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# Eco-hydrology of Pollardstown Fen,

# Co. Kildare, Ireland

Volume I of II
Text, Figures and Tables

Presented in fulfilment
of the requirements for the degree of
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by

Anna Małgorzata Kuczyńska

Department of Civil, Structural and Environmental Engineering,
University of Dublin,
Trinity College.

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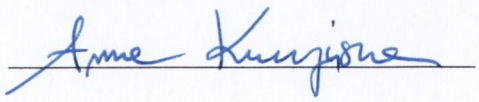

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## Summary

Calcareous fens are wetlands that accumulate peat and have alkaline groundwater as their dominant hydrologic input. This combination of environmental characteristics produces an unusual type of habitat and a large number of rare and regionally important plant and invertebrate species are found within these fens. Groundwater discharge to a fen is the critical factor controlling the ecology of a fen. An understanding of eco-hydrological links is critical in the assessment of likely impacts on the wetland, which typically could arise from groundwater abstraction, drainage or agricultural practice. The awareness of the significance of groundwater to fens was increased with implementation of the EU Water Framework Directive, under which fens classify as groundwater dependent terrestrial ecosystems (GDTE) and must be included in River Basin Management plans nationwide.

Wetland studies have a long history; however a quantitative assessment of eco-hydrological interactions within them is difficult and hardly exists in Ireland. In this study a multidisciplinary approach was adopted and the eco-hydrology of the fen of Pollardstown, Co. Kildare was examined. This investigation was focused at the fen margin, where groundwater discharges from the surrounding aquifer as springs and seepages, and creates an interesting habitat that combines a mixture of rare plants and animal species, many of which are protected under the EU Habitats Directive.

The specific interest of the study was set on the conservation requirements of *Vertigo geyeri* snail and the habitat it lives in. As such, the investigation was focused on selected areas of the fen margin where the snail was known to occur and that were considered to be potentially threatened by a combination of natural and human-induced factors. While the hydrological investigation of the fen margin included four selected study sites, the snail's microhabitat characterisation is based on a detailed investigation carried out at one selected site (Site A). The observations lasted for three and half years and were undertaken between 2001 and 2005.

The snail's preferred habitat was quantitatively defined in terms of micrometeorology and microhydrology and revealed that the snail requires a consistently damp atmosphere with relative humidity varying between 80% - 95%, very small fluctuations in phreatic level (0-20 cm) with the mean of 10 cm below the ground surface and soil moisture content within the moss substrate at 80% - 90% saturation levels. Soil water content was established between 70% - 80% and the surface wetness level was found to be greatly affected by shading vegetation. Micrometeorology was found to be uniform across the whole fen area and no major differences were found between various locations on both southern and northern sides and the weather station placed on the fen. The only exception was that incoming radiation was circa 50% less under the canopy than it was at the weather station. In order to maintain the soil continuously wet and the phreatic level at a constant level at approximately 10 cm below ground level, water needs to be delivered at rates that are at least equal to the average summer actual evapotranspiration rates and so the depletion driven by evapotranspiration is balanced by upward seepage. This seepage rate was quantitatively estimated as a minimum of 2.5 mm/day.

Hydrological characteristics of the fen were studied through a water balance analysis. The total catchment area was determined at 32.2 $km^2$ and the majority of that was located on the southern side of the fen. Meteorological inputs were collected at the weather station established within the study site. The gross rainfall was recorded between 750-850 mm/yr and potential evapotranspiration was estimated at 490-540 mm/yr. Actual evapotranspiration for the fen area was calculated by application of a crop factor and was found in a range between 547-595 mm/yr; while for the rest of the catchment it was 423-475 mm/yr. The higher evapotranspiration found within the fen area reflects high transpiration rates within a densely vegetated fen site in summer months. In total, hydrological inputs into the wetland were determined at ~ 11 x $10^6$ $m^3$/yr and discharge from the fen was measured under the Hanged Man's Arch Bridge in the range 8.6 to 11 x $10^6$ $m^3$/yr. Further assessment of flows within the Milltown Feeder revealed that about 90 - 95% discharge from the Feeder originates from the southern part of the catchment.

Hydrochemical analysis of water at three indicative depths from selected piezometers located on the southern and northern edges of the fen revealed different characteristics of water samples. Results suggest that water in the deepest piezometers at the northern side of the fen is recharged locally, rather than coming from the southern side. This conclusion is based on the relatively high concentrations of nutrients found at this location. In contrast, lower nutrient loading found in the deepest screens at the southern side suggests that water at this depth is likely to come from more distant parts of the catchment. This implies that groundwater pressures within the southern part of the fen's catchment will pose a risk mostly to the southern edge of the fen, whilst the northern fen margin will be affected by activity in the local area.

Assessment of hydrographs from four intensively monitored sites around the fen margin, two on the south side and two on the north confirmed these differences and showed varying in phase responses to rainfall. Data suggest that water levels on the northern fen margin respond faster than water levels on the southern margin. Groundwater flow was assessed at the margin of the fen, in the seepage zones, and suggests vertical specific discharge rates ranging from ~0.001 – 0.004 m/day at the northern and south eastern fen margins. The most elevated site (Site A) indicated a specific discharge one order of magnitude lower than at the other studied locations. This site is of significance due to the presence of a large population of *Vertigo geyeri sp.* and also because of its relatively high topographic elevation (2-3 m higher than the other studied sites) which makes it most vulnerable to decreases in regional water levels. Seepage rates were estimated using permeabilities assessed *in situ*. Field measurements suggest permeabilities of $1.19 \times 10^{-6}$ m/s for peat and $1.21 \times 10^{-5}$ m/s for gravel. The mean vertical permeabilities for assessed vertical profiles varied from $1.73 \times 10^{-5}$ m/s to $5.44 \times 10^{-5}$ m/s. Upward seepage, although dominating at the marginal sites, was also found in a few discrete central locations, which shows that this recharge mechanism may also occur in central parts of the fen. The stability of water levels was observed to be dependent upon the amount of seepage delivered into the peat and this was shown to be controlled by the hydraulic head in the underlying gravel strata.

While hydraulic head in the underlying gravels was found to be the primary controlling factor for distribution of seepage and its rates, geomorphology of the fen margin was determined to be the second controlling factor. A clay layer beneath the fen peat was found to be discontinuous and varying in depth and structure. The thickness of the clay strata is greater at the northern side, which results in higher hydraulic pressure and artesian heads occurring even upgradient from the fen margin. In places where the clay liner is absent, or thinner, flooding is common.

The *Vertigo geyeri* snail acted as an indicator of the specific type of fen margin environment. Based on the preferred microhabitat conditions established for the snail, it was determined that in order to maintain stable water levels and within a fluctuation range acceptable to the snail (0-0.2 m bgl) at the specific site known as Site A, the level of hydraulic head in the underlying gravel layer must be not less than 88.67 m OD in piezometer SP31 located at the southern fen margin. This level was determined as a local critical water level necessary to sustain wetness of the most elevated, southern part of the fen. Further comparison with hydraulic head levels within the Curragh aquifer facilitated establishment of critical water levels for the regional scale as 91.20 m OD and 88.92 m OD for monitoring boreholes MB29 and MB6 respectively (two monitoring boreholes within the catchment of the southern fen margin). These critical water levels can be used as indicators for a potential threat to the habitat of the snail. Mitigation threshold levels were established to be at 88.75 m OD at the fen margin in piezometer SP31, 89.06 m OD in monitoring borehole MB6 (upgradient from the fen) and 91.44 m OD in MB29 at the top of the Curragh aquifer. These groundwater levels can be adopted as triggers for action when groundwater levels approach critical levels. There is 2-month period, approximately, for preparation of an adequate mitigation strategy for the southern snail site.

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## List of abbreviations

Metric units are used throughout this thesis

| | |
|---|---|
| A | area |
| BQ | Botanical Quadrat |
| °C | degree Celsius |
| Ca | Calcium |
| $CaCO_3$ | Calcium Carbonate |
| Cl | Chloride |
| cm | centimetre |
| d | day |
| °d | German degree |
| EC | electrical conductivity |
| EPA | Environmental Protection Agency |
| ET | evapotranspiration |
| $ET_{act}$ | actual evapotranspiration |
| $ET_0$ | reference evapotranspiration |
| EU | European Union |
| gl | ground level |
| GSI | Geological Survey of Ireland |
| GWI | groundwater inflow |
| GWO | groundwater outflow |
| hPa | hectopascal |
| IWRM | Integrated Water Resourse Management |
| IQ | Intensive Quadrat |
| K | Potassium |
| *k* | hydraulic conductivity |
| $km^2$ | kilometres squared |
| l | litres |
| LAC | level of acceptable change |
| m | metres |
| $m^2$ | metres squared |
| MB | monitoring borehole |
| mg | milligram |
| Mg | Magnesium |
| mm | millimetres |
| m OD | metres Ordnance Datum (Poolbeg) |
| Na | Sodium |
| $NH_4$ | Ammonium |
| $NO_3$ | Nitrate |
| NVC | National Vegetation Classification |
| OPW | Office of Public Works |
| P | precipitation |
| pH | potential hydrogen, measure of acidity |
| PQ | Permanent Quadrat |
| $PO_4$ | Phosphate |
| Q | groundwater discharge |
| RBD | River Basin District |
| RBM | River Basin Management |
| SD | standard deviation |
| sec | seconds |
| SMD | Soil Moisture Deficit |
| $SO_4$ | Sulphate |
| SWI | surface water inflow |
| SWO | surface water outflow |
| UDFM | Ultrasonic Doppler Flow Meter |
| µS | microsiemens |
| W | Watts |
| WFD | Water Framework Directive |
| wl | water level |
| v | velocity |
| VAR | variance |
| VQ | Vertigo Quadrat |
| yr | year |

# I Chapter One: Introduction

## I - 1. Introduction

Wetlands are one of the most important ecosystems on Earth. Their unique ecological functions, on a global scale, are being compared by scientists to those of tropical forests (Mitsch & Gosselink, 2000). They act as natural treatment plants for polluted water, stabilisers of water supplies regulating floods and droughts, and aquifer recharge areas (Heathwaite, 1995). They contribute to the stability of global levels of available nitrogen, sulphur, methane and carbon dioxide causing a reduction of the greenhouse effect. They also provide unique habitats hosting a wide variety of the rarest species of flora and fauna. No other type of ecosystem is as important to millions of migratory birds, fish, amphibians, insects, plants and trees (Mitsch & Gosselink, 2000).

Wetlands are usually formed at the interface of terrestrial and aquatic ecosystems, but can also be found in isolated locations where the source of the water is usually groundwater. The main features characterising wetlands are:

- The presence of standing water for some period during the growing season;
- Unique soil conditions that differ from adjacent terrestrial habitats;
- Organisms, especially vegetation (hydrophytes), adapted to or tolerating saturated soil.

Multiple definitions of wetlands exist worldwide. A very generic definition of wetlands was established in 1971 during the Ramsar Convention (Mitsch & Gosselink, 2000) where wetlands were defined as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six metres'. As the ecology of wetlands is the key element of wetland ecosystems, a definition by the US Army Corps of Engineers and the US Environmental Protection Agency seems more appropriate, especially in a context of eco-hydrological study, and this states that wetlands are 'those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions'(US Army Corps of Engineers, 1987).

Wetlands are found all over the world, from the polar regions to the tropics. It is assumed that wetlands cover from 7 to 9 million $km^2$, which is about 4 to 6 % of the land surface of the Earth (Mitsch & Gosselink, 2000). 750000 $km^2$ of wetlands has been registered with the Convention on Wetlands of International Importance (Ramsar) as of 2000. This represents about 8 to 10% of the world's total wetlands. In many regions wetlands are deteriorating rapidly. The rate of that process on a global scale is unknown. Many wetlands were dried out centuries ago and the practice is still ongoing in present times. It is assumed that we have probably lost as much as 50% of the original wetland areas on Earth which emphasises the urgent need to end this trend. Losses of up to 90% have been reported in Europe and New Zealand (Mitsch & Gosselink, 2000). Mechanisms such as embanking a river, over exploitation of groundwater resources or building dams are only a few of the many reasons why wetlands are deteriorating. Progressive draining policy for agriculture and forestry, mosquito

control, feeling for residential and development or waste disposal, mining, as well as excessive harvesting, sea wall construction and coastal development are common practices all over the world, and contribute to widespread and fast wetland loss. Apart from the above mentioned factors, pollution from agricultural and industrial sources can increase levels of nutrients, pesticides or heavy metals and seriously impair ecological processes. Most wetland habitats are extremely vulnerable, with many threatened fish, amphibians and other species.

