164.

Bauer, D. H., Conrad, E. & Sherman, D. G. 1981. Evaluation of On-Site Wastewater Treatment and Disposal Options. *NTIS, SPRINGFIELD, VA. 1981.*

Beal, C. D., Gardner, E. A. & Menzies, N. W. 2005. Process, performance, and pollution potential: A review of septic tank–soil absorption systems. *Soil Research,* 43, 781-802.

Beal, C. D., Rassam, D. W., Gardner, E. A., Kirchhof, G. & Menzies, N. W. 2008. Influence of hydraulic loading and effluent flux on surface surcharging in soil absorption systems. *Journal of Hydrologic Engineering,* 13, 681-692.

Bergkvist, P. & Ledin, S. 1998. Stem biomass yields at different planting designs and spacing in the willow coppice systems. *Biomass and Bioenergy,* 14, 149-156.

Bialkiewicz, F. 1969. Influence of wastewater on the yield of willow plantations (in Polish). Forest Research Institute, Section of Utilization of Waste Water by Forest, Warszawa.

Bialowiec, A. & Randerson, P. F. 2010. Zero Discharge Systems - a case study. *CWA 6th Annual Conference, Wastewater Management and the Application of Constructed Wetlands.* Stoneleigh Park, Warwick,.

Bialowiec, A., Wojnowska-Baryla, I. & Agopsowicz, M. 2007. The efficiency of evapotranspiration of landfill leachate in the soil-plant system with willow Salix amygdalina L. *Ecological Engineering,* 30, 356-361.

Bialowiec, A., Wojnowska-Baryta, I. & Hasso-Agopsowicz, M. 2003. Effectiveness of leachate disposal by young willow sprouts Salix amygdalina. *Waste Management Research,* 21, 557-566.

Bouma, J. 1975. Unsaturated Flow during Soil Treatment of Septic Tank Effluent. *Journal of Environmental Engineering Division, Proceedings of the American Society of Civil Engineers.,* 101, 967-983.

Bouma, J. 1979. Subsurface applications of Sewage Effluent. *Planning the Uses and Management of Land.* Madison, Wisconsin ASA-CSSA-SSSA.

British Standards Institute 1983. Design and installation of small sewage treatment works and cesspools. *BS 6297.* British Standand Institute, UK.

British Standards Institute 1999. Code of Practice for Site Investigations. *BS 5930.* British Standards Institution, UK.

Brix, H. & Arias, C. A. Use of willows in evapotranspirative systems for onsite wastewater management - theory and experiences from Denmark. Strepow International Workshop, 23-24 February, 2011 2011 Andrevlje-Novi Sad, Serbia. 15-29.

BS 8004 1986. Code of Practice for Foundations. *British Standard 8004.* British Standards Institute,London.

Burgess, D., Hendrickson, O. Q. & Roy, L. 1990. The importance of initial cutting size for improving the growth performance of Salix alba L. *Scandinavian Journal of Forest Research,* 5, 215-224.

Canter, L. & Knox, R. 1985. Septic tank system effects on groundwater quality. *Lewis Publishers,* Chelsea, MI.

Carlson, M. C. 1950. Nodal Adventitious Roots in Willow Stems of Different Ages. *American Journal of Botany,* 37, 555-561.

Caslin, B., Finnan, J. & McCracken, A. 2010. *Short Rotation Coppice Willow Best Practice Guidelines,* Carlow, Ireland.

Cassel, D. K. & Nielsen, D. R. 1986. *Field Capacity and Available Water Capacity,* Madison, WI, Soil Science Society of America.

Cavanagh, A., Gasser, M. O. & Labrecque, M. 2011. Pig slurry as fertilizer on willow plantation. *Biomass and Bioenergy,* 35, 4165-4173.

Ceulemans, R., McDonald, A. J. S. & Pereira, J. S. 1996. A comparison among eucalypt, poplar and willow characteristics with particular reference to a coppice, growth-modelling approach. *Biomass and Bioenergy,* 11, 215-231.

Childs, E. C. & Collis-George, N. The permeability of porous materials. Proceedings of the Royal Society, Series A, 1950. 392-405.

Christersson, L., Sennerby-Forsse, L. & Zsuffa, L. 1993. The role and significance of woody biomass plantations in Swedish agriculture. *The Forestry Chronicle,* 69, 687-693.

Converse, J. C. & Tyler, E. J. Soil Acceptance of Onsite Wastewater as Affected by Soil Morphology and Wastewater Quality. On-Site Wastewater Treatment. Proceedings of the 7th National Symposium on Individual and Small Community Sewage Systems., 1994 St. Joseph, MI. ASAE, 185-194.

Cotteral, J. & Norris, D. P. 1969. Septic tank systems. *ASCE Journal Sanitary Engineering Division,* 95, 715-746.

Crow, P. & Houston, T. J. 2004. The influence of soil and coppice cycle on the rooting habit of short rotation poplar and willow coppice. *Biomass and Bioenergy,* 26, 497-505.

CSO 2012. Census 2011, Principal Demographic Results. *Central Statistics Office, Government of Ireland. Stationary Office Dublin.*

Cureton, P. M., Groenevelt, P. H. & McBride, R. A. 1991. Landfill leachate recirculation: effects on vegetation vigour and clay surface cover infiltration. *Journal of Environmental Quality,* 20, 17-24.

D.M.I. *Climate Normals for Denmark* [Online]. Denmark Meteorological Institute. [Accessed October 3rd 2012].

Daly, D., Henry, H. & Thorn, R. 1993. *Septic Tank Systems and Groundwater in Ireland,* Geological Survey of Ireland.

Danfors, B., Ledin, S. & Rosenqvist, H. 1998. Short rotation willow coppice - Growers Manual. The Swedish Institute for Agricultural Engineering.

Dawson, W. 2007. Short rotation coppice willow best practice guidelines. Renew Project.

Dawson, W. & McCracken, A. 1995. The performance of polyclonal stands in short rotation coppice willow for energy production. *Biomass and Bioenergy,* 8, 1-5.

DEFRA 2002. Growing Short Rotation Coppice, Best Practice Guidelines. *In:* DEPARTMENT OF ENVIRONMENT, F. A. R. A. (ed.). London: Defra Publications.

Department of the Environment and Local Government 1999. Groundwater Protection Schemes. *In:* GOVERNMENT, D. O. T. E. A. L., AGENCY, E. P. & IRELAND, G. S. O. (eds.). Dublin.

Dickinson, N. M. & Pulford, I. D. 2005. Cadmium phytoextraction using short-rotation coppice Salix: the evidence trail. *Environment International,* 31, 609-613.

Dimitriou, I. & Aronsson, P. 2010. Landfill leachate treatment with willows and poplars - Efficiency and plant response. *Waste Management,* 30, 2137-2145.

Dimitriou, I. & Aronsson, P. 2011. Wastewater and sewage sludge application to willows and poplars grown in lysimeters–Plant response and treatment efficiency. *Biomass and Bioenergy,* 35, 161-170.

Dobson, M. C. & Moffat, A. J. 1993. The potential for woodland establishment on landfill sites. Department of the Environment, HMSO.

Doody, T. & Benyon, R. 2011. Quantifying water savings from willow removal in Australian streams. *Journal of Environmental Management,* 92, 926-935.

Dubber, D. & Gill, L. W. 2013. Water saving technologies to reduce water consumption and wastewater production in Irish households. *STRIVE Report Series No. 108.* Wexford: Environmental Protection Agency.

