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Karstification and Groundwater - Surface Water Interactions in the Meath-Westmeath Lakeland Region

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Dissertation submitted to the University of Dublin, Trinity College, for the degree of Doctor of Philosophy

2010

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FRONTISPIECE

Swallow hole at White Lake

Summary

This thesis investigates the degree of karstification and the characteristics of groundwater – surface water interactions in the Meath-Westmeath Lakeland region. In particular, groundwater - lake interactions in the region are examined. The methodological framework adopted in the study involved conducting an initial pilot study over an area of 215 km² situated in the Meath-Westmeath Lakeland region. More specifically, this area comprised of the lake catchments of Lough Owel, Lough Derravaragh, Lough Lene, White Lake, the Ben Loughs, and Lough Bane, and the spring catchments of Tobernacogany and Toberfaolaigh. Following from this initial pilot study, a smaller study area was selected which was representative of the region, and which was suitable for the implementation of the methodological framework employed in the detailed study. The pilot study comprised of a desk study and a surface water data collection programme. On the basis of results obtained during the pilot study, the catchments of Lough Owel and Lough Derravaragh were omitted from further study. The detailed study was then carried out over an area of approximately 33 km² that had been selected from the initial pilot study area. The detailed study involved the collection of both groundwater and surface water data and the methods adopted included: groundwater standing water level measurement; stream flow measurement; water quality measurements; water tracing; drainage density calculation; and the calculation of water budgets.

The findings of this thesis are that karstic drainage takes place in the Meath-Westmeath Lakeland region and that the groundwater and surface water systems in the area are closely interlinked. However, while the area does share hydrological characteristics with other known Irish lowland karsts, the karst in the study area appears to be less well developed than elsewhere. The results of this thesis provide further evidence that regions which may not appear karstic, and which have almost fully integrated surface drainage systems may indeed be karstic in their hydrological functioning.

The karstic drainage system in the Meath-Westmeath Lakeland region has been deactivated to a degree by arterial drainage schemes, as has been reported for parts of east County Galway and County Roscommon, and parts of the present surface drainage system in the study area are of anthropogenic origin.

The findings show that the groundwater and surface water systems are closely interlinked in an area where a fully developed surface drainage network exists. Groundwater and surface water catchments are not spatially coincident in this area and the interactions that take place between groundwater and surface water are temporally and spatially dynamic. Some of these interactions take place across topographically delineated surface drainage catchment boundaries, including the regional drainage divide between the River Shannon and River Boyne Basins.

Each of the lakes in the study area were found to differ in the characteristics of their interactions with the groundwater system. Some of the lakes in the study area may, under certain hydraulic conditions, be surface expressions of the water table and some of the lakes are likely to be two-way zones of interconnection between the groundwater and surface water systems in the area. Variations in the way in which the study lakes interact with groundwater were analysed and, on the basis of this analysis, the lakes were classified along a continuum from karstic turlough-like lakes with a high degree of interconnectivity to the groundwater system, to less karstic or non-karstic lakes that have a lesser degree of connectivity to the groundwater system.

Acknowledgements

Firstly I would like to thank my supervisor Dr. David Drew without whose advice and patient guidance this thesis would not have been written. Dr. Drew provided encouragement and constructive criticism throughout the course of this research and gave generously of his time over the course of the past few years. I want to express my gratitude to Trinity College Dublin and the International Association of Hydrogeologists (Irish Group) who funded this research at various stages. I would like to thank the academic and administrative staff of the Geography Department TCD both past and present, particularly Dr. Pablo Fernandez de Arroyabe Hernaez, Mabel Denniston, Terry Dunne, Tara Nolan, Steve O'Connor, Elaine Treacy, and Gillian Marron. I would like to thank my fellow postgraduate students in the Department, particularly Arlene Crampsie, Dr. Barry O'Dwyer, Frank Ludlow, Julius Komolafe, and Niall McCrory for their support. For the rest too numerous to mention, you know who you are, thanks. I would especially like to thank Dr. Barry O'Dwyer and Catherine Buckley for proof reading the text with great attention to detail and for providing much appreciated constructive criticism. I would like to thank Dr. Robbie Meehan for help in the field, data, and his constructive comments during this research. I also would like to thank Dr. Catherine Coxon for her advice during the course of this work. I would like to thank Professor John Kelly of the Chemistry Department TCD for allowing me access to their lab equipment. I would like to thank Manel Leira for supplying lake data. I would like to thank the staff in the groundwater section of the Geological Survey of Ireland for lending me equipment and supplying data for this project, particularly Chris McDonnell, Clive Murray, Donal Daly, Caoimhe Hickey, Geoff Wright, Jane Coll, and Monica Lee. I would like to thank Aidan Murphy and Noreen Brennan of Met Eireann, Greg Duggan, Aphra Leavy, and Vincent Collins of Meath County Council, Anne Bonner of Westmeath County Council, Micheal MacCarthaigh of the Environmental Protection Agency, Peter Newport and Nuala Canny of the Office of Public Works, and last but by no means least Henning Moe of CDM consultants. I would like to thank Andy Day and Dr. Pablo Fernandez de Arroyabe Hernaez for their advice and help with the GIS aspects of this project. I would like to thank the landowners in Meath-Westmeath for their understanding and help, particularly Tom and Pauline from Collinstown, and Eithne Healy of Hounslow House. To those who helped with the fieldwork in rain hail

and snow – Dad, Mick, Andy, Barry, Frank, Gabes, Mark, Niall, and Pa, thanks. My mother proof read this thesis a number of times and I would like to thank her for her patience and unwavering attention to detail. I must thank my friends for putting up with me during the past number of years when they may have heard far more about groundwater – lake interactions in the Irish Midlands that they may have liked to. In particular (and in no particular order) Al, Andy, Brian, Colin, Ciaran, Frank, Gabes, Isabelle, Mark, Niall, and Pa. A special mention must go to Rachel Cullen, whose advice and friendship was much appreciated throughout this process. I would also like to thank Anne Hayes for her encouragement and advice during this process and beyond. My family have been tormented with this thesis for a long time, and without their unwavering support and understanding it would not have been completed. I would like to thank my brother Mick for helping with the fieldwork and not telling me to stop talking about lakes more often than he did. I would like to thank my parents Gerry and Eleanor, it is impossible to convey here how much I owe them, financially or otherwise. Finally, I must thank my dog Rudhan, who is the only dog I am aware of who has helped out with a PhD thesis.

Table of Contents

Chapter 1 Aims and Objectives page

1.1 Introduction 1

1.2 Thesis hypotheses 4

1.3 The study area 4

1.4 Methodological approach 4

1.5 Outline of the thesis 7

Chapter 2 Literature Review page

2.1 Introduction 9

2.2 Karst and the hydrogeology of karst aquifers 9

2.2.1 Inputs 9

2.2.1.1 Dispersed recharge 9

2.2.1.2 Concentrated recharge 10

2.2.2 Throughputs and storage 10

2.2.2.1 Matrix 10

2.2.2.2 Fractures 11

2.2.2.3 Channels / conduits 11

2.2.3 Outputs 13

2.2.3.1 Springs 13

2.3. Karst in low relief and lowland regions (excluding Ireland) 14

2.3.1 Global distribution of low relief and lowland karsts 14

2.3.2 Hydrological characteristics of low relief and lowland karsts 16

2.3.2.1 Recharge 16

2.3.2.2 Groundwater flow and storage characteristics 17

2.3.2.3 Discharge 18

2.3.2.4 Summary of differences between low relief / lowland karst and upland karst 18

2.3.3 Groundwater – surface water interactions in karst 19

2.4 Irish karst environments 21

2.4.1 Introduction 21

2.4.2 Upland karsts 22

2.4.3 Lowland karsts 25

2.4.4.Summary 35

2.5 Lakes as points of interconnection between the groundwater and Surface water systems and the classification of permanent lakes in lowland karst 36

2.5.1 Groundwater – lake interactions in non-karstic environments 36

2.5.2 Karstic groundwater – lake interactions 38

2.5.2.1 Groundwater interactions with temporary and semi-permanent lakes in karst 38

2.5.2.2 Groundwater interactions with permanent lakes in karst 43

2.5.3 Classification of non-karstic and karst lakes 46

2.5.4 Summary 47

Chapter 3 Introduction to the Meath-Westmeath Lakelands study area **page**

3.1 Introduction 49

3.2 Location 49

3.3 Climate 49

3.3.1 Introduction 49

3.3.2 Temperature 52

3.3.3 Precipitation 52

3.3.4 Effective precipitation 53

3.4 Geology, geomorphology, and soils 54

3.4.1 Solid geology 54

3.4.2 Quaternary geology 55

3.4.3 Topography and geomorphology 61

3.4.3.1 Hills 61

3.4.3.2 Glacial landforms 61

3.4.3.3 Karst landforms 62

3.4.4 Soils 63

3.5 Land use 63

3.6 Surface hydrology 64

3.6.1 Rivers 64

3.6.2 Lakes 69

3.7 Hydrogeology 69

3.7.1 Recharge 69

3.7.2 Water table configuration / flow systems 69

3.7.3 Discharge 72

Chapter 4 Methodology **page**

4.1 Introduction 75

4.2 The pilot study 75

4.2.1 Aims and objectives 76

4.2.2 Topographically defined surface catchment delineation 77

4.2.3 Desk study 78

4.2.4 Field-mapping 80

4.2.5 Identification of modified surface drainage networks and lake storage volumes 81

4.2.6 Surface water measurements 83

4.2.6.1 Introduction 83

4.2.6.2 Surface channel discharge 84

4.2.6.3 Conductivity measurements 85

4.2.6.4 Temperature measurements 85

4.2.6.5 pH measurements 86

4.3 Methods used in the detailed study 86

4.3.1 Introduction 86

4.3.2 Landform identification and measurement methods 87

4.3.2.1 Field-mapping 87

4.3.2.2 Landform measurement - GIS methods 87

4.3.3 Surface water data collection and analysis methods 87

4.3.3.1 Sampling network and period 87

4.3.3.2 Discharge, conductivity, temperature, and pH measurement 88

4.3.3.3 Lake surface level measurement 88

4.3.4 Groundwater data collection and analysis methods 89

4.3.4.1 Sampling network assembly 89

4.3.4.2 Measurement intervals, and procedure 92

4.3.4.3 Continuous groundwater level measurement 92

4.3.4.4 Construction of groundwater contour maps 93

4.3.4.5 Water tracing 93

4.3.5 Water budgets 98

4.3.6 Drainage density 99

Chapter 5 Pilot Study Results, Discussion, and Conclusions **page**

5.1 Introduction 101

5.2 Results 101

5.2.1 Delineated catchments 101

5.2.2 Desk study 101

5.2.2.1 Lough Owel 101

5.2.2.2 Lough Derravaragh 104

5.2.2.3 Lough Lene 106

5.2.2.4 Tobernacogany, Toberfaolaigh, and Fore Valley 108

5.2.2.5 White Lake 110

5.2.2.6 Ben Loughs 112

5.2.2.7 Lough Bane 114

5.2.3 Surface drainage network modification and lake surface area change 116

5.2.3.1 River Inny 116

5.2.3.2 River Deel 119

5.2.3.3 Lough Owel 120

5.2.3.4 Lough Derravaragh 121

5.2.3.5 Lough Lene 122

5.2.3.6 Tobernacogany, Toberfaolaigh, and Fore Valley 123

5.2.3.7 White Lake 125

5.2.3.8 Ben Loughs 126

5.2.3.9 Lough Bane 127

5.2.3.10 Summary of surface drainage network change and its impacts 128

5.2.4 Karstic landforms 128

5.2.5 Surface hydrological measurement results 129

5.2.5.1 Surface hydrology measurement point selection 129

5.2.5.2 Discharge 130

5.2.5.3 Conductivity 135

5.2.5.4 pH 136

5.2.5.5 Temperature 136

5.2.6 Summary of results 137

5.3 Discussion 140

5.4 Conclusions 142

Chapter 6 Detailed Study Results **page**

6.1 Introduction 145

6.2 Karstic landforms 145

6.3 Surface hydrology results 150

6.3.1 Flow measurements 150

6.3.1.1 Introduction 150

6.3.1.2 Spring flow measurements 151

6.3.1.3 Lake outflow discharges 153

6.3.1.4 Comparison of spring and lake outflows 157

6.3.2 Conductivity measurements 159

6.3.3 Temperature measurements 163

6.3.4 pH measurements 165

6.3.5 Comparison of lake water levels 166

6.3.6 Drainage density results 167

6.4 Water budgets 167

6.5 Groundwater hydrology results 170

6.5.1 Well standing water levels - point measurements 170

6.5.2 Well standing water levels - continuously recorded measurements 176

6.5.3 Water tracing 182

Chapter 7 Analysis and Interpretation **page**

7.1 Characteristics of the groundwater system in the study area 191

7.1.1 Potentiometric surface configuration 191

7.1.2 Comparison of the regional watershed and the potentiometric surface configuration 199

7.1.3 Recharge 201

7.1.4 Groundwater flow characteristics 202

7.1.5 Discharge 204

7.1.6 Spring zones of contribution 209

7.2 Groundwater – surface water interaction in the study area 211

7.3 Classification of the lakes in the study area based on their interactions with groundwater 216

Chapter 8 Discussion and Conclusions **page**

8.1 Introduction 221

8.2 Key research findings 221

8.2.1 The lowland karst of the Meath – Westmeath Lakeland region 221

8.2.2 Groundwater – surface water interactions 228

8.2.3 Interaction of the study lakes with groundwater and classification along a spectrum based on their interactions with the groundwater system 229

8.3 Successes and limitations of the study and recommendations for future work 234

8.3.1 Successes of the study 234

8.3.2 Limitations of the study 235

8.3.3 Recommendations for future work 236

References 239

Appendix A Secondary data sets 267

Appendix B Mapping and GIS techniques 275

Appendix C Groundwater sampling network 279

Appendix D Detailed study results data (spreadsheet) ..... (On CD)

Appendix E Plates 281

List of Abbreviations

cms ..... centimetres

°C ..... degrees Celsius

EPA ..... Environmental Protection Agency

ERBD ..... Eastern River Basin District

EU ..... European Union

g ..... grams

GSI ..... Geological Survey of Ireland

GWPS ..... Groundwater Protection Scheme

kg ..... kilograms

km ..... kilometres

km^2 ..... square kilometres

km/h ..... kilometres per hour

km/ km^2 ..... kilometres per square kilometre

l ..... litres

l/s ..... litres per second

l/s/ km^2 ..... litres per second per square kilometre

m ..... meters

m^2 ..... square meters

m^3 ..... cubic meters

maOD ..... meters above Ordnance Datum (Poolbeg)

m.a.s.l. ..... meters above sea level

m^3/d ..... cubic meters per day

m.b.g.l. ..... meters below ground level

m.b.s.l. ..... meters below sea level

m/h ..... meters per hour

m/km	meters per kilometre
ml	millilitres
mm	millimetres
mm/km	millimetres per kilometre
mm/year	millimetres per year
OPW	Office of Public Works
OSI	Ordnance Survey of Ireland
pH	pH units
ppb	parts per billion
RBD	River Basin District
RMS	root mean square error
s	seconds
SHRBD	Shannon River Basin District
USGS	United States Geological Survey
ZOC	Zone of Contribution
µg	micrograms
µS	microsiemens
µS/cm	microsiemens per centimetre
µg/litre	micrograms per litre

List of Equations

page

Equation 1 Lake volume estimation 81

Equation 2 Water tracing dye mass calculation 95

Equation 3 Water balance equation 98

Equation 4 Water balance equation including groundwater components 98

Equation 5 Water balance equation to calculate change in storage 99

Equation 6 Water balance equation to calculate net loss to / contribution from groundwater 99

Equation 7 Drainage density calculation 99

List of Figures

page

Figure 1.1 Topographic and hydrological map of the study area (study area boundary is the red line) (source data Ordnance Survey of Ireland (OSI) 2001) 6

Figure 2.1 Conceptual diagrams of aquifers with primary permeability (a), primary and secondary permeability (b), and triple permeability (c) (reproduced from Worthington 2003) 12

Figure 2.2 A Conceptual model for a conduit dominated karst aquifer. Transfer mechanisms numbered in diagram are: 1) overland flow; 2) throughflow; 3) subcutaneous flow; 4) shaft flow; 5) vadose flow; 6) vadose seepage (reproduced from Gunn 1986) 13

Figure 2.3 Karst spring types (reproduced from Ford and Williams 2007) 14

Figure 2.4 Surface and Groundwater catchment spatial misalignment in the Pennyroyal Karst, Kentucky, note the differences between karst groundwater catchments and topographically delineated surface drainage catchments (reproduced from Currens & Ray 1998) 20

Figure 2.5 Location of Carboniferous limestone bedrock in the Republic of Ireland (source data Geological Survey of Ireland (GSI); OSI 2001) 23

Figure 2.6 Surface drainage features, karst features, and bedrock geology in the Burren, County Clare (source data GSI; OSI 2001) 27

Figure 2.7 Surface drainage change in County Galway: A = Surface drainage in east County Galway prior to arterial drainage; B = Surface drainage in east County Galway after arterial drainage (reproduced from Coxon & Drew 1986) 29

Figure 2.8 Surface drainage features, karst features, and bedrock geology in northern County Roscommon (source data GSI; OSI 2001) 30

Figure 2.9 Surface drainage features, the absence of karst features, and bedrock geology west of Mullingar in County Westmeath (source data GSI; OSI 2001) 31

Figure 2.10 Surface water – groundwater interactions in a karst situated in County Clare. The dashed lines indicate proven underground flow routes that bypass the surface drainage network. The area within the rectangle on the left is expanded on the right hand side (reproduced from Coxon & Drew 2000) 34

Figure 2.11 Partially contributing catchment in County Galway (reproduced from Coxon & Drew 2000) 35

Figure 2.12 A: Groundwater discharging to a lake, B: Groundwater being recharged from a lake, C: A lake receiving groundwater discharge and recharging groundwater concurrently (reproduced from Winter et al. 1998) 38

Figure 2.13 Turlough surface area (Sheehy-Skeffington & Gormally 2007; Sheehy-Skeffington et al. 2006; Goodwillie et al. 1997) 42

Figure 2.14 Watertable mapping in an area of turloughs in County Mayo (reproduced from Coxon 1986) 43

Figure 2.15 Lake hydrographs typical of water bodies with differing degrees and types of connection with karst groundwater systems (1) Lakes with normal river inflows and outflows, (2) Lakes with surface inflow and outflow from shallow epikarst water, (3) Lakes fed by surface streams and drained by swallow holes, (4) Lakes fed and emptied by estavelles, (5) Lakes fed by springs and drained by swallow holes, (6) Lakes largely isolated from groundwater, (reproduced from Coxon & Drew 1998) 45

Figure 3.1 Location of lakes, surface drainage channels, topographic catchment boundaries, sub-catchment boundaries and catchment discharge points in the initial study area (basemap data OSI 2001) 50

Figure 3.2 Area inside dashed line in Figure 3.2 - Location of lakes, surface drainage channels, catchment boundaries, sub-

catchment boundaries and catchment discharge points in the initial study area (basemap data OSI 2001) 51

Figure 3.3 Mean monthly levels of precipitation recorded at Mullingar (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp) 53

Figure 3.4 Mean monthly level of effective precipitation recorded at Mullingar (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp) 54

Figure 3.5 Schematic lithostratigraphy of the study area (Morris et al. 2003) 56

Figure 3.6 Bedrock geology of the study area (source data GSI 2001, 2003) 57

Figure 3.7 3-D rendering of the study area land surface with main lakes showing hill orientation and crag and tail features (basemap data OSI 2001) 58

Figure 3.8 Topography and surface drainage of the study area (basemap data OSI 2001) 59

Figure 3.9 Location of hills (> 120 maOD) in relation to bedrock geology (basemap data GSI 2001, 2003; OSI 2001) 60

Figure 3.10 Quaternary geology and bedrock exposures (source data Teagasc 2004) 65

Figure 3.11 Quaternary landforms and orientation of hill ridges in the study area (basemap data Teagasc 2004; OSI 2001) 66

Figure 3.12 Crag and tail features (Oblique view looking north, lit from north east, OSI 10m interval contours overlain onto landsat image. Vertical exaggeration x 5) (basemap data OSI 2001; Landsat 1999) 67

Figure 3.13 Karstic Landforms identified in the study area prior to this study (source data GSI Karst Data Base; OSI 1837 6 inch map) 68

Figure 3.14 Bedrock Aquifer Map of the study area showing aquifer types and lakes (source data GSI National Draft Bedrock Aquifer Map). 70

Figure 3.15 McDonald's watertable map of the area around Fore (the blue lines indicate the approximate location of the lakes) (from McDonald 1988) 72
Figure 4.1 Project methodology outline 75
Figure 4.2 Timeline of project data collection (excluding dye tracing) 76
Figure 4.3 A simple water balance conceptual diagram 85
Figure 5.1 Topographically delineated catchments and surface outflow points (basemap data OSI 2001) 102
Figure 5.2 Lough Owel, the channel from the southeast of the lake is the Royal Canal feeder channel (basemap data OSI 2001) 103
Figure 5.3 Oblique view of Lough Owel catchment (basemap data OSI 2001; Landsat 1999) 104
Figure 5.4 Lough Derravaragh (basemap data OSI 2001) 105
Figure 5.5 Oblique view of Lough Derravaragh catchment (basemap data OSI 2001; Landsat 1999) 106
Figure 5.6 Lough Lene (basemap data OSI 2001) 107
Figure 5.7 Oblique view of Lough Lene catchment (basemap data OSI 2001; Landsat 1999) 108
Figure 5.8 Tobernacogany, Toberfaolaigh and Fore Valley (basemap data OSI 2001) 109
Figure 5.9 Oblique view of Tobernacogany, Toberfaolaigh and Fore Valley (basemap data OSI 2001; Landsat 1999) 110
Figure 5.10 White Lake (basemap data OSI 2001) 111
Figure 5.11 Oblique view of White Lake catchment (basemap data OSI 2001; Landsat, 1999) 112
Figure 5.12 The Ben Loughs (basemap data OSI 2001) 113
Figure 5.13 Oblique view of The Ben Loughs catchment (basemap data OSI 2001; Landsat, 1999) 114
Figure 5.14 Lough Bane (basemap data OSI 2001) 115
Figure 5.15 Oblique view of Lough Bane catchment (basemap data OSI 2001; Landsat, 1999) 116
Figure 5.16 Drainage Commissioners map showing Flood prone areas (in green-blue) along the course of the river Inny below Lough Derravaragh (note that there is no channel outflowing

from the southeast of Lough Owel to the river Brosna on this map) (reproduced from Bevan 1846) 117

Figure 5.17 Surface channel change on the River Glore 1837 - 2001 (basemap data OSI 1837 & 2001) 118

Figure 5.18 Lough Glore surface area change 1837 - 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 118

Figure 5.19 Lough Iron surface area change 1837 – 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 119

Figure 5.20 Drainage Commissioners map showing flood prone areas (light blue) along the course of the River Deel south of Lough Lene, red lines indicate new channel cuts (reproduced from Anon. 1846) 120

Figure 5.21 Lough Owel surface area change 1837 - 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 121

Figure 5.22 Lough Derravaragh surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 122

Figure 5.23 Lough Lene surface area change 1837 – 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 123

Figure 5.24 The surface drainage network in Fore Valley in 1837 (basemap data OSI 1837) 124

Figure 5.25 The surface drainage network in Fore Valley in 1908 (basemap data OSI 1908) 124

Figure 5.26 Change in surface area of White Lake (Summer 2006-Winter 2006) (surface channels omitted) (basemap data OSI 2001) 125

Figure 5.27 Ben Loughs surface area change 1837 - 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 126

Figure 5.28 Lough Bane surface area change 1837 - 2001 (surface channels omitted) (basemap data OSI 1837 & 2001) 127

Figure 5.29 Location of pilot study measuring points (basemap data OSI 2001) 131

Figure 5.30 Mean normalised surface outflows. Water abstractions for Loughs Owel, Lene and Bane have been included as surface outflow in calculating the data for this graph. Tobernacogany omitted for clarity due to high normalised

runoff of >560 l/s/km². Lough Derravaragh has been omitted from the total study area calculation 135
Figure 5.31 Map of the detailed study area (basemap data OSI 2001) 143
Figure 6.1 Altitude of bedrock in relation to White Lake standing water surface level (basemap data OSI 2001; GSI 2003) 148
Figure 6.2 Circular and sub-circular depressions, possibly dolines, located both in and in close proximity the basin of White Lake (Aerial Photograph OSI 2004) 149
Figure 6.3 Map of karstic surface landforms in the detailed study area (including landforms identified during the pilot study) (basemap data OSI 2001) 150
Figure 6.4 Locations of discharge measurement points employed in the detailed study (basemap data OSI 2001) 151
Figure 6.5 Flow measurement data for Tobernacogany and Toberfaolaigh springs. Flow measurement data recorded at Glore Bridge (the flows from Tobernacogany and Toberfaolaigh have been subtracted from this variable) and daily precipitation data recorded at the synoptic station at Mullingar are also shown 152
Figure 6.6 Recorded measurements of outflow rate and lake water levels for Lough Lene and daily precipitation data recorded at the synoptic station located at Mullingar. 154
Figure 6.7 Recorded measurements of outflow rate and lake water levels for the Ben Loughs and daily precipitation data recorded at the synoptic station located at Mullingar 155
Figure 6.8 Recorded measurements of outflow rate and lake water levels for Lough Bane and daily precipitation data recorded at the synoptic station located at Mullingar 157
Figure 6.9 Measured discharges of the study area catchment outflows and daily precipitation at Mullingar 158
Figure 6.10 Measured conductivity values (maximum, minimum and mean values at each site) 160
Figure 6.11 Conductivity values vs. time at each of the measuring sites 161
Figure 6.12 Measured discharge vs. conductivity data for Lough Lene (surface outflow) 161

Figure 6.13 Measured discharge vs. conductivity data for Tobernacogany.....162
Figure 6.14 Measured discharge vs. conductivity data for Toberfaolaigh.....162
Figure 6.15 Measured discharge vs. conductivity data for Fore Valley (Glore Bridge).....162
Figure 6.16 Measured discharge vs. conductivity data for the Ben Loughs.....163
Figure 6.17 Measured discharge vs. conductivity data for Lough Bane.....163
Figure 6.18 Water temperature values (maximum, minimum and mean values at each site).....163
Figure 6.19 Water temperatures at each site and mean air temperature of all measuring sites (for each sampling period).....165
Figure 6.20 Lake surface levels and precipitation amounts (lake levels have been normalised to 0 m for 1/3/07 to enable comparison).....166
Figure 6.21 Location of the groundwater sampling points in relation to the lakes (basemap data OSI 2001).....172
Figure 6.22 Comparison of normalised standing water level ranges in the study wells.....172
Figure 6.23 Fluctuations in groundwater standing water levels (groundwater sampling points that had a range of < 1.2 m have been omitted for clarity) and daily precipitation at Mullingar.....175
Figure 6.24 Standing water level fluctuations in SP 9 and daily precipitation data recorded at the synoptic station located at Mullingar.....177
Figure 6.25 Standing water level fluctuations in SP 19 and daily precipitation data recorded at the synoptic station located at Mullingar.....178
Figure 6.26 Comparison of surface water level of Lough Bane, the standing water level in SP 19 and daily precipitation data recorded at the synoptic station located Mullingar.....179
Figure 6.27 Standing water level fluctuations in SP 13 and daily precipitation data recorded at the synoptic station located at Mullingar.....180

Figure 6.28 Comparison of standing water level fluctuations in SPs 9, 19, and 13, and daily precipitation data recorded at the synoptic station located at Mullingar 181
Figure 6.29 Locations of dye injection and sampling points (basemap data OSI 2001) 183
Figure 6.30 Dye breakthrough and recovery curves (sodium fluorescein) calculated for Tobernacogany spring. Approximately 97% of the injected dye was recovered 186
Figure 6.31 Dye breakthrough and recovery curves (rhodamine WT) calculated for the Roaring Well spring. 21% of the injected dye was recovered 190
Figure 6.32 Proven underground flow routes in the detailed study area (basemap data OSI 2001). 190
Figure 7.1 Initial, uncorrected potentiometric surface interpolation (27/6/07) (basemap data OSI 2001) 192
Figure 7.2 Areas where the uncorrected potentiometric surface (26/1/07) stands higher than land surface, and the relationship of these areas to peat soils, springs (from 6 inch maps), and lakes (basemap data OSI 1837, 2001; Teagasc 2004) 193
Figure 7.3 Inferred configuration of the potentiometric surface in the study area on 26/1/2007 (basemap data OSI 2001) 196
Figure 7.4 Inferred configuration of the potentiometric surface in the study area on 27/6/2007 (basemap data OSI 2001) 196
Figure 7.5 Proven underground flow routes from water traces and inferred groundwater contours from well dipping (basemap data OSI 2001) 197
Figure 7.6 Groundwater Flowlines and topographically defined surface catchments (basemap data OSI 2001) 198
Figure 7.7 The SHRBD-ERBD (Shannon – Boyne) drainage divide and inferred groundwater flowlines in the detailed study area (SHRBD is located to the west of the black line and the ERBD to the east of the line) (basemap data OSI 2001) 200

Figure 7.8 Surface catchments together with groundwater flowlines derived from the uncorrected potentiometric surface (basemap data OSI 2001) 201

Figure 7.9 Underground flow routes and spring in relation to the location of peat and gley soils (basemap data OSI 2001; Teagasc 2004) 207

Figure 7.10 Conceptual diagram of spring location and unconsolidated deposits in the study area 207

Figure 7.11 Conceptual diagram of the Roaring Well spring 208

Figure 7.12 Areas potentially contributing recharge to Toberfaolaigh spring, based on water budget and potentiometric surface mapping results (basemap data OSI 2001) 209

Figure 7.13 Areas proven to contribute runoff to the River Glore from outside the SHRBD (basemap data OSI 2001) 212

Figure 7.14 Conceptual diagrams of groundwater interaction with White Lake: a) High water level where lake level is a surface expression of the potentiometric surface at all points in its basin; b) High water level where lake level is a surface expression of the potentiometric surface in only part of its basin; c) Low water level where lake level is surface expression of potentiometric surface in part of its basin; and d) Low water level where lake level is not a surface expression of potentiometric surface 212

Figure 7.15 Conceptual diagrams of four lake types: a) non-karstic permanent lake where interaction with groundwater is limited to the wave-washed littoral zone; b) a surface outflow is present but the lake also drains to the groundwater system via a swallow hole; c) no surface outflow is present and the lake drains exclusively to the groundwater system, but it is not a true turlough as it never empties to the necessary degree (i.e. small residual pools) during the summer months; d) this is a turlough type temporary lake that is flooded when the watertable is high and drains completely or to the point where only small residual pools remain during summer months 220

Figure 8.1 Lake classification system applied to turloughs and lakes underlain by limestone in Ireland. Lakes near the bottom right of the diagram are permanent lakes with little or no interaction with the groundwater systems and are considered non-karst. Conversely, lakes near the top left of the diagram are temporary lakes that have a high degree of interconnectivity with the groundwater system via point pathways (springs, swallow holes and estavelles). Turlough/lake positions within the diagram apart from: Lough Lene; Lough Bane; The Ben Loughs; and White Lake, are based on the following sources: Westmeath County Council (2005) (Lough Derravaragh and Lough Owel); Coxon (1986), Drew & Daly (1993) (Lough Mask, Lough Hackett, Lough Coy, Castle Lough, Coole Lough, Lough Aleenaun, Lough Mannagh, Caherglassaun Lough, and Rahasane Turlough); Drew & Burke (1996) (Lough Funshinagh, Lough Na Súil); Ragenborn-Tough et al. (1999) (Lough Bunny); D'Arcy 1992 (Lough Gealain); Fogg & Kelly (1995), Kelly et al. (2002) and Gunn (2003) (Fardrum Turlough) 233

List of Plates (Appendix E)

page

Plate 1. Lough Lene looking west, the swallow holes are located at the right of the photograph 281

Plate 2. Lough Lene looking east, note peninsula on left side of photograph, this area was a group of islands in 1837 but the lake level has dropped since and the islands have been joined to the mainland 281

Plate 3. Lough Lene looking west, the surface outflow runs along the stone wall 282

Plate 4. The surface outflow from Lough Lene at the point from where it leaves the lake 282

Plate 5. Lough Bane looking south, note the step sided hills 283

Plate 6. Steep sided hills and limestone scree south of Lough Bane 283

Plate 7. Lough Glore looking northwest 284

Plate 8. Lough Glass east looking south from the groundwater monitoring point SP19 284

Plate 9. Ben Lough south looking southwest 285

Plate 10. Small swallow hole on western shore of White Lake, this swallow hole was dry when traces were carried out (1m tape for scale) 285

Plate 11. Closer view of swallow hole at White Lake (1m tape for scale) 286

Plate 12. The lakebed of White Lake, note the change in slope along the centre of the photograph, this is the rim of a circular depression in the lakebed identified from aerial photographs 286

Plate 13. White Lake under high water conditions looking east 287

Plate 14. Small circular lake to the west of White Lake, possibly part of a compound doline feature 287

Plate 15. Glore Bridge surface stream measuring point (1.8m blue pole for scale) 288

Plate 16. Fore Valley looking north with the Ben of Fore at the distant left of the picture 288

Plate 17. Fore Valley looking south, Tobernacogany is located at the centre right of the photograph below the ruined church and yew tree 289
Plate 18. Toberfaolaigh spring under low flow conditions 289
Plate 19. The Upper River Glore downstream from Toberfaolaigh spring 290
Plate 20. Tobernacogany spring looking east 290
Plate 21. Tobernacogany spring looking west 291
Plate 22. The Roaring Well during dry conditions, when the spring is active water flows from the vertical area covered by leaf litter in the centre of this photograph and down over the rocks in the foreground 291
Plate 23. Karren on exposed bedrock (wristwatch for scale) 292
Plate 24. Mushroom stone at the southern shore of Lough Lene (wristwatch for scale) 292
Plate 25. Collapse feature near the western shore of White Lake (1 m tape for scale) 293
Plate 26. A small collapse feature at White Lake, this area is usually under water during high water conditions (1 m tape for scale) 293
Plate 27. Close up of small boulder of Derravaragh Chert, note solutional weathering at top of block and angular chert band at the bottom (tape measure for scale) 294
Plate 28. Bedrock cliff above Tobernacogany, note relatively close spacing and low angle of bedding planes 294
Plate 29. Chert bands in bedrock cliff above Tobernacogany 295
Plate 30. Swallow Hole 1 at Lough Lene, note steeply dipping angle of bedding planes (backpack for scale) 295
Plate 31. Marl and peat stratigraphy around the shore of White Lake 296
Plate 32. Marl and peat stratigraphy around the shore of White Lake 296
Plate 33. Marl exposure 3m above the present winter surface level of White Lake 296
Plate 34. Marl subsoil below fields in the White Lake catchment 297
Plate 35. Marl subsoil exposure at northern end of White Lake 297
Plate 36. Swallow Hole 1 at Lough Lene 298

Plate 37. Swallow Hole 2 at Lough Lene (blue pole centre right of picture is 1.8 m long) 298
Plate 38. Swallow Hole 3 at Lough Lene 299
Plate 39. The opening of Lough Lene Swallow Hole 3 during summer months when no water was flowing into the feature (note build up of leaf litter at base, wooden rod to left of opening is 0.3 m long) 299
Plate 40. Bedding planes in bedrock at Lough Lene Swallow Hole 1 (note darker less-soluble chert beds in bedrock exposure) 300
Plate 41. The largest swallow hole at White Lake under water (note timber chassis at bottom of photograph) 300
Plate 42. The largest White Lake swallow hole full of water (note timber chassis at bottom of photograph) 301
Plate 43. The White Lake swallow hole with rhodamine dye during tracing experiment (note timber chassis at bottom left of photograph) 301
Plate 44. White Lake looking south during early summer when lake level is receding (note position of rabbit burrow in plate 45 on right hand side) 302
Plate 45. White Lake looking north under high water conditions looking northwest (note marl and rabbit burrow from plate 44 at bottom of photograph) 302
Plate 46. White Lake looking north under high water conditions, the collapse features were observed in the area near the centre of this photograph when the lake level receded 303
Plate 47. Depression at the northern end of White Lake under high water conditions, the drainage channel at the bottom right of the photograph may be man made 303
Plate 48. Depressions linked by (possibly) man made channels at the southeastern end of White Lake under high water conditions 304
Plate 49. Steep sided limestone hills south of Lough Bane 304
Plate 50. Stepped profile on the northern shore of Lough Bane 305
Plate 51. Solutional features on dislodged limestone bedrock on shore of White Lake (measuring tape for scale) 305

Plate 52. Limestone cobbles and small boulders on the shore of Lough Lene following lowering of lake level, note white staining on rocks. This staining was not present before the lake level rose 306
Plate 53. Limestone block with solutionally enlarged joins on shore of Lough Lene (measuring tape for scale) 306
Plate 54. Well jointed bedrock exposure on western shore of White Lake, bedding planes dip 6° west-southwest (measuring tape for scale) 307
Plate 55. Well jointed bedrock exposure on western shore of White Lake, bedding planes dip 6° west-southwest (measuring tape for scale) 307
Plate 56. The largest swallow hole at white lake (orange measuring tape and fishing boat for scale) 308
Plate 57. Possible doline near White Lake 308
Plate 58. Automatic groundwater level recorder in place at SP19 north of Lough Bane, this hand dug well is 18.7m deep 309
Plate 59. View into monitoring well SP19, total depth 18.7m (shoe at right of picture for scale) 309
Plate 60. Glacial till subsoil exposure 500m east of Lough Bane (metal gate for scale) 310
Plate 61. Knockeyon Hill located at the eastern end of Lough Derravaragh, looking west 310
Plate 62. Fluorescein Dye in swallow hole 1 at Lough Lene, September 2009 (note 2l plastic bottle floating on water at top of picture for scale) 311
Plate 63. Rhodamine WT injection into swallow hole at White Lake, September 2009 311
Plate 64. The swallow hole at White Lake immediately after dye injection was carried out, September 2009 312
Plate 65. ISCO automatic water sampler deployed below the Roaring Well, September 2009 312
Plate 66. Channel constructed for discharge measurement down stream of the Roaring Well, September 2009 (blue pole on left is 1.8 m long) 313

Plate 67. Gas Activated Carbon (GAC) granules used in the fluocapteurs 313

Plate 68. Fluocapteur made with nylon fabric containing GAC granules 314

List of Tables

page

Table 3.1 Mean monthly precipitation and effective precipitation values recorded at Mullingar (Met Éireann 1961-1990) 54
Table 4.1 Example entry from the Landform Data Base 81
Table 5.1 Hydrological attributes of Lough Owel and its catchment 103
Table 5.2 Hydrological attributes of Lough Derravaragh and its catchment 105
Table 5.3 Hydrological attributes of Lough Lene and its catchment 107
Table 5.4 Hydrological attributes of Tobernacogany, Toberfaolaigh and Fore Valley 109
Table 5.5 Hydrological attributes of White Lake and its catchment 111
Table 5.6 Hydrological attributes of the Ben Loughs and their catchment 113
Table 5.7 Hydrological attributes of Lough Bane and its catchment 115
Table 5.8 Surface karstic landforms identified in the pilot study 129
Table 5.9 Surface hydrology measurement sites 130
Table 5.10 Discharge measurements and summary statistics for Lough Owel 130
Table 5.11 Discharge measurements and summary statistics for Lough Lene 132
Table 5.12 Discharge measurements and summary statistics for the Ben Loughs 132
Table 5.13 Discharge measurements and summary statistics for Lough Bane 133
Table 5.14 Discharge measurements and summary statistics for the measurement points in Fore Valley 133
Table 5.15 Mean normalised surface outflows (with lake abstractions included as surface outflow) 134
Table 5.16 Conductivity Measurements and summary statistics 136
Table 5.17 pH measurements 136
Table 5.18 Air and water temperature measurements 137
Table 6.1 Karst landforms identified during the detailed study 145
Table 6.2 Summary statistics calculated for measured levels of discharge for the spring and lake catchments included in the detailed study 151
Table 6.3 Summary statistics calculated for conductivity measurement data (based on 16 measurements at each site) 160
Table 6.4 Summary statistics calculated for temperature data (based on 16 measurements at each site) 164

Table 6.5 Summary statistics calculated for measured pH values.....165
Table 6.6 Water balance results for the study catchments (balance period 1/3/07 to 7/8/07).....169
Table 6.7 Water level fluctuations at the groundwater sampling points (minima, maxima, and ranges).....173
Table 6.8 Correlation coefficients and p values (blue text) matrix between each of the SP water levels (correlation coefficients with p values ≥ 0.05 highlighted in yellow).....174
Table 6.9 Details of dye injection points.....182
Table 6.10 Details of dye sampling points.....182
Table 6.11 Relationship of injection points to sampling points.....182
Table 6.12 Breakthrough curve statistics calculated for sodium fluorescein at Tobernacogany spring.....185
Table 6.13 Sampling results for Sodium Fluorescein at Tobernacogany spring.....186-187
Table 6.14 Sampling results for rhodamine WT at the Roaring Well spring.....188-189
Table 6.15 Breakthrough curve statistics calculated for rhodamine WT at the Roaring Well spring.....189
Table 7.1 Lake classification matrix based on degree of similarity/dissimilarity to turloughs or non-karstic permanent lakes.....219

1. Aims and Objectives

1.1 Introduction

The understanding and management of global water resources is becoming of utmost concern due to increasing, and for the most part anthropogenic, pressures on water resources (e.g. increasing human population levels, the effects of climate change, surface water and groundwater pollution). In response to these concerns, both national and international legislation has been enacted. For example, on an international level, and through legislative measures, such as the Water Framework Directive (2000/60/EC) and the Groundwater Directive (2006/118/EC) in particular, the European Union (EU) has attempted to prepare for future water resource needs and mitigate already existing and recognised detrimental effects. However, in order to implement such directives, the physical characteristics of, and inter-linkages between, surface water systems and groundwater systems must be better understood. Moreover, it is essential that this understanding encompasses ground and surface water systems located in a wide range of environments (e.g. mountainous areas, lowlands, estuaries, unconsolidated sand and gravel aquifers, and bedrock aquifers including non-karstic and karstic types).

Groundwater has been defined as "The water present beneath the earth's surface, stored in voids in bedrock and unconsolidated deposits" (Smart & Worthington 2004a, p394), and karst has been defined as *"terrain with distinctive hydrology and landforms arising from the combination of high rock solubility and well-developed solution channel porosity underground. Aqueous solution is the key process. It creates the secondary porosity and may be largely or wholly responsible for a given landform on the surface"* (Ford 2004, p473). Groundwater flow in non-karst aquifers is usually either via intergranular/matrix flow (primary permeability), or fissure/fracture flow (secondary permeability), whereas groundwater flow through a karst aquifer can be conceptualised in terms of a triple permeability model with primary permeability within the rock matrix, secondary permeability resulting from folding and fracturing of the rock, and tertiary permeability resulting from the dissolution of rock (Worthington 2003).

Interactions between groundwater and surface water are now increasingly appreciated, and in both non-karstic and karstic environments groundwater and

surface water systems are today conceptualised as two facets of a single entity (Winter et al. 1998; Sophocleous 2002). Groundwater – surface water interactions have different characteristics in karst areas compared to non-karst areas due to the fact that the surface drainage system, where one is present on a karst, is often closely intertwined with the karstic aquifer below (Coxon & Drew 1998). This close linkage between the groundwater and surface water systems in karst means that pollution of one element of the system commonly leads to pollution of the other and karst areas are particularly vulnerable to anthropogenic impacts (Parise et al. 2009). The often direct recharge pathways in karst aquifers and relatively high velocity of groundwater flow means there is commonly little attenuation of microbial pollutants compared to non-karst aquifers, and high concentrations of microbial pollutants have been measured at karst springs (Gunn et al. 1998).

Karsts can be classified according to their position in the landscape (e.g. high altitude 'alpine karsts', upland karsts, plateau karsts, and lowland karsts). Lowland karsts generally tend to have lower hydraulic gradients than upland karst and somewhat lower groundwater flow velocities than alpine or upland karsts but karsts in lowland areas can have differing hydrogeological characteristics. For example, lowland and/or low relief karst landscapes with differing hydrogeological characteristics have been described in Ireland (Drew 2008) and elsewhere, for example the Carso region in Italy (Ballarin et al. 2000), the Yucatán Peninsula in Mexico (Steinich & Marín 1996), parts of the Pennyroyal Plateau in Kentucky (Lloyde & Lyke 1995) and parts of northern Florida (Sacks et al. 1992).

Some lowland karst areas have in the past been regarded as non-karstic or relatively 'less karstic' than upland karsts or more accessible karst with less mantling deposits. However, these areas are increasingly being recognised as at least slightly karstic in their hydrogeological functioning and are currently receiving increasing attention (Bakalowicz 2005a).

The importance of groundwater in the hydrological functioning of lakes and, more specifically, the role of karstic groundwater in the hydrological functioning of lakes on karst are being increasingly appreciated by researchers (Winter et al. 1998). Lakes in karst terrains have not been satisfactorily classified according to their relationship with the groundwater system (Visser et al. 2006), and this problem is

particularly acute in the case of permanent lakes in karst (Ravbar & Šebela 2004). Furthermore, many intermittent lakes in karst areas around the world have also not yet been satisfactorily classified (Ravbar & Šebela 2004).

Karst is prevalent on the Island of Ireland and approximately 50% of the Republic of Ireland is underlain by limestone, all of which is probably karstified to some degree (Drew et al. 1996). Upland karst has been extensively documented in Counties Fermanagh, Clare, Sligo, and Leitrim, while lowland karsts exist in much of the lowland counties underlain by limestone geologies and include parts of Counties Tipperary (Jones & Gunn 1982, 1985; Gunn 1984), Kerry (Gunn 1982b, 1982c, 1984, 1985), Mayo (Coxon 1986, 1987a, 1987b; Drew & Daly 1993), Galway (Coxon 1986, 1987a, 1987b; Drew & Daly 1993), Roscommon (Hickey 2009), Westmeath (McDonald 1988), Cork (Wright 1979), and Kilkenny (Drew et al. 1996). In addition, parts of the lowland karst in Ireland are known to be hydrologically complex, where limestone that is karstified to an unknown degree is overlain by glacial or fluvio-glacial deposits (Drew 2008). Such areas may exhibit partially contributing catchments and/or areas where groundwater/surface water interactions occur, i.e. where groundwater and topographically defined catchments are not spatially coincident (Stanley & Jones 2000; Coxon & Drew 2000). Both temporary (turloughs) and permanent karst lakes are common in parts of Ireland (Coxon 1987a, 1987b). However, the distinction between turloughs and permanent lakes has not yet been clearly defined in some cases (Drew & Daly 1993; Ragenborn-Tough et al. 1999).

The focus of this thesis is on the lowland karst of the Meath – Westmeath Lakeland region, situated in the Midlands of Ireland, and as such, it primarily provides insights into the hydrology and geomorphology of the lowland karst and lakes situated in the study area. The results of this thesis can, however, be applied on a broader basis and have implications for, amongst others, the understanding of lowland karst generally in terms of further quantification of the hydrology of a previously largely unstudied (geographic) area, and our understanding of the extent and characteristics of lowland karst in Ireland as a whole, and particularly in the role and nature of permanent lakes in karst groundwater – surface water interactions in areas of lowland karst. The results of this thesis contribute to the understanding of both temporary and permanent lakes in karst in terms of how a continuum may exist between karst lake types, and how temporary and permanent karst lakes can be

classified along such a continuum. Such a classification would be beneficial for the implementation of the EU Water Framework Directive (2000/60/EC) and Groundwater Directive (2006/118/EC) in conceptualising potential pathways between, and assessing potential risks to the groundwater and surface water systems in lowland karst environments.

1.2 Thesis hypotheses

1) That the Meath-Westmeath study area can be classified as a lowland karst similar in its hydrological and hydrogeological characteristics to other lowland mantled karsts situated in Ireland, particularly in terms of geomorphology, recharge (inputs), flow characteristics (throughputs), and discharge (outputs).

2) That groundwater and surface water catchments in the study area are not spatially coincident, and that partially contributing catchments exist in the area where outflow destination changes under different hydraulic conditions.

3) That lakes in the study area can be classified along a continuum based on the characteristics of their interactions with the groundwater system.

1.3 The study area

The Meath-Westmeath Lakeland study area (Figure 1.1) is located in the Midlands of Ireland. The nearest large town is Mullingar in County Westmeath, located to the south of the study area. The initial area investigated during the pilot study comprised an area of 215km² straddling the watershed between the River Inny (River Shannon) and the River Deel (River Boyne). Several large lakes are located in the study area including Loughs Owel, Derravaragh, Lene, Bane, White Lake, and the Ben Loughs.

1.4 Methodological approach

Due to the large geographical extent of the Meath-Westmeath Lakeland region and also to the time constraints and limited resources made available for the current study, it was not feasible to examine, in detail, the entire region. As a result, to

address the research hypotheses, as previously stated, it was necessary to identify a representative area of the Meath-Westmeath Lakeland region for the purposes of a more detailed investigation. More specifically, the area selected was required to: be representative of the Meath – Westmeath Lakelands; have hydrological integrity; be spatially contiguous; and be suitable for the implementation of the chosen methods of the detailed study.

An initial pilot study was carried out during the spring and summer of 2005. Due to the size of the area, the pilot study did not incorporate a groundwater element and, as such, comprised of the following elements: desk study; field–mapping of karstic landforms; and measurement of surface hydrological parameters. This initial dataset was analysed on a catchment basis and the characteristics of these study catchments were then compared and contrasted. Importantly, each catchment was assessed in terms of their suitability for inclusion in the more detailed investigation; this assessment was based on the previously mentioned criteria. The detailed study was carried out from winter 2006 to autumn 2007 and water tracing experiments were carried out during September and October 2009.

The detailed study methods can be separated into two main elements – methods relating to surface hydrology and methods relating to groundwater hydrogeology. The results of the detailed study were then analysed to determine the prevalence, types, and locations of karstic landforms in the study area. The water budgets calculated for each of the study catchments were used to estimate the net contribution from, or loss to, groundwater for each of the topographically delineated study catchments. Potentiometric surface maps and groundwater flowlines were constructed from standing water level data. These maps were then compared to the water tracing results to determine whether the mapping and tracing results contradicted or supported each other. The potentiometric surface maps, tracing results, water budgets, and water chemistry results were then used to determine the nature of groundwater – surface water interactions in the study area, with specific reference to groundwater - lake interactions. A classification of the study lakes based on their interactions with the groundwater system and their similarity/dissimilarity to karstic turlough-type lakes or non-karstic lakes was then carried out.

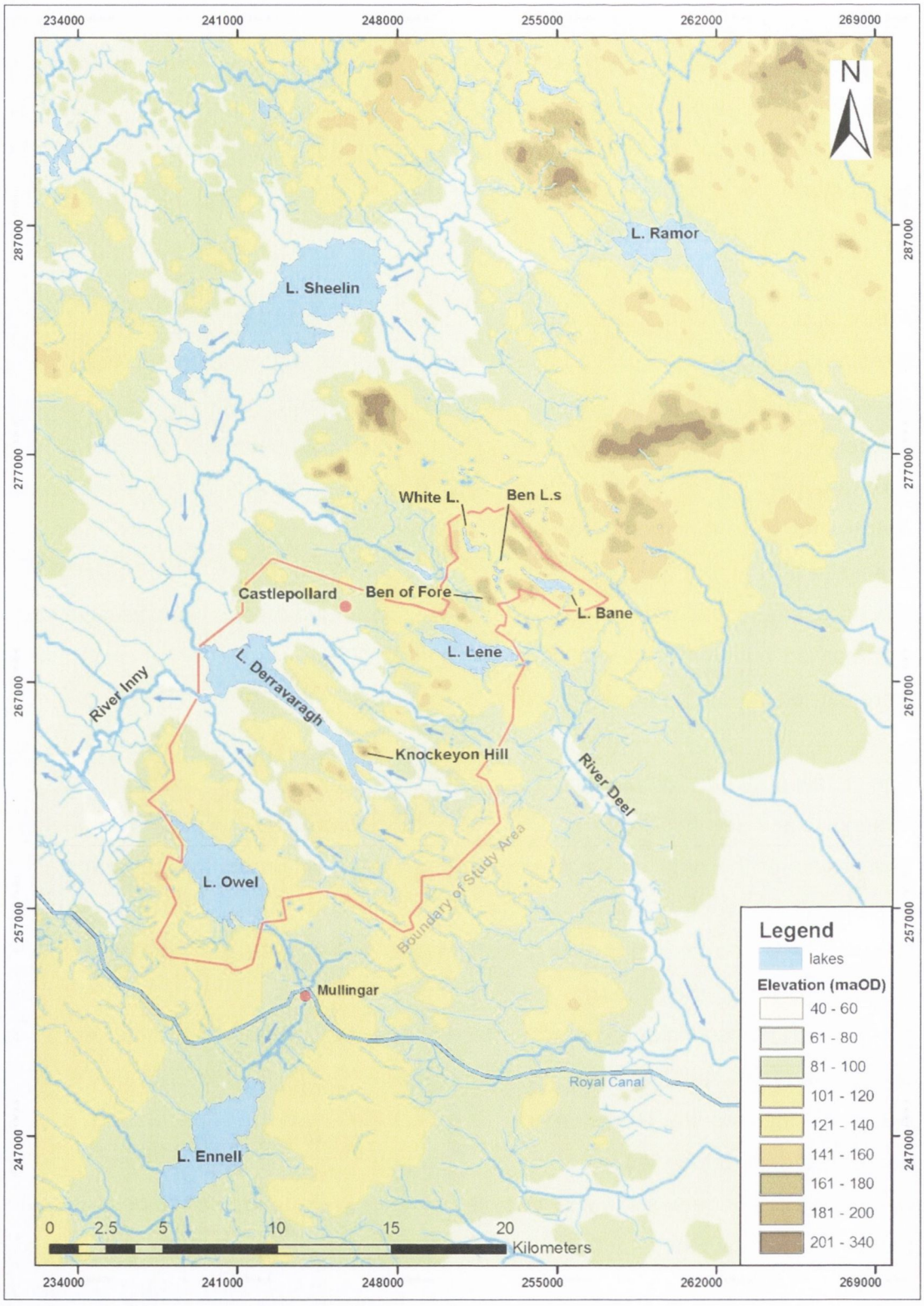

Figure 1.1 Topographic and hydrological map of the study area (study area boundary is the red line) (source data Ordnance Survey of Ireland (OSI) 2001).

1.5 Outline of the thesis

Chapter 1 provides an introduction by contextualising the research, stating the research questions and outlining the methods utilised and the structure of the thesis.

Chapter 2 provides an overview of: current and past research relating to lowland karst, gaps in our understanding of lowland karst; the characteristics of groundwater surface water interactions in lowland karst; and lake - groundwater interactions and lake classification in karst.

Chapter 3 introduces the Meath-Westmeath Lakeland study area. In doing so, secondary information regarding the climate, geology, geomorphology, soils, land use, surface hydrology, and groundwater hydrology of the area is presented.

Chapter 4 details the methodology adopted in the current research. This chapter is divided into two sections. The first section describes the methods used for the pilot study, while the second section describes the methods employed in the detailed study.
Chapter 5 presents the results of the pilot study, which are discussed in terms of the aims of the pilot study. Finally, the area selected for investigation in the detailed study is described.

Chapter 6 contains the results of the detailed study, which are presented in the following order: karstic landforms; surface hydrology measurements; water budgets; drainage density results; and groundwater hydrology results.

Chapter 7 discusses the results of the research. The characteristics of the groundwater system in the area are analysed, including a discussion on the level of karstification evident in the study area and how anthropogenic modifications (e.g. drainage works and water extractions) may have affected it to date. The nature of the groundwater system is then analysed in terms of recharge, storage, flow characteristics and discharge. Groundwater – surface water interactions are then discussed. This section includes a discussion regarding spatial and temporal variations in groundwater – surface water interaction and also interaction between groundwater and lakes. In the final section of the chapter, a classification of the lakes in the study area is detailed. This classification is based upon results

presented in this thesis but can be applied to other sites, situated both nationally and internationally, on a more general basis.

Chapter 8 presents the conclusions of the thesis, their wider implications, and recommendations for further work. The results of the thesis are contextualised in terms of how they relate to present theories regarding lowland karst and groundwater – surface water interactions in Ireland and further afield, and the classification of permanent lakes on karst.

1. Aims and Objectives

1.1 Introduction

The understanding and management of global water resources is becoming of utmost concern due to increasing, and for the most part anthropogenic, pressures on water resources (e.g. increasing human population levels, the effects of climate change, surface water and groundwater pollution). In response to these concerns, both national and international legislation has been enacted. For example, on an international level, and through legislative measures, such as the Water Framework Directive (2000/60/EC) and the Groundwater Directive (2006/118/EC) in particular, the European Union (EU) has attempted to prepare for future water resource needs and mitigate already existing and recognised detrimental effects. However, in order to implement such directives, the physical characteristics of, and inter-linkages between, surface water systems and groundwater systems must be better understood. Moreover, it is essential that this understanding encompasses ground and surface water systems located in a wide range of environments (e.g. mountainous areas, lowlands, estuaries, unconsolidated sand and gravel aquifers, and bedrock aquifers including non-karstic and karstic types).

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Karsts can be classified according to their position in the landscape (e.g. high altitude 'alpine karsts', upland karsts, plateau karsts, and lowland karsts). Lowland karsts generally tend to have lower hydraulic gradients than upland karst and somewhat lower groundwater flow velocities than alpine or upland karsts but karsts in lowland areas can have differing hydrogeological characteristics. For example, lowland and/or low relief karst landscapes with differing hydrogeological characteristics have been described in Ireland (Drew 2008) and elsewhere, for example the Carso region in Italy (Ballarin et al. 2000), the Yucatán Peninsula in Mexico (Steinich & Marín 1996), parts of the Pennyroyal Plateau in Kentucky (Lloyde & Lyke 1995) and parts of northern Florida (Sacks et al. 1992).

Some lowland karst areas have in the past been regarded as non-karstic or relatively 'less karstic' than upland karsts or more accessible karst with less mantling deposits. However, these areas are increasingly being recognised as at least slightly karstic in their hydrogeological functioning and are currently receiving increasing attention (Bakalowicz 2005a).

The importance of groundwater in the hydrological functioning of lakes and, more specifically, the role of karstic groundwater in the hydrological functioning of lakes on karst are being increasingly appreciated by researchers (Winter et al. 1998). Lakes in karst terrains have not been satisfactorily classified according to their relationship with the groundwater system (Visser et al. 2006), and this problem is

particularly acute in the case of permanent lakes in karst (Ravbar & Šebela 2004). Furthermore, many intermittent lakes in karst areas around the world have also not yet been satisfactorily classified (Ravbar & Šebela 2004).

Karst is prevalent on the Island of Ireland and approximately 50% of the Republic of Ireland is underlain by limestone, all of which is probably karstified to some degree (Drew et al. 1996). Upland karst has been extensively documented in Counties Fermanagh, Clare, Sligo, and Leitrim, while lowland karsts exist in much of the lowland counties underlain by limestone geologies and include parts of Counties Tipperary (Jones & Gunn 1982, 1985; Gunn 1984), Kerry (Gunn 1982b, 1982c, 1984, 1985), Mayo (Coxon 1986, 1987a, 1987b; Drew & Daly 1993), Galway (Coxon 1986, 1987a, 1987b; Drew & Daly 1993), Roscommon (Hickey 2009), Westmeath (McDonald 1988), Cork (Wright 1979), and Kilkenny (Drew et al. 1996). In addition, parts of the lowland karst in Ireland are known to be hydrologically complex, where limestone that is karstified to an unknown degree is overlain by glacial or fluvio-glacial deposits (Drew 2008). Such areas may exhibit partially contributing catchments and/or areas where groundwater/surface water interactions occur, i.e. where groundwater and topographically defined catchments are not spatially coincident (Stanley & Jones 2000; Coxon & Drew 2000). Both temporary (turloughs) and permanent karst lakes are common in parts of Ireland (Coxon 1987a, 1987b). However, the distinction between turloughs and permanent lakes has not yet been clearly defined in some cases (Drew & Daly 1993; Ragenborn-Tough et al. 1999).

The focus of this thesis is on the lowland karst of the Meath – Westmeath Lakeland region, situated in the Midlands of Ireland, and as such, it primarily provides insights into the hydrology and geomorphology of the lowland karst and lakes situated in the study area. The results of this thesis can, however, be applied on a broader basis and have implications for, amongst others, the understanding of lowland karst generally in terms of further quantification of the hydrology of a previously largely unstudied (geographic) area, and our understanding of the extent and characteristics of lowland karst in Ireland as a whole, and particularly in the role and nature of permanent lakes in karst groundwater – surface water interactions in areas of lowland karst. The results of this thesis contribute to the understanding of both temporary and permanent lakes in karst in terms of how a continuum may exist between karst lake types, and how temporary and permanent karst lakes can be

classified along such a continuum. Such a classification would be beneficial for the implementation of the EU Water Framework Directive (2000/60/EC) and Groundwater Directive (2006/118/EC) in conceptualising potential pathways between, and assessing potential risks to the groundwater and surface water systems in lowland karst environments.

1.2 Thesis hypotheses

1) That the Meath-Westmeath study area can be classified as a lowland karst similar in its hydrological and hydrogeological characteristics to other lowland mantled karsts situated in Ireland, particularly in terms of geomorphology, recharge (inputs), flow characteristics (throughputs), and discharge (outputs).

2) That groundwater and surface water catchments in the study area are not spatially coincident, and that partially contributing catchments exist in the area where outflow destination changes under different hydraulic conditions.

3) That lakes in the study area can be classified along a continuum based on the characteristics of their interactions with the groundwater system.

1.3 The study area

The Meath-Westmeath Lakeland study area (Figure 1.1) is located in the Midlands of Ireland. The nearest large town is Mullingar in County Westmeath, located to the south of the study area. The initial area investigated during the pilot study comprised an area of 215km^2 straddling the watershed between the River Inny (River Shannon) and the River Deel (River Boyne). Several large lakes are located in the study area including Loughs Owel, Derravaragh, Lene, Bane, White Lake, and the Ben Loughs.

1.4 Methodological approach

Due to the large geographical extent of the Meath-Westmeath Lakeland region and also to the time constraints and limited resources made available for the current study, it was not feasible to examine, in detail, the entire region. As a result, to

address the research hypotheses, as previously stated, it was necessary to identify a representative area of the Meath-Westmeath Lakeland region for the purposes of a more detailed investigation. More specifically, the area selected was required to: be representative of the Meath – Westmeath Lakelands; have hydrological integrity; be spatially contiguous; and be suitable for the implementation of the chosen methods of the detailed study.

An initial pilot study was carried out during the spring and summer of 2005. Due to the size of the area, the pilot study did not incorporate a groundwater element and, as such, comprised of the following elements: desk study; field–mapping of karstic landforms; and measurement of surface hydrological parameters. This initial dataset was analysed on a catchment basis and the characteristics of these study catchments were then compared and contrasted. Importantly, each catchment was assessed in terms of their suitability for inclusion in the more detailed investigation; this assessment was based on the previously mentioned criteria. The detailed study was carried out from winter 2006 to autumn 2007 and water tracing experiments were carried out during September and October 2009.

The detailed study methods can be separated into two main elements – methods relating to surface hydrology and methods relating to groundwater hydrogeology. The results of the detailed study were then analysed to determine the prevalence, types, and locations of karstic landforms in the study area. The water budgets calculated for each of the study catchments were used to estimate the net contribution from, or loss to, groundwater for each of the topographically delineated study catchments. Potentiometric surface maps and groundwater flowlines were constructed from standing water level data. These maps were then compared to the water tracing results to determine whether the mapping and tracing results contradicted or supported each other. The potentiometric surface maps, tracing results, water budgets, and water chemistry results were then used to determine the nature of groundwater – surface water interactions in the study area, with specific reference to groundwater - lake interactions. A classification of the study lakes based on their interactions with the groundwater system and their similarity/dissimilarity to karstic turlough-type lakes or non-karstic lakes was then carried out.

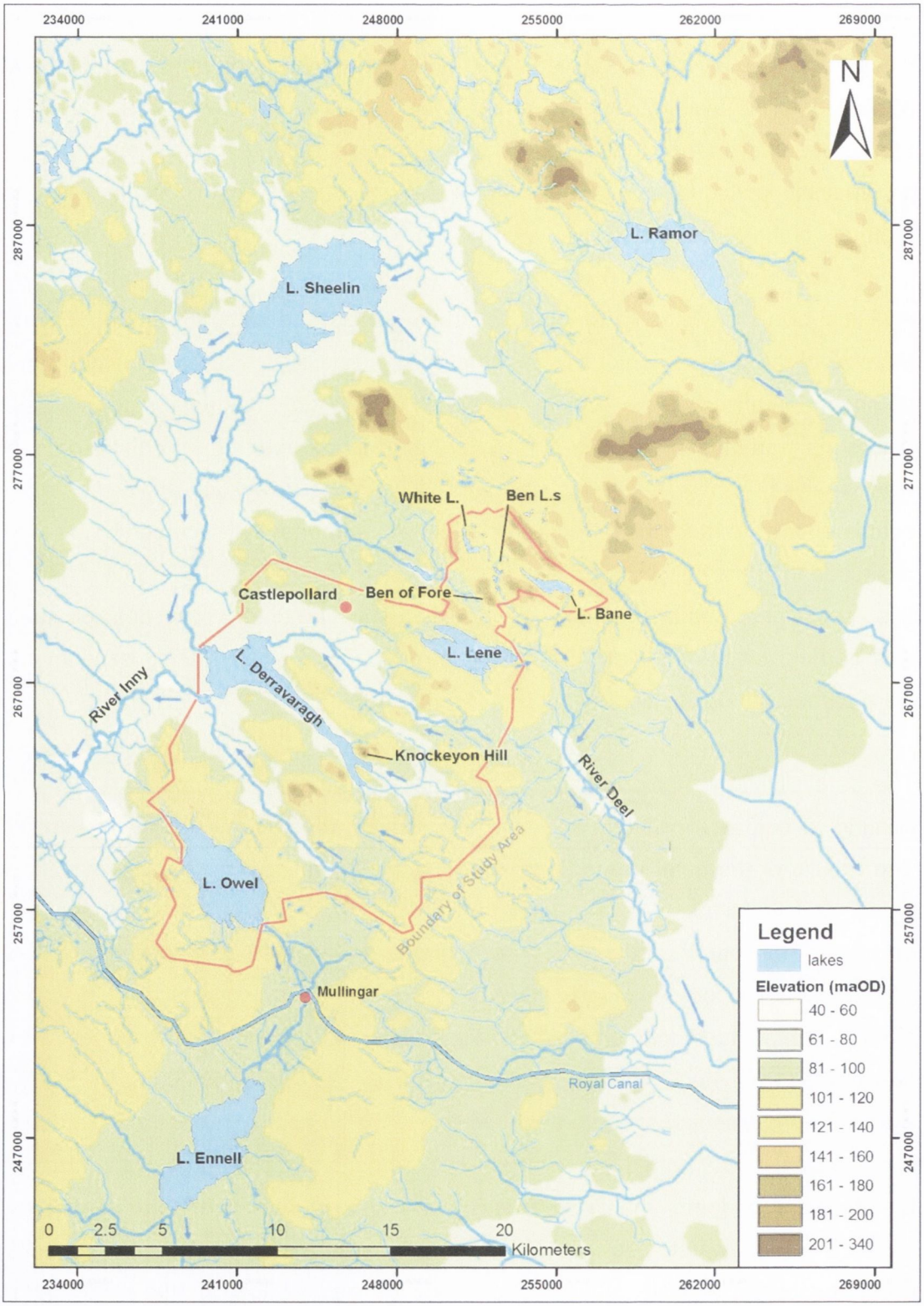

Figure 1.1 Topographic and hydrological map of the study area (study area boundary is the red line) (source data Ordnance Survey of Ireland (OSI) 2001).

1.5 Outline of the thesis

Chapter 1 provides an introduction by contextualising the research, stating the research questions and outlining the methods utilised and the structure of the thesis.

Chapter 2 provides an overview of: current and past research relating to lowland karst, gaps in our understanding of lowland karst; the characteristics of groundwater surface water interactions in lowland karst; and lake - groundwater interactions and lake classification in karst.

Chapter 3 introduces the Meath-Westmeath Lakeland study area. In doing so, secondary information regarding the climate, geology, geomorphology, soils, land use, surface hydrology, and groundwater hydrology of the area is presented.

Chapter 4 details the methodology adopted in the current research. This chapter is divided into two sections. The first section describes the methods used for the pilot study, while the second section describes the methods employed in the detailed study.
Chapter 5 presents the results of the pilot study, which are discussed in terms of the aims of the pilot study. Finally, the area selected for investigation in the detailed study is described.

Chapter 6 contains the results of the detailed study, which are presented in the following order: karstic landforms; surface hydrology measurements; water budgets; drainage density results; and groundwater hydrology results.

Chapter 7 discusses the results of the research. The characteristics of the groundwater system in the area are analysed, including a discussion on the level of karstification evident in the study area and how anthropogenic modifications (e.g. drainage works and water extractions) may have affected it to date. The nature of the groundwater system is then analysed in terms of recharge, storage, flow characteristics and discharge. Groundwater – surface water interactions are then discussed. This section includes a discussion regarding spatial and temporal variations in groundwater – surface water interaction and also interaction between groundwater and lakes. In the final section of the chapter, a classification of the lakes in the study area is detailed. This classification is based upon results

presented in this thesis but can be applied to other sites, situated both nationally and internationally, on a more general basis.

Chapter 8 presents the conclusions of the thesis, their wider implications, and recommendations for further work. The results of the thesis are contextualised in terms of how they relate to present theories regarding lowland karst and groundwater – surface water interactions in Ireland and further afield, and the classification of permanent lakes on karst.

2. Literature Review

2.1 Introduction

This chapter contains sections relating to: the hydrogeology of karst aquifers; karst in regions of low relief (excluding Ireland); Irish karst environments; and Lakes as points of interconnection between the groundwater and surface water systems and the classification of permanent lakes in karst.

2.2 Karst and the hydrogeology of karst aquifers

Karst has been defined as: *terrain with distinctive hydrology and landforms arising from the combination of high rock solubility and well-developed solution channel porosity underground. Aqueous solution is the key process. It creates the secondary porosity and may be largely or wholly responsible for a given landform on the surface* (Ford 2004, p473). As in classical Darcian hydrogeology, karst hydrogeology can be described in terms of recharge (inputs), flow and storage characteristics (throughputs), and discharge (outputs). The general principles of karst hydrogeology are outlined below.

2.2.1 Inputs

2.2.1.1 Dispersed recharge

Dispersed recharge to karst aquifers is generally of autogenic origin, i.e. derived from precipitation falling directly onto the karst or directly onto overlying deposits, as opposed to allogenic recharge which refers to recharge running off or through neighbouring non-karstic rocks (Worthington and Smart 2004). Autogenic runoff tends to be spatially uniform in its distribution in exposed karsts where precipitation percolates through innumerable pores and fissures across a karst bedrock outcrop (White 2002). Karsts which are covered with overlying deposits such as glacial tills or solid rocks are known as mantled karsts (Quinlan 1978). Where overlying deposits are unconsolidated (such as glacial tills or deep soils) recharge penetrating the karst aquifer through such soils is considered to be autogenic. However, if the mantling deposits comprise of non-karstic permeable solid geology (caprock), recharge penetrating through such rock is classified as diffuse allogenic recharge. In

either case the overlying deposits can act as recharge regulators by buffering recharge to the karst aquifer (Worthington and Smart 2004).

2.2.1.2 Concentrated recharge

Where surface drainage networks exist on or adjacent to karst it is common for streams to sink underground via swallow holes and become point sources of recharge to the aquifer. This commonly occurs either in close proximity to where an allogenic stream crosses a geologic contact onto karstified bedrock or where deposits over which an autogenic stream flows become thinner or change to more permeable material. The capacity of a swallow hole to accept recharge governs the rate at which recharge can occur and if the amount of water flowing into a swallow hole exceeds this capacity then water will back up and surface flooding may occur (Currens and Graham 1993). In some areas the altitude of the unconfined watertable rises above the level of a swallow hole entrance and the swallow hole or sinking stream will experience reverse flow – becoming a spring and discharging water from the aquifer, this type of recharge/discharge feature is known as an estavelle (Bonacci 2004a) and they are commonly found in Irish turloughs (Coxon 1987a) and in parts of Kentucky (Quinlan 1983). Autogenic concentrated recharge can occur via dolines (enclosed depressions) in a karst aquifer or overlying deposits. Such dolines are commonly found in doline fields in well developed karsts and have the effect of concentrating recharge before it reaches the saturated zone (Williams 1985). Dolines formed primarily by the solution of bedrock (solution dolines) can be conceptualised as being similar in function to drainage basins in non-karstic lithologies as precipitation is channelled towards an outlet at the lowest point in the doline (analogous to the catchment outflow point) before entering a karst aquifer (Gunn 1981). Concentration of recharge may also occur in the epikarst layer (Klimchouk 1995).

2.2.2 Throughputs and storage

2.2.2.1 Matrix

The karst aquifer can be conceptualised in terms of a triple porosity (or triple permeability) model with primary porosity within the rock matrix, secondary porosity resulting from folding and fracturing of the rock, and tertiary porosity resulting from the dissolution of rock (Figure 2.1) (Worthington 2003). In relatively young limestones primary porosity may be relatively high compared to older rocks, while in

older limestones primary porosity may be much lower (Worthington and Smart 2004). In some cases where primary porosity is high, permeability may be low due to the poor interconnectivity between the intergranular pore spaces (Worthington 2003). In rock with reasonable levels of primary porosity and permeability, the greatest proportion of groundwater held in storage in the aquifer may be in the intergranular matrix of the bedrock while the greatest proportion of groundwater flow in the aquifer commonly occurs in fractures or conduits where present (Worthington 2003).

2.2.2.2 Fractures

Secondary porosity in karst aquifers is provided by fractures in the bedrock such as bedding planes and joints. These fractures are typically 0.01 - 0.1 mm wide and collectively may have a much lower porosity than the matrix (especially in younger rocks) but often have much higher permeability values than the matrix due to the interconnectivity between the fractures (Worthington and Smart 2004). Moreover, the predominant alignment of fractures in an aquifer means that permeability will be enhanced in particular directions, i.e. anisotropy. This is exemplified in aquifers with horizontally bedded strata where vertical permeability can be 10 or 100 times less than horizontal permeability (Worthington 2003).

2.2.2.3 Channels / conduits

Tertiary porosity in karst aquifers is provided by solutionally enlarged channels and conduits (Worthington and Smart 2004). Conduit networks can be conceptualised as pipe networks that are analogous to channelised surface drainage systems (Field 2002). A hierarchy of solutionally enlarged channel sizes can be discerned in karst aquifers where a large number of small channels (up to 1 mm in width) feed into a smaller number of progressively larger channels, with the largest conduits located in the down gradient parts of the aquifer close to springs (Worthington and Smart 2004). Solutionally enlarged channels may account for the majority of groundwater flow in a karst aquifer, the tertiary porosity element commonly accounts for a relatively small proportion of the storage in the aquifer – precisely due to the high groundwater flow rates in conduits (Worthington 2003). The uppermost few meters of a karstic aquifer may be characterised by extreme fracturing and enhanced solution creating a complex zone of higher permeability and storage relative to deeper parts of the aquifer. This zone is known as the epikarst or subcutaneous

zone (Bakalowicz 2004). It has been estimated that 80% of solution occurs in the top 10m of a karst aquifer with a corresponding increase in the porosity and permeability of this top layer of an aquifer, in effect this means that transmissivity or storage in an epikarst (where present) may be greatly enhanced relative to the rest of the aquifer (Jones et al. 2004; Klimchouk 2004). Moreover, some studies suggest that storage in the epikarst (where present) can be more significant than storage in the phreatic zone (Perrin et al. 2003).

Rapid groundwater flow velocities are a characteristic of karstic drainage. Flow velocities can be rapid relative to porous media aquifers and flow rates of up to several hundred m/hour are not exceptional (Bakalowicz 2005a). Rapid flow rates are evident in conduit flow aquifers where turbulent flow conditions dominate. Fracture/conduit dominated karst aquifers are heterogeneous in nature (Figure 2.2), i.e. there will be a difference in hydraulic conductivity between a conduit and the bedrock beside it, as has been shown by Stewart and Wood (1984) in the carbonate Floridan aquifer. As stated in section 2.2.2.2, due to the fact that flow in many karst aquifers is dominantly through fissures or solutionally enlarged conduits, hydraulic conductivity varies with direction (i.e. it is higher in the direction parallel to the main fracture lines in the bedrock) and this is known as anisotropy. In contrast, isotropy, refers to a situation where hydraulic conductivity is equal in all directions.

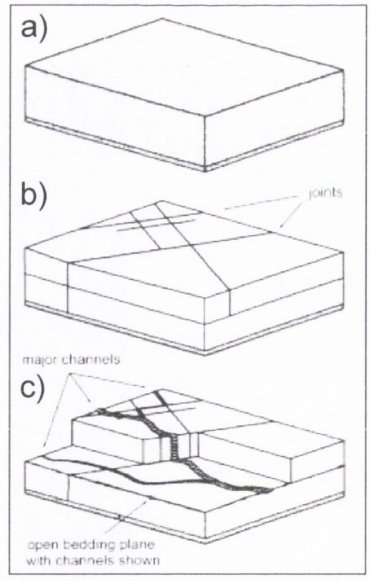

Figure 2.1 Conceptual diagrams of aquifers with primary permeability (a), primary and secondary permeability (b), and triple permeability (c) (reproduced from Worthington 2003).

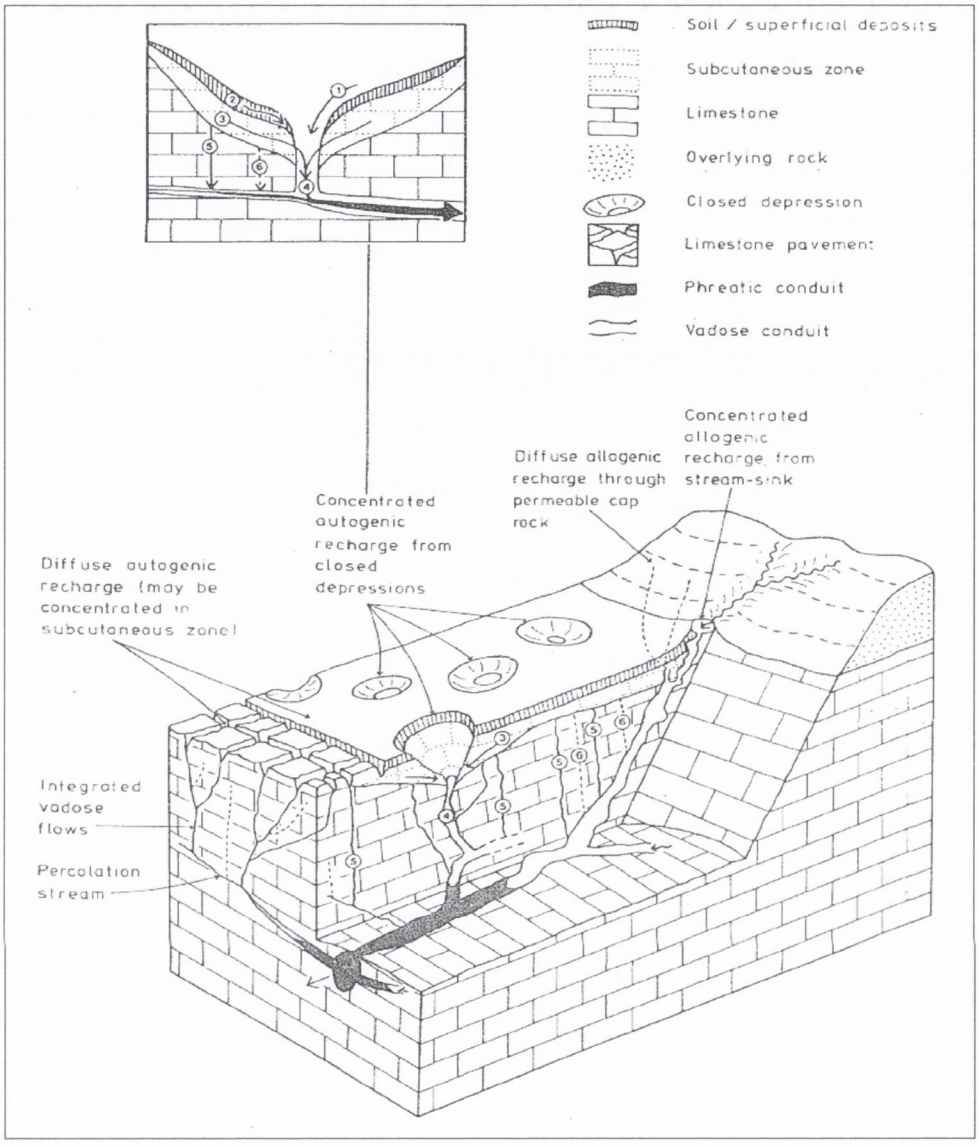

Figure 2.2 A Conceptual model for a conduit dominated karst aquifer. Transfer mechanisms numbered in diagram are: 1) overland flow; 2) throughflow; 3) subcutaneous flow; 4) shaft flow; 5) vadose flow; 6) vadose seepage (reproduced from Gunn 1986).

2.2.3 Outputs

2.2.3.1 Springs

Discharge from karst aquifers is commonly via springs. Springs are outlets of water that was recharged to the aquifer at a higher altitude and has been conveyed through the aquifer to the point of discharge. Karst spring discharge can range over several orders of magnitude from seepage flows of a < 0.1 l/s to large springs of > 100 m^3/s and flow can be steady, seasonal, periodic, intermittent, and in some cases (estavelles) reversed (Smart and Worthington 2004b). There are a number of

karst spring types (Figure 2.3) and these include free draining springs (Bögli 1980), dammed springs (Smart 1983), or confined springs (Blavoux et al. 1992). The discharge capacity of a spring (amongst other elements such as precipitation rates) is a controlling factor in the determination of the elevation of the watertable and thus the amount of water stored in the aquifer (Bonacci 1987, 2001; Ford and Williams 2007).

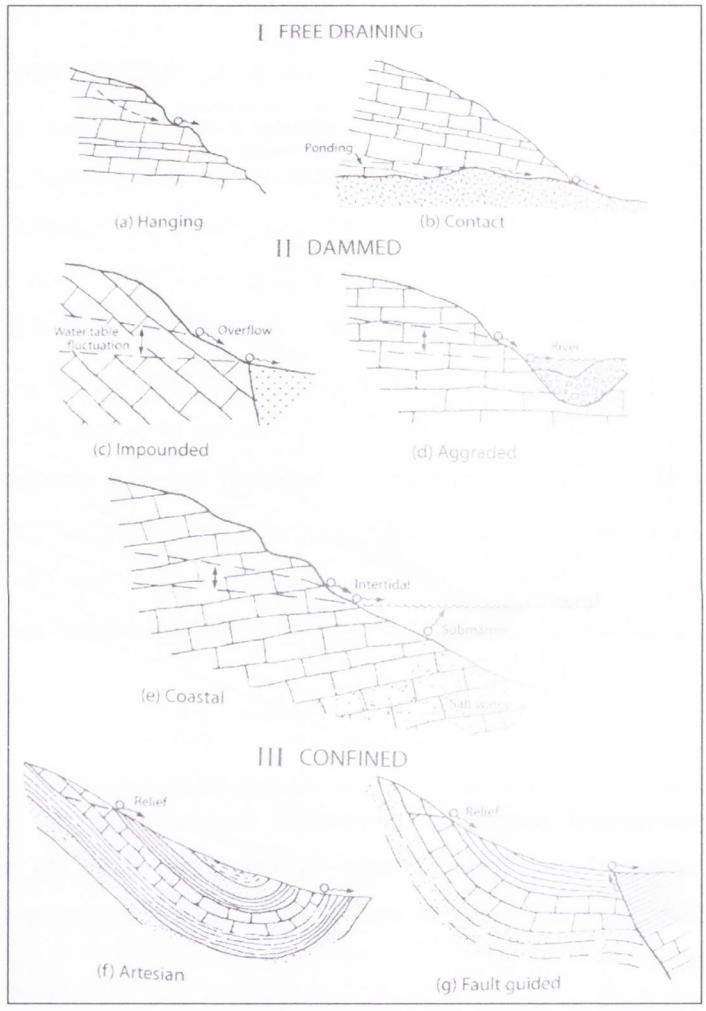

Figure 2.3 Karst spring types (reproduced from Ford and Williams 2007).

2.3 Karst in low relief and lowland regions (excluding Ireland)

2.3.1 Global distribution of low relief and lowland karsts

A distinction has been made between karsts depending on their position in the landscape. Karsts situated in high altitude or mountainous regions are commonly referred to as alpine or upland karsts (Field 2002) while karsts situated on low relief

platforms which are raised relative to the surrounding landscape have been referred to as plateau karsts, such as the Barkly Tableland in Queensland Australia (Williams 1978). Karsts located in low lying regions (<150 m.a.s.l.) have been classified as lowland karsts, such as the karst areas of central Ireland by Drew (2008). Where such lowland karsts are located in regions of low relief they have been referred to as low relief lowland karsts, for example the Maya lowland karst in Mexico (Beach et al. 2008). Lowland karst can contain residual hills which provide localised topographic highs (> 150m.a.s.l.) within the predominantly lowland landscape (Williams 1987). In areas entirely underlain by carbonate rocks such isolated hills can be formed on either a planed carbonate surface veneered by unconsolidated deposits or on a karst topography buried beneath a mantle of unconsolidated deposits which masks the topographic variation of the karst surface (Williams 1987). The relative height and number of such hills can be used to make a distinction between lowland karsts of low, moderate or high relief.

Historically, research has focussed upon upland karsts due to their striking physical features and, due to their often large expanses of exposed bedrock, the relative ease with which they can be studied (e.g. Miall 1870). Some low relief or lowland karsts are less karstified than others and historically such areas have received little attention. However, these areas are now receiving attention, for example the chalk of the Paris basin (Bakalowicz 2005b), southeastern England (Maurice et al. 2006), and limestone areas of Texas (Smith & Veni 1994) and Missouri (Vineyard 1997) in the USA.

Lowland and low relief karst may exhibit similarities in their hydrogeology due to shallow land surface and hydraulic gradients (e.g. parts of the Pennyroyal plateau karst in Kentucky and Irish lowland karsts (Drew 2008)). However, the classification of a karst as either a low relief or lowland karst does not imply a common morphogenesis or hydrogeology, and low relief and lowland karst landscapes with differing hydrological and geomorphological characteristics exist around the world. The karst around Poitiers in central France and the Monfalcone karst in northeastern Italy has been identified by Drew (2008) as sharing certain characteristics with the Irish lowland karst in terms of their surface relief and extent, however the Monfalcone karst differs from Irish karsts in terms of the possible source of its water, with complex interactions suspected between intrusive seawater and water

originating from deep (1,500 – 3,000 m.b.s.l.) thermal sources (Ballarin et al. 2000). Distinctive lowland high relief karst is found in China consisting either of clusters of limestone cones which share footslopes – fengcong, or flat alluvium covered plains containing isolated limestone towers - fenglin, the Yangshuo karst containing some of the best examples of these landscapes (Daoxian 2004). Allogenic water causing lateral erosion of karst towers may be responsible for the formation of fenglin from fengcong karst, and although the exact nature of the genesis of both landscapes remains somewhat unclear (Sweeting 1995), it has recently been suggested that under certain circumstances (such as in areas where tectonic uplift occurs at particularly low rates) that fengcong karst will develop into fenglin karst (Waltham 2008, 2010). Caves in the fenglin karst are generally shorter (due to the fact that they are formed within the karst towers and the width of the towers limits the length of such caves) than caves developed in the fengcong karst (where such caves run between the karst cones (Waltham 1986).

2.3.2 Hydrological characteristics of low relief and lowland karsts

2.3.2.1 Recharge

As in upland and alpine karsts, modes of recharge in low relief and lowland karsts can be point, diffuse, or a combination of the two. For example, point recharge occurs via dolines in the Kentucky karst in the Pennyroyal Plateau (Magdalen & Alexander 1995), while diffuse recharge is prevalent in parts of Indiana (Igbal & Krothe 1995), and a combination of both recharge types has been reported in parts of Missouri (Dom & Wicks 2003). In contrast to areas of alpine karst, areas of lowland and low relief karsts are more commonly covered by overlying deposits (mantled karsts) and recharge must pass through these deposits before reaching the karst aquifer (Quinlan 1978). These mantling deposits in Florida include various sands and clays which have been eroded, collapsed, or subsided in places (Arrington & Lindquist 1987) and have become infilled with material that has a higher hydraulic conductivity than the original mantling deposits which provide pathways for recharge to enter the karst aquifer below (Sacks et al. 1992). Such lowland mantled karsts can be closely connected to the surface drainage network and, as a result, may be susceptible to pollution despite the presence of covering material, for example in Florida where some karst areas contain up to 6 enclosed depression per km² (Denizman 2003), many of which contain lakes which are

closely linked to the groundwater system (Katz & Bullen 1996; Katz et al. 1997; Bruno et al. 2003).