With regard to wetland types; numerous classes have been defined, and these depend on selection criteria adopted in the classification process. While a more extensive description of wetland classification concepts is provided in an Addendum to this volume, at the most basic level wetlands can be differentiated based on either hydrological or ecological qualities (also referred to as gradients). Within hydrological concepts, three most prominent criteria include soil substrate, hydrochemistry and hydromorphological settings; although the hydrochemical gradient (which gives rise to differentiation between bogs and fens) seems most commonly used. From the biological perspective, features that can impact upon wetland's ecological characteristics are soil base richness and soil fertility. Chemical characteristics of the subsoil and the amount of available nutrients are in fact strongly dependent on the water recharge mechanism; however, these ecological classes do not consider hydrological input and wetlands are assessed based on their floristic and faunal properties. This is important to remember in an impact assessment process as a different classification will give rise to a different characterisation of pressures. For a detailed description of different wetland types refer to the Addendum to this volume.

All wetlands, by definition, depend on water supply and form only in places where a positive water balance is achieved. Water, then, plays a critical role in sustaining a wetland's integrity. Wetland hydrology affects species composition and richness, its productivity and the build up of peat. Small changes in hydrology can result in significant biotic changes, which means that wetlands are inherently sensitive to manipulation of their water supply and water levels (Heathwaite, 1995, 2005, Grootjans *et al.*, 1996, Baird and Wilby, 1999).

## I - 2. Wetland Conservation: Current Legislative Instruments

Because of their fast diminishing rates and high ecological, economical and social values, wetlands are broadly recognised as endangered habitats which have to be preserved for future generations, and therefore they are often protected through national and international designations and legislations. Within the European Union, wetland's unique habitats are protected by E.U. Habitats Directive 92/43/EEC, which was implemented into Irish legislation in 1997 (S.I. No. 94 of 1997). This legislation protects uncommon and endangered habitats and rare species whose habitats must be protected. Sites protected under the E.U. Habitats Directive are given the designation of a Special Area of Conservation and are automatically included in the Natura 2000 network. Other relevant legislations are: the Wildlife Act 1976 and its amendment of 2000, which provides for the conservation of plants, animals and wildlife habitats of importance in Ireland; and the E.U. Birds Directive (79/409/EEC) which protects rare bird species, also often found on wetlands. Wetlands that are of the highest ecological importance can also be listed in The Ramsar List of Wetlands of International Importance, which gives worldwide sites of greatest significance. The Ramsar Convention requires signatory governments to designate and conserve wetlands that are considered as particularly good examples of a specific type of wetland,

characteristic of its region. The convention notes the presence of rare, vulnerable, endemic or endangered plants or animals as a factor in determining international importance. Natural habitats which are representative examples of natural European heritage, scientific research and exchange of information can also be given a designation of Biogenetic Reserves, which is offered by the Council of Europe (E.U.). In all the above legislation, a criterion for designating and protecting given sites is based on biotic composition of their ecosystems. This can be either a singular plant or an animal species or an unusual mix of plants creating an extraordinary habitat on which the existence of other rare species depends. However, with the continuous increase of human pressure on wetlands, which results from stable economic growth, the perception of conservation underwent evaluation in recent years. It is now accepted that wetlands have to be protected on both component and ecosystem levels, where both biotic and abiotic components that are required to sustain habitats must be cared for. In response, wetlands that are dependent on groundwater and surface water as the primary hydrological input (fens, floodplain marshes and meadows), have been included in a framework of an integrated water resource management (IWRM). In principle, IWRM is an approach to find a balance between the protection of natural resources for their long term sustainability and the utilisation of the benefits and services provided by them in order to meet social and economic development imperatives. The core component of IWRM is the catchment area (River Basin), which is a physical unit within which water resources are managed. River Basin Management (RBM) focuses on all water bodies (ground and surface) within a given catchment area and attention is given to the relationship between these elements. The RBM approach has been adopted by E.U. legislation called the Water Framework Directive (WFD; 2000/60/EC).

### I-2.1. Position of Wetlands within the Water Framework Directive

The WFD is a framework for the comprehensive management of water resources in the European Union, within a common approach and with common objectives, principles and basic measures. It addresses inland surface waters, estuarine and coastal waters and groundwater. The fundamental objective of the Water Framework Directive aims at maintaining the 'high status' of waters where it exists, preventing any deterioration in the existing status of waters and achieving at least 'good status' in relation to all waters by 2015. Member States have to ensure that a coordinated approach is adopted for the achievement of the objectives of the WFD and for the implementation of programmes of measures for this purpose (www.wfdireland.ie).

In order to fulfil its aims the WFD defines a number of objectives, one of which (Article 1a) is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. This will prevent further deterioration, protect and enhance the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly dependent on aquatic ecosystems. According to Article 5, each RBD shall be characterised in the way by which all pressures are identified and possible impacts assessed. The Water Framework Directive does not set independent ecological objectives for wetlands other than where wetlands are part of surface water bodies; however it:

a) Sets groundwater objectives that include obligations towards the wetlands ecosystem;
b) Identifies the use of wetland functions (water purification) as a possible means of achieving the Directive's objectives.

The most important WFD provisions in relation to wetlands are:

- Obligations to surface waters, which will apply to those open water wetlands which are identified as water bodies (Article 4.1[a]i) and belong to either rivers, lakes, transitional waters or coastal waters.
- Obligations to prevent more than very minor anthropogenic disturbance to the hydromorphological condition of surface water bodies of high ecological status. The hydromorphological quality elements of a surface water body include the structure and condition of riparian, lakeshore or inter tidal zones, and hence the condition of any wetland located in this zone. (Article 4.1[a]i; Annex V 1.2).
- Obligation to protect, enhance and restore wetlands identified as water bodies, where this is necessary to support the achievement of (Article 4.1[a]i & ii; Article 4.5):
    a) Good ecological status or good ecological potential;
    b) Good surface water chemical status;
    c) A less stringent objective.
- Obligations towards wetlands that are not individual water bodies, but part of a riparian zone. Member states are required under Article 11.3(i) to establish measures to control and mitigate modifications to the structure and conditions of these zones, including that of any wetland they contain, to the extent required to ensure that the hydromorphological conditions of the water bodies are consistent with the required ecological status or ecological potential.
- Obligations to achieve good groundwater status (Article 4.1 [b] i& ii; Annex V 2.1.2 and 2.3.2) and to reverse any significant and sustained upward trends in the concentration of any pollutant in groundwater in order to progressively reduce pollution in groundwater (Article 4.1 [b] iii). Member states must, among other things, control and remediate anthropogenic alterations to groundwater quality and water levels to the extent needed to ensure that such alterations are not causing, and will not cause: a) significant damage to terrestrial ecosystems that directly depend on bodies of groundwater; and b) significant diminution in the chemical and ecological quality of bodies of surface water associated with bodies of groundwater. This also includes an obligation to ensure that dependent surface waters achieve their environmental objectives under Article 4, so far as these depend on groundwater quality and quantity. Fens and marshes, which are dependent on groundwater to maintain their characteristic structure and function, may fall within the category of a dependent terrestrial ecosystem.
- Obligations to protect and restore areas registered as special areas of conservation (Natura 2000 sites) under the Habitats Directive (92/43/EEC) and special protection areas under the Birds Directive (79/271/EEC).

The E.U. Common Implementation Strategy for the WFD (2000/60/EC) Wetland Horizontal Guidance was created to provide information about how to understand WFD requirements with respect to wetlands and how to identify the role of wetlands in the implementation of the directive (CIS, 2003). It also provides best practice recommendations for actions in order to meet the legal obligations stated in WFD.

In the view of the WFD, fens as groundwater dependent ecosystems shall be included in river basin management plans with the aim of protecting and maintaining the hydrological and ecological integrity of these ecosystems. In order to do so, a firm understanding of wetland hydrology in relation to groundwater bodies (aquifers) is vital as well as hydroecological links between ecology and hydrological regimes within the wetland ecosystem itself.

Knowledge of the site's ecological sensitivity allows identifying all possible pressures on the wetland ecosystem which shall be integrated into the water resource management plans to prevent any potential ecological hazards to the protected habitats.

Because of the relatively recent implementation of WFD, such an approach is new in environmental science and results are not yet widely discussed. The majority of studies that have been reported on the hydroecology of wetland ecosystems focus on the relationship between local ecology (in terms of specific species of plants or animals) and their requirements with regard to the proximity of water level, water availability or water chemistry, which gives a fairly good understanding of some wetland habitats; however, there is little published work that would relate ecological status of fen ecosystems to the regional groundwater regime on which they depend.

## I - 3. Wetland Eco-hydrology

For years wetland studies have been conducted by ecologists, botanists, hydrologists, limnologists, etc., many of whom were interested in the structure, function and biota of different types. In recent years, more and more work has been done in an attempt to relate hydrology to ecology (or vice versa) which is commonly named as a study of eco-hydrology. Eco-hydrology is considered a relatively new discipline, and its importance has been strengthened with the implementation of the integrated river basin management concept promoted by the E.U. Water Framework Directive. From the hydrological perspective, eco-hydrology overlaps the scientific fields of hydrology and ecology, and analyses impacts that changes in hydrology may have on ecology (Kundzewicz, 2002). It aims at a better understanding of hydrological factors determining the natural development of wet ecosystems, especially in regard to their functional values for natural protection and restoration (Hannah *et al.*, 2004). As a discipline analysing functional interrelations between hydrology and biota on a catchment scale (Zalewski, 2000), eco-hydrology is often studied in the context of water resource management, risk assessment and biological conservation, particularity in terms of the need to assess ecosystem responses to natural and anthropogenically induced pollution and water stress (Hannah *et al.*, 2004).

### I-3.1. Eco-hydrological and Hydro-ecological Models

A list of studies that have contributed to the subject includes works by Boyer *et al.* (1989), van Wirdum (1991), Bernaldez *et al.* (1993), Wheeler and Shaw (1995a), Grootjans *et al.* (1996; 2005), Wheeler (1999), Baird and Wilby (1999), Johnson (2000) and others. In countries where water management practices are extensive, such as in the Netherlands or the UK, studies on eco-hydrological relationships within wetland ecosystems have an especially long history and scientific output. One of the most comprehensive reviews on eco-hydrology of wetlands is that by Grootjans *et al.* (1996) who, in their paper, reviewed the early stages of research science which developed in the Netherlands in response to the increased degradation of water controlled ecosystems caused by mainly anthropogenic and socio-economical factors. The concept of hydro-ecology that emerged at this stage demonstrates that the ecology of a given site is expressed based on a fertility gradient[1] (i.e. reflected

[1] For information about hydrological and ecological gradients refer to the Addendum to this volume.

by diversity of flora and fauna) and is conditioned by the local soil/water relationship (i.e. the local hydrological regime) and this is controlled externally by hydrological gradients (i.e. the regional hydrological regime, the water supply mechanism). This model, called a hierarchical approach, focuses on biotic receptors and has been widely acknowledged and is still valid and applied. It promotes a concept of understanding the physical functioning of ecosystems to protect them against increasing socio economic pressures. So the major focus on eco-hydrological studies has been aimed at so called 'positional and conditional factors' (Grootjans *et al.*, 1996) such as controlling water levels, which in fact leads to the integration of hydrological and ecological gradients within a wetland system, looking for a firm relationship between the two approaches. This approach stimulated works on water chemistry within ecological gradients and species distribution as a reflection of hydrological gradients. These works aimed at developing models in which hydrological data could be used for the prediction of responses of wetland vegetation and possibly be used to regenerate some already damaged sites.