Ecotec Research & Consulting, CESAM, C., University of Gothenburg, UCD & IEEP 2001. Study on the Economic and Environmental Implications of the Used of Environmental Taxes and Charges in the European Union and its Member States.

Elowson, S. 1999. Willow as a vegetation filter for cleaning of polluted drainage water from agricultural land. *Biomass and Bioenergy,* 16, 281-290.

Emerick, R., Test, R., Tchobanoglous, G. & Darby, J. 1997. Shallow intermittent sand filtration: Microorganisms removal. *Small Flows Journal,* 3, 12-22.

EPA. *Subsoils of Ireland.* Environmental Protection Agency: EPA,.

EPA 2000. Wastewater Treatment Manuals: Treatment Systems for Single Houses. *In:* AGENCY, E. P. (ed.). Johnstown Castle, Co. Wexford, Ireland.

EPA 2009a. Code of Practice: Wastewater Treatment and Disposal Systems Serving Single Houses (p.e. ≤ 10). Environmental Protection Agency, Johnstown Castle, Co. Wexford, Ireland.

EPA 2009b. Water Quality in Ireland 2007-2008 - Key Indicators of the Aquatic Environment. Johnstown Castle, Wexford, Ireland.

EPA 2012a. The Provision and Quality of Drinking Water in Ireland. Wexford: Environmental Protection Agency.

EPA 2012b. A Risk-Based Methodology to Assist in the Regulation of Domestic Waste Water Treatment Systems. Johnstown Castle, Wexford, Ireland: Environmental Protection Agency.

Ericsson, T. 1981a. Effects of varied nitrogen stress on growth and nutrition in three Salix clones. *Physiologia Plantarum,* 51, 423-429.

Ericsson, T. 1981b. Growth and nutrition of three Salix clones in low conductivity solutions. *Physiologia Plantarum,* 52, 239-244.

Ettala, M. O. 1988. Short-rotation tree plantations at sanitary landfills. *Waste Management & Research,* 6, 291-302.

Finsterwalder, K. 2003. *Bemessung der Sicherungssysteme von Deponien und Altlasten unter Einbeziehung der stochastischen Natur der Variablen (Design of barrier systems for landfills and the remediation of contaminated sites taking into account the stochasitc nature of the variables,* Universität der Bundeswehr, München.

Flowers, T. J. 1988. *Chloride as a nutrient and as an osmoticum,* New York, Praeger.

Gavilán, P., Lorite, I. J., Tornero, S. & Berengena, J. 2006. Regional calibration of Hargreaves equationfor estimating reference ET in a semiarid environment. *Agriculture Water Management,* 81, 257-281.

Gill, L. W. 2011. The development of a Code of Practice for single house on-site wastewater treatment in Ireland. . *Wat. Sci. Technol.,* 64, 677-683.

Gill, L. W., O' Luanaigh, N., Patel, T., Misstear, B. D. R. & Johnston, P. M. 2009a. On-site wastewater treatment: investigation of rapid percolating subsoils, reed beds and effluent distribution. *ERTDI Report Series No. 9.* Wexford Environmental Protection Agency.

Gill, L. W., O' Súilleabháin, C., Misstear, B. D. R. & Johnston, P. M. 2009b. A comparison of stratified sand filters and percolation trenches for on-site wastewater treatment. *ASCE Journal of Environmental Engineering,* 135, 8-16.

Gill, L. W., O'Luanaigh, N., Johnston, P. M., Misstear, , B.D.R & O`Suilleabhain, C. 2009c. Nutrient loading on subsoils from on-site wastewater effluent, comparing septic tank and secondary treatment systems. . *Water Research,* 43, 2739-2749.

Gill, L. W., O'Súilleabháin, C., Misstear, B. D. R. & Johnston, P. M. 2007. The treatment performance of different subsoils in Ireland receiving on-site wastewater effluent. . *Journal of Environmental Quality,* 36, 1843-1855.

Gill, L. W., Súilleabháin, C. Ó., Johnston, P. & Misstear, B. 2005. An Investigation into the Performance of Subsoils and Stratified Sand Filters for the Treatment of Wastewater

from On-site Systems (2001-MS-15-M1). Environmental Protection Agency: Trinity College Dublib.

Goldstein, S. N. & Wenk, V. D. 1972. Home Sewage Treatment. *Water Well Journal*, 36-40.

Grant, N. & Moodie, M. 1995. *Septic Tanks: An Overview*, Nick Grant.

Gray, D. H. & Sotir, R. B. 1996. *Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control*, John Wiley & Sons.

Gray, N. F. 1995. Composition of Septic Tank Effluent. *The GSI Groundwater Newsletter.*

Gregersen, P. & Brix, H. 2001. Zero-discharge of nutrients and water in a willow dominated constructed wetland. *Water Sci Technol*, 44, 407-12.

GSI, Meehan, R., Kelly, C., Kabza, M., Murphy, O. & Spillane, M. 2012. Subsoil Permeability Map of Ireland. *In:* IRELAND, G. S. O. (ed.). Dublin.

Guidi, W. & Labrecque, M. 2010. Effects of High Water Supply on Growth, Water Use, and Nutrient Allocation in Willow and Poplar Grown in a 1-Year Pot Trial. *Water, Air, and Soil Pollution*, 207, 85-101.

Guidi, W., Piccioni, E. & Bonari, E. 2008. Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. *Bioresource Technology*, 99, 4832-4840.

Gustafsson, J. & Larsson, S. 2007. Nordh N-E Manual for Salix growers (In Swedish).

Hakkila, P. 1985. Metsäenergian mahdollisuudet Suomessa. PERA-projektin väliraportti. Summary: The potential of forest energy in Finland. Interim report of PERA project. . *Folia Forestalia*, 624, 86.

Hall, R. L., Allen, S. J., Rosier, P. T. W. & Hopkins, R. 1998. Transpiration from coppiced poplar and willow measured using sap-flow methods. *Agricultural and Forest Meteorology*, 90, 275-290.

Halldin, S. L., Anders 1989. Water use by willow in southern Sweden. *Estimation of Areal Evapotranspiration (Proceedings of a workshop held at Vancouver, B.C., Canada, August 1987). IAHS Publ. no. 177, 1989.*

Hanley, S. & Karp, A. 2003. Improving the breeding efficiency. Department Trade and Industry.

Hargreaves, G. H. 1975. Moisture availability and crop production. *ASAE*, 18, 980-984.

Harman, J., Robertson, W. D., Cherry, J. A. & Zanini, L. 1996. Impacts on a sand aquifer from an old septic system: nitrate and phosphate. *Ground Water*, 34, 1105-1114.

Hasselgren, K. 1998. Use of municipal waste products in energy forestry: highlights from 15 years of experience. *Biomass and Bioenergy*, 15, 71-74.

Heiska, S., Tikkanen, O.-P., Rousi, M., Turtola, S., Tirkkonen, V., Meier, B. & Julkunen-Tiitto, R. 2007. The susceptibility of herbal willow to Melampsora rust and herbivores. *European Journal of Plant Pathology,* 118, 275-285.

Henry, H. 1990. *An Assessment of Septic Tank Movement in Soil and Groundwater Systems.* Ph.D, Sligo RTC.

Jackson, M. & Attwood, P. 1996. Roots of willow (Salix viminalis L.) show marked tolerance to oxygen shortage in flooded soils and in solution culture. *Plant and Soil,* 187, 37-45.