2.3.2.2 Groundwater flow and storage characteristics

There is a degree of variation in hydraulic gradients both between and within different lowland or low relief karst areas. For example, in the Wabash River basin in Indiana the regional hydraulic gradient is about 0.001, while under hills in the area a localised hydraulic gradient of 0.01 has been calculated (Lloyd & Lyke 1995). Similarly, in Kentucky hydraulic characteristics of carbonate aquifers can vary greatly over short distances (Lloyd & Lyke 1995) and hydraulic gradients exhibit similar local variations to the groundwater in Indiana. In the Monfolcone karst (Italy) hydraulic gradients are typically 0.007 - 0.01 (Ballarin et al. 2000). In contrast, hydraulic gradients have been shown to be very flat in the Yucatán Peninsula karst aquifer with measurements of 7 – 10 mm/km in the northwest of the peninsula (Marín & Perry 1994; Steinich & Marín 1996). Overall, hydraulic gradients of unconfined watertables are lower in lowland than upland karsts.

Groundwater flow in low relief and lowland karst systems (as in other karst systems) can be predominantly via solutionally enlarged conduit or channel flow (tertiary permeability), fissure flow (secondary permeability), intergranular flow (primary permeability), or a combination of these (Worthington 2003). For example, areas in the USA such as parts of the Pennyroyal plateau in Kentucky (located southeast of the Mammoth Cave region / Chester Uplands) are underlain by well-developed cave systems (Currens 2001; Palmer 2004). The Yucatán Peninsula in Mexico contains an extensive (75,000 km²) low lying karst underlain by well developed cave systems which have been shown to have formed under vadose conditions and numerous steep sided doline features called cenotes, which intersect the watertable and extend below it to depths of up to 60 m (Connors et al. 2007). In contrast, in the chalk of the Paris Basin and in parts of the English Chalk, groundwater flow is predominantly through fissures that may have only been slightly enlarged by solution (Bakalowicz 2005b; Maurice et al. 2006). Hydraulic conductivities vary between karsts in different regions and between the matrix, fissure and channel components of individual aquifers such as in the English Chalk aquifer where hydraulic conductivity of 0.000072 m/h in the matrix, 0.0144 m/h in fractures, and 0.216 m/h in the channels has been measured (Worthington et al. 2000). As in other

types of karst, water in low relief and lowland karst aquifers is stored in the intergranular matrix of the rock (primary porosity), in fractures (secondary porosity) and in solutionally enlarged channels (tertiary porosity) and the proportion of storage in each case is dependent on the lithology, degree of fracturing and prevelance of solutionally enlarged channels (Worthington 2003; Worthington & Smart 2004). Matrix, fissure and epikarstic storage have been identified in Missouri karst aquifers although the exact relative proportions of each have not been established (Lerch et al. 2005). Analysis of an English Chalk karst aquifer has shown that > 90% of the storage is in the rock matrix, while > 90% of the flow is in the solutionally enlarged channels (Worthington 2003). Significant spatial variations can exist in the storage capacity of lowland karst aquifers (as in upland aquifers) where differences in storage capacity are determined by the degree of solution that has occurred (in cases where primary porosity is negligible) such as has been observed in parts of Kentucky (Lloyd & Lyke 1995).

2.3.2.3 Discharge

Discharge from low relief and lowland karst aquifers, like other karst aquifers, is usually via different types of springs. The discharge volume between individual springs in lowland and low relief karsts, like upland karsts, can vary considerably. This can be seen in the Mississippian aquifer in Kentucky where spring discharge at selected sites can range from just over 380 l/s to over 38,000 l/s (Lloyde & Lyke 1995). However, unlike upland karsts, it is common for lowland and low relief karsts to be overlain by unconsolidated deposits such as sand and gravels (Quinlan 1978). Where such deposits are present they can mask the presence of concentrated groundwater flow and discharge can appear on the surface as diffuse seepage discharging via unconsolidated deposits such as tills or gravels, this phenomenon has been recorded in Florida where karst springs appear on the surface as diffuse seepages from soft silty deposits (Barrios 2006).

2.3.2.4 Summary of differences between low relief / lowland karst and upland karst

As has been discussed, there are many similarities between lowland and upland karst in terms of their recharge, flow characteristics, storage, and discharge. Recharge in both types of karst can be point or diffuse, allogenic or autogenic. Storage in karst aquifers of all types varies in terms of its magnitude and the location in the aquifer where water is stored. Moreover, both lowland and upland karsts

exhibit varying degrees of heterogeneity in hydraulic characteristics over short distances. Discharge from upland and lowland karsts is from springs of various types. However, there are also important differences between upland and lowland karsts. Recharge in lowland karst commonly takes place through a mantle of unconsolidated deposits such as glacial till, which can buffer input volumes or alter the hydrochemistry of water recharging the aquifer. Hydraulic gradients are generally lower in lowland karsts and while discharge is predominantly focused via springs, the presence of overlying deposits such as silt, till, or gravels can mask the focused nature of karst discharge and, as a result, it may appear on the surface as diffuse seepage (Lloyd & Lyke 1995; Olcott 1992).

2.3.3 Groundwater – surface water interaction in karst

It is common in karstic areas for groundwater catchment boundaries to be spatially different from overlying topographically delineated surface catchment boundaries, and the surface drainage system and the groundwater system can be closely and complexly interlinked (Coxon & Drew 1998, 2000; Drew 2008).

Holokarst areas may have virtually no surface drainage network, with virtually all precipitation becoming recharge (Cvijic 1925; Ford 2004). Less karstic areas, merokarsts or mantled karsts may have partially or fully developed surface drainage networks present (Cvijic 1925; Quinlan 1978). When a surface drainage system does exist above a karstic aquifer the two are frequently highly interconnected (Coxon & Drew 1998). In a conduit dominated aquifer these systems can be viewed as two fluvial systems superimposed on one another with exchanges of water occurring at various points in their catchments (Coxon & Drew 2000). It is the point nature of the interactions, i.e. swallow holes and springs, between groundwater and surface water in karsts that most clearly distinguishes them from other types of environments in terms of their groundwater – surface water interaction. In some areas, especially mantled karsts, gaining and/or losing streams may also be present and can appear to be non-point interactions (Winter et al. 1998). In many cases, however, such interactions are in fact point interactions between groundwater in the bedrock and the surface drainage system that appear to be diffuse interactions due to the fact that water is discharged from the karst aquifer through unconsolidated deposits before reaching the land surface (Winter et al. 1998).

In some low relief and lowland karsts groundwater catchments and surface water catchments are commonly not spatially coincident (Winter et al. 1998). Water tracing experiments have shown that groundwater divides and flow direction in karst systems are not always governed by topography, for example in parts of the Nanos karst plateau in Slovenia (Baker et al. 2001). This is in contrast to a classical hydrogeological system where the watertable is conceptualised as a subdued replica of the surface topography (Haitjema & Mitchell-Bruker 2005). A surface water catchment in a karst area can receive water from outside its topographically defined boundary and the areas contributing such water can change in spatial extent as hydrological conditions change, i.e. there can be areas that contribute water to a catchment at certain times, usually during high flow conditions, but not at other times (Bonacci et al. 2006). The importance of such temporal variations have been recognised in terms of managing groundwater and surface water resources, as surface and groundwater catchments are the usual units of water resource management (Winter et al. 1998). Direction of flow between the groundwater and surface water system can be reversible depending on hydrological conditions. This phenomenon of spatial misalignment between groundwater and surface water catchments has been observed in the Pennyroyal karst (Kentucky, USA) (Currens & Ray 1998) (Figure 2.4).

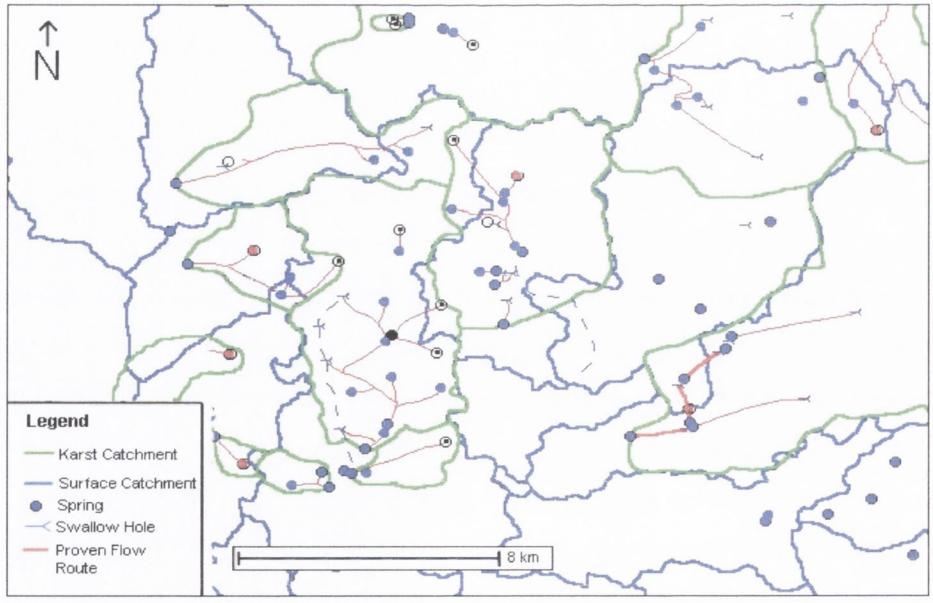

Figure 2.4 Surface and Groundwater catchment spatial misalignment in the Pennyroyal Karst, Kentucky, note the differences between karst groundwater catchments and topographically delineated surface drainage catchments (reproduced from Currens & Ray 1998).

2.4 Irish karst environments

2.4.1 Introduction

Approximately 50% of the Republic of Ireland is underlain by limestone, comprising of Carboniferous limestone of varying purity (Figure 2.5) (Drew & Jones 2000). Most, if not all of these limestones are karstifiable, but the degree to which this has occurred is dependent on a number of factors which include rock purity, altitude, Quaternary geology and anthropogenic influence (Drew 1996; Drew et al. 1996). Over 90% of the area underlain by limestone is below 100maOD (Figure 2.5) and upland karst is restricted to the Burren in County Clare and the upland plateau karst of the northwest (Drew 2008). Past research (e.g. Coxon 2001) has demonstrated that Ireland has been extensively modified by glaciations since the Tertiary. As a result, glacial and fluvio-glacial deposits blanket the bedrock to varying degrees throughout the island and much of the Carboniferous limestone is buried under these deposits, such as in parts of County Galway as described by Coxon & Coxon (1998).

Previous research has shown that these areas of till-covered limestone bedrock exhibit evidence of karstification (Coxon 1987a; McDonald 1988; Drew & Daly 1993; Brown 2002; Gibson, et al. 2004; Hickey 2009) and that flow regimes of both groundwater and surface water in such areas are both spatially and temporally complex (Coxon & Drew 1998, 2000). In addition, there is also some evidence that suggests parts of the Irish Midlands were karstified before the Quaternary (Williams 1970; Burdon 1987; Simms 1991; Kelly et al. 1996; Delaney 1997; Brown 2002), and that karstification is still actively occurring in some places (McDonald 1988; Drew 2002). It has been suggested that residual limestone hills in the Irish Midlands may be evidence of a pre-Quaternary, tower karst landscape similar to present day fenglin or fengcong landscapes in China (Herries Davies & Stephens 1978; McDonald 1988; Drew & Jones 2000; Drew 2002). Primary permeability is negligible in Irish Limestones, with either secondary (fractures) or tertiary permeability (enlarged fissures and/or conduits) locally dominant (Drew et al. 1996). However, in Irish limestone aquifers the relative importance of primary, secondary, or tertiary permeability has not yet been established (Fitzsimons et al. 2005).

2.4.2 Upland karsts

The upland areas of karst in Ireland are confined to the Burren in County Clare and the plateaux karsts situated in Counties Sligo, Leitrim, Fermanagh, and Cavan, in the northwest of the country (Drew 2008).

Precipitation in upland areas of west and northwest Ireland averages around 1500 mm/year (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp). Moreover, potential recharge in the upland areas, where exposed bedrock or thin soils are common, has been estimated at up to 75% of effective precipitation (Lee & Daly 2002).

The modes of recharge in these areas are diffuse input, allogenic sinking streams, autogenic sinking streams, and dolines. However, the dominant mode of recharge in Irish karsts are commonly affected by the presence and depth of unconsolidated deposits which generally comprise of glacial, fluvio-glacial, and/or peat deposits, and the local lithology (Drew 2008). Such unconsolidated deposits are usually thinner than in the lowlands (where they are present at all). For example, recharge in the Burren upland karst is predominantly diffuse (70 – 95%), via limestone pavement or partly vegetated limestone, while the remainder (5 – 25%) is typically via allogenic sinking streams (Drew 1990). This pattern of allogenic streams and autogenic diffuse recharge has also been identified in the Cuilcagh Karst, County Fermanagh where concentrated autogenic recharge via solution and collapse dolines also occurs (Gunn 1982a). Recharge to the Geevagh karst aquifer in the northwest of the country is approximately 50% from allogenic sinking streams with the balance comprising diffuse recharge through the epikarst (Thorn et al. 1990), while recharge to the nearby Bricklieve Mountain karst in County Sligo is entirely diffuse (Thorn et al. 1990).

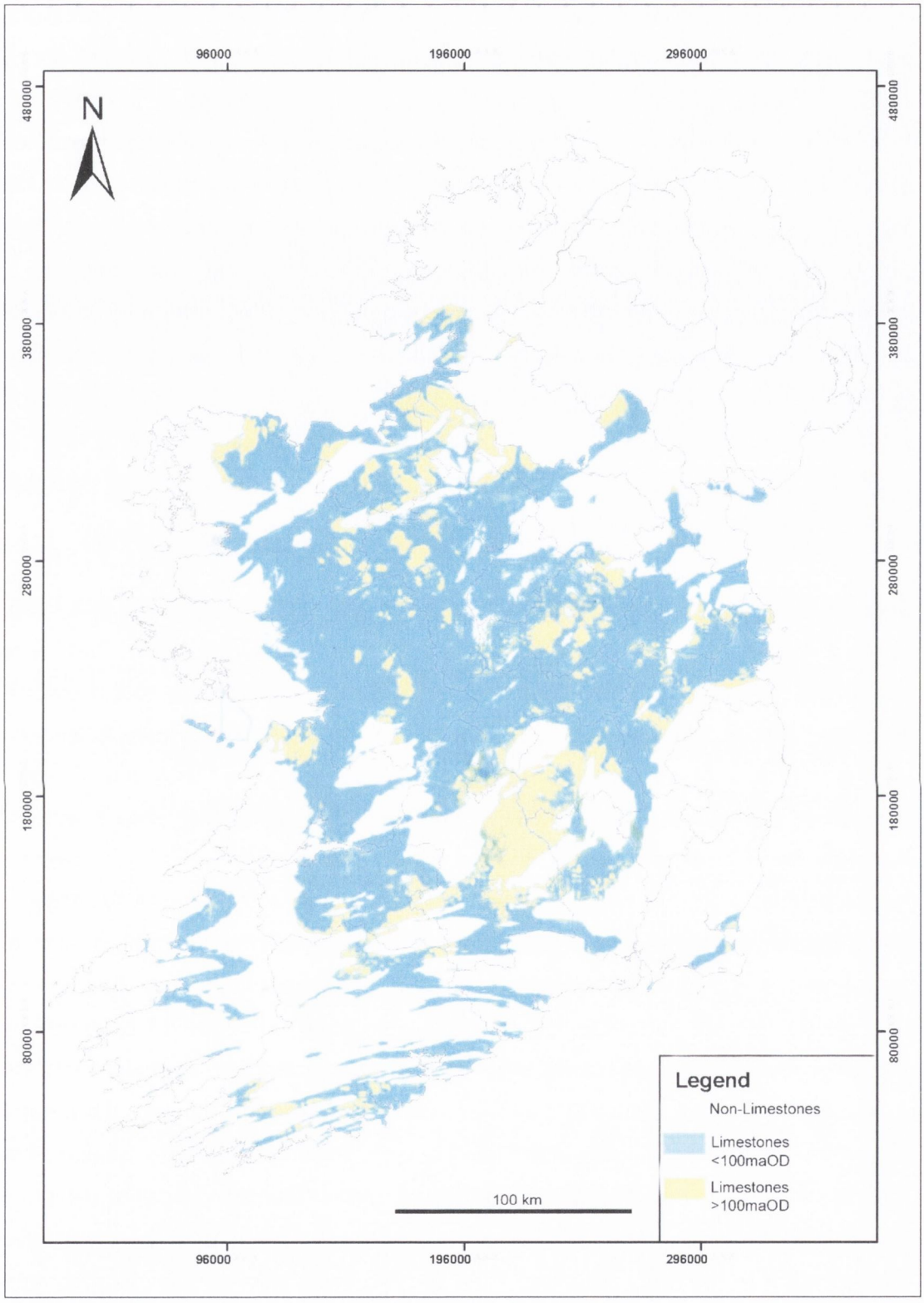

Figure 2.5 Location of Carboniferous limestone bedrock in the Republic of Ireland (source data Geological Survey of Ireland (GSI); OSI 2001).

Hydraulic gradients in the upland karsts are higher than those in lowland areas and are typically 0.01 - 0.1 with flow rates of 20 - 300 m/h (modal values 100 m/h) (Drew 2008). These ranges are consistent with flow velocities recorded in the Cuilcagh karst by Gunn (1982a). Distinctive local and regional groundwater flow systems have been shown to operate in the Cuilcagh karst where groundwater flow in the regional groundwater system has been shown to bifurcate into separate flow directions (divergent groundwater flow) (Gunn 1996). Most flow rates recorded in the Burren upland are with the 50 - 150 m/h range (Drew 1990). Hydraulic gradients of 0.02 - 0.08 m/km and groundwater flow rates of 25 - 51 m/h have been recorded in the Bricklieve upland karst, and hydraulic gradients of 0.05 - 0.11 m/km and groundwater flow rates of 3 - 90 m/h recorded in the Geevagh upland karst in Counties Sligo and Leitrim where groundwater flows predominantly through enlarged fissures and conduits (Thorn et al. 1990).

Discharge from the Burren upland karst is mainly via springs which flow into either streams or lakes or directly into the sea (marine springs) (Drew 1990). Discharge from the Bricklieve and Geevagh upland karsts is mainly via springs to the surface drainage network (Thorn et al. 1990). Discharge from the Cuilcagh karst is also via springs, in many cases located near the contact between the Dartry and Glencar Limestone Formations, the Glencar Formation being somewhat shaley and of markedly lower permeability than the Dartry Formation (Gunn 1982a). Flow rate ranges in individual upland springs are generally significantly different to those in lowland springs in Ireland. In lowland areas, the typical ratio of low to high rates of discharge at a spring has been estimated as 1:5, as opposed to ranges of up to 1:60 for upland plateaux karst springs, which may indicate a degree of buffering by overlying glacial and fluvio-glacial deposits in lowland karst that is absent from the upland aquifers (Drew 2008). Groundwater discharge from the Burren upland karst occurs mainly on the periphery of the karst and the majority of streams flowing from springs situated on the karst sink again before finally resurfacing near to the point where they leave the upland karst (Drew 1990). For example, over 150 springs have been located in this area of upland karst but the vast majority do not have large flows with one spring, Elmvale Spring (3900 l/s, mean flow), accounting for approximately 60% of groundwater discharge from the Burren upland (Drew 1990). Spring flows of 22 - 273 l/s have been recorded at springs in the Gevagh karst and 6 - 348 l/s in the Bricklieve karst (Thorn et al. 1990).

For the most part, surface drainage systems on upland karst in Ireland are sparse or absent (Drew 1990; Thorn et al. 1990). Figure 2.6 shows an area of 200 km² in northwest Clare where the Carboniferous limestone of the Burren is partly overlain by younger Namurian sandstones and shales. A normal dendritic surface drainage network exists on the relatively insoluble sandstone and shale while a surface channel network is almost completely absent from the highly karstified limestone where dry valleys are found on the land surface (Drew 1990). Swallow holes are located at the geological contact between the carbonate and non-carbonate rocks where streams flowing off the Namurian rocks sink into the karstic aquifer within a short distance of reaching the exposed limestone. In this part of Ireland, the presence or absence of a surface drainage network appears to be a function of the hydrogeological functioning of the underlying bedrock. A normal surface drainage system has formed on the Namurian rocks, while a wholly subterranean drainage system has developed on the limestone. This area represents one end of the spectrum whereby surface water – groundwater interconnection is completely controlled by the nature of the underlying geology and where karstification has led to the development of an almost entirely sub-surface drainage system (Drew 1990).

2.4.3 Lowland karsts

There are a number of different types of lowland limestone landscapes present in Ireland, which are all probably karstified to some degree (Drew 2008), with different hydrogeological characteristics and different surface drainage network responses to limestone bedrock in different areas. These include: the till covered lowlands in Counties Mayo; Galway; Clare; and Roscommon (Coxon 1987a, 1987b; Drew & Daly 1993); the Castleisland karst in County Kerry (Gunn 1982b, 1982c, 1984, 1985); valley karst in synclinal basins between sandstone outcrops in Counties Cork and Waterford (Wright 1979); low relief karst in County Tipperrary (Jones & Gunn 1982; Gunn 1984); parts of County Fermanagh (Fogg & Kelly 1995; Kelly et al. 2002; Gunn 2003); County Kilkenny (Daly 1994); and in the eastern region in Counties Longford; Meath; Westmeath; Offaly; Laois; and Dublin underlain by less pure 'Calp' limestones, which are all likely to be karstified to some degree, although little is known about the extent or nature of the karst in many of these eastern areas (McDonald 1988; Drew 2002; Brown, 2002). A particular feature of lowland low relief karst in Ireland, and of west Ireland in particular, is the presence of temporary lakes known as turloughs. These features are probably glacio-karstic in origin and are

common in lowland karst areas in the west of Ireland (Coxon 1987a, 1987b). Turloughs are discussed in relation to recharge and discharge to / from karst aquifers in this section and as a class of temporary karst lake in Section 2.5.2.1.

Precipitation in the central lowlands of Ireland averages 1000 mm/year (Toner 1986). Recharge in the lowland areas of Ireland, where bedrock is commonly mantled by varying depths of unconsolidated deposits, has been estimated at up to 50% of effective precipitation or approximately 500 mm/year (Lee & Daly 2002). The modes of recharge in Irish lowland karsts are diffuse input, allogenic sinking streams, autogenic sinking streams, loosing streams, dolines, and recharge from turloughs (Drew 2008). However, the dominant mode of recharge in a particular area is commonly affected by the presence and depth of unconsolidated deposits which usually comprise of glacial, fluvio-glacial, and/or peat deposits, and the local lithology (Drew 2008). Allogenic sinking streams are uncommon in lowland areas compared to the upland karst but do occur. For example, sinking streams have been identified near Gort in County Galway and these sink close to the limestone contact with the Devonian sandstones upon which the streams are generated (Drew & Daly 1993). Dolines are an important source of recharge in some areas with densities of up to 20 per km² in parts of County Roscommon (Hickey 2009). Recharge also occurs from turloughs during periods when the water level in the turlough is not rising. This is because the turloughs often fill and empty via two way swallowhole/spring features (estavelles) (Coxon 1987b). Diffuse recharge is also known to occur in the lowland karsts, especially in areas with a cover of unconsolidated deposits, although it is presumed that some concentration of flow takes place at or near the rockhead (Drew 2008).

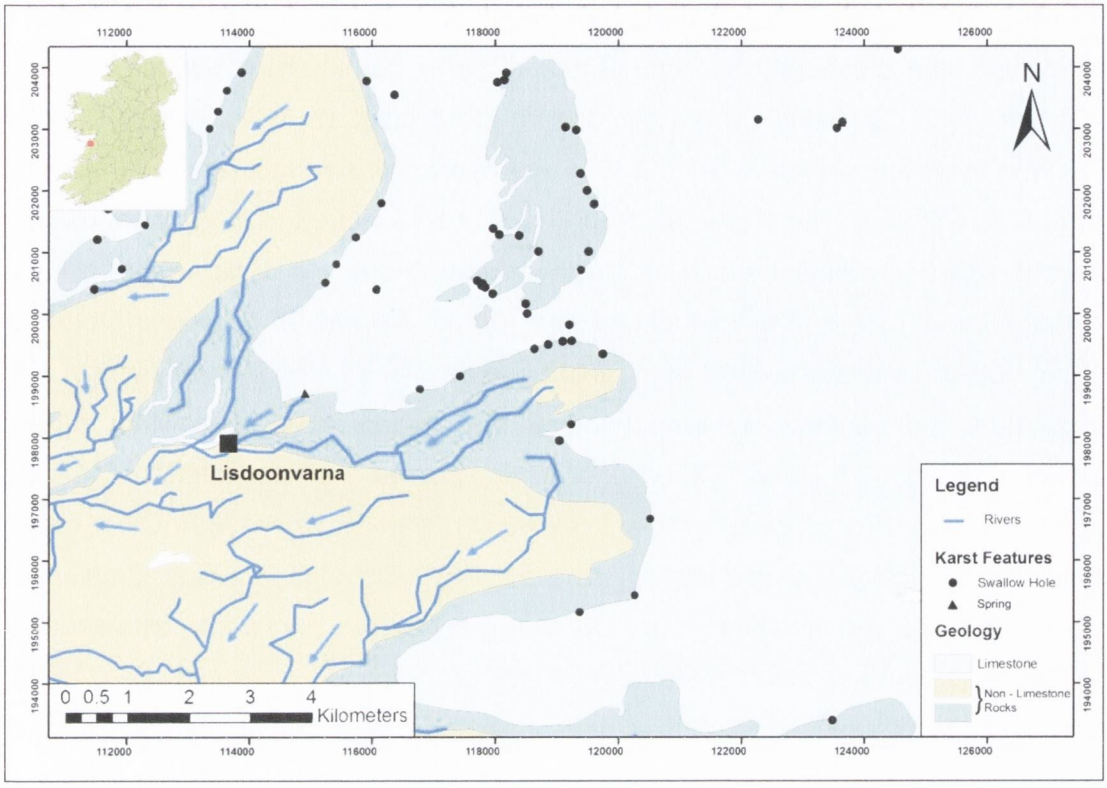

Figure 2.6 Surface drainage features, karst features, and bedrock geology in the Burren, County Clare (source data GSI; OSI 2001).

Low hydraulic gradients are common in both surface and groundwaters in Irish lowland karsts, with hydraulic gradients in Irish lowland karsts ranging from approximately 0.001 – 0.01 m/km with flow rates ranging 5 – 250 m/h (Drew 2008), although a low flow rate of 0.95 m/h has been reported by Gunn (1984) in the Castleisland karst County Kerry. Hydrogeological conditions can vary greatly over very short distances and there is usually negligible primary porosity combined with the localised importance of conduit flow, so it is common for boreholes located quite close to each other (C.10m) to have very different yields – hydraulic heterogeneity (Wright 2000). Conduit flow has been observed in parts of south and east County Galway (Drew & Daly 1993) but the overall relative importance of fracture, fissure and conduit flows in lowland Irish karst is not clearly understood at present (Fitzsimons et al. 2005). The presence of conduits has also been inferred from geophysical tests carried out in County Roscommon (McGrath & Drew 2002) and County Westmeath (Brown 2002). Mixed flow regimes where conduit and dispersed flow systems locally dominate each other may also be present in some areas such as Ballinrobe in County Mayo where water tracing results indicated groundwater flowlines parallel to flowlines inferred from borehole groundwater levels in the

northern part of the area covered by the study, but perpendicular to flowlines produced from the borehole groundwater levels in the southern part of the area (Coxon 1986). Caves including active stream caves such as the Bull's Hole Cave in County Tipperary (Jones & Gunn 1982) and hydrologically inactive caves such as the Mitchelstown Caves (Coleman 1965) have been explored in many Irish lowland karsts. The Bull's Hole Cave near Mullinahone in Tipperary is situated in a karst overlain by 2 – 15 m of glacial till and has 130 m of surveyed passages (Jones & Gunn 1982). The cave is 2 - 4 m in height and developed along major joints in 1 m wide rifts and contains a sump channel that is too wide to facilitate further exploration (Jones & Gunn 1982). Water tracing proved a groundwater flow velocity of 210 m/day with a hydraulic gradient of 0.0052 (Jones & Gunn 1982). Other caves have been explored in this region such as the Ballintaggart Quarry Cave near Ballingarry, situated in County Tipperary, and the Roaring Well Cave, also situated in County Tipperary, which contains over 700 m of flooded passages (Farr 1978). The Ballingarry cave is an active joint controlled stream cave, has ~100 m of passages, and was probably formed primarily under vadose conditions (Jones & Gunn 1985). It is suggested that the water flowing through the cave may originate from riverbed leakage from a river located 360 m to the northwest of the cave (Jones & Gunn 1985). Crag cave is located in the Castleisland Karst, County Kerry. This cave consists of approximately 3.8 km of passages, is an active stream cave and is likely to be of phreatic origin (Gunn 1985). The hydraulic gradient in this part of the aquifer is low with groundwater velocities from tracer test ranging from 20 - 75 m/h, and the water flowing through the cave has been traced to the Anglore rising 200 m south of the cave (Gunn 1984).

Discharge from lowland karst aquifers in Ireland is commonly from relatively small springs, up to 80% of which have a discharge of only a few litres per second (< 10 l/s), although there are a small number of much larger springs in some areas, such as those at Cong, County Mayo, and Kinvara, County Galway, which have discharges of > 10,000 l/s (Drew & Chance 2007). Variations in discharges between low and high flows from individual lowland karst springs are in the region of 1:5 (lowest flow : highest flow) – a narrower range than has been measured in the upland Irish karsts of up to 1:60 (Drew & Chance 2007). Springs within a short distance (< 1 km) of each other in lowland areas have been observed to have different flow regimes with some springs flowing perennially, and others flowing only

during the wetter winter and spring months, for example the springs of Toberfaolaigh (Perennial) and Tobernacogany (seasonal) in the Meath-Westmeath Lakeland region (McDonald 1988).

Surface water drainage systems commonly exist in tandem with karstic groundwater systems. Such surface drainage systems may be natural or man-made. In Ireland, much arterial drainage work has been carried out since the first edition of the 6 inch maps were surveyed in 1837 (Coxon & Drew 1986). Using these maps it is possible to reconstruct the surface drainage network that existed before the 1850s. This is important as such alterations mean that the karst system is bypassed and the karstic drainage system in the area is effectively deactivated, i.e. the karstic drainage system is now relict as water levels have been lowered (Coxon & Drew 1986). Coxon & Drew (1986) mapped the pre arterial drainage surface drainage network in part of east County Galway and compared it to the post drainage map (Figure 2.7 A and B). These maps show that a fragmented network has been connected to provide an integrated surface drainage network.

Figure 2.7 Surface drainage change in County Galway: A = Surface drainage in east County Galway prior to arterial drainage; B = Surface drainage in east County Galway after arterial drainage (reproduced from Coxon & Drew 1986).

The characteristics of the surface drainage system in Irish lowland karsts exhibit differences between various locations. Two different surface drainage network

responses to limestone bedrock in lowland regions of Ireland are presented below. The first is of north Roscommon (Figure 2.8) and the second is of part of the Westmeath Lakelands west of Mullingar (Figure 2.9).

Figure 2.8 shows an area of 200 km² in County Roscommon where Carboniferous limestones are overlain by mixed Carboniferous sandstones and shales. An integrated surface drainage system in this area exists on both limestone and non-limestone geologies, although there is an area in the centre of the map where a surface system is absent. This part of County Roscommon is farther towards the less karstified end of the spectrum than the highly karstified areas of the Burren as described previously, as both an underground karstic drainage system and an integrated surface drainage system exist, and the area could be said to be an intermediate type between a fully integrated surface drainage network and a wholly subterranean drainage system (Hickey 2009).

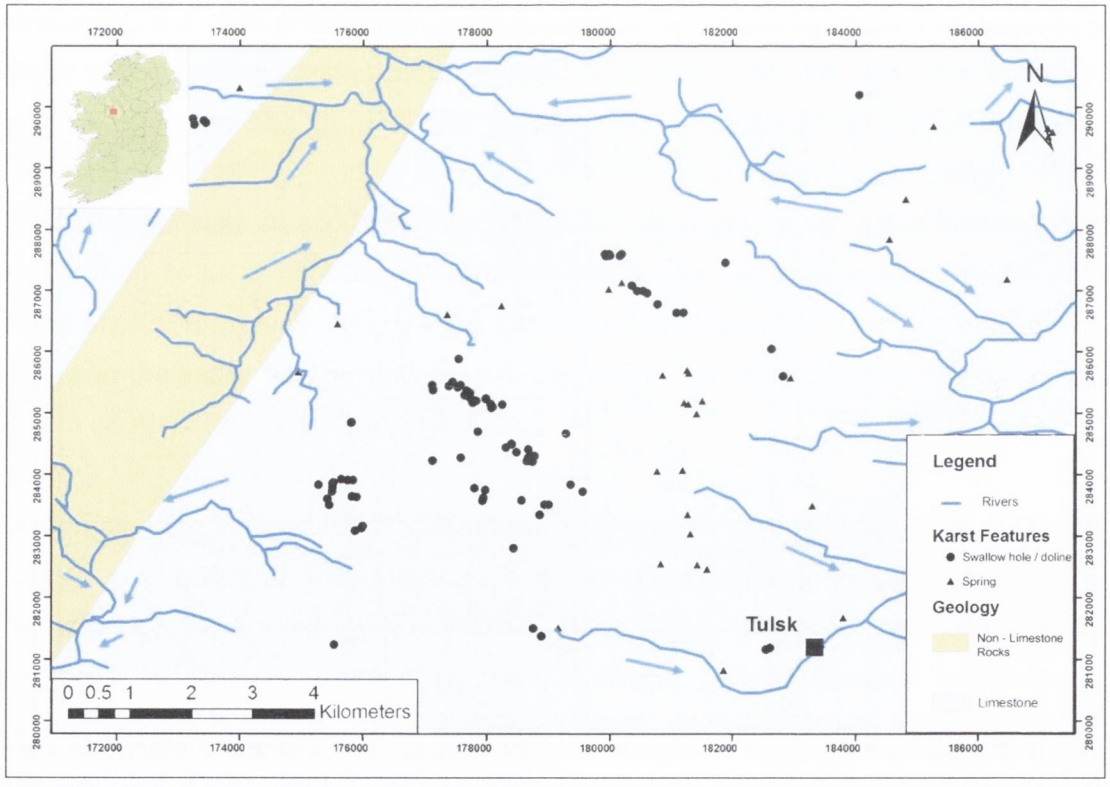

Figure 2.8 Surface drainage features, karst features, and bedrock geology in northern County Roscommon (source data GSI; OSI 2001).

Possible explanations for the differing surface drainage systems on limestone bedrock in different regions of Ireland could be the effects of the presence of

limestones of differing purities in different locations or the presence of unconsolidated glacial deposits which may carry streams in areas where the deposits are of sufficient thickness or relatively low permeability (Drew et al. 1996). Thus a patchwork exists between areas drained by surface channel networks and a subterranean karstic network. In this type of landscape the surface drainage system and the karstic aquifer are highly interconnected by point recharge/discharge from swallow holes and springs.

Figure 2.9 shows an area of 200 km² in County Westmeath west of Mullingar. The geology in this area consists of Carboniferous limestones, sandstones and shales. There is a fully developed integrated surface drainage network present which does not change in character when it passes over the geological contact from the sandstones and shales to the limestones. There are no springs or swallow holes known in the area and the surface channel network seems dense enough to efficiently drain the landscape here. Bedrock geology appears to have no influence on the surface hydrological system in this area.

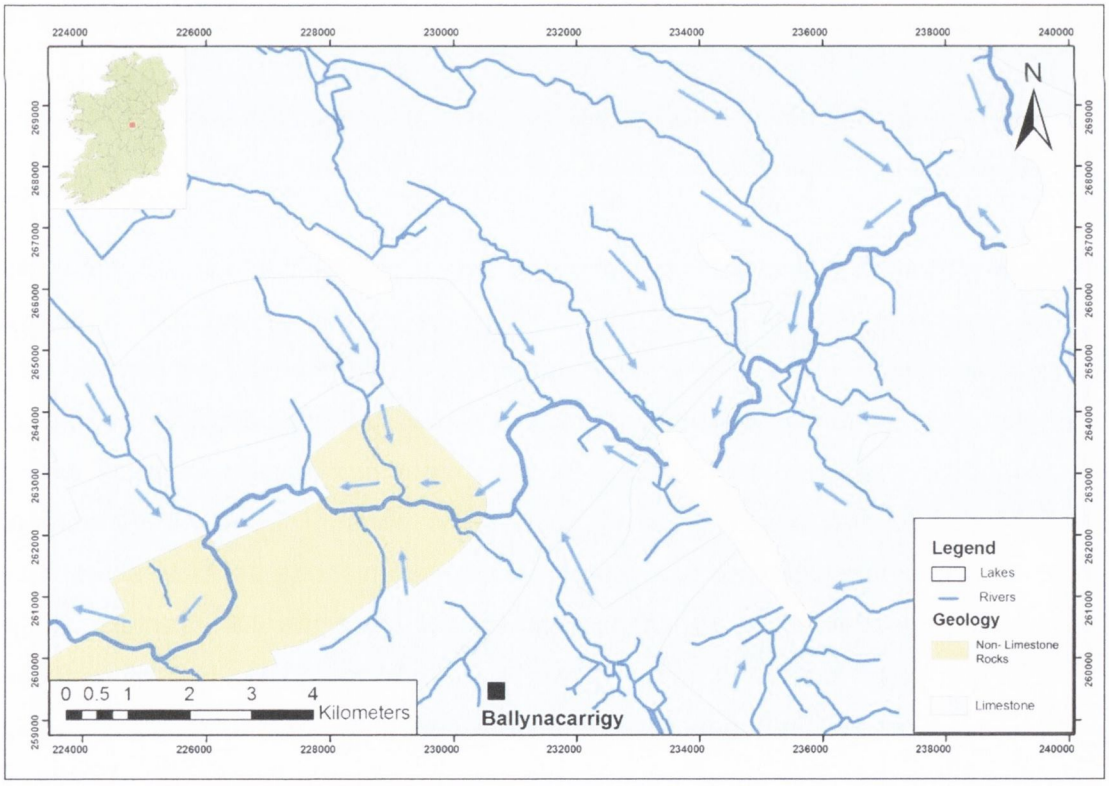

Figure 2.9 Surface drainage features, the absence of karst features, and bedrock geology west of Mullingar in County Westmeath (source data GSI; OSI 2001).

Similar to parts of Roscommon (McGrath & Drew 2002) or northern Westmeath (Brown 2002), the effects of glaciation may be a factor here, as glacial deposits may have filled in a previously existing karstic network and prevented a new network forming in post-glacial times. Alternatively, the limestone in this area may just be too impure to karstify to a large degree. Consequently, this landscape may be either the remnants of a palaeokarst landscape or it may exist at the other end of the karstified limestone spectrum as apparently it is either only slightly karstified or not karstified at all with little or no karstic-type point interaction between the groundwater and surface water systems.

The examples presented above illustrate that a range of surface drainage network types exist on lowland low relief limestone bedrock in Ireland. Differences in either the relative purities of the limestones and/or thicknesses of glacial deposits in each case are the most likely causal factors (Coxon & Drew 1998). Areas where a surface drainage network is absent, sparse, or not fully integrated are predominantly located in the west of the country and include the lowland limestone areas of east Galway, south Mayo, Roscommon, and south Clare (Drew 1973; Drew 1984; Coxon & Drew 1986; Coxon & Drew 1998). Areas where fully integrated surface drainage networks exist or exist above karst aquifers include parts of Westmeath, Tipperary, and Cork. Limestone areas that exhibit little surface evidence of karst include parts of Kilkenny and Wexford (Daly 1994).

Groundwater and surface water systems are often highly connected in Irish lowland karsts (Coxon & Drew 1998, 2000). In areas of Ireland where both a karstic groundwater system and an integrated surface drainage network are present they are often *'completely intertwined'* (Coxon & Drew 1998, p. 82).The degree of interconnection between the systems is often more pronounced in areas where glacial subsoils are thinner (< 2 m) such as in parts of County Roscommon. Investigating groundwater–surface water interactions in these areas is sometimes complicated by drainage modifications carried out since the 19th Century where artificial integrated surface drainage networks have been constructed. While these surface networks function under high flow conditions, many cease to function during periods of low flow and areas return to their natural karstic functioning (Coxon & Drew 2000).

As in other karsts, groundwater–surface water interactions are characterised by point interactions via springs, swallow holes and estavelles. These point interactions are illustrated most clearly in the case of estavelles, which act as two-way points of interconnection between the groundwater and surface water systems (Coxon 1987a; Coxon & Drew 1998, 2000). The catchment of the lower River Fergus , situated in County Clare (Figure 2.10), is a good example of an area where the surface drainage system is intimately connected to the groundwater system (Coxon & Drew 2000). Results of water tracing has shown that a proportion of water bypasses the surface network in this catchment by flowing into swallow holes located along the surface network and discharging back into the surface network via springs. Groundwater flow is complex in this area and, as such, the groundwater and surface drainage systems should be treated as one interconnected drainage system.

Groundwater and surface water catchments in Irish lowland karst are frequently not spatially coincident. The area contributing recharge to a spring is known as the zone of contribution (ZOC) (DHLG/EPA/GSI 1999) or the contributory area (Gunn 2007). Partially contributing areas exist in some groundwater basins which contribute varying proportions of recharge to groundwater catchments in particular areas under varying hydraulic conditions. For example, the Aucloggeen spring, situated in County Galway catchment, receives water from area A which is the directly contributing catchment as established by Drew & Daly (1993) (Figure 2.10) and area B which is a partially contributing catchment, i.e. some but not all of the runoff generated in area B sinks underground and flows to the Aucloggeen spring. This connection adds an area of up to 160 km² to the catchment of the springs (Coxon & Drew 2000). However, it is uncertain what proportion of surface drainage in this catchment (area B) contributes to the Aucloggeen springs and the degree of change in this proportion of contribution under different hydraulic conditions. .

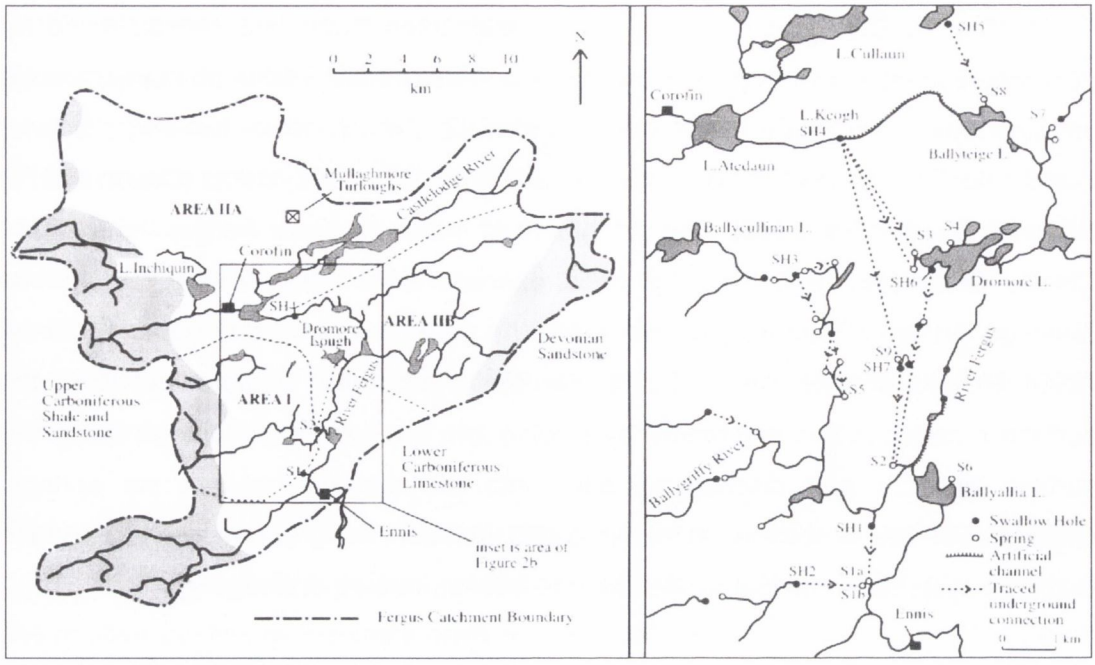

Figure 2.10 Surface water – groundwater interactions in a karst situated in County Clare. The dashed lines indicate proven underground flow routes that bypass the surface drainage network. The area within the rectangle on the left is expanded on the right hand side (reproduced from Coxon & Drew 2000).

Although these types of interactions have been documented mainly in areas situated primarily to the west of the River Shannon (e.g. Drew & Daly 1993), there is some evidence that point interactions occur in parts of the Meath-Westmeath Lakelands. Water tracing has proven that Lough Lene drains into the River Boyne through a surface channel and to the River Shannon via swallow holes on the northern shore of the lake through a spring in Fore (McDonald 1988).

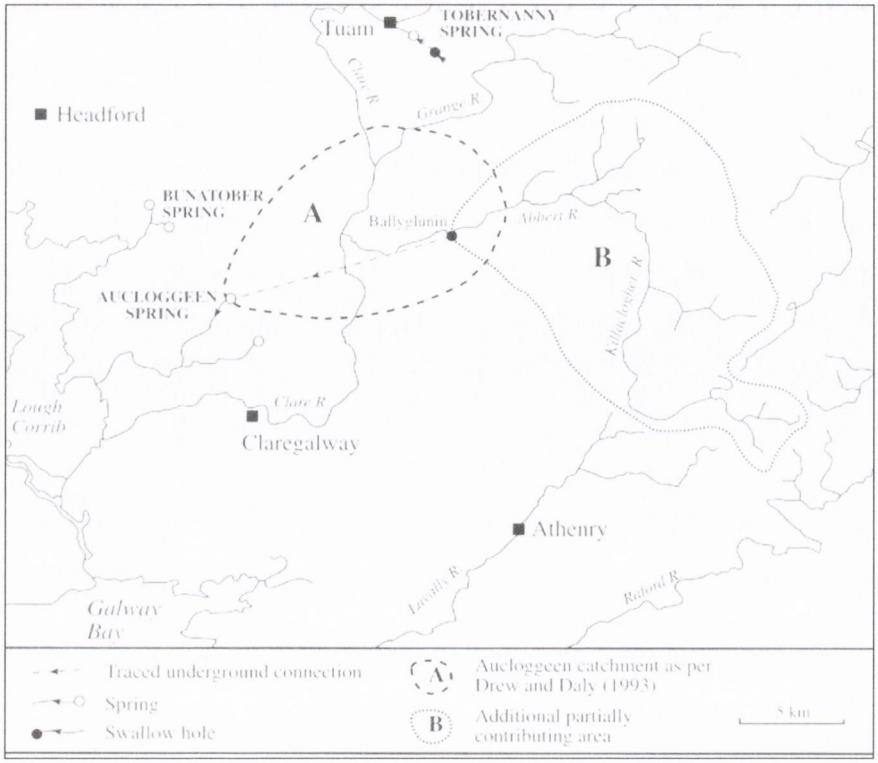

Figure 2.11 Partially contributing catchment in County Galway (reproduced from Coxon & Drew 2000).

2.4.4 Summary

- In Ireland, areas previously considered to be non karstic are increasingly being recognised as karstic to some degree.
- Lowland karst in Ireland is characterised by recharge through mantling deposits (commonly glacial deposits or peat) of varying thickness, low hydraulic gradients and springs, the majority of which have discharges of <10 l/s.
- There is some evidence that suggests that parts of the east Midland region of Ireland may be karstified similarly to other recognised lowland areas of karst situated in Ireland such as those in Counties Roscommon, Galway, Mayo, Kerry, and Tipperary), and the degree and characteristics of karstification and drainage network modification in the Meath-Westmeath Lakeland region are not clearly understood at present.
- The hydrological characteristics of lowland karsts in the west of Ireland have been modified by drainage schemes which have led in some cases to some karstic flow paths now operating either intermittently or not at all. However, it

is unclear whether or to what extent this may have occurred in the eastern Midlands of Ireland.

- Examination of less obviously karstic areas is ongoing internationally and a study of the characteristics of karst in the Meath-Westmeath Lakeland will provide further information relating to; the present understanding of the distribution and characteristics of lowland karst in Ireland and internationally; the reaction of lowland karsts to anthropogenically induced drainage network change.

2.5 Lakes as points of interconnection between the groundwater and surface water systems and the classification of permanent lakes in lowland karst

2.5.1 Groundwater-lake interactions in non-karstic environments

Most permanent lakes interact with groundwater to some extent, and these interactions can differ depending on the characteristics of an individual lake, its position in a landscape, and its particular climatic conditions (Winter et al. 1998). Due to the fact that deposition of low-permeability sediments occurs in the basins of many lakes, it would seem probable that interactions between lakes and groundwater would be minimal. Nonetheless, it has been known for many years that groundwater – lake interactions do occur (Meyboom 1966; Winter 1999).

Lakes, like streams, can interact with groundwater in three ways a) they can receive groundwater discharge (Figure 2.12 A), b) they can provide recharge to groundwater (Figure 2.12 B), or c) they can do both concurrently in different parts of the lake basin (Figure 2.12 C). Temporally, a lake may alternate between any of the above conditions (Winter et al. 1998). When, where and in which direction interactions occur is governed by the relative levels of the hydraulic head in the aquifer and the altitude of the lake surface. In non-karstic areas, groundwater lake interactions are typified by seepage flows as opposed to point interconnections. The characteristics of how and where these seepage interactions occur are outlined below.

Some theories of groundwater–lake water interactions suggest that where such interactons occur, the majority of groundwater discharge into lakes takes place in the wave-washed littoral zone, i.e. near shore (McBride & Pfannkuck 1975; Winter 1976, 1978, 1981; Winter & Carr 1980; Barwell & Lee 1981; Munter & Anderson

1981; Townley & Davidson 1988; Townley et al. 1991; Lee & Swancar 1997; Harvey et al. 2005). For example, field studies conducted by Harvey et al. (2000) on Lake Ontario showed that the pattern of groundwater inflow conformed to theory and modelling results, i.e. permeability decreases away from the shoreline with increasing depth due to increased thicknesses of low-permeability sediments. However there is also evidence to suggest that the permeability of a lakebed does not always decrease with increased distance from the lakeshore (Shneider et al. 2005). According to Mitchell et al. (1988) the belief that inflow seepage rates decrease with distance from a lakeshore and increasing depth is due to the fact that seepage measurements are usually made where the lakebed is most suitable (sand substrates). Mitchell also noted that the hydrologic properties of sediments could be nullified if (for instance) a layer of coarse gravel was underlain by thick organic or clay (low permeability) deposits. The same was true where a thin organic or clay low permeability layer is underlain by coarse, highly permeable deposits. Moreover, Schneider et al. (2005) also found no significant correlation between substrate permeability and groundwater seepage rates. This research showed that seepage rates are (at times) controlled by both on-site and distant precipitation events, with increases in seepage rates corresponding to inflow following rainfall both at the lake (which entered the lake through local groundwater flow systems) and from up to 10 km away from the lakeshore when groundwater is transported through regional groundwater systems (Schneider et al. 2005).

Bedrock joint orientation, and the stratigraphical ordering of unconsolidated sediments means that anisotropy is an important factor in determining where in a lake basin that groundwater – lake interactions will occur (Guyonnet 1991). This is because a greater magnitude of interaction between the groundwater system and a lake may take place in parts of the lake basin that intersect faults, joints, or high permeability strata compared to parts of the lake basin that do not intersect as many faults, joints or high permeability strata (Schneider et al. 2005). Where differences in seepage rates of groundwater into lakes occurs, these differences in inflow rates can take place over a very small area – on a scale of metres (Lee et al. 1980; Brock et al. 1982; Schafran & Driscoll 1990). A number of studies (e.g. Downing & Peterka 1978; Shaw & Prepas 1990a, 1990b; Snucins et al. 1992) have concluded that significant temporal variation in groundwater flow rates to lakes is a common occurrence . However, temporal fluctuations are not restricted to flow rates, but also

include changes in flow direction and in some cases flow reversal (Kenoyer & Anderson 1989). This results in situations where a lake receives groundwater discharge at one time and recharges groundwater at another time in the same location due to changes in the relative standing water levels of a lake surface and the watertable (Anderson & Cheng 1993; Sebestyen & Schneider 2001).

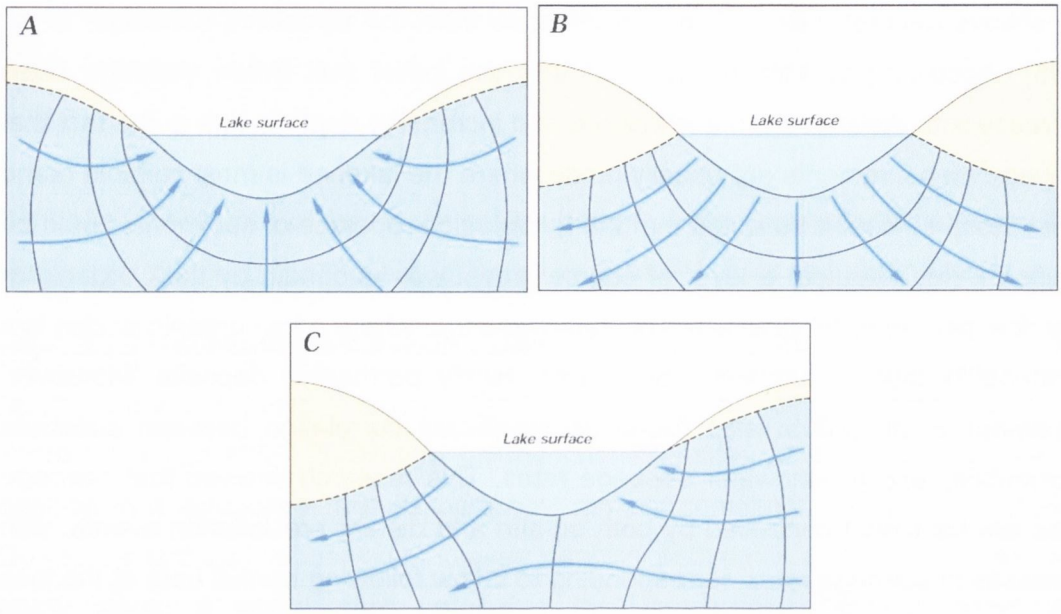

Figure 2.12 A: Groundwater discharging to a lake, B: Groundwater being recharged from a lake, C: A lake receiving groundwater discharge and recharging groundwater concurrently (reproduced from Winter et al. 1998).

2.5.2 Karstic groundwater – lake interactions

2.5.2.1 Groundwater interactions with temporary and semi-permanent lakes in karst

In karstic areas, temporary lakes have been more thoroughly researched than permanent lakes in terms of their interaction with the groundwater system. A number of types of temporary lakes are found in karstic areas. These include surface water bodies held in poljes, over 200 of which are located in parts of the Former Yugoslavia alone (Habič 1987; Petrič & Kogovšek 2005), turloughs in Ireland and various other temporarily inundated enclosed depressions around the world (Reynolds 1998; Goodwillie & Reynolds 2000). Generally, flooding of enclosed depressions occurs during the time of year when precipitation is highest, when groundwater recharge is greater than discharge capacity (Groves & Crawford 1991). Poljes are relatively large enclosed depressions in karst areas generally elliptical in shape with gently sloping floors, steep sides, and commonly containing seasonal

lakes (Ristic 1976; Gams 1978; Bonacci 1987). Poljes are typically large (0.5 – 500 km²) (Bonacci 2004b). The location and geomorphology of poljes is strongly influenced by bedrock structure and three basic polje types have been identified: border poljes; structural poljes; and baselevel poljes (the formation of in which piezometric levels are more influential than bedrock structure) (Gams 1973, 1978). Poljes are typically elongated depressions with influent spring or tributary streams located at the up gradient end connected to swallow holes (ponors) at the lowest points in their floors, by meandering surface streams (Nicod 2003). In some cases, estavelles, through which water enters and drains from the polje, are situated in the polje floor (Nicod 2003). Poljes are commonly inundated during wetter months of the year when the ability of the swallow holes to drain water is exceeded by the amount of water entering the polje or when piezometric conditions mean that an estavelle is flooding rather than draining a polje (Gams 1978). Gunn (2006) identified a number of similarities and differences between poljes and turloughs: both are periodically inundated and commonly contain lacustrine sediments; the area of inundation in poljes is typically greater than that of turloughs; poljes are more clearly defined with steeper sides and clear breaks of slope between their sides and floors; there is a much stronger tectonic influence on the location of poljes compared to that of turloughs and; poljes are not closely associated with glaciation as turloughs are. However, it has been suggested that turloughs may be a form of immature polje (Waltham 2004).

Turloughs are a type of temporary lake and are almost unique to the west of Ireland. They have been defined as:

'A karst depression that may be dry or flooded according to season or prevailing weather conditions where Oscillations in the general ground-water level, including variations in response to local or more distant tidal effects are the probable mechanism for water level changes in the true turloughs. Effects that appear similar can be produced by high surface runoff into a closed depression with only restricted capacity for the drainage to sink underground'. (Lowe & Waltham 2002, p.38).

However, turloughs have been redefined recently to include aspects of their ecological significance in their definition as:

'Depressions in karst areas, seasonally inundated mostly by groundwater and supporting vegetation and/or soils characteristic of wetlands' (Working Group on Groundwater 2004, p.1).

In total, over 300 turloughs have been identified in Ireland (Sheehy-Skeffington et al. 2006). In Wales, a landform similar to an Irish turlough has been identified in Pant y llyn, and is currently the only widely accepted example of this landform outside the island of Ireland (Campbell et al. 1992; Blackstock et al. 1993). Pant y llyn is the only currently known lake in the mainland UK that has a seasonal fill/drain cycle via groundwater, filling during autumn and draining during the spring and summer months, usually emptying completely via an estavelle in late June or July (Hardwick & Gunn 1995). Temporary lakes exist in upland karst areas such as the Pivka Valley in the Javorniki Mountains in Eastern Europe (Ravbar & Šebela 2004; Mulec et al. 2005). The surface levels of the temporary lakes in this area are directly related to fluctuations in the watertable and thus may be conceptualised as surface expression of the watertable. It has recently been proposed that a number of these lakes can be classified, at least on an ecological basis, as turloughs (Sheehy-Skeffington & Scott 2008). However, there are important differences between the lakes of Pivka and the turloughs characteristic of Ireland: the depth of flooding in the Pivka lakes is generally greater than that in turloughs; the Pivka lakes are located in an upland karst as opposed to a lowland karst in which most Irish turloughs are located; the flooding regime of the Pivka lakes is of a shorter duration to that of most Irish turloughs (Sheehy-Skeffington & Scott 2008).

Turloughs are distinguished from other temporary karst lakes by their; a) Hydrology; b) Seasonality; c) Size (Figure 2.13), and; d) Geomorphology (Coxon 1987a). Coxon (1986) lists three main criteria for distinguishing turloughs from other lakes: 1) Seasonal flooding to a depth in excess of 0.5m for part of the year and a dry floor; apart from small residual pools; for part of the year; 2) Filling via ephemeral springs or estavelles; and 3) Emptying to the watertable via swallets or estavelles, there being no surface stream outlet. Characteristics of turloughs are outlined below.

The means by which turloughs fill and empty:
In a study of 90 turloughs (Coxon 1987a, 1987b), 80 contained swallow holes and/or estavelles. These swallow holes/estavelles were located either at the edge of the

turlough floor where impermeable marl deposits meet karstified limestone bedrock, or in the floor of the turlough (either dispersed or grouped) (Coxon 1987a). In some cases, turloughs do not contain open swallow holes, but are drained through low permeability deposits occupying the base of their basins, such as the Carran Turlough in County Clare (Drew 1990).

Temporal variations between the flooding/emptying regimes of turloughs:
Four factors have been identified as important in describing the flooding and emptying characteristics of turloughs, these are: the length of the hydroperiod (flood duration); the time of the year at which flooding occurs; flood frequency (>once a year, annually, < once a year); and the depth of flooding (Southern Water Global 1998). Of the turloughs studied by Coxon (1987a) the range of flooding depth was from 0.5 – 6 m, with a median value of 1.5m. In some areas where numerous turloughs are located, they may have quite different flooding regimes, a good example of this being the area around Gort in County Galway where some of the turloughs fill and empty annually, some do not empty annually, and some rarely empty and always contain residual pools (Coxon & Drew 1998).

Inflow of water to turloughs:
In addition to direct input through precipitation, a range of possibilities exists with regard to how water reaches turloughs. Some are probably located on lines of concentrated groundwater flow in aquifers (Coxon 1987a). The relationship between the level of water in turloughs and a changing watertable is illustrated in Figure 2.14 (Coxon 1986). The turlough can be seen as an 'overflow tank' for the groundwater system that floods during periods of high flows. This type of flow system can be conceptualised as a surge tank and has been successfully modelled as a simulated pipe network (Southern Water Global 1998). Epikarst is also thought to be important in contributing water to turloughs (Coxon & Drew 1998; Drew 2003) as it has been well established that storage and permeability are greater in the epikarst than deeper down in an aquifer (Klimchouk 2004).

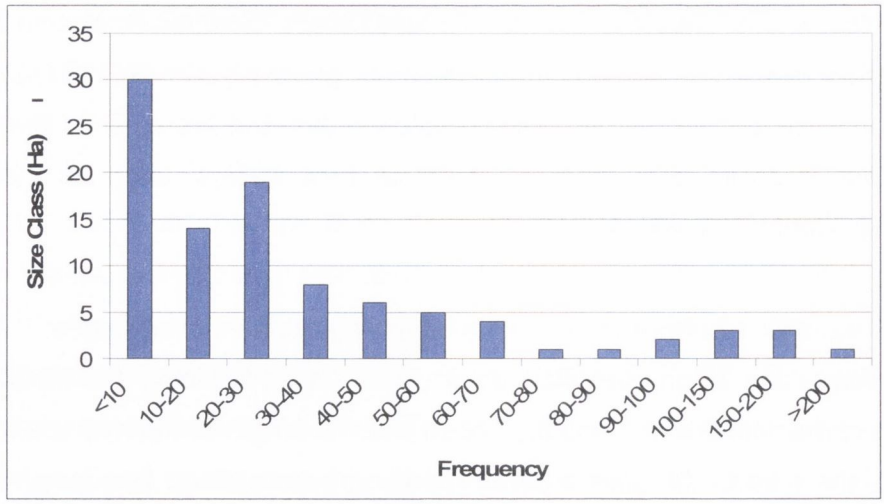

Figure 2.13 Turlough surface area (Sheehy-Skeffington & Gormally 2007; Sheehy-Skeffington et al. 2006; Goodwillie et al. 1997).

The lowland karsts of Ireland also contain semi-permanent lakes that, while sharing some features with turloughs, do not meet the criteria for classification as turloughs as they either empty only every few years or they never drain fully enough. For example, Lough Funshinagh situated in County Roscommon fully drains to groundwater in a 5 - 10 year cycle (Coleman 1965; Drew & Burke 1996). Drew & Burke (1996) concluded that the reason for the semi-regular draining of this lake was far from clear but that it was probably related to intermittent unplugging of a karstic conduit under the lake. Such plugging could be caused by natural detritus, i.e. leaf litter, sediment, or material of anthropogenic origin (e.g. plastic bags or agricultural materials such as fence wire/posts).and can be conceptualised as a temporary deactivating (by blockage) part of the karstic drainage system. Lough Nasool or Na Súil in County Sligo follows a similar drainage pattern. This lake drains completely via a swallow hole/estavelle at the bottom of its basin every 5 - 10 years, though this has never been reported to occur annually (Coleman 1965; Drew & Burke 1996). It is unlikely that these lakes are surface expressions of the watertable, as unhindered hydraulic connectivity between the lake and the groundwater system is unlikely during periods when swallow holes/estavelles are blocked and the lake level may stand above the altitude of the watertable. These lakes have neither all the characteristics of turloughs nor of permanent lakes even though they clearly show a high level of interaction with the groundwater system. Examples of temporary lakes in low relief karst which have not been examined as to their similarity or otherwise to turloughs can be found in Kentucky, such as Chaney Lake

which floods in the late autumn and empties between late spring and late summer every year. The lake occupies a gently sloping basin, fills and empties via estavelles and when at its highest level is 1.5 km in diameter (Kelley et al. 2000).

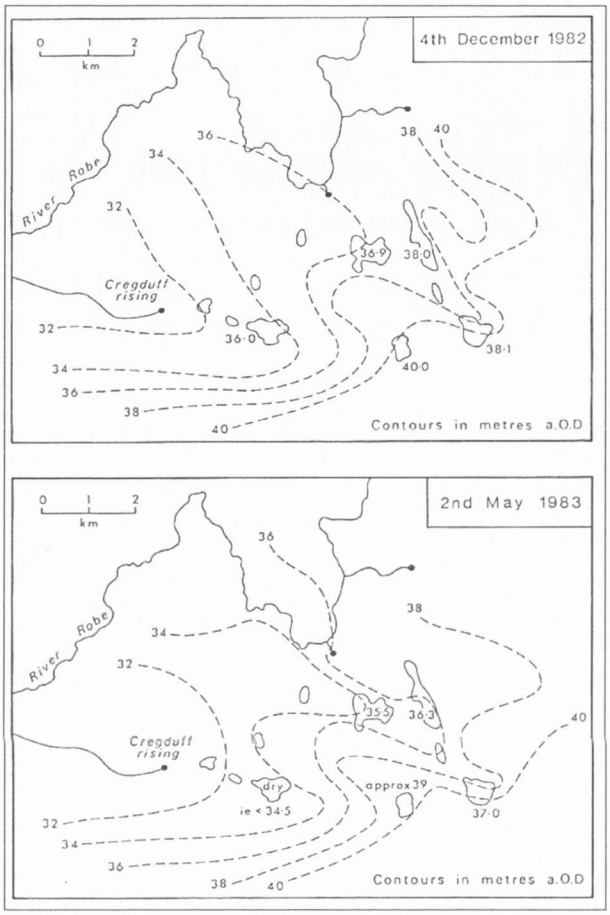

Figure 2.14 Watertable mapping in an area of turloughs in County Mayo (reproduced from Coxon 1986).

2.5.2.2 Groundwater interactions with permanent lakes in karst

As with temporary lakes, permanent lakes in karst areas can have varying levels of interaction with the groundwater system. Permanent lakes in karst have been classified as 'karst lakes', although there is no up to date and widely accepted definition. Two definitions of karst lakes are;

Lakes on karst surface, frequently connected with ground water (Monroe 1970, p.11);

And; *A large area of standing water in extensive closed depression in limestone* (UNESCO 1972, p.23).

Hydrological characteristics vary greatly between permanent lakes in karst (Winter et al. 1998). Lakes in karst can be situated in enclosed depressions and a surface outflow may not be present such as Lough Mask in County Mayo (Drew 1987; Drew & Daly 1993). Like non-karst lakes, permanent lakes in karst can receive groundwater discharge, recharge groundwater or both either simultaneously or at different times. A complex relationship can exist between permanent lakes and karstic groundwater where lakes may be receiving point discharge from groundwater in one part of their basin while point recharge to groundwater may be occurring in another part of the basin (Katz & Bullen 1996; Katz et al. 1997). Such interactions are often concentrated through springs, swallow holes and estavelles, and flow rates between the lake and groundwater are commonly much higher than in non-karstic areas (Winter et al. 1998) For example, water tracing has shown a groundwater flow velocity of 2.9 km/h between swallow holes at Prespa lake and Tushemisht spring, an upland karst situated in the mountains between Albania and the FYR of Macedonia (Amataj et al. 2007). Anisotropy in the underlying aquifer may be important in determining where these interactions occur.

A water budget prepared for Lowry Lake, Florida USA, estimated that surface channel discharge accounted for ~38% of total outflow from the lake catchment and that recharge to groundwater accounted for ~35% of lake catchment outflow, with evaporation accounting for the remaining 27%. However the hydrogeology was heterogeneous beneath the lake and it was impossible to estimate whether this recharge was occurring via seepage or concentrated flow paths (Motz et al. 2001). The springs and swallow holes where such interactions occur can be located within the lake itself or around its periphery (Winter 1999). Coxon & Drew (1998) describe hypothetical hydrograph responses of lake surface water levels in lakes with varying degrees and types of connection with karstic groundwater (Figure 2.15). These hydrographs show how lake surfaces react under idealised conditions in each case. However, in reality many lakes exist between these six distinct conditions and their hydrographs would not be so clearly representative of their groundwater connectivity.

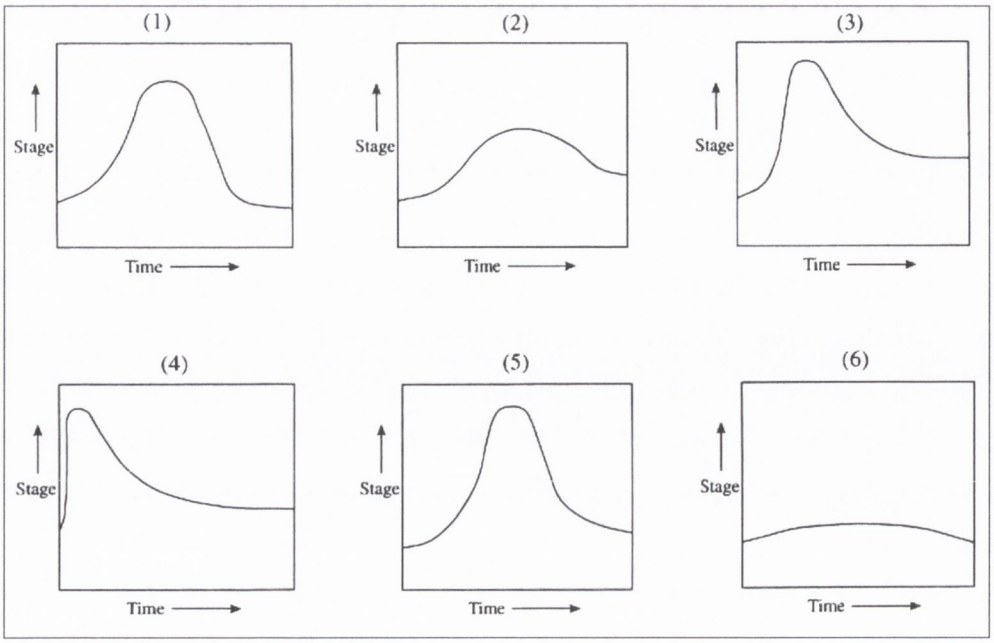

Figure 2.15 Lake hydrographs typical of water bodies with differing degrees and types of connection with karst groundwater systems (1) Lakes with normal river inflows and outflows, (2) Lakes with surface inflow and outflow from shallow epikarst water, (3) Lakes fed by surface streams and drained by swallow holes, (4) Lakes fed and emptied by estavelles, (5) Lakes fed by springs and drained by swallow holes, (6) Lakes largely isolated from groundwater, (reproduced from Coxon & Drew 1998).

Groundwater – lake interactions in a small number of permanent lakes underlain by limestone in Ireland have been investigated to date. Lough Gealain is a permanent lake in County Clare that displays some turlough-like features, in this case a wide range of seasonal variation in lake surface level and draining via swallow holes to groundwater, and it has been suggested that the lake basin was formed by a collapsed doline and may be a surface expression of the watertable (Byrne & Reynolds 1982; Watts 1984; D'Arcy 1992). Lough Bunny, also in County Clare, has no surface inflow or outflows. This lake is spring fed on its south side and it drains into a number of swallow holes on its northern shore (Ragenborn-Tough et al. 1999). A surface level altitude fluctuation of 1.2 m has been recorded for this lake, with the highest level recorded in December 1992 and the lowest in September 1993, following the general trend of other lakes in this region. On this basis, the altitudes of these lake surfaces have been assumed to be representative of the altitude of the watertable. McDonald (1988) examined Lough Lene in County Westmeath, where he noted three swallow holes located on the northern shore of

the lake. The combined discharge entering the three swallow holes was greater than that of the surface channel outflowing at the east end of the lake.

2.5.3 Classification of non-karstic and karst lakes

Lakes have been classified using various attributes and thus numerous different lake classification systems have been developed. Some of these systems classify lakes based on whether they have attributes such as surface inflow or outflow, discharge to or recharge from groundwater, or the rate of water exchange in a lake. In its simplest form, a system of lake classification can differentiate between closed and open lakes. Hutchinson (1957) defines closed lakes as those that lose water through evaporation only. It is important to note that in this system a closed lake must have a sealed bed, having no discharge to groundwater and receiving inputs only from precipitation. He defines open lakes as those with any kind of effluent. This is then sub-divided into drainage lakes, i.e. those discharging on the surface, and seepage lakes, i.e. those discharging to groundwater. Bogoslovsky (1966) developed a system that classified lakes based on the dominance of discharge method. Two main classes were distinguished, those with surface outflow predominant, and those with evaporation dominant. Subgroups were then delineated based on inflow/outflow, and precipitation/evaporation relationships. A variant of this was proposed by Born et al. (1974), who suggested that lakes fall into two main categories – surface dominated outflow, and groundwater dominated outflow. A system using two ratios of hydrological variables was proposed by Paslawski (1975). The ratios were called the water exchange index and the mean annual amplitude and were compared to denote lakes as active, medium, and passive. The water exchange index was calculated as the ratio of average annual inflow to the lakes capacity, and the mean annual amplitude was arrived at by means of an equation involving a factor named the 'lake coefficient', which was the ratio of the catchment area to the lake area. Lent et al. (1997) developed a tri-linear classification of lakes according to water loss. In this system the relative dominance of stream discharge, seepage to groundwater, and evaporation in lake discharge are taken into account, and can be used to compare the discharge characteristics of several lakes.

A distinction has traditionally been made in classifications between seasonal karst lakes and permanent karst lakes. Within the class known as temporary karst lakes a

number of further sub-divisions can be made based on differences in size, magnitudes of water level fluctuation, seasonality of flooding regime, average slope of their basins, and in the processes that led to the formation of the water bodies (Coxon 1986). The largest and perhaps best known temporary karst lake basins are located in poljes and are distinguished by their typically large size (0.5 - 500km^2), steep sides, flat floors and strong association with local geological structure, although the distinction between poljes, uvalas, and other doline forms is unclear especially in the smaller range of polje sizes (Nicod 2003). Within the class of landforms known as turloughs, it is now accepted that some are inundated for longer or shorter periods than others, with attendant ecological differences, and has resulted in attempts to conceptualise and classify turlough typologies along a wet-dry continuum (Visser et al. 2006). It has also been argued that turloughs exist at one end of a doline spectrum (Gunn 2006), and debate continues as to how dolines may be satisfactorily classified (Sauro 2003). Thus the science of classifying these lakes and their basins has moved towards less clear boundaries and it is now recognised that there are different types of temporary lakes, just as there are different types of permanent lakes. This is an international problem and many intermittent lakes in karst areas around the world have not yet been satisfactorily classified (Ravbar & Šebela 2004). Due to the fact that lakes such as Lough Funshinagh and Lough Na Súil do not fit comfortably into the categories of temporary or permanent lakes (in that they empty totally on occasion, but not seasonally or indeed regularly), such lakes have been described as 'lakes-cum-turloughs' (Drew & Burke 1996). There are many permanent lakes situated on limestone in Ireland, including those in the Meath-Westmeath Lakeland region, for which no attempt at classification based on their interaction with groundwater has been made to date.

2.5.4 Summary

- Most lakes interact in some way with groundwater.
- In karst areas around the world, a number of temporary surface water bodies exist. Many are conceptualised as surface expressions of the watertable.
- Turloughs, one type of temporary lake, are located mostly in the west of Ireland.
- There is evidence that permanent lakes in karst can also be highly connected to the groundwater system.

- Numerous lake classification systems exist and it is possible to classify lakes based on various attributes such as interaction with groundwater. It has been suggested that lakes situated in karst areas require further classification.
- There is evidence that lakes in the Meath-Westmeath Lakelands are interconnected to the groundwater system
- A classification of lakes in the Meath-Westmeath Lakelands region based on their interaction with groundwater has not been attempted to date.

3. Introduction to the Meath-Westmeath Lakelands study area

3.1 Introduction

In this chapter the study area is described. This description includes an overview of the study area location, climate, geology, geomorphology, land use patterns, surface hydrology, and hydrogeology.

3.2 Location

The study area is situated in the central lowlands of Ireland (Figure 3.1). The nearest large town is Mullingar (Grid. Ref. N24402530) in County Westmeath, located at the very south of the study area. The catchment divide between the River Shannon and River Boyne drainage systems runs roughly in a north-south direction through the study area. However, the study area is not drained directly by either the Shannon or the Boyne, but by the River Glore (which flows into the River Inny) and River Deel which flow into the Shannon and Boyne respectively. As illustrated in Figure 3.1, the initial study focuses on the area delimited by the topographically delimited catchments of six lake catchments: Loughs Owel; Derravaragh; Lene; Bane; White Lake; and ;the Ben Loughs (Figure 3.1 and 3.2). In addition, two springs in Fore Valley, Tobernacogany and Toberfaolaigh have been included, as an underground flow connection from Lough Lene to Tobernacogany has previously been proven (McDonald 1988). A 2 km stretch of the river downstream of these springs – the River Glore and its topographically delimited catchment was also included in this study as there are numerous small springs discharging into the upper River Glore here.

3.3 Climate

3.3.1 Introduction

Due to Ireland's location beside the Atlantic, southwesterly winds dominate and are associated with mild, moist winters, cool summers, and relatively high levels of rainfall (Rohan 1986; Sweeney 1997). Long term (30 year) climatic data are available for the weather station at Mullingar, which is the closest weather station to the study area.

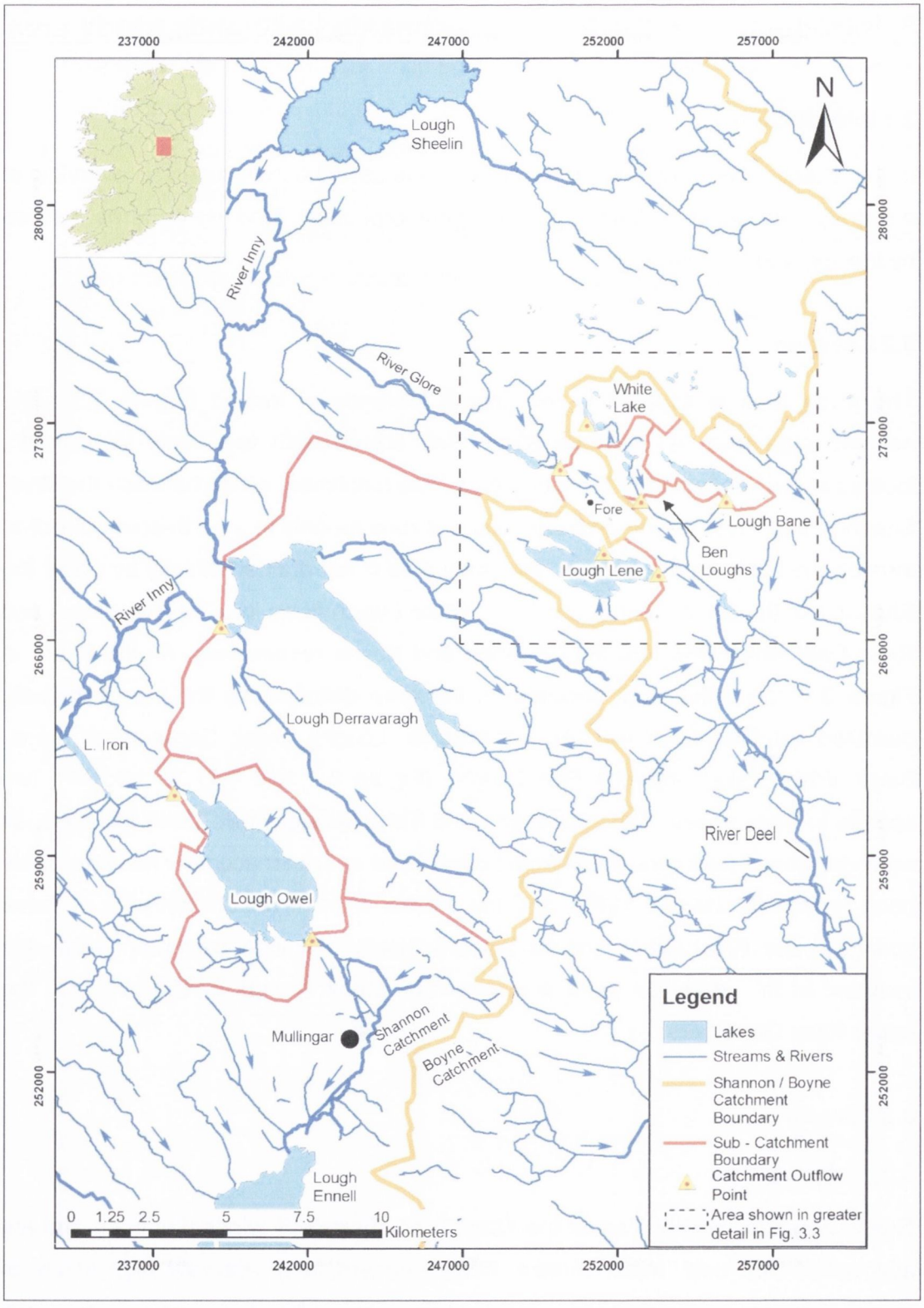

Figure 3.1 Location of lakes, surface drainage channels, topographic catchment boundaries, sub-catchment boundaries and catchment discharge points in the initial study area (basemap data OSI 2001).

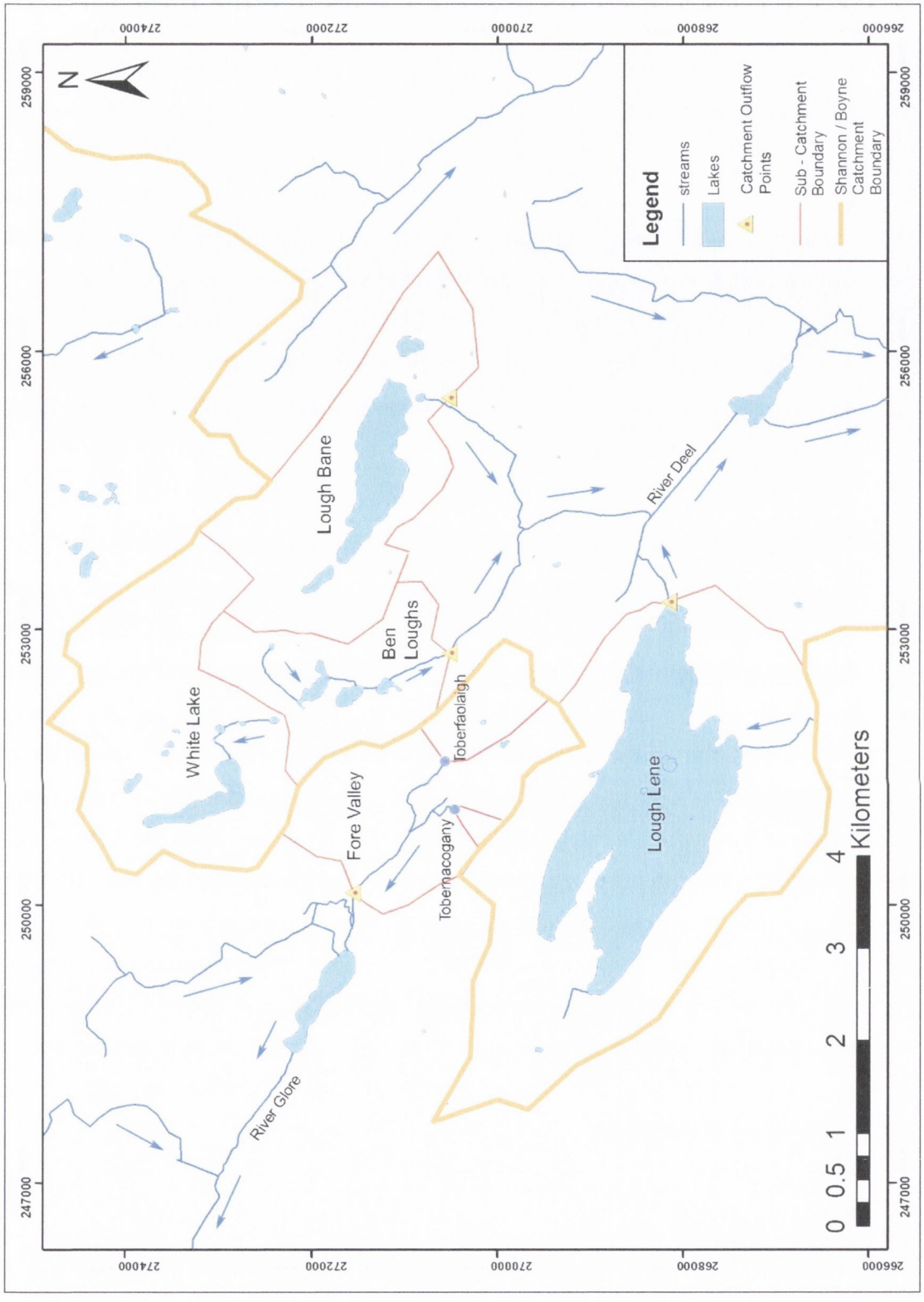

Figure 3.2 Area inside dashed line in Figure 3.2 - Location of lakes, surface drainage channels, catchment boundaries, sub-catchment boundaries and catchment discharge points in the initial study area (basemap data OSI 2001).

3.3.2 Temperature

The average annual daily maximum and minimum temperatures for the Mullingar weather station were 12.6 °C and 5.1 °C respectively (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp). The difference between summer and winter maximum daily temperatures is more pronounced in inland areas than at the coasts. The 30 year average July and January mean daily maximum temperatures recorded at the Mullingar weather station were 19.0 °C and 6.8 °C respectively (Met Éireann 1961-1990 data) (http://www.met.ie/climate/mullingar.asp). Average July and January daily minima were 10.3 °C and 1.2 °C respectively for the same period (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp).

3.3.3 Precipitation

The 30 year average annual level of precipitation recorded at the Mullingar weather station is 932 mm per year (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp). Precipitation is highest in January, where an average of approximately 92 mm was recorded for the 30 year period and July was the driest month on average in the same period, with an average of approximately 61 mm of precipitation (Figure 3.3) (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp). In terms of total rain days, the month with the least is July, and the most is January. The data for this are recorded as numbers of days in a month where precipitation >.2mm, >1.0mm, and >5.0mm. The figures for July for each of these values were 16, 11, and 4 days respectively, and for January 20, 16, and 7 days respectively (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp). Thus, the overall pattern is one of wetter winter months, with drier summer months, although heavy rainfalls frequently occur in the drier months of the year.

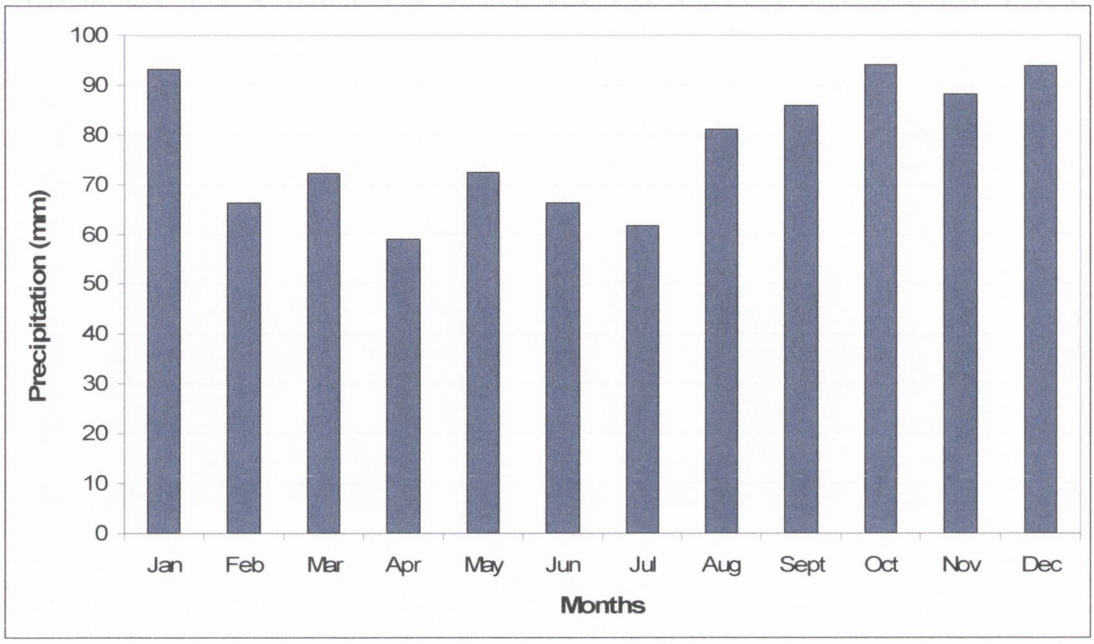

Figure 3.3 Mean monthly levels of precipitation recorded at Mullingar (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp).