Further correlation between the plant species composition (ecological receptors) and distribution with geo-hydrological data, (i.e. upwelling and calcidity of the groundwater in deep aquifers, its interactions with phreatic aquifers and the incidence of flooding with surface water) led to the formation of a landscape model where ecological zonation was related to geological information and suggested patterns of discharge from different bodies of groundwater. The model was found to have wide application in the Netherlands; however, attention was drawn to the fact that some calcareous deposits present in the subsoil may also lead to high water calcidity on a very local scale, and this could cause interpretation to be misleading. At the same time, other studies, including that by Wheeler and Shaw (1995a), and Wheeler (1999), questioned the applicability of plants as indicators of the hydrological regime, which is a basis for the landscape model. Considerable amplitude of tolerance to changing water levels presented by numerous wetland species, and plant responses to water conditions controlled by proximity of other species, soil fertility and vegetation management are major factors restricting the credibility of plants as precise hydrological indicators. Only when hydrological regimes change significantly, i.e. water level falls are large, these are considered to be the most probable causes for changes in vegetation. It is worth stating here that lack of responses in vegetation patterns should not be treated as a lack of evidence of any ecological change in the studied habitat but may just reflect the inadequate sensitivity of the receptor.

In recent times, with increasing wetland degradation, more emphasis is given to impact definition and assessment of wetlands, and this is specifically driven by the E.U. Water Framework Directive. Under the WFD, some wetlands are recognised as part of water resources (Groundwater Dependent Terrestrial Ecosystems) and protection is given to a wetland in tandem with a groundwater or surface body of water that it depends on. As eco-hydrological (hydro-ecological) links are obvious, these need to be firmly defined to offer optimum protection, and this requires systematic assessment guidelines and management protocols (conceptual models of different ecosystems). These guidelines need to address both receptors and stressors but also must define potential distribution pathways for impacts. No firm model exists so far for Ireland, but work is progressing under the auspices of the EPA. The results of this project will feed into this model.

In Great Britain, Wheeler and his team (Wheeler and Shaw, 2001; Wheeler *et al.,* 2004) have developed two systematic eco-hydrological classification models in recent years. Firstly, the WETMEC model was developed in 2001 (Wheeler and Shaw, 2001) and was based on both hydrological and ecological inputs. This classification

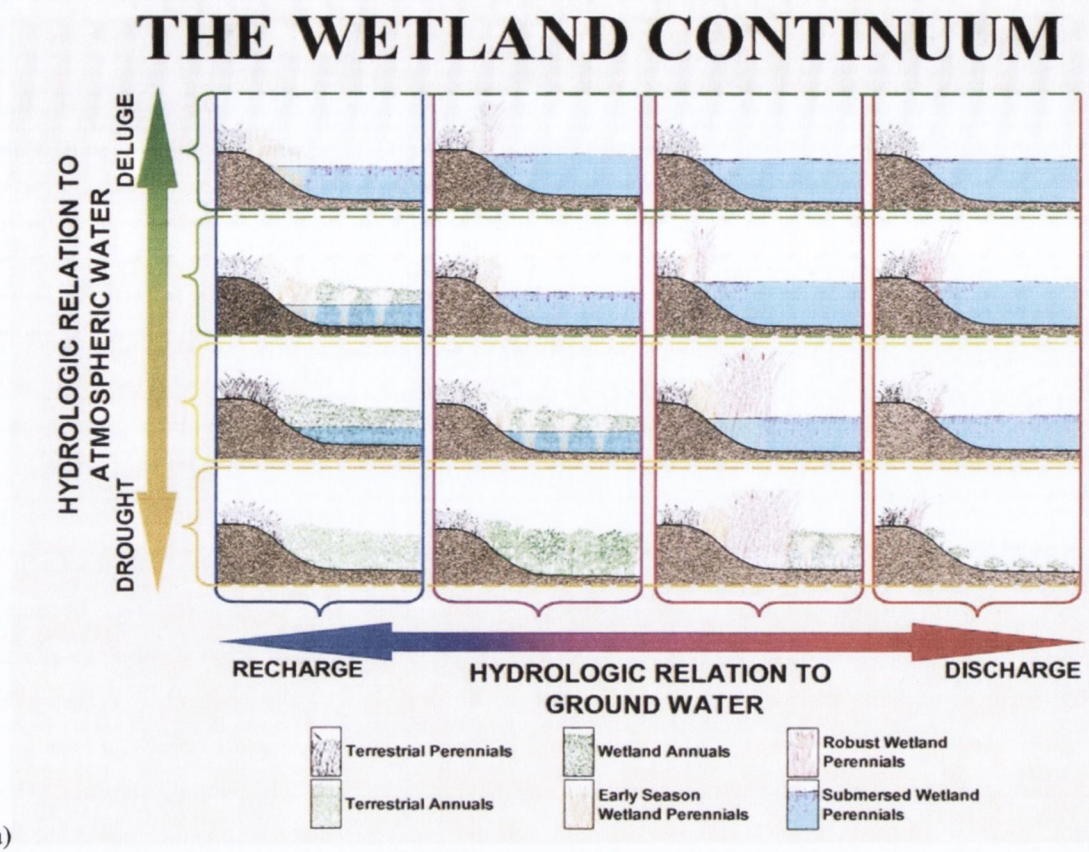
combined the following aspects: landscape settings, water supply mechanisms, topography, base status and fertility. Although this classification reveals a better understanding of links between the hydrology and ecology of different wetland sites, it did not include information regarding the impact upon water regimes and therefore was not broadly accepted. However, the following document entitled Ecohydrological Guidelines for Lowland Wetland Plant Communities developed by Wheeler *et al.* in 2004 provided comprehensive information on hydrological requirements for selected freshwater wetland communities. Acknowledging the efforts of many studies undertaken in wetland hydro-ecology and understanding the complexity of wetland ecosystems, this report 'does not provide definite and absolute figures but indicates a broad range of hydrological regimes that gives rise to specific vegetation communities'. These guidelines distinguished between three wetland classes of communities which are: lowland wet grassland, fen/mire and ditch/swamp, and, when applicable, these classes were linked with NVC[2] classifications. Based on scientific research, these guidelines provide generic information on the hydrological requirements of a plant community that can be applied broadly at any site. The output is such that three ranges of water depth (with regards to the ground surface level) are given; one that is preferred by the local community, one that is tolerable throughout a certain period of time and one that is beyond tolerable limits. Where possible, the maximum, minimum, and mean water table is specified and the cumulative duration of flooding is given. Data are grouped according to seasons. The guidelines also include information about typical water supply mechanisms (conceptual model), expected topography and typical nutrient characteristics. Information regarding characteristic species and communities' vulnerability is also given, with a view to proper management and conservation. Such guidelines are very powerful management tools, combining comprehensive research efforts and professional experience over the years. Unfortunately, not all communities are described in such comprehensive terms. Fen communities were not detailed by Wheeler *et al.*.

Outside Europe, an interesting approach was proposed by Euliss *et al.* (2004), who developed a complex model including and interlinking both abiotic and biotic elements, called the Wetland Continuum Concept. The model is an extension of hydrochemical classification gradient, but it further translates the hydrological settings into a biotic environment explaining environmental transitions on a habitat level. Although the concept was developed for the prairie pathole region in North America, its clarity in presenting the internal complexity of wetland ecosystems is worth noting and perhaps adopting for a wider range of wetlands. The Wetland Continuum model is based on two dimensional gradients, with groundwater and atmospheric water constituting the horizontal and vertical axes respectively. This allows positioning a wetland on both axes of the continuum, depending on its hydromorphological settings and then predicting potential biological responses, Figure I-1. The model provides a framework useful in the organisation and interpretation of biological data from wetlands by incorporating the dynamic changes these systems undergo as a result of normal climatic variation, rather than placing them into static categories common to many wetland classification systems, as described in the previous section. This takes into account changes in soil characteristics, nutrient and mineral availability and water hydrochemical composition which change from time to time and depend on specific hydrologic conditions. Thus, the beginning and end points on the groundwater axis represent wetlands that function hydrologically to recharge groundwater (recharge wetlands) and those that receive groundwater discharge (discharge wetlands) respectively. Wetlands

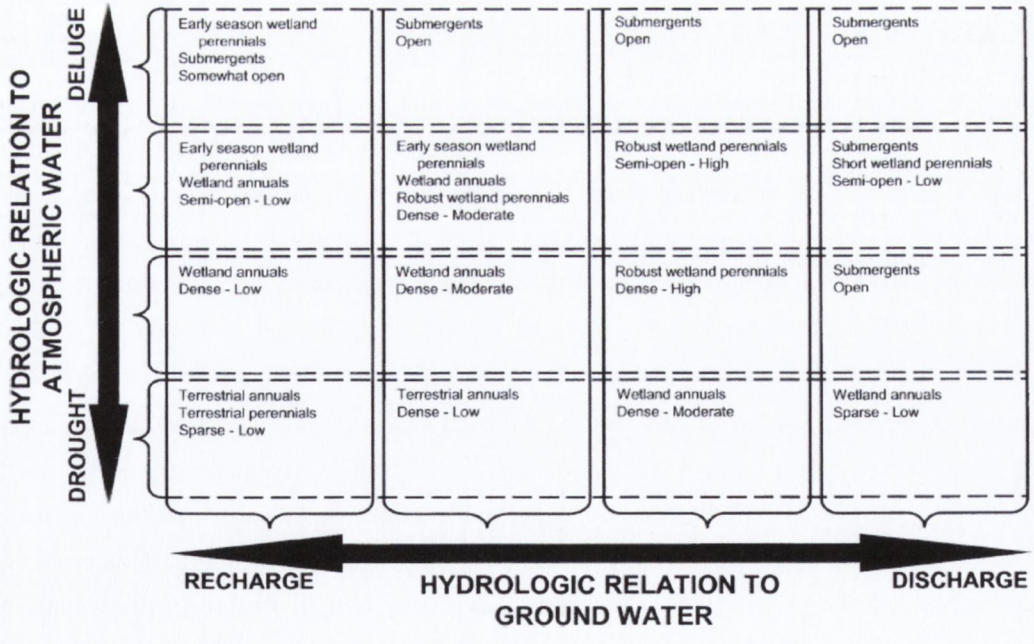
[2] All natural, semi-natural and major artificial habitats in Britain and Ireland are systemised using Rodwell's NVC (National Vegetation Communities), (Rodwell, 1991-1995) classification. This is a comprehensive and systematic account of the vegetation types of the UK (Haslam, 2003). The system provides descriptions of around 400 named plant communities, with details of their characteristic species composition and structure. Relationships with habitat factors are discussed, and the natural influences of climate, geology and soils, and the impact of man on the appearance and distribution of vegetation types is also examined.

that both recharge groundwater and receive groundwater discharge are termed 'flow through' wetlands. The proportion of groundwater discharge versus water loss to recharge strongly influences the hydrochemistry of flow through wetlands. Although the physical location of wetlands does not change, its relationship to groundwater does change on a seasonal and inter annual basis. The vertical axis in the continuum concept reflects the dynamics of atmospheric water input which responds to the climatic variability, and specifically precipitation – evapotranspiration ratio. The end points on this axis range from extremely dry to extremely wet. At any given time, the relative location of a wetland on this axis determines the potential condition of the biological community. However, the position of a wetland on the atmospheric axis is constrained by the position along the groundwater axis, and hence both axes of the wetland continuum must be considered simultaneously to interpret observed biological associations correctly. This system allows the prediction of biological conditions at any point in time and it also allows for seasonal changes in biological associations in response to changes in climatic conditions. Eulliss *et al.* (2004) have shown that these biological changes occur within floral as well as within faunal communities such as those of aquatic invertebrates and wetland birds. While the continuum concept, as driven by hydrological controls, may be considered as a very useful classification idea from the risk assessment perspective, the question is how to separate the different classes. Lack of well defined boundaries and lack of time dependency built into the drought deluge scale are obvious drawbacks with this classification system.