Jenssen, P. & Siegrist, R. 1990. Technology assessment of wastewater treatment by soil infiltration systems. *Water Science & Technology,* 22, 83-92.

Jenssen, P. D. 2001. Wastewater treatment by soil infiltration systems - Comments on treatment process. Department of Agricultural Engineering: Agricultural University of Norway.

Jones, R. A. & Lee, G. F. 1979. Septic tank wastewater disposal systems as phosphorus sources for surface water. *Journal (Water Pollution Control Federation),* 51, 2764-2775.

Keenan, T. 1983. *A Review of Current Practices to the Design and Operation of Septic Tank Treatment Systems in Ireland.* M.Sc Thesis, Trinity College Dublin.

Klang-Westin, E. & Eriksson, J. 2003. Potential of Salix as phytoextractor for Cd on moderately contaminated soils. *Plant and Soil,* 249, 127-137.

Kozlowski, T. T. 1999. Soil Compaction and Growth of Woody Plants. *Scandinavian Journal of Forest Research,* 14, 596-619.

Krasny, M. E., Zasada, J. C. & Vogt, K. A. 1988. Adventitious rooting of four Salicaceae species in response to a flooding event. *Canadian Journal of Botany,* 66, 2597-2598.

Kreissel, J. F. 1982. On-Site Wastewater Disposal Research in the United States. *Alternative Wastewater Treatment* Boston, MA: D. Reidel Publishing Co.

Kuzovkina, Y., Knee, M. & Quigley, M. 2004. Soil compaction and flooding effects on the growth of twelve Salix L. species. *J. Environ. Hort,* 22, 155-160.

Laak, R. 1980. Multichamber Septic Tanks. *Journal of Environmental Engineering,* 106, 539-546.

Laak, R., Healy, K. A. & Hardisty, D. M. 1974. Rational Basis for Septic Tank System Design. *Groundwater,* 12, 348-351.

Larsson, S. 1998. Genetic improvement of willow for short-rotation coppice. *Biomass Bioenergy,* 15, 23-26.

Larsson, S., Clause, P., Jakobsson, I., Dawson, M., Backlund, A.; Mavrogianopoulus, G. 2003. Short-rotation Willow Biomass Plantations Irrigated and Fertilised with Wastewaters. *European Commission DG VI,* Agriculture.

Larsson, S. & Pirrwitz, D. 1998. Genetic improvement of willow (*Salix*) as a source of bioenergy, produced for the EC. Biomat Net.

Lawrence, C. H. 1973. Septic Tank Performance. *journal of Environmental Health,* 36, 226-228.

Ledin, S. 1996. *The Swedish Energy Forestry Research Programme at the Department of Short Rotation Forestry, SUAS, Uppsala: Supported by NUTEK ; Summary Report Prepared for the Evaluation of the Short-rotation Forestry Research 1993 - 1996.*

Ledin, S. 1998. Environmental consequences when growing short rotation forests in Sweden. *Biomass and Bioenergy,* 15, 49-55.

Ledin, S., Willebrand, E. & Forestry, S. l. D. o. S. R. 1996. *Handbook on how to Grow Short Rotation Forests,* Swedish University of Agricultural Sciences, Department of Short Rotation Forestry.

Lindegaard, K. N. & Barker, J. H. A. 1997. Breeding willows for biomass. *Aspects of Applied Biology,* 49, 155-162.

Lindegaard, K. N., Carter, M. M., McCracken, A., Shield, I. F., Macalpine, W., Hinton Jones, M., Valentine, J. & Larsson, S. 2011. Comparative trials of elite Swedish and UK biomass willow varieties 2001-2010. *Aspects of Applied Biology,* 112.

Lindroth, A. & Båth, A. 1999. Assessment of regional willow coppice yield in Sweden on basis of water availability. *Forest Ecology and Management,* 121, 57-65.

Lindroth, A., Cermak, J., Kucera, J., Cienciala, E. & Eckersten, H. 1995. Sap flow by the heat balance method applied to small size salix trees in a short-rotation forest. *Biomass and Bioenergy,* 8, 7-15.

Lindroth, A., Verwijst, T. & Halldin, S. 1994. Water-use efficiency of willow: Variation with season, humidity and biomass allocation. *Journal of Hydrology,* 156, 1-19.

Liu, S., Butler, D., Memon, F. A., Makropoulos, C., Avery, L. & Jefferson, B. 2010. Impacts of residence time during storage on potential of water saving for grey water recycling system. *Water Research,* 44, 267-277.

Lowery, B. & Schuler, R. T. 1994. Duration and effects of compaction on soil and plant growth in Wisconsin. *Soil and Tillage Research,* 29, 205-210.

Martin, P. J. & Stephens, W. 2006. Willow growth in response to nutrients and moisture on a clay landfill cap soil. II: Water use. *Bioresource Technology,* 97, 449-458.

Martínez-Cob, A. & Tejero-Juste, M. 2004. A wind-based qualitative calibration of the Hargreaves ETоestimation equation in semiarid regions. *Agriculture Water Management,* 64, 251-264.

McGauhey, P. H., Winneberger, J. H. T. & Program, U. S. F. H. A. T. S. 1964. *Causes and Prevention of Failure of Septic-tank Percolation Systems: A Report,* U.S. Government Printing Office.

McLaren, R. G. & Smith, C. J. 1996. Issues in the disposal of industrial and urban wastes. *In:* NAIDU, R., KOOKANA, R. S., OLIVER, D. P., ROGERS, S. & MCLAUGHLIN, M. J. (eds.) *Contaminants and the Soil Environment in the Australasia-Pacific Region.* Kluwer, Dordrecht.

Meehan, R. T. & Lee, M. 2012. Subsoils across the Irish Landscape; their textural and bulk density characteristics, and resultant variations in permeability. *International Symposium on Domestic Waste Water Treatment and Disposal Systems.* Trinity College Dublin.

Melchior, S., Steinert, B. & Flöter, O. A comparison of traditional clay barriers and the polymer-modified material trisoplast in landfill covers. *In:* COSSU, R., CHRISTENSEN, H. & STEGMANN, R., eds. Eighth International Waste Management and Landfill Symposium, 2001 Environmental Sanitary Engineering Center (CISA), Cagliari (Italy).

Mengel, K. & Kirkby, E. A. 1996. *Principles of Plant Nutrition,* Panima Publishing Corporation.

Mensar, H. A., Winant, W. M. & Bennett, O. L. 1983. Spray irrigation with landfill leachate leachate. *BioCycle,* 24, 22-25.

Metcalf & Eddy 1991. *Wastewater Engineering: Treatment, Disposal, Reuse.,* New York, McGraw-Hill Inc.

Miljøstyrelsen 2003. Retningslinier for etablering af pileanlæg op til 30 PE. *Økologisk byfornyelse og spildevandsrensning, Nr. 25, Miljøstyrelsen, Copenhagen.*

Mirck, J. & Volk, T. A. 2010. Response of three shrub willow varieties (Salix spp.) to storm water treatments with different concentrations of salts. *Bioresource Technology,* 101, 3484-3492.

Mitchell, C. P., Ford-Robertson, J. B., Hinckley, T. & Sennerby-Forsse, L. 1992. *Ecophysiology of Short Rotation Forest Crops,* Essex, England, Elsevier Science Publications.