3.3.4 Effective precipitation

In Ireland, the mean annual level of precipitation is estimated to be 1,150 mm, and the mean annual level of evapotranspiration is estimated to be 450 mm (Toner 1986). Therefore, mean effective precipitation nationally over the period 1961 - 1990 is approximately 700 mm per annum. Due to the fact that the spatial distribution of precipitation is uneven – with highest rates recorded on the west coast - and that evapotranspiration rates are affected by temperature, vegetation type, soil moisture deficit values and land use amongst other factors, actual effective rainfall will vary significantly from the average figure on a regional, and a local basis. Soil moisture deficit values are estimated for three soil groups in Ireland: well drained; moderately drained; and poorly drained soils. Estimates of actual evapotranspiration rates are calculated from potential evapotranspiration rates for each of these three soil groups. In areas where there is no limit to the availability of water for evapotranspiration (such as lake surfaces) the actual evapotranspiration figure equals the potential evapotranspiration figure. The 30 year (1961 - 1990) effective rainfall estimates for the Mullingar station (calculated using 1961 – 1990 mean monthly potential evapotranspiration data) show a clear seasonal variation with highest levels of effective precipitation in the winter and lowest (no effective precipitation) in the summer months (Figure 3.4, Table 3.1).

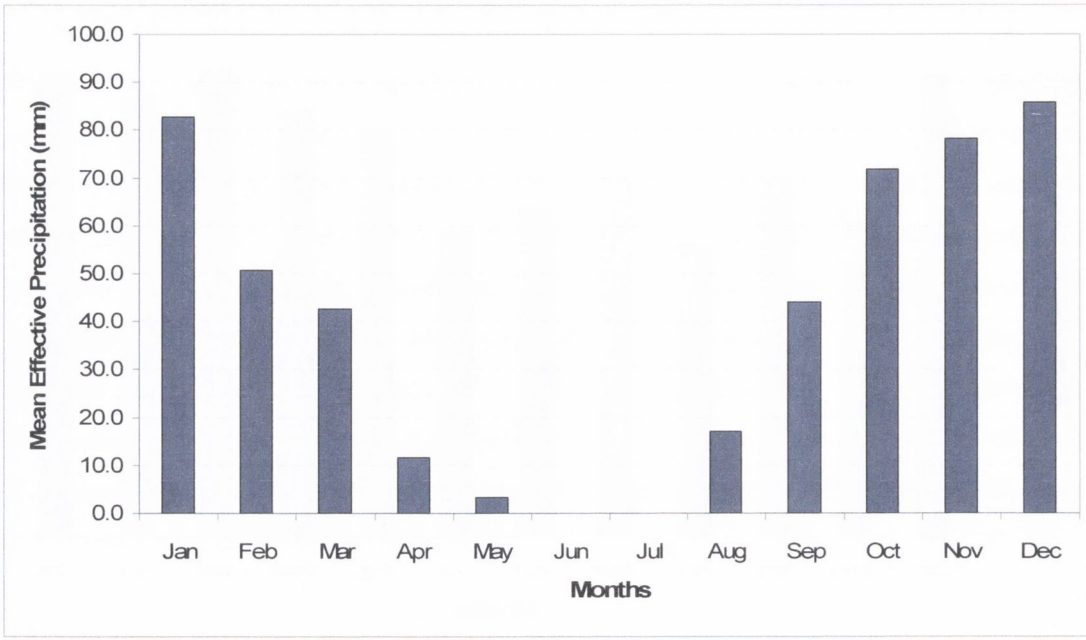

Figure 3.4 Mean monthly level of effective precipitation recorded at Mullingar (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp).

Month	Precip. (mm)	PET (mm)	EP (mm)
January	93.1	10.4	82.7
February	66.3	15.7	50.6
March	72.3	29.6	42.7
April	59.1	47.5	11.6
May	72.4	69.2	3.2
June	66.2	79.6	0.0
July	61.8	82.6	0.0
August	81.2	64.0	17.2
September	85.9	41.9	44.0
October	94.0	22.2	71.8
November	88.2	10.1	78.1
December	93.8	8.0	85.8

Table 3.1 Mean monthly precipitation and effective precipitation values recorded at Mullingar (Met Éireann 1961-1990) (http://www.met.ie/climate/mullingar.asp).

3.4 Geology, geomorphology, and soils

3.4.1 Solid geology

The study area is underlain by Carboniferous limestone. These rocks date from the Upper Dinantian (Lower Carboniferous), specifically comprising of argillaceous limestones known as the Derravaragh Cherts (Figure 3.5). This limestone is well bedded and jointed. Although the study area is elevated relative to the drainage

basins of the Rivers Inny and Deel to the west and east, it is situated in a geological structure known as the Lough Owel Syncline, the axis of which runs in a sinuous line northeast from Lough Owel to a location in close proximity to Lough Lene (Figure 3.6). This structure contains the Ballinalack-Mullingar basin, comprising of a thick succession of basinal rocks of the Tober Colleen and Lucan Formations with the Derravaragh Cherts exposed in the syncline core (Figure 3.6). The structure of the Derravaragh Cherts varies considerably over relatively short distances. The bedrock outcrops at Fore and south of Lough Bane are gently dipping (approximately 5 ° – 10 °), while those exposed at the north shore of Lough Lene and at Knockeyon Hill on the southeastern shore of Lough Derravaragh dip at > 80 ° and appear to have undergone considerable deformation (Drew 2002; McConnell et al. 2001; Morris et al. 2003). The topography of the bedrock surface is uneven, and is marked by the presence of numerous isolated hills which for the most part are positioned along a ridge running through the centre of the study area (Figure 3.7). The hills are oriented in a northwest-southeast direction, the same direction as ice movement is reported to have occurred here in the last glaciation of Ireland. The altitude of the hills ranges from approximately 140 - 170 maOD, 60 - 90m above the lake surface levels (Figure 3.8) and the orientation of the surface drainage channels and lakes in the study area mirrors the orientation of some of these hills closely (Figure 3.7). The hills are located mainly on the Derravaragh Cherts, but steep-sided hills are also located in differing lithologies to the northwest, northeast and southeast of the study area located (Figure 3.9) including pure unbedded limestones, assorted metasediments, and impure bedded limestones (McConnell et al. 2001; Morris et al. 2003).

3.4.2 Quaternary geology

The study area has been subject to glaciation a number of times, most recently by the Midlandian Glaciation. This has resulted in glacial and fluvio-glacial deposits blanketing the bedrock to depths exceeding 25 m. The direction of ice movement in the last glaciation was northwest-southeast. The tills in the area are largely derived from cherty limestone (Fealy et al. 2004). The till blanket varies in thickness, and has been measured as at least 10 m deep in Fore Valley (Brown 2002), but anecdotal evidence from borehole drilling suggests that it may be up to 25 m thick near the flanks of Knockeyon Hill at the east end of Lough Derravaragh. There are significant fluvio-glacial deposits (Gravels in Figure 3.10) to the north of White Lake, and smaller fluvio-glacial deposits (Gravels in Figure 3.10) scattered throughout the

area (Figure 3.10). Many of the valleys between the hill ridges in the area contain deposits of marl which in many cases is overlain by fen peat, which suggests the presence of paleo-lakebeds (Figure 3.11). Some of these marl deposits have been shown to have a depth in excess of 3 m. Much of the glacial overburden in the northern section of the study area has been classified as kame and kettle material (Finch 1977; Finch et al. 1983).

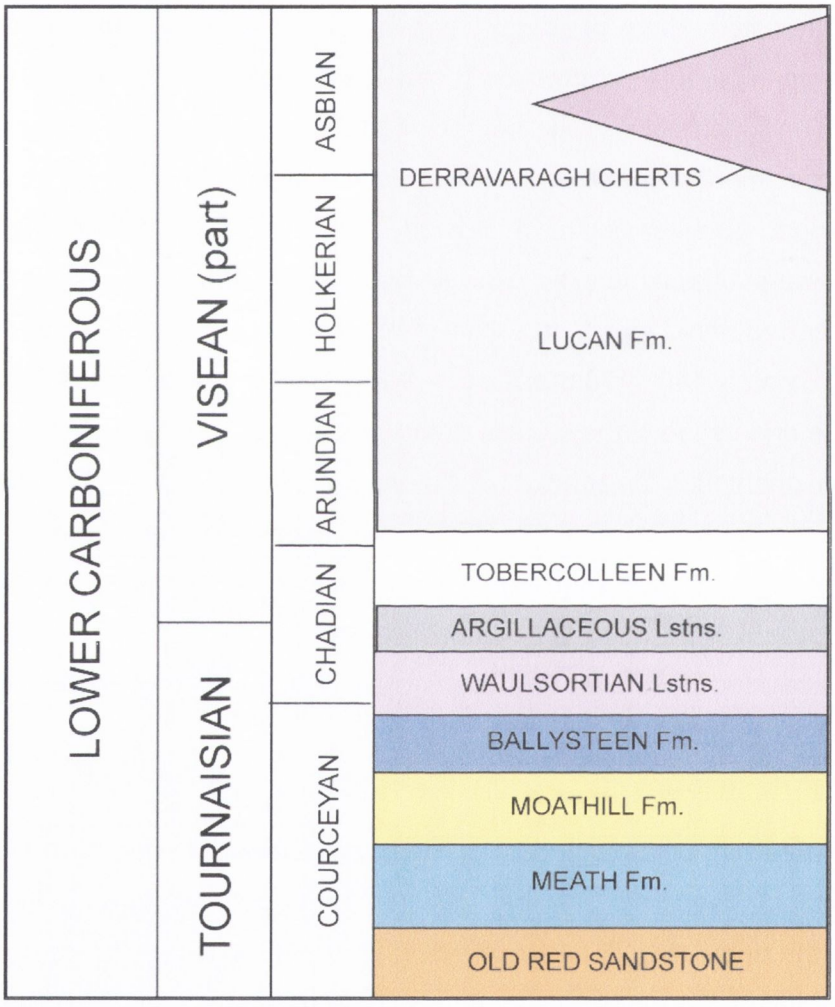

Figure 3.5 Schematic lithostratigraphy of the study area (Morris et al. 2003).

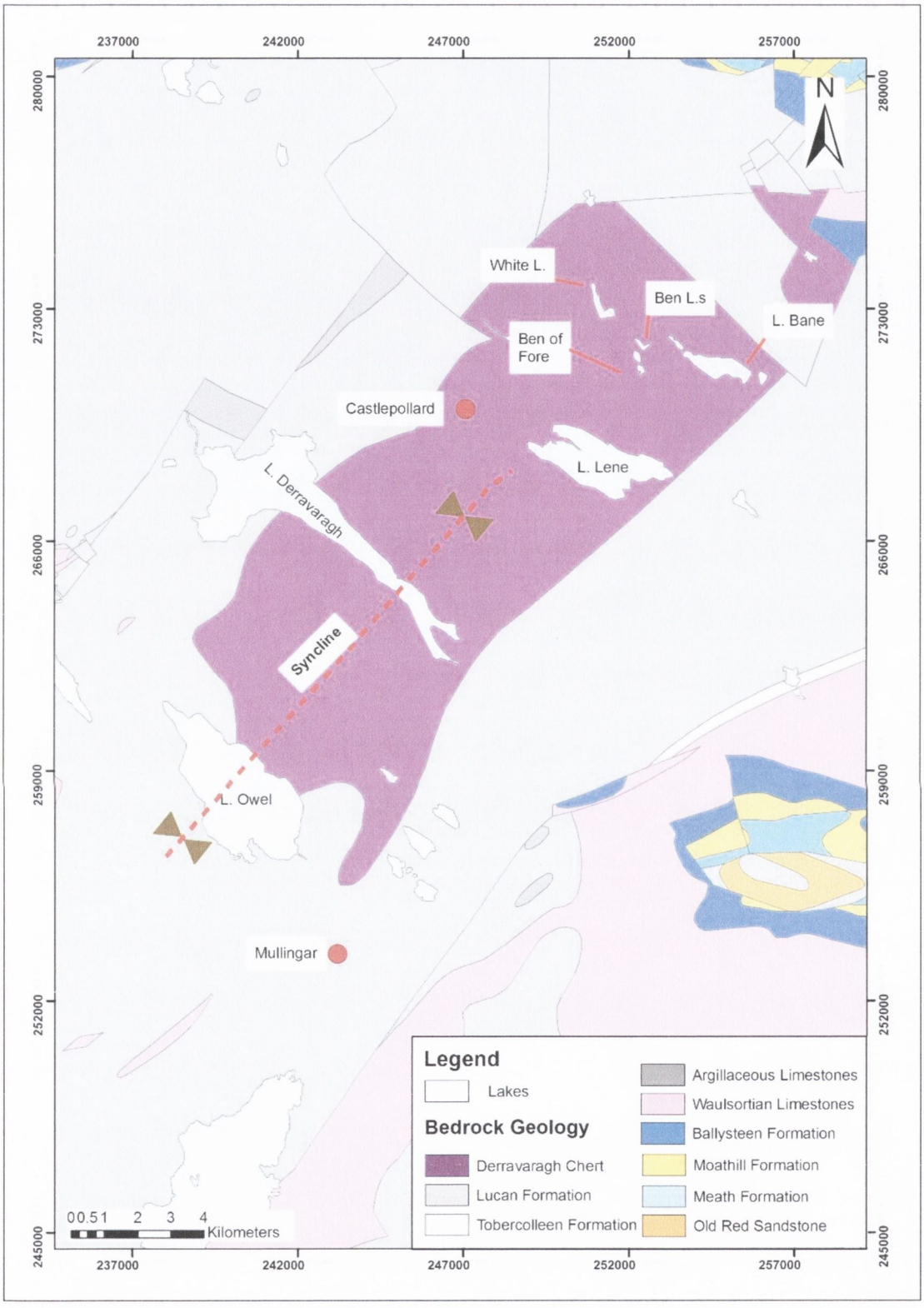

Figure 3.6 Bedrock geology of the study area (source data GSI 2001, 2003).

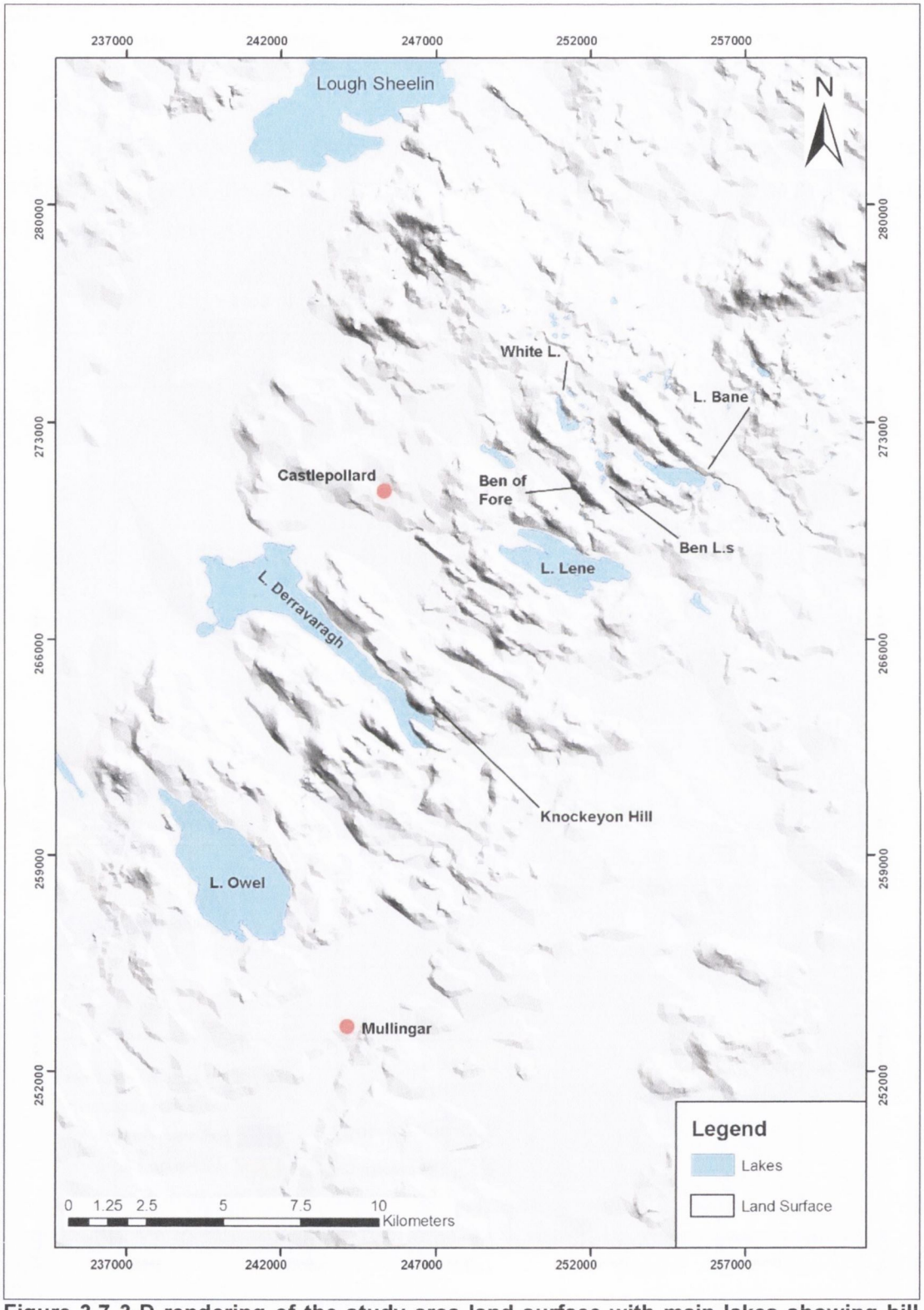

Figure 3.7 3-D rendering of the study area land surface with main lakes showing hill orientation and crag and tail features (basemap data OSI 2001).

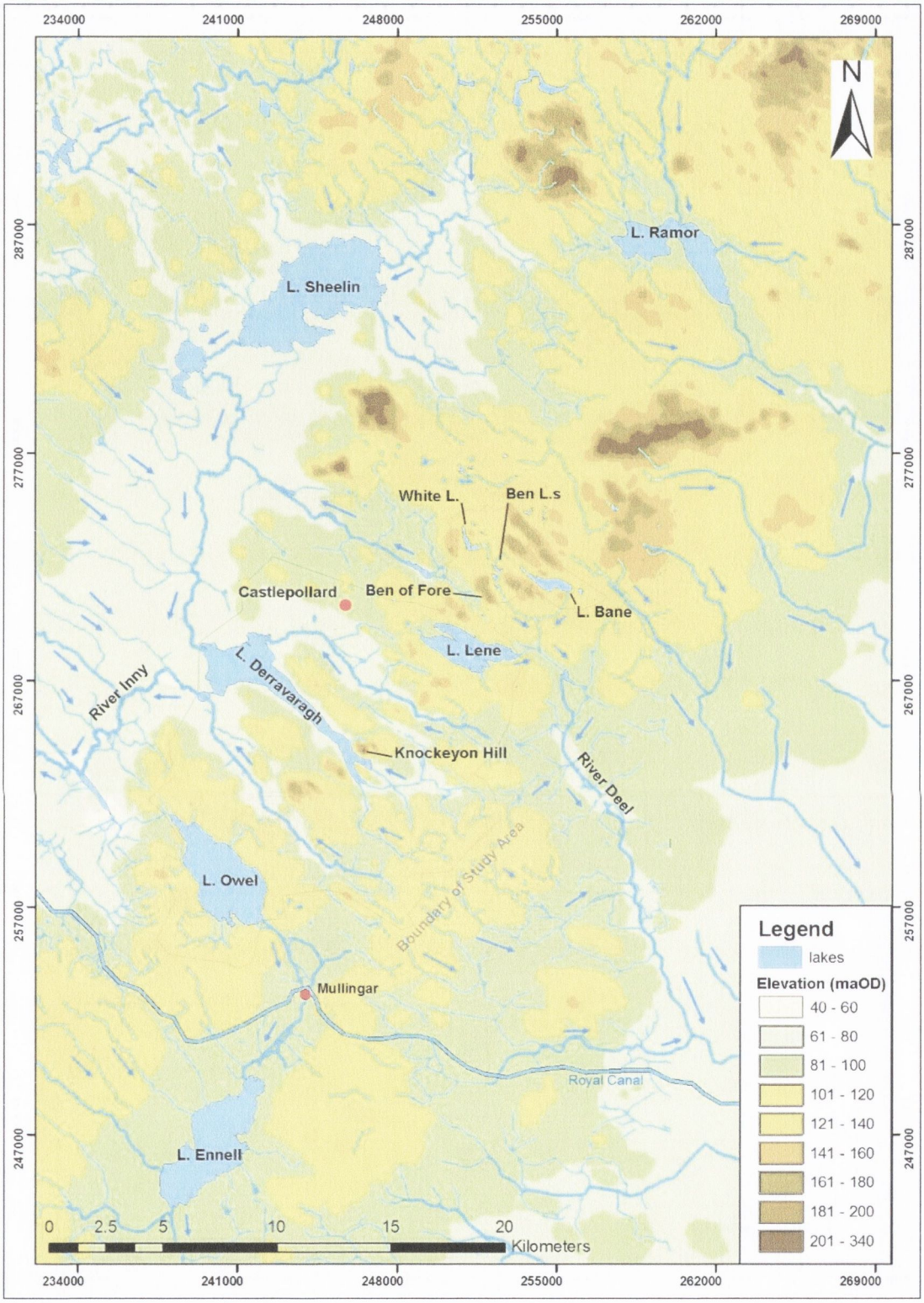

Figure 3.8 Topography and surface drainage of the study area (basemap data OSI 2001).

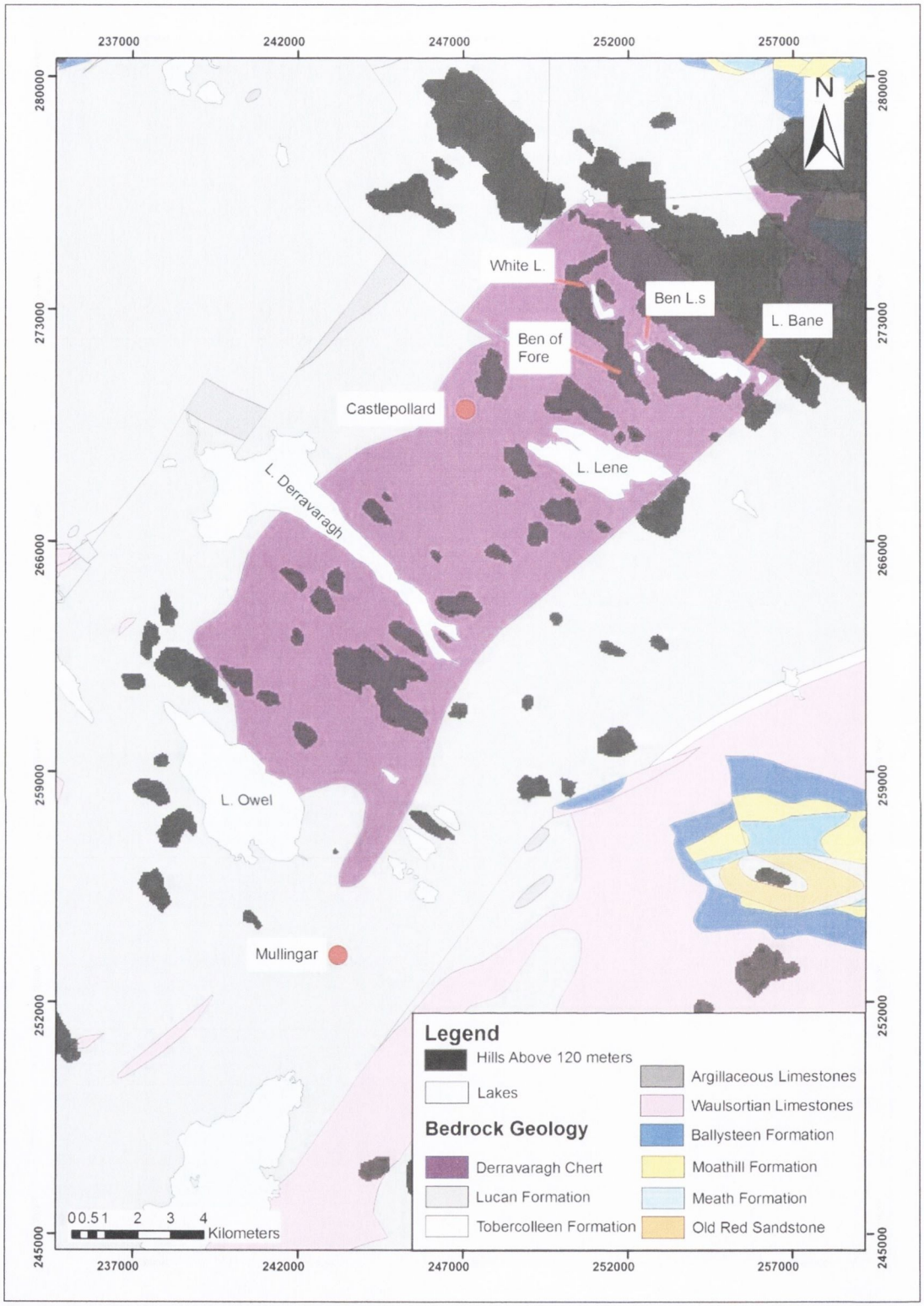

Figure 3.9 Location of hills (> 120 maOD) in relation to bedrock geology (basemap data GSI 2001, 2003; OSI 2001).

3.4.3 Topography and geomorphology

3.4.3.1 Hills

There are about 20 hills with spot height altitudes of > 120 maOD in the study area. These hills are mostly oriented northwest-southeast, and are composed mainly of bedrock that protrudes through the overlying till blanket. The orientation of the hills illustrated in Figure 3.7. The highest hill in the study area is the Ben of Fore (216 maOD). As mentioned in section 3.4.1, there are isolated hills located to the northwest, northeast, and southeast of the study area. For example, cliffs occur in a number of locations, notably on the south side of Fore Valley, South of Lough Bane, and on Knockeyon Hill at the east end of Lough Derravaragh. The cliffs south of Lough Bane are the highest (approximately 20 m in height). These cliffs are found at all orientations (Drew 2002). Some of the cliffs may have been formed and/or modified by anthropogenic activities such as quarrying during the past, and it is difficult to identify whether a cliff has been formed by natural processes or as a result of anthropogenic actions. The reason for the existence of these hills is unknown and it has been proposed that they may be glacial crag and tail features (Clarke & Meehan 2001), or glacially modified karst hums from an earlier Tertiary karst landscape (Drew & Jones 2000). The till blanket masks the true depth of the bedrock valleys and possibly obscures some altogether (Drew 2002). The hills located to the northwest, north, and northeast of the study area are formed in different lithologies to those in the study area and suggest that there may not be a straightforward lithological explanation for the morphology of the hills.

3.4.3.2 Glacial landforms

The midlands of Ireland were covered by ice during the Midlandian (Devensian) glaciation. The general direction of ice movement in the study area was northwest – southeast, although a north-south orientation north of Lough Glore has been postulated by Meehan (1999). Many of the hills in the study area exhibit crag and tail attributes with a steeper crag oriented to the northwest and a tail oriented to the southeast (Meehan 1999). This northwest-southeast orientation is also reflected by numerous striae etched on the hills during the last glaciation (Finch 1977). A Digital Terrain Model (constructed by the author for use in this study) of the study area land surface and illuminated from the northeast (Figure 3.12), demonstrates the orientation of the hills and the crag and tail phenomena very effectively. Loughs Owel and Derravaragh are also aligned in a northwest-southeast direction as they

occupy the valleys between the hill ridges in the area and opinion has been divided as to whether the lakes were held in bedrock basins or were dammed by moraine deposits (Charlesworth 1963; Finch 1977; Drew 2002). The northwest-southeast orientation can also be observed in an area to the immediate west of the study area which was classified as a drumlin field by Finch (1977). However, Clarke & Meehan (2001) have reclassified many of these features as rogen (ribbed) moraine. The northern part of the study area (North of Lough Lene and east of White Lake) contains numerous ice stagnation landforms, typically kames and kettle holes which give the landscape in this area a hummocky appearance (Figure 3.11). It is thought that these landforms were formed by melt-out of the Midlandian ice sheet (Synge 1979). This theory was refined by Delaney (1995) who suggested that such landforms were formed by the northwestward migration of a narrow zone of stagnant ice instead of the mass downwasting of the Midlandian ice sheet.

3.4.3.3 Karst landforms

A number of karstic and possible karstic landforms have been identified and mapped in the study area (Figure 3.13). By landform type, the most numerous are springs, all but 2 of which have discharges < 5 l/s and only 2 of the springs in the area are known to flow all year round or nearly all year round and which are the largest springs in the area - Tobernacogany and Toberfaolaigh in Fore Valley. Three swallow holes are also known to exist in the study area. All of these swallow holes are located around the margins of Lough Lene and no swallow holes in the area have their input from streams. There is a small turlough located to the south east of Lough Derravaragh (Sheehy-Skeffington et al. 2006).

The only evidence of caves in the study area though is a feature on the 6 inch map, marked as a cave and located to the south of Lough Derravaragh and a small rift cave (< 2 m long) located in the cliffs above Fore (Drew 1997). The cave near Derravaragh was not located in the field and a coniferous plantation now covers the area where it was shown on the 6 inch map. There is geophysical evidence from Fore Valley in the north of the study area (Brown 2002) that karstic conduits filled with glacial sediments may exist, although this is only based on an interpretation of one set of geophysical measurements. Caves have been described on the Rock of Curry and the Hill of Usineach (Simms 1991) to the west of the study area, but they are located in a different lithology comprised of purer limestones than the

Derravaragh Cherts. No dolines had been identified in the area. Small enclosed depressions do exist in the area but these have been classified as kettle holes in the glacial tills (Finch 1977). Figure 3.13 is a map of all karstic landforms reported in the study area prior to this study.

3.4.4 Soils

The soil types in the study area are greatly influenced by the bedrock, glacial deposits, and their relative position in the landscape. Glacial processes such as the formation of kames and kettle holes have resulted in a confused pattern of soil complexes being formed. Generally, soils found on the higher ground in the study area are better drained than soils found in the topographical hollows. Many of the valleys in the area contain fen peat that has been drained to varying degrees. The soils of the study area consist mainly of grey-brown podzolics (Rathowen Series). Near rivers, streams and lakes, this is usually replaced by fen peat (Banagher and Pollardstown Series). Brown earths (Baggotstown and Ladestown Series) are located throughout the study area, but on a relatively small scale, and lithosols (Knockeyon Series) are commonly found crowning the limestone hills in the area (Finch 1977; Finch et al. 1983).

3.5 Land use

The land in the study area is predominantly used for pasture. There are small forestry plantations - < 5% of the total study area (based on interpretation of 2004 OSI aerial photography), located primarily on marginal land where either poor drainage or steep slopes precludes grazing, or the production of silage. In such low lying, marginal areas where forestry is not present peat bog is commonly present. Industrial peat production is practiced along the course of the River Inny, to the west and northwest of Lough Derravaragh. The land use of the area can for the most part be classified as pasture with marginal land either used for forestry or left as bog in low-lying areas, or gorse scrub on higher ground.

3.6 Surface hydrology

3.6.1 Rivers

The study area straddles the topographic catchment divide between the Shannon and Boyne Basins. On modern 1:50,000 OSI maps (OSI 2001) Lough Lene and Lough Bane are mapped as flowing into the River Boyne system through surface channels via the River Deel. The springs Tobernacogany and Toberfaolaigh are mapped as flowing into the Shannon system via the River Glore and River Inny. Lough Owel and Lough Derravaragh are mapped as also flowing into the Shannon system through surface channels via the River Inny (Figure 3.1 and 3.2). The River Inny is located to the west of the study area and flows in a southwesterly direction from north of the study area, before flowing into the Shannon further downstream. The River Deel flows in a southeasterly direction from Lough Bane, before flowing into the River Boyne. The Inny has a trellised drainage pattern as the river itself flows to the southeast while most of its tributaries are oriented northwest-southeast. The Deel system is more dendritic in appearance, with tributaries following no dominant pattern of orientation. The streams and lakes of the study area largely follow a northwest-southeast orientation. There is evidence from Drainage Commissioners Reports that the surface drainage in many of the catchments in the study area has been modified over the past 150 years, for example Battersby (1851), Gray (1850), Bevan (1846), and Jones & Mulvaney (1846).

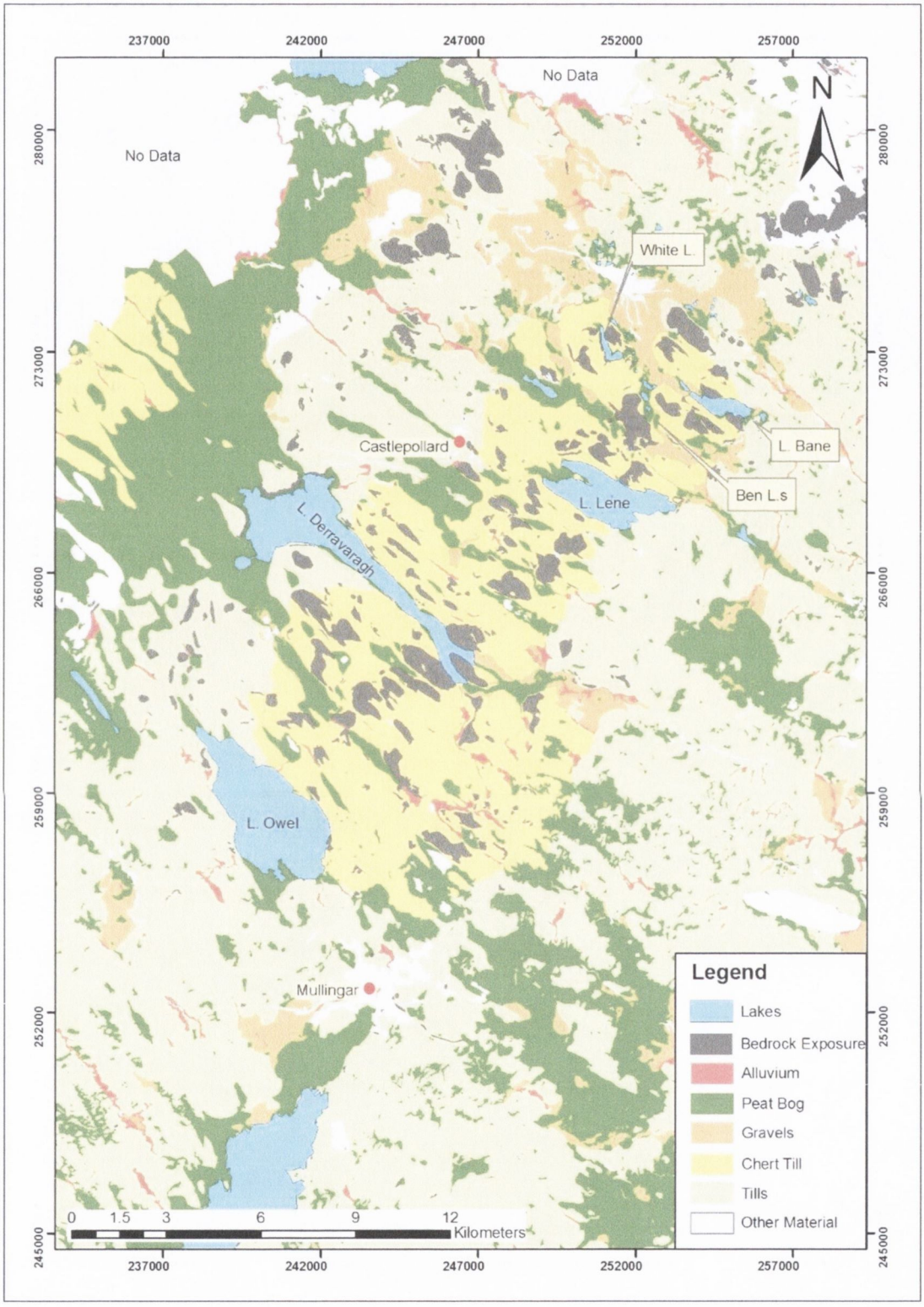

Figure 3.10 Quaternary geology and bedrock exposures (source data Teagasc 2004).

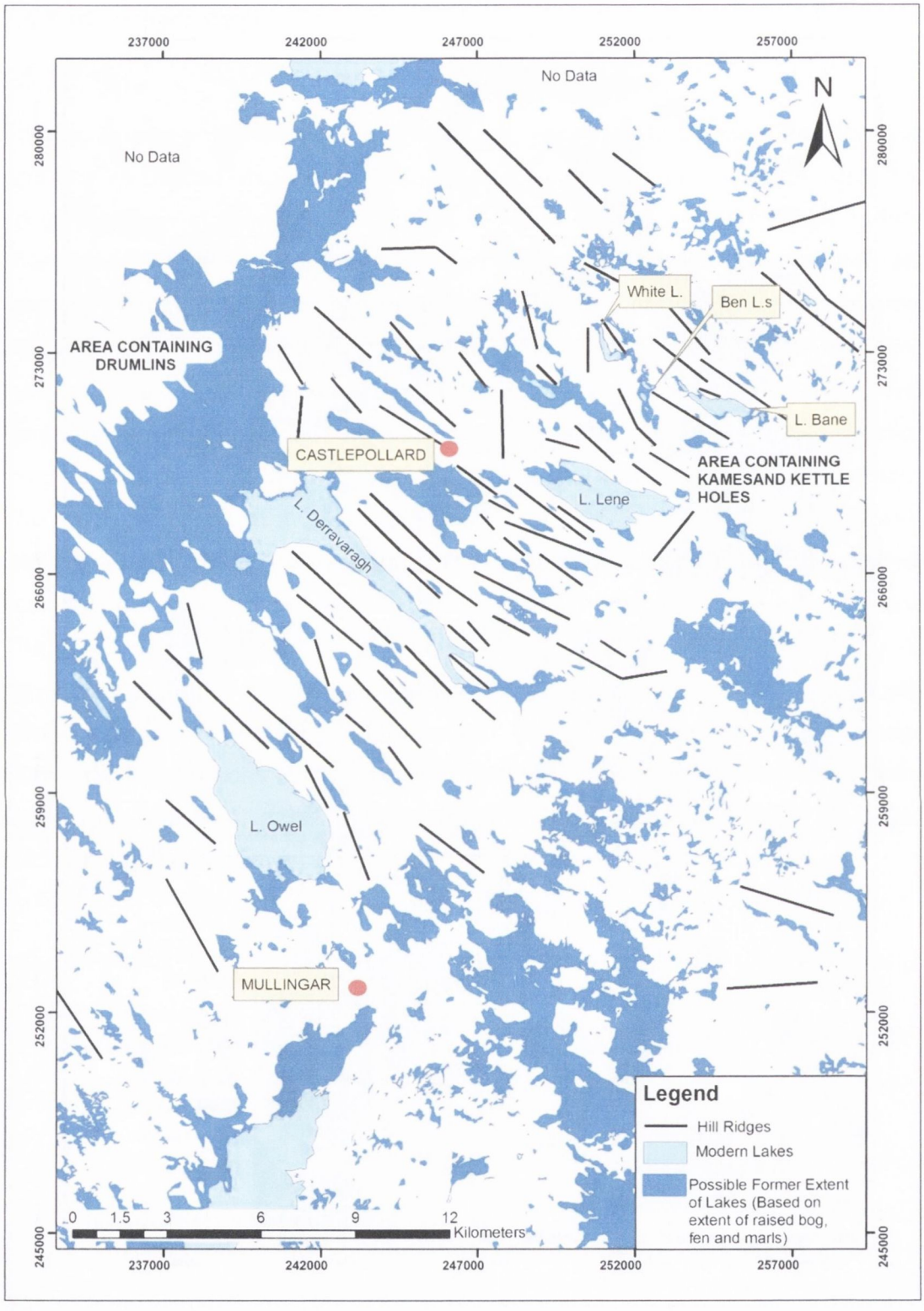

Figure 3.11 Quaternary landforms and orientation of hill ridges in the study area (basemap data Teagasc 2004; OSI 2001).

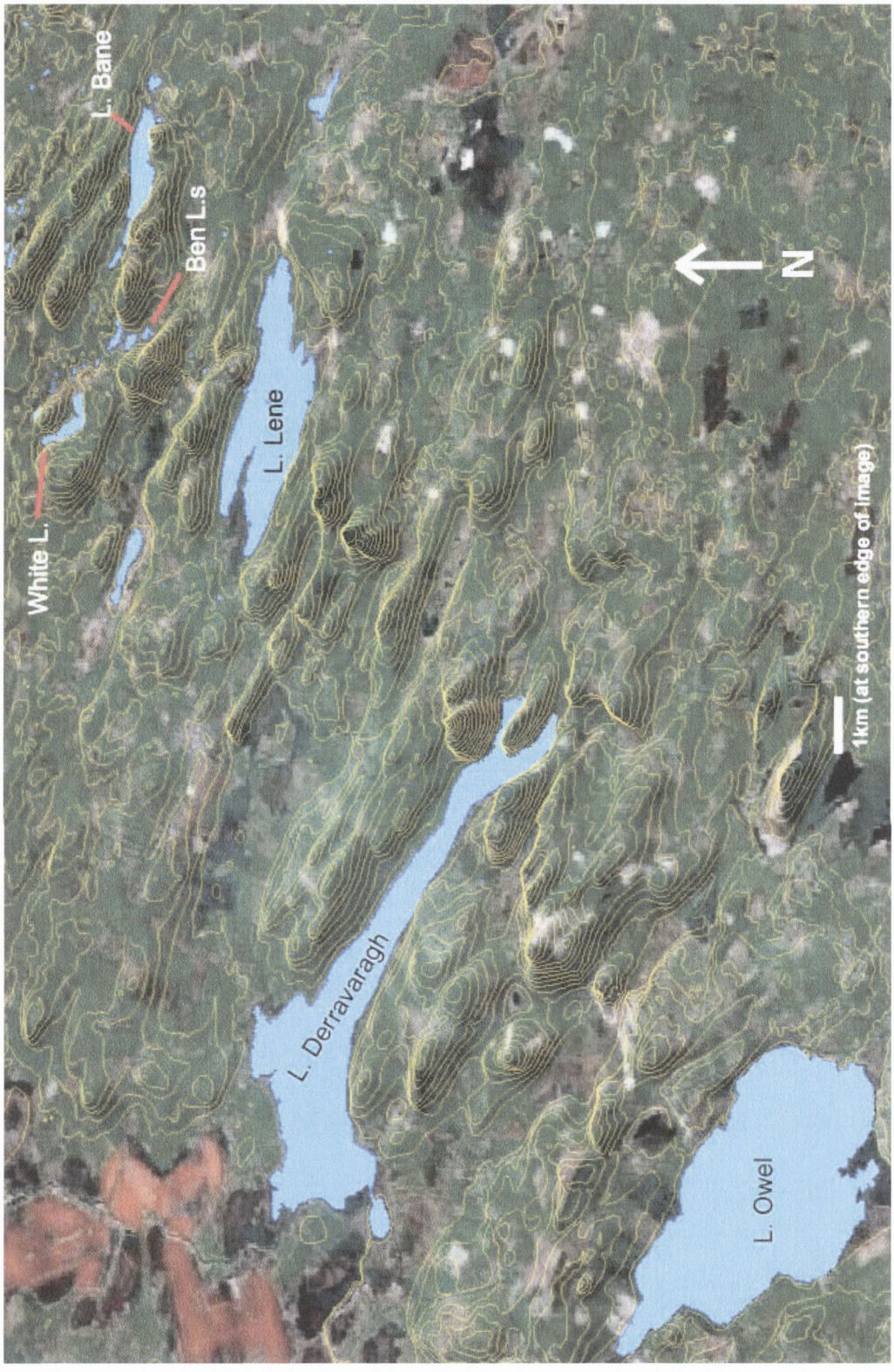

Figure 3.12 Crag and tail features (Oblique view looking north, lit from north east, OSI 10m interval contours overlain onto landsat image. Vertical exaggeration x 5) (basemap data OSI 2001; Landsat 1999).

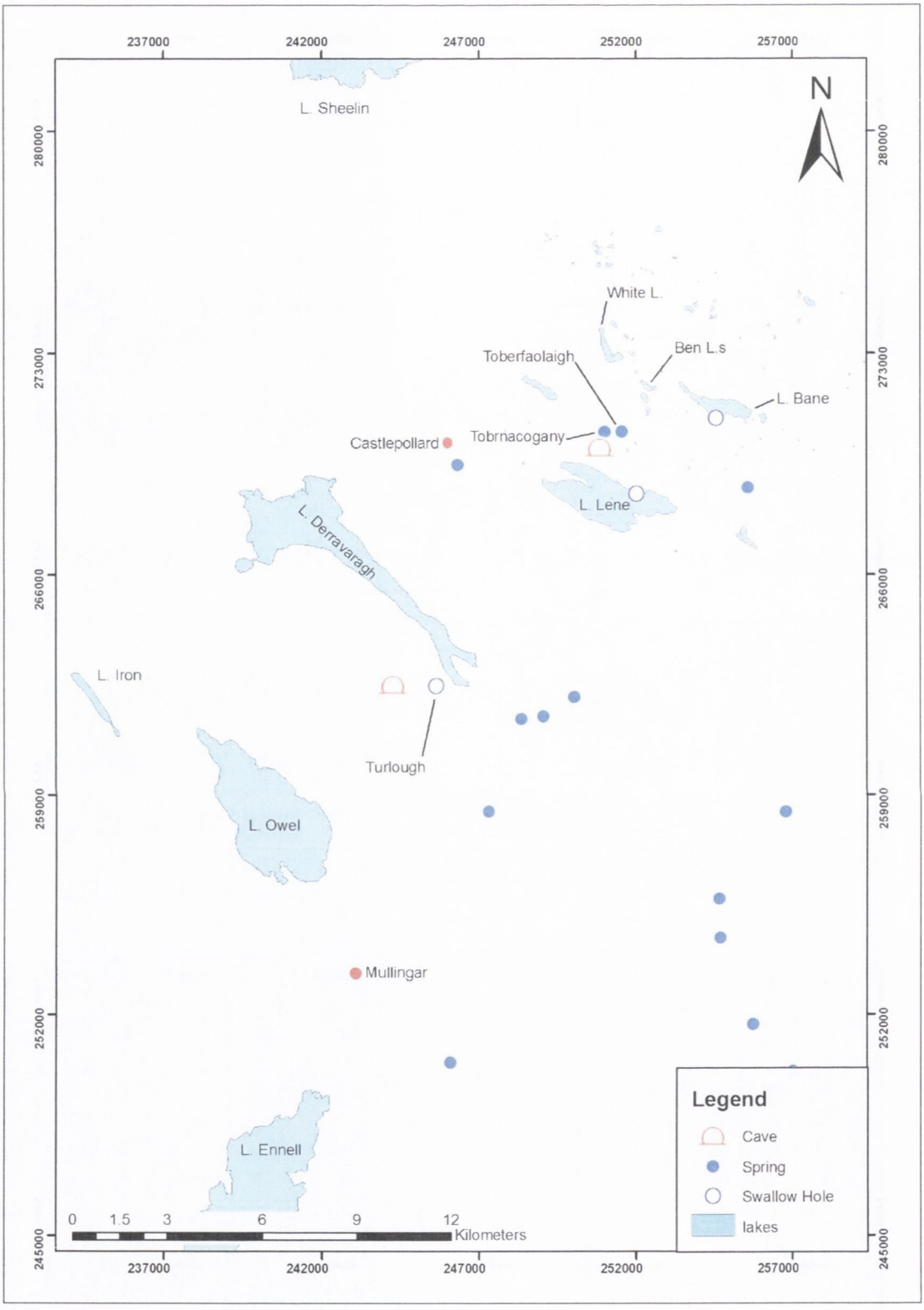

Figure 3.13 Karstic Landforms identified in the study area prior to this study (source data GSI Karst Data Base; OSI 1837 6 inch map).

3.6.2 Lakes

There are six lake catchments in the study area: Lough Owel; Lough Derravaragh; Lough Lene; White Lake; The Ben Loughs; and Lough Bane. The surface levels of the lakes range in altitude from 97 m (Lough Owel, Lough Lene) to 112 m (Lough Bane). Most of the lakes are oriented northwest-southeast. Only Lough Derravaragh is situated along the course of a large river (the River Inny). The other lakes have either small influent streams or no surface inflow at all. As regards the study area itself, its total area is approximately 215 km², of which lakes make up over 25 km² (about 12%).

3.7 Hydrogeology

3.7.1 Recharge

The study area is underlain by the Derravaragh Chert and Lucan Formation limestones (Figure 3.6) (McConnell et al. 2001; Morris et al. 2003). These rocks are buried in places by glacial and fluvio-glacial deposits of varying thicknesses through which recharge must be transmitted. Recharge in the lowlands of Ireland has been estimated at up to 50% of precipitation and up to 75% of precipitation in upland areas where thinner soils are commonly present (Lee & Daly 2002). This suggests that recharge in the study area could be as high as 460 mm annually. Three swallow holes had been identified in the area prior to this study and the volume of water flowing into them does not account for the total volume of water discharging from Tobercognay and Toberfaolaigh springs. No sinking streams had been identified in the study area prior to this study.

3.7.2 Watertable configuration / flow systems

On the National Draft Bedrock Aquifer Map (Figure 3.14) the Derravaragh Chert is classified as a 'Locally important aquifer – karstified'. Primary porosity is negligible in this rock type and groundwater flow occurs via fractures and fissures in this well bedded and jointed rock (McDonald 1988). The Lucan Formation is classified on the National Draft Bedrock Aquifer Map as a 'Locally important aquifer – bedrock which is productive only in local zones', although this is a large formation and borehole yields vary significantly in different areas (Wright 2000). The Derravaragh Chert has

been characterised as having low storativity and to be dominated by fissure flow , with conduit flows occasionally encountered (GSI 2003).

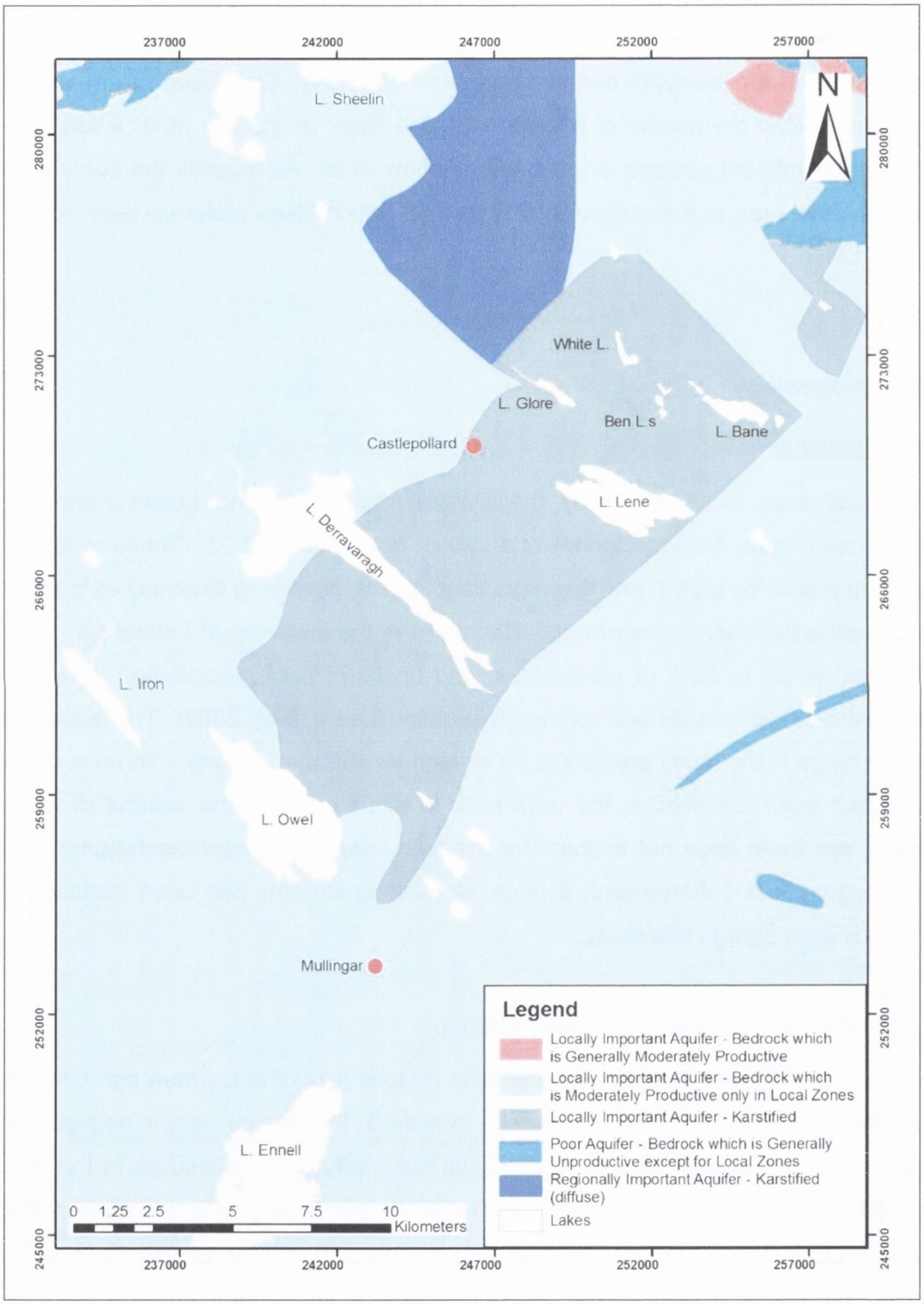

Figure 3.14 Bedrock Aquifer Map of the study area showing aquifer types and lakes (source data GSI National Draft Bedrock Aquifer Map).

McDonald (1988) examined the configuration of the watertable in the northern part of the study area - the catchments of Lough Lene, Ben Loughs, and Lough Bane, Tobernacogany and Toberfaolaigh (Figure 3.15). This investigation consisted of one set of standing water level measurements from wells and boreholes located in the study area. The altitude of springs in the area was also measured and these springs were assumed to be surface expressions of the altitude of the saturated zone for the purposes of watertable mapping.

According to this map, the watertable in the area exhibits a high degree of localised variation in terms of both altitude and flow direction. The altitude of the watertable generally rises to the northeast, in common with the altitude of the land surface. Groundwater mounds were mapped under some of the hills in the area such as the hill ridge south of Lough Lene. The most distinctive feature of the map is a trough in the watertable located around Fore Valley. Groundwater flow is inferred (from the map) to be converging on Fore Valley and discharging in a line of springs which run from Fore Village to west of Lough Glore. In McDonald's work (1988) the highest recorded altitude of borehole standing water levels within the study area was to the northeast (128 maOD) and the lowest altitude of borehole standing water levels was measured near Fore village (82 maOD). This represents a hydraulic gradient of just over 0.01, which is at the higher end of the scale for the Irish Midlands described by Drew (2008). This map was constructed from one set of well standing water level measurements and as a result it is a single recording of the position of the watertable in this part of the study area and no information about groundwater level change was available prior to this present study. It is difficult to ascertain what proportion of flow in the aquifer is conduit flow and what proportion is in fissures. In many eastern areas of the lowland limestones of the midlands, fissure flow is assumed to be dominant (Marchant & Sevastupolo 1980; Wright 2000). However, there is evidence of conduit flow in parts of the study area. McDonald (1988) successfully traced the source of Tobernacogany spring to the swallow holes at the north shore of Lough Lene, with a flow of approximately 70 l/s, at 80 m/h, and a hydraulic gradient of just under 0.005. No traces of the dye were recorded in samples taken from nearby Toberfaolaigh spring.

Geophysical evidence from Fore Valley suggests that glacial overburden and fen peat overlies bedrock that is highly karstified in places (Brown 2002). The existence

of a turlough southeast of Lough Derravaragh is further evidence for karstic conduit flow. This landform also suggests a seasonal variability in the position of the watertable and that the watertable is close to (and above part of) the land surface in the study area for at least part of the year. Such conduit flows, if present, contrast with the small springs and relatively low productivity wells known to predominate in the eastern parts of the Lucan Formation (Wright 2000; Drew 2008).

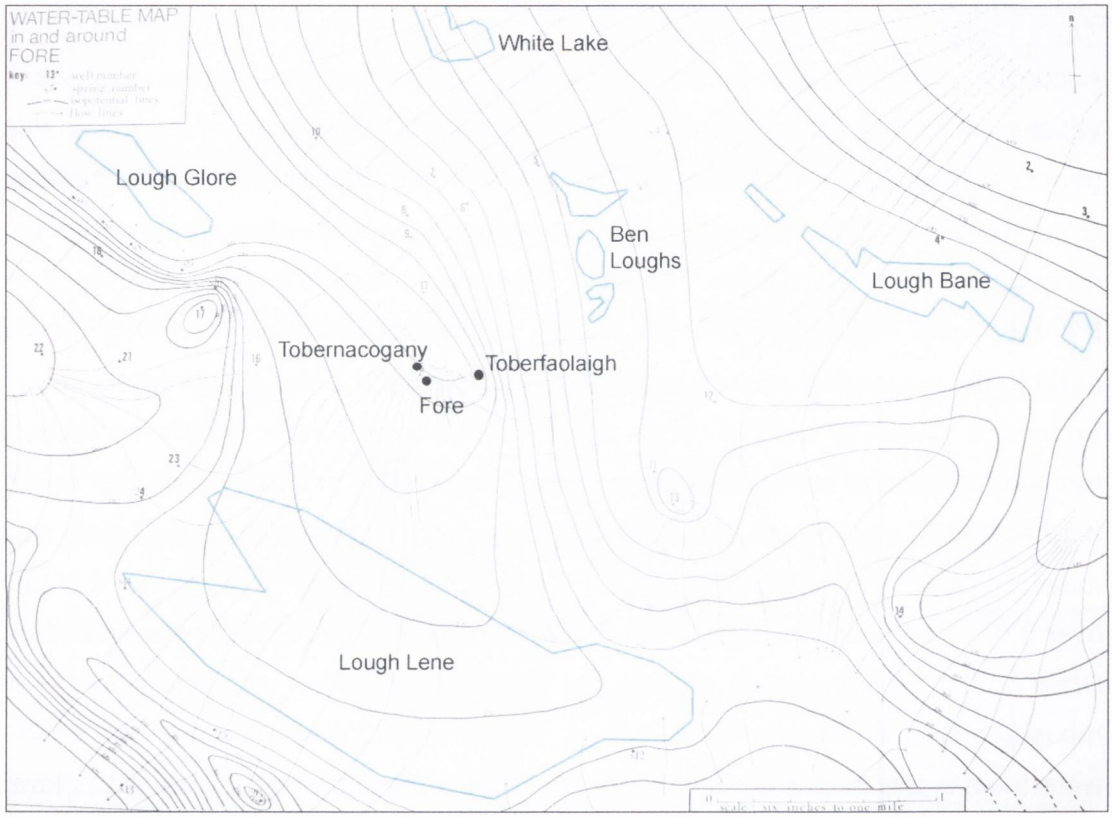

Figure 3.15 McDonald's watertable map of the area around Fore (the blue lines indicate the approximate location of the lakes) (from McDonald 1988).

3.7.3 Discharge

There are numerous springs mapped in the study area, most of which have small discharges (in the region of 1 - 5 l/s) in common with the majority of springs in the Irish Lowlands (Drew & Chance 2007). It is possible that the discharge from many of these small springs is not derived from groundwater discharging from the saturated zone, but from throughflow derived from the glacial/fluvio-glacial overburden (Drew 2008). Prior to this study only two strong springs (Toberfaolaigh and Tobernacogany) had been recorded in the area. McDonald (1988) states that

Toberfaolaigh is active all year round and has an average conductivity of about 450 µS/cm, while Tobernacogany commonly dries up from late summer to winter and has an average conductivity of about 200 µS/cm, less than half the value recorded at Toberfaolaigh. McDonald recorded water temperature at Toberfaolaigh as 9.0 °C, and at Tobernacogany as 7.1 °C when the air temperature was 4.3 °C. The horizontal distance between these springs is 530 m and the vertical difference is approximately 2.4 m (Tobernacogany is higher than Toberfaolaigh). Thus there are striking differences in the behaviour of springs located within 2 km of each other. These measurements may indicate that the water discharging from Toberfaolaigh has spent a considerably longer time in the aquifer than that of Tobernacogany. Such highly localised variations in spring characteristics are indicative of karstic groundwater flow where different groundwater flow systems co-exist and a clearly definable watertable is difficult to discern.

Previous research on the study area has suggested that groundwater discharge is likely to occur into Lough Lene, and possibly Lough Bane, below the level of the lake surface (McDonald 1988). A study carried out by Westmeath County Council in 2003 as part of their long term environmental strategy estimated that 21% of all inputs to the Lough Owel catchment were groundwater discharge into the lake (Westmeath County Council 2005). Other studies carried out on Lough Lene (For Westmeath County Council) and Lough Bane (For Meath County Council) in the 1970s are discussed by McDonald (1988) but the reports are now unobtainable. According to McDonald (1988), these reports concluded that Lough Lene and Lough Bane were spring-fed lakes and that actual catchment delineation for these catchments was impossible. Thus, previous research has shown that permanent lakes appear to be an important point for groundwater discharge in the study area.

4. Methodology

4.1 Introduction

The aims of this research were addressed by employing the following methodological approach. A pilot study of a large area of the Westmeath Lakelands (215km²) was carried out in order to select a smaller representative area for a detailed study. In the pilot study, a desk study, field mapping programme, and surface water data collection programme were carried out to refine the study area to a spatially contiguous, representative area. It was necessary to investigate the degree of anthropogenic modification evident in the various catchments in the pilot study area. This was because the catchments selected for further study were required to have hydrological integrity, i.e. they must not have been extensively modified by anthropogenic actions. The pilot study did not include a groundwater element, as its purpose was to define an area for detailed study. The aims of this project were addressed using a range of methods including both surface water and groundwater elements. The structure of the methodology used in this project is presented in Figure 4.1.

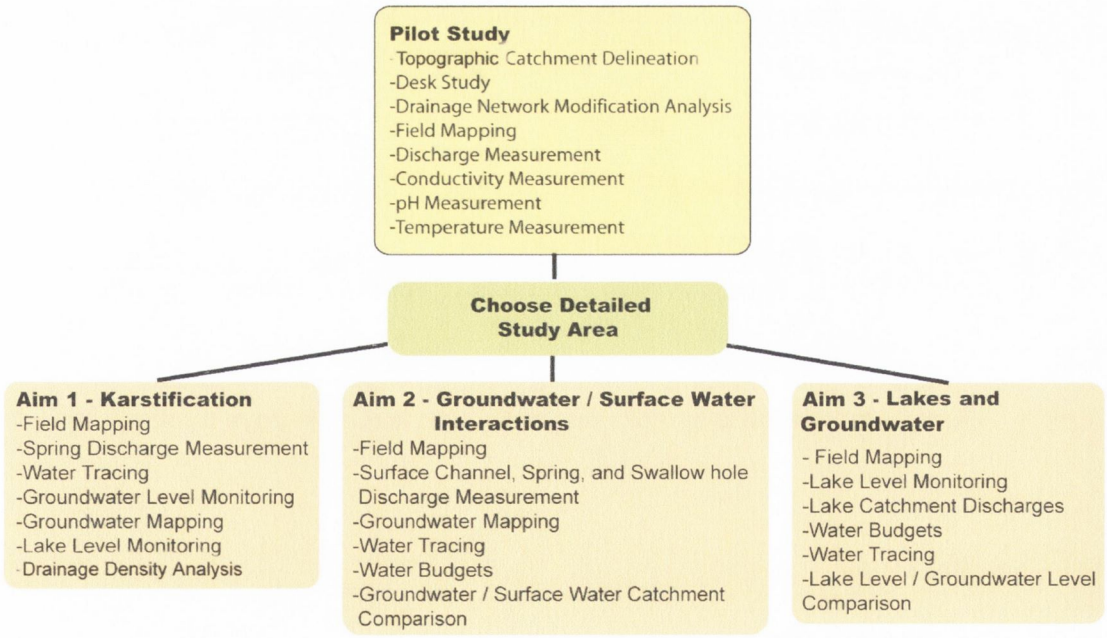

Figure 4.1 Project methodology outline.

As summarised in Figure 4.2, data collection for this project was carried out over a three year period, from October 2004 to September 2007. An initial desk study was undertaken and selection of measurement sites commenced in October 2004. The field-based element of the pilot study ran from March to June 2005. On this basis, the lake and spring catchments to be included in the detailed study area were then selected. The desk study was continued for the detailed study catchments until January 2006 and the field mapping until January 2007 to ensure that as much information as possible was collected. The assembly of the well network was undertaken from June 2005 to October 2006. This element took longer than expected due to a number of factors. The automatic well recorders were installed in October 2006 and removed in August 2007. The groundwater and surface water elements of the detailed study overlapped from March 2007 to August 2007. Dye tracing was carried out in September 2009. In this chapter the aims, objectives and methods of the pilot study are described first. The methods employed in the detailed study are then described.

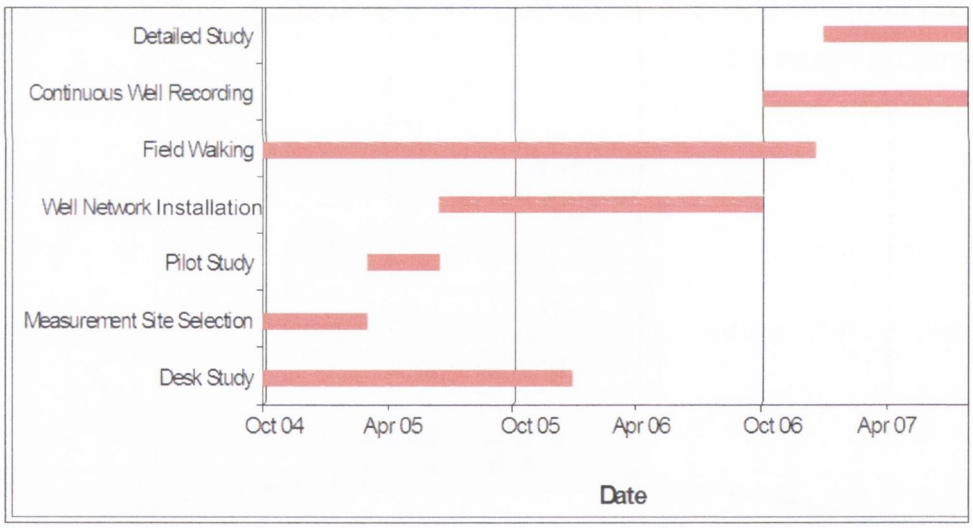

Figure 4.2 Timeline of project data collection (excluding dye tracing).

4.2 The pilot study

4.2.1 Aims and objectives

The aim of this study was to examine a number of topographically defined lake and spring catchments in the Meath-Westmeath Lakelands in order to select a smaller number of these catchments for a more detailed, longer-term study. The pilot study

examined the topographically defined catchments of: Lough Owel; Lough Derravaragh; Lough Lene; Lough Bane; the Ben Loughs; White Lake; Tobernacogany spring; Toberfaolaigh spring; and Fore Valley upstream of Lough Glore (Glore Bridge). The smaller area chosen as a result of the pilot study had to:

- be representative of the Meath-Westmeath Lakelands
- have hydrological integrity
- be spatially contiguous
- be suitable for the implementation of the chosen methods

The above aim was achieved by completing the following objectives:

1. The surface catchments in the study area were topographically delineated and catchment surface outflow measurement points were chosen for each of these catchments.
2. A desk study of existing available data was completed.
3. A field-mapping data collection programme was carried out to validate existing information collated in 2 (above) and to collect new information, in particular identifying and mapping of karstic landforms.
4. GIS based and cartographic analyses were used to identify whether/how the surface drainage system in the study area has been changed and/or is affected by anthropogenic actions such as drainage schemes or water extractions.
5. Measurements were made of the following variables at the catchment outflow points: discharge; conductivity; temperature; and pH.

4.2.2 Topographically defined surface catchment delineation

Surface catchments have been defined as '*The area that topographically appears to contribute all the water that passes through a given cross section of a stream*' (Dingman 1994, p. 14). For this study lake and spring catchments were defined as the topographically defined area contributing runoff to a stream measuring point, or if no surface outflow from a lake is present then the topographically defined limit of the area of the enclosed depression contributing runoff to the lake. Delineation of surface catchments is usually carried out using topographic maps. Topographical catchment delineation was carried out for this study so that surface discharge measurements from the different catchments could be normalised to discharge per

unit of area and compared to each other, i.e. this would indicate whether the amount of discharge from a study catchment could be accounted for by the topographically defined surface area of the catchment based on precipitation inputs. This delineation was achieved through combining observations from field-mapping and topographic map data. The map data used were OSI 1:50,000 and 6 inch elevation data, and 1:50,000 lake and stream data in digital format. The data sets were overlain in ArcGIS 9.1. Topographically defined surface catchment boundaries were then delineated for each catchment, with the outflow points situated in places where surface channel discharge volume could be accurately measured downstream of the lakes - in catchments where a surface outflow was present. If no surface outflow existed in a catchment, i.e. if it was an enclosed topographic depression, the limit of the area contributing runoff to the enclosed depression was delineated.

4.2.3 Desk study

The desk study involved compiling and evaluating existing and available data pertaining to the study catchments. The desk study involved assessing and evaluating records kept by the GSI, the Office of Public Works (OPW), Meath County Council, Westmeath County Council, the Inland Waterways Association of Ireland, Teagasc, and the Environmental Protection Agency (EPA). In addition, OSI maps were studied. Descriptions of the sources used can be found in Appendix A. The following is a list of topics and sources utilised in the desk study:

- Structural geology

GSI 1:100,000 bedrock geology map
GSI open source files

- Lithology

GSI 1:100,000 Bedrock maps and accompanying booklets

- Geomorphology

Academic papers and field guides such as "The bathymetry and origin of the larger lakes in Ireland" by Charlesworth (1963)

- Quaternary deposits

Teagasc subsoil maps (2004)

- Soils

Teagasc soil maps (2004)

- Topography

OSI 1:50,000 elevation data (2001)

- Precipitation

Met Éireann precipitation, evapotranspiration, and soil moisture deficit records from the Mullingar synoptic station

- Groundwater

GSI National Draft Aquifer Map

GSI Karst Database

- Surface hydrology

Drainage channels from the OSI 1st edition 6 inch maps (1837, dates of individual lake surveys in Appendix A)

Drainage channels from the OSI 25 inch maps (1889 & 1908, dates of individual lake surveys in Appendix A)

Drainage channels from the OSI 1:50,000 maps (2001)

Inland Waterways Association of Ireland (Royal Canal)

Assorted Drainage Commissioner Reports (Arterial drainage schemes)

GSI Karst Database

OPW hydrometric data

EPA water quality data

Meath-Westmeath County Council hydrometric data

River Basin District Authorities (RBDs) (River Basin District boundaries)

Data relevant to the study area were extracted from the above for each study catchment. This included: lake and catchment areas; geology; soil and subsoil types; topography; karst features present; available sources of hydrometric data; and anthropogenic influences on the catchment. Possible anthropogenic influences include: extraction from lakes; artificially induced changes in outflow discharge such as moveable sluices; and drainage schemes.

4.2.4 Field-mapping

The field-mapping was carried out for each catchment in the initial study area to aid in accurate catchment delineation, selection of lake and spring catchment discharge measurement sites and for geomorphological interpretation. Due to time constraints and the size of the initial study area, field-mapping had to be confined to areas that evidence from the desk study suggested might contain karstic features such as springs and swallow holes or areas where changes in the surface drainage network have been undertaken in order to ground-truth these changes. Anecdotal evidence was gathered from informal interviews with locals. When a landform was located, its location was recorded using a handheld GPS unit. A Garmin GPS76 unit was used for field mapping. This unit has an accuracy of <15 m RMS 95% (root mean square error) (Garmin International Inc. 2002) and was used in this study for horizontal but not vertical positioning. Where possible, features were also photographed, both close-up and at distance to record their detail and to contextualise their position in the landscape (selected photographs are presented in Appendix E). The appropriate dimensions of the feature were then measured using an engineers measuring tape. Appropriate dimensions depended on the feature type, e.g. in the case of a doline the length, width, and depth were measured, while in the case of mushroom stones the height from base of stone to the mushroom lip was measured. All features and possible features identified during the field-mapping programme were recorded in a database, an example of which is contained in Table 4.1 (full list of karst features and their attributes is contained in Appendix D). The fields that were recorded in this database for all features were:

1) Feature Type (such as swallow hole, doline, etc.)
2) Feature Name (if applicable e.g. Tobernacogany)
3) Grid Reference
4) Altitude
5) Dimensions (if appropriate)
6) Previously mapped/not mapped,
7) Townland name.
8) For certain features such as swallow holes, additional fields were included such as: active/inactive; input type (stream/lake).

Feature Type	Swallow Hole
Feature Name	White Lake SH1
Grid Ref.	5102472906
Altitude	106
Dimensions	1.6 m deep ~2 m wide
Previously Mapped	No
Townland	Carpenterstown
Active	Yes
Input Type	Lake

Table 4.1 Example entry from the Landform Data Base (Appendix D).

4.2.5 Identification of modified surface drainage networks and lake storage volumes

Three approaches were employed to establish whether the surface drainage system had been anthropogenically modified by drainage schemes: informally interviewing locals; reading the reports of Drainage Commissioners (e.g. Bevan 1846); and examining changes in the surface drainage network and lake surface areas from OSI 6 inch, 25 inch and 1:50,000 maps produced between 1837 and 2001. Mapping and spatial analysis were carried out in a GIS environment using ArcGIS 9.1. The GIS techniques used are described in Appendix B. Where survey dates at a monthly or daily resolution for individual lakes in the 1st edition 6 inch maps were not available, the 6 inch maps were overlain with the 25 inch maps (which contain survey dates in the form day/month/year for all of the study lakes) to identify differences in lake outlines. No differences were observed between the 6 inch lake maps and the 25 inch lake maps. The 6 inch maps were then used for the comparative analysis described below.

By comparing the 1837 lake perimeters with modern OSI 2001 1:50,000 elevation data it was possible to estimate the degree of change in terms of storage volume in each lake between 1837 and 2001 by calculating the change in storage volume as the volume of a truncated regular cone:

$\Delta S = [(a+b)/2) \,.\, h]$ **Equation 1.**

Where ΔS = storage change in m^3; a = 2001 lake surface area in m^2; b = 1837 lake surface area in m^2; and h = the height difference between the 1837 and 2001 lake levels in m.

The altitude of the land surface around the 1837 lake perimeters was estimated using scanned, georeferenced 1st edition 6inch maps and OSI 1:50,000 elevation data in the form of a Digital Elevation Model (DEM) in a GIS program. The DEM is accurate to within 2m in most places but different altitudes for the 1837 lake surfaces were obtained from the DEM around the lake perimeters. These differences could be due to errors in the DEM, or infilling or excavation of the lakeshore since 1837. For each lake the highest, lowest, and median altitude figures from the DEM for the 1837 lake surface level were recorded. The difference between each of these figures and the 2001 lake surface was then calculated. 2001 and 1837 lake surface areas were computed by measuring the area of the respective lake surface polygons in the GIS. The volume in m^3 of the space between the 2001 lake surface and the 1837 lake surface was then calculated using the formula shown above. Three estimates for storage change were calculated for each lake: a maximum figure based on the highest estimated altitude difference between the 1837 and 2001 lake levels; a minimum figure based on the lowest estimated altitude difference between the two lake levels; and a median estimate halfway between these two extremes. Lake bathymetry data was available from the **I**dentification of refere**N**ce-**S**tatus for **I**rish lake typolo**G**ies using palaeolimnological met**H**ods and **T**echniques INSIGHT project (Taylor et al. 2007) for Lough Lene and Lough Bane. Lake bathymetries were calculated for these lakes with the bathymetrical data contained in the INSIGHT report using the same method as for the lake storage change volumes. The volumes between bathymetrical contours (i.e. 5m, 10m depth contours etc.) were treated as truncated cones and the volume of each truncated cone was calculated separately before adding the resulting individual volumes between depth contours to calculate the total lake volume for each lake.

Survey dates for the lakes were included on the 1st edition 6inch maps and these dates had to be taken into account (i.e. were the lakes surveyed during winter or summer) when drawing conclusions from the lake storage change data. The volumetric results had to be considered as only indicative of possible storage changes, as elevation data in gently sloping areas near lake shores can be

inaccurate or at too low a resolution to allow such volumetric estimates to be reliably calculated. These estimates are indicative only and a rigorous assessment of their accuracy is outside the remit of this study. The lake surface area and storage change information was used in conjunction with the analysis of surface drainage network change to identify areas where the surface drainage system has been significantly altered.

4.2.6 Surface water measurements

4.2.6.1 Introduction

Site selection for stream discharge measurement was governed by the availability of suitable sites for using the velocity-area method. As part of the pilot study salt dilution method was employed on the River Inny inflow and outflow to/from Lough Derravaragh as this channel is too deep and the flow in these locations too strong to use the velocity-area method. However, this attempt was unsuccessful and the suitability of stream channels for the velocity area method was used as one factor in site selection for the detailed study. It must be borne in mind that the error estimate of this method under ideal circumstances is ±9%, detailed explanations of this method can be found in Dingman (1994) and Shaw (1994). Where possible, sites with straight-sided, clean-bedded channels where turbulence would be minimised were selected. As outlined in section 4.2.2, the outflow points for the topographically delineated catchments were chosen based on their suitability for measurement of channel discharge volume, i.e. places where the channel had minimal turbulence with smooth sides and floor.

The most suitable measuring sites were found to be under bridges, where channel floors and walls were constructed from concrete. This had the effect of reducing turbulence and making flow gauging considerably more accurate than measuring in a natural channel. Many of the sites required some cleaning to remove blocks, boulders, and vegetation from them before they were suitable.

The Following parameters were measured at each of the flow measurement sites:

- surface channel discharge (litres/second)
- conductivity (µS/cm)
- temperature

- pH

4.2.6.2 Surface channel discharge

Discharge was determined using the velocity-area method except in the case of Lough Derravaragh which is detailed separately below. The instrument used was a Global Water electromagnetic rotary impeller type current meter. This method can give accuracies to within ±5% under ideal conditions (Sauer & Meyer 1992).Three sets of data, each of which was collected within an eight-hour period were collected for the pilot study. The discharges were measured during spring/early summer when effective precipitation and stream discharges should be broadly representative of annual mean flows as this period does not, on average, have the highest or lowest effective rainfall amounts according to 30 year data from Met Éireann (Met Éireann 1961 - 1990 data) (http://www.met.ie/climate/mullingar.asp).

Due to the large size of the River Inny channels entering and exiting Lough Derravaragh, it was not possible to use the velocity-area method to record discharge. An attempt was made to estimate discharge from this lake using a dilution method as described by Mesnier (1966), and Rantz et al. (1982). This attempt was unsuccessful and it was not possible to measure the discharge from the Lough Derravaragh catchment.

The mean stream discharge figures, i.e. the mean values of the three sets of measurements for each catchment, were divided by the area of the catchment in question to calculate specific runoff (SR). These figures allow comparison between catchments as they express how much runoff was produced per unit area of surface catchment. Differences in SR between catchments may be caused by such factors as water extraction, differences in precipitation amounts, varying levels of evapotranspiration, and/or transfers of groundwater between catchments (Shaw 1994) (Figure 4.3).

Only an approximate figure was required for the pilot study and, as a result, a comparison of normalised catchment discharges with extractions accounted for would be sufficient, and precipitation and evapotranspiration were taken to be the same per unit area of catchment for the purposes of the pilot study. The SR figures

for the study catchments were compared to each other and to EPA SR figures for the entire Boyne and Shannon catchments.

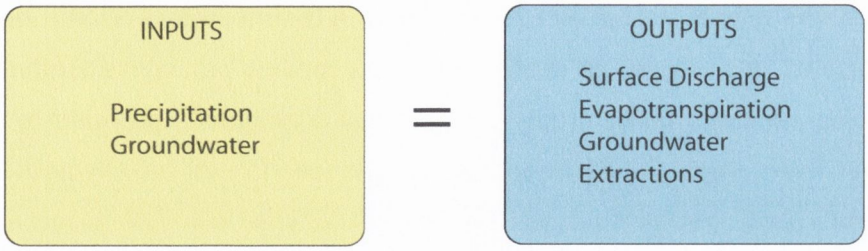

Figure 4.3 A simple water balance conceptual diagram.

4.2.6.3 Conductivity measurements

Electrical conductivity readings were taken at the same locations as the discharge measurements. Electrical Conductivity was recorded in µS/cm using a WTW LF 330 Conductivity meter. Electrical conductivity is usually positively correlated to calcium hardness, bicarbonate, and total dissolved solids and along with precipitation, discharge, and temperature, is part of the most fundamental set of hydrological variables in hydrochemical studies (Hunkeler & Mundry 2007). Analysis of the coefficient of variation of electrical conductivity values from springs has been utilised as a means of classifying whether flow to a spring is predominantly fed by matrix flow, fissure flow, or conduit flow (White 2003). However, the results of such analysis must be integrated with other data before firm conclusions may be drawn as such a hydrochemical approach alone does not always provide an accurate indication of the dominant flow type to a spring (Massei et al. 2007). Furthermore, while the relationship between electrical conductivity and residence time is complex, changes in the electrical conductivity of discharge water during a flood event can provide information as to the nature of the overall functioning of the system under investigation, such as the occurrence of piston effects from increase in recharge, for example the investigation of karst aquifer storm response in Kentucky by Hess & White (1988).

4.2.6.4 Temperature measurements

The water and air temperature measurements at each site were analysed to examine their variability, maximum and minimum values and to examine whether sites displayed water temperatures typical of groundwater (~10.5°C) in Ireland (Burdon et al. 1983) , especially at times when the air temperature at the same

location was markedly different, e.g. a water temperature of 10.5°C and an air temperature of 24°C would suggest that groundwater discharge had contributed to discharge at the measuring point in question. Temperature was measured using a field thermometer with probe (Rototherm Therma thermometer). Water temperature was measured by inserting the probe into a slow moving part of the stream that was not in direct sunlight. Time of day and weather conditions were also recorded as differences in temperature between sampling locations can be affected by diurnal fluctuations.

4.2.6.5 pH measurements

Accurate measurement of pH in the field is important in order to enable comparison between different streams/springs/ lakes etc. in terms of their relative acidities and their saturation state with respect to calcium carbonate. pH can be difficult to measure accurately in the field and care is required to ensure consistency in sampling methods and locations (Sasowsky & Dalton 2005). To reduce the possibility of cross contamination, the measuring probe was rinsed with de-ionised water between measurements. The pH measurements were examined to ascertain whether they were in the range of pH values typically recorded in Irish karst spring waters (6.8 – 7.9 pH units) (Drew & Chance 2007), although it was noted that water discharging from a karst spring may occasionally have a pH value outside this range, possibly as a result of coming in contact with peat deposits or contamination from human or agricultural waste (i.e. organic acids) such as has been suggested for rainwater percolating through peat in Venezuela (Piccini & Mecchia 2009). It was also necessary to measure pH at all injection and sampling sites where Fluorescein dye was being used in a tracer test as Fluorescein loses fluorescence in water with pH <5.5. pH was measured using a WTW pH 330i meter.

4.3 Methods used in the detailed study

4.3.1 Introduction

Section 4.3 is divided into sections detailing methods used for: 1) Identifying and mapping landforms such as dolines and swallow holes; 2) Measuring surface water parameters; catchment discharge, water conductivity, pH, temperature, and lake level oscillations; 3) Measuring groundwater parameters -standing water levels,

watertable mapping and dye tracing; 4) Water Budgets; and 5) Drainage density calculation.

4.3.2 Landform identification and measurement methods

4.3.2.1 Field-mapping

Due to time constraints during the pilot study it was not possible to survey all parts of the study catchments on foot. To ensure that all surface landforms relevant to this study were identified, field-mapping was also carried out during the detailed study. This was not duplicating work carried out previously as only areas not accessed during the pilot study were examined. Landform measurement and recording techniques during this field-mapping programme were the same as those described in Section 4.2.4 except in cases where landforms were too large to be accurately measured in the field. In such cases GIS techniques were used to measure the features concerned. Field mapping was used: 1) to determine the amount of surface karstic landforms in the study area, 2) to provide information about potential points of interconnection between the groundwater and surface water systems, and 3) to identify possible groundwater - lake interactions.

4.3.2.2 Landform measurement - GIS methods

Where landforms such as dolines were too large to be accurately measured with an engineers measuring tape in the field (taken in this study to be any landform >50m long or wide), a GPS measurement of their location was taken. These features were then located on georeferenced ortho-photographs (in ArcGIS) and accurately measured. Detailed descriptions of GIS methods used in this project are presented in Appendix B. These measurements were then entered into the Landform Data Base

4.3.3 Surface water data collection and analysis methods

4.3.3.1 Sampling network and period

The surface water measurement programme was carried out using the same sampling sites that were used in the pilot study (except those in the catchments that were excluded as a result of that study). Discharge, electrical conductivity, pH, temperature, weather conditions, and time of day were recorded at each site.

Under ideal conditions a data collection period for a detailed hydrological study would run for at least one hydrologic water year (October 1st – September 31st) (Todd & Mays 2005). As the aims of this study were to investigate groundwater – surface water interactions, it was necessary for the surface hydrology and groundwater measurements to be recorded simultaneously. However, assembling the well network took longer than expected. As a result, the simultaneous data collection period was reduced to a five-month period. The five-month period can be justified as this period ran from the time of year when precipitation was high to when it was low, i.e. from winter to summer (Rohan 1986). Thus hydrological variables were measured during a period which encompassed the full range of high to low flow hydrological conditions. Measurements were recorded every one to two weeks.

4.3.3.2 Discharge, conductivity, temperature, and pH measurement

Discharge at all sites was measured using the velocity – area method described in Section 4.2.6.2. The discharge measurements recorded were tabulated and compared with precipitation measurements recorded at the Met Éireann Mullingar Synoptic Station. This was done to investigate the response of the surface drainage system to variations in levels of inputs (precipitation). Conductivity was measured using the methods outlined in Section 4.2.6.3. Air and water temperatures were recorded using the same methods detailed in Section 4.2.6.4, and pH was measured using the methods presented in Section 4.2.6.5. During an attempted water tracing experiment in July 2007 discharge measurements at the Roaring Well spring were undertaken using a bucket/bin and stopwatch method due to the fact that this spring flows from a slightly elevated position in the side of a hill. However, it was felt that accurately measuring the time needed to fill a receptacle while minimising/accounting for spillages may lead to inaccuracies. Therefore, during the September 2009 water trace a 4 m long channel was constructed downstream from the spring and the springflow was diverted into it, thus facilitating discharge measurement using the same velocity area method as at the other sites.

4.3.3.3 Lake surface level measurement

Lake level fluctuations were deemed to be of importance as they may relate to turlough type behaviour in the hydrological functioning of the study lakes. If a lake is spring fed, a clear relationship may exist between changes in groundwater level, and changes in spring discharge to the lake and possible lake surface level (Bonacci

1993). Initially this involved talking to local people, to gather anecdotal evidence relating to lake surface level fluctuations. During the first year of the study the lake levels were monitored by eye for changes (this was done while field mapping etc. was being carried out). Continuous lake level recorders are maintained by the EPA on Lough Lene and Lough Bane, and these data were obtained for use in this study. Thus there was no need to separately measure the levels in these lakes. On the Ben Loughs the lake surface levels were monitored by measuring with a staff gauge. A staff gauge could not be installed at White Lake as both field observations and anecdotal evidence suggested that the range of seasonal fluctuations in the surface level of this lake were too great to permit the satisfactory installation of a staff gauge.