Purely ecological models also exist. The most common is the Ellenberg Moisture Value Numbers (1974), known also as the Ellenberg Wetness Index (F) which provides an indication of water levels associated with particular plant species (Wheeler *et al.*, 1995a, 1999). This index allocates an indicator of moisture value from 1 to 12 to some 2000 species of vascular plants, where 1 reflects dry soil and 12 fully inundated. This was first developed for western and central Europe (1974) and was further adapted for British and Irish Flora by Hill *et al.* (1999). The problem with using the Ellenberg Wetness Index is that the system was originally developed for grasslands; therefore most fen species may occur in a very narrow range of 8-9 on the scale. This implies that the method may not be sensitive enough to represent ongoing trends, especially when working on groups rather than single species which may have higher tolerance of water changes.




a)




b)

*Figure I-1 Euliss's concept of wetland continuum (from Eulliss et al., 2004). a) Wetlands located on the left on the groundwater axis recharge into groundwater but do not receive any groundwater discharge. On the right of that axis are wetlands for which the main water source comes from the groundwater. These wetlands do not recharge any groundwater. The climatic condition axis varies from drought to deluge conditions and represent different atmospheric water inputs. Plant communities on the above figure were systemised to reflect four different discrete points along both groundwater and climatic axes. b) General pattern of plant community variation in wetlands along the spatial and temporal gradients of the wetland continuum.*

## I - 4. Review of Eco-hydrological Research

The most commonly studied aspects in eco-hydrological studies include changes in water levels, fluctuation ranges and comparison between rainfall, surface water and groundwater contributions to the overall water balance, including its hydrochemical implications. These characteristics are believed to induce changes in plant and animal species' communities and cause shifts in habitat characteristics within the wetland ecosystem. Moving water in either the form of springs or run off streams delivers more chemicals than still water. When water is moving or seeping, soil, vegetation and living microorganisms are exposed to it, which allows the plants to absorb nutrients. Spring fed wetlands have a relatively constant inflow and outflow of water. As they do not accumulate water, water seeps through at a constant (or seasonal) rate. Any difference in the rate at which water flows through a wetland will significantly affect the effective soil minerotrophy. In highly soligenous (flowing) fens, water moves rapidly through the acrotelm, causing a large influx in nutrients across root uptake zones. It may also bring oxygenated water into the root zone. If the recharge mechanism is changed, and this results in a reduction of nutrient rich groundwater being supplied to the wetland surface, the wetland with time becomes dependent on rainfall. Then more acidophilic vegetation can invade. If rainfall does not provide enough water to sustain waterlogged conditions, the lack of water can lead to the drying out of a wetland, a decrease in productivity of fen vegetation, intrusion of grasses and ultimately transformation into a grass fen. Fen peat soil, when dried and exposed to the air, mineralises, oxidises and having negligible ash content, vanishes. This highlights the importance of a hydrological balance within wetland ecosystems to sustain unchanged habitat existence and also imposes a need for advanced wetland management systems.

The effects of drainage on wetland ecology have been extensively studied in the literature (e.g. Bernaldez *et al.*, 1993; Harding, 1993; Hudges and Heathwaite, 1995; Grootjans *et al.*, 1996; Gowing *et al.*, 1998; Haslam, 2003; Grootjans *et al.*, 2005) and all conclude that unless a hydrological regime is managed, habitat changes will occur. These changes can sometimes be irreversible, even when hydrology was returned to its original state. For example, extensive groundwater extraction and subsequent declining water tables in Central Spain have been recognised as major causes of impacts on a number of wetland ecosystems in the area, and effects varied depending on the wetland's relationship with an underlying aquifer. Groundwater extraction at a rate of 3.5 $l/sec/km^2$ in the Douro basin in the early 1950s and during the period 1970-1987 caused the average annual decline, ranging from between 0.9-1.2m/yr. As a result, the habitat loss in early 1990 reached astonishing rates which ranged from between 39%-82.2%, depending on the habitat type. Accompanying processes such as increased nitrification due to mineralisation of unstable organic matter in the new moisture regime, soil desiccation, wind erosion, soil salinisation have been proven to dictate changes in botanical successions and subsequent habitat transformations. Also Hudges and Heathwaite (1995) strongly stress the permanent alteration of the substrate structure that results from uncontrolled drainage. The increased rate of organic decomposition that accompanies a reduced water table results in primary consolidation followed by shrinkage, secondary compression and finally wastage of the upper layers in the wetland. These processes are believed to be irreversible and as such lead also to irreversible changes in a wetland's ecology and its ability to buffer against external influences such as changing rainfall patterns. As a result, drainage reduces the stability of a wetland so that it becomes more sensitive to external pressures. Furthermore, drier conditions induce vegetation pattern shifts toward more aeration tolerant and deeper rooting species, which in turn causes increased evapotranspiration losses and this augments hydrological changes on water balance.

Groundwater abstraction in a nearby borehole and dredging of drainage channels have been found to cause significant degradation of Redgrave and Lopham Fens in East Anglia between 1959 and 1991 (Harding, 1993). Declining water levels resulted in the following change processes being identified: alteration of the competitive balance of the community dominants; changes in environmental conditions required by individual species; an increase in site fertility, an increase in scrub cover on the fen; and a change from groundwater to rain fed hydrology. The importance of the stability of water levels in view of sustainability of species composition was also discussed by Grootjans *et al.* (1996, 2005), who emphasised that a small lowering of the water table can lead to dramatic changes in species composition and impact on soil mineralisation and water chemistry. However, increasing water levels resulting from land use changes - for instance harvesting forest - can also be undesirable as some wetland species such as *Howellia aquatis* require wetlands to dry up seasonally in their annual cycle (Reeves and Woessner, 2004). This shows that regional water management is vital to control stable ecological conditions within wetland habitats.

The second, parallel to the change in the hydrological regime, cause for a change in wetland ecology (i.e. diversity of plants and animals) has been attributed to changes in nutrient budgets which could be triggered either by hydrological gradients (i.e. changes in distribution of groundwater *vs.* precipitation in water budgets) or possibly by external modification of the groundwater and surface water chemical signatures in response to agricultural fertilisation. Changing land use on the wetland's surroundings may often affect the chemical status of both surface runoff and groundwater, which may possibly discharge into wetland. Considering the high sensitivity of wetland ecology to nutrient availability, this alteration of the hydrochemical regime may have a significant implication on species richness in given habitats. Nutrient availability is specifically of high importance in fens (Heathwaite *et al.*, 1995; Pauli *et al.*, 2002, Haslam, 2003) as it controls ecological gradients and can lead to changes to a habitat. Pauli *et al.* (2002) examined such influences on calcareous fen meadows of low productivity in Switzerland. Simulating atmospheric nitrogen deposition by adding nitrogen fertilisers and the influx of combination of nutrients by adding a nutrient mixture containing phosphorus, potassium and nitrogen over a two year experiment resulted in significant increases in plant biomass and an increase in the number of generalist species, suggesting that species composition and richness would change over longer periods if eutrophication persisted. These results demonstrated that both atmospheric nitrogen deposition and the influx of a mixture of nutrients can drastically change the characteristics of fen meadows.

In recent times, more attention has been given to new external stressors. Weltzin *et al.* (2003) investigated an effect of climate change, reflected in changing air temperature and shallow water table regimes on bogs and fens in northern Minnesota, USA. This research examined plant community responses to soil warming and drying using infrared warming and modifying the water table regime at the same time. The study revealed that in fens, changes in plant cover were driven primarily by changes in the water table, and responses were species specific. Increasing water table elevations increased the cover of grass as well as moss. In contrast a decrease of water table elevation increased shrub cover. The response of grasses and shrubs to the water table treatments illustrated apparently different thresholds of response to water table elevation for these life forms and suggest that depths greater than 10cm are most conducive to shrubs and that a water table shallower that 10cm is more favourable to grasses. This contradicts the findings of a similar study carried out by Kotowski *et al.* (2001) who investigated the effects of water table depth and differences in light intensity on the performances of four specific fen species,

namely *Carex curta, Viola palustris*, *Hydrocotyle vulgaris* and *Poa trivialis*. The study proved that for all species light availability had a larger effect on biomass production than differences in the water level. It further suggests that the occurrence of fen species in the landscape is directly related to the availability of light, whereas the relationship between fen species' occurrence and hydrological conditions seems to be an indirect one. This shows that although water availability is crucial for existence of wetland habitats, other environmental conditions are important and it is a combination of factors that govern habitat transitions. Intensity and rapidity of these changes is likely to vary between different sites, even though these can belong to the same wetland types. As such, the emphasis is on site specific assessments as generalisation may not be possible or not be sensitive enough adequately to cover the impact on all sites.

In summary, wetland studies have a long history and the majority stress that wetland ecology is very sensitive to external pressures and specifically to the water regime. These pressures can also easily induce internal stressing factors, for example changes in soil chemistry in response to a changing hydrological regime. Some contradicting opinions suggest, however, that sensitivity of receptors to certain triggers can vary depending on environmental settings and can be more important at one site than at others.

Within an Irish context, published works on eco-hydrology are rare, although studies on turloughs and fens are ongoing. Works on wetland hydrology are available but the majority of them have been focussed on raised bogs, mainly investigating their degradation related to the nationwide harvesting of peat.

## I - 5. Measuring Eco-hydrological Links: Challenges and Obstacles

Given the complexity of wetlands on both a community and species level, assessing an eco-hydrological wetland's health is a multifarious task and studies by many, including Lloyd *et al.* (1995), Wheeler *et al.* (1995 a&b), Ertsen *et al.* (1995), Toner & Keddy (1997), Wierda *et al.* (1997), Keddy (2000), Pezeshi, (2001), Porporato *et al.* (2002), Reeves *et al.* (2004), McCartney *et al.* (2004), Rodriguez-Iturbe & Porporato (2004), Niemi & McDonald (2004), often proved inconclusive or contradictory. Although much effort has been put in to quantitative analysis, authors stress that since observations usually refer to a small range of wetlands and over short periods, results are very site specific and only general trends can be distinguished on a bigger scale. There are still many uncertainties regarding the best quantitative measuring approaches. Water level availability can affect vegetation in many different ways depending on various characteristics such as magnitude, duration, frequency, and periodicity; and it still is not clear which of these parameters is the most important for plant distribution. As previously stated, groundwater levels not only regulate the water supply but also the availability of nutrients (Wierda *et al.*, 1997). Okruszko (1995) identifies transformations that peat soils undergo after dehydration, such as secondary humification, compactness, disintegration, and chemical changes in soil fertility. These changes and their effects on plant distribution are very difficult to quantify and not well understood. Some researchers concentrate their efforts on specific plant species (Kennedy *et al.*, 2003), which gives a very good understanding of physiology and response mechanisms of specific plants. It is difficult to say, however, which parameters are more significant for assessing the environmental health of habitats. If we use single species as indicators, their spatial distribution is clearly defined; on the other hand, some species have wide ecological tolerances and can survive long periods in conditions outside their preferred habitat (*Cladium mariscus* for

example which is usually found in very wet conditions; however, studies have shown that it is able to withstand water levels at 72 cm below ground level (Wheeler *et al.,* 1995a). Vegetation communities, which in turn represent plant associations, also usually have a very narrow ecological tolerance. The disadvantage of using associations is that, with increasing anthropogenic pressures, they are losing their characteristics and sometimes it is difficult to define a vegetation community. Nevertheless, Wierda (1997) found a better correlation with hydrological regimes on a community level than on a species level. He also concluded that vegetation distribution is mainly determined by the highest water table and the fluctuation of the water table during the vegetation period. Plants used as indicator species for specific habitats should demonstrate that their occurrence and abundance indicates a clear relationship to a specific water level. Wheeler (1995a) recognises three groups of fen species: principal, affiliated and accidental. The principal species are acknowledged as the best indicators, as they are particular and sometimes exclusive to fens. A good example of a principal fen species is *Schoenus nigricans* (black bog rush). Affiliated species occur widely in fens, however may also be found in dryer habitats. Accidental species occur rarely on fens and are usually associated with other habitats. The last two groups should not be used as indicator species.

Animals are also studied in the context of environmental change assessment; however, they are rarely ever used explicitly as ecohydrological indicators. For animals, factors controlling habitat selection are food availability and the presence of safe land for breeding. Depending on the species, different parameters would be therefore considered; for example, insects will be sensitive to changing vegetation patterns not only as a food source but also as hibernation sites, and more specifically soil moisture, may be important to larvae development. Amphibians may rely more on water levels as they use water gathered in hollows for laying eggs and for their tadpoles. Birds may be sensitive to changing vegetation patterns as a food source (both plants, and insects that rely on plants) and as breeding sites. Many reported works on specific wetland species describe responses to habitat change on a taxonomic basis rather than on an ecological basis (Rossell & Rossell, 1999; Paillisson J., *et al.*, 2002; Jansen & Healey, 2003). For example Jansen and Healey (2003) looked into frog communities in relation to floodplain wetland conditions that were undergoing intense grazing. The study proved that overgrazing of a wetland has a serious impact on wetland quality, particularly on vegetation but also on water quality which had a serious impact on frog communities. Some of the species are, however, more sensitive to hydrological regimes than others and may be indicative of specific hydrological conditions. Paillisson *et al.* (2002), for example, concentrated his interests on trends in water birds' occurrence in relation to water regimes, concluding that the species studied lived within range of their preferred habitats.