Montgomery, D. C., Peck, E. A. & Vining, G. G. 2012. *Introduction to Linear Regression Analysis,* John Wiley & Sons.

Mulqueen, J. & Rodgers, M. 2001. Percolation testing and hydraulic conductivity of soils for percolation areas. *Water Research,* 35, 3909-3915.

Nixon, D. J., Stephens, W., Tyrrel, S. F. & Brierley, E. D. R. 2001. The potential for short rotation energy forestry on restored landfill caps. *Bioresource Technology,* 77, 237-245.

O' Súilleabháin, C. 2000. *Assessing the Boundary Between High and Moderately Permeable Subsoils.* MSc, Trinity College Dublin.

O' Súilleabháin, C. 2004. *The Attenuation Capacity of Different Subsoils receiving Domestic Wastewater Effluent.* Ph.D, Trinity College Dublin.

O' Sullivan, D. & Quigley, P. 2002. Geotechnical engineering and environmental aspects of clay liners for landfill projects. *In:* LTD., F. T. C. A. I. G. S. (ed.). Institute of Engineers of Ireland.

O'Luanaigh, N. D., Gill, L. W., Misstear, B. D. R. & Johnston, P. M. 2012. The attenuation of microorganisms in on-site wastewater effluent discharged into highly permeable subsoils. . *Journal of Contaminant Hydrology* 142-143, 126-139.

O'Luanaigh, N. D., Goodhue, R. & Gill, L. W. 2010. Nutrient removal from on-site domestic wastewater in horizontal subsurface flow reed beds in Ireland. *Ecological Engineering,* 36, 1266-1276.

Obarska-Pempkowiak, H. Application of willow and reed vegetation filters for protection of a stream passing through a zoo. Willow Vegetation Filters For Municipal Wastewater and Sludges - A Biological Purification System., 5-10 June 1994 1994 Sweden. Swedish University of Agricultural Sciences, Section of Short Rotation Forestry., 59-67.

Old Testament 1456. *Psalm 137,* Mainz, Germany, Johann Gutenberg.

Osman, K. T. 2012. *Soils: Principles, Properties and Management,* Springer.

Patterson, J. W., Minear, R. A. & Nedved, T. K. 1971. Septic Tanks and the Environment *Illinois Institute for Environmental Quality.* Distrib. by National Technical Information Service (N.T.S.I).

Pauliukonis, N. & Schneider, R. 2001. Temporal patterns in evapotranspiration from lysimeters with three common wetland plant species in the eastern United States. *Aquatic Botany,* 71, 35-46.

Peeples, J. & Mancl, K. 1998. Laboratory scale septic tanks. *J. Sci,* 98, 75-79.

Pei, M. H., Lindegaard, K., Ruiz, C. & Bayon, C. 2008. Rust resistance of some varieties and recently bred genotypes of biomass willows. *Biomass and Bioenergy,* 32, 453-459.

Pei, M. H. & McCracken, A. 2005. Rust diseases of willow and poplar. UK: CABI Publishing

Pei, M. H., Ruiz, C., Hunter, T. & Bayon, C. 2003. Rust resistance in Salix induced by inoculations with avirulent and virulent isolates of Melampsora larici-epitea. *Forest Pathology,* 33, 383-394.

Persson, G. 1995. Willow stand evapotranspiration simulated for Swedish soils. *Agricultural Water Management,* 28, 271-293.

Persson, G. & Lindroth, A. 1994. Simulating evaporation from short-rotation forest: variations within and between seasons. *Journal of Hydrology,* 156, 21-45.

Perttu, K. L. 1993. *Biomass production and nutrient removal from municipal wastes using willow vegetation filters.*

Perttu, K. L. & Kowalik, P. J. 1997. Salix vegetation filters for purification of waters and soils. *Biomass and Bioenergy,* 12, 9-19.

Pettygrove, G. S., Davenport, D. C. & Asano, T. 1985. *California's reclaimed municipal wastewater resources,* California State Water Resources Control Board, Sacramento, CA.

Philippot, S. 1996. Simulation models of short-rotation forestry production and coppice biology. *Biomass and Bioenergy,* 11, 85-93.

Pistocchi, C., Guidi, W., Piccioni, E. & Bonari, E. 2009. Water requirements of poplar and willow vegetation filters grown in lysimeter under Mediterranean conditions: Results of the second rotation. *Desalination,* 246, 137-146.

Plaster, E. 2013. *Soil Science and Management,* Delmar, Cengage Learning.

Rastas Amofah, L., Mattsson, J. & Hedström, A. 2012. Willow bed fertigated with domestic wastewater to recover nutrients in subarctic climates. *Ecological Engineering,* 47, 174-181.

Ritchie, J. T. 1981. Soil Water Availabiity. *Plant Soil,* 58, 327-338.

Rosenqvist, H., Aronsson, P., Hasselgren, K. & Perttu, K. 1997. Economics of using municipal wastewater irrigation of willow coppice crops. *Biomass and Bioenergy,* 12, 1-8.

Rossi, P. 1999. Length of cuttings in establishment and production of short-rotation plantations of Salix 'Aquatica'. *New Forests,* 18, 161-177.

Royle, D. J. & Hubbes, M. 1992. Diseases and pests in energy crop plantations. *Biomass and Bioenergy,* 2, 45-54.

Ruark, G. A., Mader, D. L. & Tattar, T. A. 1982. THE INFLUENCE OF SOIL COMPACTION AND AERATION ON THE ROOT GROWTH AND VIGOUR OF TREES—A LITERATURE REVIEW. PART 1. *Arboricultural Journal,* 6, 251-265.

Running, S. W., Nemani, R. R., Peterson, D. L., Ban, L. E., Potts, D. F., Pierce, L. L. & Spanner, M. A. 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. . *Ecology,* 70, 1090-1101.

Ryszkowski, L., Bartoszewicz, A. and Marcinek, J. 1990. Biogeochemical barriers (in Polish). . *In Obieg wody i bariery biogeochemiczne w krajobrazie rolniczy.* Zaklad Badan Srodowiska Rolniczego i Lesnego, PAN, Poznan.

Rytter, R.-M. & Hansson, A.-C. 1996. Seasonal amount, growth and depth distribution of fine roots in an irrigated and fertilized Salix viminalis L. plantation. *Biomass and Bioenergy,* 11, 129-137.

Sage, R. B. 1999. Weed competition in willow coppice crops: the cause and extent of yield losses. *Weed Research,* 39, 399-411.

Salvato, J. 1992. Environmental Engineering and Sanitation. New York, John Wiley & Sons. Inc.

Schmid, J. & Schulz, H. Vergleich von Wirtschaftlichkeit und Wirksamkeit bei Maßnahmen und Konzepten zur Deponiesicherung mit der Software BLACE—Minimierung von Risiken und Dauer der Nachsorge (Comparison of cost-effectivness and performance of landfill liners with the software BLACE—Minimizing risks and duration of after care.

Deponienachsorge, 2004 GSB Sonderabfall-Entsorgung Bayern GmbH, Baar-Ebenhausen.

Shield, I. F., Macalpine, W. & Karp, A. 2008. The effect of the size of the cuttings planted on the subsequent performance of three contrasting willow cultivars for short rotation coppice. *Asp Appl Biol,* 90, 225-231.

Siegrist, R. L. & Boyle, W. C. 1987. Wastewater induced Soil Clogging Development. *Journal of Environmental Engineering,* 113, 550-566.