The fluctuation of the surface level of White Lake was measured as follows:

1. A reference point above the highest level of the lake was selected (this had to be changed as the lake rose to an abnormally high level during the winter of 2006/2007)
2. As the lake level receded, a surveying level and ranging pole were used to measure the difference in altitude between the reference point and the present lake level. As two people were required to do this, it was not possible to measure the lake level during each visit to the study area. When such instances occurred, a photograph was taken of an identifiable, fixed object (such as a fence post) with a mark on it to indicate the lake level. The previous lake level could then be measured with the level on a subsequent visit.

4.3.4 Groundwater data collection and analysis methods

4.3.4.1 Sampling network assembly

Groundwater standing water level measurements were carried out and subsequently watertable contour maps were constructed: 1) to establish groundwater standing water levels fluctuations in the study area; and 2) to investigate the direction of groundwater flow in the study area.

In karst aquifers borehole / well standing water level fluctuations are commonly not representative of other parts (or the majority) of the aquifer due to the heterogeneous nature of karst aquifers in which two boreholes only a few meters

apart may yield very different hydrometric results due to the presence or absence of conduits, fractures and fissures in each borehole (Bakalowicz et al. 1995). When variance in permeability is so unevenly distributed and as a borehole is representative of only a small fraction of an aquifer there will always be uncertainty as to the actual hydraulic properties of the overall aquifer under investigation (Milanovic 1981). Hydrometric data from boreholes must be analysed together with tracer test results, spring hydrograph results and hydrochemistry data to arrive at a more complete understanding of the nature of flow though and storage in a karst aquifer (Kresic 2007).

Bearing the above in mind, and in order to establish the configuration of the watertable it was necessary to assemble a suitable well network in the study area from which point standing water level data could be obtained. For regional studies a sampling point density of 1 per 25 km² is sufficient, but for smaller areas such as 1 hectare, a much higher density with a minimum of three wells is required (Brassington 1998). As the study area under investigation covered an area of approximately 35 km², the number of sampling points required would lie between the extreme values. The actual density of sampling points was dictated by the availability of suitable wells/boreholes, but based on estimates of Irish well numbers (e.g. Wright 1999), a suitable sampling point density was assumed to be obtainable. It was necessary to locate all available wells and boreholes and examine each to evaluate their suitability for use as groundwater monitoring points. Different types of wells/boreholes exist in Ireland including:

1. Boreholes, a) in use and regularly pumped, and b) not in use and not pumped.
2. Hand-dug water supply wells with/without hand pumps, not in use.
3. Smaller pools of standing water, e.g. holy wells.

1, a) Boreholes, in use and regularly pumped. This type of well was unsuitable for establishing the altitude and fluctuations of the watertable as the standing water level is artificially lowered and changed by the pumping of water from these wells (Brassington 1998). Consequently the danger that drawdown could give misleading standing water level data was deemed too great to include this type of well in the

sampling network. Borehole diameters are commonly around 15 cms with borehole depth depending on local conditions.
b) Boreholes, not in use and not pumped. The disused status of these boreholes was verified before inclusion in the well network and permission obtained where necessary.

2. Hand-dug water supply wells with/without hand pumps (not in use). These wells were located either by field-mapping or by locating them on the 6 inch and 25 inch maps. Once located, the suitability of each well for inclusion was assessed. The easiest wells to exclude were those which had been filled in, of which type there were many examples. As these wells were hand dug, they commonly only penetrate 2m below the mean watertable surface and either do not reach the bedrock or terminate at the rockhead (Johnston 1986). Anecdotal evidence, and the fact that they were hand dug suggests that some of these wells are relatively low-yield, drawing water from low-permeability tills or that they tap into perched watertables which may be situated atop lenses of clay in the glacial overburden. It was therefore difficult to arrive at a decision as to which of these wells would be included or excluded.

3, Smaller pools of standing water, i.e. 'holy wells'. These were assessed as possible monitoring points but were discounted as they appear to be simply shallow pits located in marshy ground. An example of this is the holy well at Fore Abbey which was 'relocated' by Westmeath County Council in the 1980s in order to accommodate a new car park at the abbey.
Once a well of any of the three types above was located it was recorded as follows (Groundwater sampling network data is contained in Appendix C & Appendix D):

1. Assignation of a well network number, e.g. W1,W2, etc.
2. Grid Reference
3. Construction method – Borehole/dug and discernable lining type
4. Status – in use/out of use
5. Diameter
6. Total Depth
7. Surface altitude

4.3.4.2 Measurement intervals, and procedure

Once each well was located in the field, well dipping was carried out during each visit to the study area. When the sampling network was fully assembled, groundwater levels were measured over the same 6 month period as the surface hydrology measurements were made (1/3/2007 – 7/8/2007). Sampling took place every one or two weeks. All wells were dipped using a Hydrotechnik Kabellichtlot Type 10, 30 m well dipper. All measurements were converted to meters above Ordnance Datum (maOD) by subtracting the depth to water from the altitude of the measurement reference point (listed in Appendix D). The altitude of the well top was determined by levelling in from OSI benchmarks (where they could be found) or from spot heights on the 6 inch map. In all cases the altitudes of these points were converted from the old Poolbeg Datum to the new Malin Datum. The resulting data set was used to construct watertable maps and also to help choose which wells would be fitted with continuous water level recorders.

4.3.4.3 Continuous groundwater Level measurement

Groundwater standing water levels in 3 wells were continuously measured with automatic groundwater recorders. This was done to measure short term oscillations in the standing water level of the chosen wells. To record the standing water levels, three clockwork-operated groundwater level recorders were obtained from the GSI. These recorders plot groundwater levels on a rotating drum which has a revolution period of 28 days. The groundwater level is gauged by means of a float and counterweight which are suspended from a gearing mechanism in the recorder housing. The recorders are primarily designed for borehole recording and are made to be bolted to special flanges that attach to a flange on a borehole top. In this case, as they were used to record standing water levels in large diameter (1.5 - 2 m) hand-dug wells, individual metal and wood mountings had to be manufactured to secure them in location. This did not affect the operation of the recorders. The results were digitised by marking 12 hour intervals on the X axis of the recorder graph sheets and reading standing water levels from the recorded graphs at each 12 hour interval. This data was then entered into a spreadsheet from which digital graphs were produced.

Preliminary results obtained during the well network assembly period were used to decide which wells would have continuous recorders installed. Wells were initially

prioritised for recorder installation based on the range of oscillation in standing water level recorded during well dipping. The suitability of the well construction to attach a recorder to was also taken into account. This meant that only wells to which the recorders could be securely and safely affixed could be chosen.

The continuously recorded groundwater levels were compared to each other and to precipitation. Cross correlation analysis was used to estimate the most highly correlated lag time between changes in water level in each well and between each well and rainfall events. For the cross correlation analysis the effective daily rainfall was calculated using Met Éireann daily rainfall and potential evapotranspiration data recorded at the Mullingar synoptic station (http://www.met.ie/climate/mullingar.asp). The Minitab 14 statistics programme was used to calculate all cross correlations.

4.3.4.4 Construction of groundwater contour maps

The results of the well dipping programme were used to construct watertable maps. This was done by interpolating (linear interpolation) the point data provided by each set of well standing water level data which were recorded approximately once every one to two weeks. To do this it had to be assumed that the standing water level recorded in a given well was an accurate reading of the altitude of the unconfined watertable, and also assumes linearity in the rate of change between data points. The following steps were taken to construct the watertable maps:

1. The groundwater monitoring wells were mapped in ArcGIS shapefile format.
2. The standing water level (adjusted to maOD) of each well was added to the shapefile as the z co-ordinate.
3. A nearest neighbour interpolation was carried out using these data points to create a raster surface in ArcGIS from which watertable contours could be constructed.
4. The groundwater surface was overlain onto the topographic contours of the study area and the groundwater contours were altered in areas where they showed a higher elevation than the land surface.

4.3.4.5 Water tracing

Water tracing was undertaken: 1) to investigate the sources of springs and to determine the characteristics of the aquifers under investigation; 2) To determine

groundwater pathways between surface catchments; and 3) to determine the resurgence point of water draining into swallow holes from lakes. Detailed descriptions of tracing techniques can be found in Benischke et al. (2007). The following steps were followed in conducting the traces.

Selection of dye injection points and sampling points:

1. The input and possible output points for the traces were identified from documentary evidence collected during the pilot study desk study and the field-mapping.
2. The altitude of the injection point was determined, and all springs under this elevation within 10 km of the injection point were identified as per the technique of Mull (1988).
3. The straight line distance and altitude difference between the injection points and the sampling points were then calculated.
4. Suitable stream channels for discharge measurement were also located as near to the sampling points to measure discharge volumes from the springs.

Background fluorescence

It is important to be able to separate fluorescence caused by the addition of the tracing dye to water from fluorescence caused by other sources. These other sources of fluorescence are known as background fluorescence, defined by Benischke et al. (2007, p. 163) as 'that part of measured tracer concentration not arising from the tracer injected'. This problem was overcome by sampling for a period before the dye was injected – the level of fluorescence measured during this pre-trace period (if any) was then assumed as background during the trace period and the pre-trace fluorescence level was subtracted from the results of all the trace samples. In addition, Gas Activated Carbon (GAC) fluocapteurs were deployed at all sites where there was a possibility of tracer emergence 3 days prior to dye injection. The fluocapteurs were replaced at all sites immediately prior to dye injection.

Dye selection

The dyes selected for injection were sodium fluorescein (CAS RN 518-47-8), and rhodamine WT (CAS RN 37299-86-8). These dyes were selected as they are particularly suited for traces designed to characterise the movement of groundwater and are detectable in very low concentrations (Benischke et al. 2007; Smart 2005).

Dye mass calculation

The equation used to calculate the amount of dye to be injected was that proposed by Worthington and Smart (2003).

$M = 1.9 \cdot 10^{-5} \cdot (LQC) \cdot 0.95$ **Equation 2.**

Where, M= mass of dye in kilograms; L= length from injection to main sample point in km; Q= discharge at sampling point in litres/second; and C= target peak concentration in µg/litre.

Injection techniques

As the aims of the tracer tests were to establish groundwater flow routes and to characterise them hydraulically, the dye was injected into the swallow holes as quickly as possible, i.e. a discrete spike injection as per the technique described by Benischke et al. (2007). To minimise the risk of cross contamination during dye injection the dye was injected by an assistant, extreme caution was exercised, and latex gloves were worn at all times.

Sampling procedures

Gas Activated Carbon (GAC) Fluocapteurs

GAC fluocapteurs were made by enclosing a few grams of activated coconut charcoal in nylon bags. These bags (fluocapteurs) were then placed in the stream channel at the sampling locations out of direct sunlight (under stones, trees, or bridges). The fluocapteurs were held in the centre of each channel by pushing wire coat hangers into the streambed and tying the fluocapteurs to the coat hangers with nylon fishing line. The first set of fluocapteurs were put in place three days before the traces were carried out and then replaced at intervals during the sampling period. The last set of fluocapteurs were removed 56 days after dye was injected. When the fluocapteurs were removed they were placed in ziplocked polyethylene bags and stored in darkness at <4°C until they were analysed.

Water sampling

In this case, a detailed multi-aim test was performed, which was intended to establish connectivity, transit times/flow velocities, tracer concentrations, transport parameters, tracer load, and tracer recovery. One automatic (discrete) water

sampler was obtained and the other three sites were sampled by taking grab samples. The ISCO 6712 Series automatic sampler was used at the Roaring Well sampling point and was set up to take 24 1 litre samples and to self purge before each sample was taken. The intake hose was positioned in the stream channel at a point where it would take a sample of flowing water. For the first 25 hours the sampler was set to sample every 30 minutes. From 25 to 35.5 hours it was set to sample every 2 hours. From then until 73 hours the sampler was set to sample every three hours. As the automatic sampler was unavailable due to its prior reservation, grab samples were taken at the Roaring Well from this point on. When the automatic sampler had finished a cycle, samples were transferred to opaque plastic 100ml sample bottles. Each bottle was rinsed three times with sample water before it was finally filled. The samples were then directly packed into a lightproof bag and transferred to lightproof cardboard boxes to prevent photo-degradation of the samples. The samples were then stored refrigerated <4°C in darkness until they were analysed. The sample holders in the automatic sampler were then rinsed three times before the next cycle of sampling was started.

Grab samples

The grab samples were taken in opaque plastic 100ml sample bottles. Care was taken not to enter the stream and to sample with the mouth of the bottle pointing upstream to obtain as untainted a sample as possible. Each bottle was rinsed three times in the stream before it was filled. The samples were then directly packed into a lightproof bag and transferred from here to lightproof cardboard boxes to prevent photo-degradation of the samples. The samples were then stored refrigerated <4°C in darkness until they were analysed. It is well established that the shorter the travel time, the greater the rate of change in concentration at the sampling point will be (Benischke et al. 2007). Therefore sampling intervals were shorter during the early stages of sampling and became progressively longer. The final grab samples were taken 41 days after dye had been injected.

Fluorometer calibration and analysis procedure

All water samples were analysed in the Geomorphology laboratory in TCD using a Turner designs TD 700 fluorometer. The fluorometer was calibrated in multi-optional mode calibration for both fluorescein and rhodamine WT, and three calibration solutions with respective concentrations 1000ppb, 100ppb, and 10ppb of each dye

were prepared using appropriate dye amounts and deionised water. Each calibration solution was put into the fluorometer and the appropriate level of fluorescence (i.e. 1000, 100, or 10 ppb) was set. In the case of each dye type calibration was completed by analysing a sample of deionised water in a cuvete. The samples were removed from refrigerated storage and analysed within 2 hours. Each sample was analysed three times to reduce the likelihood of errors in analysis. Water from each sample was removed with a disposable pipette and placed in a disposable cuvete. The pipette and cuvete were disposed of after each sample was analysed. Following analysis the samples were returned to refrigerated storage.

Gas Activated Carbon (GAC) Fluocapteurs

The fluocapteurs were first rinsed under distilled water. A few grams of charcoal were then removed from each fluocapteur and placed in 100ml glass jars. The charcoal in each jar was then covered with eluant solution. The eluant solution was prepared following the method described by Smart (1972) and Smart & Simpson (2002) where 1-propanol, distilled water, and 30% ammonium hydroxide was mixed in a 5:3:2 ratio, and the eluant was decanted off once it separated out from this solution. The charcoal and eluant mixtures were left for 1.5 hours to let any dye contained in the charcoal fully elute. The eluant from each sample was then filtered through coarse filter paper into cuvetes. The samples of eluant in these cuvetes were then visually analysed against a white background for the presence of fluorescein or rhodamine. A blank cuvete containing eluant that had not been placed with a charcoal sample was then analysed in the fluorometer under fluorescein and rhodamine settings to measure the background fluorescence of the eluant. The eluant from each sample was then analysed in the fluorometer for the presence of fluorescein and rhodamine.

Breakthrough curve

The breakthrough curves were constructed by plotting the volume of recovered dye per litre of water against time. The following descriptive statistics were then calculated: time of first detection; time of concentration peak; time of concentration centroid; time when half recovered dye has passed; and the end of the observation period.

Mass recovery curve

This curve illustrates the proportion of the total amount of injected dye that passes a sampling point through time and provides information about the hydrological characteristics of the aquifer (Schulz 1998). This is achieved by determining the percentage of the injected dye that passed the sampling point, which is an indicator of the amount of dilution, storage, and flow characteristics that are taking place between the injection site and the sampling point. The mass recovery curve is constructed as the cumulative total of the dye passing the sampling point as a percentage of the total injected dye. Variations in discharge may be accounted for by adjusting for temporal variations in the tracer load (concentration-discharge product).

4.3.5 Water budgets

As this project is concerned with groundwater surface water interactions water budgets for each of the study catchments were calculated. A water budget can be used to estimate net groundwater contributions/losses to/from a catchment by calculating groundwater as the residual of the equation. All the catchments in the detailed study were included. A water budget can be described by the following equation:

$$\Delta S = P - (Qout + ET) \qquad \textbf{Equation 3.}$$

Where: ΔS = Changes in storage; P = Precipitation; $Qout$ = Discharge leaving the catchment (surface and groundwater); and ET = Evapotranspiration. ΔS can be assumed to be negligible over long time periods (Shaw 1994). A more complex version of this equation which takes account of groundwater flows can be expressed as:

$$\Delta S = (P + GWin) - (Qout + ET + GWout) \qquad \textbf{Equation 4.}$$

Where $GWin$ = Groundwater input to the surface drainage, and $GWout$ = Losses to groundwater from the surface drainage system and will be a negative value. As inputs from, and losses to groundwater are usually the most difficult variables of this equation to accurately estimate, this equation can be used to quantify the magnitude

of trans-catchment boundary groundwater transfers. This may be achieved as follows:

$\Delta S = (P + GWin) - (Qout + ET + GWout)$ **Equation 5.**

$\therefore GWout - Gwin = P - Qout - ET \pm \Delta S$ **Equation 6.**

The storage change volume for each lake was calculated as the product of the lake surface area and the change in lake water surface level. Precipitation input was calculated as the product of catchment area and precipitation depth as recorded at the Mullingar weather station. Evapotranspiration was estimated by calculating the areas of well drained, moderately drained and poorly drained soil in each catchment. The relevant Met Éireann evapotranspiration estimate for each soil type from the Mullingar weather station was then multiplied by the area (m^2) of that soil in each catchment. Potential evapotranspiration was used as the evapotranspiration estimate for lake areas as the availability of water would not be a limiting factor in evapotranspiration rates in a lake, which is a free water surface (Allen et al. 1998). Surface stream discharge volume was calculated by linear interpolation of discharge measurements take during the course of this study.

The time period chosen over which to average the data for the water budgets was 6 months. This was done in order to ensure that complete data sets for surface discharge, precipitation, and evapotranspiration were available, and to minimise likely errors in the equations. Approximate error margins for each of the variables used in calculating the water budgets are presented with the water budget results in Chapter 6.

4.3.6 Drainage density

Drainage density can be calculated as the ratio of the total length of stream channels of all orders in a catchment to the catchment area (Black 1996, p. 297):

$DD = TCL / TCA$ **Equation 7.**

Where; DD = drainage density; TCL = total channel length (km); and TCA = total catchment area (km^2). Differences in the drainage densities of surface catchments

may indicate whether relatively more or less precipitation becomes groundwater recharge in particular catchments (Lee 1999). Drainage density ratios for the detailed study catchments were calculated in a GIS program using catchment areas derived from the topographically delineated catchment boundaries and OSI surface drainage network data. Lake surface areas (in all catchments except Fore Valley) were subtracted from the total area of each study catchment. The length of each lakeshore was then divided by 2 (as each channel in a catchment drains the land on 2 sides and a lakeshore only drains land on one side) and the resulting figure added to the total stream channel length for each catchment. In the case of White Lake in which there is a marked difference between the summer and winter surface area of the lake the lake area was calculated from georeferenced 2004/2005 OSI aerial photography. The resulting total channel measurement for each catchment in m was then divided by the total catchment area in m^2.

5. Pilot Study Results, Discussion, and Conclusions

5.1 Introduction

The results and conclusions of the pilot study are presented in this chapter. The chapter is structured as follows: Results (catchment delineation, desk study, landforms, surface drainage network change, and surface hydrology); Summary of results; Discussion; and Conclusions.

5.2 Results

5.2.1 Delineated catchments

The topographically delineated catchments are shown in Figure 5.1.

5.2.2 Desk study

5.2.2.1 Lough Owel

Lough Owel is a tear-drop shaped lake, oriented along a northwest-southeast axis and located to the northwest of Mullingar (Figure 5.2, Table 5.1). Water abstractions from Lough Owel provides 2/3 of County Westmeath's drinking water requirements. A study by Westmeath County Council (2005) estimated that groundwater inflows below the surface level of the lake accounted for 21% of total inputs to the catchment. Before construction of the Royal Canal (1789 - 1817) Lough Owel had two surface outflow points: one at its northwestern end flowing into the River Inny (via Lough Iron); and one at its southeastern end flowing into the River Brosna (located 50 m west of the present canal outflow channel) according to the Inland Waterways Association of Ireland (IWAI) (1997). This pattern was altered by the construction of the main feeder channel for the canal, which outflows at the southeastern end of the lake and the River Brosna outflow is now blocked. The volume of discharge in the canal channel is controlled by means of a sluice, the height of which can be altered. The hydrological behaviour of the lake was further changed when Westmeath County Council began extracting water from the lake in the late 20th Century. The River Inny (Lough Iron) and River Brosna outflows are now defunct, as the lake surface level is now below the base levels of these channels (although the Lough Iron outflow channel still exists). Land use in the catchment is predominantly pasture, with some forestry (Figure 5.3). Lough Owel is located in the Shannon River Basin District (SHRBD).

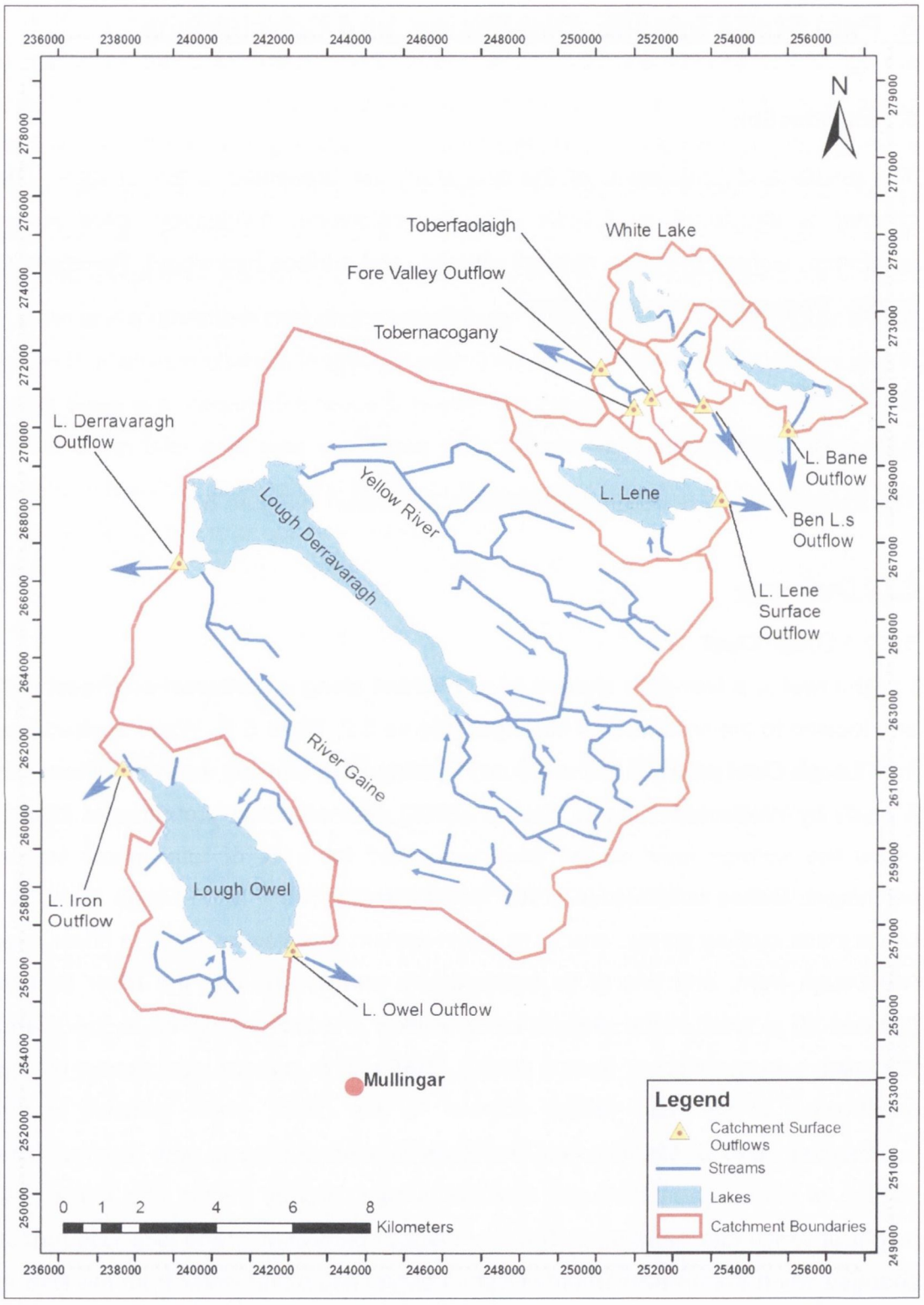

Figure 5.1 Topographically delineated catchments and surface outflow points (basemap data OSI 2001).

Catchment Area (km²)	32.06
Lake Area (km²)	10.22
% of catchment occupied by the lake	31.9
Lake surface altitude (maOD)	97
Estimated lake volume (m³)	unknown
Individual surface inflows >10 l/s	None
Lake water extractions during pilot study (l/s)	263
Surface Outflows	1 (active)
Swallow holes	None

Table 5.1 Hydrological attributes of Lough Owel and its catchment.

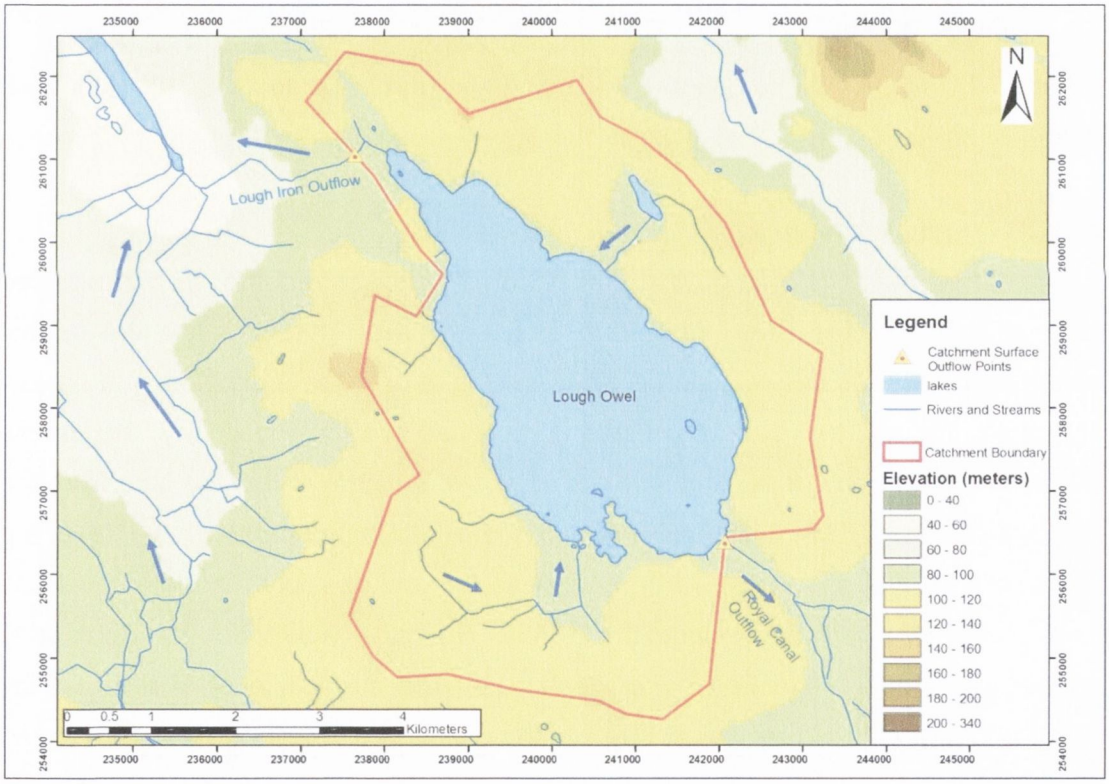

Figure 5.2 Lough Owel, the channel from the southeast of the lake is the Royal Canal feeder channel (basemap data OSI 2001).

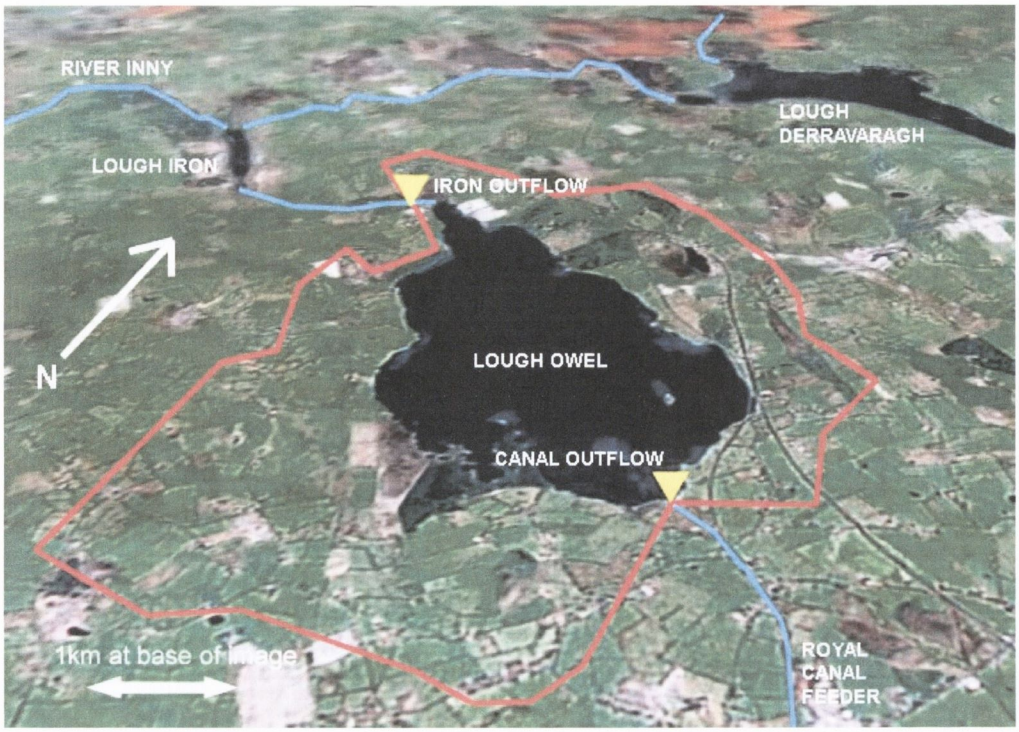

Figure 5.3 Oblique view of Lough Owel catchment (basemap data OSI 2001; Landsat 1999).

5.2.2.2 Lough Derravaragh

Lough Derravaragh is a long thin lake, oriented northwest-southeast, and situated on the course of the River Inny north of Lough Owel This lake has the largest catchment in the study area, and it is the only lake of those examined with named rivers flowing into it (Figure 5.4, Table 5.2). These are the River Inny, the Yellow River, and the River Gáine. These rivers enter the Western end of the lake from the north and south. The rivers flowing into the southeastern end of the lake are unnamed. No water is extracted from the lake for public supply. The lake level has been reduced significantly since the 1840s. Drainage works on the River Inny around the time of The Great Famine lowered the surface level of the lake by approximately 2 m (Battersby 1851). Further drainage works in the 1970s lowered the surface level by a further 2 m (Delaney 1987). This change is mirrored in other lakes on the course of the River Inny. Land use in the catchment is predominantly pasture, with some forestry (Figure 5.5). Lough Derravaragh is located in the SHRBD.

Catchment Area (km²)	150.63
Lake Area (km²)	9.16
% of catchment occupied by the lake	6.1
Lake surface altitude (maOD)	61
Estimated lake volume (m³)	unknown
Individual surface inflows >10 l/s	Yes
Lake water extractions during pilot study (l/s)	0
Surface Outflows	1
Swallow holes	None

Table 5.2 Hydrological attributes of Lough Derravaragh and its catchment.

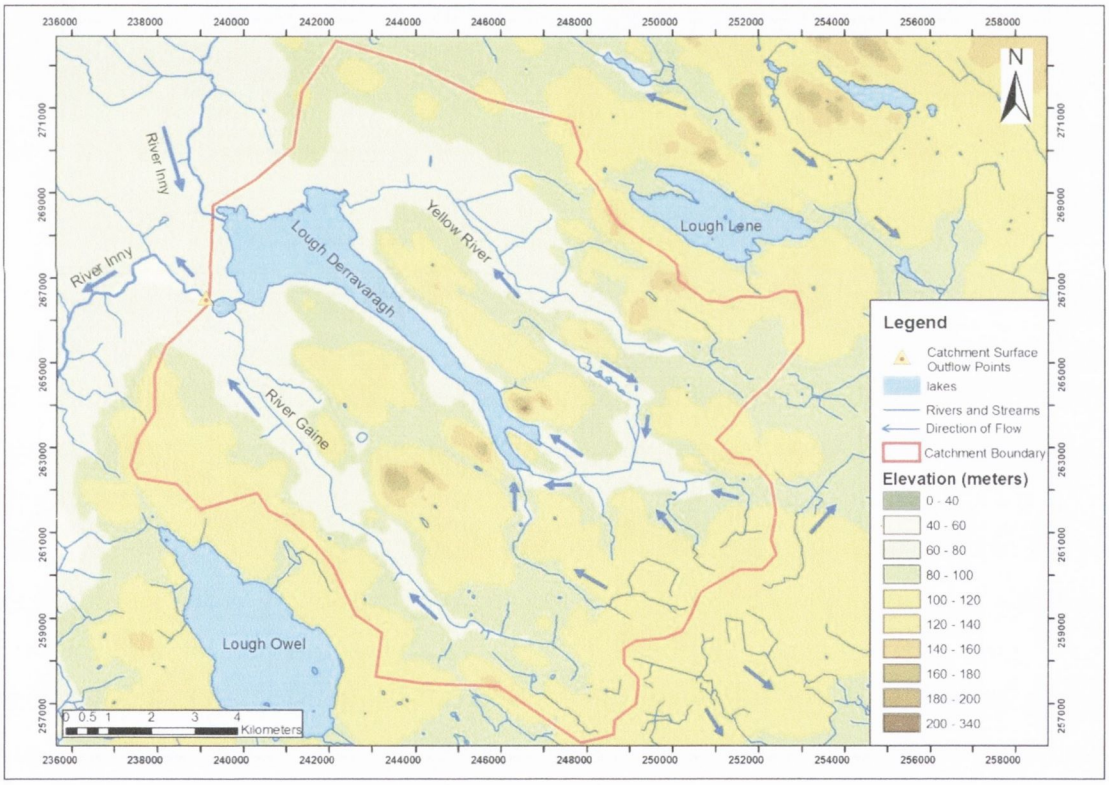

Figure 5.4 Lough Derravaragh (basemap data OSI 2001).

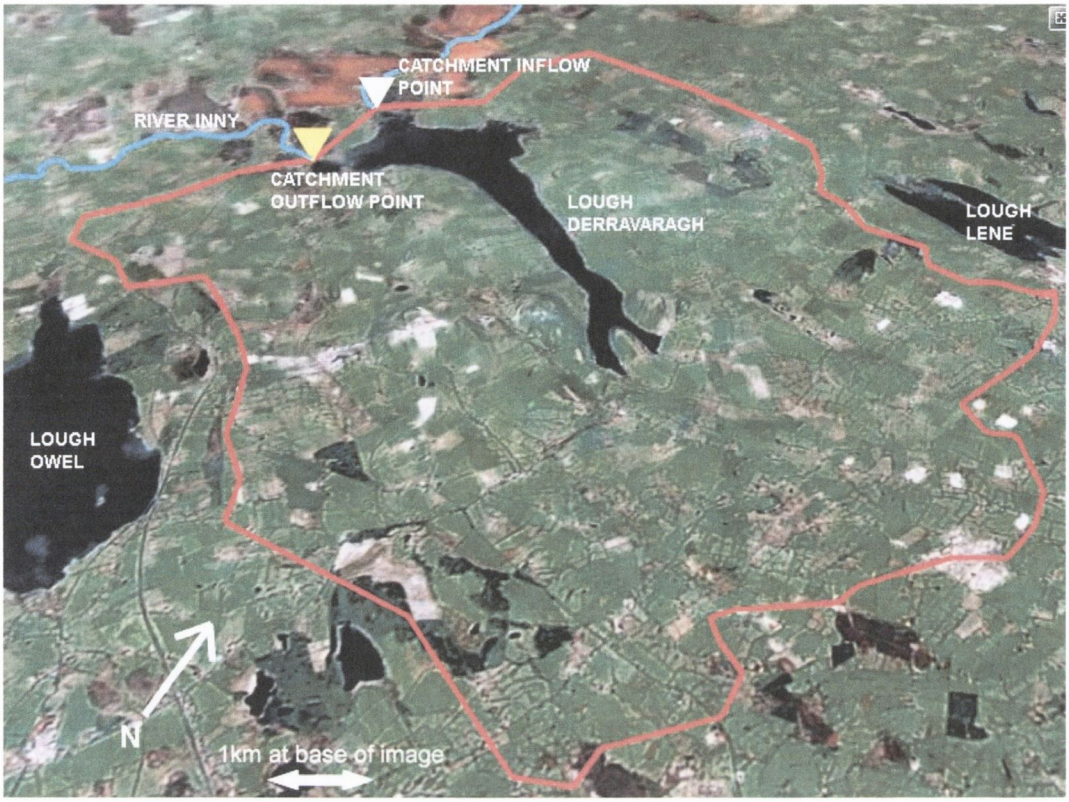

Figure 5.5 Oblique view of Lough Derravaragh catchment (basemap data OSI 2001; Landsat 1999).

5.2.2.3 Lough Lene

Lough Lene is a rhombus-shaped lake oriented northwest-southeast with a prominent peninsula that juts out into the lake from its western shore (Figure 5.6, Table 5.3). Lough Lene is used for water supply, supplying one third of County Westmeath's public requirements. There is evidence of karstification on the northern shore of the lake where six swallow holes are located. Three of these swallow holes are now permanently inactive and three are active for part of the year. Water tracing experiments carried out by McDonald (1988) showed that the water flowing into the sinks resurfaces at the Tobernacogany spring (which drains via the Rivers Glore and Inny to the River Shannon) in the Village of Fore, to the north. Tobernacogany is approximately 7.6m lower in altitude than the swallow hole channels at Lough Lene. The only surface outflow from the lake is located at its eastern end, flowing into the River Deel. The lake level fell below the base level of this channel for 2 - 4 months during the summer and autumn of 2005 and 2006, but not during 2007. When this occurs, discharge from the lake occurs only into the swallow holes and it ceases to drain into the River Deel. There is anecdotal evidence to suggest that this

lake is spring fed. Land use in the catchment is mainly pastureland with small area of forestry on marginal land (Figure 5.7). Lough Lene is located in the Eastern River Basin District (ERBD). Bathymetrical data was available for this lake as it had been gathered as part of a study into lake water quality in Ireland (Taylor et al. 2007). An estimate of the lake volume was calculated using this data.

Catchment Area (km²)	13.4
Lake Area (km²)	4.17
% of catchment occupied by the lake	31.1
Lake surface altitude (maOD)	97
Estimated lake volume (m³) (source data: Taylor et al. 2007)	32547820
Individual surface inflows >10 l/s	None
Lake water extractions during pilot study (l/s)	37
Surface Outflows	1
Swallow holes, (active)	6 (3)

Table 5.3 Hydrological attributes of Lough Lene and its catchment.

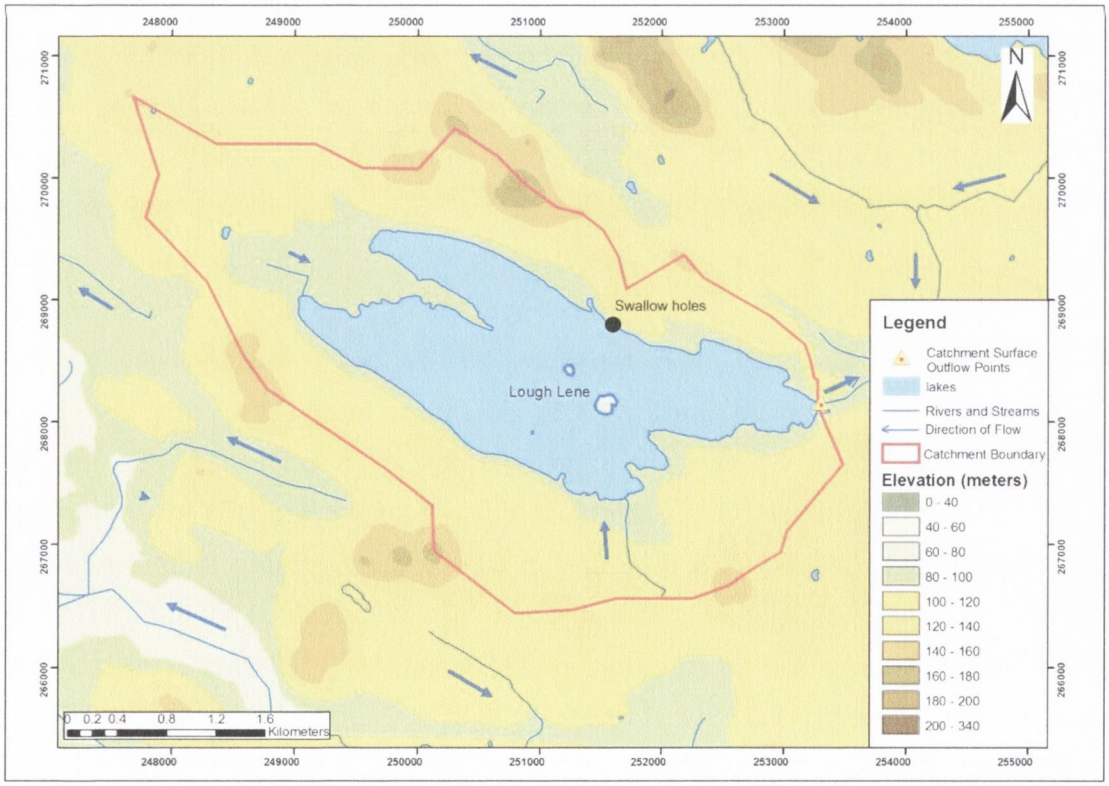

Figure 5.6 Lough Lene (basemap data OSI 2001).

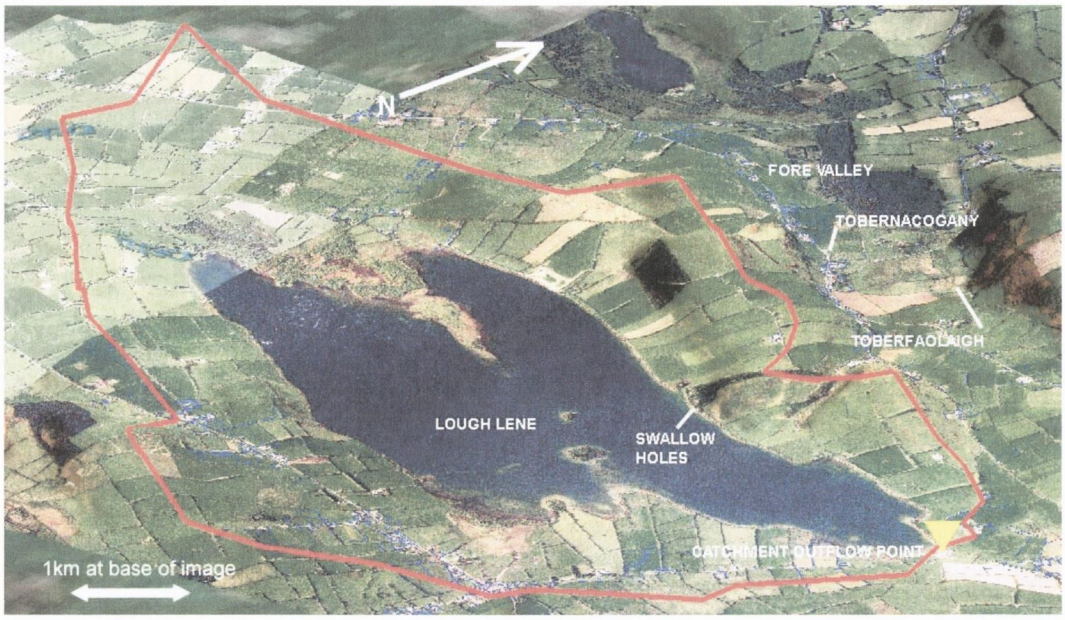

Figure 5.7 Oblique view of Lough Lene catchment (basemap data OSI 2001; Landsat 1999).

5.2.2.4 Tobernacogany, Toberfaolaigh, and Fore Valley

The Valley of Fore is located north of Lough Lene and south of White Lake. It is a steep-sided valley characterised by a flat peat-covered floor framed by the Ben of Fore (217 m) to the north and a limestone cliff to the south (Figure 5.8, Table 5.4). The hydrology of the valley is dominated by two large springs that discharge here: Toberfaolaigh; and Tobernacogany. Discharge occurs from Toberfaolaigh spring all year round. The source of the water discharging from this spring has not been traced but the conductivity of this water is high (averaging 513 µS/cm), and the volume of discharge from the spring (usually > 100 l/s) compared to the topographically defined catchment area of the spring (1.65 km²), suggests that at least some of this water originates from outside the topographically defined catchment of the spring (McDonald 1988). Discharge from Tobernacogany spring ceases around late July most years, and may not begin again until late winter or early spring. The conductivity of water discharging from this spring is lower than that of Toberfaolaigh, (averaging 300 µS/cm), mean winter discharge is approximately 60 l/s, and water discharging from this spring has been proven by tracing to originate in the Lough Lene swallow holes (McDonald 1988). The water discharging from these springs forms the headwaters of the River Glore, which flows out of Fore Valley and into Lough Glore from where it eventually flows into the River Inny. Land use in the catchment is a mixture of rough grazing and forestry (Figure 5.9).

Catchment Area of the valley (km²)	4.53
Toberfaolaigh Catchment Area (km²)	1.65
Tobernacogany Catchment Area (km²)	0.12
Lake Area (km²)	No Lake
% of catchment occupied by the lake	0
Lake surface altitude (maOD)	n/a
Estimated lake volume (m³)	n/a
Individual surface inflows >10 l/s	None
Lake water extractions during pilot study (l/s)	n/a
Surface Outflows	1
Swallow holes	None

Table 5.4 Hydrological attributes of Tobernacogany, Toberfaolaigh and Fore Valley.

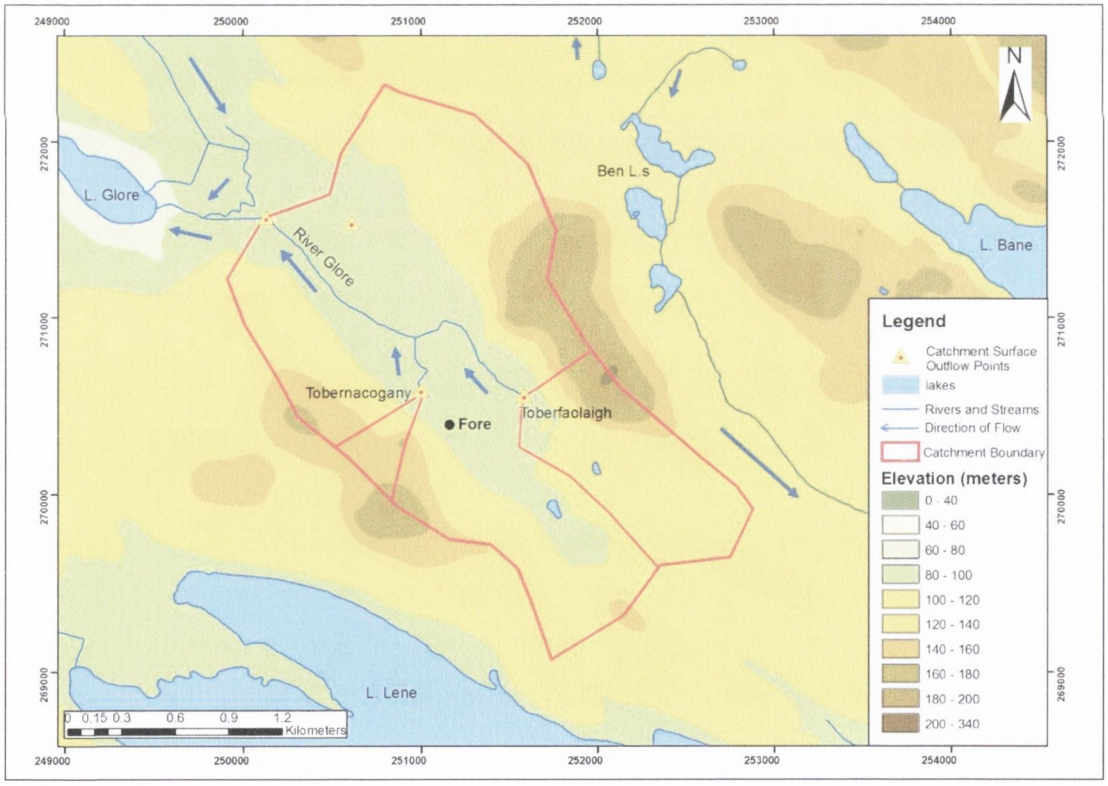

Figure 5.8 Tobernacogany, Toberfaolaigh and Fore Valley (basemap data OSI 2001).

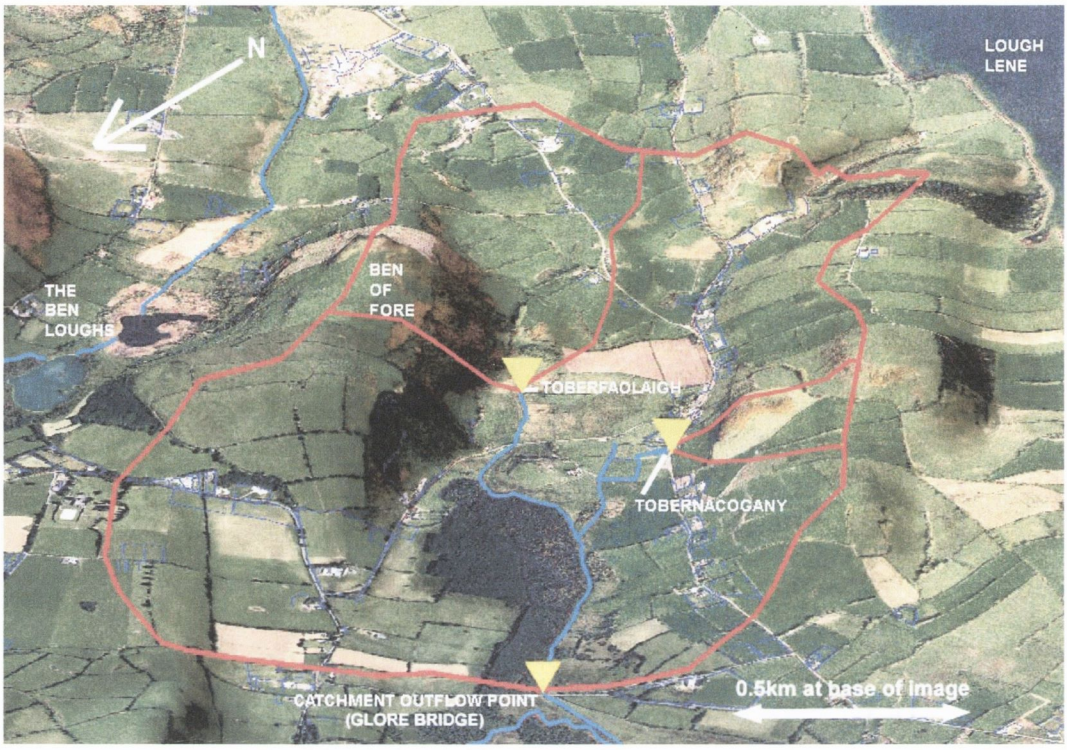

Figure 5.9 Oblique view of Tobernacogany, Toberfaolaigh and Fore Valley (basemap data OSI 2001; Landsat 1999).

5.2.2.5 White Lake

White Lake is a small L-shaped lake located in the northwestern corner of the study area, immediately northwest of the Ben Loughs and north of Lough Lene (Figure 5.10, Table 5.5). White Lake is incorrectly shown on the current OSI 1:50,000 maps (2001) as draining into the Ben Loughs. There are three swallow holes located along the western shore of the lake. The bed of this lake is composed of white marl and analysis of aerial photographs has revealed the presence of numerous circular basins that look like flooded dolines within the lake basin. This pattern is continued onto the land surface to the east of the lake, where three smaller permanent lakes linked to White Lake by a man made drainage channel and numerous temporary ponds are located. There is a range of ~ 3 m between the summer and winter surface water levels in White Lake. As a result, there is a large difference between the summer and winter lake surface area, the winter surface being often more than twice as large as the summer surface area. Land use in the catchment is predominantly pasture, with some forestry on the hills (Figure 5.11). White Lake is located in the ERBD, even though there is no surface channel connecting it to the drainage system of this RBD.

Catchment Area (km²)	6.06
Lake Area (km²)	0.17 (summer area) 0.31 (winter area)
% of catchment occupied by the lake	2.8
Lake surface altitude (maOD)	106
Estimated lake volume (m³)	unknown
Individual surface inflows >10 l/s	None
Lake water extractions during pilot study (l/s)	0
Surface Outflows	0
Active swallow holes	3

Table 5.5 Hydrological attributes of White Lake and its catchment.

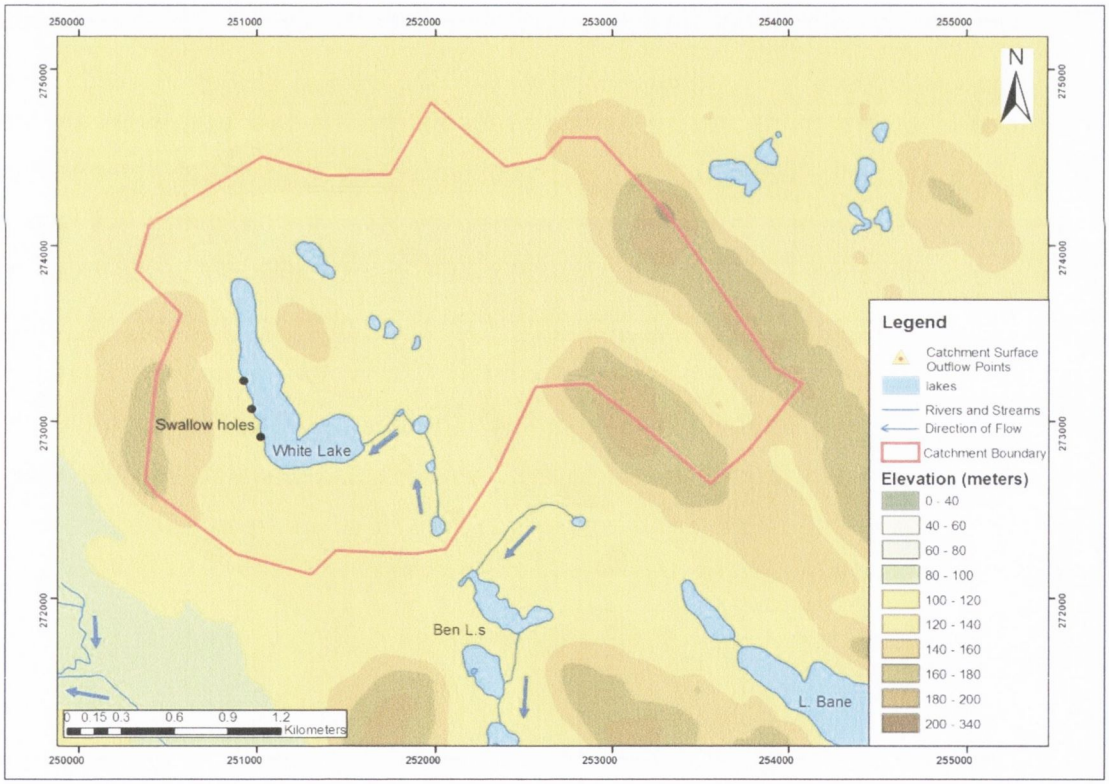

Figure 5.10 White Lake (basemap data OSI 2001).

Figure 5.11 Oblique view of White Lake catchment (basemap data OSI 2001; Landsat, 1999).

5.2.2.6 Ben Loughs

The Ben Loughs are three small lakes (Ben Lough North, Middle, and South) situated southeast of White Lough and west of Lough Bane (Figure 5.12, Table 5.6). The three lakes are connected by surface channels and their surface levels are the same. As a result, the lakes can be treated essentially as one body of water held in three connected basins. The lakes are believed by locals to be spring fed, and a number of springs were discovered while field-walking the perimeter of the lakes. In many maps, including the RBD maps, the Ben Loughs are plotted as being connected to White Lake by a stream channel. This is not the case, as the two catchments are separated by a low ridge of till to the northwest of Ben Lough North. No water is extracted from these lakes and they drain southwards into the River Deel. Land use in the catchment is rough grazing with small areas of pasture land (Figure 5.13). The Ben Loughs are located in the ERBD.

Catchment Area (km²)	3.0
Lake Area (km²)	0.13
% of catchment occupied by the lake	4.3
Lake surface altitude (maOD)	107
Estimated lake volume (m³)	unknown
Individual surface inflows >10 l/s	None
Lake water extractions during pilot study (l/s)	0
Surface Outflows	1
Active swallow holes	None

Table 5.6 Hydrological attributes of the Ben Loughs and their catchment.

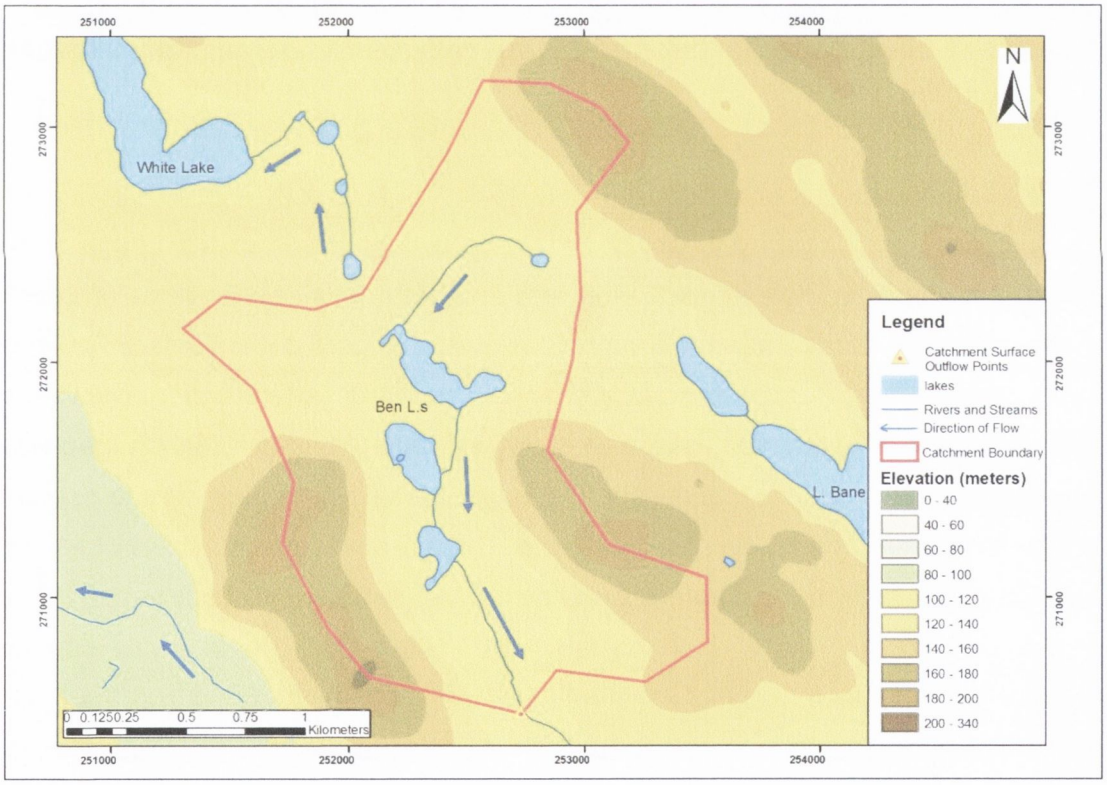

Figure 5.12 The Ben Loughs (basemap data OSI 2001).

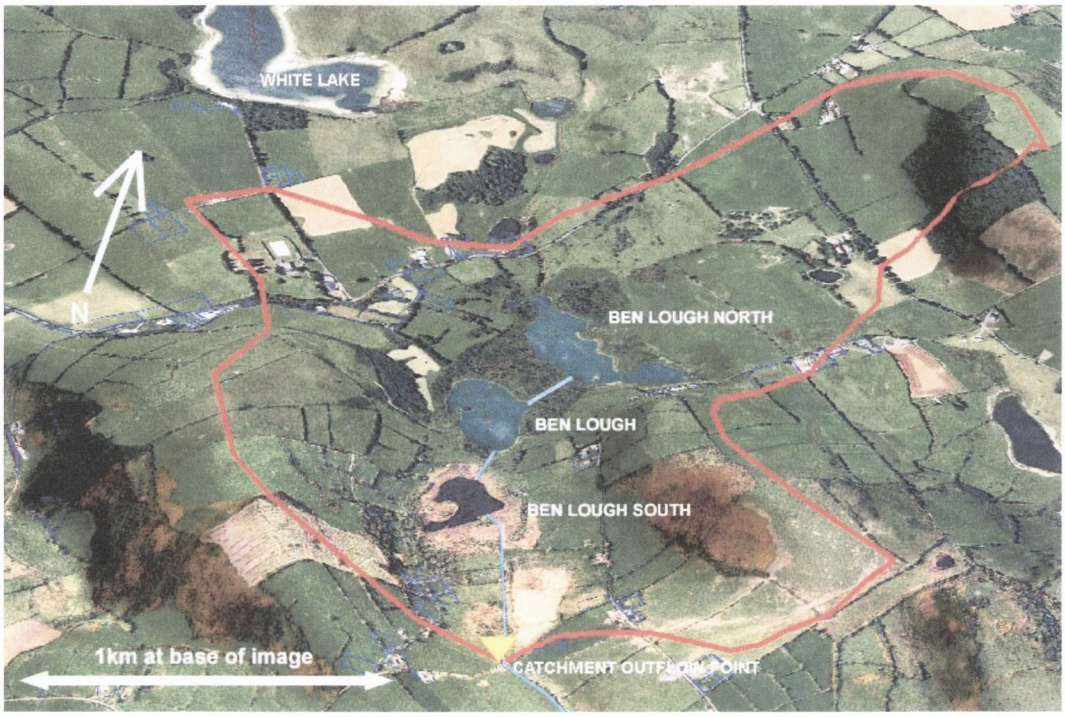

Figure 5.13 Oblique view of The Ben Loughs catchment (basemap data OSI 2001; Landsat, 1999).

5.2.2.7 Lough Bane

Lough Bane is situated northeast of Lough Lene. In addition to the Lough Bane basin, and there are two smaller lakes at the western and eastern ends of Lough Bane – Loughs Glass East and Lough Glass West (Figure 5.14, Table 5.7). They were joined to Lough Bane by surface channels and their surface water levels were the same as that of the main lake as recently as 1908 (when the 25 inch map was surveyed), but the channel connecting to Lough Glass East now appears to operate only intermittently under high flow conditions. There are no surface inflows of >10 l/s into Lough Bane. A report commissioned by the Meath County Council in the 1970s concluded that the lake was spring fed (McDonald 1988). There is one surface outflow from this lake situated at its southeastern end which drains into the River Deel. Water is extracted from this lake for public water supply by Meath County Council. There has been controversy in recent years as this lake has experienced unusually low summer water levels, resulting in the lake level falling below the altitude of the surface outflow channel. This means that for part of the year, Lough Bane has no surface outflow. Local fishing groups have accused the County Council of extracting too much water from the lake, although this has yet to be proven. A swallow hole is mapped on the southern shore of Lough Bane on the 1st edition of

the 6 inch map (1837), however no evidence of this feature was found in the field. Lough Bane is located in the ERBD. Land use in this catchment is a mixture of pasture and forestry (Figure 5.15). Bathymetrical data was available for this lake as it had been gathered as part of a study into lake water quality in Ireland (Taylor et al. 2007). An estimate of the lake volume was calculated using this data.

Catchment Area (km²)	6.26
Lake Area (km²)	0.84
% of catchment occupied by the lake	13.5
Lake surface altitude (maOD)	112
Estimated lake volume (m³) (source data: Taylor et al. 2007)	6691010
Individual surface inflows >10 l/s	None
Lake water extractions (l/s)	44
Surface Outflow	1
Swallow holes	1 (possibly)

Table 5.7 Hydrological attributes of Lough Bane and its catchment.

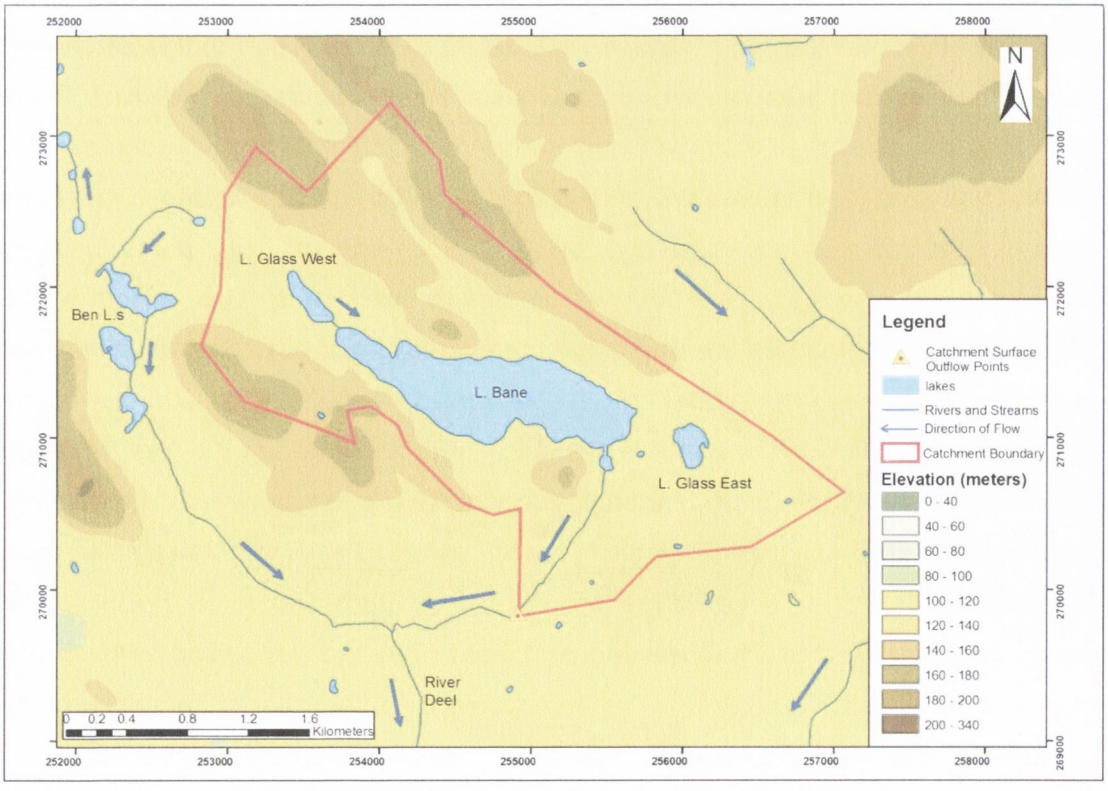

Figure 5.14 Lough Bane (basemap data OSI 2001).

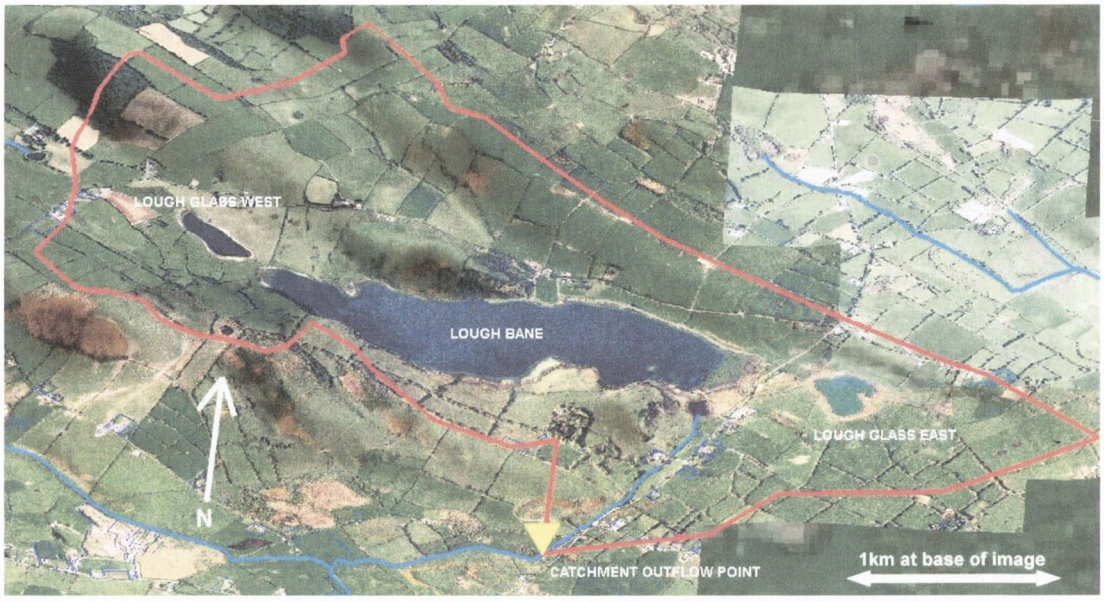

Figure 5.15 Oblique view of Lough Bane catchment (basemap data OSI 2001; Landsat, 1999).

5.2.3 Surface drainage network modification and lake surface area change

5.2.3.1 River Inny

The channel of the River Inny has been modified substantially between 1837 and the present day. A map produced by the Drainage Commissioners (Bevan 1846) (Figure 5.16) shows the 1837 surface area extent of lakes in part of this catchment as well as land that was regularly inundated along the course of the river. Plans were put forward by the Drainage Commissioners to straighten and deepen parts of the river channel and to remove or rebuild obstacles such as bridges and weirs (Bevan 1846; Jones and Mulvaney 1846). One version of these plans involved building a weir across the Inny outflow from Lough Derravaragh and using the lake as a reservoir to attenuate flooding along the course of the river. This plan was not carried out. The plan that was completed involved deepening the channel of the river, removing some tight meanders along its length and lowering the level of Lough Derravaragh by up to 2 m. Although the course of the Inny was not altered appreciably this is not true of some of its tributaries. The River Glore flows from Toberfaolaigh spring in Fore Valley through Lough Glore and on to the Inny. The River Glore has been straightened and deepened since the first edition of the 6 inch map was surveyed (Figure 5.17). The original length of this river channel (From the outflow of Lough Glore to where it joins the Inny) was 12.24 km. This had been shortened to 9.87 km by the early 1900s (25 inch map). The course of the Inny has

never been substantially altered, with drainage modification confined to channel deepening. The surface level of Lough Derravaragh was lowered by a further 2 m in the 1970s by a deepening of the outflow channel (River Inny). The effects of these works can be seen in the surface areas of the lakes along the course of the Inny and its tributaries. In 1837 Lough Glore had a surface area of about 0.752 km², and by 2001 this had reduced to about 0.243 km² (Figure 5.18). Similarly the surface area of Lough Iron (Located west of Lough Owel) in 1837 was about 1.842 km², which had been reduced to 0.46 km² by 2001 (Figure 5.19). Anecdotal evidence gathered from informal interviews with local people suggest that further channel deepening work was carried out well into the 20th Century and channel maintenance works (re-excavating) were observed on the River Glore during the pilot study.

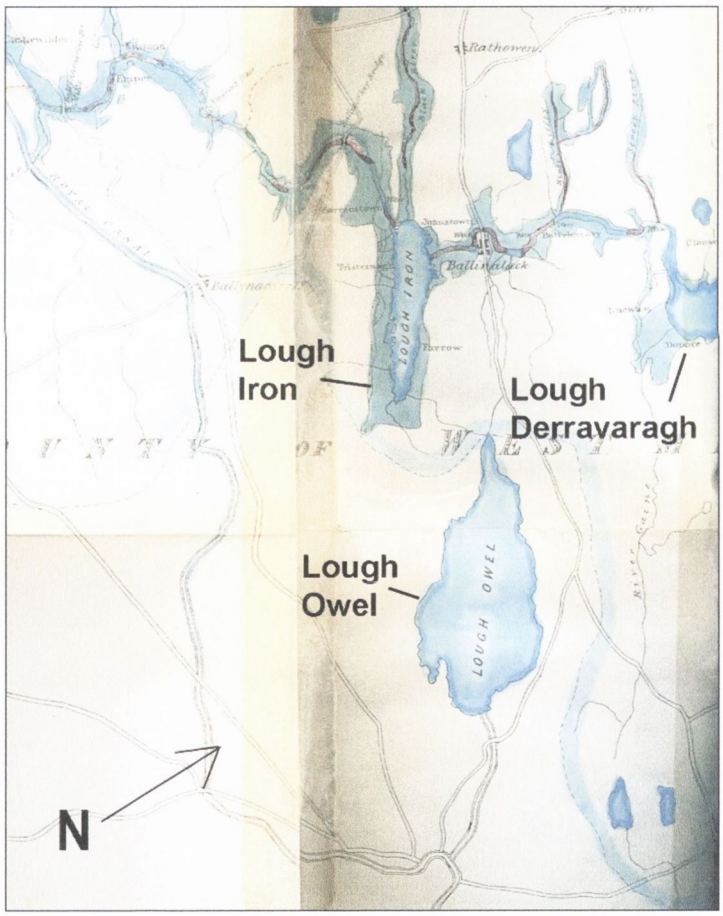

Figure 5.16 Drainage Commissioners map showing Flood prone areas (in green-blue) along the course of the river Inny below Lough Derravaragh (note that there is no channel outflowing from the southeast of Lough Owel to the river Brosna on this map) (reproduced from Bevan 1846).

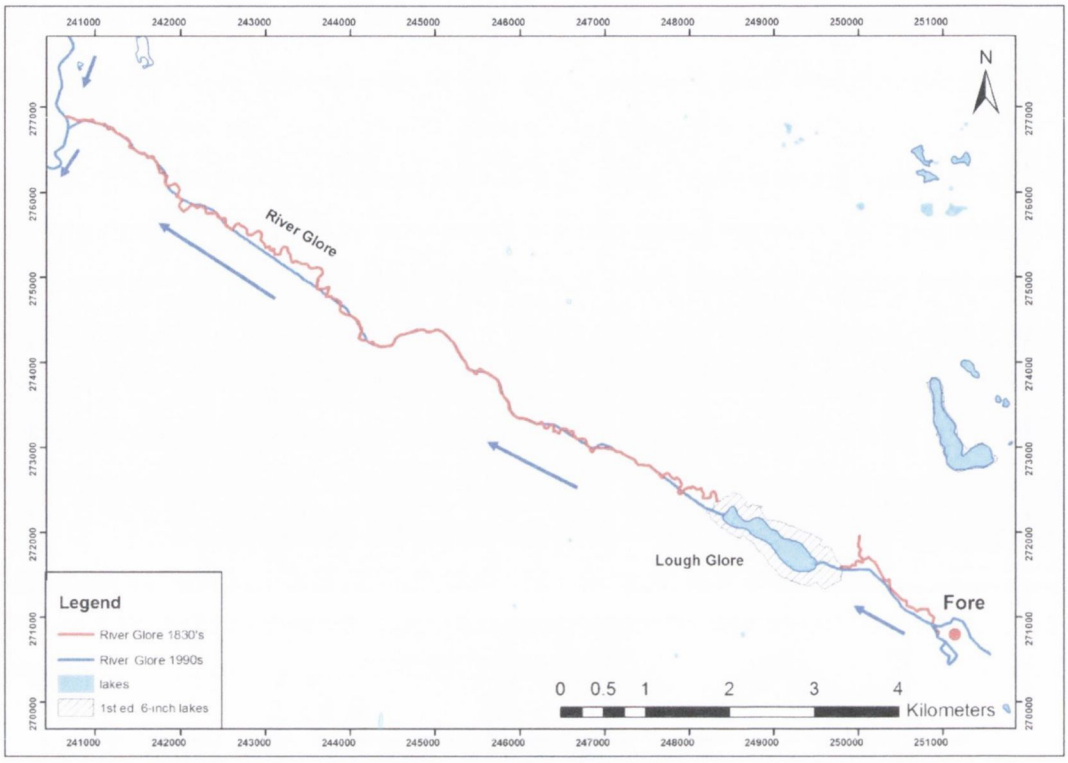

Figure 5.17 Surface channel change on the River Glore 1837 - 2001 (basemap data OSI 1837 & 2001).

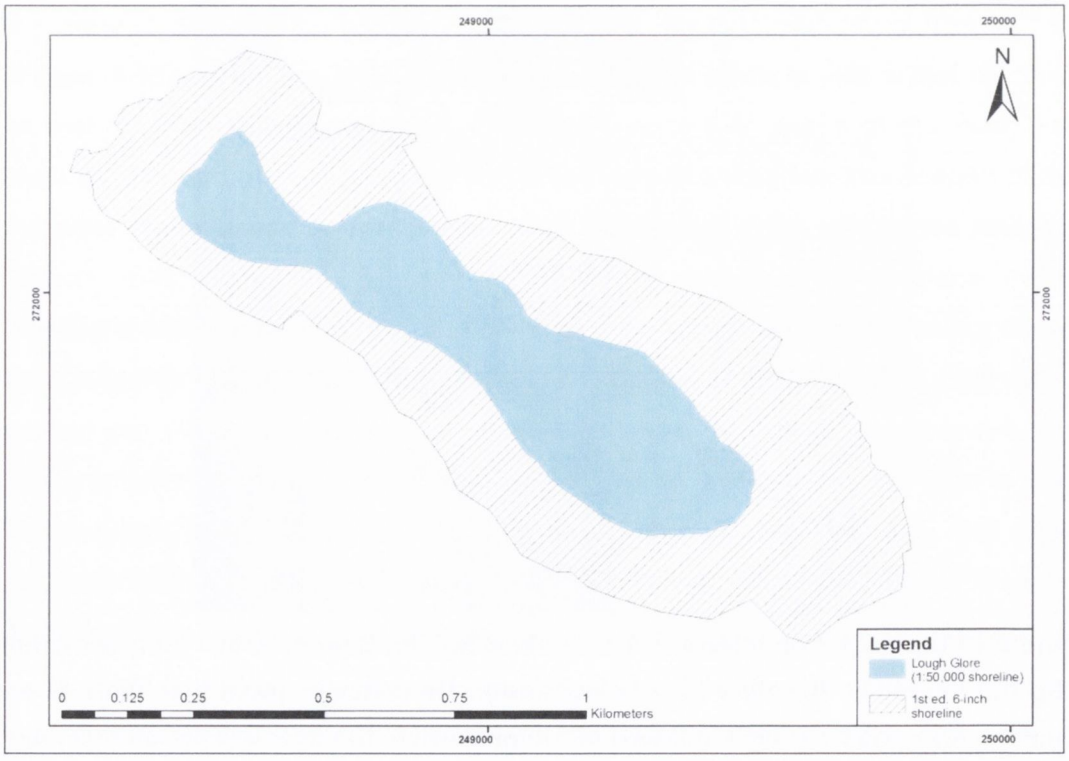

Figure 5.18 Lough Glore surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

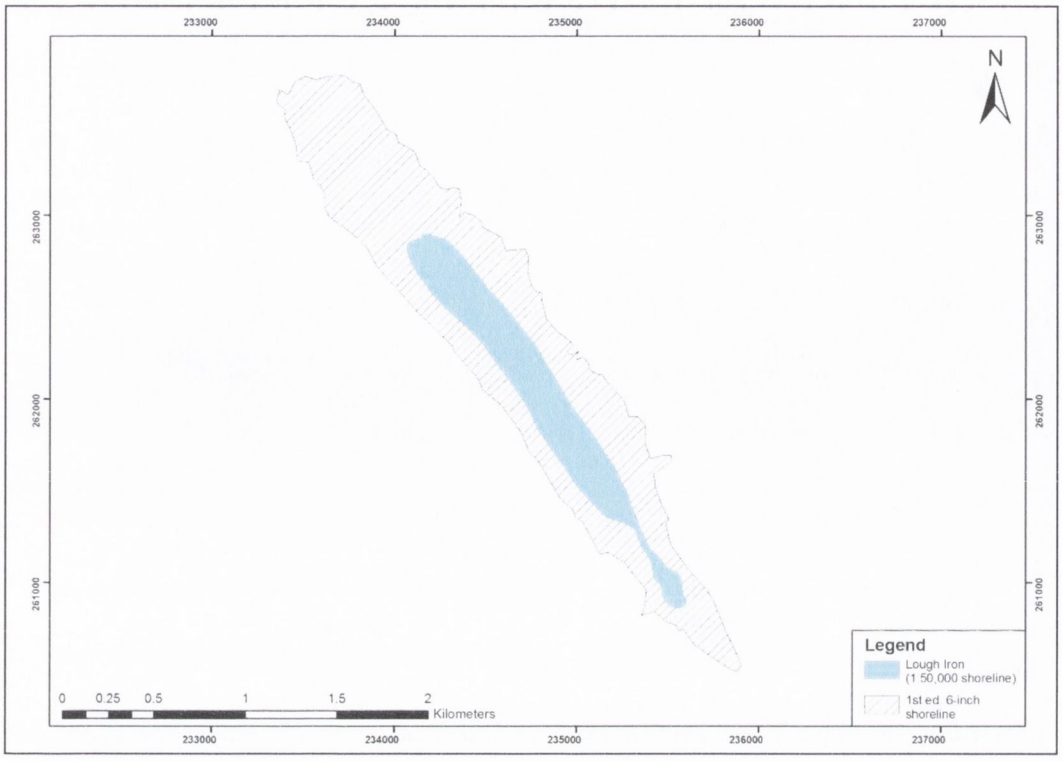

Figure 5.19 Lough Iron surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.2 River Deel

Like the River Inny, the channel of the River Deel has been modified somewhat over the past c.180 years. The Drainage Commissioners carried out a programme of channel straightening, deepening, and obstruction removal on the Deel in the mid 19th Century (Anon. 1846; Gray 1850). The areas of land subject to seasonal inundation before this work was carried out can be seen in Figure 5.20. This land does not flood anymore. Very few new sections of channel were cut during these works. The longest new channel section was located immediately south of Lough Adeel (Coloured red in Figure 5.20). However, the old river channel was not sealed off and is still the main channel route. No significant new tributary channels appear to have been cut in the northern section of the Deel catchment (the section near the present study area) although the outflow channel leaving Lough Lene has been deepened (This is explained in section 5.2.3.5). The drainage works on the River Deel do not appear to have lowered the base level of the outflow channels from Lough Adeel or Lough Analla as the surface areas of these lakes as surveyed on the first edition 6 inch map and the 1:50,000 data are not appreciably different.

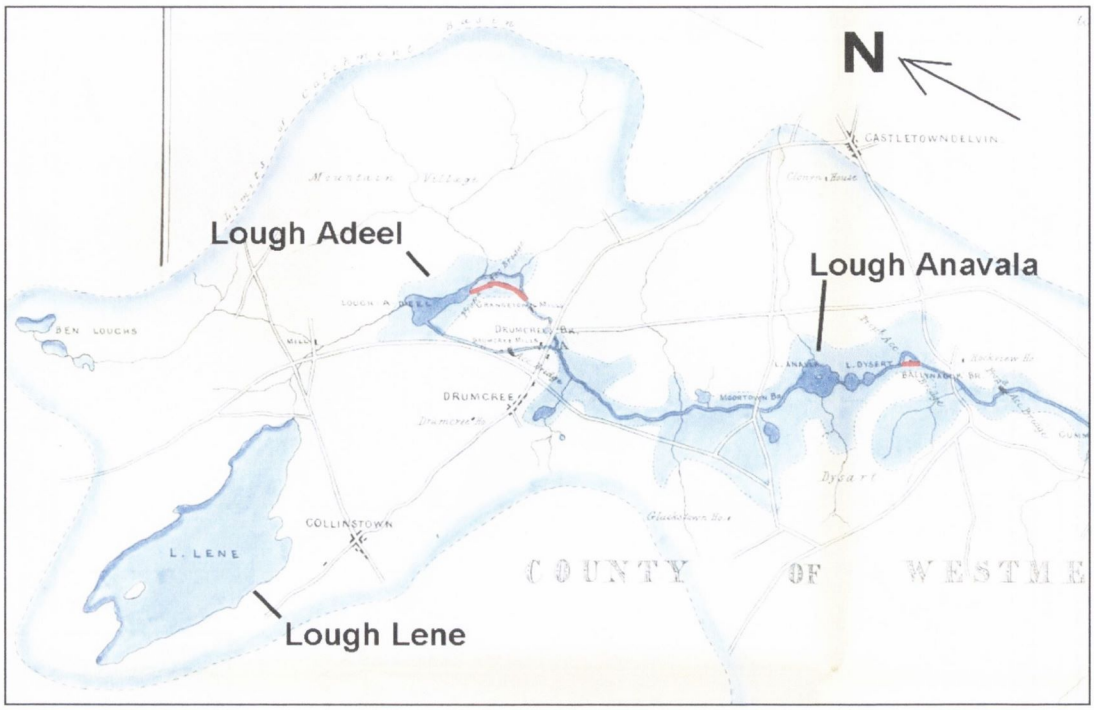

Figure 5.20 Drainage Commissioners map showing flood prone areas (light blue) along the course of the River Deel south of Lough Lene, red lines indicate new channel cuts (reproduced from Anon. 1846).

5.2.3.3 Lough Owel

Analysis of 1st edition 6 inch maps and modern maps indicate that no significant modifications in the surface drainage network in this catchment have been carried out since the 6 inch map was surveyed. The present surface area of Lough Owel is not significantly different from its surface area in 1837 (Figure 5.21). The major modifications to the surface drainage system in this catchment were carried out when the Royal Canal was constructed, before 1837. Prior to construction of the canal, Lough Owel outflowed to both the River Inny (via Lough Iron), and to the River Brosna (outflowing near the present location of the canal feeder channel). The canal feeder channel (described in section 5.2.2.1) is now the only functioning outflow from the catchment. On the 2001 1:50,000 map the old outflow to the River Brosna is still shown. Field investigation has revealed that while the ground in the area where the old channel was located is boggy, no clearly identifiable surface drainage channel exists.

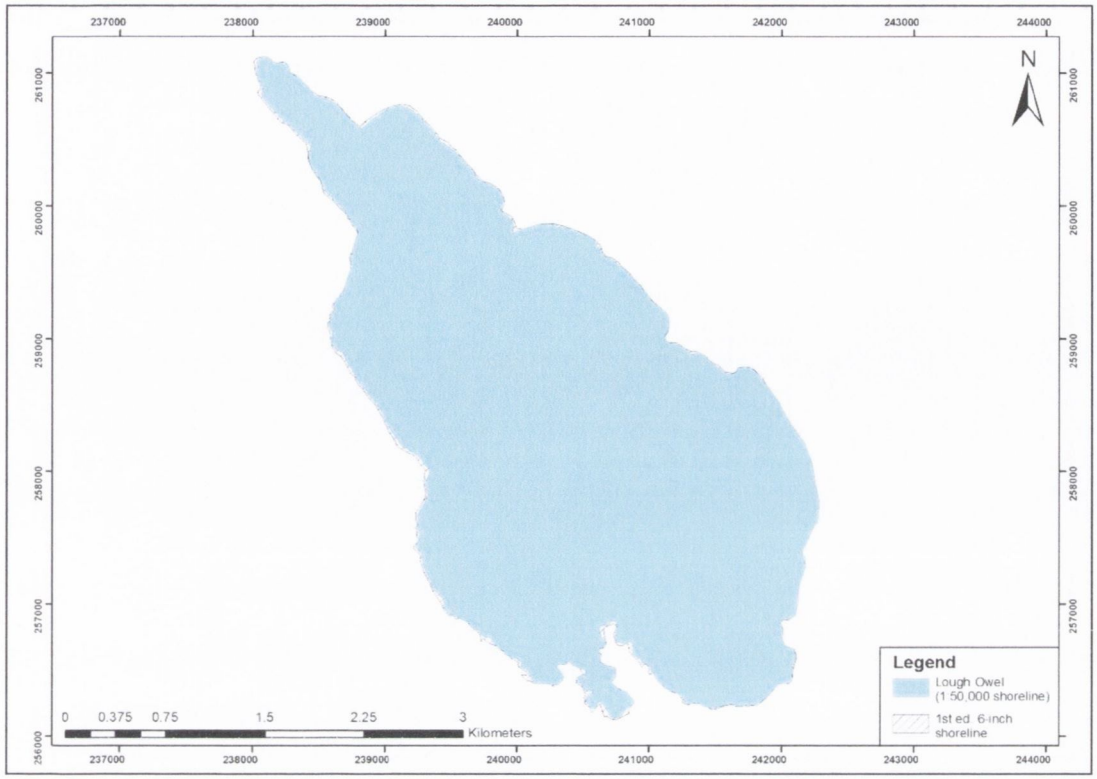

Figure 5.21 Lough Owel surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.4 Lough Derravaragh

Lough Derravaragh is the only lake in this study that has surface inflows of any significant size (The Inny, Yellow, and Gaine Rivers). The channels and tributaries of the Yellow and Gaine Rivers do not appear to have been significantly altered since the 6 inch map was first surveyed although they do have a canalised appearance in places. The most significant changes in the surface drainage of this catchment have been brought about by the drainage schemes implemented on the River Inny. According to Drainage Commissioners reports, the surface level of the lake was lowered by 2 m as a result of drainage works carried out since the 1830s. The surface level of the lake was lowered by a further 2 m in the 1970s by a deepening of the outflow channel (River Inny). The results of the above drainage schemes on the surface extent of Lough Derravaragh can be seen in Figure 5.22. Note that in places (at the northwestern end of the lake, for example) the present lakeshore is up to 0.5 km from its location before the drainage schemes commenced. In other areas the lakeshore is close to its location in 1837 but the land surface is much steeper in these places. The lake had a surface area of approximately 11.077 km² in 1837. This had been reduced to about 9.158 km² by

2001. Assuming the estimate of the lake's surface level change of 4 m to be correct, this means that the storage capacity of the lake has been reduced by approximately 40470700 m^3 since the mid 19th Century.