## I - 6. Wetland Risk Assessment Framework

The high sensitivity of wetland to small environmental changes has been well defined by others. Therefore, in order to protect these habitats, the sensitivity of these ecosystems to different pressures must be well understood and quantified. Identification of these pressures ultimately leads to ecological risk assessment. By definition, risk is a product of the probability that an ecosystem suffers damage from exposure to some eco-environmental hazard (Equation I-1) and the damage thus caused. Ecological risk assessment (ERA) is a quantitative evaluation of the risk, and its aim is to provide scientific information for planning so that environmental damage can be minimised. Ecological risks have two important characteristics: damage and uncertainty (Xu *et al.,* 2004). Risks have the potential to cause long term and even irreversible damage to the environment, which may affect the quality of life both of people and other living species. Stochastic and possibly cumulative risks are difficult to forecast, hence the uncertainty.

$$R = P \cdot D$$

*Equation I-1*

where: R – risk
P – probability of an event
D – possible damage arising from an event

Ecological risk assessment has been developed as an environmental management concept with a view to natural resource protection and biodiversity conservation. Up until recently risk assessment was focused on the biology of particular species and population receptors. However, since the nature of living ecosystems is dynamic and they have complex structures with a sophisticated hierarchy which may lead to knock on effects on other components, it has been now accepted that ERA shall evaluate the risk on both ecosystems and on its component's scales as well as the magnitude of the likely damage; nevertheless, very little work has been so far published on this approach (Lemly, 1996; Xu *et al.*, 2004). The concept of an ecosystem approach is that abiotic and biotic components that determine the structural and functional characteristics of wetlands are inseparable. Each of these components should be identified, and their contribution to ecosystem functions determined in order to assess whether the stressor is a risk to the sustainability of a given wetland. An understanding of external and internal factors regulating the functioning of a wetland is critical for risk characterisation. Determining the links between these factors and how they influence the way 'stressors' affects wetlands is the basis for an ecosystem approach. Consideration of all components such as ecology, hydrology, geomorphology and soils can greatly reduce the uncertainty associated with risk assessment and lead to more effective risk management.

### I-6.1. Source – Pathway – Receptor Concept

The Source – Pathway – Receptor (S-P-R) framework has been broadly accepted in hydrogeological risk assessment and is a technique to define pressures and targets and links between them, as suggested in the above

ecosystem approach. Most common pressures on groundwater and further groundwater dependent terrestrial ecosystems of wetlands are: groundwater abstraction, drainage and groundwater pollution from diffuse or point sources. These pressures impact upon the state of groundwater body, causing a reduction in the groundwater heads, affecting flow rates, changing flow patterns and the deteriorating quality of the groundwater in aquifers. In hydrogeological risk assessment, groundwater and the groundwater body as a whole is usually considered as a target in itself. But in the case of wetlands, the groundwater aquifer, and more precisely the groundwater flow is a pathway through which the effects resulting from pressure are propagated and passed on to wetlands ecosystems causing environmental damage. Therefore there are two elements within the S-P-R wetland framework that are sensitive to these pressures; firstly the pathway and secondly the receptor.

The sensitivity of the first of the two elements is very much controlled by the physical properties of the aquifer, which further controls groundwater flow rates and impact transmission. The intrinsic properties of the medium will have an important bearing on flow patterns and rates and thus a good understanding of the local geology in a spatial sense becomes vital when evaluating the vulnerability of the aquifer. For example, superficial aquifers which usually have higher permeability than bedrock aquifers have higher a potential to propagate impacts across the aquifer in relatively short periods. Nevertheless, preferential flow paths found in karstified bedrocks usually have even higher flow velocities than superficial deposits and their largely unknown flow paths (which are difficult to detect) give rise to many uncertainties which again induce high sensitivity of the pathway element. Large aquifers with long pathways, long residence time and significant storativities will be less sensitive to drainage and abstractions than small aquifers; nevertheless, the distance between stressor and target is important.

Every ecological receptor (e.g. wetland, selected protected species) has it own vulnerability to certain impacts. It is very important to define the receptor precisely, as in systems as complex as wetlands are, different species of fauna and flora have different levels of tolerance to change. Therefore, firm definitions and criteria are needed to evaluate the sensitivity of a receptor. The sensitivity of a receptor is likely to be correlated to the size of a receptor, but in the case of a plant species will depend on its ability to adapt physiologically. The most sensitive receptors are often used as early warning indicators, which will be discussed in more detail in I-6.3.

To conclude; when assessing risks to wetland groundwater dependent ecosystems, a broad picture of this system, including these variable elements which define a wetland, and their accessibility to impact shall also be considered. Only then, when impact transferring mechanisms are known, will a risk evaluation be valid.

## I-6.2. Risk Sssessment Procedures

The Convention on Wetlands (Ramsar, 1971) drew a conceptual framework for wetland risk assessment, which was adopted during the 7$^{th}$ meeting of the Conference of the Contracting Parties in San José, Costa Rica, in May 1999. This framework provides guidelines on how to predict and assess change in the ecological character of wetland and promotes the usefulness of early warning systems. The Wetland Risk Assessment Framework is presented as an integral component of the management planning process for wetlands (Ramsar Convention, 1999). To ensure the appropriate application of early warning indicators (systems), it is necessary that selecting,

assessing, analysing and basing decisions on indicator responses are structured in an assessment framework. A basic model for wetland risk assessment consists of 6 steps- Figure I-2:

1. **Identification of a problem** identifies the nature of the problem and defines the objectives and scope of, and provides the foundation for risk assessment. In general it identifies a source of impact, possible receptors and possible pathways of an impact.

2. **Identification of adverse effects** evaluates the extent of possible impact on a wetland. This information should be derived from field studies and cover quantitative field experiments and qualitative observational data.

3. **Identification of the extent of the problem** shall consider known previous behaviour of the wetland with reference to a given impact. Historical information based on other studies providing information about pathways of impact and reaction with an ecosystem, field and laboratory experiments and modelling are used for complimentary characterisation of the probable extent of an impact.

4. **Identification of the risk** consists of the integration of the assessment of likely effects and its level of adverse ecological change on wetland. Often, GIS techniques are used in characterising the risk. In this approach. various assessments are overlaid onto a map of the region of interest in order to link possible effects and identify problematic areas of impact.

5. **Risk management and risk reduction** is a final, decision making process utilising achieved information and understanding of a system with an attempt to minimise the risk without compromising other societal, community or environmental values. The risk management considers all possible aspects; including political, social, economic, and technical as well as other benefits and the limitations of risk reducing actions. It requires communication between experts in different disciplines.

6. **Monitoring** is an action taken to verify the effectiveness of the risk management decisions. It should incorporate components that function as a reliable early warning system, detecting the failure or poor performance of risk management decisions prior to the onset of serious environmental harm. Effective monitoring is necessary for the evaluation of a risk assessment and managerial action. The choice of end points to measure in the monitoring process is critical. A further GIS based approach is a useful technique for wetland risk assessment as it incorporates spatial dimensions.

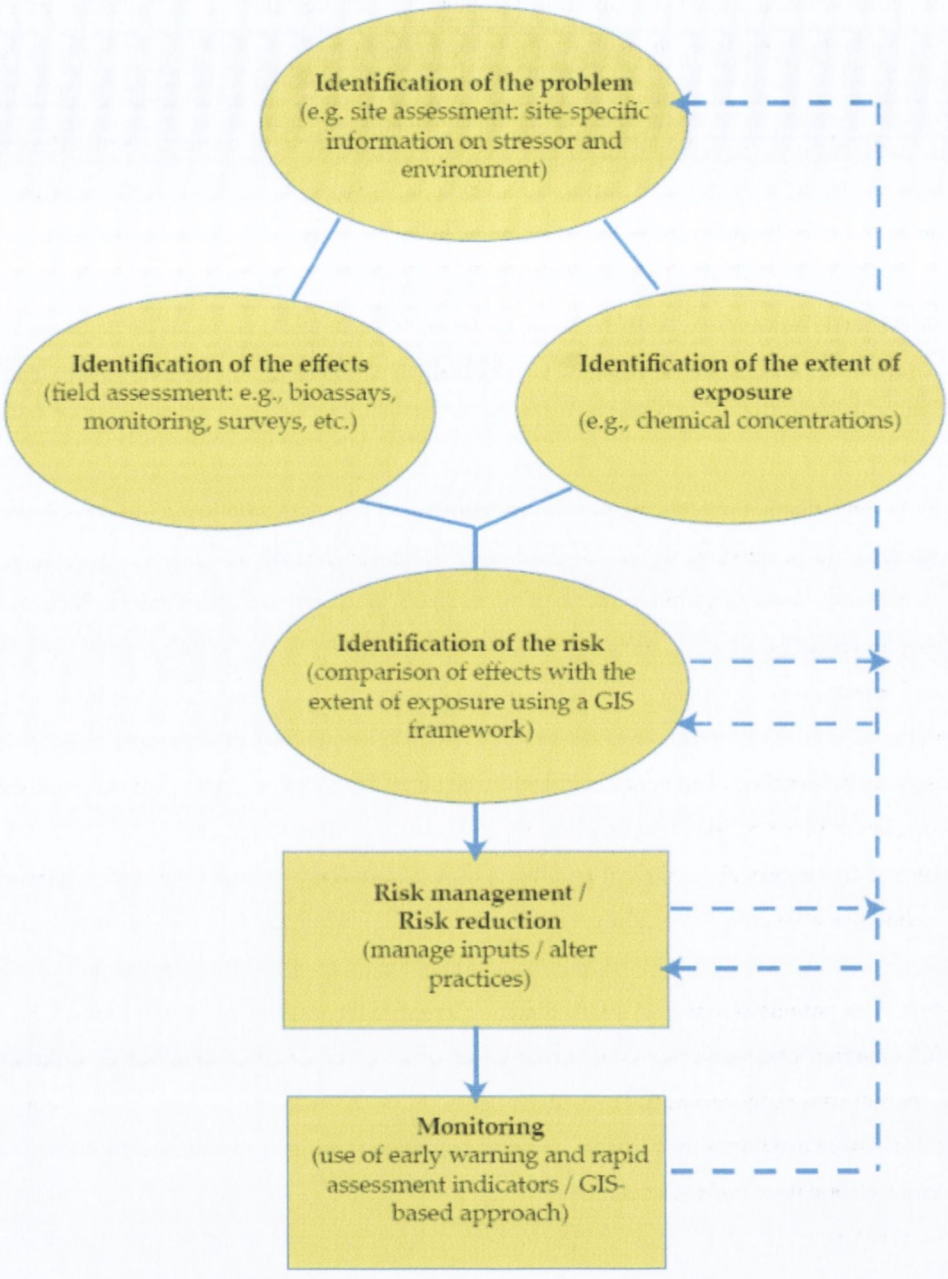



*Figure I-2 Elements of Wetland Risk Assessment Process, Ramsar Convention, 1999*

## I-6.3. Early Warning Indicators

The concept of early warning indicators is such that the effects of an impact can be detected and taken as a precursor of an actual environmental change. Such early warning indicators do not necessarily provide evidence of large scale environmental degradation; they provide an opportunity to determine whether intervention or further investigation is required. Early warning indicators, therefore, can be defined as the measurable biological, physical or chemical responses to a particular stress, preceding the occurrence of potentially significant adverse effects on the system of interest.