Siegrist, R. L., Tyler, E. J. & Jenssen, P. D. Design and Performance of Onsite Wastewater Soil Absorption Systems. Proceedings of Nat. Research Needs Conference, Risk-Based Decision Making for Onsite Wastewater Treatment,, 19-20 May 2000 2000 Washington University, St. Louis, Missouri.

Simon, F.-G. & Müller, W. W. 2004. Standard and alternative landfill capping design in Germany. *Environmental Science & Policy,* 7, 277-290.

Sirén, F. 1983. Energiskogsodling. Nämnden för energiskogsodling. (in Swedish). *Rep. NE 1983:11,* Stockholm., 255.

Skidmore, E. L., Jacobs, H. S. & Powers, W. L. 1969. Potential Evapotranspiration as Influenced by Wind. *Agron. J.,* 61, 543-546.

Soil Science Society of America 1997. Glossary of Soil Science. Madison, WI: Soil Science Society of America.

Spano, D., Snyder, R. L., Sirca, C. & Duce, P. 2009. ECOWAT—A model for ecosystem evapotranspiration estimation. *Agricultural and Forest Meteorology,* 149, 1584-1596.

Spiers, A. G. 1989. Introduction of poplar and willow pathogens in New Zealand and their effect. *New Zealand J. For. Sci.,* 19, 347-352.

Stephens, W., Tyrrel, S. F. & Tiberghien, J. E. 2000. Irrigating short rotation coppice with landfill leachate: constraints to productivity due to chloride. *Bioresource Technology,* 75, 227-229.

Stevik, T. K., Ausland, G., Jenssen, P. D. & Siegrist, R. L. 1999. Removal of *E. Coli* during intermittent filtration of wastewater effluent as affected by dosing rate and media type. *Water Research,* 33, 2088-2098.

Sugiura, A., Tyrrel, S. & Seymour, I. 2008. Growth and water use of Salix viminalis, Populus trichocarpa and Eucalyptus gunnii field trial plantation irrigated with secondary treated effluent. . *Aspects of applied biology, Biomass and energy crops* 3, 119-126.

Swartz, M. 1999. *Assessing the Permeability of Irish Subsoils.* MSc Thesis, Trinity College Dublin.

Swartz, M., Misstear, B. D. R., Daly, D. & Farrell, E. R. 2003. Assessing subsoil permeability for groundwater vulnerability. *Quarterly Journal of Engineering Geology and Hydrogeology,* 36, 173-184.

TCC, GSI & FÁS 1998. Site Suitability Assessments for On-Site Wastewater Management. *In:* IRELAND, T. S. C. C. I. A. W. T. G. S. O. (ed.).

Tisdale, S. L., Havlin, J. L., Beaton, W. L. & Nelson, W. L. 1999. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*, Prentice Hall.

Toome, M., Heinsoo, K., Ramstedt, M. & Luik, A. 2009. Rust severity in bioenergy willow plantations treated with additional nutrients. *Forest Pathology,* 39, 28-34.

Trajkovic, S. 2007. Hargreaves versus Penman-Monteith under Humid Conditions. *Journal of Irrigation and Drainage Engineering,* 133, 38-42.

Tubby, I. & Armstrong, A. 2002. *The establishment and management of short rotation coppice - a practitioner's guide.*, Edinburgh, Forestry Commission.

USEPA 1980a. Design Manual: Onsite Wastewater Treatment and Disposal Systems. *In:* EPA (ed.). Cincinnati, Ohio.

USEPA 1980b. Hazardous Waste Land Management. *In:* SW-874, O. O. W. A. W. M. (ed.). Washington, DC: US Environmental Protection Agency.

USEPA 1987. On-Site Meteorological Program Guidance for Regulatory Modelling Applications. *In:* OFFICE OF AIR QUALITY PLANNING AND STANDARDS (ed.). Research Triangle Park, North Carolina 27711: USEPA.

Van Cuyk, S., Siegrist, R., Logan, A., Masson, S., Fischer, E. & Figueroa, L. 2001. Hydraulic and purification behaviors and their interactions during wastewater treatment in soil infiltration systems. *Water Research,* 35, 953-964.

Verwijst, T. 2001. Willows: An underestimated resource for environment and society. *The Forestry Chronicle,* 77, 281-285.

Viraraghavan, T. 1976. Septic Tank Efficiency. *ASCE Journal Environmental Engineering Division,* 102, 505-508.

Vogel, H. J. 2000. A numerical experiment on pore size, pore connectivity, water retention, permeability, and solute transport using network models. *European Journal of Soil Science,* 51, 99-105.

Weih, M. & Nordh, N.-E. 2002. Characterising willows for biomass and phytoremediation: growth, nitrogen and water use of 14 willow clones under different irrigation and fertilisation regimes. *Biomass and Bioenergy,* 23, 397-413.

White, P. J. & Broadley, M. R. 2001. Chloride in Soils and its Uptake and Movement within the Plant: A Review. *Annals of Botany,* 88, 967-988.

Whitehead, D. C. 2000. *Nutrient Elements in Grassland: Soil-Plant-Animal Relationships,* CABI Pub.

Wickham, J., Rice, B., Finnan, J. & McConnon, R. 2010. A review of past and current research on short rotation coppice in Ireland and abroad. Dublin, Ireland: COFORD.

Wilhelm, S. R., Schiff, S. L. & Cherry, J. A. 1994a. Biogeochemical Evolution of Domestic Waste Water in Septic Systems: 1. Conceptual Model. *Ground Water,* 32, 905-916.

Wilhelm, S. R., Schiff, S. L. & Robertson, W. D. 1994b. Chemical Fate and Transport in a Domestic Septic System: Unsaturated and Saturated Zone Geochemistry. *Environmental Toxicology and Chemistry,* 13, 193-203.

Wilkinson, A. G. 1999. Poplars and willows for soil erosion control in New Zealand. *Biomass and Bioenergy,* 16, 263-274.

Withers, P. J. A., Jarvie, H. P. & Stoate, C. 2011. Quantifying the impact of septic tank systems on eutrophication risk in rural headwaters. *Environment International,* 37, 644-653.

Wong, M. H. & Leung, C. K. 1989. Landfill leachate as irrigation water for tree and vegetable crops. *Waste Management and Research,* 7, 311-324.

WSP 2010. The Plan - Demand Appendix. Dublin: Water Supply Project - Dublin Region.

Wu, S., Austin, D., Liu, L. & Dong, R. 2011. Performance of integrated household constructed wetland for domestic wastewater treatment in rural areas. *Ecological Engineering,* 37, 948-954.