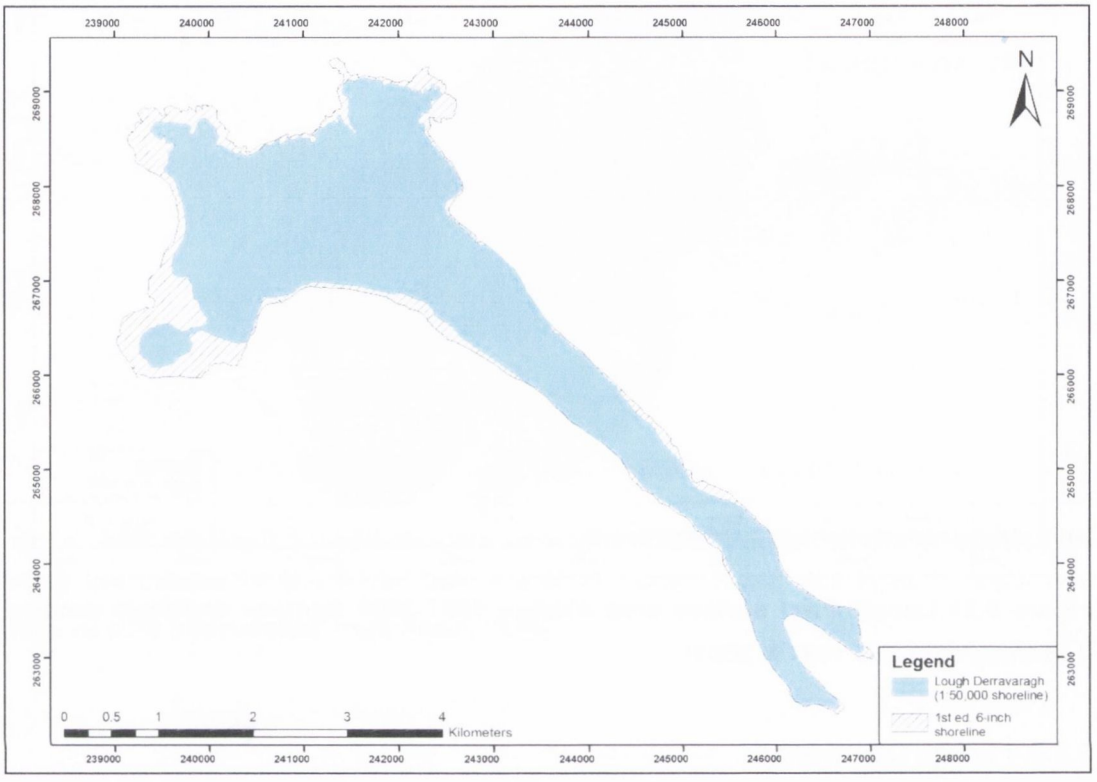

Figure 5.22 Lough Derravaragh surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.5 Lough Lene

No new surface channels have been dug in this catchment since the 6 inch maps were surveyed in 1837. According to locals the surface outflow at the east end of the lake was deepened between the 1950s and 1970s. No evidence detailing this work or by how much the channel was lowered could be found but locals estimate that the channel was deepened by, at most, 1m. The surface area of the lake has also reduced in size since 1837, from about 4.647 km^2 in 1837 to 4.168 km^2 in 2001 (Figure 5.23). The effects of this lowering can be seen at the western end of the lake where a peninsula has been formed. The southern edge of this peninsula is made up of what was a series of islands known as 'The Monks Islands' which were noted on the 6 inch map. The estimates of reduction in storage volume for Lough Lene since 1837 are: maximum 1,762,900 m^3; minimum 9,696,200 m^3; and median 5,729,500 m^3.

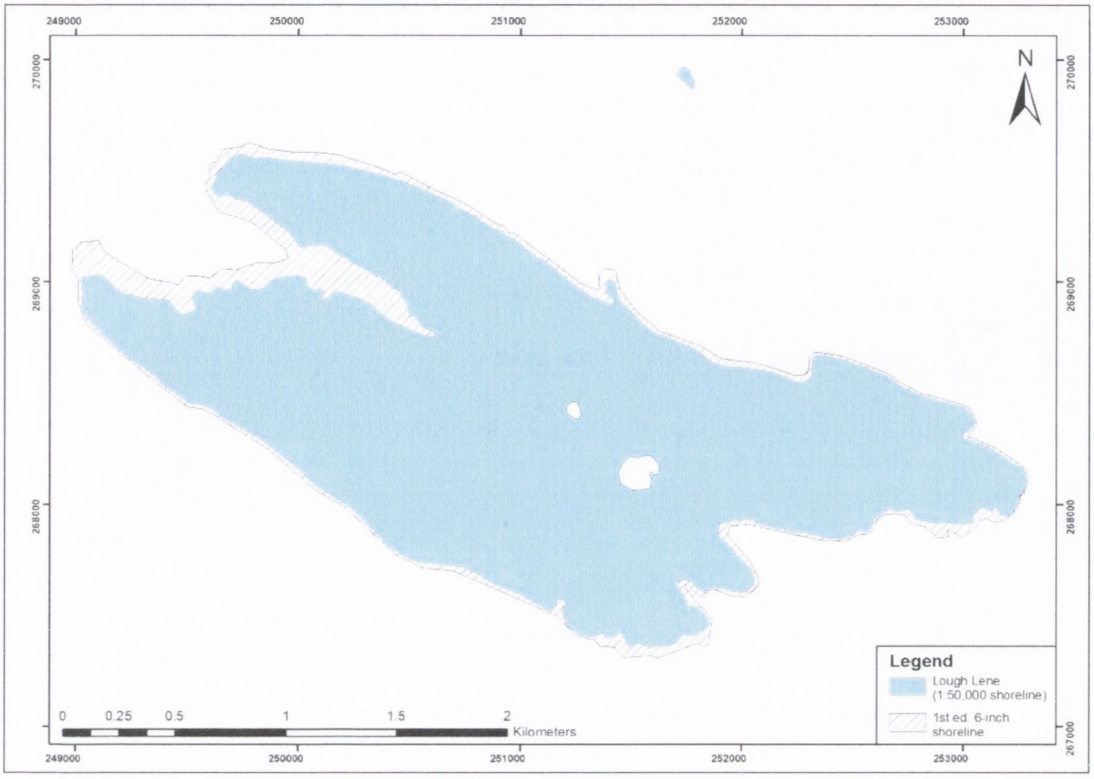

Figure 5.23 Lough Lene surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.6 Tobernacogany, Toberfaolaigh, and Fore Valley

The surface drainage network in the Fore Valley has changed since the first edition of the 6 inch maps were surveyed in 1837. The main outflow channel (outflowing to the northwest in Figures 5.24 and 5.25) has been straightened and deepened. A series of smaller drainage channels have also been constructed to facilitate the draining of the bog that occupies the floor of the valley. In the 1800s a mill was located at the Tobernacogany spring, indicating that the flow issuing from this spring must have been powerful enough to power a mill wheel. Since 1837 drainage channels have been dug from the north and south sides of Toberfaolaigh spring. The spring catchments do not appear to have been altered in any other way apart from these modifications. The surface drainage network as it is shown in Figure 5.25 was taken from the 25 inch map (surveyed 1908) and the drainage network has not changed appreciably in its spatial extent since. Drainage works are ongoing in the valley and surface channel dredging works were carried out three times while the present study was being conducted (during 2005, 2006, and 2007).

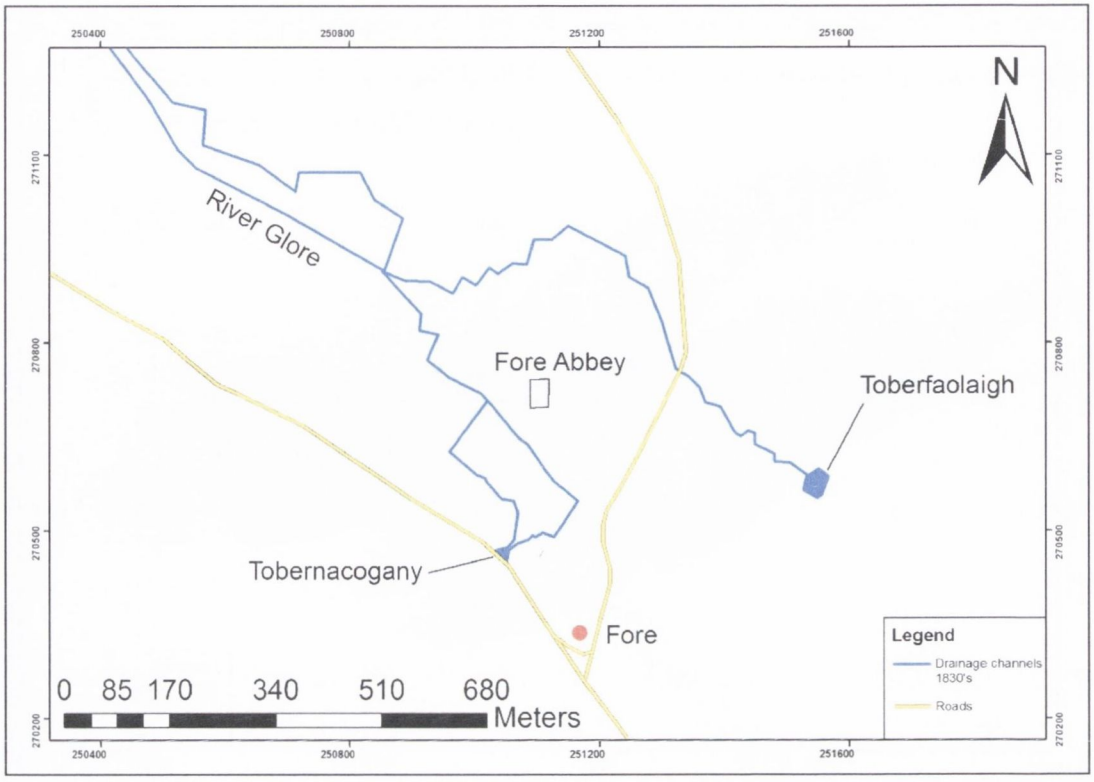

Figure 5.24 The surface drainage network in Fore Valley in 1837 (basemap data OSI 1837).

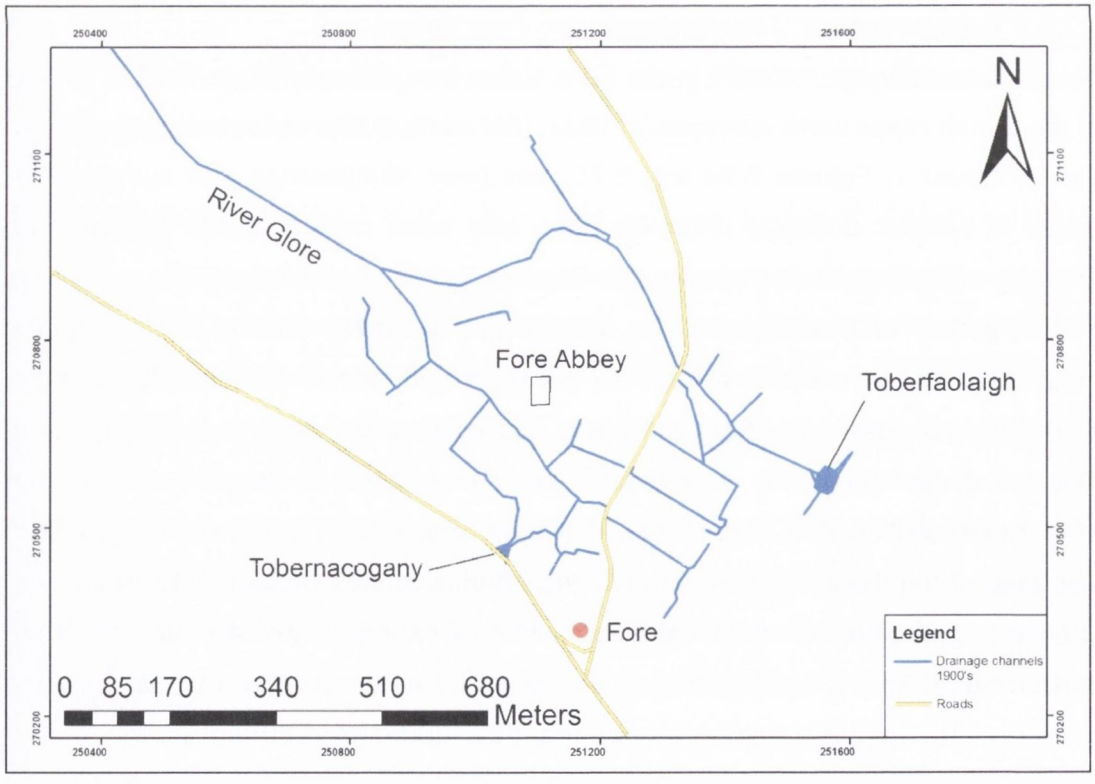

Figure 5.25 The surface drainage network in Fore Valley in 1908 (basemap data OSI 1908).

5.2.3.7 White Lake

The surface drainage network in the White Lake catchment has not been modified (except for the possible dredging of some channels) since the 6 inch maps were surveyed in 1837. A series of straight channels link a number of ponds in the catchment (southeast of White Lake) to White Lake. Water only flows in these channels during the winter months (they flow into White Lake) and they appear to be man made. Some maps show these channels as outflowing into the northwestern corner of the Ben Loughs catchment. There is no evidence on the ground that this was ever the case, and the catchments are separated by a ridge approximately 10m in height. The surface area of White Lake exhibits a wide range of seasonal fluctuation (Figure 5.26) and there is no evidence to suggest that the magnitude of this variation has changed since the 1837. The approximate change in lake storage volume between the highest and lowest lake surface levels recorded during this study is 797,000 m^3.

Figure 5.26 Change in surface area of White Lake (Summer 2006-Winter 2006) (surface channels omitted) (basemap data OSI 2001).

5.2.3.8 Ben Loughs

No new surface channels have been constructed in this catchment since the 6 inch maps were surveyed. Anecdotal evidence from locals suggests that the channels between the lakes are periodically cleaned out and deepened to facilitate flow between the lakes. This would appear to be true as the lakes all have the same surface elevation and the channels connecting them appear well maintained. The outflow channel from the catchment is periodically deepened (by up to 3 m in places), and the spoil heaps from this are clearly visible along the bank of the outflow channel. The surface areas of the lakes themselves appear to have reduced by ~ 27% since the 6 inch map was surveyed, from 0.177 km² to 0.130 km² (Figure 5.27), although this may have been caused by the encroachment of vegetation. The three lakes are joined by wide channels of standing water and all of the lakes have the same surface altitude. Considering the lakes as a whole, estimates of reduction in lake storage volume in this catchment since 1837 are: maximum 168,900 m³; minimum 0 m³; and median 84,400 m³.

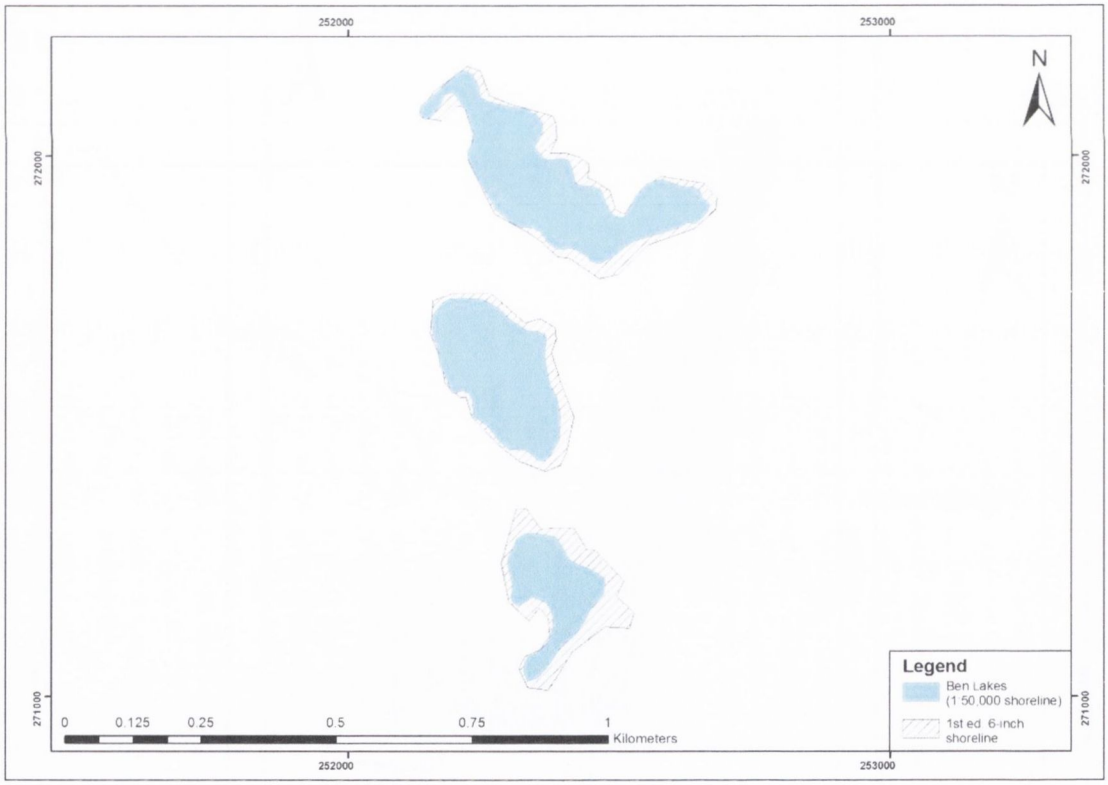

Figure 5.27 Ben Loughs surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.9 Lough Bane

No new surface channels have been constructed in this catchment since 1837. Lough Glass East was, until at least 1908, connected to Lough Bane by a surface channel but this channel was not observed to be active during the present study. The outflow channel from the catchment has been cleaned out at various times but there is no evidence that substantial deepening of this channel has been carried out. On the first edition of the 6 inch map a mill is shown on the outflow channel and the level of the lake was controlled at this point by means of a sluice which has now been removed. The surface areas of Lough Bane, and Lough Glass East and West have been reduced significantly between 1837 and 2001, from 1.013 km² to 0.844 km² (Figure 5.28). The shore of Lough Bane is now located up to 200 m away from its position on the 6 inch maps. Estimates of the reduction in storage volume in Lough Bane over this period are: maximum 5,107,400 m³; minimum 185,700 m³; and median 2,646,600 m³.

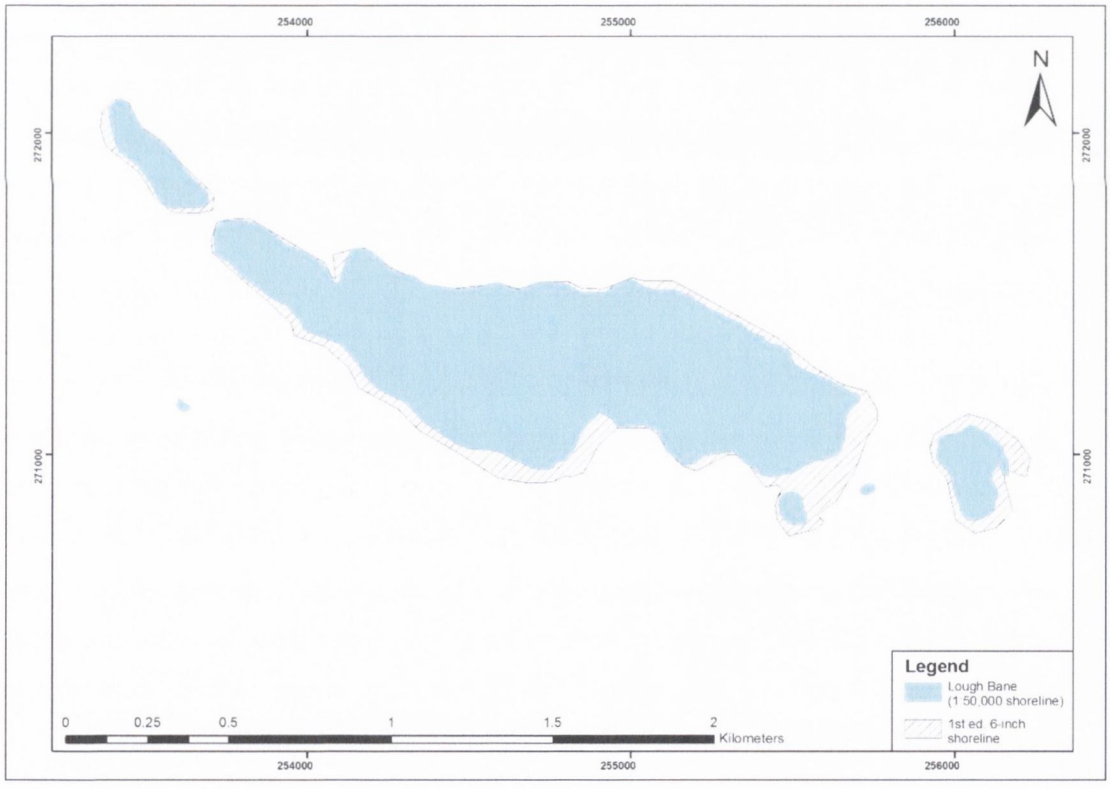

Figure 5.28 Lough Bane surface area change 1837-2001 (surface channels omitted) (basemap data OSI 1837 & 2001).

5.2.3.10 Summary of surface drainage network change and its impacts

Due to the lowering of lake levels and canalisation of surface channels, less water is stored in the surface drainage system, and it is stored for a shorter time than it would have been before the 1840s. This means that flow in surface streams is likely to be 'flashier', due to increased efficiency of the drainage network in transmitting water. In a situation where a lake is a surface expression of the watertable, lower lake levels could result in lower groundwater levels. In a catchment where surface outflow is controlled by means of a sluice, storage and streamflow become functions of the height of the sluice. If the height of the sluice is changed, discharge, lake surface levels, and groundwater levels cannot be compared to precipitation as the base level of the catchment outflow is an independent and unknown variable.

5.2.4 Karstic landforms

Surface karstic landforms were identified in five of the study catchments (Table 5.8). No surface karstic landforms were identified in the Lough Owel or Ben Loughs catchments. A turlough containing a swallow hole is recorded in the GSI Karst Database in the Lough Derravaragh catchment. However, no surface ponding of water was observed at this location during the fieldwork period and it is unknown if this turlough basin continues to flood seasonally following the drainage modifications carried out during the late 20th Century to the Derravaragh catchment. The swallow holes located in the Lene and White Lake catchments are sited at the shore of the lakes and no swallow holes were found in the study area that received water inflow from sinking streams. A cave called Pollnagat (which may translate to cave of the cats), reportedly a low passage 12 m in length (Dowds 1987) and shown on the 6 inch map in the Derravaragh catchment, could not be located on the ground (The area is presently covered by a young conifer plantation). A swallow hole is also shown on the 6 inch map on the southern shore of Lough Bane. No evidence of this could be found in the field. While 14 surface karstic features were located, the study area for its size, contains less karstic landforms than areas farther west in the midlands, such as Roscommon.

Catchment	Total	Landform Type	Grid Ref.	Alt. (maOD)	Previously Mapped
Owel	0	n/a	n/a	n/a	n/a
Derravaragh	4	Turlough	N2456526245	105	Yes
		Swallow Hole (Inactive)	N2456526245	105	Yes
		Karren	N2464726376	143	No
		Doline	N2464726375	131	No
Lene	6	Swallow Hole (Active)	N2515526882	92.5	Yes
		Swallow Hole (Active)	N2515726880	92.5	Yes
		Swallow Hole (Active)	N2515726879	92.5	Yes
		Swallow Hole (Inactive)	N2515826879	93	No
		Swallow Hole (Inactive)	N2515926878	93	No
		Swallow Hole (Inactive)	N2516026878	93	No
Fore Valley	2	Large Spring	N2516027048	82.5	Yes
		Large Spring	N2510527050	84.9	Yes
White Lake	3	Swallow Hole (Active)	N2510227290	105	No
		Swallow hole	N2509427318	106	No
		Swallow hole	N2509827303	106	No
Ben Loughs	0	n/a	n/a	n/a	n/a
Bane	1	Karren	N2553327075	135	No

Table 5.8 Surface karstic landforms identified in the pilot study.

5.2.5 Surface hydrological measurement results

5.2.5.1 Surface hydrology measurement point selection

In addition to the measurement points located at the surface outflow points of the six lake study catchments, three measurement points were located at swallow holes on the northern shore of Lough Lene, one each at the Tobernacogany and Toberfaolaigh springs, and one farther Down Fore Valley at Glore Bridge. This last point was included due to anecdotal evidence suggesting the presence of seepage springs influent to the River Glore upstream of this point. Two measurement sites were chosen for Lough Derravaragh, one at a point where the River Inny enters that lake and one where the River Inny outflows from the lake. It proved impossible to measure discharge at either of these sites using velocity/area or dilution methods as the channel was too deep and the current too strong to use the velocity area method, and a salt tracer used in the attempted dilution method was not detectable despite injecting 20 kg of dissolved salt into each channel. Thus, the Derravaragh catchment is excluded from further mention in this section. A map showing the location of the measurement points excluding those in the Derravaragh catchment is presented in Figure 5.29. Not counting the Derravaragh measuring points, there were 10 measuring points in all (Table 5.9).

Surface Stream Outflows	Grid Reference
Lough Owel canal feeder outflow	N2424125616
Lough Lene surface outflow	N2532926815
Fore Valley (Glore Bridge)	N2501327156
Ben Loughs outflow	N2527427052
Lough Bane outflow (at bridge ~1km south of lake)	N2549026902
Swallow Hole inflows	
Lough Lene SH1	N2515326884
Lough Lene SH2	N2515426883
Lough Lene SH3	N2515526881
Springs	
Tobernacogany	N2510627055
Toberfaolaigh (at bridge 240 m northwest of spring)	N2513327076

Table 5.9 Surface hydrology measurement sites.

5.2.5.2 Discharge

The discharge was measured at each site on three occasions. There is no surface runoff from the White Lake catchment but its area was included in the calculation of the total normalised runoff estimate for the study area.

Lough Owel

There is one outflow measurement point in this catchment. In addition to surface runoff, water is extracted from the lake to supply mains water to County Westmeath. During the period that this study was carried out the average rate of extraction based on the total amount extracted during this period was 263 l/s. The County Council would not release detailed abstraction data and would only agree to release monthly abstraction totals, thus more detailed analysis of abstraction pressures was impossible. The results of the surface discharge measurements (excluding extractions) are presented in Table 5.10.

	16/3/2005 (l/s)	26/3/2005 (l/s)	6/5/2005 (l/s)	Mean (l/s)
Surface channel	112	133	140	128

Table 5.10 Discharge measurements and summary statistics for Lough Owel.

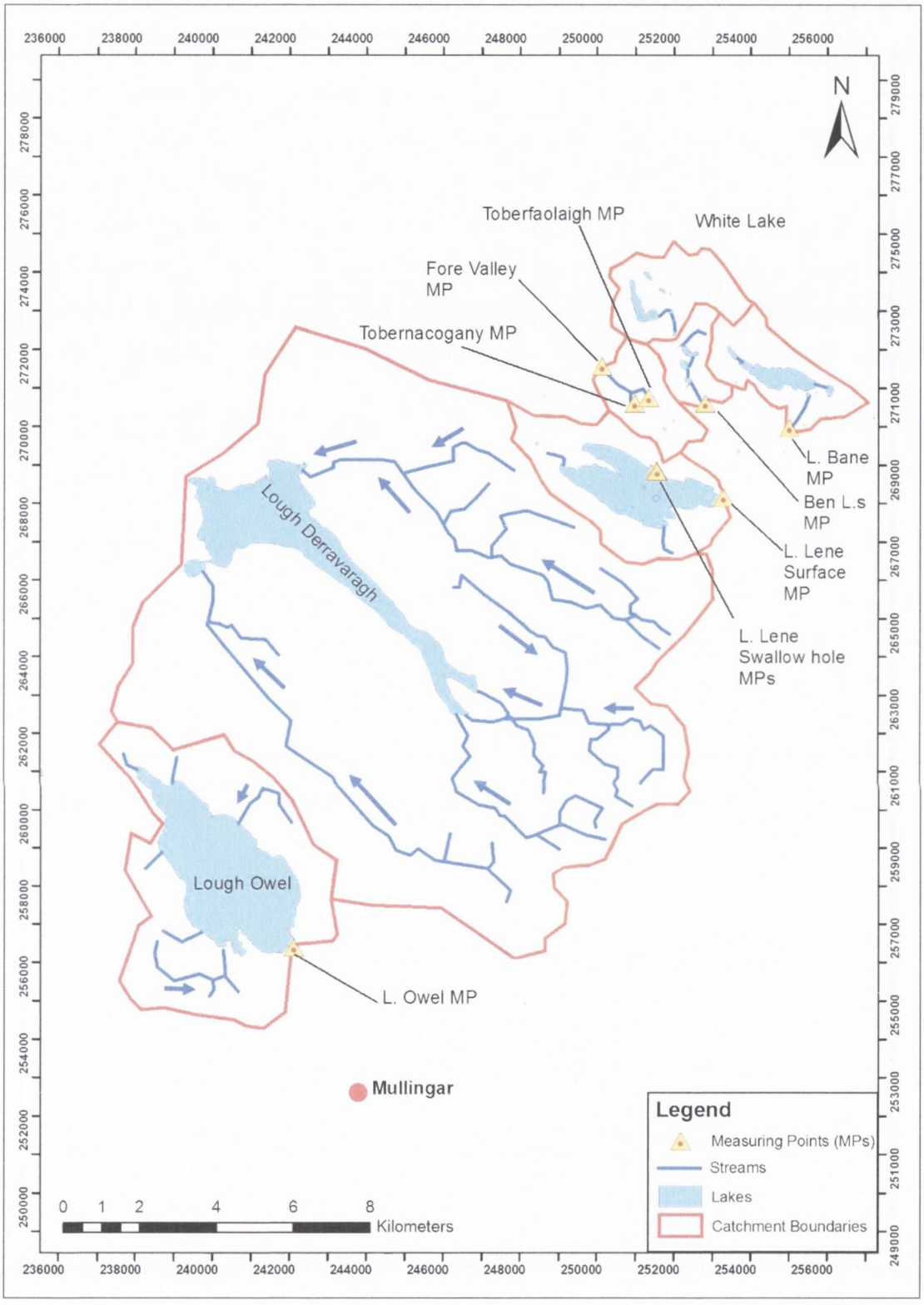

Figure 5.29 Location of pilot study measuring points (basemap data OSI 2001).

Lough Lene

Four measurement points were located in this catchment, one surface outflow and three swallow holes. Water is also extracted from this lake for mains supply. During the course of this study the average rate of extraction based on monthly totals was 37 l/s. As in the case of Lough Owel, the County Council would not release more detailed information. The results of the surface discharge measurements excluding extractions are presented in Table 5.11 below. As can be seen from these results, approximately twice as much water in total entered the 3 swallow holes as left via the surface channel. No flow could be detected in the channel leading to swallow hole 2 (SH2) during the course of the measurement period. Changes in discharge volume entering the swallow holes is at variance to change in surface channel flow due to periodic clogging and unclogging of the swallow holes during the measurement period.

	16/3/2005 (l/s)	26/3/2005 (l/s)	6/5/2005 (l/s)	Mean (l/s)
Surface channel	40	25	30	32
SH 1	35	21	31	29
SH 2	0	0	0	0
SH 3	51	24	30	35

Table 5.11 Discharge measurements and summary statistics for Lough Lene.

The Ben Loughs

One measurement point was located in this catchment. The results of the surface discharge measurement are presented in Table 5.12 below.

	16/3/2005 (l/s)	26/3/2005 (l/s)	6/5/2005 (l/s)	Mean (l/s)
Surface channel	110	73	90	91

Table 5.12 Discharge measurements and summary statistics for the Ben Loughs.

Lough Bane

One measurement point was located in this catchment. Water is also extracted from this lake for mains supply. During the course of this study the average rate of extraction was 44 l/s. The results of the surface discharge measurements (excluding extractions) are presented in Table 5.13 below.

	16/3/2005 (l/s)	26/3/2005 (l/s)	6/5/2005 (l/s)	Mean (l/s)
Surface channel	118	78	96	97

Table 5.13 Discharge measurements and summary statistics for Lough Bane.

Fore Valley

Discharge measurements at Glore Bridge, and the two springs of Tobernacogany and Toberfaolaigh are presented in Table 5.14. The springs have very high discharges in terms of the size of their topographically defined catchments which are 0.123 km² and 1.65 km² for Tobernacogany and Toberfaolaigh respectively.

	16/3/2005 (l/s)	26/3/2005 (l/s)	6/5/2005 (l/s)	Mean (l/s)
Glore Bridge	346	231	291	289
Tobernacogany	101	46	60	69
Toberfaolaigh	133	101	126	120

Table 5.14 Discharge measurements and summary statistics for the measurement points in Fore Valley.

Normalised Surface Discharges

The normalised surface discharges in the form of l/s/km² are presented in Table 5.15 and graphically in Figure 5.30. In addition, the Specific runoff of the Shannon catchment (19 l/s/km²) (Banagher station hydrometry data OPW 2006) (http://www.opw.ie/hydro/>) the Boyne catchment (16 l/s/km²) (Ballinter Bridge station hydronet data, EPA 2006) (<http://www.hydronet.epa.ie>), and the total pilot study area excluding the Lough Derravaragh catchment are displayed in Figure 5.30. The normalised runoff of the total pilot study area at 15 l/s/km² is slightly less than either the Shannon or Boyne catchments. However, this can be explained by the fact that the pilot study measurement period does not include either the typically wettest or driest months of the year.

Within the study area a large degree of variation is present. While there is no surface runoff from the White lake catchment, the normalised discharge from Tobernacogany spring is 561 l/s/km². This is clearly too high for the topographic catchment of this spring to be correct. This extra water can be accounted for by water draining into the swallow holes at Lough Lene, as McDonald (1988) has proven a connection between these swallow holes and the spring. Normalised discharge from Toberfaolaigh of 73 l/s/km² is also higher than could be accounted

for by its topographic catchment. The topographically defined catchment of this spring is clearly not its actual catchment. The normalised discharge at Glore Bridge farther down Fore Valley (minus spring discharge and minus spring topographic catchment areas) is also higher than regional averages. If the discharge volumes and topographic catchments of the springs are subtracted from the valley above Glore Bridge as a whole, the normalised runoff for the rest of the valley is 36 l/s/km² - still over twice the expected regional value. No large springs are influent to the stream channel upstream of this point and if groundwater is entering the stream channel above this point, it is doing so as seepage, not point inflow. The Lough Bane and Ben Loughs catchments generate slightly more runoff than would be expected from regional values while runoff from the Lough Owel catchment is less than the regional values. Lough Lene has a low normalised surface runoff but this figure does not include water flowing into the swallow holes at the northern shore of the lake. If the water flowing into the swallow holes is included in a calculation of total measured discharge from the catchment, the normalised runoff value is approximately 7.3 l/s/km², still below expected regional values.

Catchment	Mean (l/s)	Catchment area (km²)	l/s/km²	Catchment area (km²) if outflow was normalised to regional average (during pilot study period) (15 l/s/km²)
Lough Owel	391	32.07	12.19	26.07
Lough Lene	68.6	13.4	5.12	4.57
Tobernacogany	69	0.12	560.98	4.60
Toberfaolaigh	120	1.65	72.73	8
Fore Valley	100	3.75	26.62	6.67
White Lake	0	6.06	0.00	0
Ben Loughs	91	3	30.33	6.07
Lough Bane	141	6.26	22.52	9.40

Table 5.15 Mean normalised surface outflows (with lake abstractions included as surface outflow).

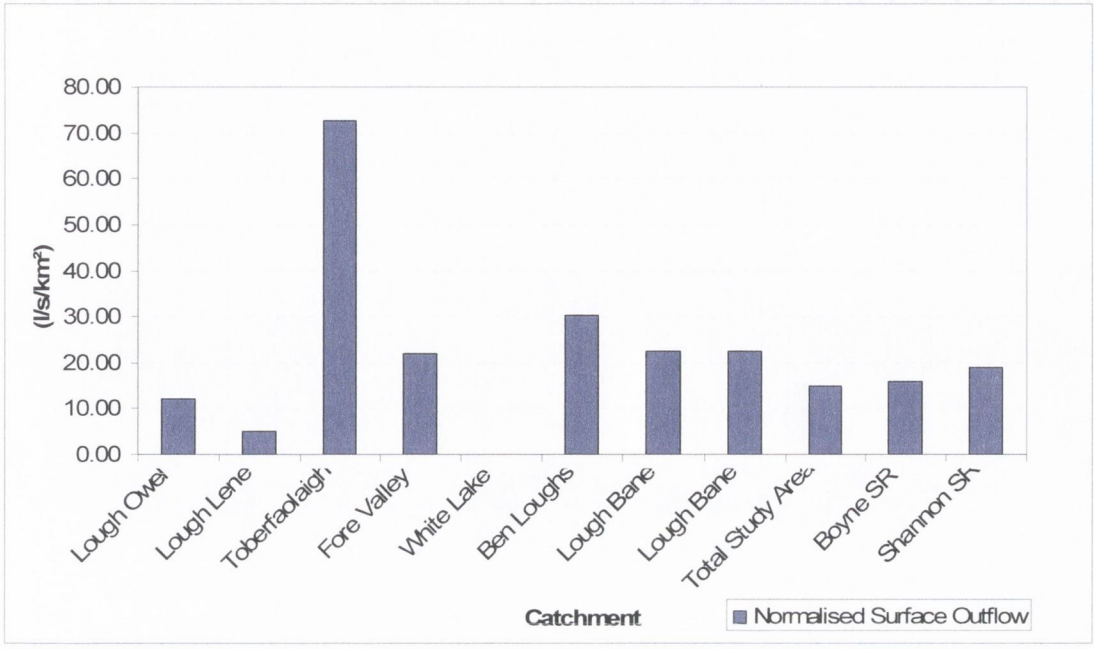

Figure 5.30 Mean normalised surface outflows. Water abstractions for Loughs Owel, Lene and Bane have been included as surface outflow in calculating the data for this graph. Tobernacogany omitted for clarity due to high normalised runoff of >560 l/s/km². Lough Derravaragh has been omitted from the total study area calculation.

5.2.5.3 Conductivity

The conductivity measurements are presented in Table 5.16. The conductivity measurements in the catchments of Loughs Owel, Derravaragh and Lene are lower than the other lake catchments. The conductivity measurement at Tobernacogany spring is slightly higher (~ 50 µS/cm higher, on average) than those recorded at Lough Lene. This may be as a result of the water having a higher amount of dissolved calcium carbonate following its passage from Lough Lene. The streams of White Lake, the Ben Loughs, and Lough Bane all have higher conductivities (502 - 511 µS/cm on average). The highest mean conductivity values were recorded in Toberfaolaigh spring (572 µS/cm). It is noteworthy that the conductivity values of the two large springs in Fore Valley are quite different from each other

	16/3/2005 (µS/cm)	26/3/2005 (µS/cm)	6/5/2005 (µS/cm)	Mean (µS/cm)	Std. Dev
Lough Owel	317	308	325	317	8.50
L. Derravaragh	265	267	263	265	2.00
Lough Lene	245	247	241	244	3.06
Lene SH 1	244	250	245	246	3.21
Lene SH 2	244	252	246	247	4.16
Lene SH 3	248	252	246	249	3.06
Fore Valley	511	518	510	513	4.36
Tobernacogany	300	311	301	304	6.08
Toberfaolaigh	573	571	573	572	1.15
White Lake	503	501	505	503	2.00
Ben Loughs	498	506	502	502	4.00
Lough Bane	506	510	517	511	5.57

Table 5.16 Conductivity Measurements and summary statistics.

5.2.5.4 pH

The pH results are presented in Table 5.17. The pH measurements are all higher than 7, typical of water in limestone bedrock areas, or water that has been in contact with a limestone derived till. The pH values recorded at White Lake and Lough Bane are the highest, at 8 or above.

	16/3/2005	26/3/2005	6/5/2005	Mean
Lough Owel	7.7	7.7	7.6	7.7
L. Derravaragh	7.6	7.6	7.6	7.6
Lough Lene	7.7	7.5	7.8	7.7
SH 1	7.6	7.5	7.7	7.6
SH 2	7.6	7.5	7.7	7.6
SH 3	7.6	7.4	7.7	7.6
Fore Valley	7.5	7.4	7.6	7.5
Tobernacogany	7.4	7.4	7.4	7.4
Toberfaolaigh	7.4	7.3	7.4	7.4
White Lake	8.2	8.2	8.2	8.2
Ben Loughs	7.7	7.6	7.7	7.7
Lough Bane	8.0	8.0	8.0	8.0

Table 5.17 pH measurements.

5.2.5.5 Temperature

Water temperatures, simultaneously-recorded air temperatures, and time of measurement are presented in Table 5.18. Water temperatures at the measuring points increase between the first and last sampling periods except in the case of Fore Valley (Glore Bridge) and Toberfaolaigh. The water temperatures at these measuring points are consistently within the 9.5 - 11 °C range. Water temperatures

at Tobernacogany were in between the range of those recorded in lake outflows and those recorded at Toberfaolaigh.

Site	16/3/2005 (C°)			26/3/2005 (C°)			6/5/2005 (C°)		
	Air	Water	Time	Air	Water	Time	Air	Water	Time
Lough Owel	11.2	6.1	8:10am	8.1	7.7	8:00am	9.2	10.4	8:30am
L. Derra -varagh	11.7	6	8:55am	8.2	7.9	8:40am	9.1	9.6	9:15am
Lough Lene	12.3	6.3	9:30am	9.5	7.9	9:15am	9.9	9.3	9:45am
Lene SH 1	12.1	6.4	9:55am	10.3	8	9:45am	9.8	9.6	10:25am
Lene SH 2	11.9	6.3	10:00am	10.4	8	9:50am	10	9.6	10:30am
Lene SH 3	11.9	6.3	10:05am	10.3	7.9	9:55am	9.8	9.5	10:35am
Fore Valley	12.2	10.3	11.50am	11.1	11.3	11.20am	9.9	11	12.20am
Tobern-acogany	12.1	7.4	11:35am	11.1	7.5	10:30am	9.9	8.2	11:10am
Toberf-aolaigh	13.1	9.8	11:15am	10.6	10.7	10:50am	9.8	10.1	11:25am
White Lake	12.7	6.2	12:00pm	10.8	7.1	11:45am	10.3	9.9	12:45pm
Ben Loughs	12.9	5.9	12:40pm	10.7	6.6	12:20pm	11	9.7	1:15pm
Lough Bane	13.2	6.1	1:05pm	10.6	7.4	12:55pm	10.7	10.5	1:50pm

Table 5.18 Air and water temperature measurements.

5.2.6 Summary of results

In this section the results of the pilot study are summarised by individual lake or spring catchment before they are discussed in the following section (5.3).

The hydrological functioning of Lough Owel does not appear to have been altered to the same degree as other lakes in the Inny catchment as a result of drainage works carried out on the River Inny. However, the hydrological functioning of Lough Owel has been modified by the construction of the canal feeder channel and extraction of water. The canal channel is now the main outflow and discharge is controlled by means of a sluice. This means that surface discharge from the catchment is a function of the height of the sluice which, it was noted, was changed at least twice during the pilot study period. However, no information was available as to when or how often this sluice was altered. No surface karstic landforms were identified in this

catchment. Normalised surface discharge for this catchment of ~ 12 l/s/km² is less than would be expected from regional averages ~ 16 - 19 l/s/km², and less than the study area average during the pilot study of 15 l/s/km².

There is evidence that the hydrological functioning of Lough Derravaragh has been altered by drainage schemes in the River Inny catchment. The surface area of the lake has been significantly reduced in size following lake surface level reductions of up to 4 m, and the lake does not store as much water as it did in the past. The discharge from this lake is therefore not representative of the lake discharge had the modifications to the catchment not occurred. A number of karstic landforms were identified in this catchment including a turlough. It is unclear if this turlough still floods regularly though, following the drainage schemes, which may have deactivated a karstic drainage system that operated in this catchment. The channels of the River Inny flowing into and out of the lake are too large to measure discharge using the methods employed in this study.

There is evidence that the surface drainage network has been modified in the Lough Lene catchment by lowering the base level of the surface outflow channel from the lake. This change has led to the lowering of the lake level, and a reduction in the storage of the lake. The base level is fixed, i.e. not sluice-controlled, and it was reduced by < 0.5 m during the past c. 50 years, but this does not represent a major change. A number of active and inactive swallow holes were identified in this catchment, suggesting that karstic processes are occurring in at least part of the catchment. The inactive swallow holes could be evidence that the karstic drainage system in this catchment has been deactivated to a degree as a result of modifications to the lake outflow channel. Normalised surface discharge from the catchment of ~ 5 l/s/km² is lower than regional averages of ~ 16 - 19 l/s/km², and lower than the study area average during the pilot study of 15 l/s/km².

The surface drainage network in the Fore Valley has been extensively modified with many new drainage channels constructed since 1837. The River Glore and Lough Glore have also been extensively modified. This means that water probably has a shorter residence time in this catchment than it had previously. The artificial channels dug in the centre of the valley may reduce the flow attenuation effects of the peat and till deposits in the valley floor. However, there is no evidence that these

drainage modifications have led to a deactivation of karstic drainage systems in the River Glore, Tobernacogany, or Toberfaolaigh. The discharge volumes from both Tobernacogany and Toberfaolaigh springs are much higher than would be expected based on the area of their topographically defined catchments. Conductivity measurements of water discharging from Toberfaolaigh and in the stream channel at Glore Bridge are relatively high compared to the other pilot study catchments. Water temperatures are more constant than average surface water temperatures in the study area, remaining close to 10 - 11°C during warm and cold times of the year.

There is no evidence of drainage works in the White Lake catchment. The lake experiences a large seasonal fluctuation in surface water level (3 - 5 m, depending on the year in question). A large swallow hole (1.5 m in diameter) is located on the shore of the lake. There is no surface discharge from this catchment. Conductivity and pH values are also relatively high in White Lake compared to the other study catchments.

There is evidence that the base level of the surface outflow from the Ben Loughs catchment has been lowered since 1837. The surface area of the lakes appears to have reduced since 1837. No surface karstic landforms were located in this catchment. Normalised surface discharge from this catchment is higher at ~ 30 l/s/km² than expected regional values of ~ 16 - 19 l/s/km² and higher than the study area average during the pilot study of 15 l/s/km². Conductivity values are higher than the study area average. Although the surface drainage network in this catchment does not appear to have been modified since 1837, the lake has been reduced considerably in surface area and in its storage capacity. This could be as a result of public water supply extractions from the lake. Small solution features were found on exposed bedrock in this catchment, but no other karstic landforms were identified. Normalised surface discharge from the catchment is higher at ~ 22 l/s/km² than expected regional averages of ~ 16 - 19 l/s/km² and higher than the study area average during the pilot study of 15 l/s/km².

5.3 Discussion

As stated in Section 4.2, the aim of the pilot study was to identify a smaller area for detailed study. The area selected had to:

- Be representative of the Meath – Westmeath lakelands
- Have hydrological integrity
- Be spatially contiguous
- Suitable for the implementation of the chosen methods

For a lake catchment to be representative of the wider area it had to be broadly typical of other catchments in the region in terms of its hydrology and geomorphology. Typically, lakes in the region do not have significant (> 10 l/s) surface inflows. Lough Derravaragh is different in that it has a large influent river, the River Inny. None of the other lakes in the pilot study area have significant surface inflows. The geomorphology of the area is characterised by steep-sided isolated hills and a small number of surface karst landforms such as swallow holes and Karren forms. The topography in all of the catchments is dominated by these hills, but two catchments, the Lough Owel and Ben Loughs catchments do not contain any evidence of surface karst landforms.

It is important that the catchments included in the detailed study area had hydrological integrity, i.e. that karstic drainage systems had not ceased to function as a result of drainage schemes and that their hydrological behaviour is at or close to its natural state prior to anthropogenic modifications,. While surface drainage network modification is not as extreme in this part of the country as in other areas such as east Galway, most of the catchments have been affected by drainage schemes in some way. This can range from slight (< 1 m) lowering of outflow base levels and construction of field drainage ditches to large reductions in outflow base levels (up to 4 m in the case of Lough Derravaragh) to large scale river straightening and canalisation. Of the seven catchments included in the pilot study, the Lough Owel and Lough Derravaragh catchments have undergone the most extensive modifications since 1837. The main outflow channel from Lough Owel has been changed by the construction of the Royal Canal feeder channel. It is possible that this has significantly altered the hydrological integrity of this catchment. The other catchments have not been as extensively modified and are therefore likely to be closer to their 'natural' state in terms of hydrological behaviour.

The catchments chosen for the detailed study had to be spatially contiguous, as groundwater mapping was to be carried out in the chosen area. Interactions between groundwater and surface water could occur between the study catchments and catchments that had been excluded, which would mean that it would be impossible to accurately investigate the pathways that water took through the study area. Evidence from the surface channel discharge measurements suggests that significant non-point groundwater discharge occurs in Fore Valley down stream from Tobernacogany and Toberfaolaigh, and this catchment must be included as the likely sources of this higher than expected discharge are Lough Lene, White Lake, or the Ben Loughs. There is no suitable measuring point located downstream of Glore Bridge, consequently, the catchment of Fore Valley must be defined as the topographically defined contributing area upstream of this point. The pilot study area was spatially contiguous, but if the exclusion of a catchment meant that another catchment became spatially separated from the other study catchments, this catchment would also have to be excluded from the detailed study area. Therefore, if the Lough Derravaragh catchment was excluded then the Lough Owel catchment would also have to be disqualified from the detailed study.

The catchments chosen for the detailed study must be suitable for the successful implementation of the methods used in the detailed study. The measurement sites in all catchments were suitable for the implementation of the detailed study methodology except Lough Derravaragh. Due to the width, depth, and velocity of the River Inny channel it was impossible to use the velocity-area discharge estimation technique in this catchment. As water budgets were to be calculated for the study lake catchments and the detailed study area as a whole, it was necessary to include areas identified as proven or possible discharge areas outside of the topographically defined study catchments. Water discharging from Tobernacogany spring has been traced to Lough Lene and this spring catchment had to be included. The source of water discharging from Toberfaolaigh had not been identified but it is possible that this spring is recharged from the Lough Lene, Lough Bane, Ben Loughs catchments, or from outside the study area and thus this spring catchment also had to be included in the detailed study.

5.4 Conclusions

The Lough Derravaragh catchment failed to meet a number of the criteria for inclusion in the detailed study area. It is not representative of the wider area in that it is the only lake in the area with a significant surface inflow. This catchment also does not have hydrological integrity, as the lake has been greatly modified in terms of the altitude of its surface water level. The inflow and outflow channels for the River Inny to/from Lough Derravaragh are also unsuitable for the detailed study discharge measurement techniques. As a result of these findings the Lough Derravaragh catchment was excluded from the detailed study area.

The Lough Owel catchment meets the inclusion criteria in terms of being representative of the wider area, but it does not have hydrological integrity as the surface discharge from this catchment is controlled by a movable sluice. The catchment would also be spatially separated from the other study catchments once Lough Derravaragh was excluded. Thus, this catchment was not included in the detailed study area.

The Lough Lene, White Lake, and Lough Bane catchments met all of the requirements for inclusion in the detailed study area as they are representative of the wider areas, their hydrological functioning has not been greatly modified They contain surface karst landforms and they are suitable for the detailed study methodology. The Ben Loughs catchment met all of the criteria except that there is no evidence of surface karstic features in the catchment. This was not considered as important as hydrological integrity, which this catchment has, and the inclusion of the Ben Loughs catchment was necessary to ensure the spatial contiguity of the detailed study area. The topographically defined catchments of Tobernacogany spring, Toberfaolaigh spring, and Fore Valley upstream of Glore Bridge must be included for the reasons presented at the end the preceding section in this chapter.

As a result of the conclusions reached in the pilot study a representative, spatially contiguous area with hydrological integrity and suitability for the detailed study methodology was chosen. This area comprised of 4 lake catchments: Lough Lene; White Lake; Ben Loughs; Lough Bane; and 2 spring catchments; Tobernacogany and Toberfaolaigh, and the topographically defined area of Fore Valley contributing runoff to the river Glore above the Glore Bridge measuring point (Figure 5.31).

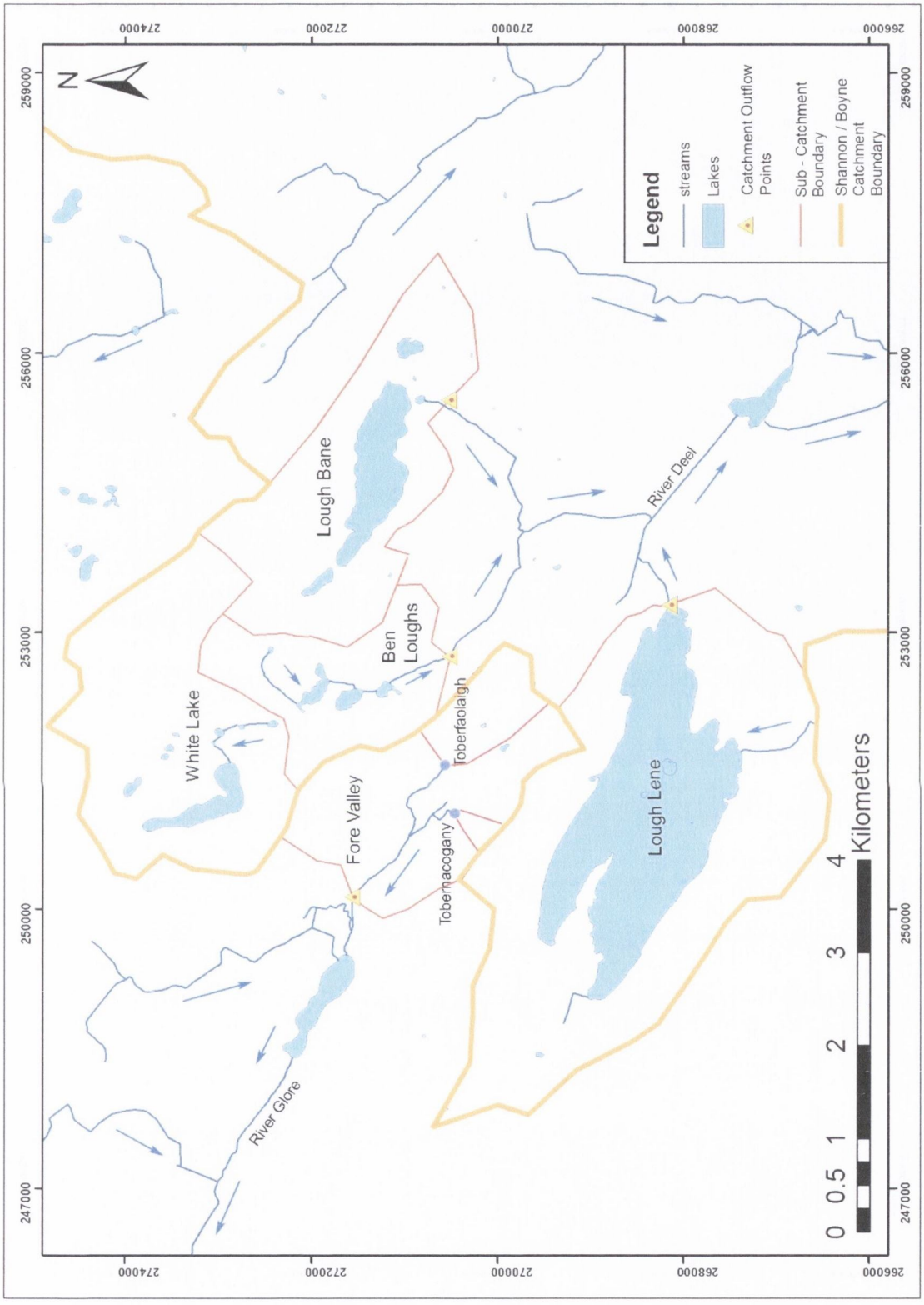

Figure 5.31 Map of the detailed study area (basemap data OSI 2001).

6. Detailed Study Results

6.1 Introduction

The results of the detailed study are presented in this chapter. They are presented on an individual basis and in the following order: karstic landforms; surface hydrology and water budgets; and groundwater hydrology.

6.2 Karstic landforms

A number of different types of karstic surface landforms were identified in the study area. These included; swallow holes (possibly estavelles in the case of White Lake); karren forms; enclosed depressions; a small cave; mushroom stones; and springs. For the purposes of the detailed study results, all of the aforementioned landforms have been included in an inventory of landforms. In contrast to other lowland karstic areas in Ireland, no dry valleys, turloughs, or other landforms typical of these areas were encountered. The results are presented in Table 6.1 and Figure 6.3 and are summarised on a lake/spring catchment basis. Photographs of karstic features identified in the study area are also presented in Appendix E.

Catchment	Total	Landform Type	Grid Ref.	Alt. (maOD)
Lene	2	mushroom stone	N2524926786	93
		springs	N2527626856	93
Fore Valley	3	karren	N2513627091	101
		karren	N2520627073	196
		cave	N2508927027	145
White Lake	8	karren	N2511327325	107
		Karren	N2509627312	107
		enclosed depression	N2507627373	109
		enclosed depression	N2516127278	107
		enclosed depression	N2517127288	107
		collapse feature	N2510027300	106
		collapse feature	N2510227299	106
		collapse feature	N2510127296	106
Ben Loughs	1	springs	N2524127199	107
Lough Bane	2	karren	N2555427130	114
		enclosed depression	N2535127225	118

Table 6.1 Karst landforms identified during the detailed study.

Lough Lene catchment

On the southern shore of Lough Lene three mushroom stones were located (Appendix E Plate 24). These mushroom stones were detached from the bedrock and were found lying on their sides. The distance from the base of the stone to the point where the 'head of the mushroom' protruded from the 'mushroom stalk' on each stone ranged between 0.35 - 0.4 m. Although mushroom stone morphology cannot be used to conclusively reconstruct past surface water levels, on the basis of this evidence, it is possible that in the past lake surface water level may have been at least 0.35 - 0.4 m higher than the present level. In addition, five small springs (< 5 l/s) were identified on the northern shore of the lake (N2527626856) and, during the period of sampling, these springs were found to be only active during the late winter/spring months.

Tobernacogany, Toberfaolaigh and Fore Valley

Near the Toberfaolaigh spring, karren features were identified on bedrock cliffs at the base of the Ben of Fore and also on loose limestone blocks near the summit of the Ben. These karren features took the form of irregular etchings and rillenkarren measuring 1 - 2 cms wide by 3 - 10 cms long. In contrast, the adjacent beds of rock showed no signs of solutional erosion but exhibited angular fracture surfaces typical of mechanical erosion. A 2 m long cave is located in the cliff overlooking Tobernacogany spring. This is a relict rift cave (Drew 1997). This cave may have been exposed through natural or anthropogenic processes as it is unknown how this cliff and indeed the other exposed bedrock in Fore Valley were affected by quarrying activities undertaken for construction of Fore Abbey during the Middle Ages. A spring known locally as the Roaring Well is situated approximately 2 km northwest of Fore Village within the River Glore / Fore Valley. Water from this spring flows into the River Glore via bog drainage channels upstream of Lough Glore but downstream of Glore Bridge.

White Lake catchment

In addition to the swallow hole located as part of the pilot study, two more swallow holes / swallets were identified and mapped as part of the detailed study. These swallow holes / swallets were located on the lakeshore to the north of the swallow hole identified during the pilot study. The swallow hole located in the pilot study was 1.6 m deep and 1.5 m wide while the other two swallow holes or swallets are

measured 0.1 m and 0.05 m in width respectively. These relatively small swallets are located at points where the lake surface intersects outcropping bedrock and water enters the bedrock matrix through joints in the rock. During the sampling period, these swallow holes were found to be functioning for less than a week when they became visible (as the lake level dropped) before the lake level fell below their inflow base levels.

Three collapse features were discovered in August 2007 and were located < 50 m from the swallow hole identified during the pilot study. These features were not apparent before the lake level rose in autumn 2006. All three features measured approximately 0.4 - 0.8 m in diameter and were sub-circular in shape (Appendix E Plates 25 and 26). They ranged from 0.15 - 0.25 m in depth. Probing results suggest that cavities were present beneath these features, as the probe fell suddenly into a sub-surface void when pushed into the ground. In addition, three larger depressions were identified in close proximity to the lake. One was located 20 m to the northwest of the lake and two others 20 m and 50 m to the southeast of the lake. These features were sub-circular in shape with the following long/short axes: 1) 95 m x 48 m, 3 m deep; 2) 66 m x 40 m, 3 m deep; 3) 60 m x 29 m, 3.5 m deep. It was not possible to determine definitively whether these features are glacial kettle holes or dolines. Karren features were discovered on exposed bedrock on the western shore of the lake in between the swallow holes. These karren features were classified as irregular etchings which were approximately 0.5 - 1 cm deep x 0.5 - 1 cm long along their longest axis. White Lake itself may be contained in an enclosed depression in the bedrock. Apart from two points to the southeast and northeast of the lake where depth to bedrock is unknown, the bedrock on all sides of the lake is at a higher altitude than the altitude of the winter standing surface water level (Figure 6.1). As a result, it is not known whether the bedrock depression containing White Lake was formed by solution, glacial processes, or a combination of the two.

From an examination of aerial photographs (Figure 6.2, these features have not been included in Figure 6.3), a number of sub-circular depressions were identified in the basin of White Lake and, similar to the wider lake basin itself, it is not known whether these depressions were formed by glacial action, solution, or a combination of both. Notably, the morphologies of these depressions are similar to those of the depressions identified on the land surface in proximity to White Lake.

Figure 6.1 Altitude of bedrock in relation to White Lake standing water surface level (basemap data OSI 2001; GSI 2003).

Ben Loughs catchment

A line of small springs and seepages were identified in the catchment area of the Ben Loughs, more specifically around the shore of Ben Lough North. No other surface karst landforms were discovered and none of the springs had a measured flow of > 0.5 l/s.

Lough Bane catchment

Karren features were identified in the Lough Bane catchment (Appendix E Plate 23), both on the bedrock and on loose blocks of limestone located on the northern shore of the lake. In addition, an enclosed depression situated to the northwest of the lake was identified and mapped, with dimensions of 68 x 84 m, and a depth of approximately 2.5 m.

Figure 6.2 Circular and sub-circular depressions, possibly dolines, located both in and in close proximity the basin of White Lake (Aerial Photograph OSI 2004).

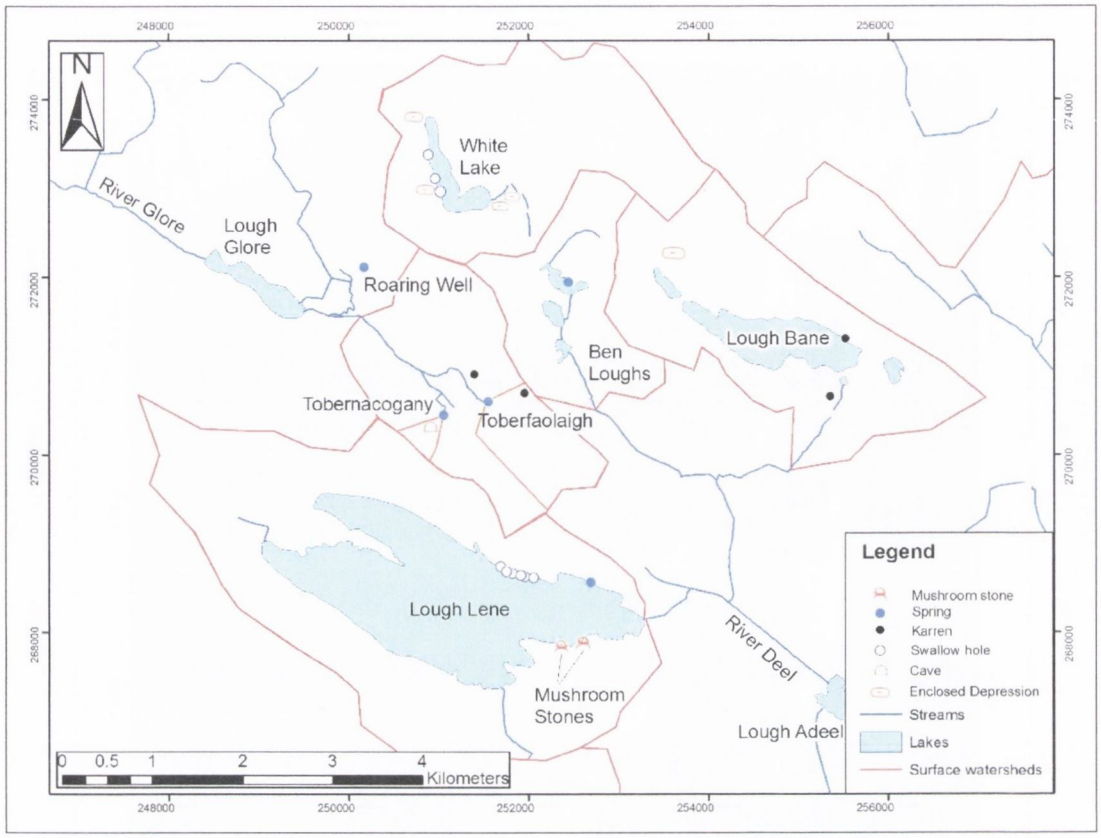

Figure 6.3 Map of karstic surface landforms in the detailed study area (including landforms identified during the pilot study) (basemap data OSI 2001).

6.3 Surface hydrology results

6.3.1 Flow measurements

6.3.1.1 Introduction

In this section, discharge measurements for the springs of Tobernacogany and Toberfaolaigh are presented while discharge measurements at Glore Bridge are also described. These data are followed by details of the measured levels of discharge from the lake catchments and the measured surface water levels for all lakes examined. Over the period 1/3/2007 to 7/8/2007, 16 sets of discharge measurements were made; summary statistics of these data are presented in Table 6.2. Finally, discharge measurement for both spring and lake catchments are compared and contrasted. The locations of measuring points are illustrated in Figure 6.4.

	Max (l/s)	Min (l/s)	Mean (l/s)	Std. Dev.	CV
Lene Surface	183.5	9.3	74.6	56.86	0.76
Lene SH1	64.3	15.3	38.1	14.14	0.37
Lene SH2	10.9	0.0	3.3	4.21	1.28
Lene SH3	50.7	6.0	23.0	11.44	0.50
Fore- Springs	213.0	59.3	111.0	42.60	0.38
Fore Valley	455.7	226.4	314.8	68.13	0.22
Tobernacogany	84.0	36.0	60.6	13.67	0.23
Tobefaolaigh	202.4	106.1	143.2	30.96	0.22
Ben Loughs	84.5	15.7	39.6	18.90	0.48
Lough Bane	154.1	14.9	50.0	42.20	0.84

Table 6.2 Summary statistics calculated for measured levels of discharge for the spring and lake catchments included in the detailed study.

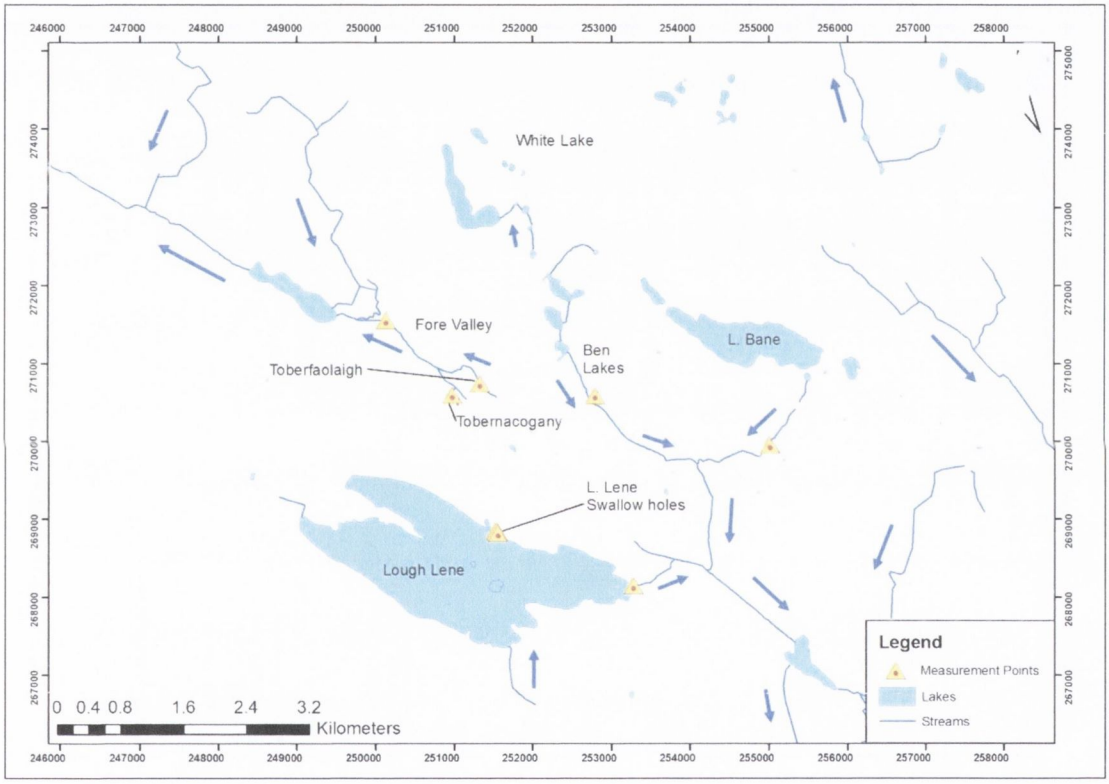

Figure 6.4 Locations of discharge measurement points employed in the detailed study (basemap data OSI 2001).

6.3.1.2 Spring flow measurements

Average levels of discharge from Tobernacogany spring was highest in March (84 l/s) and was lowest in July (36 l/s), with a mean flow of 60 l/s (Figure 6.5). Flow from this spring decreased during the summer months but, following a period of heavy rain, increased in late July (65 l/s). An underground flow route from the Lough Lene swallow holes to Tobernacogany was proven by McDonald (1988) and, on this basis, the source of at least some of the water in this spring is known. Toberfaolaigh

had a mean discharge of 143 l/s during the period of the detailed study. Discharge from Toberfaolaigh spring was highest in March and April (202 l/s) and was lowest in June (107 l/s) (Figure 6.5). Flow from this spring then remained relatively constant over the remainder of the summer showing only small fluctuations and no clear upward or downward trend was apparent. Following a rainfall event of approximately 25 mm over three days during late April (23rd, 24th, and 25th April), flow from Toberfaolaigh increased noticeably (25th April) while flow at Fore Bridge decreased. The opposite was true in early July, when flow from Toberfaolaigh decreased and flow at Glore Bridge increased following prolonged precipitation. On the basis of these measurements, it is postulated that no clear relationship exists between temporal variations in levels of flow at these sites, although the coefficients of variation of discharge measurements at all three sites were similar ranging from 0.22-0.23.

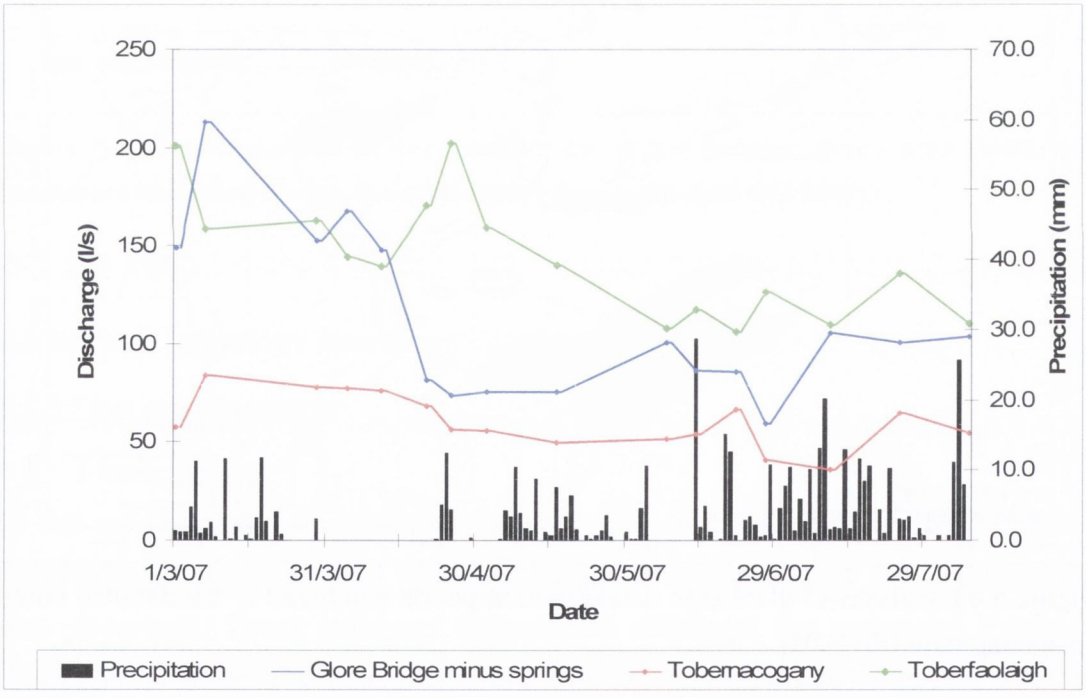

Figure 6.5 Flow measurement data for Tobernacogany and Toberfaolaigh springs. Flow measurement data recorded at Glore Bridge (the flows from Tobernacogany and Toberfaolaigh have been subtracted from this variable) and daily precipitation data recorded at the synoptic station at Mullingar are also shown.

6.3.1.3 Lake catchment outflow discharges

Lough Lene (Figure 6.6)

Four measurement sites were located in this catchment: the surface outflow; and the three active swallow holes at the northern shore of the lake. Flow from the surface outflow was highest in early March (183 l/s) and lowest in August (16 l/s). Flows in this channel continued to decrease during the late spring and summer 2007 even though levels of precipitation increased. This can be explained by an increase in rates of evapotranspiration due to relatively high summer temperatures (as described in section 3.3.4). Combined flow entering the three swallow holes broadly followed the same pattern as the surface channel, but was more stable than that in the surface channel. Flows entering the swallow holes remained greater than 40 l/s throughout the summer as the swallow hole channels have lower outlet levels than the surface channel. For the most part, during the winter months, water flowing from this catchment flows into the River Deel via the surface channel. Conversely, most of the water flowing out of the catchment during the summer months discharges via the swallow holes to the River Shannon. Overall, variations in water level of the lake (Top graph in Figure 6.6) followed the same pattern as the surface and swallow hole flows, decreasing towards the summer with a sharp increase in levels evident following a rainfall event in mid-June. During March, precipitation amounts of (~10 mm/day) were sufficient to maintain the lake water level. In contrast, in May the lake level fell even when precipitation amounts were greater than 10 mm/day. This seasonal difference is also evident in the flow entering the swallow holes. For example, a rainfall event of ~5 mm at the end of March resulted in a ~20 l/s rise in rates of flow to the swallow holes whereas a larger rainfall event of ~30 mm in mid-June resulted in a smaller rise in flow (< 15 l/s). Cross correlation analysis was performed on the precipitation (Met Éireann daily totals recorded at the Mullingar station) and lake water level data. Results of this analysis indicate a weak and positive level of correlation with a highest value of r = 0.317 at lake level lagging precipitation by 19 days. The average total measured discharge in this catchment over the course of the study period was 139 l/s, giving a specific runoff of 10.37 l/s/km^2 which is less than the specific runoff range calculated for the Shannon/Boyne catchments of 16 - 19 l/s/km^2.

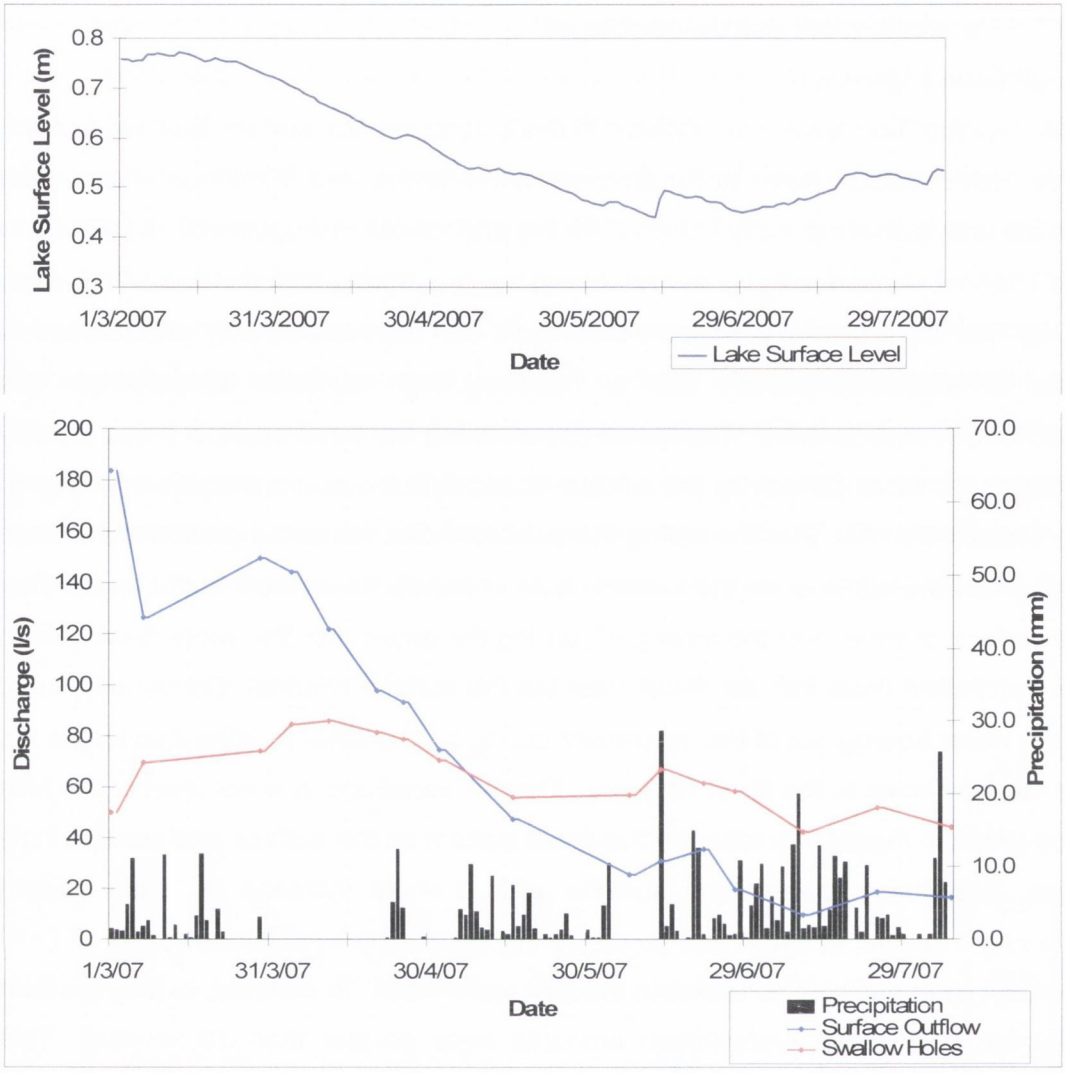

Figure 6.6 Recorded measurements of outflow rate and lake water levels for Lough Lene and daily precipitation data recorded at the synoptic station located at Mullingar.

Ben Loughs (Figure 6.7)

One measuring point was located in this catchment – in the lake outflow channel. Flow in this channel was highest in March (85 l/s) and lowest towards the end of June (15 l/s). Flow then increased steadily to 49 l/s in response to increased levels of rainfall in July. Notably, there would appear to be a lag time of 10 - 15 days between increased levels of precipitation and increased levels of discharge. This could be due to the attenuating effects of either groundwater seepage or lake storage but it is difficult to discern a clear association between precipitation amounts and lake stage or outflow at this site due to the fact that an automatic water level recorder was not installed at this lake and, as a result, the data set is too sparse to conduct cross correlation analysis. During the pilot study specific runoff from this

catchment was almost twice as high as regional averages. However, and in contrast, during the detailed study average normalised average runoff calculated for the Ben Loughs catchment was just over 13 l/s/km², lower than Shannon/Boyne averages. The water level in the Ben Loughs declined slightly and steadily during the study period.

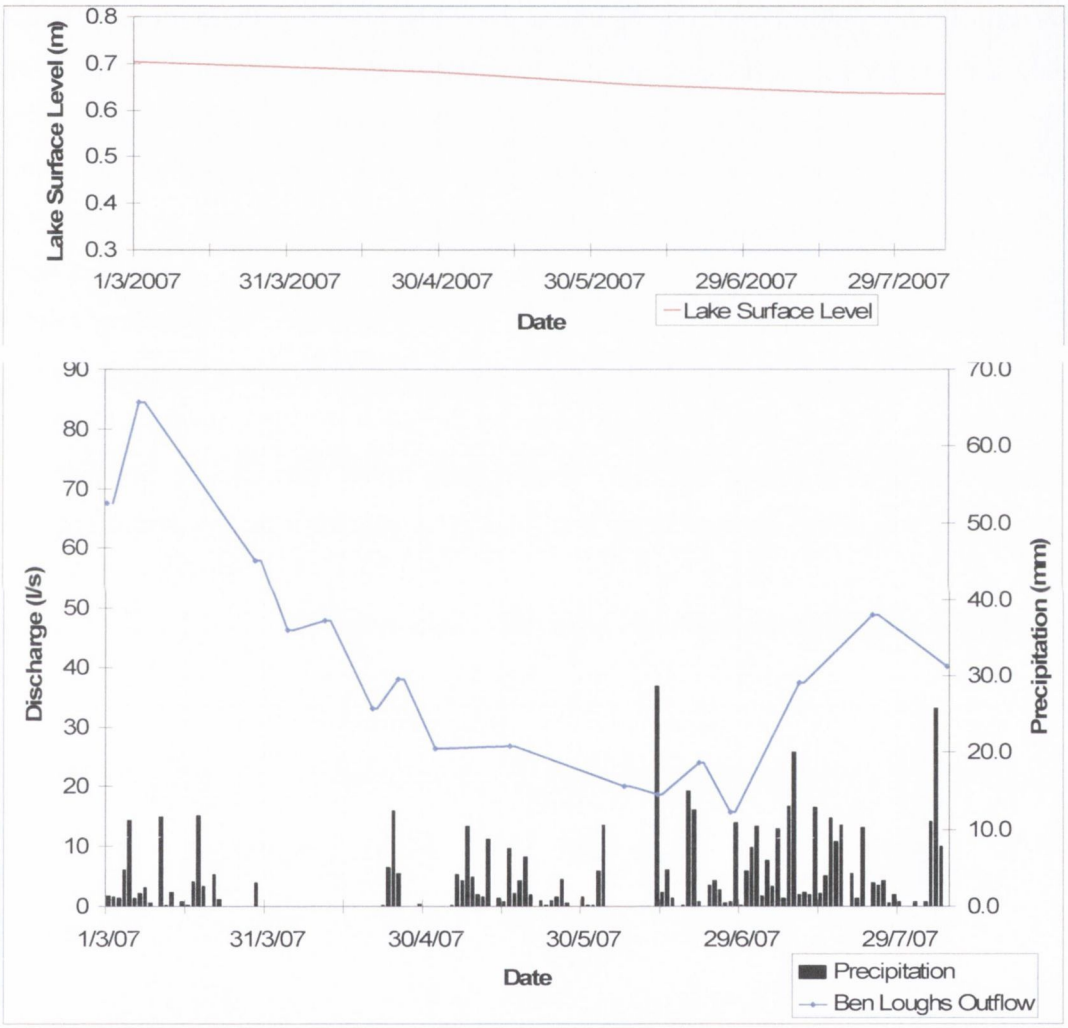

Figure 6.7 Recorded measurements of outflow rate and lake water levels for the Ben Loughs and daily precipitation data recorded at the synoptic station located at Mullingar.

Lough Bane (Figure 6.8)

One measurement point was located in this catchment – in the lake outflow channel. Flow rate was highest in this channel during March (154 l/s), the rate then fell sharply between March and May, and was lowest in July (15 l/s). Rates then

became relatively stable for the remainder of the summer months and discharges do not appear to have been affected by heavy precipitation events throughout June and early July. However, rates of discharge increased towards the end of July and into August. Like the Ben Loughs catchment, the average measurement of specific runoff from this catchment during the pilot study was higher than regional averages and, in contrast, this was not reflected in the detailed study. Specific runoff during the detailed study for Lough Bane was 7.9 l/s/km², less than half the Shannon/Boyne mean. This result however may reflect the time of year during which the detailed study was carried out as, due to decreased levels of precipitation, levels of specific runoff are generally lower during the summer months compared to the winter months. The lake water level follows the same pattern as the catchment discharge. No lake level data were available until the middle of April as the level of the lake was too high for the EPA maintained data logger to work. From mid April, the lake level and surface discharge react similarly and quickly following rainfall events. Following a prolonged period of heavy rainfall during July both the level of the lake water and surface discharge begin to increase. Cross correlation analysis was performed on precipitation (Met Éireann daily totals recorded at the Mullingar station) and lake level data sets for this lake. The results indicate that there is a weak and positive correlation with an r value of 0.39 and a lag time of 3 days between precipitation events and an increase in lake level.

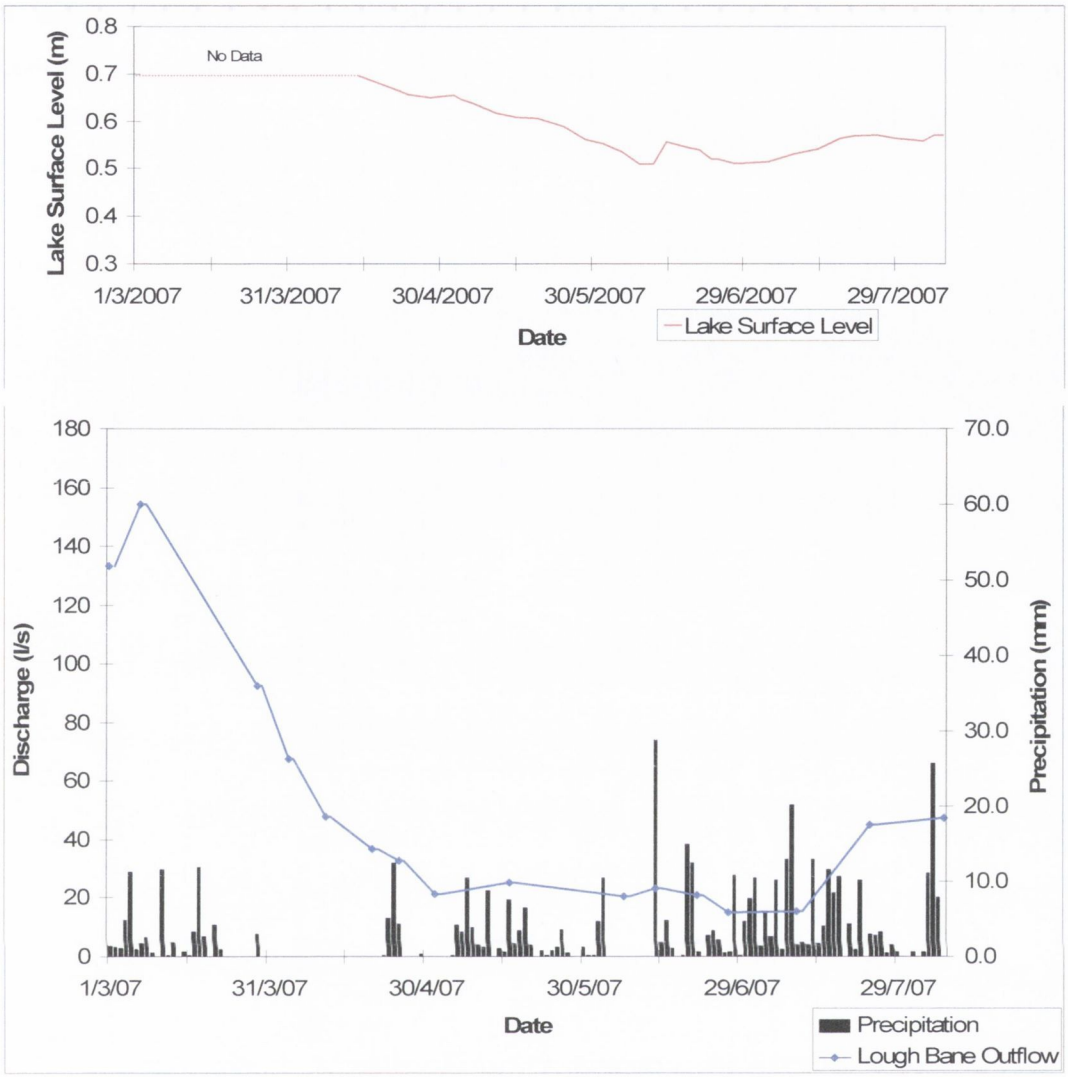

Figure 6.8 Recorded measurements of outflow rate and lake water levels for Lough Bane and daily precipitation data recorded at the synoptic station located at Mullingar.