The choice of early warning indicators shall be preceded by careful analysis of an issue of concern, and determining the environmental value to be protected. Measurement of an ecosystem's 'surrogates' is usually required to determine the effect upon the ecosystem as a whole. Typically, these surrogates are communities or assemblies of organisms; or habitat's species indicators where these were closely liked to ecosystem level effects. When selecting an ecological indicator, it is necessary to consider different types of possible effects (such as biological, chemical and physical) on the ecosystem. It is therefore advisable to select such indicators that will be susceptible to all of these three components. Ideal attributes of early indicators are (Ramsar Convention, 1999):

- Anticipatory – it should occur at the levels of organisation, either biological or physical, that provide an indication of degradation, or some form of adverse effect, before serious environmental harm has occurred;
- Sensitive - in detecting potentially significant impacts prior to them occurring, an early warning indicator should be sensitive to low levels, or early stages of the problem;
- Diagnostic - it should be sufficiently specific to a problem to increase confidence in identifying the cause of an effect;
- Broadly acceptable - it should predict the potential impact from a broad range of problems;
- Correlated to actual environmental effects and ecological relevance - an understanding that continued exposure to the problem, and hence continued manifestation of the response, would usually or often lead to significant environmental (ecosystem-level) adverse effects;
- Timely and cost effective - it should provide information quickly enough to initiate effective management action prior to a significant environmental impact being felt, and be sufficiently inexpensive to measure while providing the maximum amount of information per unit of effort;
- Regionally or nationally relevant - it should be relevant to the ecosystem being assessed;
- Socially relevant - it should be of obvious value to, and observable by, stakeholders or predictive of a measure that is socially relevant;
- Easy to measure - it should be possible to measure using a standard procedure with known reliability and low measurement margin of error;
- Constant in space and time - it should be capable of detecting small changes, and of clearly distinguishing a response that is caused by some anthropogenic source and not by natural factors as part of the natural background (that is, high signal to noise ratio);
- Non-destructive - measurement of the indicator should be non-destructive to the ecosystem being assessed.

The importance of these attributes cannot be over emphasised, since any assessment of actual or potential changes in ecological character will only be as effective as the indicators chosen to assess them. However, an early warning indicator possessing all of the ideal attributes cannot exist, as in many cases some of the attributes will conflict, or will simply not be identifiable.

Inclusion of early warning indicators in a monitoring programme implies a protective management approach; that is, intervention before real and important ecosystem level changes have occurred. Intervention in response to changes in an early warning indicator, therefore, occurs at a conservatively specified threshold trigger value.

The most powerful impact assessment programmes will generally be those that include two types of indicator, namely those associated with early warning of change and those closely associated with ecosystem level effects. The 'ecosystem-level' type indicator might include ecologically important populations (e.g. indicator species) or habitat, or communities of organisms that serve as suitable ecosystem 'surrogates'. With both types of indicators measured in a monitoring programme, information provided by 'ecosystem level' indicators may then be used to assess the ecological importance of any change observed in an early detection indicator.

## I - 7. Study Overview

### I-7.1. Reason for the Study

Fen margins are considered to be very rich and biologically diverse ecosystems. Complexity of groundwater delivery to these sites through complicated systems of springs and seepages, although hydrologically difficult to describe, is acknowledged by the presence of many semi aquatic species of wetland plants, which flourish along the edge of a wetland supporting a plentiful variety of fauna (O'Connell, 1987; Otte, 2003). These species often include rare and protected types of animals, which are restricted to these ecosystems only. The availability of minerals and nutrients being delivered with groundwater fluxes is what makes margins of fens favourable habitats for many alkaline water loving species (Porporato *et al.*, 2002). Usually the supply of alkaline groundwater takes place all year round; however, discharge rates and seepage areas vary seasonally depending on groundwater heads. These are jeopardised by local abstractions, dewatering and drainage, decreased recharge due to climatic change or alteration in catchment structure. Hydrological controls of these habitats have not been widely examined as yet, especially not in a quantitative manner. It is, however, accepted that water supply is the key for sustainability of these habitats. Hydrogeology and its relationship to ecology in this kind of environment are believed to be site specific. There is no published information on fen margin hydrology in Ireland.

Pollardstown Fen is the largest calcareous, spring fed fen in Ireland, and has been designated a Special Area of Conservation under the EU Habitats Directive and a European Council Biogenetic Reserve. Three habitats listed in Annex I of the EU Habitats Directive occur in the area: alkaline fen, calcareous fen and petrifying springs with tufa[3] formation. Annex II of the Habitats Directive lists species whose habitat must be protected and these include a number of species from Pollardstown Fen of which Geyeri's whorl snail (*Vertigo geyeri*), Des Moulin's whorl snail (*Vertigo moulinsiana*) and the narrow mounted whorl snail (*Vertigo angustior*) are known to be rare and declining species in Europe.

Ecological monitoring of the fen has been carried on since 1994, although the site had already gained the attention of scientists in 1976, when it was included in the list of Areas of Scientific Interest in Kildare (WYG Ltd, 2004). It was 1994 when, following the EU Habitats Directive obligations, Pollardstown Fen was selected

[3] Tufa formation is associated with hard water springs, where groundwater which is rich in calcium bicarbonate comes to the surface. On contact with the air, carbon dioxide is lost from the water and a hard deposit of calcium carbonate (tufa) is formed; $Ca(HCO_3)_2\ (aq) \rightarrow CO_2\ (g) + H_2O\ (l) + CaCO_3\ (s)$. These conditions occur most often in areas underlain by limestone or other calcareous rocks. Tufa is white or cream in colour and forms on plant stems or between moss patches. The deposit may be quite solid and crunchy or be present in the form of a soft coat on the ground surface.

for inclusion in the Special Area of Conservation list. Hydrological monitoring began in 1997 and was initiated to facilitate ecological monitoring.

More intensive monitoring of the fen was initiated in 2001 as a result of the construction of the Kildare town bypass, a new road scheme proposed approximately 3.5 km southwest of the site. The reasons for monitoring originated from an unusual design proposal, which suggested building the road in a 4.5 km long deep cutting, 3.5 km of which was below the water table. Because of this cutting, 5.5 million gallons of water would have been lost per day from the Curragh aquifer – an extensive gravel plain of an area of more than 200 $km^2$ with discharge into, among others, Pollardstown Fen. The first plan of the road was proposed in 1982 and the E.I.S. was completed in 1993. This was objected to particularly regarding dewatering, which was necessary for the duration of the road construction project. The proposed design caused a vigorous public debate about how the road would affect nearby sites like Pollardstown fen, whose ecology was believed to be highly dependent on the water supply from the Curragh aquifer; however, specifics of the ecosystems' dynamics and eco-hydrological links were not well defined at the time. Disagreement over the design and possible environmental impacts were heard by the Minister of the Environment (1996) who ordered the road to be raised by 2 metres (which was still below the water table). This did not satisfy objectors (e.g. An Taisce) and the case was brought to the EU council, which ordered a halt to construction until a full hydrological investigation was completed. Numerous hydrogeological investigations were conducted and a numerical groundwater flow model was designed by Rushton (Entec, 1999). The assessment concluded that any loss of water to the fen could be replaced with artificial recharge *i.e.* pumping water back into the aquifer, so that it would then flow to the fen. This proposal was again rejected and construction was postponed until an agreement was reached between interested parties (the county council, hydrogeologists and ecologists) with regard to a new design for the road. Kildare County Council proposed tanking[4] underneath the road, protecting the regional flow patterns but requiring temporary dewatering within short sections of the road during construction. A full monitoring and assessment of possible ecological impacts on the Curragh aquifer and adjusted locations including Pollardstown Fen was ordered. This consisted of several components including hydrological modelling, monitoring at the regional scale, a 'fen interface study' (designed to describe the connection between the local and regional water systems), and detailed hydrological and ecological monitoring of relevant snail sites within the fen (K.T. Cullen, 2001). This thesis results from this order. Specifically, this project was initiated to observe and analyse the eco-hydrological regime of the fen margins.

## I-7.2. Aims, Objectives and Originality of this Work

This project was designed to study hydrological conditions existing within the fen margin and to define how this hydrological regime controls a specific habitat typical to the fen's margin only. This habitat specifically refers to seepage zones, where many protected species and habitats listed in the EU Habitats Directive tend to occur. Following the Environmental Risk Assessment framework, the project focuses on assessment of the margin's ecological sensitivity to changes in hydrological regime. The sensitivity of this environment will be studied using an early warning indicator species of snail *Vertigo geyeri*. Knowledge of the wetland's sensitivity to

[4] Tanking involves placing an impermeable liner underneath the road in a cutting and maintaining local water levels above the road level by means of control drains. Such design allows the post-construction water levels to rise above the pre-construction summer levels but not the original winter water levels, i.e. there will be some long-term dewatering during winter periods.

changes in hydrological regime is a vital element in wetland management practices and can be used to comply with objectives of the Water Framework Directive. This project aims, therefore, to enhance knowledge and understanding of these relationships and specifically to find out the following:

1) How the relevant changes in the water regime of the fen margin are transferred to the apparent operational environment of critical habitats and species?

2) What are the regional aquifer conditions that sustain the water regime of the fen margin as required by critical habitats and species?

The critical habitat was defined as the suitable environmental conditions for the existence of the mollusc species *Vertigo geyeri*, listed in Annex II of the Habitats Directive. The snail was chosen as an indicator species due to its very small size (1-2 mm) and limited movement abilities, which infers that the species is very sensitive to environmental change and will quickly reflect undesirable trends. The stability of the habitat that the mollusc lives in is of high importance for the survival of the species. The hydrological controls of the snail habitat are unknown at present, although humidity is considered to be an important factor.

Although extensive dewatering of the aquifer due to construction of the Kildare bypass was ongoing while this study was carried out, assessment of the effects of dewatering was not the aim of this research.

In order to address the research questions, work was focussed on the following three specific objectives:

1) Firstly, the work focussed on developing a comprehensive understanding of the workings of the Pollardstown fen ecosystem and its relationship with regional hydrogeology. Emphasis was put on quantitative flow analysis, flow directions, interface with the Curragh aquifer and different mechanisms of discharge (springs and seepage zones). This facilitated building a conceptual model about how the groundwater is being discharged into the fen margins. Water balance analysis was employed to quantitatively assess all hydrological inputs and outputs.

2) Secondly, the microhabitat of the indicator species *Vertigo geyeri* in terms of micrometeorology, microtopography and microhydrology was studied in order to establish the key local elements controlling the presence of the indicator species on site.

3) The third objective was to establish hydrological controlling factors for the sustainability of the habitat in which the indicator species lives. These controlling factors were established on both local and regional scales. This allowed assessing sensitivity of this habitat to changes in regional hydrogeology *i.e.* potential anthropogenic pressures.

The originality of this work lies in the following:

a) Fen's margin microhabitats have not been studied on a similar scale before and this study provides new information about the micrometerological and microhydrological conditions of this environment.

b) Quantitative information on *Vertigo geyeri's* preferred habitat was not available before this study was initiated, and provides the first description of microhydrological and micrometerological conditions that the species requires for living. Specific emphasis was placed on the hydrological regime that supports the snail habitat; and this was achieved.

c) Also, taking into account the complexity of wetland ecosystems, and the physical difficulties restricting measurements, quantitative hydrological regime analyses are not very common at a similar scale to this study is. In this study, in total 46 observation points were monitored and the comprehensive groundwater flow regime was determined. Detailed survey of springs and seepages provides in-depth documentation on Pollardstown Fen's hydrological inputs. Employment of a weather station within the fen site allowed precise measurement of climatic conditions and subsequently estimation of evapotranspiration losses within a fen wetland. This improves understanding of Pollardstown Fen's hydrology and provides more information for general wetland studies.

d) The final outcome of the project is that critical groundwater levels controlling the existence of the species at the fen margin were defined locally and translated into regional trigger levels. These define minimum groundwater levels within the Curragh aquifer that are required to sustain the fen margin in its optimum state of conservation. This is valuable information for further management of groundwater resources in the Curragh aquifer, specifically in light of the Water Framework Directive.

## I - 8. Structure of the Thesis

Because of the complexity of this project and extremely wide range of data that were collected during the project, the thesis was structured into six chapters, which hopefully will make it easy for the reader to follow. This chapter is an introduction to the project and focuses on theoretical background about wetlands and wetland eco-hydrology, legislation and risk assessment. The second chapter summarises the geographical, geological and hydrological features of the study area and introduces the investigation sites including the instrumentation. A review of the literature concerning the *Vertigo* family is also provided to introduce the reader to the indicator species. Chapters three and four focus on experimental aspects of the work and summarise the results of the research that refers to the first two objectives stated above. Hence, chapter three describes the hydrogeology of the fen from the view of its regional settings and chapter four describes the microhabitat of the snail *Vertigo geyeri*. Quantitative analyses are followed by presentation of a conceptual model of the groundwater discharge mechanism at the fen margin and micro meteorological and hydrological requirements for the preferred snail habitat. Chapter five fulfils the third objective of the study and presents the hydrological conditions that control the snail's presence within the fen margin. These local controlling factors were translated into the regional picture and so are available on two levels. The sixth and final chapter provides the summary and the synthesis of the project. Recommendations are included.