Appendix A:

Site Layouts and Photos

Sites A and B: Fardystown, Co. Wexford

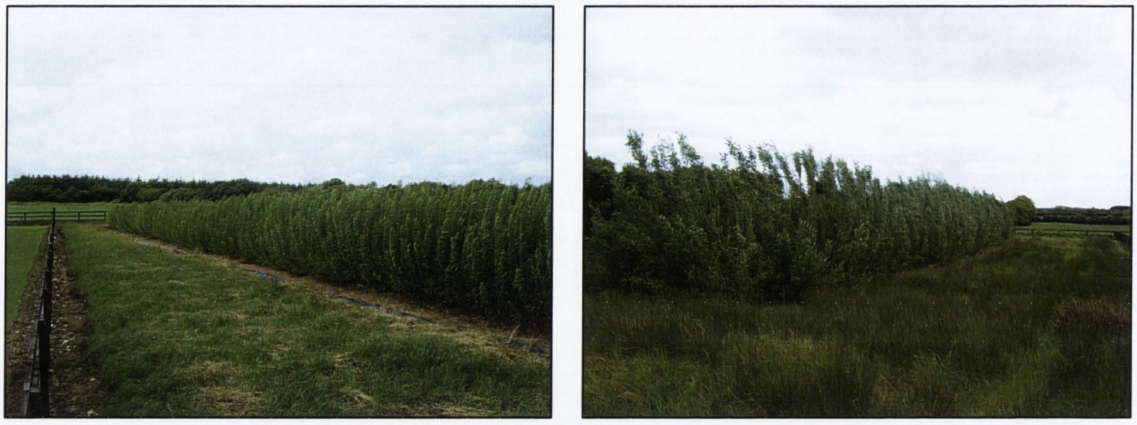


Figure A.1 Aerial view of Sites A and B (with the systems highlighted in yellow)



(A) (B)

Figure A.2 (A) Willow cuttings on system A shortly after being planted (2009); (B) System A during second growing season (2010)



(A) (B)

Figure A.3 (A) System B during second growing season (2010); (B) System A during third growing season (2011)

Site C: Borehovel, Co. Wexford

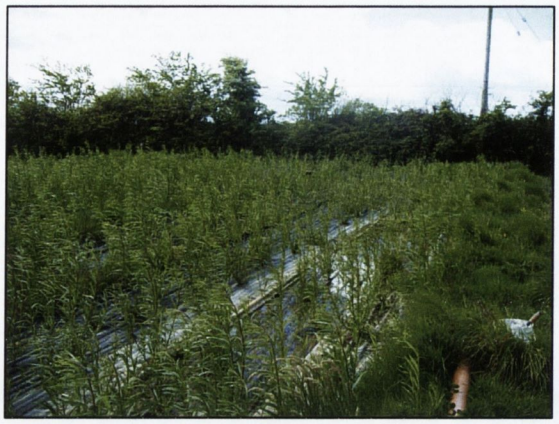


Figure A.4 Aerial view of Site C (with the willow system highlighted in yellow)



(A) (B)

Figure A.5 (A) Completed willow system before planting (2010); (B) System C after willows were cutback for the first time (2011)



(A)



(B)

Figure A.6 (A) Willow trees at the start of the second growing season (2011); (B) Willow trees at the end of the second growing season (2011)



(A)



(B)

Figure A.7 (A) Willow trees at the middle of the second dormant season (2011); (B) Willow system during the fourth growing season (most recently coppiced trees at the fore) [2011]

Site D: Ballask, Co. Wexford



Figure A.8 Aerial view of Site D (with the willow system highlighted in yellow)



(A) (B)

Figure A.9 (A) Willow system during second season - poor development of willow is evident (2011); (B) Willow system during second season after replanting with larger cuttings (2011)



(A)



(B)

Figure A.10 (A&B) Willow system at the start of third growing season - poor development is still apparent (2012);



(A)



(B)

Figure A.11 (A&B) Willow system during fourth growing season - willow development has improved but is still relatively poor (2013)

Site E: Jamestown, Co. Wexford

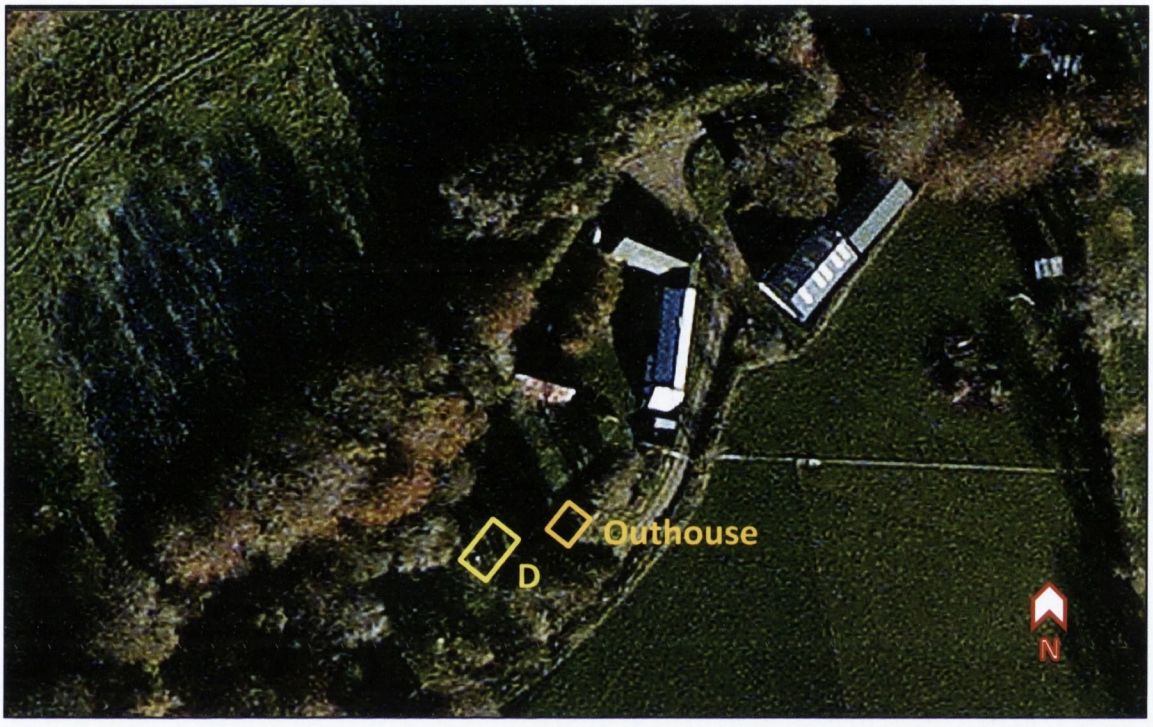


Figure A.12 Aerial view of Site E (with the willow system highlighted in yellow and the outhouse highlighted in orange)



(A) (B)

Figure A.13 (A) Outhouse containing two toilets; (B) Coppiced willow shoots



(A) (B)

Figure A.14 (A) Willow system at start of second growing season (2011); (B) Willow system in August of second season (2011)