6.3.1.4 Comparison of spring and lake outflows

The flows from the springs and lakes are presented together in Figure 6.9. Volumes of flows from the study springs and lakes decrease from March to June and they rise again towards the end of July and into August. However, there is less seasonal variation apparent in the levels of spring flows than those of the lake outflows, i.e. the spring flows are less flashy than flows in surface streams out flowing from the lakes. During May a prolonged period of precipitation did not affect the discharge in these outflow channels as flows continued to fall into June. Discharge at all sites rose during late July – early August following repeated rainfall events during July. In previous years all of the lake outflow channels, the Lough Lene swallow holes and Tobernacogany have ceased to flow from June-July until the following winter. This

did not occur during the 2007 study period, as 2007 was an exceptional year in Ireland in terms of increased rainfall in June and July (http://www.met.ie/climate/mullingar.asp).

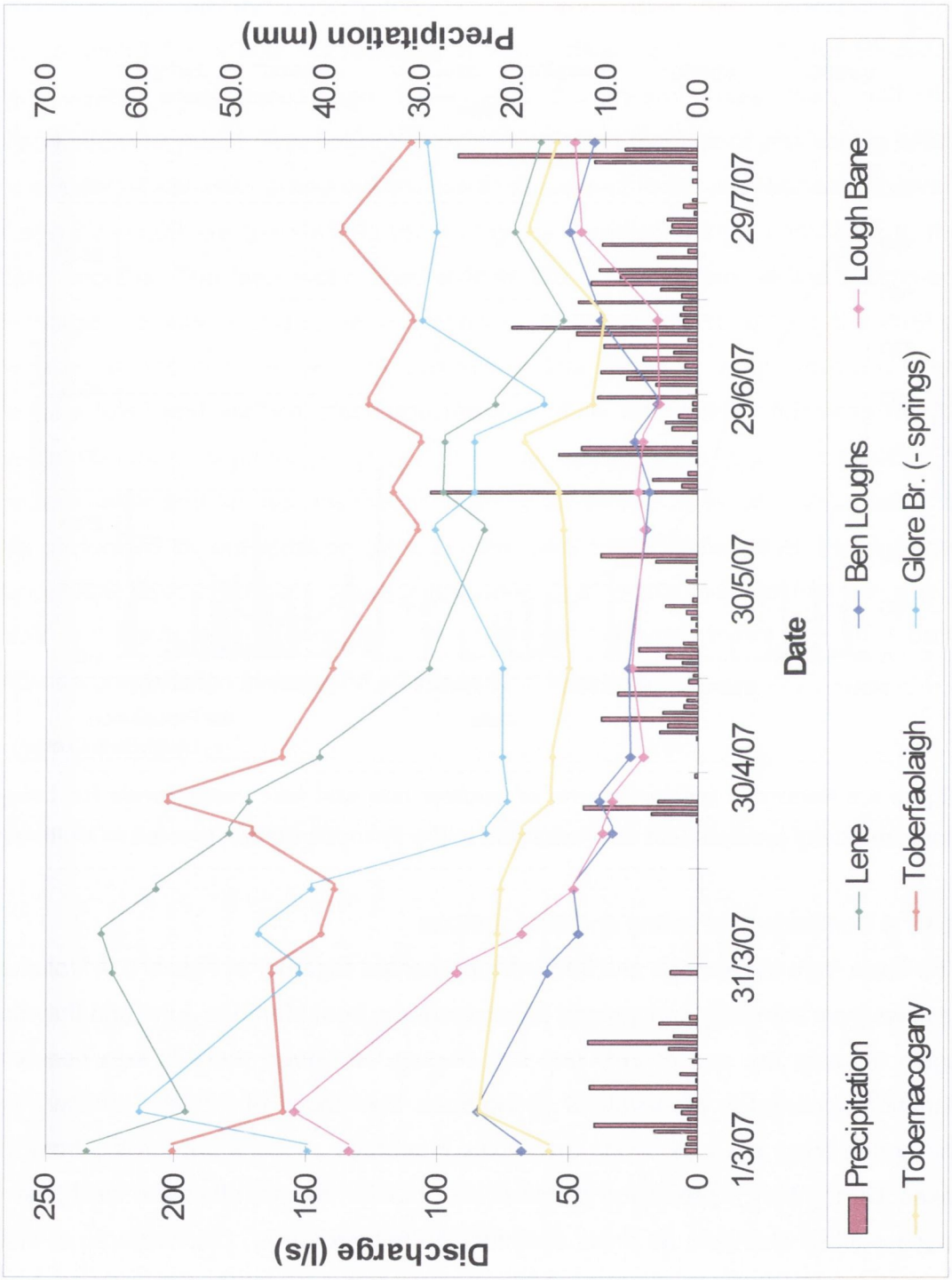

Figure 6.9 Measured discharges of the study area catchment outflows and daily precipitation at Mullingar.

6.3.2 Conductivity measurements

The results of conductivity measurements are presented in Table 6.3 and Figure 6.10. Conductivity measurements for Lough Lene had a mean value of 237 µS/cm and a range of 37 µS/cm. Water flowing from Tobernacogany spring had a range of 24 µS/cm and a mean conductivity of 303 µS/cm, approximately 70 µS/cm higher than water entering the Lough Lene swallow holes which are connected to this spring. The Toberfaolaigh spring had the highest conductivity values for any of the sites examined in the detailed study area (average 560, range 69 µS/cm). The conductivity values at this spring can at least partly account for the values recorded at the Glore Bridge site (mean 511 µS/cm, range 18 µS/cm) which is located downstream. Conductivity measurements at the Ben Loughs outflow were also relatively high (average 495 µS/cm, range 72 µS/cm) and have the widest range of any of the sites surveyed. The conductivity measurements at the Lough Bane outflow are also relatively high (average 426 µS/cm, range 61 µS/cm), but lower than those recorded at the Ben Loughs. Conductivity values at each site through time are presented in Figure 6.11. This graph shows that variation in conductivity values was greater during the summer months when levels of flow were low and precipitation high. The conductivity values recorded at the Ben Loughs outflow are of particular interest as they fall from a 555 µS/cm in the spring to 427 µS/cm in summer and this change is not reflected at any of the other measuring sites except the Lough Bane outflow, where the fall is not as clearly defined. Conductivity results are plotted against discharge measurements in Figures 6.12 to 6.17. The results for the two springs are markedly different from each other in that there does not appear to be a discernable relationship between discharge and conductivity at Tobernacogany ($r = 0.1$, $p = 0.71$) while at Toberfaolaigh conductivity generally increases when discharge increases ($r = 0.74$, $p = < 0.01$). Variation in levels of conductivity at Fore Valley (Glore Bridge) do not appear to be synchronous with variations in levels of discharge ($r = - 0.17$, $p = 0.54$) and the highest conductivity value was recorded at this site when the lowest levels of discharge was recorded. The three lake sites, Lough Lene (surface outflow) ($r = 0.86$, $p = < 0.01$), the Ben Loughs ($r = 0.63$, $p = < 0.01$), and Lough Bane ($r = 0.39$, $p = 0.14$) are interesting as the association between discharge and conductivity at all of these sites appears to be similar in that conductivity increases with increasing flow before conductivity stabilises despite increasing flow, although the p values indicate a degree of variation in the significance of these results. That is, conductivity does not appear to

be related to discharge during periods of low flow but rises when flows increase above a certain point (~40 l/s at Lough Lene, ~50 l/s at the Ben Loughs, and ~60 l/s at Lough Bane). Conductivity then stabilises and does not appear to rise or fall significantly with further increases in flow.

Measuring Site	Max (µS/cm)	Min (µS/cm)	Range	Mean (µS/cm)	Std. Dev.	CV
Lough Lene	252	215	37	237	14.2	0.06
Tobernacogany	313	289	24	304	3.7	0.01
Toberfaolaigh	576	507	69	560	6.7	0.02
Glore Bridge	523	505	18	511	6.4	0.01
Ben Loughs	555	427	128	495	54.8	0.11
Lough Bane	454	393	61	426	20.0	0.05

Table 6.3 Summary statistics calculated for conductivity measurement data (based on 16 measurements at each site).

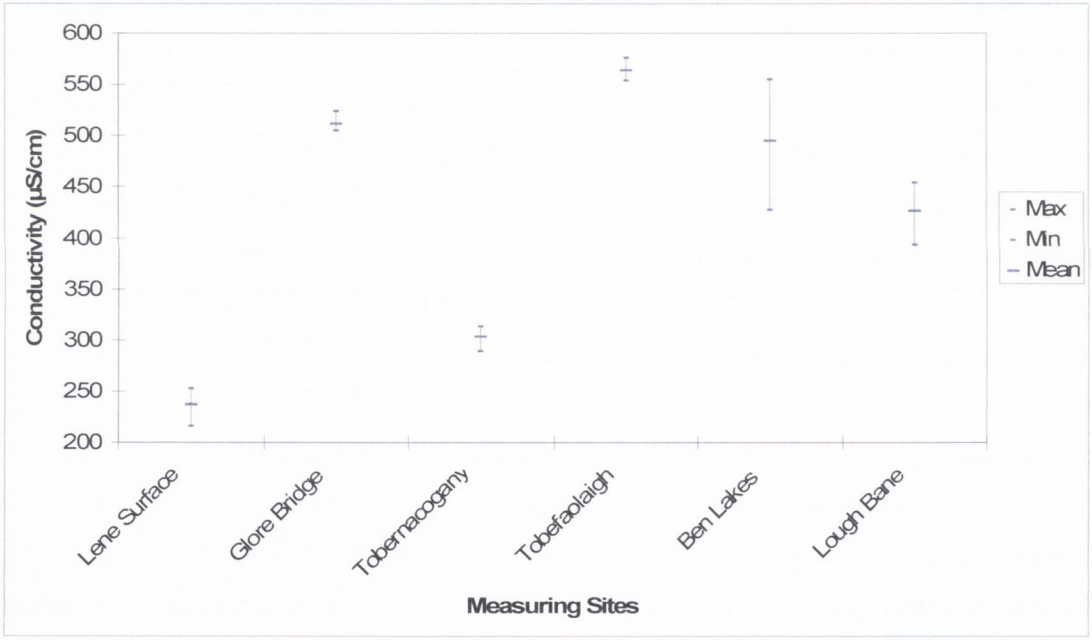

Figure 6.10 Measured conductivity values (maximum, minimum and mean values at each site).

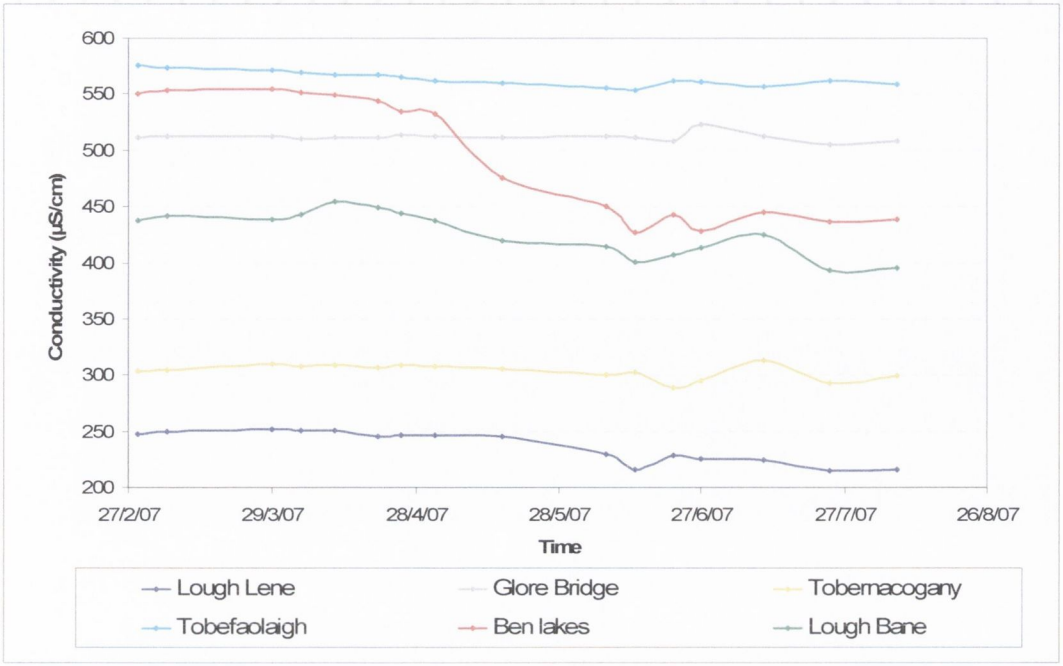

Figure 6.11 Conductivity values vs. time at each of the measuring sites.

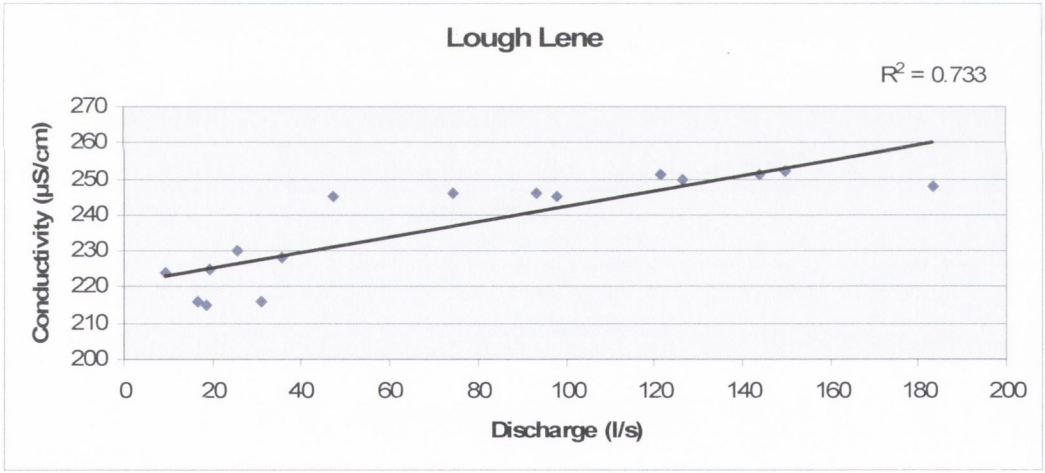

Figure 6.12 Measured discharge vs. conductivity data for Lough Lene (surface outflow).

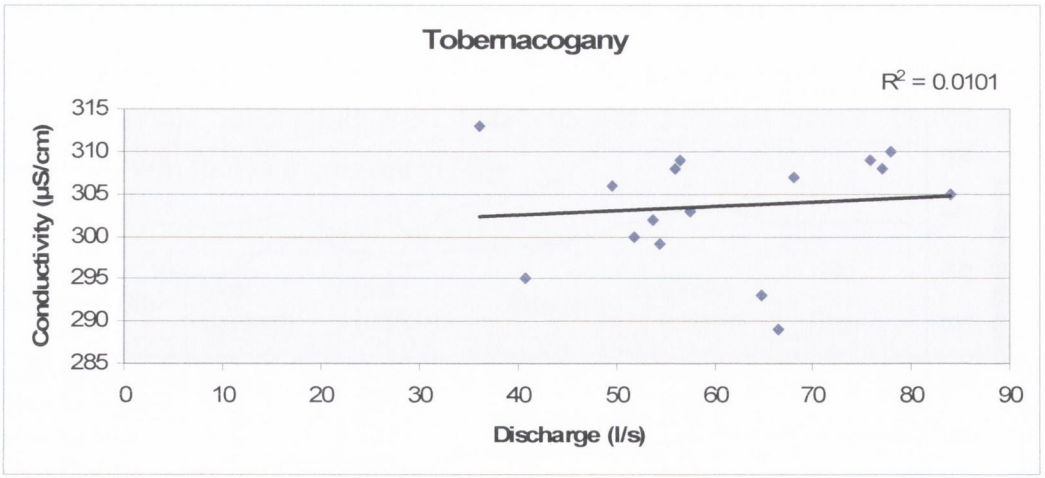

Figure 6.13 Measured discharge vs. conductivity data for Tobernacogany.

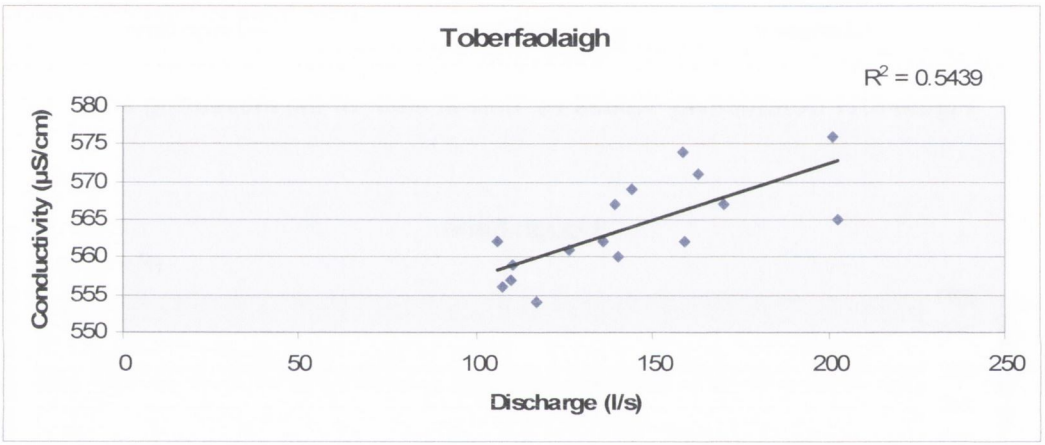

Figure 6.14 Measured discharge vs. conductivity data for Toberfaolaigh.

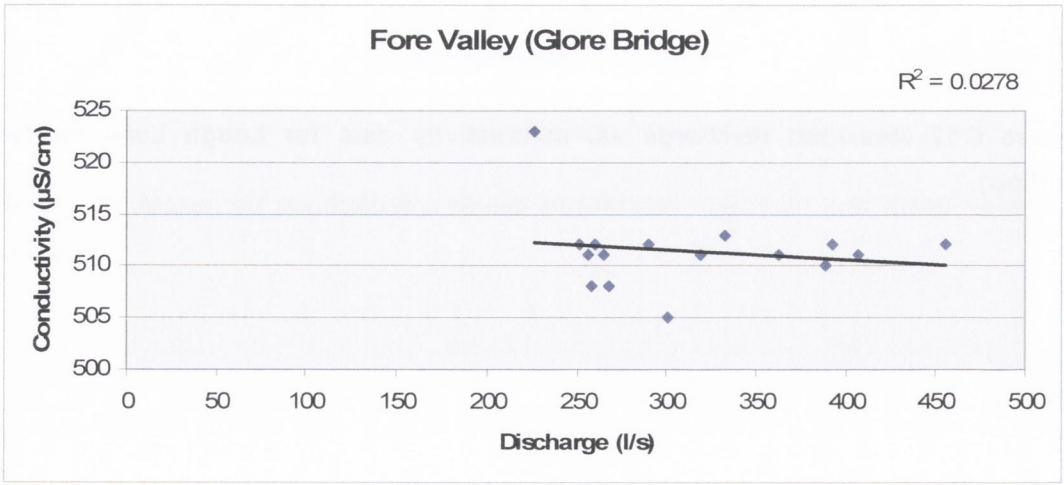

Figure 6.15 Measured discharge vs. conductivity data for Fore Valley (Glore Bridge).

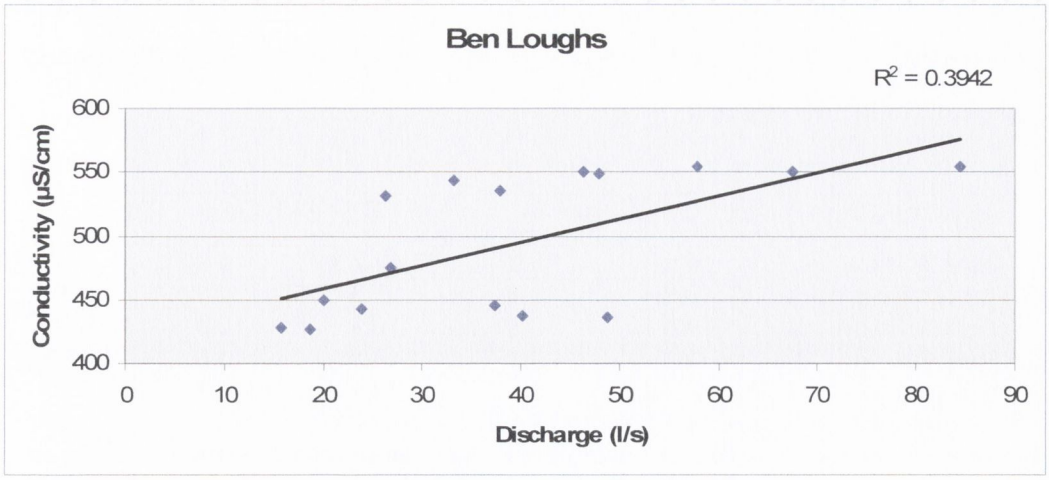

Figure 6.16 Measured discharge vs. conductivity data for the Ben Loughs.

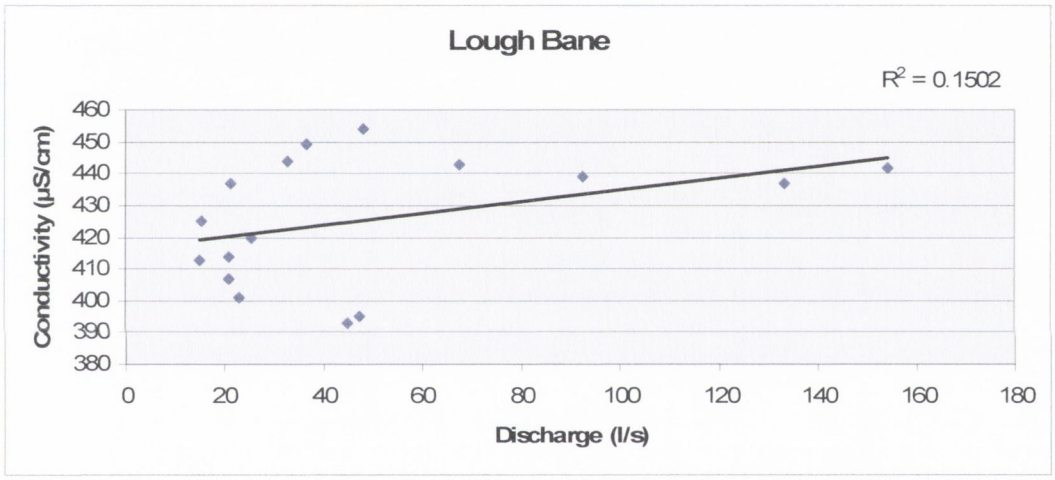

Figure 6.17 Measured discharge vs. conductivity data for Lough Bane.

6.3.3 Temperature measurements

The temperature measurements collected as part of this study are presented in Table 6.4 and Figures 6.18 and 6.19. The range of water temperatures at Toberfaolaigh was 1.5 °C and at Glore Bridge 3 °C. Tobernacogany exhibits a wider temperature range but this can be explained by the length of time water may spend underground between the Lough Lene swallow holes and the spring (less than 24 hours according to McDonald (1988)). The other measuring sites have average temperatures 2 – 3 °C higher than typical groundwater values and they all have much wider ranges of fluctuation. The broken blue line in Figure 6.19 indicates the mean air temperature for all measurements sites on each sampling date. It can be seen that water temperatures at all sites follow air temperatures. The water

temperatures at the Toberfaolaigh and Glore Bridge and, to a lesser extent, at Tobernacogany remain relatively constant throughout the study period in comparison to the other sites.

Measuring Site	max (°C)	min (°C)	mean (°C)	Std. Dev.	CV
Lene Surface	16.9	5.9	12.7	3.9	0.31
Tobernacogany	13.8	8.4	11.3	2.1	0.18
Toberfaolaigh	11.8	10.3	10.9	0.4	0.04
Fore Valley	12.2	9.2	10.8	1.0	0.09
Ben Loughs	17.4	6.2	13.3	3.7	0.28
Lough Bane	16.7	6.1	12.7	3.5	0.27

Table 6.4 Summary statistics calculated for temperature data (based on 16 measurements at each site).

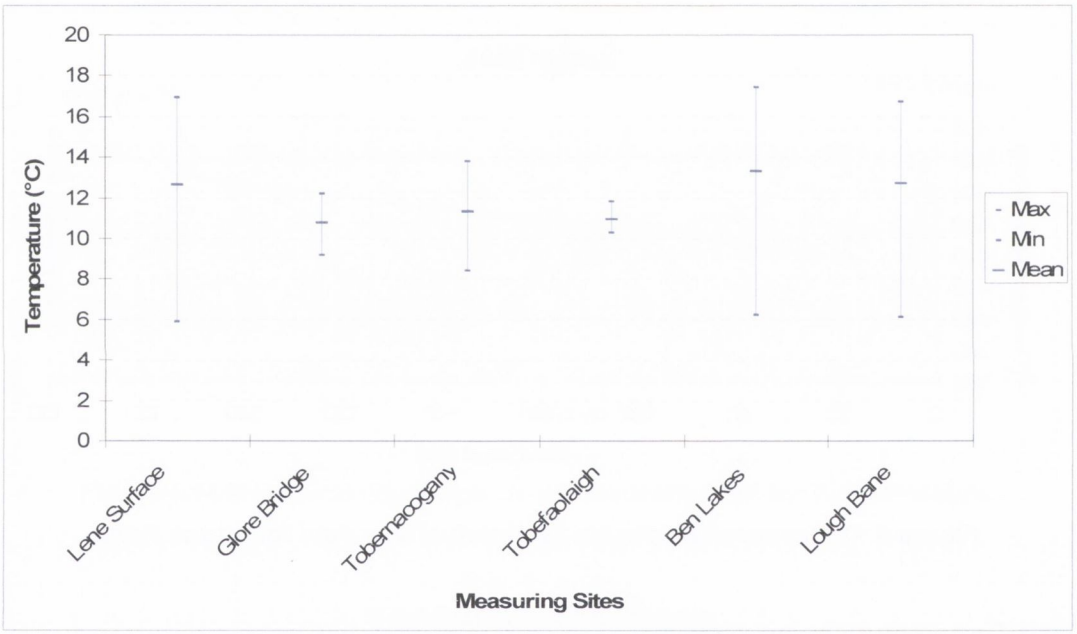

Figure 6.18 Water temperature values (maximum, minimum and mean values at each site).

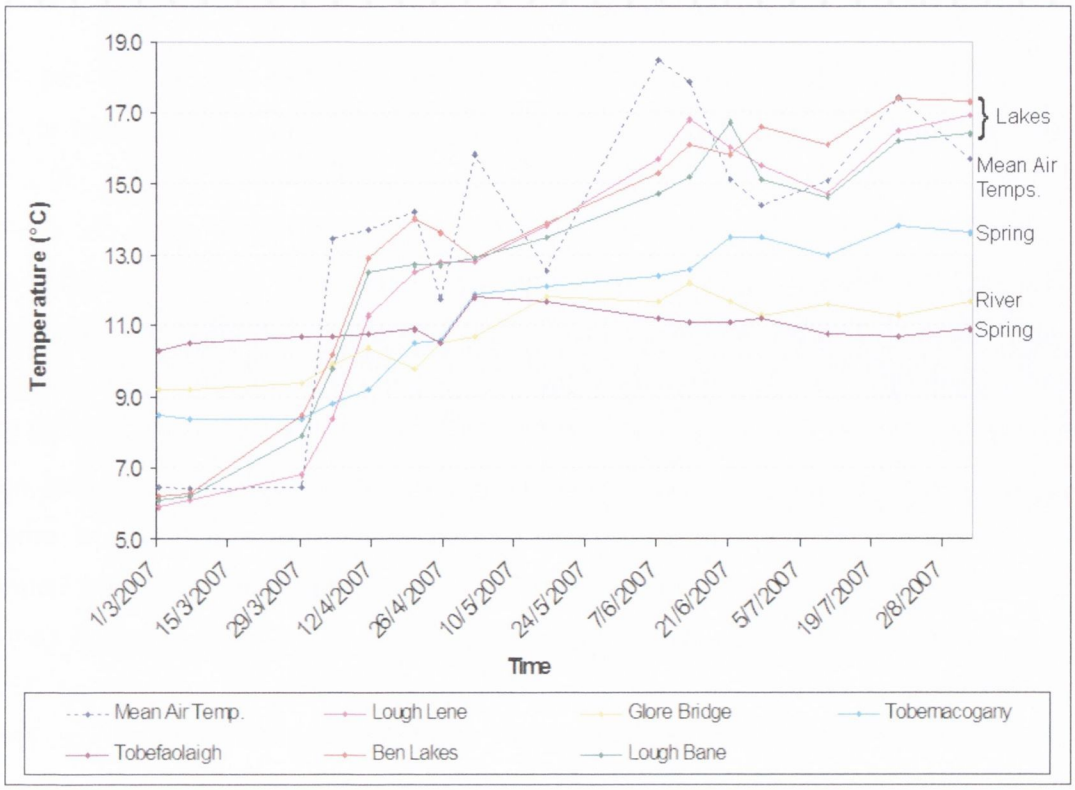

Figure 6.19 Water temperatures at each site and mean air temperature of all measuring sites (for each sampling period).

6.3.4 pH measurements

The pH summary statistics for each measuring site are presented in Table 6.5 below. At all of the measuring sites, pH was higher than 7 (alkaline) which is within the range reported from spring waters in Irish karst areas of 6.8 – 7.9 pH units (Drew & Chance 2007). Average pH values were similar at all sites with lows of approximately 7.5 - 7.8 and high values of 7.6 - 8.2. The widest ranges of pH values were recorded at the four sites in the Lough Lene catchment and at Tobernacogany.

Measuring Site	Min	Max	Range
Lene Surface	7.54	8.19	0.65
Glore Bridge	7.5	7.66	0.16
Tobernacogany	7.58	8.1	0.52
Toberfaolaigh	7.47	7.63	0.16
Ben Loughs	7.6	7.8	0.2
Lough Bane	7.8	7.96	0.16

Table 6.5 Summary statistics calculated for measured pH values.

6.3.5 Comparison of lake water levels

Lake surface level data are presented in Figure 6.20. White Lake experienced the greatest variation in its surface water level during the period of the detailed study (1/3/2007 – 7/8/2007) falling by 1.8 m. The surface water levels of Lough Lene and Lough Bane are recorded daily by the EPA. Fluctuations in the surface water levels of Lough Lene and Lough Bane are very similar. These lakes do not experience as wide a range of fluctuation as White Lake and the range of fluctuation in these lakes is approximately 0.3 m. However, in late June both lake surface levels show a marked response to precipitation inputs. The Ben Loughs surface water level fell by 0.2 m during the study period. The surface level of the Ben Loughs was not monitored daily, thus high-resolution hydrographs are not available and small oscillations in the surface level such as those recorded at Lough Lene and Lough Bane would not be recorded on this graph. The surface water levels of Lough Lene, Lough Bane, and the Ben Loughs fluctuated by < 0.5 m during the study period. The surface level of White Lake dropped by almost 2 m during the same period. This lake has no surface outflow and outflow from this catchment is through swallow holes only. Clogging and unclogging of swallow holes around the shore of White Lake occurred during the study period. Thus flow rates into the swallow holes did not appear to be constant, although it was impossible to accurately measure these discharges.

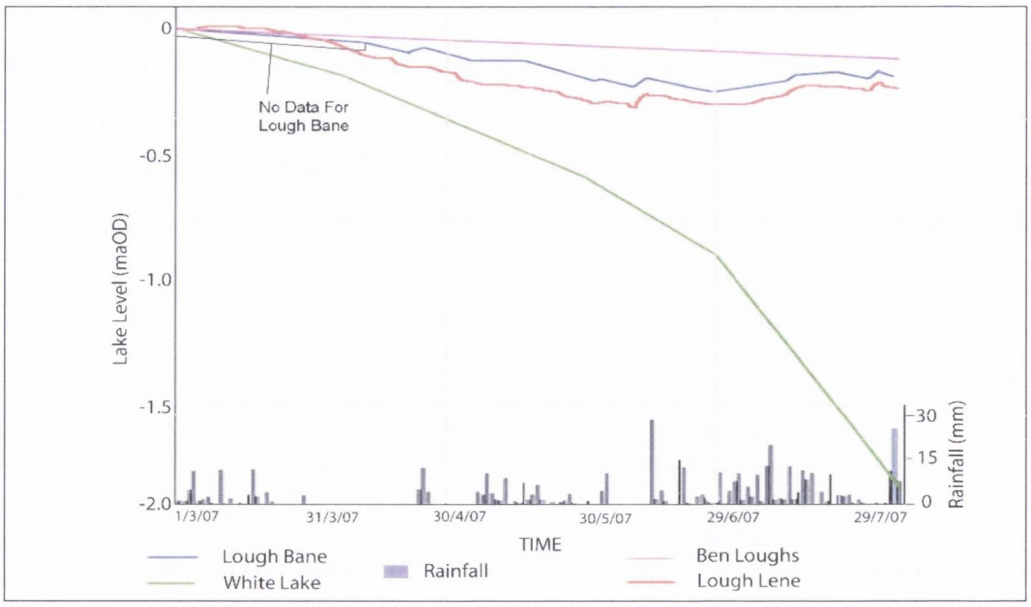

Figure 6.20 Lake surface levels and precipitation amounts (lake levels have been normalised to 0 m for 1/3/07 to enable comparison).

6.3.6 Drainage density results

The drainage densities were calculated for each of the detailed study catchments as described in Chapter 4. The results show that the Ben Loughs catchment had the highest density of drainage channels at 1.2 km/km² followed by the Lough Bane catchment at 0.81 km/km². The catchments of Lough Lene and Fore Valley (including the topographically delineated spring catchments of Tobernacogany and Toberfaolaigh) were lower but similar to each other at 0.65 km/km² and 0.62 km/km² respectively. The White Lake catchment had the lowest drainage density at 0.48 km/km². The drainage density of the entire detailed study area was calculated as 0.69 km/km². The drainage density in all of the study catchments is higher than the figure of 0.5 km/km² which has been defined as the upper limit of the low drainage density classification that is typical of Irish karstic or gravel aquifers where a relatively high proportion of precipitation becomes recharge (DHLG/EPA/GSI 1999).

6.4 Water Budgets

As stated in Chapter 4 a water budget can be expressed as:

$$GW_{out} - GW_{in} = P - Q_{out} - ET \pm \Delta\ Lake\ S \qquad \textbf{Equation 6.}$$

Where: GW_{out} = Groundwater loss from a catchment; GW_{in} = *Groundwater contribution to a catchment;* P = Precipitation; Q_{out} = Discharge leaving the catchment (surface and extractions); ET = Evapotranspiration; and $\Delta\ Lake\ S$ = Change in lake storage. All variables except GW_{out} *and* GW_{in} were calculated for each spring and lake catchment and balancing equations were constructed. Water is extracted from Lough Lene and Lough Bane and these volumes have been included as part of Q_{out}. Where the volume of groundwater entering a catchment is greater than the volume leaving it, the figure in the Balance column should be positive. The Loss/Gain is an estimate of the mean rate of extra flow into or out of a catchment that would be needed to balance the budget equations over the budget period. The figures contained in the bottom row of the Tables 6.6 are for the entire detailed study area.

From Table 6.6 it can be seen that the budget for Tobernacogany spring suggests that this spring catchment is receiving runoff from an additional 5.32 km² of land

area than can be accounted for by its topographic catchment. The budget result for Toberfaolaigh spring shows an imbalance of larger magnitude with the Toberfaolaigh spring requiring an additional 11.04 Km^2 of land area to generate sufficient runoff to account for the discharge from this spring.

As anecdotal evidence existed suggesting that a series of small springs discharged into the stream channel downstream of the above two springs and above Glore Bridge, a budget was computed for the area contributing runoff directly to this area. The topographic catchments and flows from Tobernacogany and Toberfaolaigh were excluded from this calculation, the result of which indicated that an additional 7.29 km^2 of land area is required to provide runoff sufficient to sustain the flow of the river Glore at this location.

The estimate of Q_{out} for Lough Lene includes the water flowing through the surface outflow channel, flowing into the three swallow holes on its northern shore and public water supply extractions. The results from the Lough Lene catchment indicate that this catchment may have been contributing runoff to other topographically defined catchments during the study period as the balancing equation indicates that only 13.19 km^2 out of a total of 13.4 km^2 of the catchment would be required to generate enough runoff to balance the equation.

The White Lake catchment has no surface outflow and no water is abstracted from it. The lake therefore, must drain to groundwater. The result of the balancing equation shows that, when changes in lake storage are taken into account, the area required to generate sufficient runoff to balance the equation is 3.0 km^2. This indicates that runoff from approximately 3 km^2 must become groundwater recharge in this catchment and be discharged in (an) other topographically defined catchment(s).

Budget results indicate that the Ben Loughs catchment gains a small amount of water from groundwater discharge. The surface area required to generate this additional runoff is estimated as 0.50 km^2. The results for the Lough Bane catchment are similar but slightly more pronounced than those of the Ben Loughs in that an additional contributing surface area of 0.97 km^2 would be required to balance the water budget in this catchment.

Catchment	Topographic catchment area	Δ Lake Storage (m^3)	P (m)	ET (m)	Area (km^2) if A= (Q+Δ)/P-ET)	Additional (+)or Reduced (-) Contributing Area km^2
Springs						
Tobernacogany	0.123	0	0.45	0.297	5.444	5.32
Toberfaolaigh	1.65	0	0.45	0.297	12.685	11.04
Fore Valley - springs	2.76	0	0.45	0.296	10.046	7.29
Lakes						
Lough Lene	13.4	-4168000	0.45	0.31	-13.192	-0.21
White Lake	6.06	-483000	0.45	0.292	-3.057	-3.00
Ben Loughs	3	-25960	0.45	0.299	3.494	0.50
Lough Bane	6.25	-151963	0.45	0.300	7.220	0.97

Table 6.6 Water balance results for the study catchments (balance period 1/3/07 to 7/8/07).

The results of the water budgets must be treated with caution due to errors associated with estimates of the variables used in the calculations. Calculating accurate estimates for precipitation, evapotranspiration and surface channel discharge is difficult and the timing of precipitation events relative to the sampling times and the size of a lake surface area relative to its catchment size (in terms of its affect on evapotranspiration) can all introduce inaccuracies. Previous research has

estimated that precipitation estimates generated from a single rain gauge over a similar distance as that in the case of this study will have an error margin of ± 10 – 20% on a monthly basis and ~ ± 5% seasonally (Winter 1981). Evapotranspiration is difficult to estimate accurately and the Penman-Monteith method as used by Met Éireann has been shown to yield results of ± 20% of the true value (Allen et al. 1998; Burt et al. 2002; Schulte et al. 2005). The Met Éireann evapotranspiration estimates have been assessed by previous researchers to be reasonably accurate for modelling purposes (Fitzsimons 2000). Surface discharge and lake storage change estimates as calculated for this study have been estimated to have ±12% and ±3% error margins respectively (Scheider et al. 1979; Dudley 2004).

No estimates of error for pumped extractions from lakes were available from the Meath or Westmeath County Councils but similar studies have estimated error margins of ~± 5% or less for pumped lake extractions (Dudley 2004). With the exception of evapotranspiration, the error margins are relatively small and the results of the water budget calculations are likely to be representative of reality. Using a midpoint estimate of ± 7.5% for storage change and surface discharge error, the non-weighted cumulative error estimate for this type of water budget is ± 37.5%.

Never the less, the results of the water budgets suggest that the catchment of Lough Lene and White Lake provide groundwater recharge (during the study period at least) and that groundwater discharges to the surface drainage system in the catchments of Fore Valley. Also, the Ben Loughs and Lough Bane could be both recharge and discharge areas for groundwater, depending on the season in question.

6.5 Groundwater hydrology results

6.5.1 Well standing water levels - point measurements

The location of the groundwater sampling points is shown in Figure 6.21 (details of individual sampling points are contained in Appendix C & Appendix D). The standing water levels in all of the wells were measured for the detailed study over the period 1/3/2007 to 7/8/2007. The ranges of fluctuation in standing water levels during the detailed study are presented in Table 6.7 and Figure 6.22. There were 8 wells that

had water levels with ranges of < 1 m over the study period, and 12 with ranges of > 1 m. The well SP19 showed the largest fluctuation with a range of 5.1 m.

Fluctuations in the standing water levels in 10 of the wells during the detailed study period are presented in Figure 6.23. Wells that are in use have been omitted from this graph as the standing water level in such wells may not be representative of natural variation. Wells that have a standing water level fluctuation range < 1 m have also mostly been omitted from this graph for visual clarity. The general patterns in standing water levels of the wells omitted from Figure 6.23 follow those described here. The standing water levels in the wells in Figure 6.23 follow the same general pattern through time. They rise from the beginning of the detailed study period and begin to drop from April until the end of the detailed study period with some rising during late July/August 2007. During mid April and late June a number of the wells experienced a drop in water levels. The magnitude of this drop is greater for some wells relative to others, suggesting that the character of groundwater flow is not uniform throughout the area. However, these data are point measurements and locations that experience short-term oscillations in their standing water levels may not have been identified by measurements recorded on a weekly or bi-monthly basis.

Correlation coefficients for the standing water levels between wells are presented in Table 6.8 With the exception of SP10, SP11, SP17, SP18, and to a degree SP9, the water levels between wells have high and positive correlations ($r > 0.5$) with p values generally <0.05. SP10 and SP11 are dug wells, and in the case of SP11 the water level flows out in a stream channel so while it does indicate the actual position of the watertable at this point, it is unlikely to reflect the potentiometric surface at this location. The correlation results indicate that standing water levels across the study area are for, the most part, associated with each other. However, and as detailed in Table 6.7 the magnitude of change in standing water levels between sampling points shows a high degree of variation.

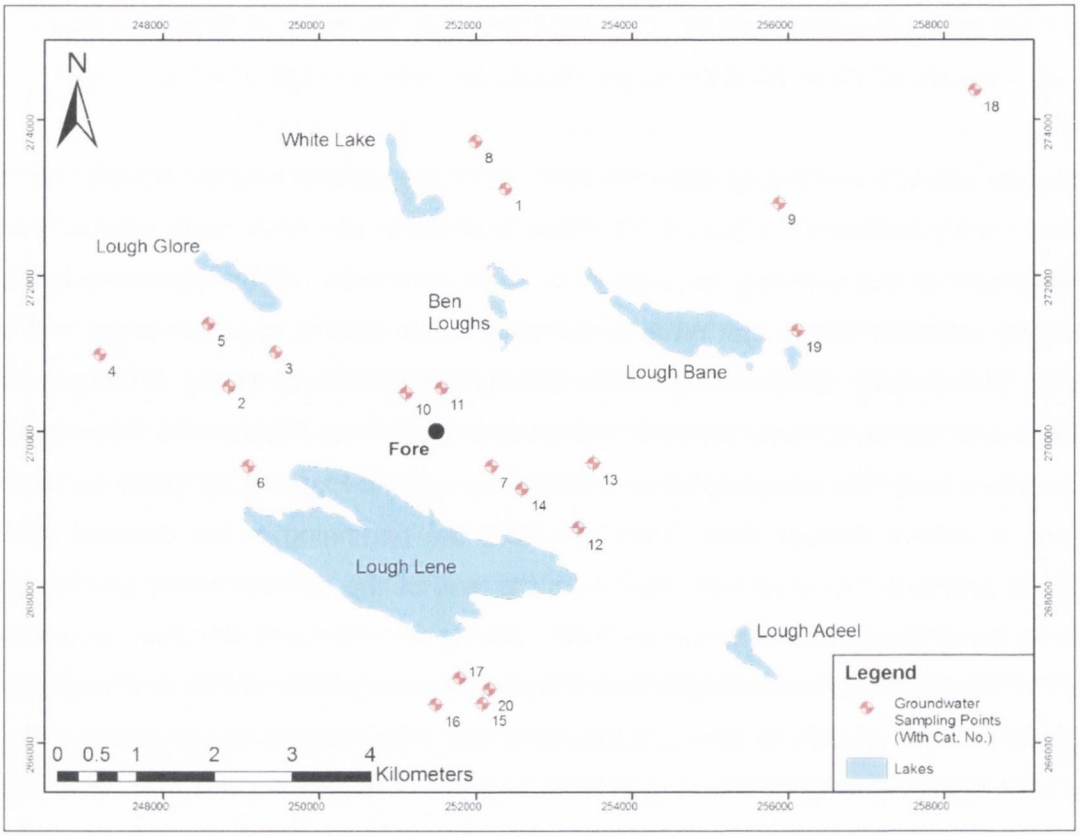

Figure 6.21 Location of the groundwater sampling points in relation to the lakes (basemap data OSI 2001).

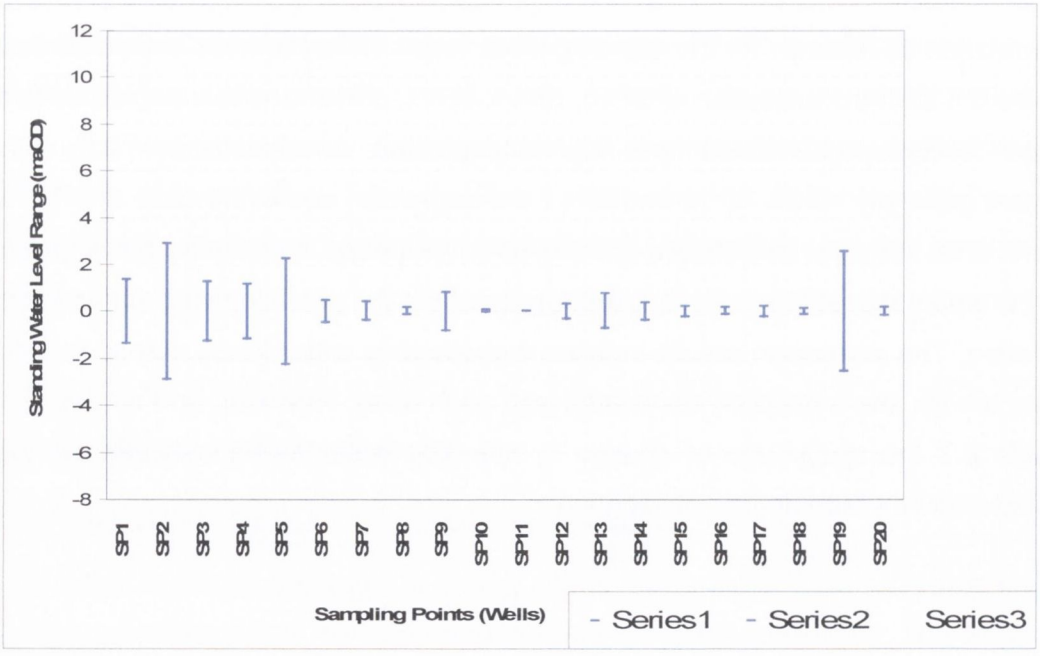

Figure 6.22 Comparison of normalised standing water level ranges in the study wells.

Cat. No.	Max (maOD)	Min (maOD)	Range (m)
SP1	114.7	112	2.7
SP2	100.23	94.47	5.76
SP3	106.66	104.11	2.55
SP4	98.15	95.86	2.29
SP5	101.85	97.38	4.47
SP6	98.28	97.3	0.98
SP7	96	95.2	0.8
SP8	117.1	116.8	0.3
SP9	125.5	123.88	1.62
SP10	87.1	87	0.1
SP11	87.28	87.32	0.04
SP12	95.67	95.02	0.65
SP13	106.73	105.24	1.49
SP14	99.3	98.56	0.74
SP15	104.55	104.13	0.42
SP16	113.65	113.35	0.3
SP17	104.18	103.73	0.45
SP18	160.54	160.31	0.23
SP19	121.3	116.2	5.1
SP20	111.55	111.2	0.35

Table 6.7 Water level fluctuations at the groundwater sampling points (minima, maxima, and ranges).

	SP20	SP19	SP18	SP17	SP16	SP15	SP14	SP13	SP12	SP11	SP10	SP9	SP8	SP7	SP6	SP5	SP4	SP3	SP2	SP1
SP1	0.28	0.04	0.74	0.81	<0.01	0.18	<0.01	<0.01	0.01	0.08	0.13	0.04	<0.01	<0.01	<0.01	0.02	<0.01	0.02	<0.01	
SP2	0.02	<0.01	0.57	0.54	<0.01	0.06	<0.01	<0.01	<0.01	0.10	0.13	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		0.83
SP3	0.01	<0.01	0.52	<0.01	<0.01	0.08	<0.01	<0.01	<0.01	0.29	0.15	0.02	<0.01	<0.01	<0.01	<0.01	<0.01		0.85	0.59
SP4	0.03	<0.01	0.50	0.74	<0.01	0.04	<0.01	<0.01	<0.01	0.13	0.22	<0.01	<0.01	<0.01	<0.01	<0.01		0.79	0.97	0.82
SP5	<0.01	<0.01	0.39	<0.01	<0.01	0.05	<0.01	<0.01	<0.01	0.27	0.22	0.03	<0.01	<0.01	<0.01		0.80	1.00	0.85	0.58
SP6	<0.01	<0.01	0.39	0.27	<0.01	0.03	<0.01	<0.01	<0.01	0.10	0.19	0.01	<0.01	<0.01		0.92	0.94	0.91	0.98	0.77
SP7	<0.01	<0.01	0.19	0.05	0.01	0.04	<0.01	<0.01	<0.01	0.09	0.25	0.13	<0.01		0.86	0.90	0.74	0.89	0.80	0.65
SP8	<0.01	<0.01	0.34	0.74	<0.01	0.02	<0.01	<0.01	<0.01	0.13	0.31	<0.01		0.79	0.92	0.78	0.94	0.76	0.94	0.82
SP9	0.25	<0.01	0.71	0.63	<0.01	0.11	<0.01	0.06	0.15	0.38	0.52		0.66	0.41	0.62	0.57	0.70	0.58	0.67	0.53
SP10	0.50	0.35	0.05	0.60	0.14	0.16	0.20	0.86	0.86	1.00		0.18	0.28	0.31	0.36	0.34	0.34	0.39	0.41	0.41
SP11	0.34	0.32	1.00	0.78	0.08	0.64	0.15	0.05	0.04		0.00	0.24	0.41	0.45	0.44	0.30	0.41	0.29	0.44	0.47
SP12	<0.01	<0.01	<0.01	0.05	<0.01	0.01	<0.01	<0.01		0.55	0.05	0.39	0.74	0.90	0.85	0.88	0.71	0.86	0.78	0.62
SP13	0.01	<0.01	0.04	0.56	<0.01	<0.01	<0.01		0.86	0.52	0.05	0.49	0.83	0.81	0.82	0.72	0.79	0.70	0.80	0.85
SP14	0.01	<0.01	0.70	0.23	<0.01	0.47		0.74	0.77	0.39	0.35	0.79	0.89	0.76	0.95	0.90	0.93	0.90	0.95	0.72
SP15	<0.01	0.02	<0.01	0.54	0.27		0.52	0.74	0.62	0.13	-0.38	0.43	0.59	0.54	0.55	0.52	0.54	0.47	0.50	0.36
SP16	0.33	<0.01	0.61	0.40		0.31	0.89	0.67	0.65	0.46	0.40	0.83	0.78	0.62	0.84	0.75	0.85	0.78	0.86	0.76
SP17	0.23	0.07	0.70		-0.23	-0.18	-0.34	-0.17	-0.51	0.08	-0.15	-0.14	-0.10	-0.52	-0.31	-0.65	-0.09	-0.67	-0.17	0.07
SP18	<0.01	0.47		-0.12	-0.13	0.86	0.13	0.54	0.47	0.00	-0.52	-0.09	0.28	0.37	0.26	0.25	0.20	0.19	0.17	0.10
SP19	<0.01		0.22	-0.49	0.82	0.60	0.92	0.71	0.78	0.27	0.26	0.79	0.81	0.80	0.88	0.91	0.81	0.92	0.86	0.59
SP20		0.67	0.66	-0.34	0.27	0.76	0.61	0.63	0.73	0.26	-0.19	0.32	0.66	0.70	0.66	0.68	0.56	0.63	0.60	0.30

Table 6.8 Correlation coefficients and p values (blue text) matrix between each of the SP water levels (correlation coefficients with p values <0.01 highlighted in red and those with correlation coefficients of <0.05 highlighted in yellow).

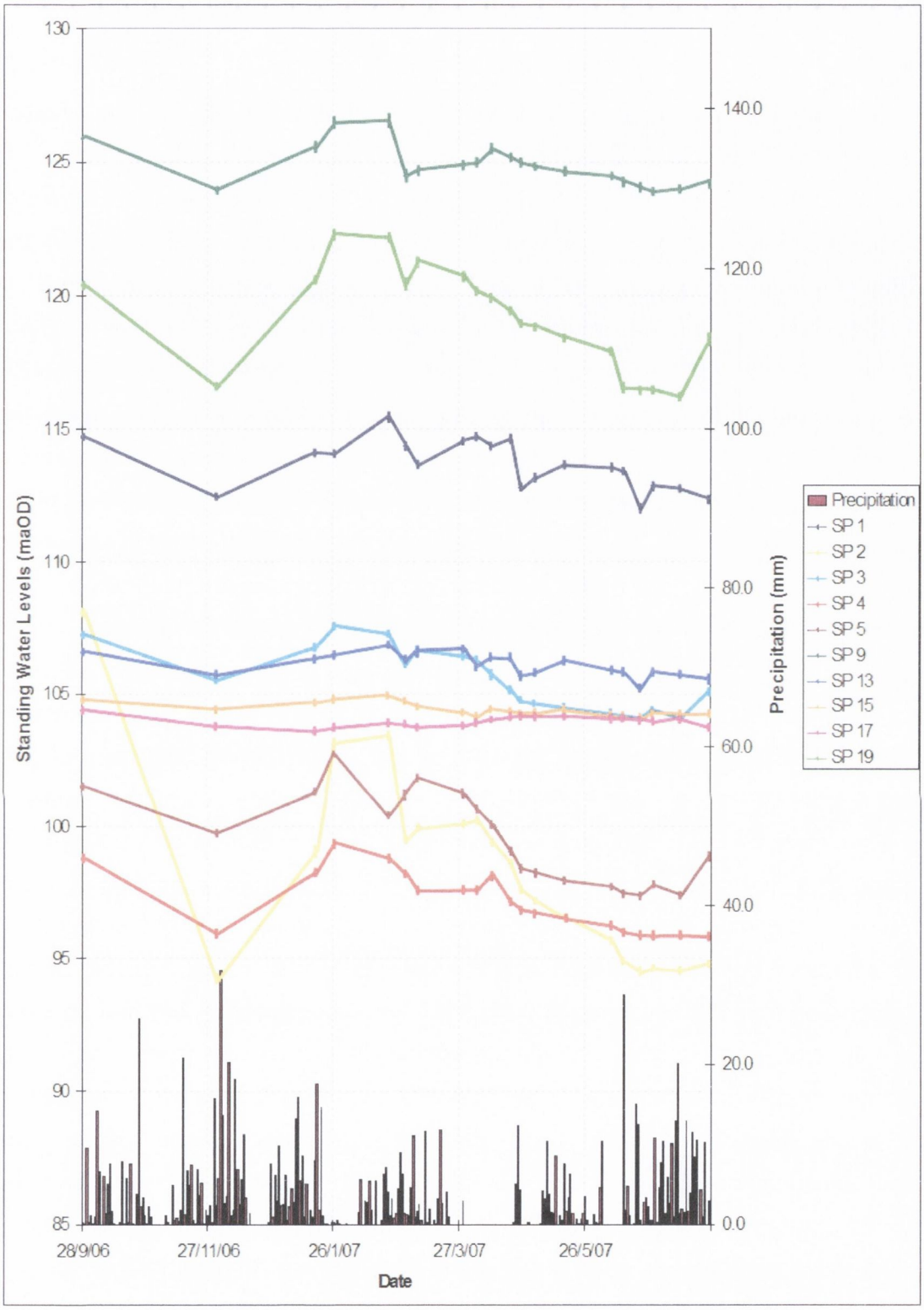

Figure 6.23 Fluctuations in groundwater standing water levels (groundwater sampling points that had a range of < 1.2 m have been omitted for clarity) and daily precipitation at Mullingar.

6.5.2 Well standing water levels - continuously recorded measurements

SP 9

The well SP 9 is located about 1.5 km north of Lough Bane. A recorder was installed here from 6/10/2006 to 7/8/2007. Measurements for the standing water level in this well, as derived from continuous recording (blue line) and weekly or bi-monthly measurements (red line), became more frequent from the 1/3/2007, when the detailed study monitoring period began, than they had been up to that point. In addition, precipitation measurements are also shown in Figure 6.24. The response of the standing water level to precipitation is much clearer in the continuously recorded data than it is with weekly point measurements. For this reason the continuously recorded measurements are a more reliable data set for characterising the nature and magnitude of temporal fluctuations in the standing water level of the wells in the study area. The standing water level in this well appears to respond to precipitation relatively soon after the onset of rainfall but the lag time between the onset of precipitation and groundwater level response varied considerably. In the period 6/10/2006 – 6/3/2007 cross correlation analysis of the water level in SP9 with the effective rainfall (P – AET) data gave a lag of 6 days with a cross correlation coefficient of 0.36 while a lag of 3 days with a cross correlation coefficient of 0.54 was calculated for the period 25/12/2006 – 14/1/2007. Cross correlation analysis was not carried out on data obtained during the summer months as zero effective rainfall (P – AET) meant that the groundwater level in May and June did not rise in response to rainfall inputs. Rainfall events in autumn/winter 2006 and spring 2007 were followed by rises of up to 2 m in the water level of this well. A period of high precipitation from the beginning of June 2007 to the beginning of July had no effect on the standing water level, while a relatively small increase in precipitation in July led to a steep rise in the water level. This difference in response can be explained by higher evapotranspiration rates in June 2007 which were greater than precipitation amounts during that period. Overall, the pattern suggests that the standing water level was higher in the winter months than it was in the summer months and that the water level in this well is closely related to precipitation inputs.

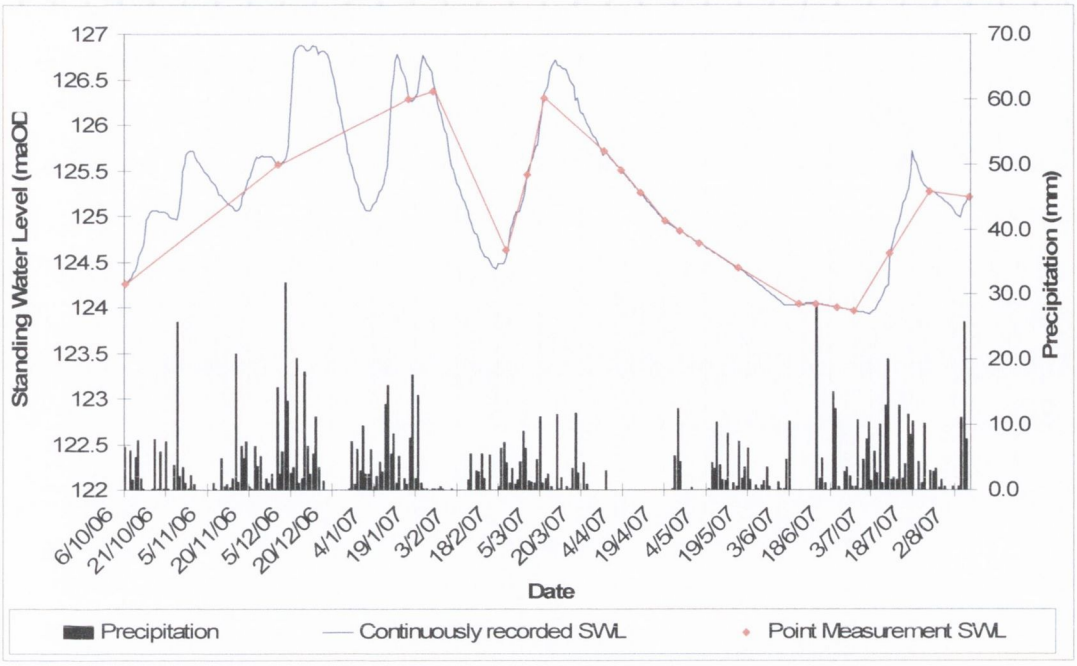

Figure 6.24 Standing water level fluctuations in SP 9 and daily precipitation data recorded at the synoptic station located at Mullingar.

SP 19

SP 19 is located about 0.4 km northeast of Lough Bane. A recorder was installed here from 6/10/2006 to 7/8/2007. The recorder operated continuously throughout this period with no breakdowns but there were four periods where the water level rose to a level higher than could be recorded on the rotating drum of the recorder. The standing water level from both continuous and weekly or bi-monthly measurements in this well is presented alongside precipitation data in Figure 6.25. During the winter and spring months, the standing water level in this well appears to respond to precipitation events within 24 - 48 hours of the beginning of a rainfall event, rising as much as 2 m in this timeframe. Based on the shape of the recorded water level peaks, the water level may have risen 4 – 5 m over the periods shown in Figure 6.25 as 'No data', but there are no data for these periods as the recorder pen was pushed off the recording drum by high water levels (the flowat and drum cable were then reset at a higher level). As was the case for SP 9, rainfall in the winter months of 2006/2007 leads to a clear rise in the water level in this well but groundwater levels fail to respond to precipitation in May and June 2007 when evapotranspiration rates were greater than precipitation and soil moisture deficit data (Met Eireann) suggests that soils in the area were relatively unsaturated and had a high assimilative capacity during this period. Due to the malfunction of the

automatic recorder during high flows, cross correlation analysis could only be carried out between the effective rainfall (P – AET) data and the standing water level data for this well for the period 6/10/2006 – 5/12/2006. The cross correlation analysis for this period shows that the groundwater level in SP19 lags the effective rainfall by 2 days with a cross correlation coefficient of 0.43. Rainfall in October and November 2006 caused the water level in this well to rise rapidly with the resulting hydrograph typical of a borehole that intercepts a conduit (Shevenell 1996). The drum cable on the automatic recorder was reset to a new level following the periods recorded as no data on the graph below.

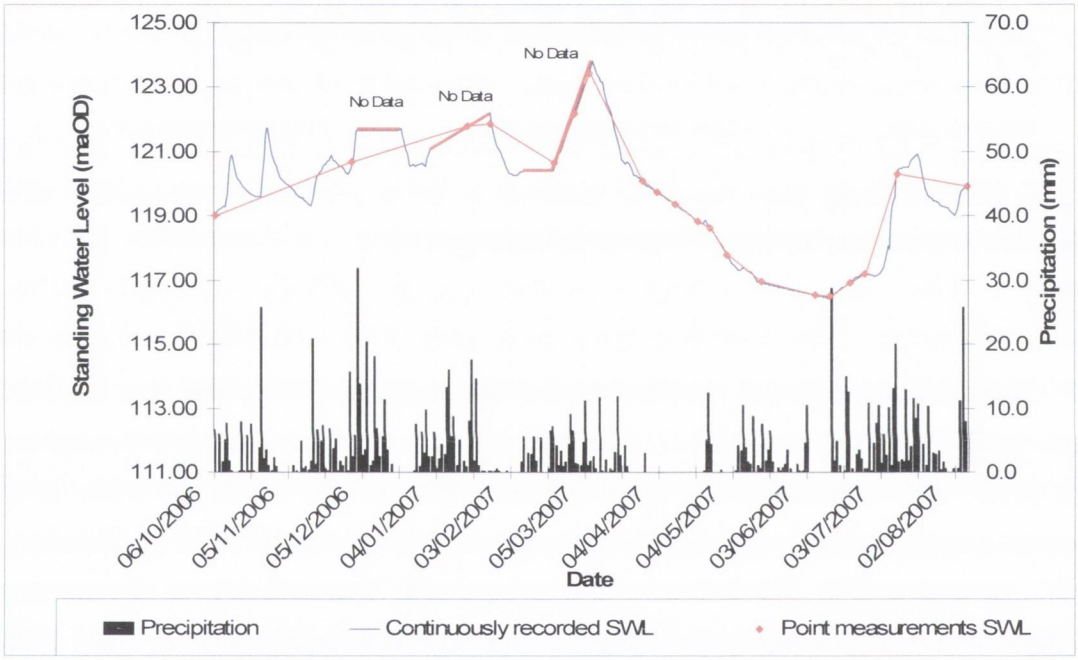

Figure 6.25 Standing water level fluctuations in SP 19 and daily precipitation data recorded at the synoptic station located at Mullingar.

Lough Bane lake level and SP 19 standing water level

As SP 19 is located 400 m from Lough Bane, the standing water level in the well was compared to the lake surface level to investigate similarities/differences between variations in the two respective water levels (Figure 6.26). There are missing data in both data sets due to increases in water levels which were beyond the capacity of the recording equipment during winter 2006/2007 (both the EPA lake level recorder and the automatic groundwater level recorder used in the present study). Both water levels follow a similar pattern, increasing from October 2006 into the winter of 2006/2007 and decreasing in spring/summer 2007 with an increase

again apparent in late summer 2007. Cross correlation analysis of the lake level and water level in SP19 for the period 6/10/2006 – 5/12/2006 (before water levels rose beyond the capacity of the recording equiptment) shows a lag of 0 days with a cross correlation coefficient of 0.42 between the lake level and the water level in SP19. However, the magnitude of change in the lake level is less than that of SP 19. Increases in water level of SP 19 are mirrored in that of the lake, especially increases in December 2006, May, June, and July 2007. It is difficult to estimate the maximum level reached by the lake during the missing data period. The rate of rise in the lake level increased significantly in early December 2006 before the recorder broke down and there is no way of establishing the shape or height of the lake level hydrograph for this period.

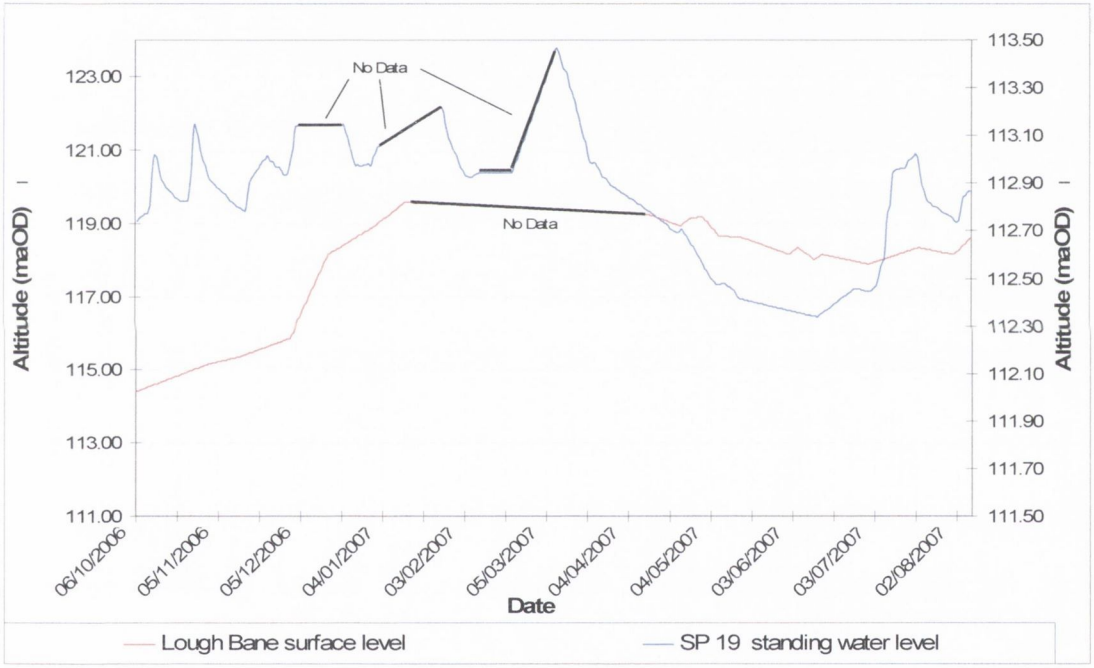

Figure 6.26 Comparison of surface water level of Lough Bane, the standing water level in SP 19 and daily precipitation data recorded at the synoptic station located Mullingar.

SP 13

SP 13 is located about 2 km south of Lough Bane and a recorder was installed here from 6/10/2006 to 6/3/2007. The recorder broke down at the end of this period and as no replacement was available, continuous recording ceased on the 6/3/2007 (blue line in Figure 6.27). The red line in Figure 6.27 is the standing water level from weekly point measurements which were continued until the end of the detailed study

period. The magnitude of standing water level response to precipitation in this well is less than was the case for SP 9 or SP 19. Groundwater variations in this well are not as 'flashy' as either of the other two wells with the hydrograph exhibiting a slower and more subdued response to rainfall events. In addition, the recession apparent on the hydrograph for this well is not as steep as those of the others. Cross correlation analysis between the effective rainfall data and the groundwater level at SP13 during the period 6/10/2006 – 6/3/2007 gives a lag of 6 days with a cross correlation coefficient of 0.31, for the period 7/11/2006 - 2/12/2006 a lag of 6 days with a correlation coefficient of 0.32, and for the period 25/12/2006 – 14/1/2007 a lag of 5 days with a correlation coefficient of 0.47. The period where both weekly and continuous data were recorded shows that a hydrograph constructed from point measurements does not illustrate the short term oscillations in the standing water level of this well, although general changes were recorded.

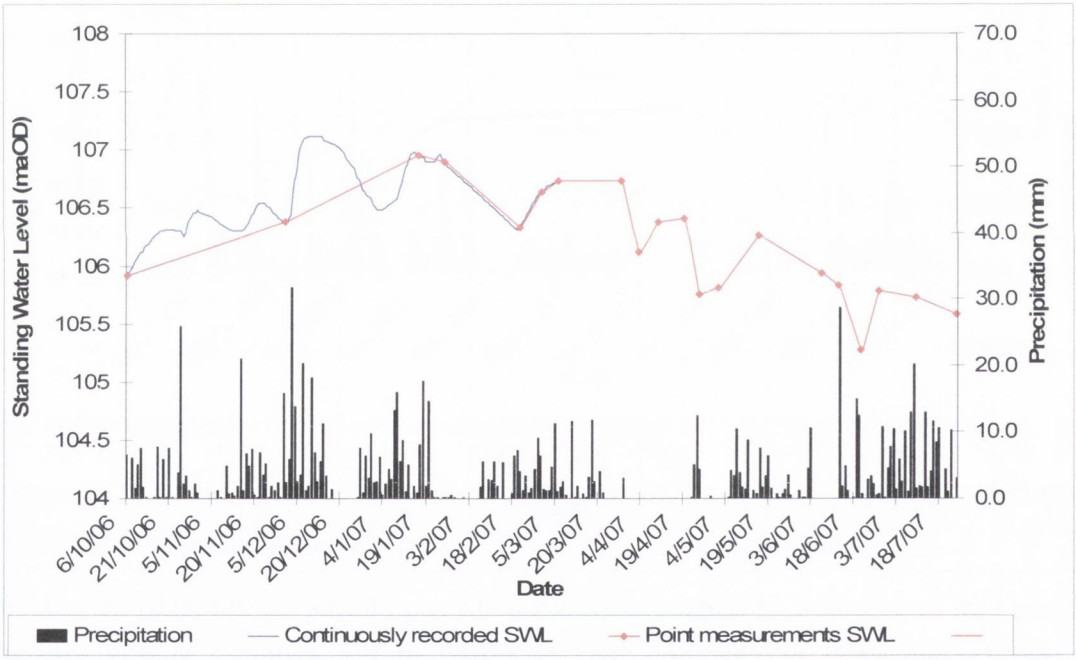

Figure 6.27 Standing water level fluctuations in SP 13 and daily precipitation data recorded at the synoptic station located at Mullingar.

Comparison of the continuously recorded well hydrographs

The standing water levels in the three wells (Figure 6.28) all show a degree of response to rainfall events, but the three sites exhibit differences in terms of the magnitude and shape of their responses. Of the three wells, the water level in SP 19 exhibits the greatest magnitude of response to precipitation inputs (> 3 m in March

2007). The water level in SP 9 responds to precipitation similarly to that of SP 19 but, in terms of magnitude, the greatest increase in SP9 recorded following a rainfall event during the study period of approximately 2 m. Finally, the water level in SP 13 does not increase in response to rainfall events to the same extent as the other two wells. Cross correlation analysis between the standing water levels in each of the three wells was carried out for the period 6/10/2006 – 5/12/2006 (when uninterrupted data was available for SP19) shows that while the magnitude of groundwater level response was markedly different between the wells, the lag times were not. The lag time between SP19 and SP9 during the period 6/10/2006 – 5/12/2006 was 1 day with a correlation coefficient of 0.72, the lag time between SP9 and SP13 was 0 days with a correlation coefficient of 0.94, and the lag time between SP19 and SP13 was 0 days with a correlation coefficient of 0.65.

The varying standing water level responses indicate that there are different groundwater flow regimes present in the detailed study area or that the wells are monitoring different parts of the aquifer, i.e. conduits, fractures or matrix flow. In places the altitude of the potentiometric surface has a range of > 5 m (SP 19). In other areas (SP 9) the magnitude of fluctuation in standing water levels is less (~ 3 m). While in other places (SP 13), the fluctuation in groundwater levels are even less (< 1 m).

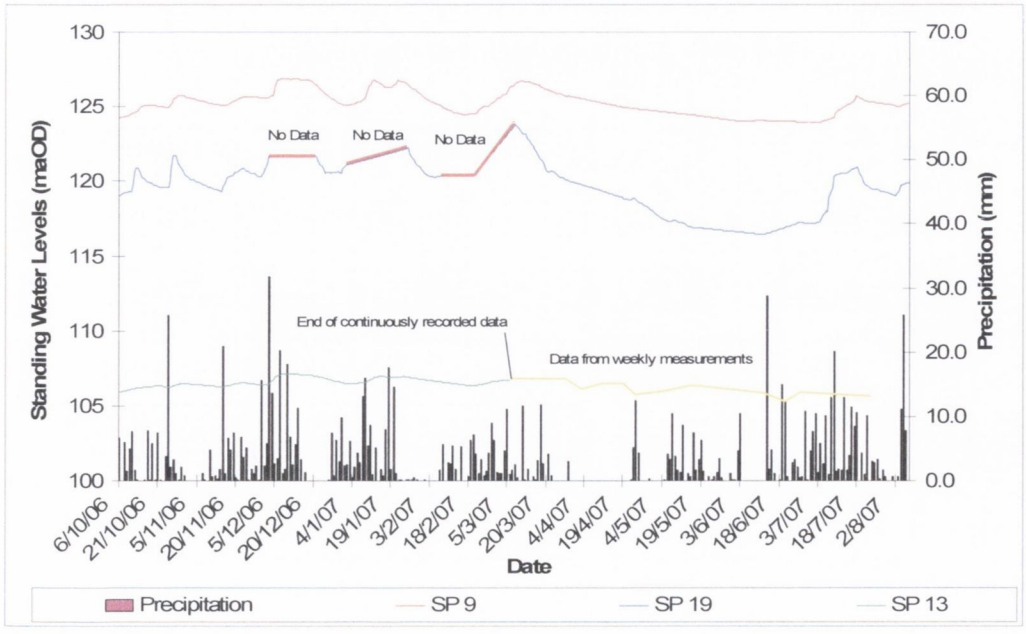

Figure 6.28 Comparison of standing water level fluctuations in SPs 9, 19, and 13, and daily precipitation data recorded at the synoptic station located at Mullingar.

6.5.3 Water tracing

Two tracing experiments were carried out in September 2009 with dye being injected at two sites: 1) the Lough Lene swallow holes; and 2) the large swallow hole at White Lake. Samples were then taken from four sampling sites: 1) Roaring Well; 2) Tobernacogany spring; 3) Toberfaolaigh spring; and a stream (Drain 1) south of the Roaring Well where water draining from the bog below the Roaring Well flows into the River Glore (Figure 6.29). During winter 2006/2007 a number of other small springs were identified as possible sampling points, including a stream channel 250m northwest of Drain 1, but there was no flow from/in these springs/streams when the traces were carried out in autumn 2009. Details of the altitudes and locations of the injection and sampling points are presented in Table 6.9 and Table 6.10 respectively. In addition, the altitudes, locations, distances between sampling points and the straight line distance between them are detailed in Table 6.11.

Injection Point	Grid Ref.	Alt. (maOD)
White Lake swallow hole	N2510227290	105
Lough Lene swallow hole	N2515726879	92.5

Table 6.9 Details of dye injection points.

Sampling Points	Grid Ref.	Alt. (maOD)
Roaring Well	N2501427204	92.5
Tobernacogany	N2510527050	84.9
Toberfaolaigh	N2516027048	82.5
Drain 1	N2499427164	81.0

Table 6.10 Details of dye sampling points.

	Alt. Diff. (m)	Dist (km)	Gradient
White Lake injection point			
Roaring Well	12.5	1.23	0.0101
Tobernacogany	20.1	2.43	0.0083
Toberfaolaigh	22.5	2.39	0.0094
Drain 1	24.0	1.65	0.0146
Lough Lene injection point			
Roaring Well	0	3.53	0
Tobernacogany	7.6	1.74	0.0044
Toberfaolaigh	10	1.77	0.0057
Drain 1	11.5	3.21	0.0036

Table 6.11 Relationship of injection points to sampling points.

Discharge measurements for quantitative tracing were taken at the first suitable point down stream of the sampling sites. In the case of the Roaring Well this was

10m from the spring, Tobernacogany approximately 60 m from the spring and Toberfaolaigh 270m from the spring. Two measurements were taken at each site on the 14/9/2009, two on 15/9/2009, and one each on 16/9/2009, 17/9/2009, 20/9/2009, and 25/9/2009. The quantity of dye injected into each site was determined using the equation developed by Worthington & Smart (2003). Dye amounts were rounded off to the nearest 100 g for simplicity and as a result 1 kg of Sodium Fluorescein diluted in 5 litres of water was injected into the Lough Lene swallow hole and 0.5 kg of Rhodamine WT diluted in 5 litres of water was injected into the White Lake swallow hole. Dye was injected into the Lough Lene swallow hole at 8.30pm on the 13/9/2009. Dye was injected into the White Lake swallow hole at 7.00am on the 14/9/2009. Water sampling began at 6:50 am on the morning of 14/9/2009 at all sites, and carried on until 26/10/2009 (final batch of fluocapteurs were removed on 8/11/2009).

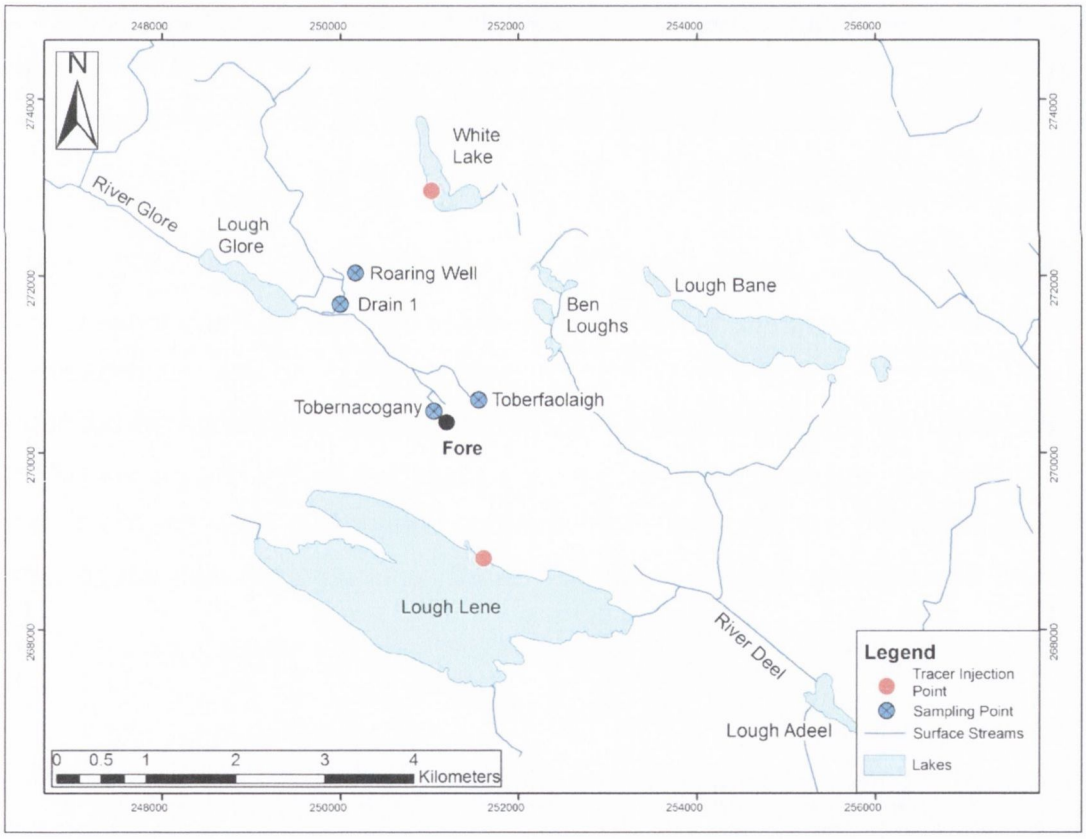

Figure 6.29 Locations of dye injection and sampling points (basemap data OSI 2001).

Gas activated carbon (GAC) fluocapteurs were placed in each of the four sampling locations on 11/9/2009, 3 days before dye injection and replaced immediately before dye was injected. The GAC fluocapteurs were then replaced on 14/9/2009,

16/9/2009, 20/9/2009, 25/9/2009, 12/10/2009, and 23/10/2009, with the last fluocapteurs removed on 8/11/2009. When the samples of carbon were eluted, rhodamine WT was visually observed in samples from 2 fluocapteurs from the Roaring Well (fluocapteurs from 14/9/2009-16/9/2009 and 16/9/2009-20/9/2009). Rhodamine WT was not visually observed in eluant from any other sample. Fluorescein was not visually detected in eluant from any sample. The eluant from all samples was filtered and analysed in a filter fluorometer (calibration procedure described in section 4.3.4.5 using eluted samples from fluocapteurs inserted on 11/9/2009 to establish background levels) for the presence of fluorescein and/or rhodamine WT. Rhodamine WT was detected above background levels (36 ppb) in eluant from 2 fluocapteurs from the Roaring Well (again the fluocapteurs from 14/9/2009-16/9/2009, 268 ppb and 16/9/2009-20/9/2009, 104 ppb). Rhodamine was not detected above background levels in eluant from any other fluocapteurs from any site. Fluorescein was detected above background levels (46 ppb) in 3 fluocapteurs from Tobernacogany (the fluocapteurs from 14/9/2009-16/9/2009, 874 ppb; 16/9/2009-20/9/2009, 102 ppb; and 16/9/2009-20/9/2009, 78 ppb). Fluorescein was not detected above background levels in eluant from any other samples from any site.

Quantitative tracing results

The results of the Lough Lene trace are presented in Table 6.13 and those for the White Lake trace in Table 6.14. Of the three sampling sites, no dye was detected at Toberfaolaigh or Drain 1, rhodamine WT was detected at the Roaring Well but not at Tobernacogany, and sodium fluorescein was detected at Tobernacogany but not the Roaring Well. Thus, an underground connection was proven between White Lake and the Roaring Well, and the previously traced connection between Lough Lene and Tobernacogany was verified (Figure 6.32).

Toberfaolaigh results

No fluorescence was detected above background concentrations at this sampling point. This could be due to one of three reasons: Either there is no connection between the injection points and this spring; there is a connection, but water entering the ground at the injection points takes longer than the sampling period to reach this spring; the tracer is too dilute to detect by the time it reaches the spring. If this spring is connected to the Lough Lene swallow holes but the travel time is

greater than the sampling period of this trace it would mean a straight line velocity of < 1.8 m/h. If this spring is connected to the White Lake swallow hole but the travel time is greater than the sampling period of this trace it would mean a straight line velocity of < 2.4 m/h.

Drain 1

No fluorescence was detected above background concentrations at this sampling point. Again the possible reasons for non detection at Toberfaolaigh may apply at this sampling point. This drain is connected to the Roaring well but water from the Roaring Well flows slowly through 400 m of bog in ill defined channels and over peaty deposits. As a result adsorption of dye before it reaches this point is also a possibility, especially as rhodamine can be prone to adsorption (Käss 1998). While there is always a possibility that a negative result may be a false negative, this negative result is important if true as it indicates that there is no resurgence of water from the White Lake swallow hole to the bog between the Roaring Well and the point where the stream draining the bog enters the River Glore.

Tobernacogany

Fluorescein was first detected at Tobernacogany 24.5 hours after it had been injected at Lough Lene. This gives a straight line velocity between the injection and sampling point of 71 m/h, less than the ~80 m/h recorded by McDonald (1988) for the same site and possibly within the margin of error. The mean travel time of the dye mass (the centroid) was 39.6 hours (Table 6.12), which is a velocity of 43.9 m/h. The breakthrough curve of the dye mass has one peak with steep rising and falling limbs (Figure 6.30). The last dye was recovered at this site 158 hours after injection. By the end of the observation period 97% of the injected dye had been recovered. No rhodamine WT was detected above background levels at Tobernacogany.

Parameter	Time (hours)
Time of First Detection	24.5
Time of Peak Concentration	34.2
Time of Concentration Centroid	39.6
Time Half of Recovered Dye	46.03
End of Observation Period	761
End of Breakthrough Curve	261

Table 6.12 Breakthrough curve statistics calculated for sodium fluorescein at Tobernacogany spring.

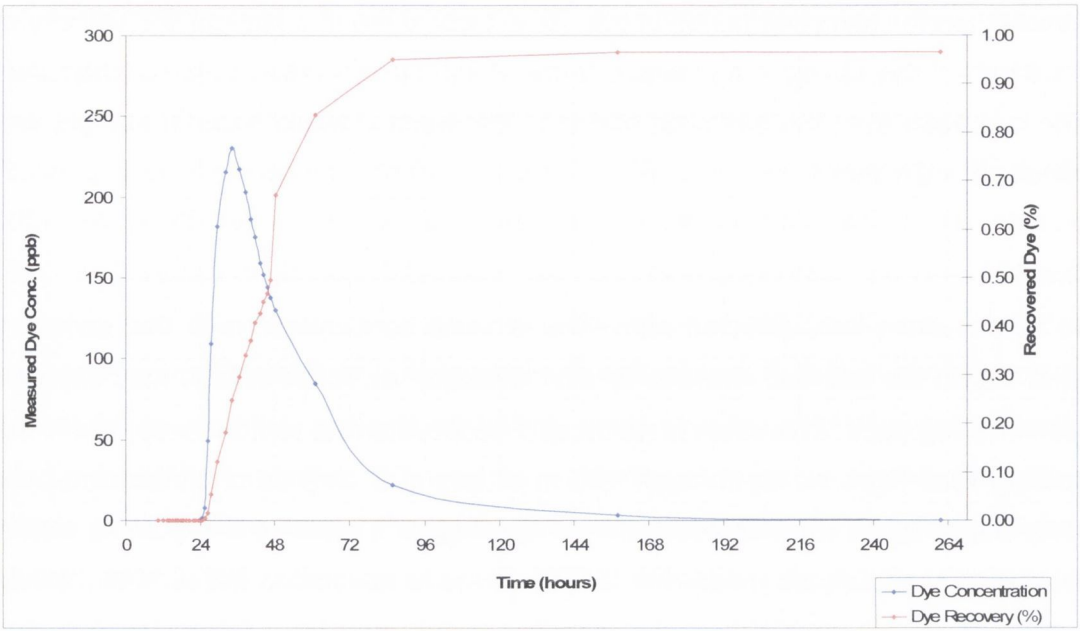

Figure 6.30 Dye breakthrough and recovery curves (sodium fluorescein) calculated for Tobernacogany spring. Approximately 97% of the injected dye was recovered.