# II Chapter Two: Pollardstown Fen: Hydrology, Geology and Ecology

The ecology of Pollardstown Fen depends on groundwater supply from the Curragh aquifer, which constitutes the largest gravel aquifer in Ireland and for its large area and high yields it is recognised in the country as 'regionally important' (Hayes *et al.*, 2001). During the Pleistocene period, a series of glacial retreats resulted in current Irish geomorphology, particularly the Curragh glacial outwash plain. A short geological description of the region is a necessary precursor to an understanding of the characteristics of Pollardstown Fen.

## II - 1. Regional Settings: Physiology, Geology and Hydrogeology

### II-1.1. Introduction

County Kildare is an inland county of 1,688 $km^2$ located in the east of Ireland between 275 494 E and 215 390 E and 268 653 N and 222 058 N. It is bounded on the south by County Carlow, to the west by counties Laois and Offaly and to the east by counties Dublin and Wicklow. Meath bounds Kildare to the north. The county is dominated by low lying and flat topography. Approximately two thirds of the county is less than 100 m OD. The county may be divided into three main physiographic regions, which are presented in Figure II-1:

- The Plainlands occupy the central and southern plains, the west central lowlands and the northwest boglands. The plain of central and southern Kildare varies from very flat to strongly undulating. The west central lowlands are characterised by raised bogland, which was formed after the last glaciation. This region is drained by the River Barrow and its tributaries. Elevation in this area varies from 60 m to 100 m OD.
- The East Kildare uplands – these uplands occupy a narrow strip which runs along the Kildare/Wicklow county boundary to the southeast of Kill and host the highest point in the Kildare region, which is 349 m OD.
- The Chair of Kildare and the Newtown Hills comprise a ridge of low hills trending northeast-southwest between Kildare and Rathangan. Redhills, the most southerly of the hills, rises to a height in excess of 138 m OD. Dunmurray Hill, immediately to the north of Redhills, reaches 234 m OD and Grange Hill (known as Chair of Kildare) reaches 226 m OD. These three hills are separated from the Hill of Allen (202 m OD) by almost 3 km of lower plain (92 m OD).

Pollardstown Fen lies on the northern edge of the central Curragh Plain, which is the dominant landscape surrounding Kildare town. The Curragh Plain will be described in more detail in a later section.

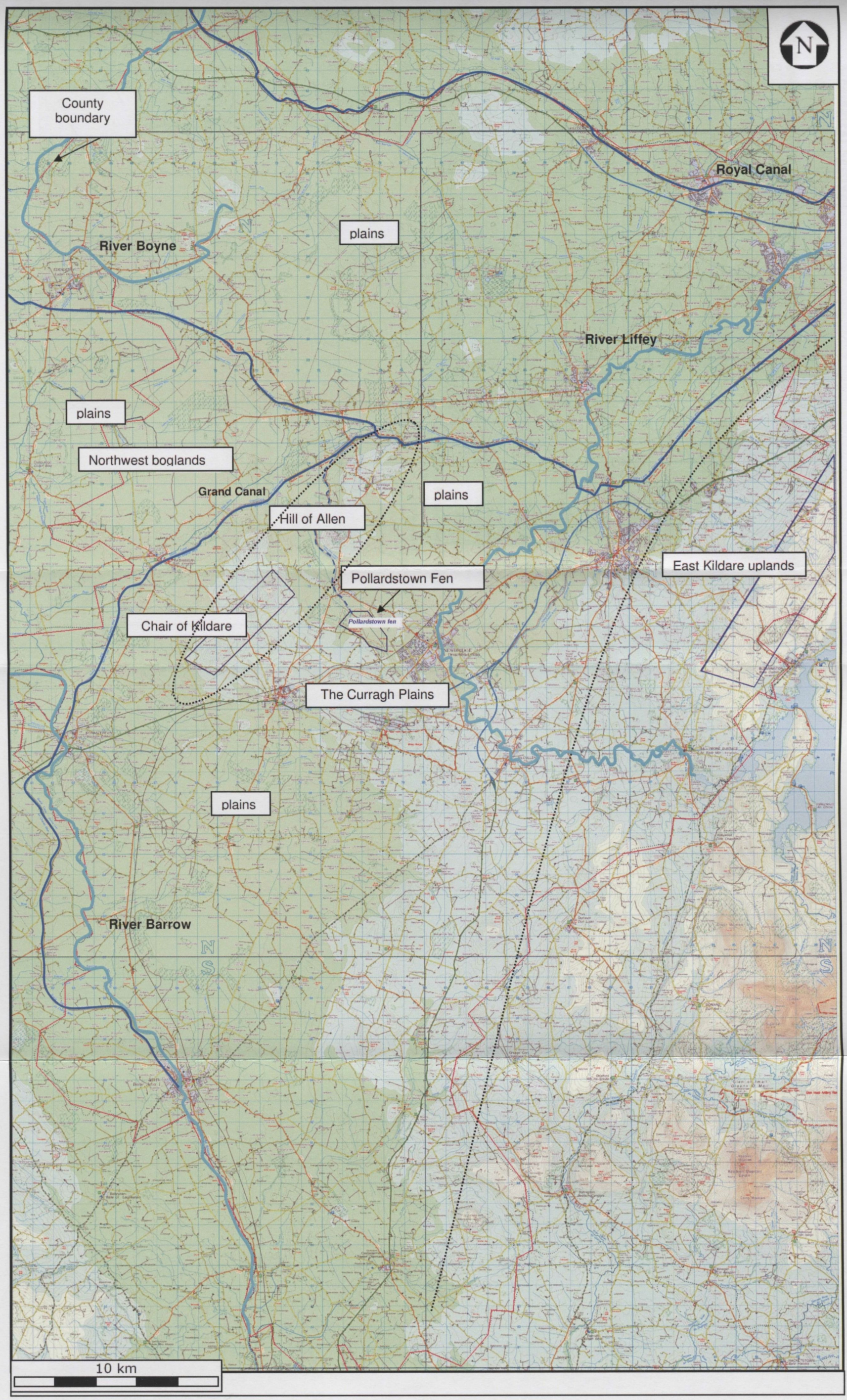



*Figure II -1. Physical Characteristics of County Kildare*

## II-1.2. Geological Settings

The bedrock geology of Kildare County is discussed in the GSI publication 'Geology of Kildare – Wicklow', (McConnell *et al.*, 1994). The bedrock geology in the region can be divided into four groups based on lithological variation (Figure II-2):

1. Lower Palaeozoic slates, volcanic rocks and Old Red Sandstone formations.
2. Silurian rocks.
3. Tullon Granite Pluton.
4. Carboniferous limestone.

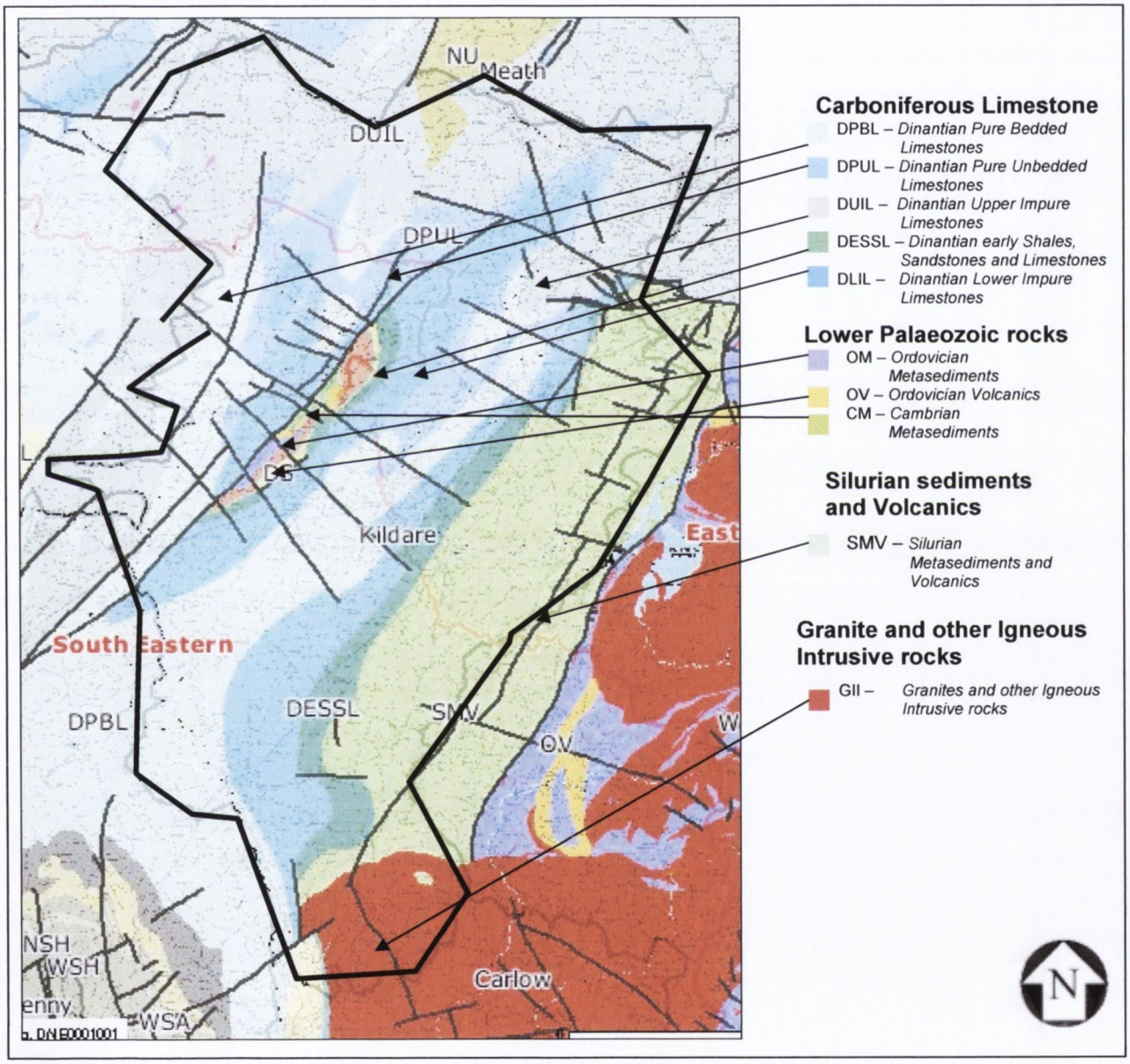



*Figure II-2 Bedrock geology map of Kildare County. Not to scale. Source: www.gsi.ie*

The oldest rock units in the area are Cambrian Metasediments, Ordovician Volcanics and Ordovician Metasediments which were deposited in the Lower Palaeozoic. These rocks outcrop in the northeast trending line of hills, from Hill of Allen to Grange Hill and to Dunmurry Hill (Chair of Kildare). The northwestern margin of this inlier (known also as Kildare Inlier) is a fault, lying against Carboniferous limestone and the southern margin is an unconformity with overlying Old Sandstone conglomerates and other sandstone. Old Red

Sandstones are Devonian sediments, which were deposited following the uplift and partial erosion of the Lower Palaeozoic rocks. Lower Palaeozoic rocks are also found in the southeastern part of the county (Silurian Metasediments and Volcanics), which consist mainly of greywacke and shale and were deposited primarily as turbidities. Granite and other igneous rock intrusions originated during the Devonian period, Caledonian orogeny, and are found mainly on the southern edge of the county. These rocks are part of the Wicklow Mountains chain.