Site F: Ballywilliam, Co. Wexford

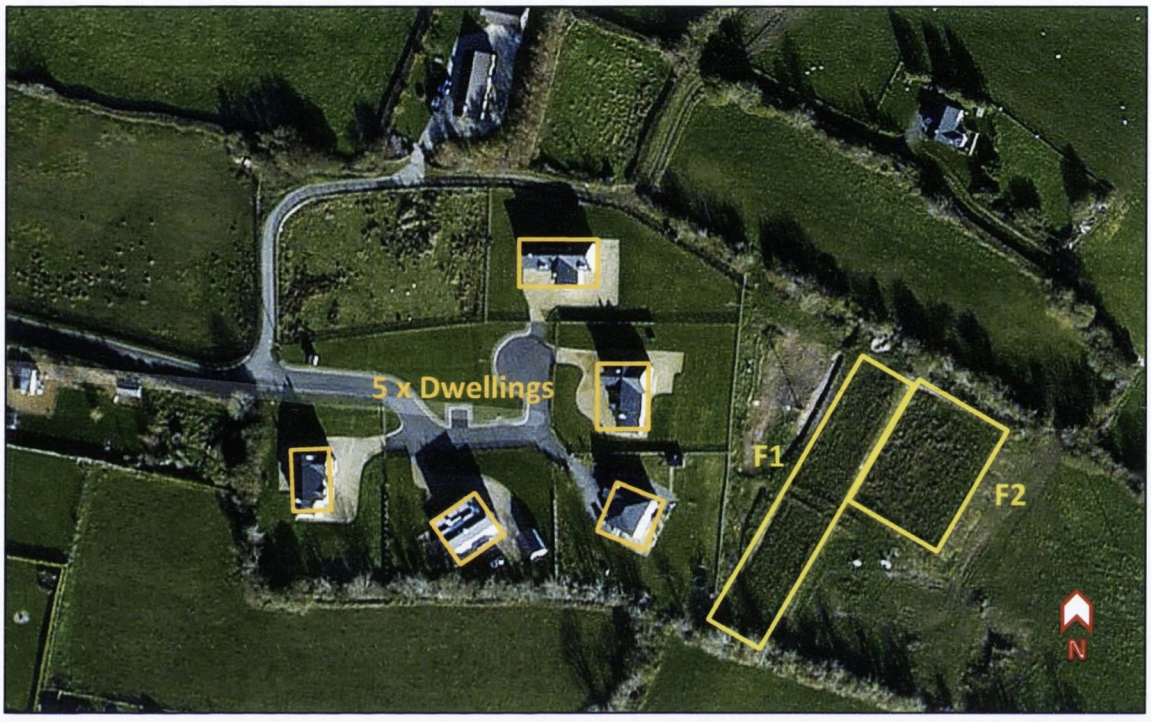


Figure A.15 Aerial view of Site F (with the willow systems highlighted in yellow and the houses highlighted in orange)



(A) (B)

Figure A.16 (A) Poor initial development of willow cuttings (2011); (B) Willows in middle of second growing season – it can be seen that willow development improved greatly (2012)



(A) (B)

Figure A.17 (A) Willows on System F(1) at end of second growing season (2012); (B) Willows in middle of third growing season on System F(2) - weed growth was still quite prevalent on the system (2013)



(A) (B)

Figure A.18 (A) Willows on System F(1) at end of third growing season (2013); (B) Willows on System F(2) at end of third growing season (2013)

Site G: Ardcavan, Co. Wexford

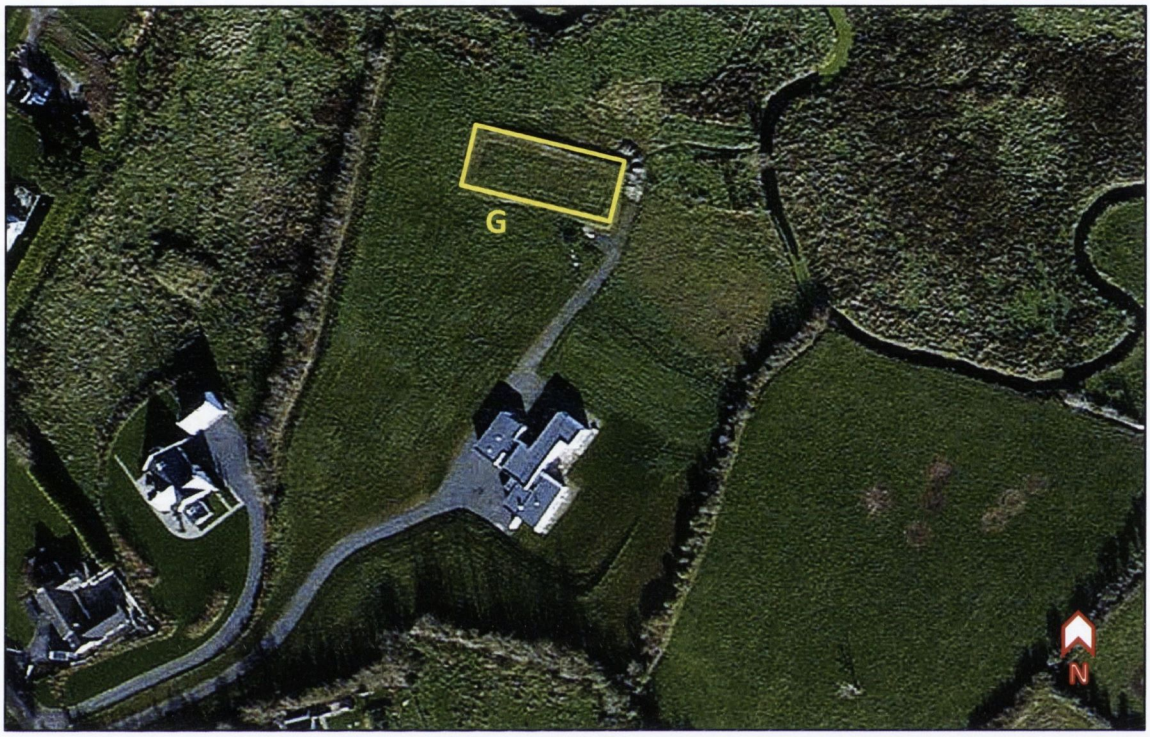
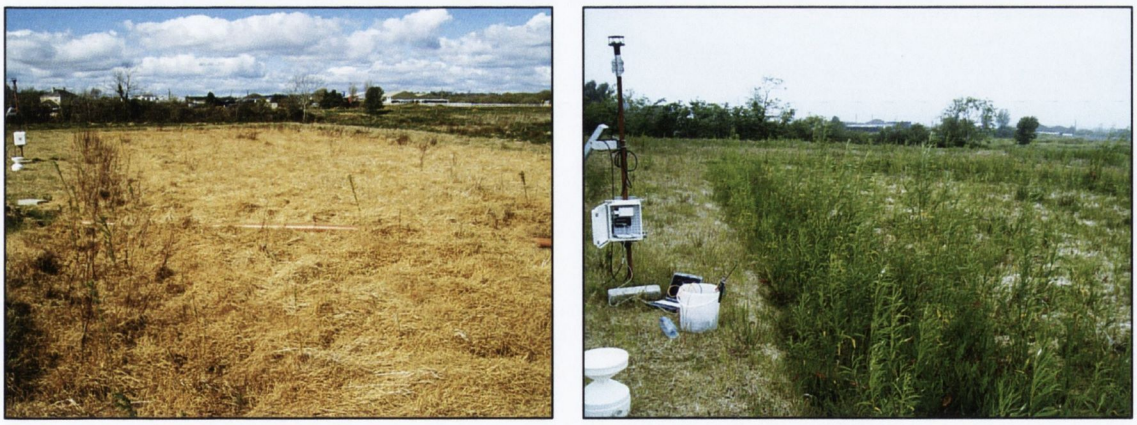


Figure A.19 Aerial view of Site G (with the willow system highlighted in yellow)



(A) (B)

Figure A.20 (A) Willow system after weed killer was applied before the second growing season – willow development had been quite poor in the first year (2012); (B) Willow system in middle of second growing season – it can be seen that development is still quite poor(2011)



(A)



(B)

Figure A.21 (A) Willow development had improved in some areas of the system by the end of the second growing season (2012); (B) Willow system in September of the third season – development had improved at the edges, but was still poor in the middle of the system (2013)