Sample No.	Time elapsed (hrs)	Measured conc. minus background (ppb)	Q (l/s)	time interval (hrs)	ave conc. (µg)	water vol per interval (Litres)	dye recovered per interval (µg)	cumulative dye volume recovered (grams)	Cum. dye recd (%)
1	10.3	0	37	n/a	n/a	n/a	n/a	n/a	n/a
2	12.2	0	37	1.8	0	244200	0	0.00	0
3	13.3	0	37	1.1	0	144300	0	0.00	0
4	14.2	0	37	0.9	0	122100	0	0.00	0
5	15.1	0	37	0.9	0	122100	0	0.00	0
6	16.2	0	37	1.1	0	144300	0	0.00	0
7	16.8	0	37	0.6	0	77700	0	0.00	0
8	17.7	0	37	0.9	0	122100	0	0.00	0
9	18.5	0	37	0.8	0	111000	0	0.00	0
10	19.5	0	37	1.0	0	133200	0	0.00	0
11	20.5	0	37	1.0	0	133200	0	0.00	0
12	21.6	0	37	1.1	0	144300	0	0.00	0
13	22.5	0	37	0.9	0	122100	0	0.00	0
14	23.5	0	37	1.0	0	133200	0	0.00	0
15	24.5	1	37	1.0	0.5	133200	66600	0.07	0
16	25.3	8	37	0.8	4.5	110556	497502	0.56	0
17	26.3	49	37	1.0	28.5	133200	3796200	4.36	0
18	27.3	109	37	1.0	79	133200	10522800	14.88	1
19	29.3	182	35	2.0	145.5	265068	38567394	53.45	5
20	32.0	215	35	2.7	198.5	337680	67029480	120.48	12
21	34.2	230	35	2.2	222.5	272160	60555600	181.04	18
22	36.5	217	35	2.3	223.5	294840	65896740	246.93	25
23	38.3	203	35	1.8	210	230580	48421800	295.35	30
24	40.2	186	35	1.8	194.5	230580	44847810	340.20	34

Sample No.	Time elapsed (hrs)	Measured conc. minus background (ppb)	Q (l/s)	time interval (hrs)	ave conc. (µg)	water vol per interval (Litres)	dye recovered per interval (µg)	cumulative dye volume recovered (grams)	Cum. dye recd (%)
25	41.5	175	35	1.3	180.5	168840	30475620	370.68	37
26	43.3	159	35	1.8	167	220500	36823500	407.50	41
27	44.3	152	35	1.0	155.5	126000	19593000	427.09	43
28	45.5	144	35	1.3	148	157500	23310000	450.40	45
29	46.5	138	35	1.0	141	126000	17766000	468.17	47
30	48.2	130	35	1.7	134	209160	28027440	496.20	50
31	61.0	85	35	13	107.5	1617840	173917800	670.12	67
32	85.5	22	35	24	53.5	3087000	165154500	835.27	84
33	158.0	3	30	72	12.5	9135000	114187500	949.46	95
34	261.5	0	30	103	1.5	11178000	16767000	966.22	97
35	761.5	0	0	500	0	54000000	0	966.22	97

Table 6.13 Sampling results for Sodium Fluorescein at Tobernacogany spring.

Roaring Well results

Rhodamine WT was first detected at the Roaring Well almost 9 hours from when it was injected into the White Lake swallow hole. This gives a straight line velocity of 137 m/h. This is almost twice as high as the velocity of the trace from Lough Lene to Tobernacogany. The gradient between White Lake and the Roaring Well is approximately twice as steep as that between Lough Lene and Tobernacogany. The rising and falling limbs of the breakthrough curve are steep (Figure 6.31). However, only a small proportion of the injected dye was recovered at the sampling point (21%). No rhodamine was detected in Drain 1, approximately 400 m downstream of the Roaring Well. The bog in this area is cutover fen peat. It is likely that water is flowing from White Lake to this fen at other points as yet unidentified besides the Roaring well or that water is flowing directly into Lough Glore below the lake surface. It is also possible that much of the dye had been adsorped by clay particles either in the aquifer or in overlying deposits before the water re-emerges at the Roaring Well (Käss 1998). The battery of the automatic sampler was disturbed by cattle 33.5 hours after dye injection and 5 samples (3-hour interval) were missed due to this disturbance, however, as can be seen from Figure 6.31 the peak of the dye cloud had passed the sampling point by this time and the fluocapteur was in place. Time of peak concentration of dye at the Roaring Well sampling point occurred 14.5 hours after injection and the time when half of the recovered dye passed the sampling point was 26.23 hours (Table 6.15). Due to the low dye recovery at this site a dye concentration centroid was not calculated. No fluorescein was detected above background levels at the Roaring Well.

Sample No.	Time elapsed (hours)	Measured conc. minus background (ppb)	Q (l/s)	time interval	ave conc. (µg)	water vol per interval (Litres)	dye recovered per interval (µg)	cumulative dye volume recovered (grams)	Cum. dye Recd. (%)
1	4.00	0	16	n/a	n/a	n/a	n/a	n/a	n/a
2	4.50	0	16	0.50	0	28800	0.00	0.00	0
3	5.00	0	16	0.50	0	28800	0.00	0.00	0
4	5.50	0	16	0.50	0	28800	0.00	0.00	0
5	6.00	0	16	0.50	0	28800	0.00	0.00	0
6	6.50	0	16	0.50	0	28800	0.00	0.00	0
7	7.00	0	16	0.50	0	28800	0.00	0.00	0
8	7.50	0	16	0.50	0	28800	0.00	0.00	0
9	8.00	0	16	0.50	0	28800	0.00	0.00	0
10	8.50	0	16	0.50	0	28800	0.00	0.00	0
11	9.00	8	16	0.50	3.9366	28800	113374	0.11	0
12	9.50	14	16	0.50	10.82565	28800	311779	0.43	0
13	10.00	22	16	0.50	18.04275	28800	519631	0.94	0
14	10.50	34	16	0.50	28.2123	28800	812514	1.76	0
15	11.00	43	16	0.50	38.38185	28800	1105397	2.86	1
16	11.50	54	16	0.50	48.22335	28800	1388832	4.25	1
17	12.00	60	16	0.50	56.75265	28800	1634476	5.89	1
18	12.50	64	16	0.50	62.00145	28800	1785642	7.67	2
19	13.00	67	16	0.50	65.61	28800	1889568	9.56	2
20	13.50	69	16	0.50	67.90635	28800	1955703	11.52	2
21	14.00	69	16	0.50	68.8905	28800	1984046	13.50	3
22	14.50	70	16	0.50	69.21855	28800	1993494	15.49	3
23	15.00	70	16	0.50	69.5466	28800	2002942	17.50	3
24	15.50	68	16	0.50	68.56245	28800	1974599	19.47	4
25	16.00	66	16	0.50	66.59415	28800	1917912	21.39	4
26	16.50	63	16	0.50	64.2978	28800	1851777	23.24	5
27	17.00	63	16	0.50	62.9856	28800	1813985	25.06	5
28	17.50	62	16	0.50	62.3295	28800	1795090	26.85	5
29	18.00	62	16	0.50	61.6734	28800	1776194	28.63	6
30	18.50	61	16	0.50	61.34535	28800	1766746	30.39	6
31	19.00	59	16	0.50	60.03315	28800	1728955	32.12	6
32	19.50	58	16	0.50	58.3929	28800	1681716	33.80	7
33	20.00	57	16	0.50	57.40875	28800	1653372	35.46	7
34	20.50	55	16	0.50	56.09655	28800	1615581	37.07	7
35	21.00	54	16	0.50	54.4563	28800	1568341	38.64	8
36	21.50	52	16	0.50	52.81605	28800	1521102	40.16	8
37	22.00	51	16	0.50	51.1758	28800	1473863	41.64	8
38	22.50	49	16	0.50	49.8636	28800	1436072	43.07	9
39	23.00	49	16	0.50	48.87945	28800	1407728	44.48	9
40	23.50	47	16	0.50	47.56725	28800	1369937	45.85	9
41	24.00	45	16	0.50	45.927	28800	1322698	47.17	9
42	24.50	43	16	0.50	44.28675	28800	1275458	48.45	10
43	25.00	43	16	0.50	42.97455	28800	1237667	49.69	10
44	25.50	41	16	0.50	41.9904	28800	1209324	50.90	10
45	27.50	39	16	2.00	40.35015	115200	4648337	55.54	11
46	29.50	36	16	2.00	37.72575	115200	4346006	59.89	12
47	31.50	33	16	2.00	34.44525	115200	3968091	63.86	13

Sample No.	Time elapsed (hours)	Measured conc. minus background (ppb)	Q (l/s)	time interval	ave conc. (µg)	water vol per interval (Litres)	dye recovered per interval (µg)	cumulative dye volume recovered (grams)	Cum. dye Recd. (%)
48	33.50	30	16	2.00	31.4928	115200	3627971	67.49	13
49	35.50	28	16	2.00	29.19645	115200	3363431	70.85	14
50	52.00	16	16	16.50	22.3074	950400	21200953	92.05	18
51	55.00	14	16	3.00	15.0903	172800	2607604	94.66	19
52	58.00	11	16	3.00	12.4659	172800	2154108	96.81	19
53	61.00	9	16	3.00	9.8415	172800	1700611	98.51	20
54	64.00	5	16	3.00	6.88905	172800	1190428	99.70	20
55	67.00	3	15	3.00	4.26465	172800	736932	100.44	20
56	70.00	2	15	3.00	2.6244	162000	425153	100.87	20
57	73.00	1	15	3.00	1.3122	162000	212576	101.08	20
58	145.5	1	10	72.50	0.6561	3915000	2568632	103.65	21
59	273.5	0	8	128	0.32805	4608000	1511654	105.16	21

Table 6.14 Sampling results for rhodamine WT at the Roaring Well spring.

Parameter	Time (hours)
Time of First Detection	9
Time of Peak Concentration	14.5
Time Half of Recovered Dye	26.23
End of Observation Period	750.5
End of Breakthrough Curve	145.5

Table 6.15 Breakthrough curve statistics calculated for rhodamine WT at the Roaring Well spring.

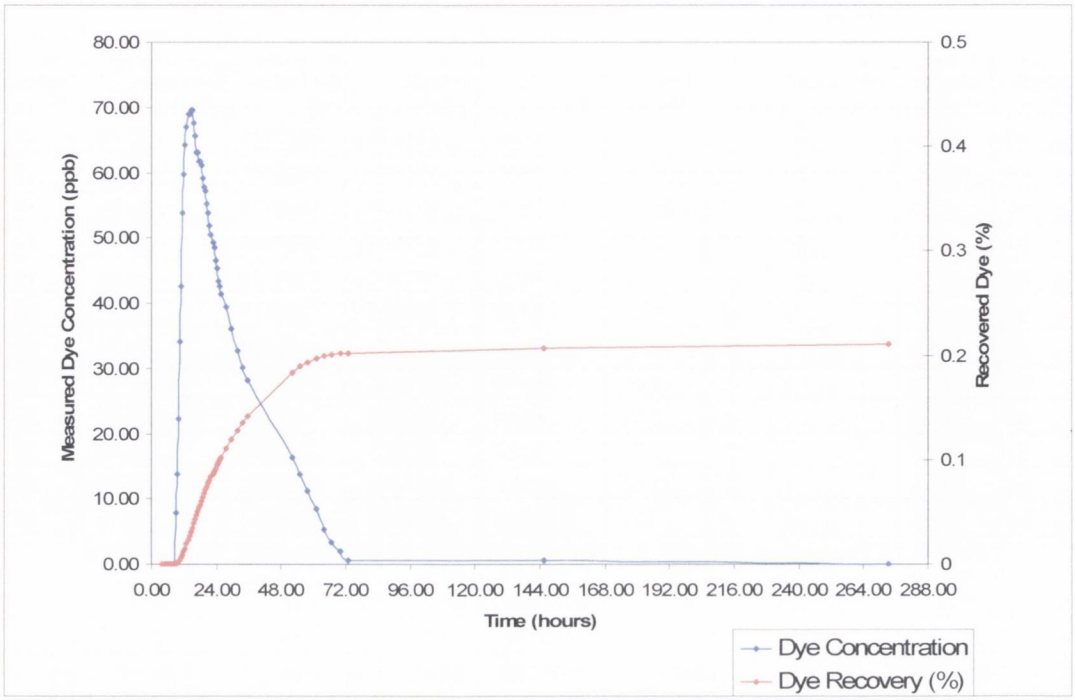

Figure 6.31 Dye breakthrough and recovery curves (rhodamine WT) calculated for the Roaring Well spring. 21% of the injected dye was recovered.

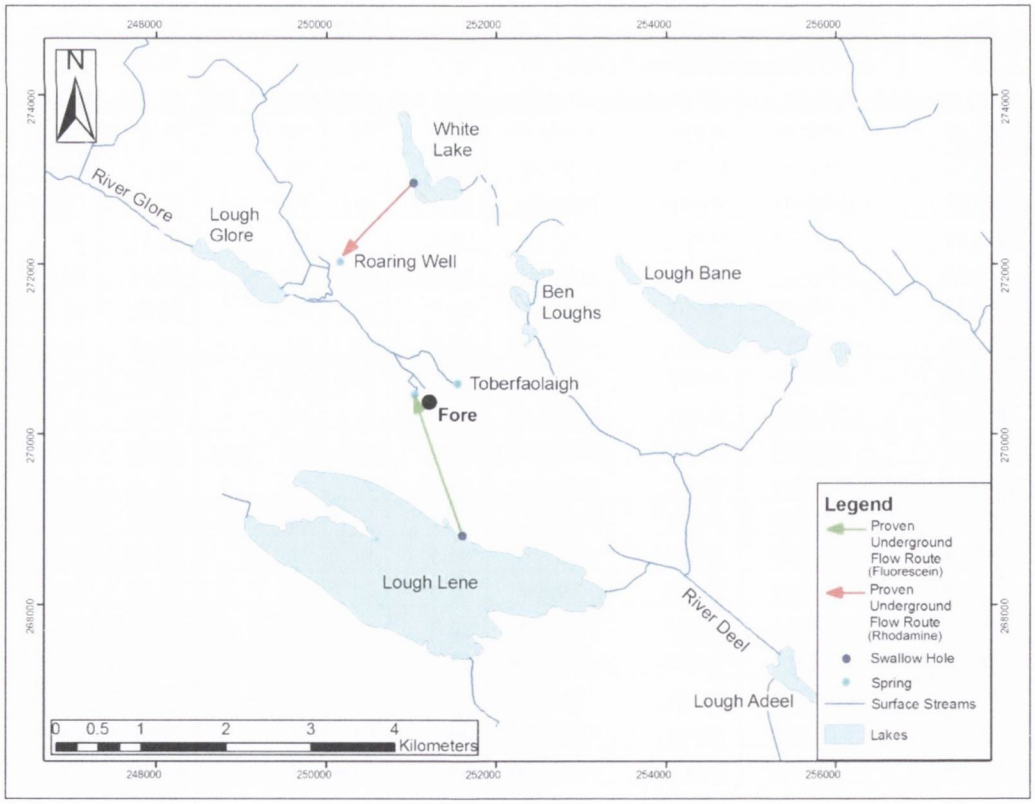

Figure 6.32 Proven underground flow routes in the detailed study area (basemap data OSI 2001).

7. Analysis and Interpretation

7.1 Characteristics of the groundwater system in the study area

7.1.1 Potentiometric surface configuration

Employing a full set of standing water level measurement data recorded on a single day, as presented in section 6.5, potentiometric surface water maps were constructed. . However, due to the relatively limited spatial distribution of sampling points the potentiometric surface configurations suggested in these maps should be treated with caution. The issues encountered during the construction of these maps are described below.

The groundwater sampling points are not evenly spaced and no sampling points were located to the southwest, or southeast of the study area. As a result, groundwater contours were constructed from a relatively limited spatial distribution of sampling points. For example, none of the sampling points included in the study are situated on hills. Thus it was impossible to map the configuration of the potentiometric surface under the hills in the area, to investigate whether it mirrored the topography or whether the potentiometric surface configuration is independent of topography. There is also a degree of uncertainty as to whether the standing water levels in the sampling wells represent the actual potentiometric surface, i.e. the top of the continuous, unconfined saturated zone, or the water level in a till-based, perched aquifer. None the less, potentiometric surface maps were drawn in order to examine the monitoring point standing water levels in relation to each other, bedrock geology and unconsolidated deposits and the location of springs in the study area.

The initial unedited groundwater surfaces that were produced took no account of whether the contours stood above or below the land surface (Figure 7.1). This apparent potentiometric surface was then analysed to identify areas where it stood at a higher elevation than land or lake surfaces and the results of this analysis are presented in Figure 7.2. in which the orange areas corresponding to locations where the apparent potentiometric surface was higher than land or lake levels. Also included in Figure 7.2 are lakes, springs (identified both in the field and from the 6 inch map), and areas of peat and gley soils. The beige areas in Figures 7.1 and 7.2 represent areas for which there are no standing water level data.

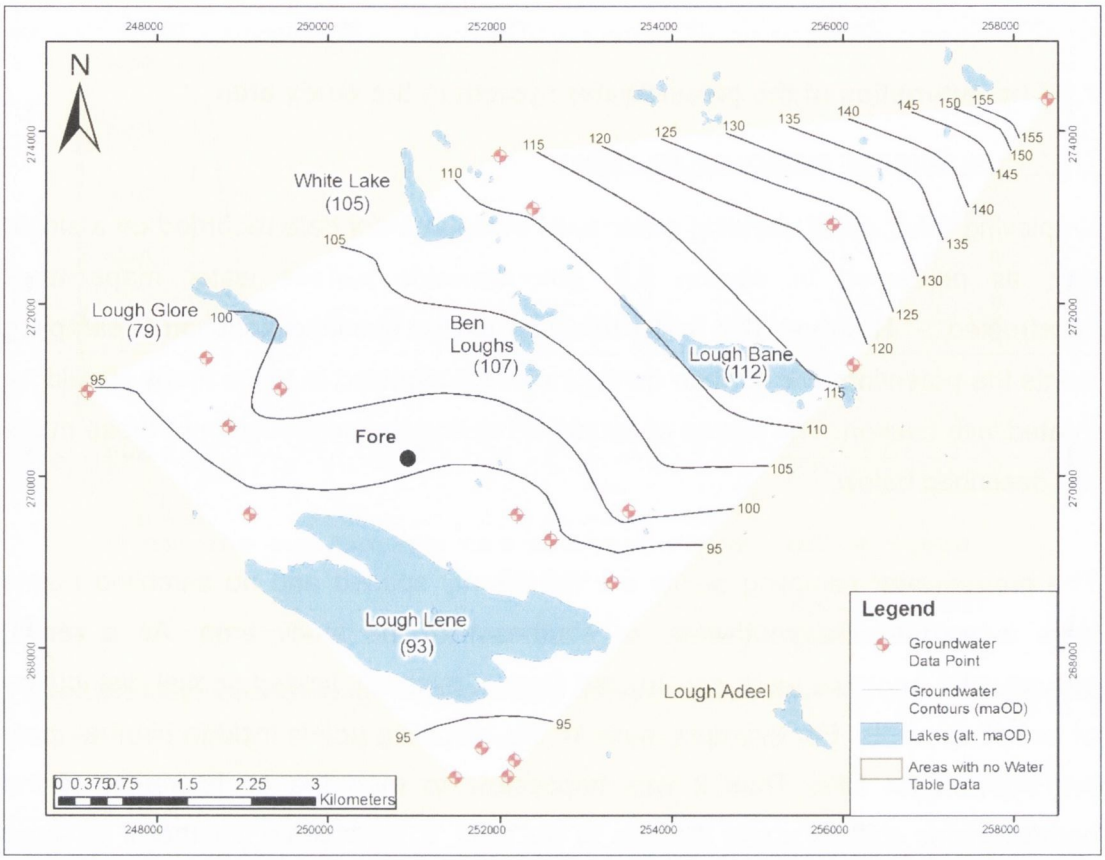

Figure 7.1 Initial, uncorrected potentiometric surface interpolation (27/6/07) (basemap data OSI 2001).

There are two possible explanations for the potentiometric surface standing higher than the land surface – either the aquifer is confined or the map is inaccurate. As previously described, inaccuracies in the map could result from the spatial distribution of the groundwater sampling points, i.e. that localised fluctuations in the potentiometric surface are unaccounted for. However, as an exploratory investigation, results suggest a relationship between the areas where the interpolated potentiometric surface extends above the land surface and areas of peat soils in the study area (Figure 7.2). For the most part, areas of peat and gley soils coincide with areas where the apparent potentiometric surface is higher than the land surface. This is also true of the springs in the area – all of which are located within the orange areas on the map (except those located outside the area for which there is groundwater data). This suggests that the interpolated potentiometric surface is possibly partially representative of an unconfined watertable in the overburden. Due to their relatively low permeability, the areas of peat soils could act

as confining layers and the springs may mark the locations where the saturated zone intersects the land surface and groundwater discharge from the saturated zone occurs. Alternatively, the peat and gley soils may be caused by a high, unconfined potentiometric surface.

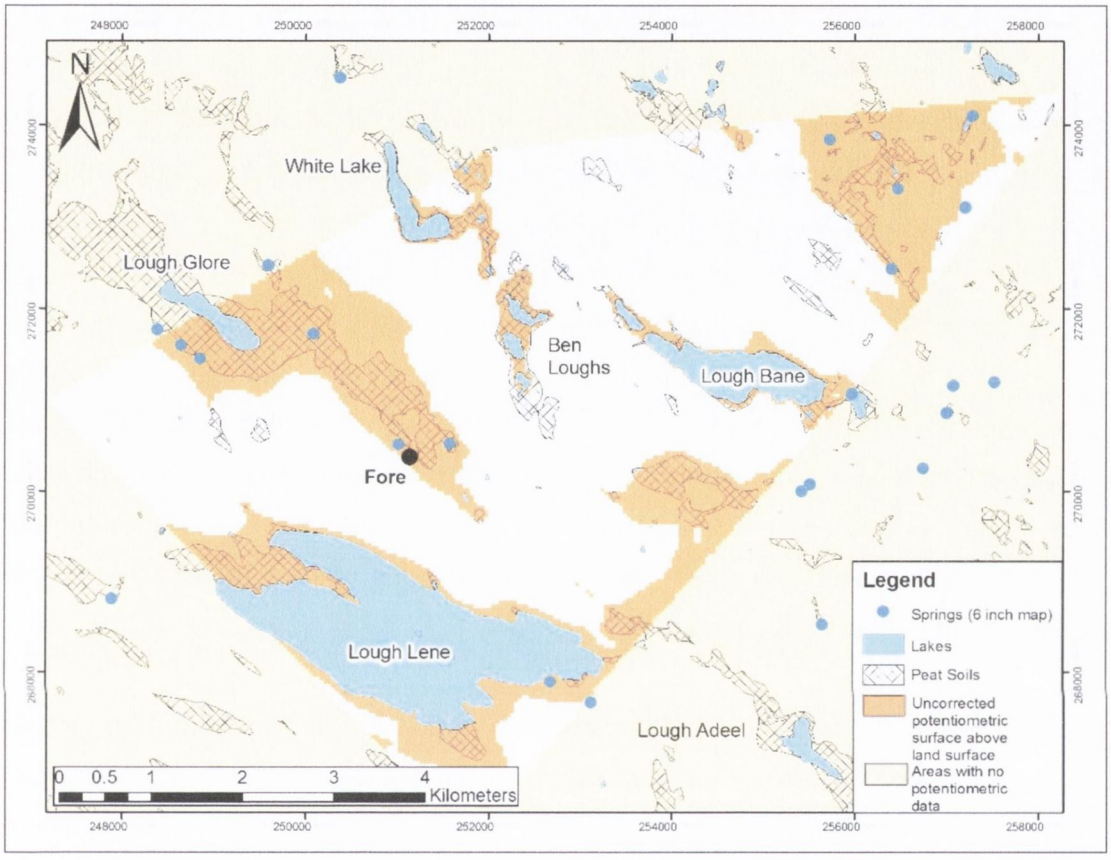

Figure 7.2 Areas where the uncorrected potentiometric surface (26/1/07) stands higher than land surface, and the relationship of these areas to peat soils, springs (from 6 inch maps), and lakes (basemap data OSI 1837, 2001; Teagasc 2004).

In such a conceptual model as outlined above it would be possible to view the lakes as surface expressions of the potentiometric surface. However, there are difficulties with this idea though, as in a number of places the potentiometric surface may not be contiguous with lake surface levels. For example, at Lough Lene some of the lake water drains into swallow holes that water tracing has shown are connected to a spring (Tobernacogany) that is 7.6 m below the lake surface. As a result, in this part of the lake basin at least, the potentiometric surface may be below the lake surface. Alternatively, the connection between Lough Lene and Tobernacogany may flow through a conduit or conduits that are unconnected to the saturated zone of the

aquifer. In such a case it is possible that the potentiometric surface of the main aquifer is higher than this conduit system but cannot infiltrate it as there is no hydraulic connection between the conduit and the main aquifer. In White Lake a number of swallow holes drain the lake for part of the year. When the lake is full, these swallow holes are submerged and no flow could be observed into two of these swallow holes when they were submerged in winter 2006/2007. This could mean either that the swallow holes were not operating, or if they were, that they were acting as estavelles, and as such, the lake surface could be regarded as a surface expression of the potentiometric surface. However, in the summer months when the lake level drops, the water level at the bottom of the swallow holes is approximately 2m below that of the lake and so the lake surface in this part of the lake basin could not be considered as representative of the potentiometric surface locally. This does not necessarily mean that the potentiometric surface is not at the same level as the lake surface in other parts of the lake basin. However, it is also possible that the entire lake surface is higher than the potentiometric surface in summer months but that water is held in the lake basin by the low permeability sediments that characterise the lake basin and that the swallow holes provide a pathway into the aquifer through these low permeability deposits.

The potentiometric surface was then adjusted so that it was no higher than land or lake surfaces at any point. This was done because there was no conclusive proof that the groundwater was confined in the study area. The actual altitude of the potentiometric surface was unknown in areas where the interpolated surface stood higher than land or lake surfaces, and in such areas the potentiometric surface in the map was positioned at the land surface, i.e. at the highest possible level it could be. Thus the resulting maps cannot be treated as definitive maps but only indications of the potentiometric surface configuration in the area. Each of the weekly/bi-monthly recorded sets of groundwater levels were plotted in this manner and the results for each date were found to be remarkably similar. Thus, two maps are presented below, one depicting a potentiometric surface interpolated from winter groundwater levels (Figure 7.3, 26/1/2007) and one from summer groundwater levels (Figure 7.4, 27/6/2007). These dates represent extremes of the range in terms of the groundwater levels that were recorded during the study.

The inferred directions of groundwater flows are virtually identical in both maps. The general direction of groundwater flow is northeast to southwest. To the south of Lough Bane groundwater flow diverges with groundwater flow to the south and southwest. Groundwater flowlines converge on the area around Fore Valley. Flows converge on this hydraulic low from the north and south from an area west of Lough Lene. Lough Lene itself seems to be in a hydraulic low, with groundwater flowing towards the lake from the east, west and north. The position of the potentiometric surface to the southwest of the lake is unknown due to the absence of sampling points but a valley is located in this area the floor of which is some 20m lower than the lake surface level and it is improbable that a groundwater mound is located here unless it is confined. The main seasonal difference is localised changes in the altitude of the potentiometric surface. The mound of groundwater to the south of Lough Lene is approximately 5m higher in winter and the potentiometric surface around Lough Bane, the Ben Loughs, and White Lake is between 5m and 2.5m higher in winter than in summer.

It is possible that these maps are an accurate depiction of the potentiometric surface of the detailed area in some respects. If the maps were wholly inaccurate, it is unlikely there would be such a strong relationship between the intersection of the interpolated potentiometric surface and the lakes, peat, and springs. However, it is known that the potentiometric maps are probably erroneous around at least part of some lake basins (i.e. Lough Lene) and that conduit flow occurs in at least part of the study area (McDonald 1988). For example, the underground flow directions proven from water tracing are compared to the inferred groundwater contours from the well monitoring programme in Figure 7.5. The water trace results contradict the groundwater flow directions suggested by the potentiometric surface maps in the Lough Lene catchment, while the water trace results agree with the groundwater flowlines in the White Lake catchment. The straight line flow routes of both successful water traces pass under limestone hills and there is no evidence of dry valleys in the surface topography overlying these flow routes.

The configuration of the potentiometric surface in relation to the topographically delineated spring and lake catchments is outlined below. The groundwater flowlines are shown with the study surface catchments in Figure 7.6.

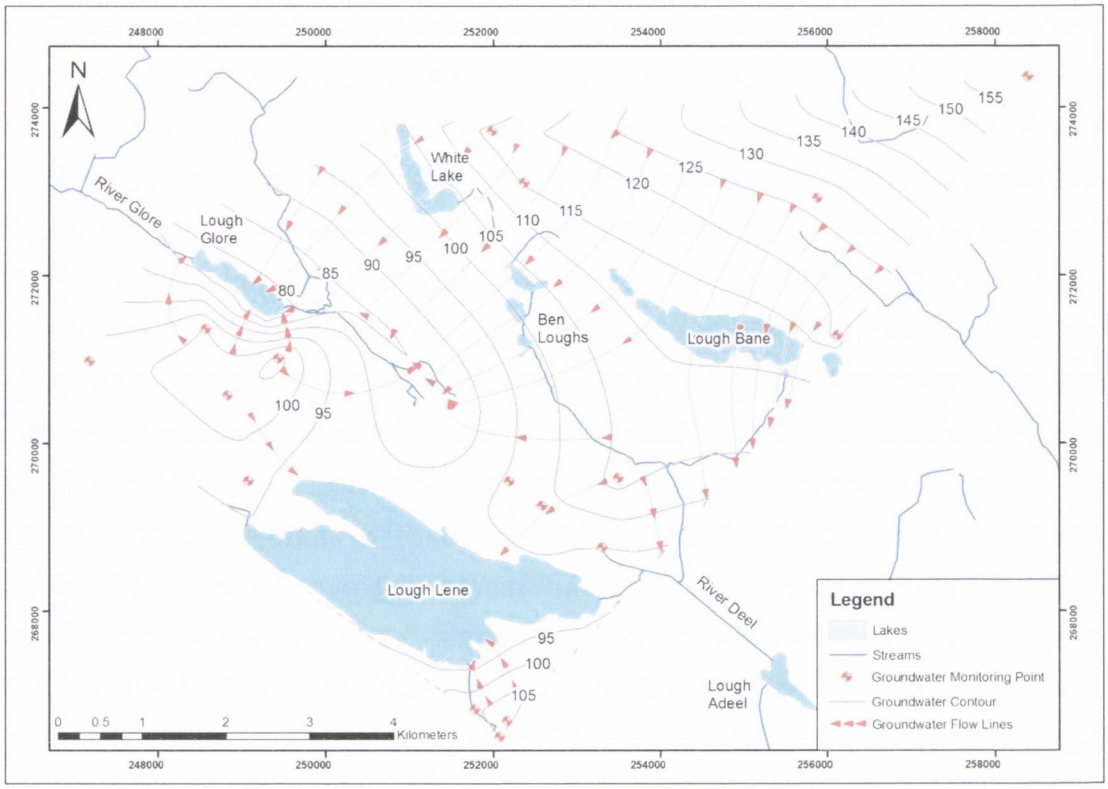

Figure 7.3 Inferred configuration of the potentiometric surface in the study area on 26/1/2007 (basemap data OSI 2001).

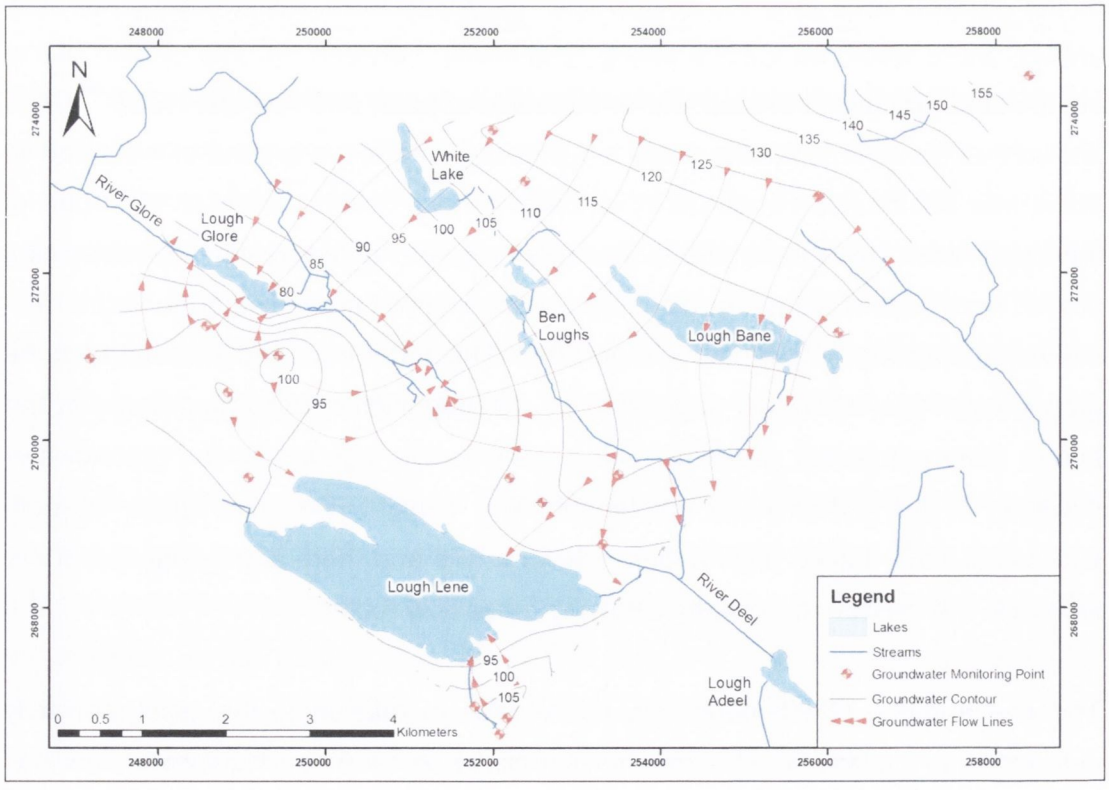

Figure 7.4 Inferred configuration of the potentiometric surface in the study area on 27/6/2007 (basemap data OSI 2001).

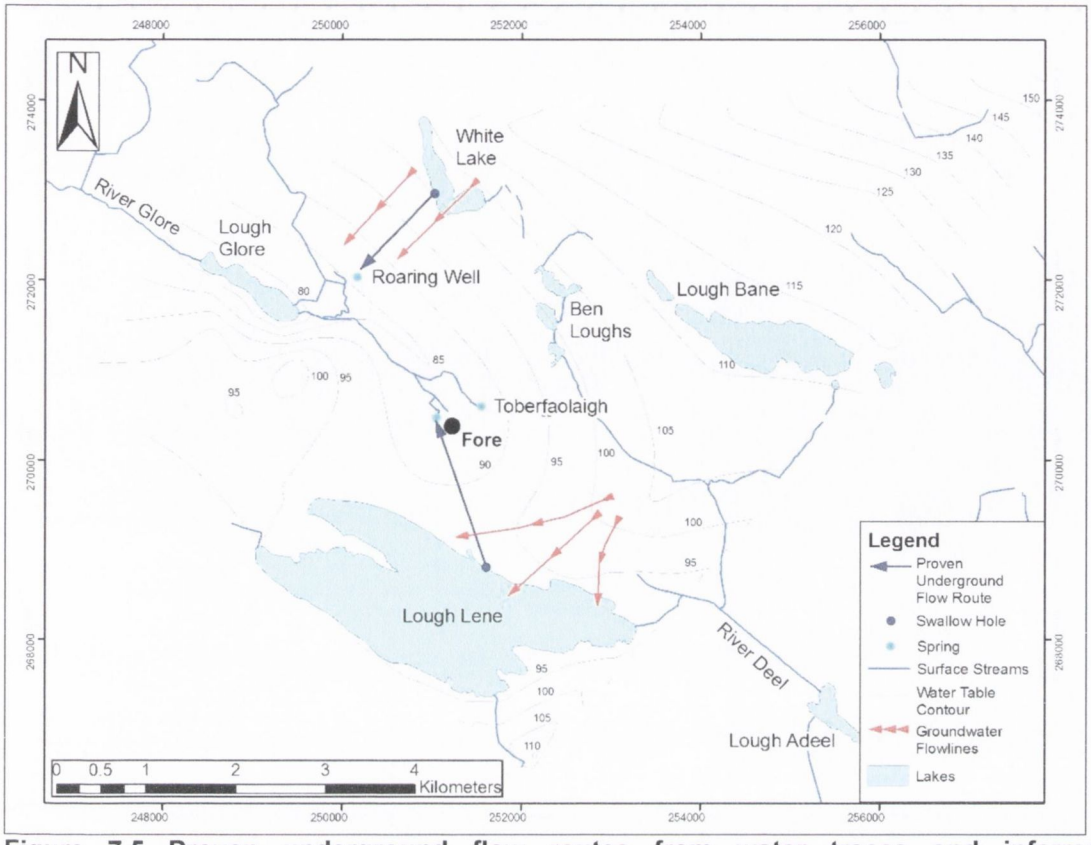

Figure 7.5 Proven underground flow routes from water traces and inferred groundwater contours from well dipping (basemap data OSI 2001).

Tobernacogany, Toberfaolaigh, and Fore Valley

Based on the potentiometric surface maps, groundwater flow converges on the springs of Tobernacogany and Toberfaolaigh from the northeast, east, southeast, and southwest and Fore Valley appears to be a hydraulic low. As attested by the results of water tracing analyses, water discharging from Tobernacogany has been traced from Lough Lene and this lake is the main source for the spring. The source of water flowing from Toberfaolaigh has not been established, and based on the above potentiometric surface maps the contributing area for this spring is a potentially large area located to the north, east and south. In Fore Valley, downstream of the two springs as far as Glore Bridge, the potentiometric surface configuration suggests that the valley is a groundwater discharge zone. Groundwater discharged here could have originated from locations in the north, northeast, or southwest and the springs situated around Lough Glore (Figure 7.6) could be locations for some of these groundwater discharges.

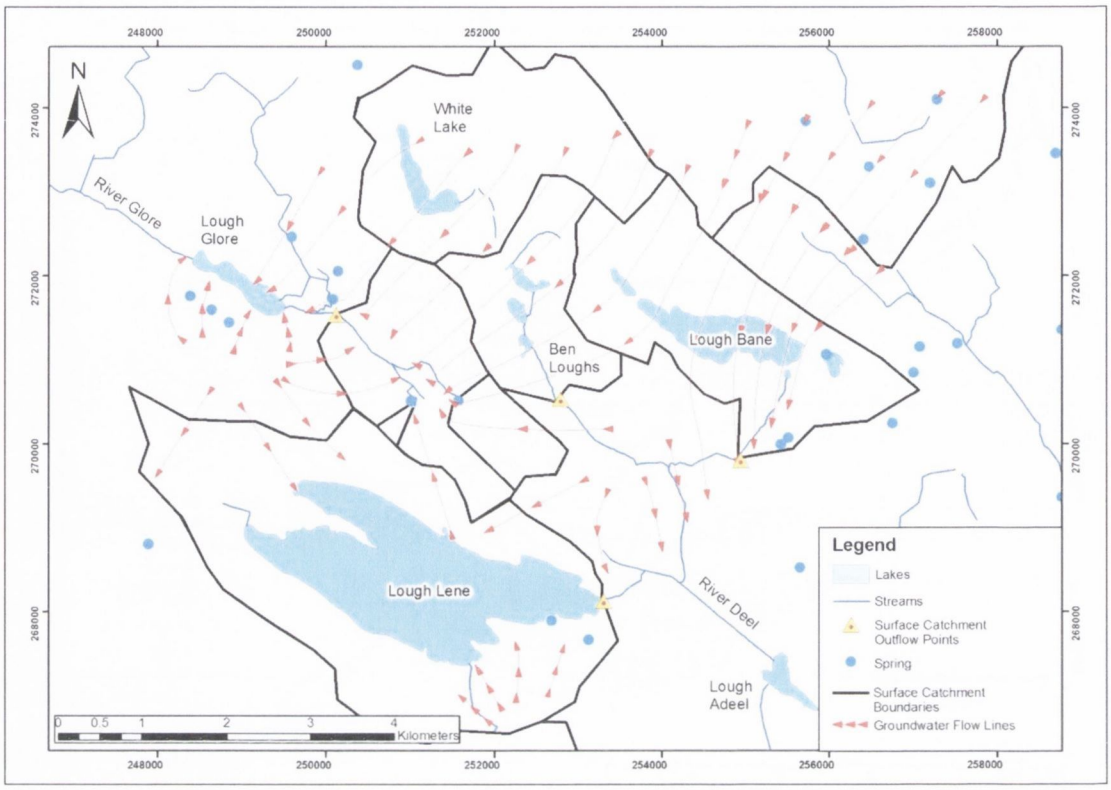

Figure 7.6 Groundwater Flowlines and topographically defined surface catchments (basemap data OSI 2001).

Lough Lene

The configuration of the potentiometric surface in and around this catchment is difficult to discern due to the size of the lake and the small number of groundwater monitoring points in the lake catchment. There are groundwater mounds to the south, northeast and northwest of the lake. According to the results of potentiometric mapping, groundwater flows towards the lake from the north-northeast. This contradicts the results of water tracing which show groundwater flow in the opposite direction to the map.

White Lake

The potentiometric surface in the lake catchment dips from the northeast to the southwest. Groundwater flowlines do not diverge or converge in this catchment but flow from the northeast towards Lough Glore and the Roaring Well spring.

Ben Loughs

The potentiometric surface gradient is from the northeast to the southwest. However the groundwater flowlines begin to converge towards the southwest in the vicinity of

Toberfaolaigh spring. Groundwater flowing through/from this catchment could contribute to the discharge from Toberfaolaigh or the smaller springs that discharge into the River Glore downstream of it. The lake levels in this catchment could be a surface expression of the potentiometric surface. This is supported by evidence collected in the field, for example, springs were located in the north of the catchment during field mapping.

Lough Bane

Groundwater in this catchment flows from a highpoint in the northeast towards the lake. To the south of the lake the groundwater flowlines diverge to flow south and west. The groundwater flow south is towards the River Deel, while the westerly groundwater flow is towards Fore Valley and Toberfaolaigh spring. It is possible that this groundwater could also contribute to Toberfaolaigh or the smaller springs that discharge into the River Glore further downstream.

7.1.2 Comparison of the regional watershed and the potentiometric surface configuration

The regional watershed, i.e. the topographically defined watershed between the SHRBD and ERBD, is compared to groundwater flowlines in Figure 7.7. According to this map, groundwater flows from the Shannon drainage basin to the Boyne drainage basin from the northeast. The groundwater flowlines diverge south of Lough Bane and some turn west, entering the Shannon drainage basin again at Fore Valley. Groundwater flow converges on Fore Valley from the Boyne drainage basin on three sides (north, east, and south), while the direction of groundwater flows in the Lough Lene catchment are difficult to distinguish as there are too few data points around Lough Lene for this purpose. Overall, groundwater flow is not closely related to the regional surface divide in this map.

The study surface catchments were compared to the uncorrected potentiometric surface shown in Figure 7.1. This map (Figure 7.8) shows the relationship between groundwater flow direction and surface catchments if the uncorrected groundwater map was representative of the general trend of groundwater flow in the study area. This map suggests that groundwater flows from the northeast to the southwest with the exception of the extreme east of the study area where groundwater flow direction is oriented north-south. According to this map groundwater moves from the

Shannon to the Boyne catchment in the northeast and then flows back to the Shannon catchment in the southwest.

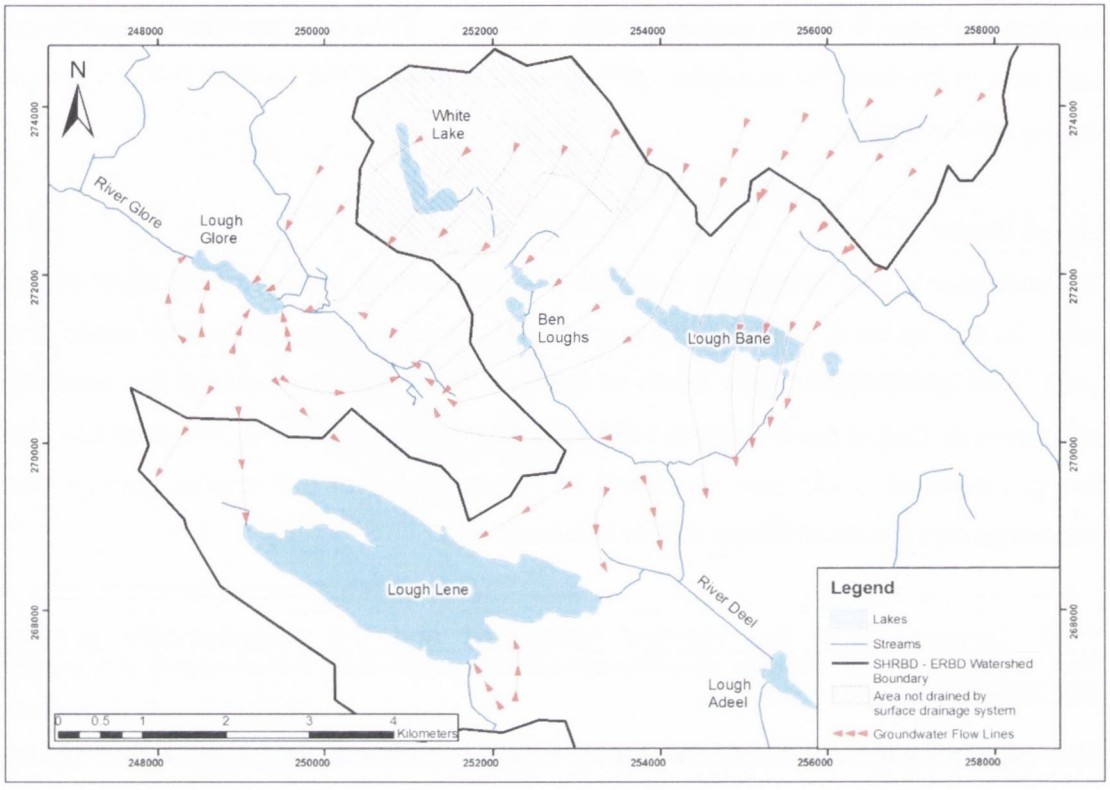

Figure 7.7 The SHRBD-ERBD (Shannon – Boyne) drainage divide and inferred groundwater flowlines in the detailed study area (SHRBD is located to the west of the black line and the ERBD to the east of the line) (basemap data OSI 2001).

If the standing water levels in the sampling wells are not indicative of the regional groundwater configuration, but represent perched groundwater bodies then this suggests that a complex groundwater system exists in the area. It is also possible that the springs and peaty areas represent places where local-scale groundwater systems are discharging. In contrast, the intermediate or regional groundwater (deep) flow systems appear to flow northeast-southwest in common with the trend of the topography in the area into which the northwest-southeast valleys are superimposed. As the altitudes of the standing water levels in the wells are similar – and they broadly follow the northeast – southwest trend in the landscape, it is more likely that the second of these scenarios is correct.

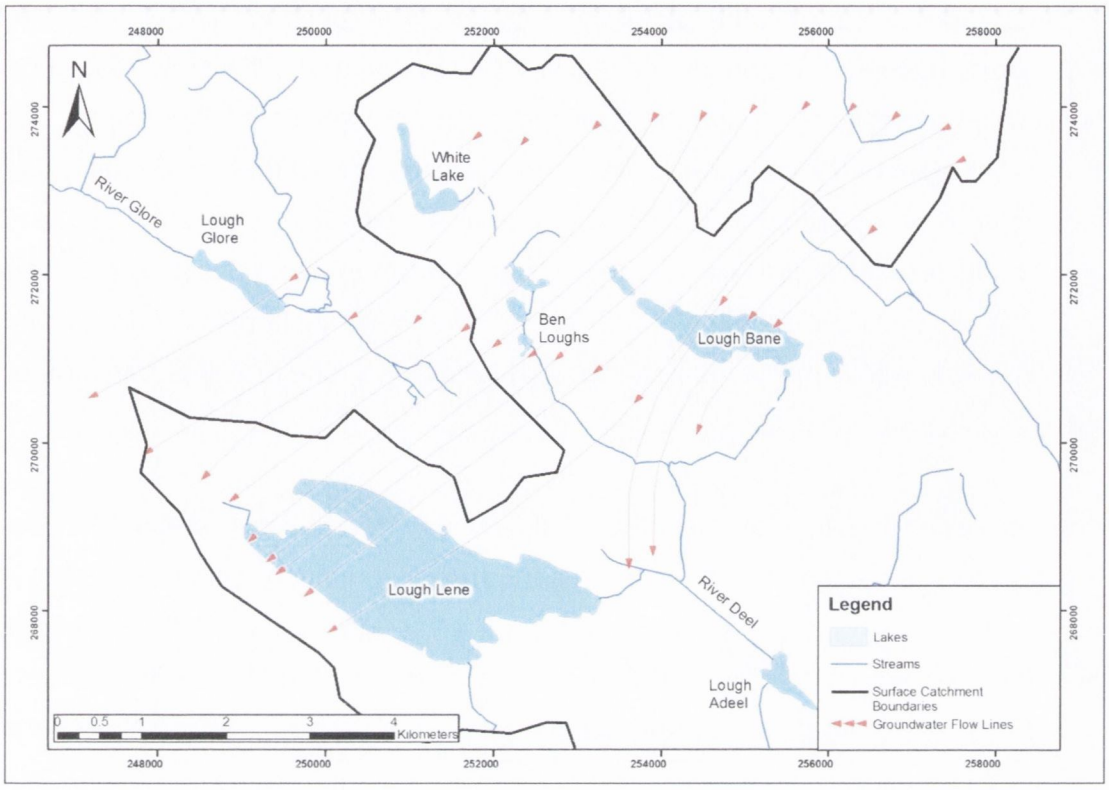

Figure 7.8 Surface catchments together with groundwater flowlines derived from the uncorrected potentiometric surface (basemap data OSI 2001).

7.1.3 Recharge

Groundwater recharge in the study area is via a combination of point and diffuse recharge. The swallow holes at White Lake and Lough Lene are evidence of point recharge to groundwater. There is also evidence of de-activated or episodically active point recharge pathways in the study area, i.e. the three inactive swallow holes at Lough Lene and the swallow hole at Lough Bane which appears on the 6 inch maps but that could not be located in the field. The presence of these active and inactive features suggests that while point recharge still occurs in this area, it was more important in the past and that anthropogenic modifications in the form of surface channel deepening have reduced the amount of point recharge occurring, and parts of the karstic drainage system in the study area have experienced a degree of de-activation following drainage schemes.

There is also evidence of diffuse recharge in the study area. Of the three large springs in the vicinity of Fore, water tracing has shown that at least two (e.g. Tobernacogany and the Roaring Well) are at least partially fed by point recharge.

However, the source of recharge for the third spring – Toberfaolaigh, is unknown. This spring has been shown by the results of water budget analyses to discharge more water than can be accounted for by its topographically defined catchment. As a result, Toberfaolaigh appears to be receiving water from either: the other study catchments; from outside the study area; or a combination of areas inside and outside the detailed study area. If Toberfaolaigh is fed from within the study area this recharge must be either point recharge from the identified swallow holes, point recharge from within one or more of the study lakes, or diffuse recharge from one or more of the study catchments.

The drainage densities of the study catchments may indicate areas that are inadequately drained by the surface stream network. In Ireland, catchments with a drainage density of < 0.5 km/km² have been classified as having low drainage densities and are commonly underlain by karstic or gravel aquifers with relatively high rates of recharge (DHLG/EPA/GSI 1999). The white lake catchment was the only study catchment to have a drainage density below < 0.5 km/km² (0.48 km/km²). This catchment also contains karst landforms, has no surface outflow and has been shown to provide point recharge to groundwater. Conversely, the Ben Loughs catchment has the highest drainage density (1.2 km/km²) and contained the least evidence of karstification in terms of landforms or groundwater surface interaction of any of the study catchments. The catchments of Lough Bane, Lough Lene and Fore Valley lie between these extremes at 0.81, 0.65, and 0.62 km/km² respectively and these values are close to the threshold value of 0.5 km/km² for areas underlain by karst or gravel aquifers.

7.1.4 Groundwater flow characteristics

Groundwater flow gradients from water traces in the study area range from 0.01 - 0.004. Recorded groundwater velocities in the study area range from 71 m/h for the Lough Lene to Tobernacogany connection to 137 m/h for the White Lake to Roaring Well connection. If Toberfaolaigh is fed from the Lough Lene swallow holes (assuming that results obtained from water samples and fluocapteurs deployed at the sampling locations are accurate) the straight line velocity of water between the swallow holes and the spring must be <1.3 m/h. If this spring is receiving inputs from the White Lake swallow hole the velocity must be <1.8 m/h. The proven flow velocities from the present study are broadly inline with the range of flow velocities

determined from water traces in other Irish lowland karsts of 5 - 250 m/h (Drew 2008). However, they are high compared to flow velocities recorded in the Mullinahone lowland of 11.25 and 8.75 m/h (Jones & Gunn 1982; Gunn 1984). A number of tracing experiments carried out in the Castleisland karst also by Gunn (1984) recorded average groundwater flow velocities of 20 - 75 m/h, with a flow velocity of 0.95 m/h recorded for one connection. It must be considered that the flow velocities measured during the present study were measured from water traces carried out at the end of September 2009 – a time of the year when effective rainfall and water levels are usually relatively low compared to the winter/spring months and groundwater flow velocities may also be somewhat lower than they would be in the winter months. A water trace carried out during the winter of 1987 by McDonald (1988) from Lough Lene to Tobernacogany recorded a flow velocity of 80 m/h as opposed to a velocity of 71 m/h recorded during the present study.

The quantitative water tracing results allow inferences to be drawn regarding the hydraulic characteristics of those parts of the aquifer through which the dye passed based on the relationship between flow at the dye injection point, outflow point, and the proportion of dye recovered (Benischke et al. 2007). In the case of the Lough Lene, input and spring flows were approximately equal and >95% of the dye mass was recovered during the sampling period. This similarity in flows indicates that a connection with little dilution or divergence exists between the points. It appears that this underground flow route is isolated and not connected to a wider network in the aquifer. The result for the White Lake trace is somewhat different. Discharge into the injection point was higher than discharge at the sampling point, and only 21% of the dye was recovered at this point. An explanation for this result is that there is divergence in flow between the injection and sampling points. Thus, this flow route is probably not a point to point connection as in the case of Lough Lene to Tobernacogany. A possible explanation of this is discussed below.

Groundwater level fluctuations from wells in the study area, for example between SP9, SP13, and SP19 show differences between each other in their reaction to precipitation inputs as cross correlation analysis showed the water level in SP13 to lag rainfall by 5 – 6 days compared to3 - 6 days for SP9 and 2 days for SP19, i.e. groundwater flow in the study area is heterogeneous. Water level data from a number of wells shows pronounced responses to precipitation events compared to

the standing water level fluctuations in other wells which respond in a slower manner with a smaller range of oscillation to the same precipitation events. The well SP 19 which was fitted with an automatic recorder shows direct responses to variations in levels of precipitation with changes in its standing water level that are indicative of karst conduit type flows (Worthington 2003). Results of water tracing analysis have indicated the existence of fissure/conduit flows from White Lake to the Roaring Well and from Lough Lene to Tobernacogany. Overall, differing patterns of well standing water level fluctuations recorded in wells located in the study area in combination with evidence from the results of water tracing analysis suggest that karstic type fissure and/or conduit groundwater flow exists along side 'Darcian' groundwater flow through the unconsolidated overburden.

7.1.5 Discharge

Groundwater discharges via three springs with flows > 5 l/s (up to 202 l/s in the case of Toberfaolaigh) and numerous other smaller springs (flow rates of <5 l/s) in the study area. While Tobernacogany (maximum recorded flow rate 202 l/s), Tobernacogany (maximum recorded flow rate of 84 l/s), and the Roaring Well (maximum recorded flow rate during water tracing experiment of 16 l/s) are considered fourth order springs by Drew & Chance (2007), it is likely that Tobernacogany and Toberfaolaigh are within the top 10% of springs in Ireland in terms of their peak flow rates (Drew & Chance 2007). There is also evidence from water budget calculations that diffuse discharge is occurring to the stream channel of the River Glore and that either point or diffuse recharge, or possibly both, may be occurring via lake basins below the level of the lake surface.

The springs in the study area varied in terms of their measured discharge volume from 202 l/s (Toberfaolaigh) to < 1 l/s (observed discharge from small springs). Only Toberfaolaigh had a mean discharge of >100 l/s and the only other large springs in the area are Tobernacogany (mean discharge of 60 l/s) and the Roaring Well, the discharge of which was only measured after it was first discovered in August 2007 at 18 l/s and in September 2009 at 16 l/s.

The range of discharge of Toberfaolaigh during the study period was ~1:2 and in the case of Tobernacogany ~1:2.3. These are similar to those recorded for springs in Irish lowland karsts (Drew & Chance 2007). The springs in the study area differ from

each other though in terms of their flow regimes and water chemistry. Toberfaolaigh is perennial and has a mean water conductivity of 560 µS/cm, while Tobernacogany has a mean conductivity of 304 µS/cm and ceases to flow in most years by the end of the summer until late autumn/early winter (anecdotal evidence), which is because discharge volume from this spring may be related to the surface level of Lough Lene (During field walking undertaken as part of this study, Tobernacogany was observed to cease flowing during autumn 2005 and 2006 around the same time as flow into the swallow holes at Lough Lene ceased). Conductivity increases with flow at Toberfaolaigh spring (correlation coefficient 0.74, $p=<0.01$), a characteristic of a minority of karst springs in Ireland according to Drew & Chance (2007). It is possible that occurred due to a combination of a piston effect pushing stored water through the aquifer following a rainfall event (Lakey & Krothe 1996) and the timing of sampling events (which did not pick up a possible fall in conductivity following the increase due to the piston effect) or a characteristic of this spring may be increasing conductivity with increasing discharge due to the nature of recharge to this spring. Water flowing from the Roaring Well had a measured conductivity of 593 µS/cm, and this spring is usually only active for 2 - 3 months of the year. Observations during the autumn of 2009 showed that this spring ceased to flow when the level of White Lake fell below the level of the inflow channel to the White Lake swallow hole. Thus the springs in the study area are not similar in terms of the temporal variations in conductivity and discharge.

Some of these differences can be explained by examining each spring in the context of their position in the landscape relative to the bedrock and unconsolidated sediments. The relationship between the proven underground flow routes and peat and gley soils is shown in Figure 7.9. In the case of both flow routes, the discharge springs are located at the edge of areas underlain by peat and/or gley soils. Although the source of water discharging from Toberfaolaigh was not determined this spring is also located on a similar type contact.

The three springs are located at or near where the peats and gleysols – low permeability deposits, meet bedrock at the land surface. This suggests that the peats and gleysols are acting as a confining layer (Figure 7.10). As a result, all three springs can be classed as aggraded dammed springs (Smart & Worthington 2004); however there are differences between the three springs. Tobernacogany is directly

linked to Lough Lene and the volume of discharge from this spring is at least partially controlled by the surface level in Lough Lene. From observations during the fieldwork, another controlling factor on the discharge of this spring appears to be the amount of leaf litter and other debris (such as discarded plastic bags) that enter the swallow hole channels and reduce the rate at which water can infiltrate the swallow holes. This spring is situated on the floor of the valley and was observed to cease flowing when flow into the Lough Lene swallow holes ceased in September 2005, autumn 2006 and October 2009. Toberfaolaigh flows permanently from a contributory area that is most likely located to the north, east or south of the spring. The conductivity of water flowing from this spring is consistently higher than that of Tobernacogany, suggesting that water flowing from Toberfaolaigh is either polluted or contains higher levels of naturally occurring dissolved minerals than Tobernacogany. Roaring Well is the only spring located above the valley floor and there is a marshy area of bog located directly below the spring in the valley. While no clearly defined spring exists in this area, it is permanently water-logged and may be a year-round groundwater discharge zone. However, conductivities measured in surface ponds in this bog were 200 - 250 µS/cm which could include a groundwater element with higher conductivity that has been diluted by surface runoff as water flowing from the Roaring Well had conductivities ranging from 540 - 650 µS/cm. This area may be the location of discharge from the White Lake catchment during periods when the Roaring Well is not functioning. Moreover, the Roaring Well could be an overflow spring connected to this lower system which becomes active under high flow conditions (Figure 7.11). However, no dye was recovered in the outflow drain from this bog during the water tracing experiment. The non-recovery of dye at this location could be explained by adsorption of the dye by unconsolidated deposits between the bedrock aquifer and the bog surface as has been shown possible for rhodamine WT by Käss (1998), or by the possibility that water from White Lake does not flow into this bog but either flows into Lough Glore below the lake surface or some other (unidentified) location. It is likely though that groundwater flow out of White Lake is towards the direction of the Roaring Well and Lough Glore as exposed bedrock was observed along the western shore of White Lake with a north-northwest/south-southeast strike and dipping 3° - 8° to the southwest, which corresponds to the general direction of the White Lake/Roaring Well connection and, as a result, is likely to influence other groundwater connections in the area.

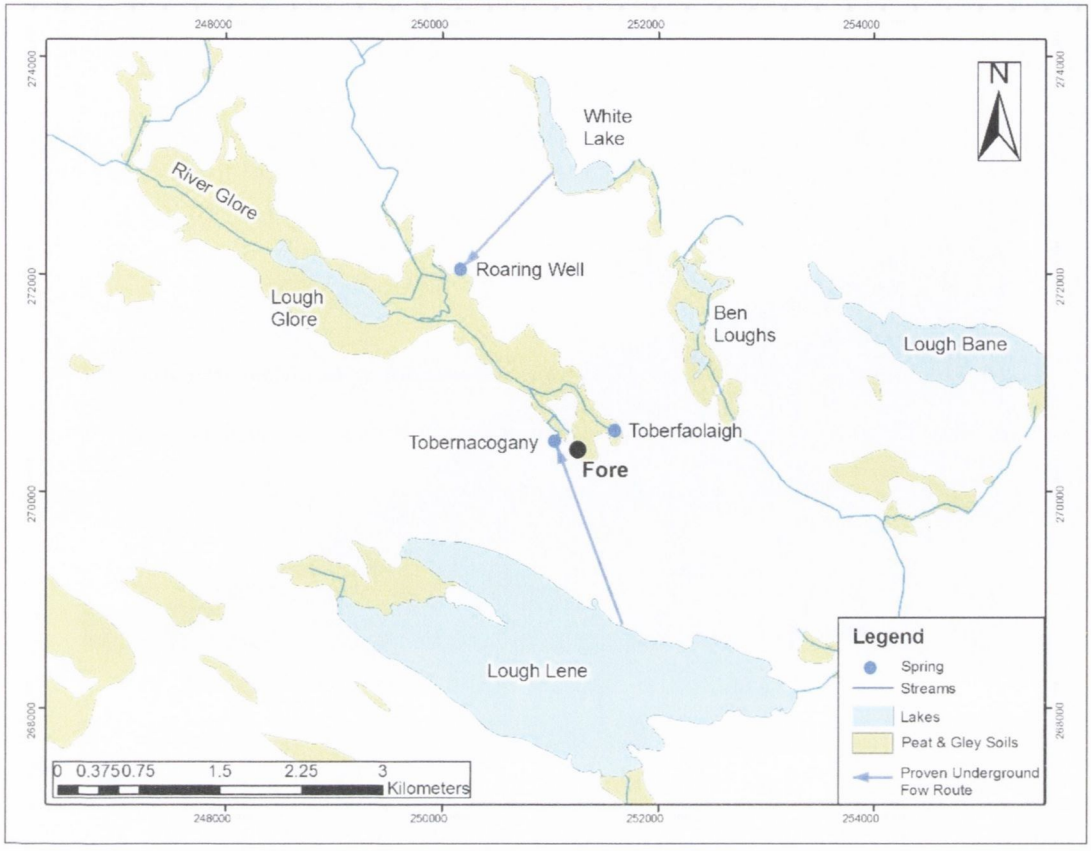

Figure 7.9 Underground flow routes and springs in relation to the location of peat and gley soils (basemap data OSI 2001; Teagasc 2004).

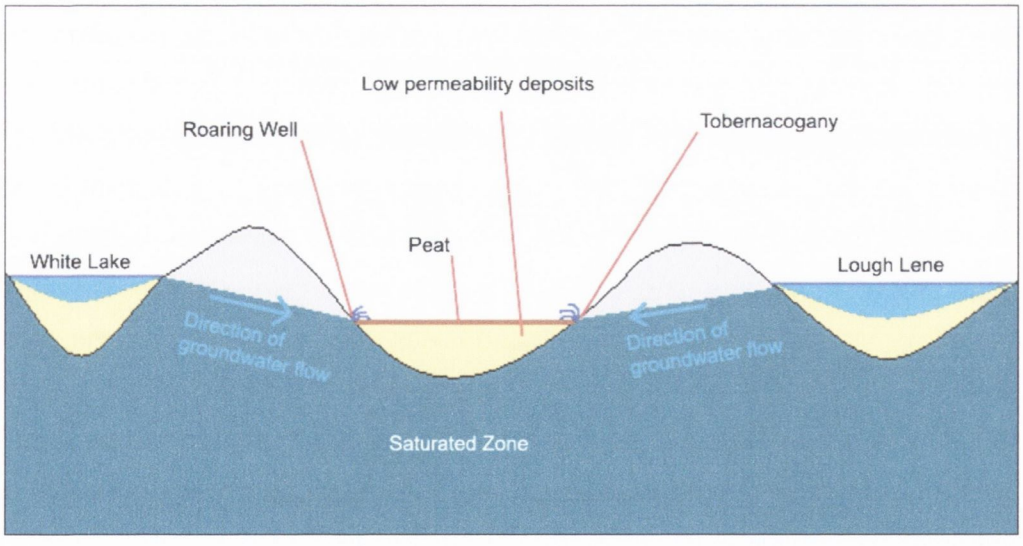

Figure 7.10 Conceptual diagram of spring location and unconsolidated deposits in the study area.

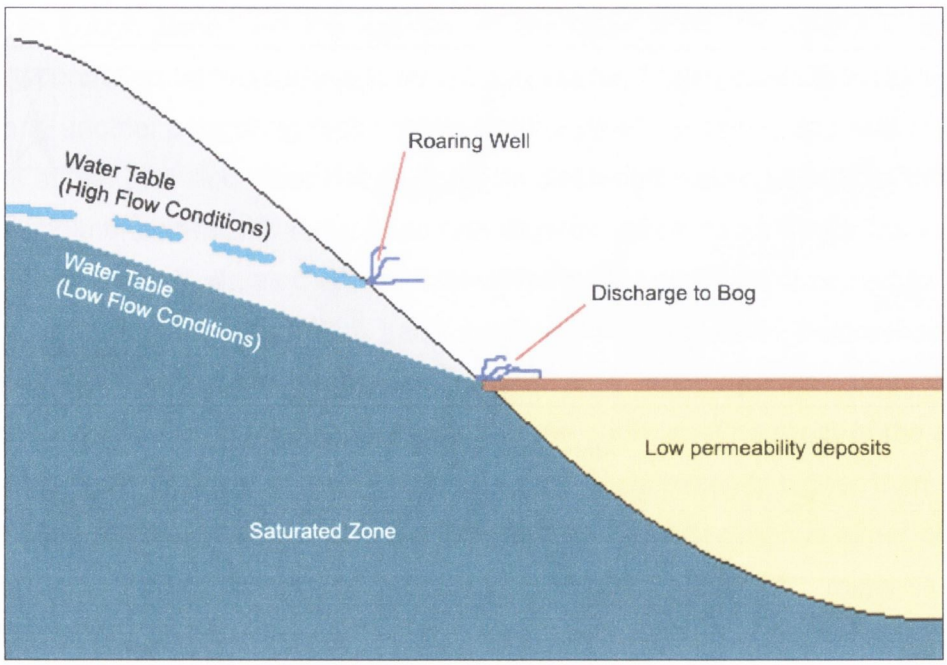

Figure 7.11 Conceptual diagram of the Roaring Well spring.

Groundwater may diffusely discharge into the River Glore above Glore Bridge, as attested by the results of water budget analysis which showed a positive imbalance in the amount of water out-flowing from this channel. Moreover, there is no evidence of a clearly defined spring flowing into the channel along this stream channel. Alternatively, the discharge into this channel may not be true diffuse discharge, but focused, point recharge that has been forced to diffuse through the low permeability peats and gleysols that underlie the channel before reaching this stream, as has been reported elsewhere by Lloyd & Lyke (1995), and Olcott (1992). However, employing results presented in this thesis, there is no way to definitively identify which type of discharge is taking place into the River Glore. Water budget results suggest that Lough Bane and the Ben Loughs may be receiving groundwater discharge for at least part of the year. It is unclear whether this disharge is point or diffuse or a combination of the two. Again, groundwater discharge that appears to be diffuse into a lake may in fact be point discharge that has been forced to diffuse by deposits either in the wave washed littoral zone or less permeable deposits deeper in the lake basin.

Overall, groundwater discharge in the study area is via springs with a likely smaller but difficult to quantify diffuse seepage element. The large springs – Tobernacogany, Toberfaolaigh, and the Roaring Well, while different in some

respects, all appear to be aggraded dammed springs. Their location is determined by the position of the low permeability deposits in Fore Valley which may infill and therefore block a pre-existing karstic conduit network flowing through conduits such as that potentially located near Fore Abbey by Brown (2002).

7.1.6 Spring zones of contribution

Based on the results of the water budgets and groundwater mapping, a possible contributory area for Toberfaolaigh has been defined (Figure 7.12). The limits of this area were delineated based on the altitude of the land surface, direction of groundwater flowlines, and the location of the other study lake catchments, and it assumes that point or diffuse recharge to groundwater could be occurring in any of the study lake beds. The boundaries of this area can only be considered to be approximations, as conduit type flow is known to occur in the area and the spatial distribution of groundwater sampling points was not ideal. Therefore, groundwater flowlines may not be entirely representative of groundwater flow direction. This area includes the White Lake and Lough Lene catchments and represents the largest area that could potentially be contributing recharge to Toberfaolaigh and seepage discharge in the Fore Valley. It is not possible that the entire area is contributing recharge at all times, as it is larger than necessary to account for the discharge from Toberfaolaigh and seepage into the River Glore. However, it is impossible to definitively exclude parts of it and so must be considered as a potential, as opposed to an exact contributory area.

The contributory area for Tobernacogany includes at least some of the topographically defined catchment of Lough Lene plus the topographically defined catchment of the spring itself. It is also possible that the higher ground to the north is contributing water to this spring, for the same reasons as outlined for Toberfaolaigh above, but if this is the case it would only be a relatively small amount, based on the results of the water tracing. As there is a surface outflow from Lough Lene it is impossible that all of this area contributes recharge to the spring at all times or even intermittently but no part of the catchment can be omitted. It is also possible that there is a degree of divergent flow operating, i.e. some of the water flowing into the Lough Lene swallow holes may be contributing to the smaller intermittent springs in Fore Valley. Thus the Lough Lene catchment is a partially contributing catchment for Tobernacogany spring.

Similarly, the contributory area for the Roaring Well includes at least part of the topographically defined catchment of White Lake plus the topographically defined catchment of the spring itself. It is also possible that the higher ground to the north is contributing water to the Roaring Well. As there was low dye recovery at this point from the White Lake swallow hole it is possible that water entering the White Lake swallow hole flows to more than one discharge point (divergent flow) or that it is being diluted with groundwater from other parts of the White Lake catchment or further afield from the areas to the north and east. As the measured flow from the Roaring Well are <20 l/s less than 1km² would be required to generate the runoff required for this spring. However, as with the other two springs it is impossible to accurately ascribe a contributing area for this spring.

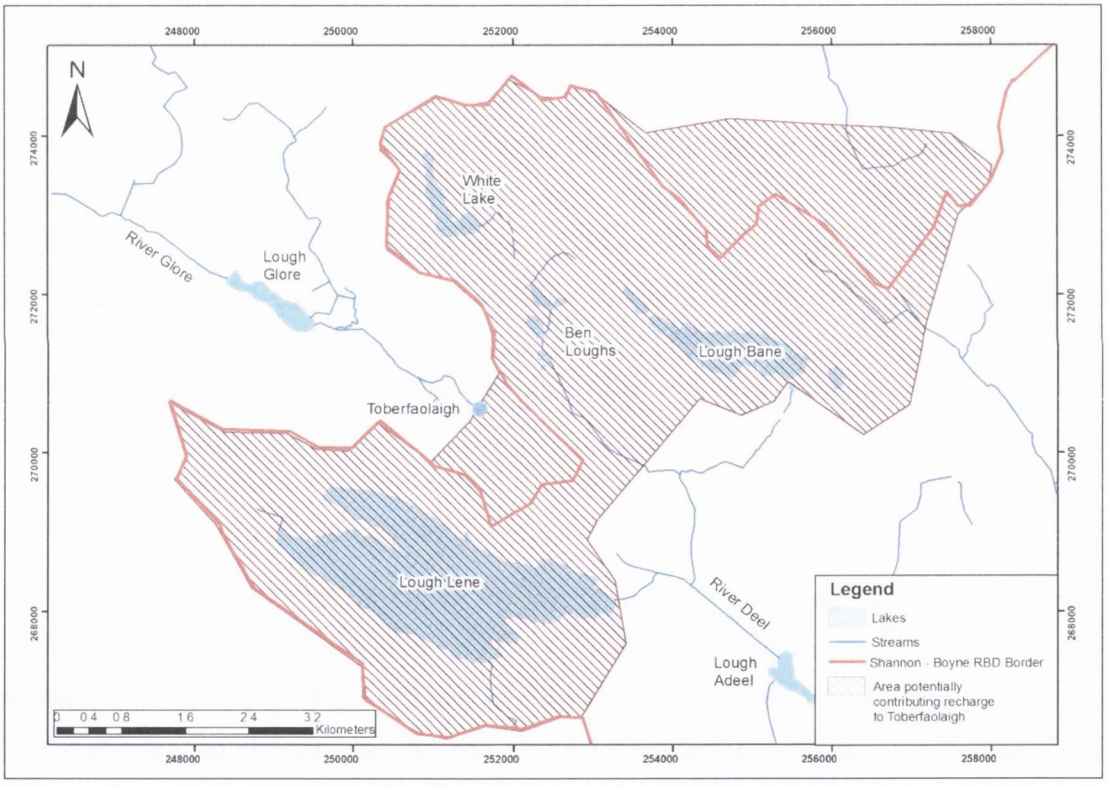

Figure 7.12 Areas potentially contributing recharge to Toberfaolaigh spring, based on water budget and potentiometric surface mapping results (basemap data OSI 2001).

The most striking characteristic of the shaded area shown in Figure 7.12 is that most of it - 80%, is located in the ERBD while Toberfaolaigh is located in the SHRBD. Furthermore, the northeastern section of the shaded area is located in the SHRBD but if this is part of the recharge zone for Toberfaolaigh, then recharge from this area would have to pass through the ERBD via the Ben Loughs or Lough Bane

catchments before discharging at the spring. If this type of trans-catchment flow is occurring, it is unknown whether it passes through the Ben Loughs and/or Lough Bane, or whether it flows underneath them.

7.2 Groundwater – surface water interaction in the study area

The surface drainage system in the study area is fully integrated apart from the White Lake catchment which is an enclosed depression, i.e. ~18% of the surface area in the study area is not drained at all by the surface channel network but by the groundwater system via White Lake. Water tracing, water budget, potentiometric surface mapping results, and the presence of springs suggest that Fore Valley is a groundwater discharge zone. Water tracing results show that subterranean connections exist between surface catchments in at least two cases in the study area. A point connection between White Lake and the Roaring Well in Fore Valley was proven. The existence of a point connection between Lough Lene and Tobernacogany in Fore Valley was also verified. The surface catchments proven to contribute water to the River Glore in Fore Valley via groundwater pathways are shown in Figure 7.13. There was no evidence of point connections between the other two lake catchments - Lough Bane and the Ben Loughs. Thus, two of the large springs in Fore Valley have been proven to receive point recharge, and Toberfaolaigh has been shown to be fed by diffuse recharge from an area outside its topographically defined catchment.

It is possible that all discharge from the White Lake catchment enters the River Glore, either through the Roaring Well system, the marsh downhill from the well, or as seepage into the river channel. In the case of Lough Lene, previous work (McDonald 1988) and the results presented in this thesis show that a proportion of discharge from this catchment flows into the River Deel, so the Lough Lene catchment must be considered as a partially contributing area for both the River Glore and the River Deel. However, mean discharge to groundwater from Lough Lene is lower overall than mean discharge to the surface drainage network, at 46% and 53% of total discharge from the catchment, respectively.

Water levels of permanent lakes can be surface expressions of the potentiometric surface in places (Winter 1998; Ravbar & Šebela 2004). This is possibly the case in

some or of the study lakes in parts of their basins. The swallow holes at White Lake may be estavelles, as no flow could be observed into them during the winter of 2006/2007 when the lake level was high (Figure 7.14). They could also have ceased to flow due to clogging, but this is impossible to verify. If these swallow holes are estavelles then the surface level of White Lake can be viewed as a surface expression of the potentiometric surface for certain periods, i.e. when flow direction is from the swallow holes to the lake. When the lake level dropped in summer 2007 a waterfall was formed at the lip of the swallow hole and the potentiometric surface must have been at least 1m below the lake level. Thus during this time the lake surface was not a surface expression of the potentiometric surface in this part of the lake basin. It is unknown whether the lake level was indicative of the potentiometric surface level in other areas of the lake basin such as its northeastern side, which potentiometric surface maps suggest is higher than the southwestern side where the swallow holes are located. In short, the surface level of White Lake may be indicative of the potentiometric surface position around the entire lake during winter months under high flow conditions. But it may be either indicative of the potentiometric surface position in none or only part of the lake basin during low flow periods where the lake is draining into the swallow hole. These scenarios could be caused by differing permeabilities in the bedrock or (more likely) in the unconsolidated deposits under and around the lake.

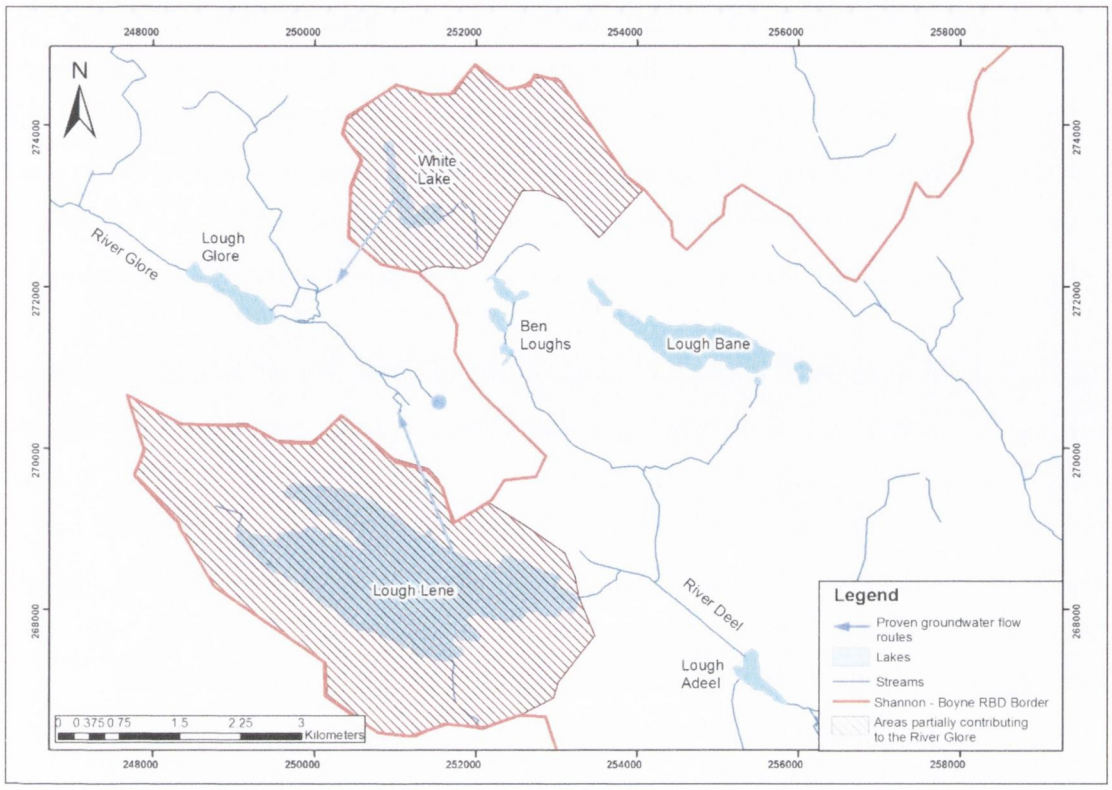

Figure 7.13 Areas proven to contribute runoff to the River Glore from outside the SHRBD (basemap data OSI 2001).

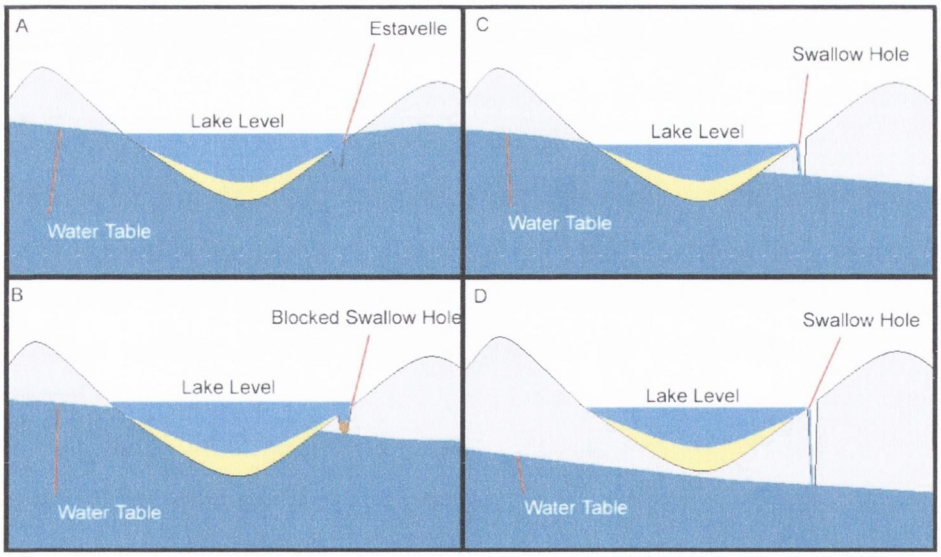

Figure 7.14 Conceptual diagrams of groundwater interaction with White Lake: a) High water level where lake level is a surface expression of the potentiometric surface at all points in its basin; b) High water level where lake level is a surface expression of the potentiometric surface in only part of its basin; c) Low water level where lake level is surface expression of potentiometric surface in part of its basin; and d) Low water level where lake level is not a surface expression of potentiometric surface.

The groundwater maps indicate that groundwater flow direction shows little seasonal variation to any great degree in the study area and changes in the potentiometric surface seem to be limited to its seasonal altitude. This is important as it means that temporal changes in contributing areas to the surface drainage system in the area may not be governed by changes in groundwater flow direction but by changes in relative hydraulic head values between the surface and groundwater systems.

The temporal dynamics of groundwater – surface water interactions vary between the study catchments. The flows recorded during the summer of 2007 were not typical of the study catchments in that this was a particularly wet year and flow did not cease from the surface channels from Lough Lene, the Ben Loughs, and Lough Bane, and Tobernacogany and Roaring Well springs as is generally the case in other years according to information gleaned from informal interviews with local people. However, the following inferences can still be drawn from the results.

In the Lough Lene catchment the proportion of flow leaving the catchment via the surface channel was greater than that leaving via the swallow holes during the winter – 2:1, In contrast, during the summer months the proportion of flow leaving the catchment via the surface channel was less than that leaving via the swallow holes (1:4). In other years flow has been known to cease in the surface channel in June, but not in the swallow holes until July/August.

In the case of the White Lake catchment, there is no evidence that discharge from this catchment occurs anywhere other than to the River Glore. During winter months discharge occurs via the Roaring Well and probably the marsh below it, and in summer months there may be seepage flow through the marsh – if discharge is occurring from this catchment at all during this time. The catchment may become isolated from the River Glore system once the surface level of White Lake falls below the intake level of the lowest swallow hole in the lake. However it not possible to determine the location of the lowest swallow hole in the lake.

Water budget results suggest that the Ben Loughs catchment is a groundwater discharge zone, probably through diffuse discharge, although it not possible to say this with certainty. It is likely, based on the potentiometric surface maps that the

location of the source of groundwater discharging into this lake does not vary seasonally.

Lough Bane may also be a groundwater discharge zone. In previous years the surface outflows from both the Ben Loughs and Lough Bane have ceased to flow by July and these catchments could recharge groundwater during such periods when they are not discharging water to the surface drainage system.

The point connections between the surface drainage and groundwater systems in the study area suggest that karstic type interactions are important, but non-karstic, i.e. diffuse groundwater – surface water interactions also occur in the area. This could mean that a dual system of groundwater – surface water interactions is in operation. Karstic type interactions may occur in the bedrock, while diffuse interactions may be confined to the unconsolidated overburden. The location of point interactions between the surface drainage and groundwater systems is closely related to places where exposed bedrock comes into contact with impermeable or low permeability deposits such as the location of the springs around the edge of the peat and gley deposits in Fore Valley and the position of swallow holes around the lakeshores of White Lake and Lough Lene. The importance of the location, type and depth of unconsolidated deposits has previously been noted in other Irish Lowland Karsts (Coxon & Drew 1998).

The nature of the interaction between the River Glore and White Lake (via the Roaring Well) and Lough Lene (via Tobernacogany) is analogous to a surface drainage network with partially contributing areas. It is difficult to establish when exactly these areas contribute, as seepage flow directly to the River Glore channel may occur at times when the spring flow connections have ceased to operate. In the case of Lough Lene it is impossible to determine which parts of the catchment are actually contributing water to the River Glore due to the existence of the surface outflow from the lake.

Overall, the surface drainage and groundwater systems in the study area are closely interconnected and could be said to be *'completely intertwined'* as per Coxon & Drew (2000, p. 82). There is evidence from the White Lake catchment, that all of the runoff generated there becomes groundwater recharge. There is evidence from the

Lough Lene catchment that close to 50% of the runoff generated there becomes groundwater recharge. There is limited evidence from the other two study lake catchments – the Ben Loughs and Lough Bane that groundwater is diffusely discharged to the surface drainage network. In the case of Lough Bane, a swallow hole may have existed in the past on the southern shore of the lake but has disappeared. There is no evidence of point recharge to Toberfaolaigh spring and the spring is probably diffusely recharged from an area outside the topographically defined catchment area of the spring. There is evidence that diffuse groundwater discharge takes place into the River Glore channel upstream of Glore Bridge. Thus, there is evidence that interactions are occurring between the surface drainage and groundwater systems in all of the study catchments.

The groundwater – surface water interactions that occur in the study area are similar to interactions described in other Irish lowland karsts such as the River Fergus catchment in County Clare and the Clare River system in County Galway (Coxon & Drew 1998, 2000) in that the close interaction of the groundwater and surface water systems is important, but difficult to quantify in terms of the spatial and temporal dynamics of the interactions. The interactions in the Westmeath Lakelands study area are different though, in that the surface catchments connected by underground flow routes are not part of one surface drainage system, and water exchange across a topographically defined regional watershed takes place.

7.3 Classification of the lakes in the study area based on their interactions with groundwater

All of the study lakes in the detailed study area are permanent lakes. However, evidence presented in this thesis suggests that there are differences between the lakes in terms of: how they interact with groundwater; their connectivity to the surface drainage system; the fluctuation of their water levels; and their similarity or dissimilarity to temporary karst lakes such as turloughs and lakes in poljes. If a gradation between lakes based on such attributes could be established then the study lakes could be conceptualised as existing along a continuum, from lakes that have much in common with temporary karstic lakes to those progressively less similar to temporary karstic type lakes. The attributes of each lake are outlined

below and a classification of the lakes based on their individual attributes is presented.

White Lake

White Lake is located in an enclosed depression, is not connected to the surface drainage system, and all discharge from the lake becomes groundwater recharge. The mean conductivity of the lake water is also high compared to the other study lakes at 503µS/cm, indicating that the lake may be receiving groundwater discharge. The lake water level had a range of just less than 2 m during the study period, although this range has reportedly been larger in other years when there was less rainfall during the summer months. Three swallow holes were identified in the catchment and a number of enclosed depressions and sub-circular lakebed features were located both around and in the lake basin. Some or all of the swallow holes in the catchment and the depressions in the lake basins could be estavelles and the lake surface may be a surface expression of the potentiometric surface, although this is difficult to prove. This lake is similar to a turlough in terms of its flooding regime, the range of fluctuation in its water level, and the swallow holes and possible estavelles located in the catchment. In effect, this lake may be considered a turlough that never empties to a degree accepted within current definitions of a turlough, which would require either total emptying of the basin or emptying except for small residual pools (Coxon 1986; 1987a). Thus White Lake is ineligible to be classified as a turlough hydrologically even though this lake has numerous turlough-like characteristics hydrologically and may contain turlough-type vegetation.

Lough Lene

Lough Lene is connected to the surface drainage system via the channel at the eastern end of the lake. The recorded difference between the maximum and minimum levels of its water surface was < 0.5 m and the recorded conductivity of the lake water measured 237 µS/cm and was lower than that of White Lake. This suggests that groundwater discharge does not constitute a high proportion of input of water into the lake or possibly that groundwater does constitute a high proportion of water in the lake but that calcium carbonate held in solution in this groundwater is precipitated out in unconsolidated sediment between the bedrock aquifer and the lakebed. The lake recharges groundwater via the three swallow holes on its northern shore and water budget results suggest that further recharge to groundwater occurs

below the surface of the lake. Thus this lake is closely linked to the groundwater system and has some similarities to temporary karst lakes, including draining via swallow holes and possible groundwater recharge below its surface level. However, it also shares attributes with non-karstic permanent lakes, such as integration with the surface drainage network, a relatively small surface water level fluctuation, and a relatively low conductivity.

Lough Bane

Lough Bane is connected to the surface drainage network and has a surface water level fluctuation similar to that of Lough Lene. The conductivity of the water in Lough Bane at 426µS/cm is almost twice that of Lough Lene and suggests that groundwater discharge makes up a significant proportion of the water in the lake or, possibly that calcium carbonate is being taken into solution from exposed limestone bedrock or rock fragments within the glacial deposits or the lakebed itself. The groundwater discharge theory is supported by water budget results which indicate that groundwater discharge may occur in this catchment. There is also map evidence from the OSI 6 inch map that a point recharge to groundwater operated here in the past (swallow hole on the 6 inch map) and an enclosed depression similar to those located near White Lake exists here also. However there is no evidence that any form of groundwater recharge occurs in this catchment at the present time. It is impossible to ascertain whether this change, if it has taken place, is due to natural or anthropogenic factors. This lake is different to Lough Lene in that it appears to be an area of groundwater discharge as opposed to an area of groundwater recharge. It is less similar to karstic type lakes in that there is no present day evidence of point interactions with the groundwater system, unless such points exist under the surface level of the lake.

The Ben Loughs

The Ben Loughs are connected to the surface drainage system and have the narrowest range of surface level fluctuation of all the study lakes. There is no evidence of past or present point connections between the lakes and the groundwater system and no evidence that the Ben Loughs recharge groundwater. On the contrary, water budget results and conductivity measurements of 495µS/cm suggest that the Ben Loughs receive groundwater discharge or again possibly that calcium carbonate is being taken into solution from exposed limestone bedrock or

rock fragments within the glacial deposits or the lakebed itself.The Ben Loughs are similar to Lough Bane in terms of their interactions with the groundwater system, except that there is no evidence of point interactions. Thus the Ben Loughs have least in common with karstic type lakes out of all the study lakes.

It is clear that the lakes in the study area differ with regard to their hydrology. They all appear to have some connection with the groundwater system, although this connection is stronger in some cases than others. Based on the attributes described above, the study lakes can be conceptualised as existing along a continuum from lakes that have much in common with temporary karstic lakes, i.e. White Lake, to those progressively less similar to temporary karstic lakes, i.e. Lough Lene and Lough Bane Finally the Ben Loughs have little in common with temporary or permanent karst lakes and are more similar to non-karstic lakes that interact diffusely with the groundwater system. Each study lake has been assigned a number (0 or 1) based on whether they are similar to a turlough or a non-karstic permanent lake in particular respects. A lake which is a turlough will have a score close to 0 and a lake at the opposite end of the continuum, i.e. a non-karstic glacial type lake will have a score of 5. This continuum is summarised in Table 7.1. Four types of lake that can be conceptualised as existing along this continuum are shown in Figure 7.15.

Turlough-like (0)					non-karstic (1)
	White Lake	Lough Lene	Lough Bane	Ben Loughs	
drains via swallow holes or estavellses at present	0	0	1	1	drains to surface drainage network at present
drained via swallow holes or estavellses in the past	0	0	0	1	no evidence of past discharge to groundwater
fills via groundwater discharge or through flow	0	0	0	0	fills via surface channel
not connected to surface drainage network	0	1	1	1	connected to surface drainage network
temporary lake	1	1	1	1	permanent lake
Total	1	2	3	4	

Table 7.1 Lake classification matrix based on degree of similarity/dissimilarity to turloughs or non-karstic permanent lakes.

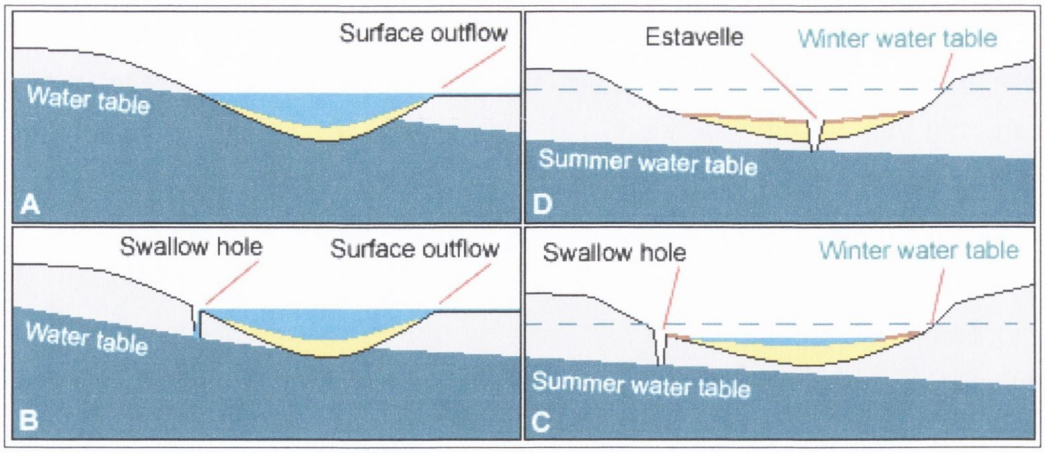

Figure 7.15 Conceptual diagrams of four lake types: a) non-karstic permanent lake where interaction with groundwater is limited to the wave-washed littoral zone; b) a surface outflow is present but the lake also drains to the groundwater system via a swallow hole; c) no surface outflow is present and the lake drains exclusively to the groundwater system, but it is not a true turlough as it never empties to the necessary degree (i.e. small residual pools) during the summer months; d) this is a turlough type temporary lake that is flooded when the watertable is high and drains completely or to the point where only small residual pools remain during summer months.

8. Discussion and Conclusions

8.1 Introduction

There is an increasing global awareness that lowland areas underlain by limestone which were not previously recognised as karst may in fact be karstified Moreover, many such areas have not been satisfactorily classified in terms of their hydrogeological characteristics. In addition, permanent lakes situated in karstic areas are poorly understood both in terms of the nature of their linkages with the groundwater system, and in terms of their classification when compared to temporary lakes in karst areas. As a result, the research hypotheses stated in the introductory chapters of this thesis were:

1) That the Meath-Westmeath study area can be classified as a lowland karst similar in its hydrological and hydrogeological characteristics to other lowland mantled karsts situated in Ireland, particularly in terms of geomorphology, recharge (inputs), flow characteristics (throughputs), and discharge (outputs).

2) That groundwater and surface water catchments in the study area are not spatially coincident, and that partially contributing catchments exist in the area where outflow destination changes under different hydraulic conditions.

3) That lakes situated in the study area can be classified along a continuum based on the characteristics of their interactions with the groundwater system.

8.2 Key research findings

8.2.1 The lowland karst of the Meath – Westmeath Lakeland region

Karstic landforms have been identified in the study area and include a small rift cave, swallow holes, springs, karren features, and enclosed depressions (possibly dolines). However, relative to other lowland karsts situated in Ireland, this is a poor assemblage of karstic landforms. For example, no caves were identified of types such as those situated in County Tipperary (Jones & Gunn 1982) and County Kerry (Gunn 1982b, 1982, 1985). Similarly, no dry valleys, as have been identified in County Roscommon by Hickey (2009), or turloughs ≥ 10 ha in extent as reported by

Coxon (1987b) in Counties Mayo, Galway, Roscommon, Sligo, Longford, Tipperary, Limerick, and Kilkenny were identified.

The results of this thesis attest that groundwater recharge in the study area is autogenic and, similar to other Irish lowland karsts, both point and diffuse recharge occur within the study area. However, as shown in this thesis, diffuse recharge appears to be the dominant recharge type, as the results identify only two locations, (specifically Lough Lene and White Lake) where point recharge occurs. These point recharge locations are both situated at the perimeter of permanent lakes. Moreover, further evidence can be gleaned from the identification of deactivated swallow holes at Lough Lene, and cartographic evidence (1st edition 6 inch map) from Lough Bane, that such lake perimeter point recharge were possibly of greater importance in the past. No sinking streams were identified in the study area. This is in contrast to other reported locations of point recharge situated in other Irish lowland karsts, for example, those identified in Counties Roscommon (Hickey 2009), Tipperary (Jones & Gunn 1982; Gunn 1984), and in the Castleisland karst in County Kerry (Gunn 1984) where point recharge from sinking streams was identified. In addition, recharge via turloughs, as described by Coxon (1987a), was not identified in the study area and no doline fields of the density recorded by Hickey (2009) in County Roscommon were identified. However, the study area does show similarities to parts of the lowland karst in Counties Clare, Galway and Mayo where point recharge to the aquifer takes place via swallow holes located at the perimeter of permanent lakes such as Lough Bunny in County Clare (Southern Water Global 1998), Lough Mask in County Mayo, and Lough Hackett in County Galway (Drew & Daly 1993). Diffuse groundwater recharge is likely to predominate in the study area (unless Toberfaolaigh is fed either by point recharge originating from outside the study area or from beneath the surface of one of the study lakes). Such diffuse groundwater recharge is similar to that described by Drew (2008) in Irish lowland karst with a mantling of till >5 m in depth.

The study area shows similarities with other areas of lowland or low relief karst in terms of recharge, in that unconsolidated mantling deposits are an important controlling factor in where, and the rate at which recharge to the aquifer occurs, such as described by Quinlan (1978). Point recharge takes place in the study area at the edge of lakes where bedrock is exposed at the wave washed littoral zone.

Such an erosion zone between unconsolidated mantling deposits and the lake sediments is described by Lee & Swancar (1997), and Harvey et al. (2005). This is also similar to the recharge described by Katz & Bullen (1996) occurring in Florida. There is also evidence of small collapse features located in the White Lake basin that are analogous to the doline forms identified by Quinlan (1978) which provide recharge pathways directly through the mantling deposits. However the study area differs from low relief karst such as the Pennyroyal (Kentucky, USA), as mapped by Currens & Ray (1998), where there are extensive doline fields providing point recharge to the aquifer. In the study area the identification of only two point recharge areas indicates that a greater proportion of the recharge to the aquifer is diffuse in origin (which would account for the lack of an identified point recharge source for Toberfaolaigh), and that this recharge is concentrated below the ground surface, possibly at or near the rockhead in the epikarst (if present) as described by Klimchouk (1995). This study has provided evidence that in glaciated lowland karsts, where a karst aquifer is mantled by low permeability deposits, wave washed littoral zones around lakes, where bedrock is exposed due to erosion as a result of wave action, may be of particular importance in the creation of pathways through mantling deposits, through which point recharge to the aquifer takes place.

Hydraulic gradients measured in the study area, of 0.01 and 0.004 are similar to those reported by Drew (2008) for other Irish lowland karsts. In addition, measured flow velocities of 71 and 137 m/h are within the range of those summarised by Drew (2008) (5 – 250 m/h) and greater than the lowest velocity flow rate recorded for the Castleisland karst in County Kerry (0.95 m/h) (Gunn 1984). Examination of the bedrock underlying the study area confirmed previous reports that primary permeability in the Derravaragh Chert is negligible and that a heterogeneous groundwater flow system is likely to operate in the area, similar to that reported for Irish Carboniferous limestones by Wright (2000), as attested by groundwater level fluctuations measured for the area from well level measurement data. Water table mapping, water trace results and groundwater level fluctuations in the study area suggest that a continuous unconfined water table may not exist in the area, and that a mixed flow regime may be operating, similar to that in the area near Ballinrobe, County Mayo (Coxon 1986). There is geophysical evidence for the presence of conduits in the study area (e.g. Brown 2002) as have been reported for other lowland karst areas of Ireland such as County Roscommon (McGrath & Drew 2002).

However, it remains unclear whether these conduits are sediment filled or not. The results of water tracing presented in this thesis show that conduit flow is likely to occur in the study area, if to a lesser extent than is the case for other areas of Irish lowland karst such as those located in east County Galway (Drew & Daly 1993) and Roscommon (Hickey 2009). The relatively low dye recovery recorded in the results of water tracing analysis from White Lake to the Roaring Well may indicate that divergent flow takes place here. Alternative flow routes for the dye that was unaccounted for may be either into the River Glore via the lower permeability deposits below the Roaring Well, into Lough Glore below the lake surface water level, or to some other unidentified destination. The Roaring Well only flows under high water conditions and may represent a divergence of groundwater flow under high flow conditions similar to that recorded from the Badger Pot to the Shannon Pot in the Cuilcagh upland karst identified by Gunn (1996).

As shown in this thesis, the study area is not underlain by an active cave system. Hydraulic gradients measured in the study area (0.01 – 0.004) are in line with values from other low relief karsts, for example hydraulic gradients of 0.01 - 0.001 were measured in Kentucky (Lloyd & Lyke 1995). Groundwater flow velocities in the study area (71 - 137 m/h) are also within ranges reported elsewhere and are considerably higher than those recorded in the channel component of the English Chalk aquifer of 0.216 m/h (Worthington et al. 2000). Primary permeability in the bedrock aquifer of the study area is negligible, but continuously recorded groundwater levels (automatic recorder data), show variations inter-borehole, particularly in the reaction of their water levels to inputs, with some exhibiting a relatively quick and high magnitude response and some displaying a more buffered response. This is evidence of hydraulic heterogeneity and is comparable to that reported for a Floridian karst aquifer by Stewart & Wood (1984). In the absence of significant primary storage in the aquifer, such localised flow buffering may be caused by mantling deposits which attenuate recharge (Worthington & Smart 2004) or by variations in the hydraulic conductivity of the aquifer, caused by the localised relative magnitude of secondary or tertiary permeability (Worthington 2003). In addition to the fact that most of the area is mantled by glacial deposits of varying permeability, contradictions exist between groundwater maps constructed from the study wells and water tracing results from the study area. This indicates that it may be advantageous to conceptualise the groundwater system in some lowland mantled

karsts as comprising of two distinct parts: 1) an overlying Darcian type aquifer developed in the mantling deposits; and 2) a karst aquifer receiving point recharge through apertures in the mantling deposits and diffuse seepage recharge via the mantling deposits. In such a model, it is possible that the karst aquifer may be confined in places by low permeability deposits, such as clays or silts, and groundwater flow in such areas would be independent of and possibly contradictory to flow in the unconfined mantling deposit based aquifer.

The presence of the three springs: Tobernacogany; Toberfaolaigh; and the Roaring Well with mean recorded flows of respectively, 60, 143, and 12 l/s (note that measurements for Roaring Well were made during the water tracing experiment only), supports the idea that karstic drainage occurs in the study area and that the high peak flow volumes recorded for Tobernacogany and Toberfaolaigh are likely to be in the top 10% of Irish springs in terms of mean flow volume (Drew & Chance 2007). The spring flow volumes and low flow to high flow ratios measured in this study are inline with previously measured spring discharges in lowland karsts, but, on a global basis, are towards the lower end of internationally reported ranges. For example, spring discharges of 38,000 l/s have been measured at springs in a low relief karst in Kentucky (Lloyde & Lyke 1995). These springs can be classified as aggraded dammed springs (Smart & Worthington 2004b), the locations of which are controlled by the presence and position of low permeability glacial and peat deposits. The springs differ from the majority (70%) of Irish karst springs, as surveyed by Drew & Chance (2007), as their conductivity values increase or at least do not drop as discharge increases. In the case of Tobernacogany, this stability may result from the fact that this spring is predominantly fed by lake water. However, in the case of Toberfaolaigh, the reason for this stability is less clear, although a more a continuous recording type sampling strategy may identify an as yet unidentified piston effect in operation at this spring such as that shown to occur in the Lost River catchment, southern Indiana by Lakey & Krothe (1996). The Roaring Well may be a periodic overflow spring connected to a more permanent groundwater discharge area located in the glacial and peat deposits in the valley below it such as reported by Smart (1983) in relation to an alpine karst spring in Canada. Groundwater discharge may occur diffusely into the peaty area situated between the north bank of the River Glore and the Roaring Well and / or into the streambed of the River Glore

in the Fore Valley, similarly to the groundwater to stream discharge reported by Drew & Daly (1993) in the western Irish lowland karst of Counties Clare and Mayo.

This thesis presents evidence that suggests that arterial drainage works undertaken in the study area have caused the karstic drainage system to become partially deactivated. It is likely that this deactivation has reduced the proportion of water becoming point recharge to groundwater, and it may, particularly in the cases of Lough Lene and Lough Bane, have reduced the amount of water that is transferred between topographically defined catchments via the groundwater system. This is similar to the modification of the surface drainage network mapped by Coxon & Drew (1986) which facilitated the draining of numerous permanent lakes and caused the cessation of seasonal flooding of many turloughs in Counties Galway and Mayo.

The results of this research demonstrate that a lowland karst broadly similar to those located in Counties Roscommon, Galway, and Mayo exists in the Meath-Westmeath Lakeland region. Previous research had identified only a few isolated examples of karstic phenomena in the study area. This research has added substantially to these previous and reported findings through the identification of karstic landforms and processes in all but one of the study catchments (the Ben Loughs). However, the relatively small number and range of karst landform types identified in the study area, compared to other Irish lowland karsts, suggests that the overall degree of karstification may be lower in this area compared to parts of Counties Roscommon, Mayo, Galway, and Clare. Notably, an important distinction between the Meath-Westmeath Lakeland region and other Irish lowland karsts is that, in the study area, identified point recharge to the karst aquifer occurs only via swallow holes located at the perimeters of permanent lakes as opposed to sinking streams or temporary lakes (turloughs). This difference in recharge characteristics may reflect a different type, as well as a different degree of karstification in the study area.

The geomorphology and hydrology of the study area raise questions regarding the history of this landscape and the processes that led to its present appearance. The bedrock topography of the area is characterised by isolated hills and valleys in-filled to varying depths with glacial and fluvio-glacial deposits (Drew 2002). Morphological evidence, presented in this study, suggests that White Lake may be held in a compound doline feature and that doline forming processes continue to operate

there. Straight line flow velocities derived from water trace results suggest that conduit groundwater flow occurs through the limestone hills in the area. There is also geophysical evidence (Brown 2002) that a bedrock conduit (probably in-filled with glacial or fluvio-glacial material) exists in Fore Valley. Present day base levels are provided by glacial deposits but it is possible that prior to glacial modification, that this area may have been similar in morphology and hydrology to a cone karst fengcong type landscape as described by Daoxian (2004). The study area is more likely to be the remains of a fengcong rather than a fenglin type landscape due to the fact that there is no evidence of pre-glacial alluvial deposits in the valleys as found in fenglin landscapes (Williams 1987). Moreover, if, as has been hypothesised, a conduit exists in the Fore Valley, this would suggest that caves may have developed between hills as is common in fengcong instead of being largely confined to within the hills above the level of alluvial deposits as is common in fenglin karst (Williams 1987; Daoxian 2004). It is also possible that the study area contains the remains of a fengcong type landscape that was prevented by the effects of glaciations since the tertiary (which may have interrupted such a process) from developing into a fenglin type landscape in a manner similar to that described by Waltham (2008, 2010). It is difficult, however, to determine how steep the bedrock topography is in places due to the presence of till around them, such as Knockeyon Hill at the eastern end of Lough Derravaragh (Appendix E plate 61) but the only instances of near-vertical sided hills within the study area (excepting a 5 m high cliff near Lough Bane) are situated in Fore Valley, an area that contains an abbey and was once surrounded by town walls, the remains of which can be identified as Derravaragh Chert. It is possible that the vertical bedrock exposures in Fore may be the remains of Medieval quarries from where this stone was taken. However, there are other examples of steep-sided hills in the area, such as the Rock of Curry (Drew 2002), approximately 8 km northwest of Fore Village. These hills are similar in their morphology to the steep-sided limestone hills known as The Doons in County Leitrim, which have been interpreted as the remains of tower karst landscapes (Herries Davies & Stephens 1978; Drew & Jones 2000). In any case, hill slopes in both fenglin and fengcong can vary from steep-sided to conical (Sweeting 1995). In order to answer this question, further research into the geomorphology and sedimentology of the bedrock topography, the existence of sediment filled karst conduits, and unconsolidated valley deposits in the study area is required.

8.2.2 Groundwater – surface water interactions

Results attest that the groundwater and surface water drainage systems operating in the study area are closely interlinked and water is exchanged between the systems via both point and (possibly) diffuse connections. Thus, the groundwater and surface networks here can be considered to be completely intertwined as described by Coxon & Drew (1998). Point interconnections and a high degree of interconnectivity between the surface drainage network and groundwater in Irish lowland karsts are known to occur in areas such as east County Galway (Drew & Daly 1993), County Mayo (Coxon 1986), County Clare (Coxon & Drew 2000), County Roscommon (Hickey 2009), County Tipperary (Jones & Gunn 1982), and County Kerry (Gunn 1984).

Water tracing results from this study indicate that discrete surface catchments are connected via groundwater flow paths and that the topographic catchment boundaries in the study area do not correspond to the groundwater catchment divides, i.e. they are not spatially coincident. The Lough Lene and White Lake catchments have been shown to contribute water to surface drainage systems outside their own topographically delineated catchments. A greater proportion of the possible contributory area for Toberfaolaigh spring suggested by this study is located in the topographically delineated River Boyne catchment as opposed to the topographic River Shannon catchment and suggests that diffuse recharge from outside the topographic catchment is being transferred to the Tobefaolaigh spring via the karst aquifer. A similar contributory area was mapped in County Galway by Drew & Daly (1993) where a contributory area for the Aucloggeen spring (which flows into Lough Corrib) was shown to be located in part of the Clare River system situated to the east (which also, but separately, flows into Lough Corrib).

Point groundwater recharge from the swallow holes at Lough Lene and White Lake ceases periodically under low flow conditions and, in this sense, these catchments are similar to the partially contributing catchments identified in Counties Galway and Clare by Coxon & Drew (2000). Under high flow conditions water flows out of the Lough Lene catchment via a surface channel, and via swallow holes to Tobernacogany. In contrast, under low flow conditions, flow ceases in the surface channel but continues (for a time at least) into the swallow holes. This characteristic of the drainage system of an anthropogenically modified catchment to revert to

purely karstic type (sub-surface) drainage under low flow conditions is comparable to drainage systems identified in the west of Ireland lowland karst by Coxon & Drew (1986, 1998, 2000).

The surface water network of the River Fergus in County Clare has been shown to be bypassed by karstic flowpaths linking upper and lower reaches of the stream network in the catchment (Coxon & Drew 2000). The results of this study have not identified this type of surface network bypass in the study area. However, this research has shown that partially contributing areas and divergence between groundwater and topographically delineated surface water catchment boundaries are important in the Meath-Westmeath Lakeland region, in a similar manner to other lowland Irish karst areas.

8.2.3 Interaction of the study lakes with groundwater and classification along a continuum based on their interactions with the groundwater system.

All of the study lakes are likely to interact with the groundwater system to some degree. Although the lakes: Lough Lene; White Lake; the Ben Loughs; and Lough Bane were all found to be different in the characteristics of their interactions with the groundwater system.

In terms of its hydrology, White Lake shares a number of characteristics with turloughs as described by Coxon (1986; 1987a) – a relatively wide range of seasonal water level fluctuation, draining exclusively to the groundwater system, and is possibly a surface expression of the water table for at least part of the year. Lough Lene also drains to the groundwater system, but shows a smaller range of seasonal water level fluctuation and also drains via the surface drainage network. Lough Bane may in the past have drained via the groundwater system by means of a now inactive swallow hole, and it is unclear as to whether and to what degree it is still connected to the groundwater system. Of the study lakes, the Ben Loughs exhibited the least evidence to suggest that they are in hydraulic connectivity with the groundwater system. The lakes in the study area may be surface expressions of the potentiometric surface at least in part of their basins. It is possible, although not proven, that Lough Lene and White Lake are two-way points of interconnection between the surface and groundwater systems. Moreover, there is no evidence that any of the study lakes ever empty episodically in the manner of Lough Funshinagh,

situated in County Roscommon or Lough Na Súil, situated in County Sligo (Coleman 1965; Drew & Burke 1996).

It has been noted from previous research that there are other examples of temporary (Coxon 1986, 1987a, 1987b), semi-permanent (Coleman 1965; Drew & Burke 1996) and permanent lakes (Drew & Daly 1993; Southern Water Global 1998; Raghenborn-Tough et al. 1999), situated on Irish karsts that differ to each other in terms of their hydrology, specifically in the nature of their interactions with the groundwater system. Hydrologically, White Lake has similarities to Lough Bunny in County Clare (Ragenborn-Tough et al. 1999), Caherglassaun Lough, Lough Coole, Lough Coy and Lough Hackett in County Galway (Drew & Daly 1993), in that it is a permanent lake fed and drained via the groundwater system. However, in contrast to the basin of White Lake which is characterised by isolated limestone hills that pierce a blanket of glacial till and lacustrine marl deposits, the area around Lough Bunny is characterised by exposed limestone bedrock and limestone pavement (Ragenborn-Tough et al. 1999), Caherglassaun Lough is affected by tidal fluctuations (i.e. it experiences 2 fill / drain cycles per day) under low water conditions, and Lough Coole has been shown to be part of a sinking and rising river network (Drew & Daly 1993). Lough Mask in County Mayo also drains entirely via the groundwater system under low flow conditions (and previously did so under all circumstances until the cong canal was constructed), but is much larger than any of the above lakes and has large surface inflows of water (Drew 1987; Drew & Daly 1993). Aside from morphogenic considerations, these examples emphasise the variations that have been recorded in the hydrology of permanent karst lakes in Ireland.

Questions remain as to the specific formative processes of turloughs (Coxon 1986; 1987a), and to distinctions between compound dolines (uvalas), poljes, and other doline forms – especially in the smaller size range (Nicod 2003). A classification based on lake hydrology would not be directly concerned with such morphological or morphogenetic issues in so far as they do not affect the lake hydrology. For example, poljes and turloughs are thought to have been formed by different processes – karstic or glacio-karstic in the case of turloughs (Coxon 1986; 1987a), while bedrock structure is thought to be more important in the formation of most polje types (with the exception of baselevel poljes) (Gams 1973, 1978). Until

recently, temporary karst lakes in poljes have been classified separately to turloughs for a number of reasons including: poljes are thought to be larger; flood for longer; to much greater depths; and commonly have rivers running through them (Sweeting 1972; Coxon 1986, 1987a). However, hydrological and ecological similarities have been drawn by Sheehy-Skeffington & Scott (2008) between turloughs and temporary karst lakes held in poljes in the Upper Pivka, Slovenia which were examined by Ravbar & Šebela (2004). If poljes and turloughs are fundamentally different in terms of their morphogenesis, then another means of classifying the lakes held in their basins based solely on their hydrology, would allow comparison to other temporary and permanent lakes on karst.

The classification of lakes in karst areas based on the characteristics of their interaction with the groundwater system has been detailed in section 7.3, i.e. lakes are assigned numbers (0 or 1) based on whether they are similar to turloughs or non-karstic permanent lakes in particular respects: if they are permanent or temporary; if point interaction with the groundwater system takes place; and whether they are connected to the surface drainage system. A turlough / polje type lake will have a score close to 0 and a lake at the opposite end of the spectrum, i.e. a non-karstic glacial lake will have a higher score. This approach offers a means of classifying lakes based on their hydrology and is separate to, but informed by, their geomorphology and formative processes. Such a technique mirrors that put forward by surface hydrologists for general lake types (e.g. simple input / output type lake models proposed by Hutchinson (1957) Bogoslovsky (1966) through to more complex but essentially similar models using a tri-linear approach as suggested by Lent et al. (1997)). This approach allows temporary and karst lakes such as turloughs and lakes held in poljes to be classified alongside permanent lakes situated in karst areas along a continuum based on their interactions with the groundwater system.

Subdivisions within classes could be made based on the degree of connectivity to the karst drainage system, i.e. whether the lake is connected to the aquifer predominantly via the primary, secondary or tertiary permeability component of the groundwater system. This subdivision would be informed by the geomorphology and suspected formative processes of the lake in question. The concepts of a doline spectrum as described by Gunn (2006) with turloughs and tiankengs at opposite

ends, or of a wet-dry continuum classification of temporary lakes as described by Visser et al. (2006) could also be used to inform such a subdivision. For example, a lake held in a collapse doline could be considered 'more karstic' in the classification than a lake held in a basin partly composed of bedrock and partly composed of unconsolidated deposits. Turloughs containing marl deposits were considered by Coxon (1986, 1987a) to have held permanent lakes in the past and it has been suggested by Waltham (2004) that turloughs are immature polje forms. It is possible that semi-permanent lakes such as Lough Na Súil, Lough Funshinagh, and permanent lakes such as Lough Mask, Lough Coole, Lough Coy, Lough Hackett and White Lake are immature turloughs or polje type landforms. The results of this study also provide evidence of collapse in low permeability lake sediments (collapse features in the White Lake basin) which may represent evidence of ongoing doline development in this basin. It is also likely that lakes which currently have little or no identifiable interconnectivity with the groundwater system may previously have had point connections with the groundwater system (such as the possible swallow hole at Lough Bane) which have now ceased to function as a result either of anthropogenic modifications (i.e. drainage works, water extractions) or sedimentation of lake basins, particularly if lakes are thought of as ephemeral landforms which inevitably cease to function/exist by infilling. On this basis, there must be a temporal dynamism to any classification of karst lakes with such lakes conceptualised as moving progressively closer to, or farther away from, the karst lake type with the progression of time.

Using this classification approach, the lakes in the study area can be compared to other karst lakes ranging from temporary turloughs such as Fardrum and Rooskey turloughs in County Fermanagh (Fogg & Kelly 1995; Kelly et al. 2002; Gunn 2003) or Turloughmore in County Galway (Coxon 1986), (and including turloughs outside Ireland such as the Welsh example described by Hardwick & Gunn (1995)) and polje type lakes, to permanent lakes, likely to be held, or certainly held, in enclosed depressions in the bedrock such as Lough Bunny County Clare (Ragenborn-Tough et al. 1999), Lough Mask County Mayo (Drew 1987). Lake Barco in Florida investigated by Katz & Bullen (1996) and Lowry (Sand Hill) Lake also in Florida (Motz et al. 2001) would be classified as 'more karstic' than the Ben Loughs in the proposed system as there is evidence that these lakes provide groundwater recharge via the mantling deposits of the Upper Floridian aquifer, but they would be

classified as 'less karstic' than Lough Bane as there is historical cartographic evidence that Lough Bane provided point recharge to groundwater in the past and may still do so below the lake surface level. Prespa lake, a karst lake situated in the mountains between Albania and the FYR of Macedonia would be classified as 'more karstic' than Lough Lene because, while it drains via swallow holes in a similar manner to Lough Lene, water tracing experiments indicated a straight line velocity of 2.9 km/h between swallow holes at this lake and Tushemisht spring (Amataj et al. 2007) which greatly exceeds 71 m/h, as was measured between Lough Lene and Tobernacogany. A conceptual diagram illustrating this classification system as applied to a group of Irish turloughs and permanent lakes on limestone in Ireland (all with differing hydrological characteristics) is presented in Figure 8.1.

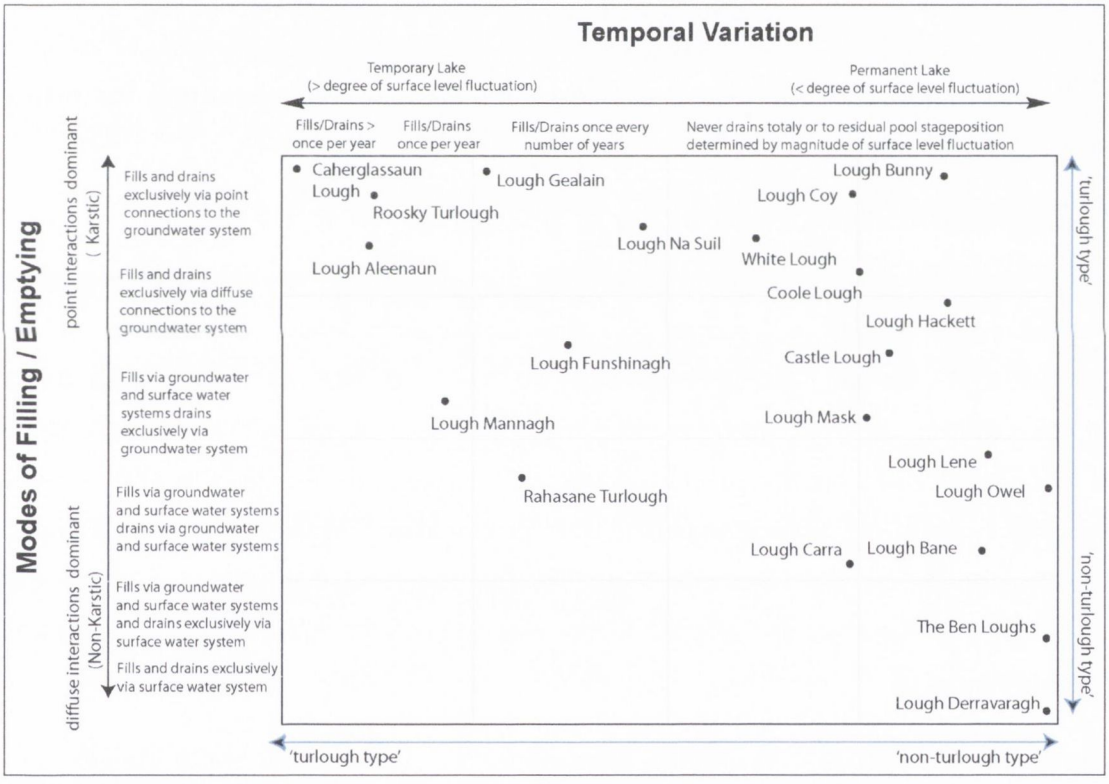

Figure 8.1 Lake classification system applied to turloughs and lakes underlain by limestone in Ireland. Lakes near the bottom right of the diagram are permanent lakes with little or no interaction with the groundwater systems and are considered non-karst. Conversely, lakes near the top left of the diagram are temporary lakes that have a high degree of interconnectivity with the groundwater system via point pathways (springs, swallow holes and estavelles). Turlough/lake positions within the diagram apart from: Lough Lene; Lough Bane; The Ben Loughs; and White Lake, are based on the following sources: Westmeath County Council (2005) (Lough Derravaragh and

Lough Owel); Coxon (1986), Drew & Daly (1993) (Lough Mask, Lough Hackett, Lough Coy, Castle Lough, Coole Lough, Lough Aleenaun, Lough Mannagh, Caherglassaun Lough, and Rahasane Turlough); Drew & Burke (1996) (Lough Funshinagh, Lough Na Súil); Ragenborn-Tough et al. (1999) (Lough Bunny); D'Arcy 1992 (Lough Gealain); Fogg & Kelly (1995), Kelly et al. (2002) and Gunn (2003) (Roosky Turlough).

This classification highlights the fact that in terms of their hydrology, turloughs and other temporary karst lakes do not exist in complete separation from semi-permanent or permanent lakes. The present delineation between turloughs, lakes held in poljes and other non-turlough, permanent karst lakes is an inadequate distinction and an intermediate category or categories should exist that takes account of natural gradations between lake types.

8.3 Successes and limitations of the study and recommendations for future work

8.3.1 Successes of the study

This study sought to measure surface hydrological and groundwater hydrogeological variables concurrently in order to draw conclusions about the nature of the groundwater system, surface drainage system, and interactions between these same systems in the study area. Although this was not without its problems (described in section 8.3.2), this approach was broadly successful and allowed conclusions to be drawn regarding the groundwater system, surface drainage system, and interactions between them. This approach highlighted the importance of measuring surface water variables when investigating the groundwater system and visa versa.

The water budget approach in conjunction with topographic mapping and groundwater maps was successful in calculating the recharge area required to feed springs in the study area and the possible or likely location of such areas of recharge.

The approach of combining historic map data from 6 inch and 25 inch maps with modern spatial data in a GIS was successful and would be of benefit to future studies of this type. Used carefully, paying attention to correct georeferencing,

datum changes, and dates of map survey, such an approach can be used to quantify anthropogenic changes to drainage systems in terms of channel modifications and changes in lake storage. Such an approach is particularly useful for the Island of Ireland as Ireland was accurately surveyed at an early date (surveying for the 1st edition of the 6 inch map was undertaken between 1837 - 1842) and there are few areas outside mountainous regions on the island that have not experienced modifications to their surface drainage networks since that time.

The GIS based combination of georeferenced spring location data from the 1st edition 6 inch map with subsoil data and the interpolated groundwater level data was successful and emphasises the importance of a holistic approach to studies where many data sets can be brought together and analysed side by side to explain environmental phenomena.

8.3.2 Limitations of the study

Assembling the groundwater monitoring network took much longer than expected due to the relatively low number of wells in the area (most of the locals do not use wells as, for many years, mains water has been readily available in the area). This limited the time remaining in which to carry out the concurrent groundwater and surface water measurement programme and it was not possible to carry this measurement programme on for one full year as had originally been intended. This obviously limits the range of conclusions that can be drawn from the study.

The study was limited by the lack of availability of automatic continuous surface and groundwater level recorders. Had such recorders been available, groundwater and surface water level data with a higher temporal resolution would have been recorded, removing ambiguities that result from data sampled at point time intervals.

The water budget results were valuable in estimating net groundwater contribution to/from individual catchments but the refusal of the County Meath and County Westmeath County Councils to release detailed abstraction information for these lakes creates a degree of doubt as to the veracity of the monthly mean abstraction volumes that were (eventually) obtained. However, the reticence of the County Councils to release more detailed (i.e. daily) water abstraction data may be intended to mask periods (instances of a day or a number of days) where water extractions

were above their licensed limits and that the overall monthly figures may in fact be accurate.

8.3.3 Recommendations for future work

There is clear scope for further work investigating the degree and characteristics of karstification in the Carboniferous limestone lowlands of Ireland, and particularly into how drainage schemes or other anthropogenic modifications (e.g. drainage works, water extractions) may have deactivated karstic drainage networks in parts of Ireland. Detailed research into the pre-Quaternary history of karstification in Ireland is needed both in terms of the extent and degree of karstification and dating of karst features.

Further research is also required to investigate the extent of groundwater - surface water interactions in Ireland. Such research would include an investigation of the effects of unconsolidated Quaternary deposits on groundwater – surface water interactions and the seasonal dynamics of such interactions. There is also a need for long-term studies which would record the responses of groundwater – surface water interactions in both relatively wet and relatively dry years.

Additional research is required to fully understand groundwater flow in both the bedrock and overlying unconsolidated deposits, where present, around permanent lakes in limestone areas in Ireland and further afield. Further investigation of groundwater interactions with lakes through lakebeds below lake surface levels is also required both in Ireland and internationally. This would facilitate the satisfactory classification of lakes based on the nature of their interactions with karstic groundwater systems and would include investigations on the magnitude of interaction, where in lake beds interactions with karstic drainage systems occur, and the seasonal dynamics of such interactions.

Quantifying lake - groundwater interactions that take place below the surface of the lake is difficult and, in the case of this study, the results of water budget analysis were the only means used to estimate this variable. If undertaking such a study in the future, it would be advisable to position nests of drive-in piezometers at various points around a lake in order to measure the hydraulic gradient present in unconsolidated deposits around a lake basin. Evidence for the presence or location

of point groundwater discharge into a lake might be obtained by photographing the lake surface with an infrared camera on either cold or hot days to test whether groundwater discharge to the lake can be identified by plumes of either relatively warm (on cold days) or relatively cold (on hot days) water on the lake surface.

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Appendix A Secondary Data Sets

The following is a list of the secondary data sources identified during the desk study, with a description of the nature and limitations of the data that were utilised from these sources.

Soils and Geology

Bedrock Geology

The GSI 1:100,000 geological maps. The relevant maps and the accompanying interpretative guides from this series were produced in the early 2000s and offer the most up to date geological knowledge regarding the study area. The spatial extent of the Derravaragh Chert and all the mapped fault lines in and around the study area were taken from this data set. The author's estimate that the maps are probably only 30 % correct overall, as they can only be verified where boreholes have been drilled or where exposures exist (this accuracy level may be higher in the study area due to the large number of exposures on hill slopes in the area). These maps are still however the best source of information about the structural geological framework that underlies the study area.

GSI Open Source Files

This database includes Land Commission borehole locations – many of which are only located by townland and thus not of high enough spatial resolution for use in this study. This database also contains reports from mineral exploration companies. These reports contain little in the way of groundwater data, but geological maps containing lineament features were produced for the study in the 1970s - 1980s. It is not known how these features were identified and mapped, thus this data must also be used with extreme caution. Few of the linear features drawn on these maps feature in the GSI 1:100,000 geology data set.

Lithology

The accompanying guides to the 1:100,000 GSI geological maps provide the best source of information about the lithology of the study area. However, due to the relatively small scale of the maps many lithologies are included and as a result, the information listed about many of them (Including the Derravaragh Chert) is limited.

Geomorphology

Relevant academic papers relating to the geomorphological history of the study area were studied. These papers are referenced in the main text of the thesis in the appropriate section. Examples of these papers include; 'The bathymetry and origin of the larger lakes of Ireland' (Charlesworth 1963); 'Directions of ice flow during the last glaciation in Counties Meath, Westmeath and Cavan' (Meehan 1999); and 'Landforms and hydrology of the County Westmeath Lakeland area' (Drew 2002).

Soil maps

The soils of Meath and Westmeath were mapped in detail by An Foras Talúantais (The Agricultural Institute). Soils were mapped as soil series and as soil complexes where two or more soil series existed side by side in an area too small to be individually represented on the published soil maps. These maps can be used very effectively to identify bogs, bedrock outcrops, and differing glacial deposits.

Subsoil maps

These maps were produced by Teagasc for the entire Republic using a combination of remote sensing, GIS, and field-based techniques. They can be used to identify areas where changes in glacial and fluvio-glacial deposits lead to changing hydraulic properties in the unconsolidated substrate such as sand and gravel deposits (relatively high permeability) or marls and peats (relatively low permeabilities). They may also be used to identify bedrock outcrops and areas where enclosed depressions in the bedrock may exist in the study area. Due to the fact that these maps were produced largely be remotely sensed imagery, it is important to conduct ground-truthing when basing inferences on data drawn from them.

Topography

Topographical data for the study area was obtained from the OSI. This data was supplied in ArcGIS Shapefile format in contours of 10 m intervals. Additional topographical data was obtained from spot heights and benchmarks contained in the 6 inch and 25 inch maps. This data was converted to the modern Ordnance Datum and was combined with the modern OSI topography data to form a third, more detailed topographical data set. It was necessary to augment the modern

topographical information thus, due to the fact that the 10 m contour interval was too great in places to accurately delineate topographically defined catchments.

Precipitation

Precipitation data

Precipitation data was obtained from Met Éireann. This data was provided in the format of a long term annual average for the period 1961 - 1990 (30 years) for the weather station at Mullingar. Data was also obtained in monthly totals from the weather station at Mullingar to examine precipitation patterns in the preceding period to when the surface discharge measurements for this study were taken. In addition, the EPA has estimated 30 year average precipitation values for the catchments of Loughs Owel, Derravaragh, Lene, and Bane. These figures are interpolated from relatively distant rain gauges and so may not be highly reliable but may be used to infer the general pattern of precipitation in the study area.

Groundwater

Aquifer charactristics

The national draft aquifer map was produced by the GSI and is, as its name implies, a draft map. It is based on information about bedrock and groundwater that was known before the Groundwater Protection Schemes (GWPS) were begun, and cannot be used to infer anything but the broadest of conclusions about the nature of groundwater characteristics in an area. The groundwater flow regime of the large study area was established from the data contained in this map. For parts of the country where GWPSs have not been carried out though (Including Counties Meath and Westmeath), this is be best available synthesis of current information and as such cannot be completely discounted.

GSI Karst data base

The data contained in this resource have been compiled by the GSI from various sources including field studies, 6 inch maps, GWPS, well drillers, and consultants reports. The existence of many of the features contained in it has not been validated and it cannot be viewed as an exhaustive list of Ireland's surface karstic features. Never the less, it is an important starting point in compiling an inventory of karstic features located in the study area. A number of springs and swallow holes were

located through this data base. There was also some time wasted trying to identify features contained in the data base in the field of which no trace could be found. The data collected in the present study have been given to the GSI for inclusion in the Karst database.

Surface Hydrology

OSI maps and data sets

Drainage network spatial extent data (OSI 6 inch, 25 inch, and 1:50,000 maps)

1 mile : 6 inch maps (1 :10560).
The information for this series of maps was first surveyed in the period 1829 - 1842. They are extremely detailed, and are an excellent source of information relating to the extent of surface drainage networks and surface water bodies which were surveyed very accurately. This series of maps was produced before many drainage schemes were carried out in the 1800s and are very useful in mapping changes since the 1830s. As lakeshores were also accurately surveyed, changes in the surface area of lakes may also be quantified thus indicating where the drainage of a particular area may have changed during the same time period. The study area was surveyed during 1837 for the first edition 6 inch map.

25 inch maps.
These maps were produced from surveys carried out during the period 1887 - 1913 on the same base triangulation as the 6 inch maps. They provide similar data as the 6 inch maps, for a later period.

1:50,000 Digital Data.
The OSI 1:50,000 (2001)data is supplied in ArcGIS Shapefile format using the Irish National Grid as its co-ordinate system. The surface drainage network mapping carried out for this project was carried out in a GIS environment using ArcGIS 9.1 using the OSI 1:50,000 data as a base. Two 1:50,000 data sets were used; 1) 1:50,000 vector topographic data in shapefile format with 10 m contour intervals (described above), and 2) 1:50,000 vector line data in shapefile format containing all linework used in the production of the 1:50,000 discovery series maps. This data provided the most accurate delineation of modern lakeshores and surface drainage channels.

Drainage channels and lakes from the OSI 1st edition 6 inch maps (1837)
Drainage channels and lakes from the OSI 25 inch maps (1889 - 1908)
Drainage channels and lakes from the OSI 1:50,000 maps (2001)

OSI aerial photography (2004)

Lake	Date of survey	Date of survey
	1st edition 6 inch map	25 inch map
Lough Owel	31/March/1837	21/November/1889
Lough Derravaragh	No date on map	11/July/1908
Lough Lene	10/May/1837	25/September/1908
Lough Bane	No date on map	13/July/1908
The Ben Loughs	No date on map	9/July/1908
White Lake	No date on map	6/July/1908
Lough Glore	No date on map	23/June/1908
Lough Iron	No date on map	8/August/1908

6 inch and 25 inch map lake survey dates.

Royal Canal Information

The main feeder channel for the Royal Canal extracts water from Lough Owel via a man-made channel at the southeastern end of the lake. The Inland Waterways Association of Ireland provided information on the construction of the canal and thus the construction of this feeder channel. The flow in this channel is controlled by means of a sluice at the edge of the lake. No information on if or when this sluice is adjusted could be obtained.

Drainage commissioner's reports

Drainage Commissioner Reports. The OPW maintains a large library including historic documents from both the OPW and the Land Commissioners. Amongst these are the Reports of the Drainage commissioners from the 1800s relating to drainage schemes located in the large study area. The material contained in these reports includes planned drainage works, progress reports from works underway, completion reports, and financial accounts of works. This documentary record

appears to be incomplete and it was difficult to ascertain exactly which schemes were carried out from those that were not, from the proposal documents. As a result, only documents relating to the completion of works can be in used for the purpose of compiling evidence of drainage projects. In a number of cases, field investigations and OSI map analysis may show evidence that some proposed drainage projects were indeed carried out. However, even if it may be substantiated that at least part of a drainage project was completed this does not mean that the project was carried out in entirety and so this information must be used with caution.

GSI Karst data base

The Information contained in the GSI karst data base is relevant to the surface hydrology of the study area as well as the groundwater system. The usefulness and problems associated with the use of information from this data base is outlined above.

OPW Hydrometric Data

The OPW maintains a network of hydrometric recording stations on rivers and lakes in Ireland including some that are located in the large study area. These stations record lake surface levels and stream stage, from which surface discharge volumes are estimated. Many of the stations are now non operational though, and of those stations still in operation, a distinction exists between those which automatically record data and those with staff gauges, for which only intermittently recorded data is available. These stations are located on the River Inny and the River Deel and are thus limited in their usefulness for this study.

Water quality data

The EPA monitors water quality at a number of sites in the study area on an ongoing basis. This data includes lake and river water quality measurements for Loughs Owel, Derravaragh, Lene, Bane, and White (but not the Ben Loughs) and some of the streams included in the large study area. The EPA also monitors groundwater quality but as only one monitoring site exists within the initial study area, this is of little value for this study. Another issue regarding this data is its temporal resolution. Data is recorded at these sites infrequently and as such a comprehensive record of water quality for the surface drainage network in the study area does not exist.

Water extraction data

Three of the lakes in the initial study area are used for public water supply. Westmeath County Council extracts water from Loughs Owel and Lene, while Meath County Council extracts water from Lough Bane. The County Councils have supplied average extraction figures for the lakes. This data is supplied in the form of average extractions for three month (quarterly) periods. Due to this fact, it was impossible to verify the exact extraction figures for the lakes during the period that the surface discharge measurements were carried out and averages had to be used. The resultant magnitude of error between the average daily extraction and the actual daily extraction is impossible to quantify.

RBD Boundaries

As the study area straddles the boundary between the SHRBD and the ERBD, it was nessesary to obtain the officially mapped boundary delineating them. This data was important in investigating the differences that exist in the study area between the implied surface drainage pattern as officially mapped and the actually existing drainage pattern from the fieldwork programme from this thesis.

Appendix B Mapping and GIS techniques

Software and base map data

This project necessitated a large amount of mapping and spatial data analyses. The spatial data pertaining to this project was stored, managed, and analysed in a GIS environment. Specifically, the ESRI ArcGIS 9.1 programme was utilised. All data sets were stored and mapped with reference to the Irish National Grid for which the OSI 1:50,000 digital elevation and linework vector data (2001) was used as a base map.

Integration of spatial data sets and maps

Data sets that were obtained pre-referenced to the Irish National Grid (ING) were; GSI 1:100,000 bedrock geology data, GSI aquifer data, and Teagasc sub-soil data. Map and spatial data that was not pre-referenced to the ING were; the 6 inch maps, 25 inch maps, RBD boundary maps, and OSI aerial photographs. These maps and images were converted to .TIFF files and imported into ArcGIS for Geo-rectification. The 6 inch and 25 inch maps were geo-referenced using carefully selected control points such as the location of buildings, antiquities, and such features as road intersections (where satisfied that no or anegligible degree of road realignment had taken place between the production of these maps and the 1:50,000 data). Aerial photographs of parts of the study area were geo-referenced using control points in the 1:50,000 vector data set. To accurately map the RBD boundary, an image of the boundary and the surface drainage network in the study area was scanned and converted to .TIFF format. The surface channels on this map had been originally taken from the 1:50,000 vector data set, so by using stream confluences as control points is was possible to geo-reference this image with a high degree of accuracy. This resulted in a number of layers that were then directly comparable – modern 1:50,000 data, modern OSI aerial photography, geological maps, sub-soil maps, RBD catchment boundaries, 6 inch and 25 inch maps. Consequently, it was possible to analyse these data sets to identify, investigate, and quantify changes in surface drainage patterns over the past c.170 years and physical features in the landscape. Furthermore, the combination of topographical, hydrological, hydrogeological, and geomorphological data in a GIS enabled an analysis of the broader functioning of the hydrology and hydrogeology in the landscape to be undertaken as bedrock

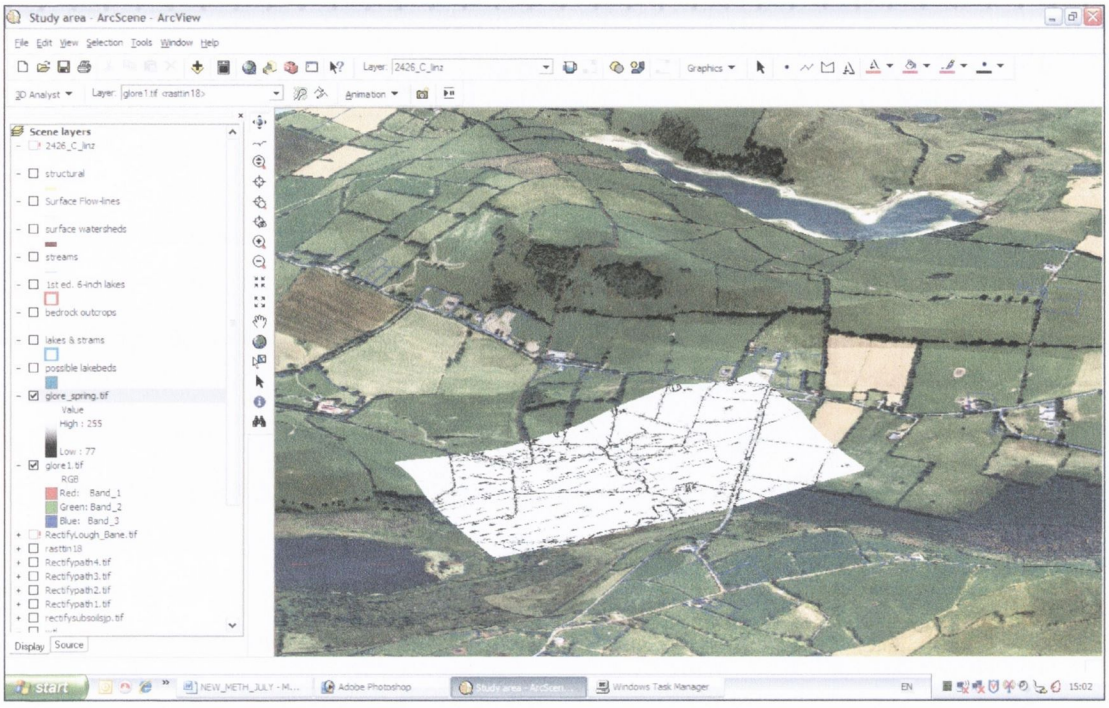
outcrops, hills, lakes, streams, springs, swallow-holes etc. could be examined in the context of their spatial distribution and spatial relationship to each other.

Elevation data augmentation

The OSI 1:50,000 elevation data was supplied in vector format with contour intervals of 10 m. As this study relates to lowland areas where entire sub-catchments commonly exist within a range of 5 - 20 m this presented some problems in catchment delineation. This was not an issue in delineating the Lough Owel, Lough Derravaragh, or Fore Valley catchments. There were ambiguities in defining the catchments of Lough Lene, Lough Bane, White Lake, and the Ben Loughs though. This problem was resolved by producing a new elevation data set for the area covering these catchments.

This data set was constructed by converting the 1:50,000 elevation (contour) data to a point format and adding spot heights taken from the 25 inch maps. The 1:50,000 data is satisfactory for hills but due to the 10 m contour interval it is less satisfactory in flatter parts of the landscape. These flatter areas are commonly the parts of the landscape where roads were constructed (as they avoided hills where possible) and the 25 inch maps contain spot heights along the length of most of these roads. These spot heights were converted from the old Poolbeg datum to the modern Malin Head datum and inserted into the point data set produced from the 1:50,000 data. An interpolation was then preformed on the point data set (using linear nearest neighbour interpolation in Arcmap) resulting in the production of a raster surface. Acceptably accurate contours may be constructed from this raster layer to an interval of ~ 5 m with significantly more accuracy in flatter parts of the landscape. While this new elevation data was greatly beneficial for this research, caution was at all times maintained when drawing inferences from it and ground-truthing was carried out as deemed necessary.

The completion of the new elevation data layer enabled the catchment mapping to be successfully completed. An example of the necessity for this mapping is illustrated by the White Lake catchment. Until the compilation of this data White Lake was mapped as flowing into the Ben Loughs and ultimately to the Boyne. Field investigations have proven that White Lake is situated in an enclosed depression with no surface outflow what so ever.



Screenshot from ArcScene showing section of 6 inch map (of the roaring well area) overlain on aerial photography, base heights are provided by the new elevation data set.

Surface drainage network change maps

These maps were made by comparing the OSI 1:50,000 lakeshore and stream data sets with lakeshore polygons and stream line features created from geo-referenced first edition 6 inch maps. Changes in stream and lakeshore locations could then be identified and analysed. To compute estimates for minimum and maximum lake volume change since the first edition of the 6 inch maps were surveyed, the following procedure was followed (also described in Chapter 4 section 4.2.5). The altitudes of the 6 inch map lake surfaces were estimated by overlaying the 6 inch map lakeshore polygons onto the elevation raster created from the 6 inch and 1:50,000 data (described in the above section). The elevation of the raster surface was noted at points around the lake shore. The present day lake surface elevations (1:50,000 map, maOD) were subtracted from these elevation values. Two figures were extracted from these results; the minimum estimate of lake surface level change; and the maximum level of lake surface level change. Minimum and maximum lake storage volume change estimates were calculated by adding the lake surface areas from the 6 inch and 1:50,000 maps, dividing the result by 2 (to give the mean lake surface area) and multiplying the resulting figure by the minimum and

maximum lake surface level change estimates to give (in m^3) minimum and maximum lake storage volume change estimates respectively.

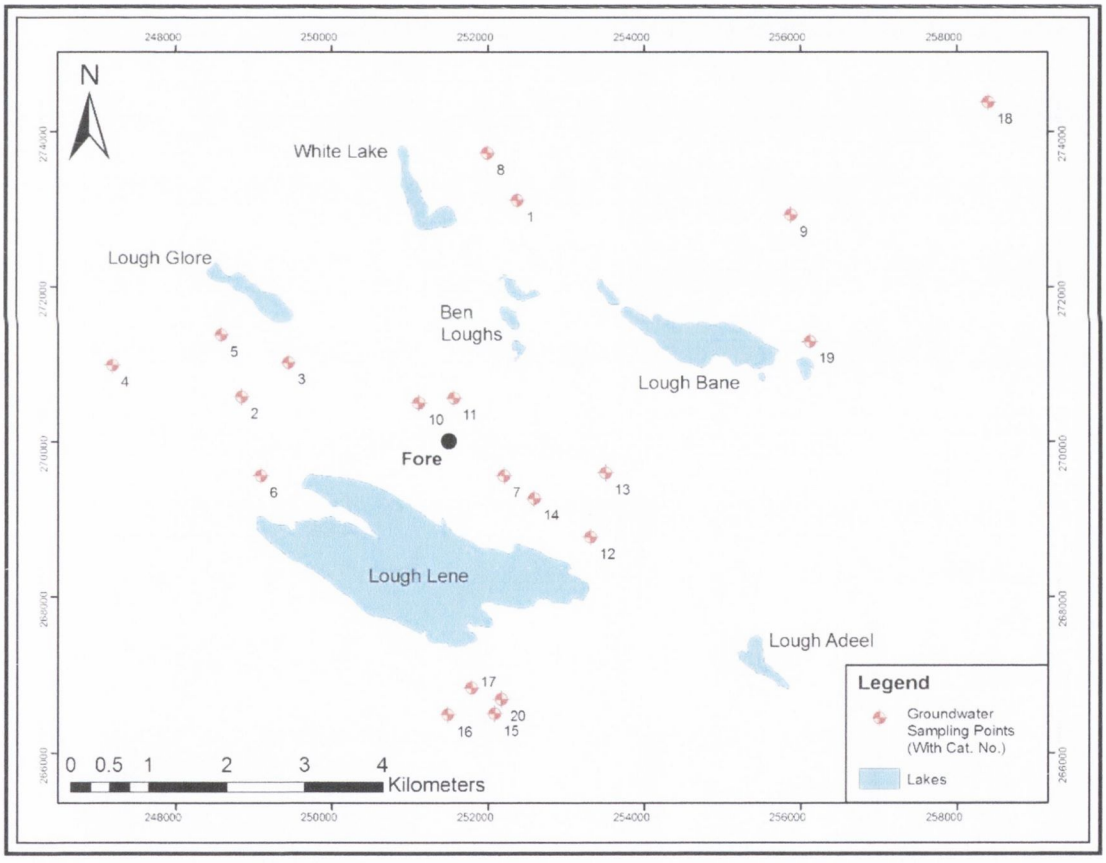
Groundwater Maps

The groundwater maps were constructed by interpolating water table surfaces from well standing water level data that had been corrected to maOD. The interpolation was carried out in ArcGIS using the nearest neighbour interpolation tool. This is a simple linear interpolation tool that does not relatively weight data points or interpolate a surface outside the polygonal extent of the data point network used for the interpolation. Once a surface had been created by interpolating between the data points it was necessary to check whether this surface was higher in elevation at any point that the land surface in the study area. This was done by using the cut/fill tool in ArcGIS which can be used to highlight areas where two three dimensional planes intersect. The interpolated water table surfaces were entered into the cut/fill tool with the land elevation surface and the resulting cut/fill raster showed areas where the interpolated water table stood higher than the land surface. The water table data set was then augmented by placing extra data points in areas where it stood higher than the land surface to 'pin it' to the land surface (which was taken to be the maximum possible, although not actual water table level). The resulting raster surfaces were used to construct groundwater flow lines.

The groundwater flow lines were constructed by using the steepest path tool in the ArcGIS 3D Analyst tool set. This tool produces a line that follows the path of steepest decent on a raster surface (which crosses elevation contours on such rasters at right-angles). These lines indicate the direction of groundwater flow on condition that the water table surface is accurate. The limitations of the results produced by these methods are dealt with in the main body of the thesis.

Appendix C Groundwater sampling network

In total 20 wells and boreholes were identified and monitored in the detailed study area. It was found that wells were not constructed on the numerous hills in the study area and that many wells that had existed in low lying parts of the study area had been filled in following the adoption of mains water supplies in the area. Of the 20 wells located, four were boreholes and 16 were hand dug wells. The location of these wells can be seen in the map below and their attributes are listed in the table on the following page (detailed notes for each well including measurement reference points are presented in Appendix D, along with measured standing water level data for each of the wells).



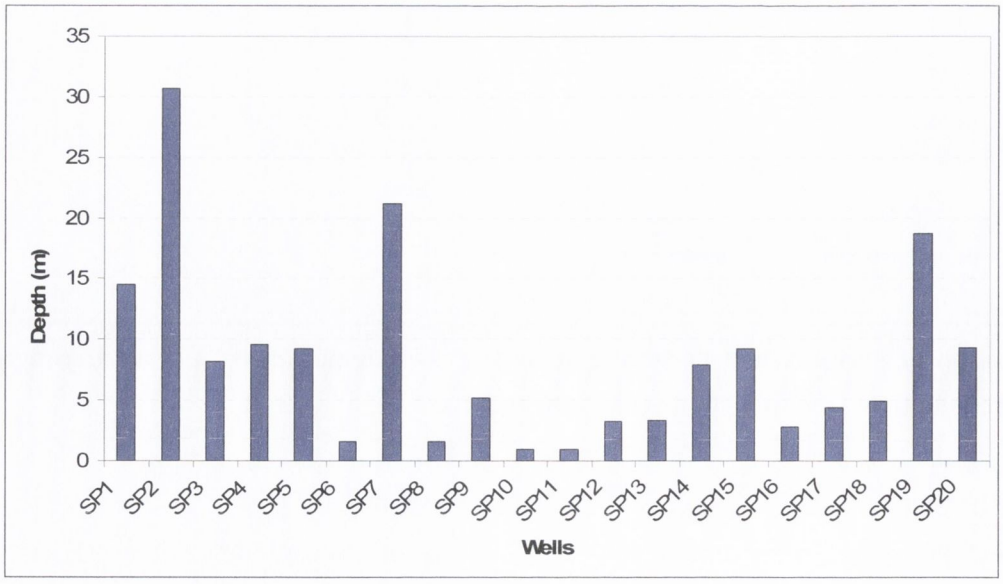
Location of all wells and boreholes identified and dipped in the detailed study area (base lake data OSI 1:50,000 vector data 2001).

The boreholes were all approximately 0.15 m in diameter while the diameters of the dug wells ranged from 0.45 m to 2 m. Only four of the wells are deeper than 10 m, the deepest being 30.7 m and nine of the wells were < 5 m in depth. While hand dug

wells are usually relatively shallow, two of the deepest wells in the study area are of this type (SP2 -30.7m deep, and SP19 – 18.7m deep). Four of the wells are in use and as such the standing water level in these wells may not have been at their natural levels.

Sampling Point No.	Surface Altitude (maOD)	Grid Ref.	Construction	Diameter (m)	In use	Depth (m)
SP1	124.2	N2524927320	borehole	0.15	No	14.5
SP2	110.18	N2488427056	dug	1.3	No	30.7
SP3	109.96	N2496027065	dug	1.3	No	8.2
SP4	99.9	N2471427098	dug	1.2	No	9.6
SP5	103.7	N2485727137	dug	1.5	No	9.2
SP6	99.1	N2490826955	dug	1.4	No	1.6
SP7	107	N2521926955	borehole	0.15	Yes	21.2
SP8	117.1	N2519927371	dug	0.45	Yes	1.6
SP9	129.3	N2558827292	dug	1.5	No	5.2
SP10	87	N2511127049	dug	2	No	1
SP11	90.5	N2516527055	dug	0	No	1
SP12	97.4	N2533026796	dug	2	Yes	3.23
SP13	108.7	N2535026962	dug	0.6	No	3.3
SP14	104.6	N2525526928	borehole	0.15	No	7.9
SP15	109.5	N2520726649	borehole	0.3	No	9.2
SP16	117	N2515626661	dug	1.5	No	2.85
SP17	105	N2517726683	dug	1.5	No	4.4
SP18	164	N2583927436	dug	1.7	No	4.9
SP19	132.5	N2560427133	dug	2	No	18.7
SP20	115.5	N2521626668	dug	1	Yes	9.3

Attributes of the groundwater sampling points.



Wells depths (m.b.g.l).

Appendix E Plates

Plate 1. Lough Lene looking west, the swallow holes are located at the right of the photograph.

Plate 2. Lough Lene looking east, note peninsula on left side of photograph, this area was a group of islands in 1837 but the lake level has dropped since and the islands have been joined to the mainland.

Plate 3. Lough Lene looking west, the surface outflow runs along the stone wall.

Plate 4. The surface outflow from Lough Lene at the point from where it leaves the lake.

Plate 5. Lough Bane looking south, note the step sided hills.

Plate 6. Steep sided hills and limestone scree south of Lough Bane.

Plate 7. Lough Glore looking northwest.

Plate 8. Lough Glass east looking south from the groundwater monitoring point SP19.

Plate 9. Ben Lough south looking southwest.

Plate 10. Small swallow hole on western shore of White Lake, this swallow hole was dry when traces were carried out (1m tape for scale).

Plate 11. Closer view of swallow hole at White Lake (1m tape for scale).

Plate 12. The lakebed of White Lake, note the change in slope along the centre of the photograph, this is the rim of a circular depression in the lakebed identified from aerial photographs.

Plate 13. White Lake under high water conditions looking east.

Plate 14. Small circular lake to the west of White Lake, possibly part of a compound doline feature.

Plate 15. Glore Bridge surface stream measuring point (1.8m blue pole for scale).

Plate 16. Fore Valley looking north with the Ben of Fore at the distant left of the picture.

Plate 17. Fore Valley looking south, Tobernacogany is located at the centre right of the photograph below the ruined church and yew tree.

Plate 18. Toberfaolaigh spring under low flow conditions.

Plate 19. The Upper River Glore downstream from Toberfaolaigh spring.

Plate 20. Tobernacogany spring looking east.

Plate 21. Tobernacogany spring looking west.

Plate 22. The Roaring Well during dry conditions, when the spring is active water flows from the vertical area covered by leaf litter in the centre of this photograph and down over the rocks in the foreground.

Plate 23. Karren on exposed bedrock (wristwatch for scale).

Plate 24. Mushroom stone at the southern shore of Lough Lene (wristwatch for scale).

Plate 25. Collapse feature near the western shore of White Lake (1m tape for scale).

Plate 26. A small collapse feature at White Lake, this area is usually under water during high water conditions (1m tape for scale).

Plate 27. Close up of small boulder of Derravaragh Chert, note solutional weathering at top of block and angular chert band at the bottom (tape measure for scale).

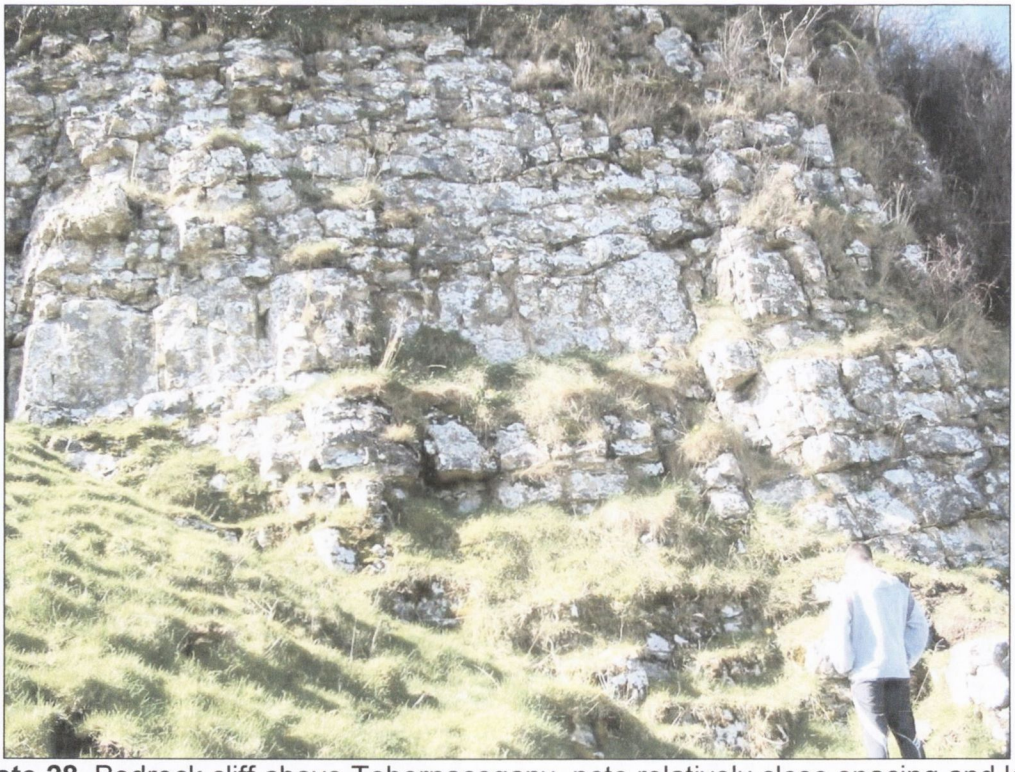


Plate 28. Bedrock cliff above Tobernacogany, note relatively close spacing and low angle of bedding planes.

Plate 29. Chert bands in bedrock cliff above Tobernacogany.

Plate 30. Swallow Hole 1 at Lough Lene, note steeply dipping angle of bedding planes (backpack for scale).

Plates 31 & 32. Marl and peat stratigraphy around the shore of White Lake.

Plate 33. Marl exposure 3m above the present winter surface level of White Lake.

Plate 34. Marl subsoil below fields in the White Lake catchment.

Plate 35. Marl subsoil exposure at northern end of White Lake.

Plate 36. Swallow Hole 1 at Lough Lene.

Plate 37. Swallow Hole 2 at Lough Lene (blue pole centre right of picture is 1.8 m long).

Plate 38. Swallow Hole 3 at Lough Lene.

Plate 39. The opening of Lough Lene Swallow Hole 3 during summer months when no water was flowing into the feature (note build up of leaf litter at base, wooden rod to left of opening is 0.3 m long).

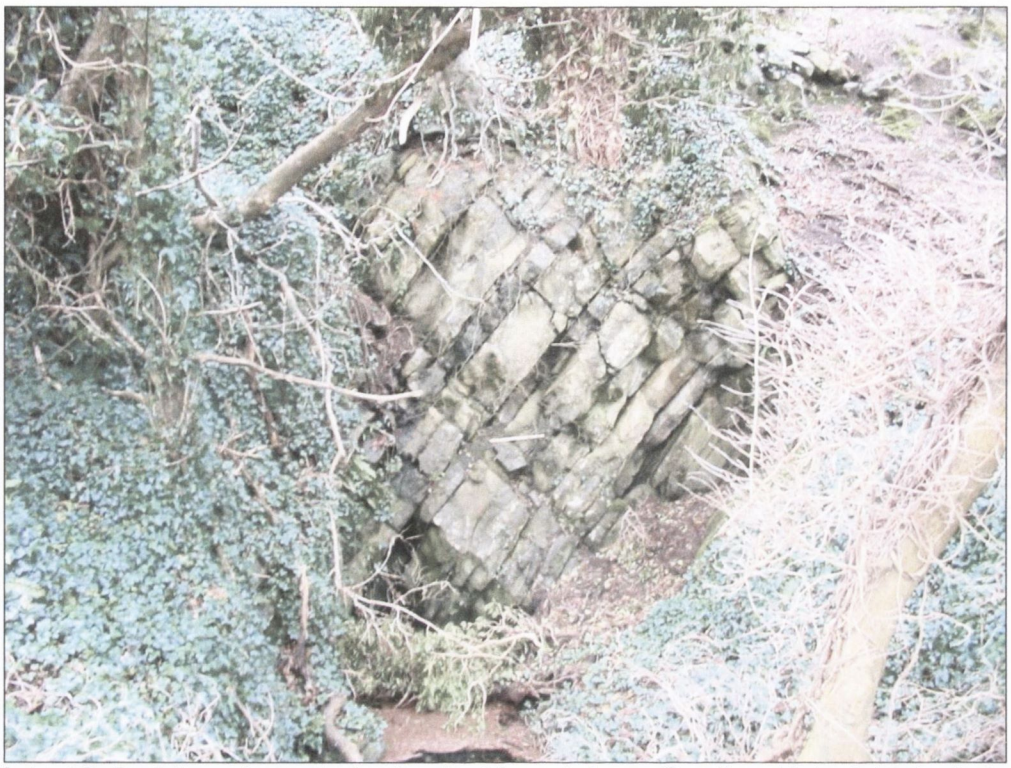


Plate 40. Bedding planes in bedrock at Lough Lene Swallow Hole 1 (note darker less-soluble chert beds in bedrock exposure).

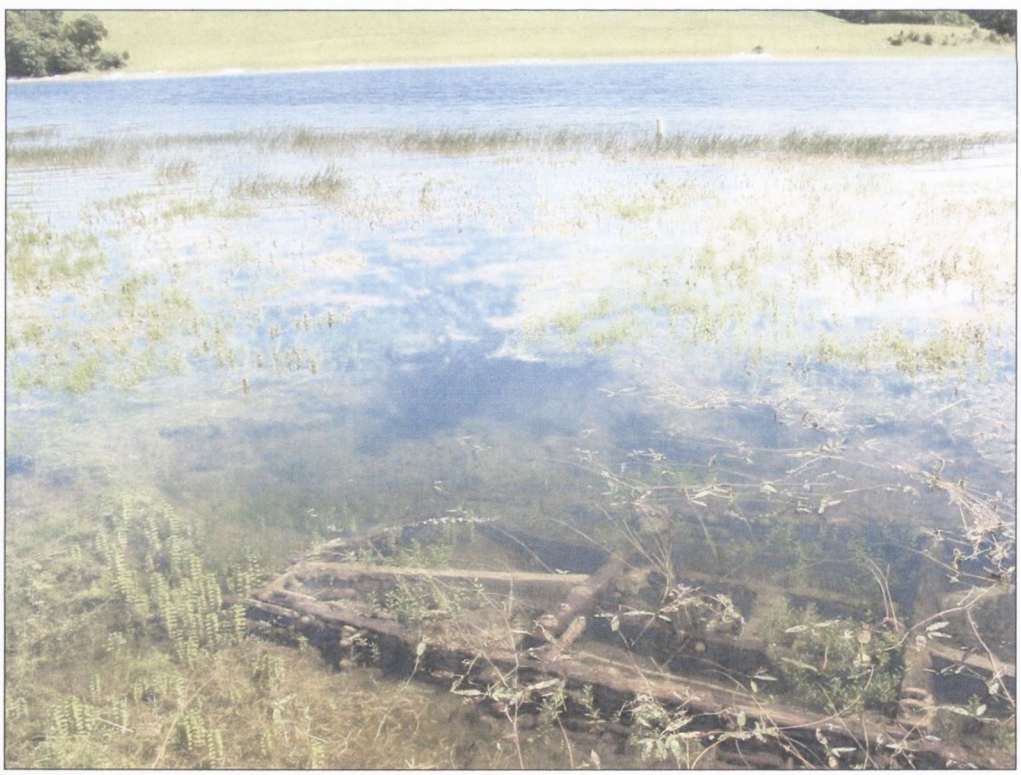


Plate 41. The largest swallow hole at White Lake under water (note timber chassis at bottom of photograph).

Plate 42. The largest White Lake swallow hole full of water (note timber chassis at bottom of photograph).

Plate 43. The White Lake swallow hole with rhodamine dye during tracing experiment (note timber chassis at bottom left of photograph).

Plate 44. White Lake looking south during early summer when lake level is receding (note position of rabbit burrow in plate 45 on right hand side).

Plate 45. White Lake looking north under high water conditions looking northwest (note marl and rabbit burrow from plate 44 at bottom of photograph).

Plate 46. White Lake looking north under high water conditions, the collapse features were observed in the area near the centre of this photograph when the lake level receded.

Plate 47. Depression at the northern end of White Lake under high water conditions, the drainage channel at the bottom right of the photograph may be man made.

Plate 48. Depressions linked by (possibly) man made channels at the southeastern end of White Lake under high water conditions.

Plate 49. Steep sided limestone hills south of Lough Bane.

Plate 50. Stepped profile on the northern shore of Lough Bane.

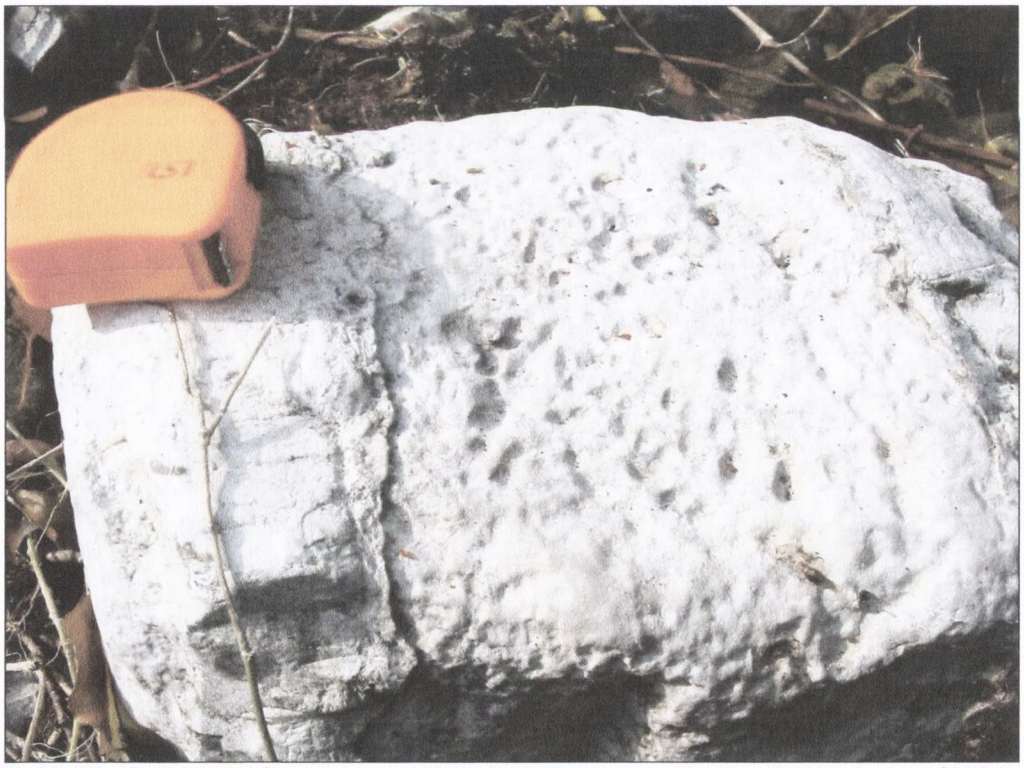


Plate 51. Solutional features on dislodged limestone bedrock on shore of White Lake (measuring tape for scale).

Plate 52. Limestone cobbles and small boulders on the shore of Lough Lene following lowering of lake level, note white staining on rocks. This staining was not present before the lake level rose.

Plate 53. Limestone block with solutionally enlarged joins on shore of Lough Lene (measuring tape for scale).

Plate 54. Well jointed bedrock exposure on western shore of White Lake, bedding planes dip 6° west-southwest (measuring tape for scale).

Plate 55. Well jointed bedrock exposure on western shore of White Lake, bedding planes dip 6° west-southwest (measuring tape for scale).

Plate 56. The largest swallow hole at white lake (orange measuring tape and fishing boat for scale).

Plate 57. Possible doline near White Lake.

Plate 58. Automatic groundwater level recorder in place at SP19 north of Lough Bane, this hand dug well is 18.7m deep.

Plate 59. View into monitoring well SP19, total depth 18.7m (shoe at right of picture for scale).

Plate 60. Glacial till subsoil exposure 500m east of Lough Bane (metal gate for scale).

Plate 61. Knockeyon Hill located at the eastern end of Lough Derravaragh, looking west.

Plate 62. Fluorescein Dye in swallow hole 1 at Lough Lene, September 2009 (note 2l plastic bottle floating on water at top of picture for scale).

Plate 63. Rhodamine WT injection into swallow hole at White Lake, September 2009.

Plate 64. The swallow hole at White Lake immediately after dye injection was carried out, September 2009.

Plate 65. ISCO automatic water sampler deployed below the Roaring Well, September 2009.

Plate 66. Channel constructed for discharge measurement downstream of the Roaring Well, September 2009 (blue pole on left is 1.8 m long).

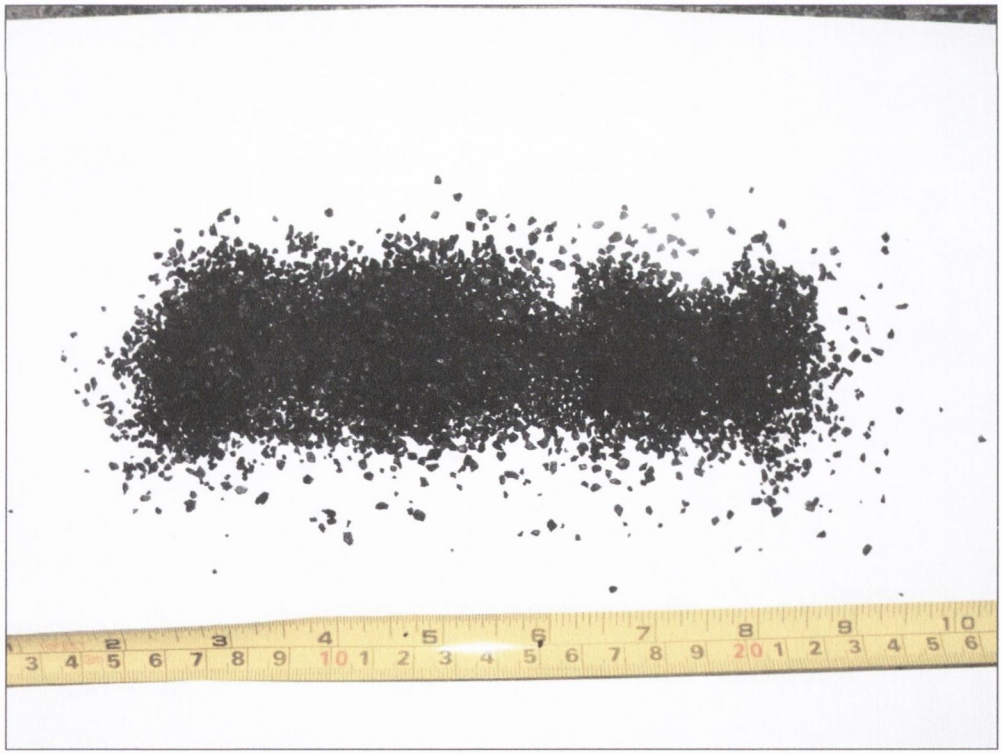


Plate 67. Gas Activated Carbon (GAC) granules used in the fluocapteurs.

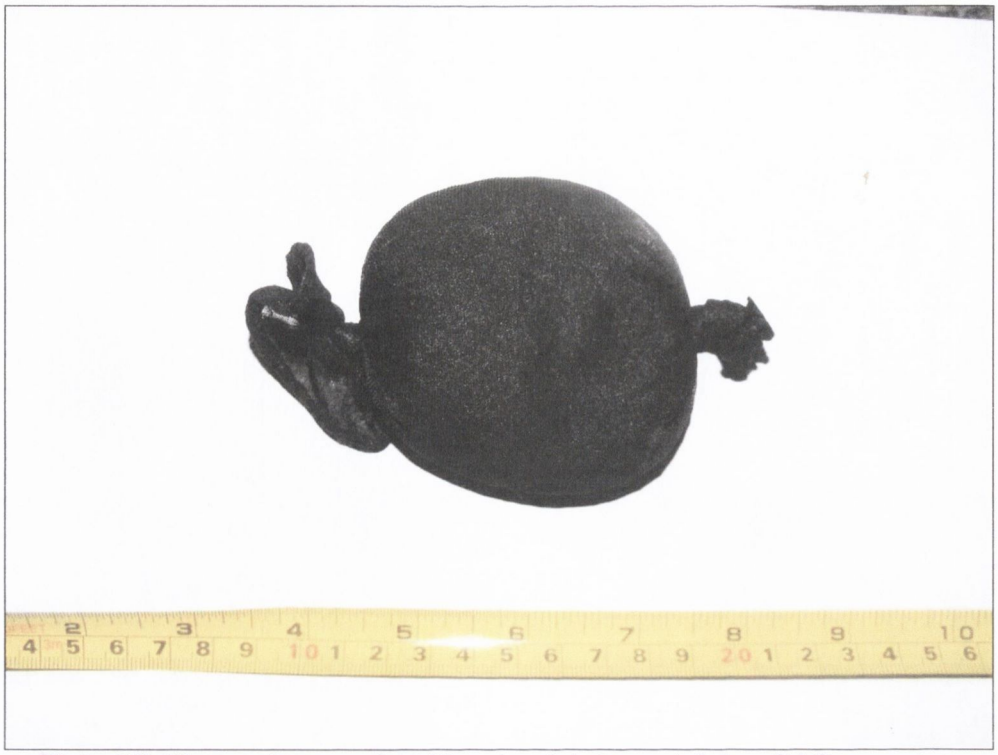


Plate 68. Fluocapteur made with nylon fabric containing GAC granules.