Site H: Duncormick, Co. Wexford

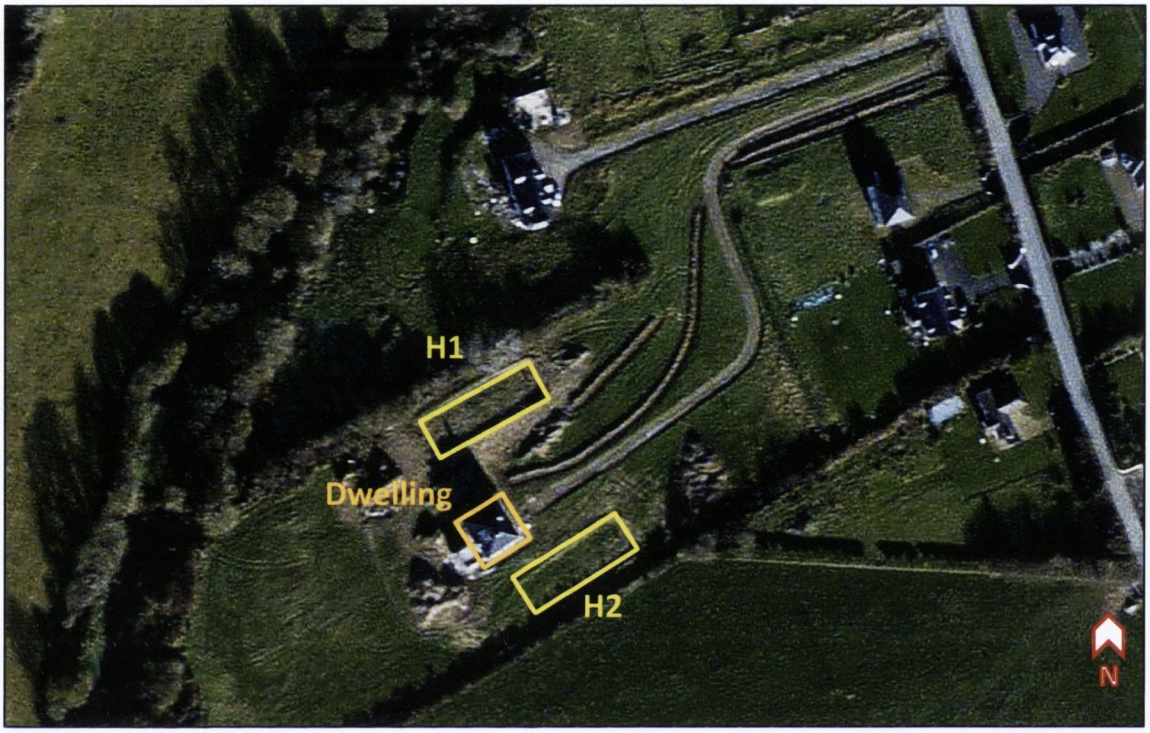


Figure A.22 Aerial view of Site H (with the willow systems highlighted in yellow and the house highlighted in orange)



(A) (B)

Figure A.23 (A) Willow cuttings at end of first season on System H(1) - cuttings were not planted until July (2011); (B) Willows in middle of second growing season on System H(2) (2012)



(A)



(B)

Figure A.24 (A) Willows in middle of second growing season on System H(1) (2012); (B) Willows on System F(2) at end of second season (2012)



(A)



(B)

Figure A.25 (A) Willows at end of third growing season on System H(1) (2013); (B) Willows at end of third growing season on System H(2) (2013)

Site I: Carrigallen, Co. Leitrim

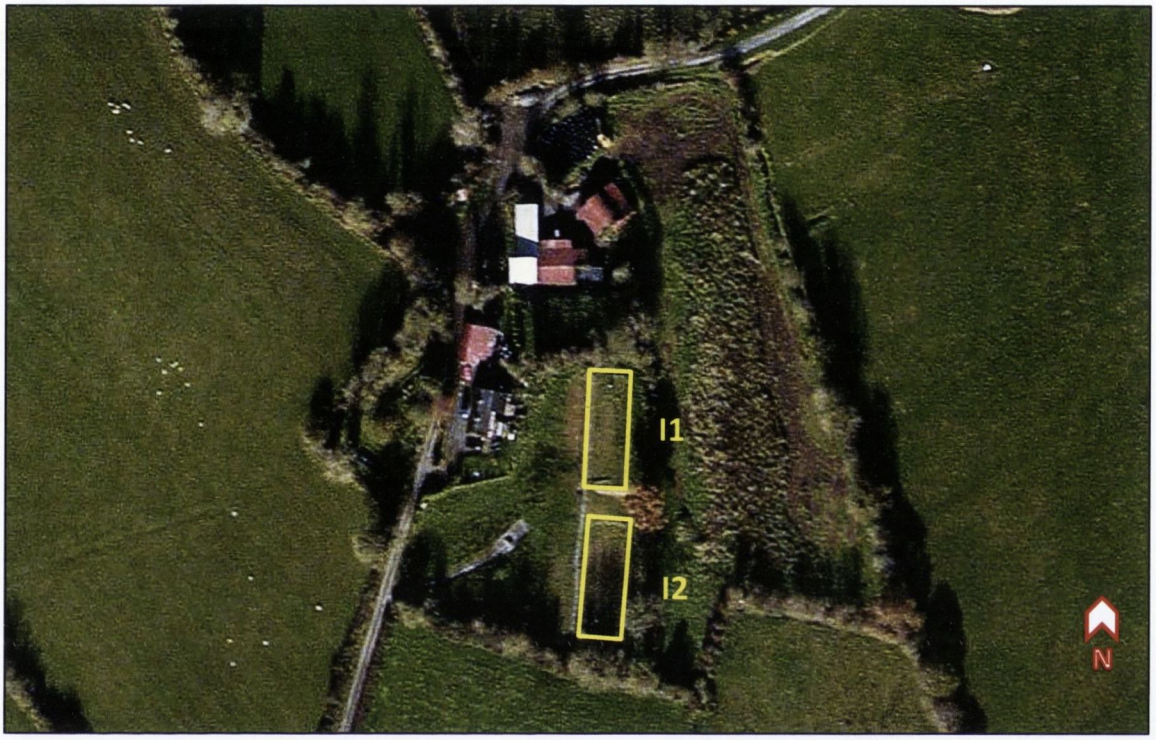


Figure A.26 Aerial view of Site I (with the willow systems highlighted in yellow)



(A) (B)

Figure A.27 (A) Willows at end of first growing season on System I(1) – cuttings were planted in July (2011); (B) Willows at end of first growing season on System I(2) – it can be seen that development was quite poor (2011)



(A) (B)

Figure A.28 (A) Willows in middle of second growing season on System I(1) – it can be seen that willow development varied quite a lot throughout the system (2012); (B) Willows in middle of second growing season on System I(2) – it can be seen that willow development was poor on the system (2012)



(A) (B)

Figure A.29 (A) Willows in middle of third growing season on System I(1) – it can be seen that willow development varied quite a lot throughout the system (2012); (B) Willows in middle of third growing season on System I(2) – it can be seen that willow development was still poor on the system (2012)

Site J: Ballylanders, Co. Limerick



Figure A.30 Aerial view of Site J (with the willow system highlighted in yellow)



(A) (B)

Figure A.31 (A) Willow cuttings on day of planting (2012); (B) Willow system in June of second season (2013)



(A) (B)

Figure A.32 (A) Willow system at end of August in second growing season (2013); (B) Willow system at end of August in second growing season (2013)