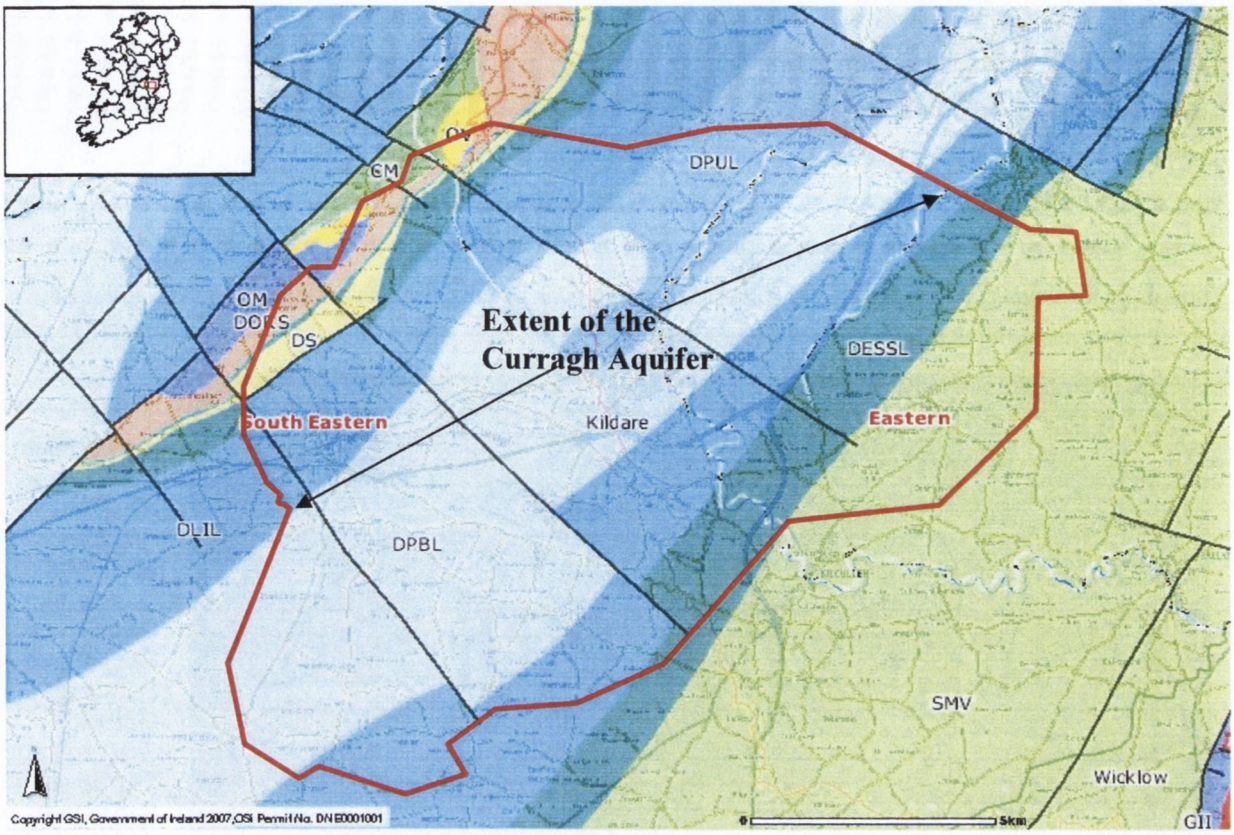
The land subsidence that occurred during the Carboniferous Period in the Upper Palaeozic led to extensive ingress of seawater into lower ground and this resulted in an accumulation of marine sediment comprising intertidal laminated mud and sand. The type of sediment being accumulated was dictated by the depth of the sea in a given location, and so progressive subsidence caused shallow water sediments to be deposited below the deep water marine sediments. These deposits are currently broadly described as Carboniferous limestone and large numbers of different formations have been identified. Based on the 1:100,000 scale bedrock geology map (GSI, Sheet 16), dominant rock units close to the study area are the Rickardstown Formation (RK), Waulsortian Limestone (WA) and the Boston Hill Formation (BN), Figure II-3. All formations were formed during the Chadian-Arundian age and belong to the Lower Carboniferous, Dinantian systems.

The Rickardstown limestone is cherty; often dolomitised limestone and the GSI distinguished two distinct horizons in this formation. The lower is notably varied and includes thin interbedded units of nodular crinoidal, cherty micrite and fossiliferous shale. The upper part consists mainly of rather uniform, moderately dark grey, fine grained dolomite with abundant chert. The Waulsortian Limestone is massive unbedded fine-grained limestone which consist mainly of pale grey biomicrite. Boston Hill Limestones consists mainly of uniform, thick successions of nodular and diffusely bedded, argillaceous fossiliferous limestone and thin shale. The Boston Hill Formation includes major units of very distinctive, laminated fine limestone, which distinguish this formation from the Ballysteen Formation.

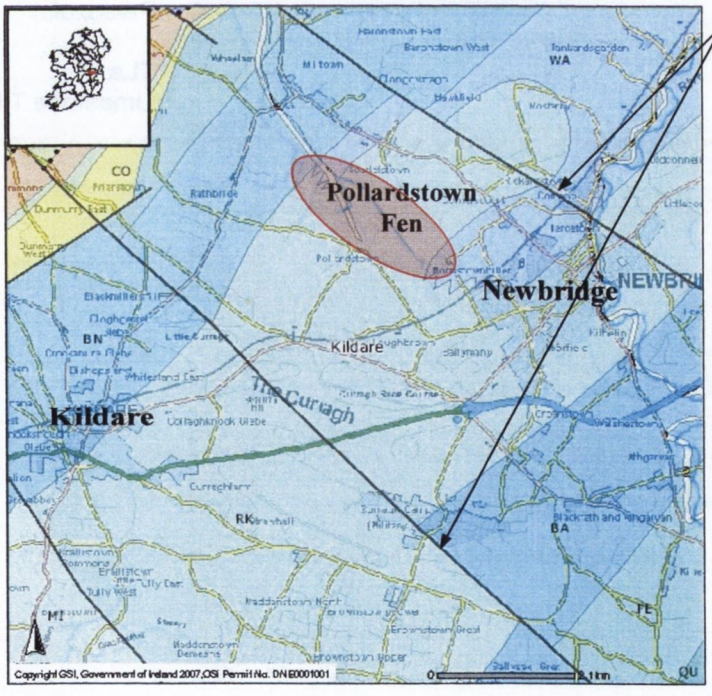
The area around Kildare, especially in a northwestern direction, is extensively cut with faults running predominantly in northwest-southeast direction. Pollardstown Fen lies between two such faults, one located approximately 1.5 km northeast and the second some 2.5 km southwest of the study area.

With respect to regional Quaternary history; this was mapped by the Geological Survey of Ireland, Teagasc and the EPA (www.gsi.ie). The following main types of subsoil were identified in the region: till (boulder clay); sand and gravel; till with gravel; alluvium and peat. Spatial regional distribution of these sediments can be seen in Figures II-4 – II-5. Generally, the majority of the county is covered with superficial deposits of till. Till, often described as boulder clay, is a diverse material, which is deposited sub glacially and has a wide range of characteristics, due to the variety of parent materials and the different processes of deposition. The majority of tills in Kildare county are derived from limestone bedrock, but some deposits derived from sandstone and shale are also present. Sand and gravel are deposited usually when glaciers melt. Large volumes of meltwater have high energy levels and cause extensive surface erosion. With the flow of meltwater, large quantities of eroded materials are transported and deposited on the bottom or dropped at the front of the glacier.

a)




b)




Faults

***Legend:***

***DPUL*** – *Dinantian Pure Unbeded Limestone*

***DPBL*** –*Dinantian Pure Bedded Limestones*

***DLIL*** – *Dinantian Lower Impure Limestones*

***SMV*** – *Silurian metasediments and volcanics*

***DESSL*** – *Dinantian Early Sandstones, Shales & Limestones*

***DS*** – *Dinantian Sandstone*

***DORS*** – *Devonian Old Red Sandstones*

***OM*** – *Ordovician Metasediments*

***CM*** – *Cambrian Metasediments*

***OV*** - *Ordovician Volcanics*

***WA*** – *Waulsortian Limestones (Carb. Limestones)*

***BA*** – *Ballysteen Formation (Carb. Limestones)*

***RK*** – *Rickardstown Formation (Carb. Limestones)*

***BN*** – *Boston HillFormation (Carb. Limestones)*

***FE*** – *Feighcullen Formation (Carb. Limestones)*

***CO*** – *Croughaun Formation (Carb. Limestone Shales)*

*Figure II-3 Bedrock geology map of the area surrounding (a) the Curragh aquifer; and (b) Pollardstown Fen. Source: www.gsi.ie*

Being of granular nature, these deposits can store water in porous spaces between their own particles and as such they act as undergroundwater reservoirs. Large quantities of sand and gravel in the Kildare region form a glacial outwash plain which hosts the present Curragh aquifer. Sand and Gravel deposition is often reflected in topography as eskers, hummocks and hollows, or large outwash deltas, all of which provide storage for groundwater. In the Kildare region, there are numerous occurrences of small eskers. Alluvial deposits are those associated with river flow aligned along the main rivers of the Kildare region: the Liffey, the Barrow and the Boyne. There are a few areas of peatland in County Kildare with the majority being raised bogs located in the middle of the county: Allen, Boora and Clonast, all raised bogs but also the groundwater fed fen at Pollardstown.

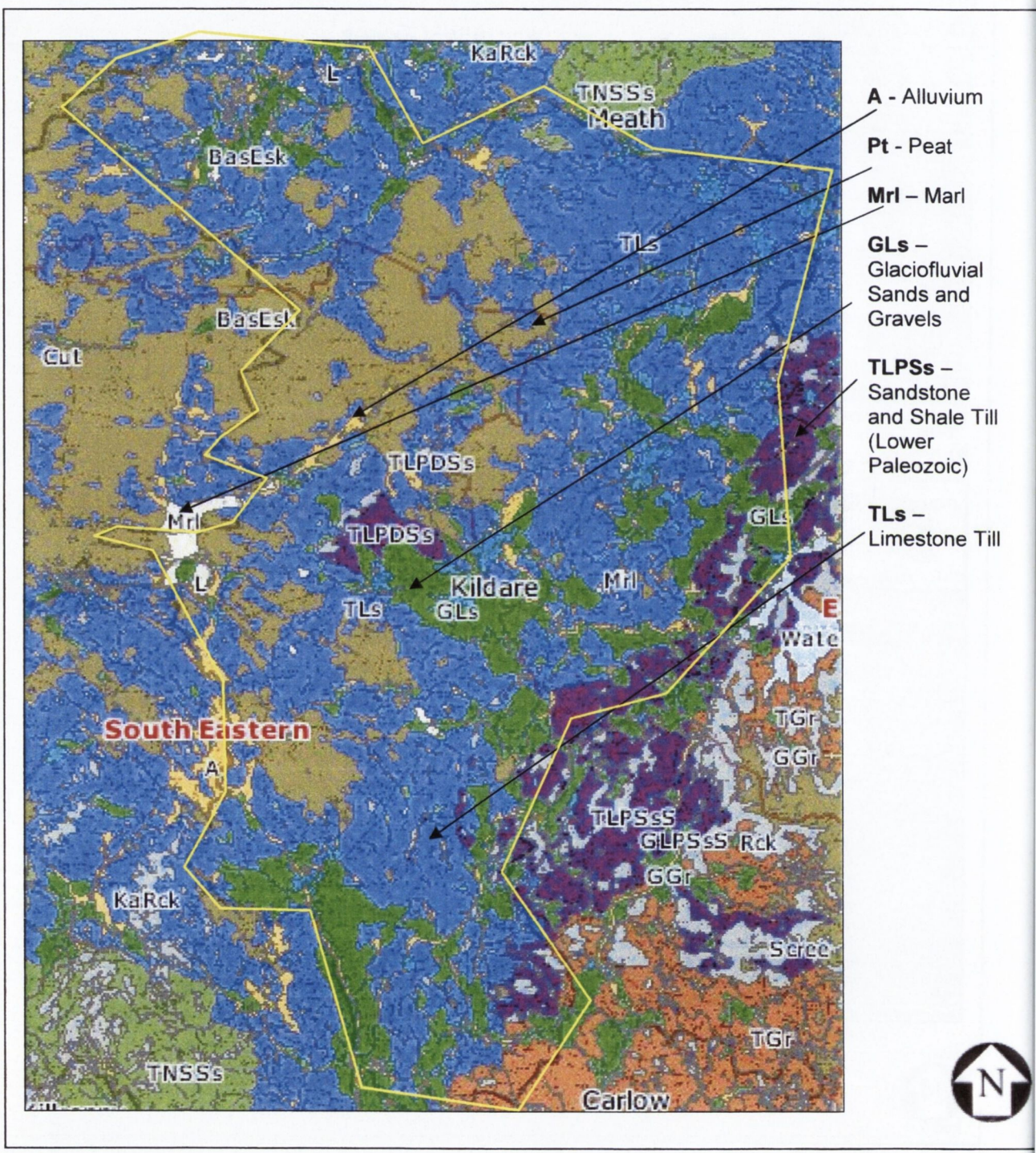



*Figure II-4 Quaternary map of Kildare County. Source: www.gsi.ie*

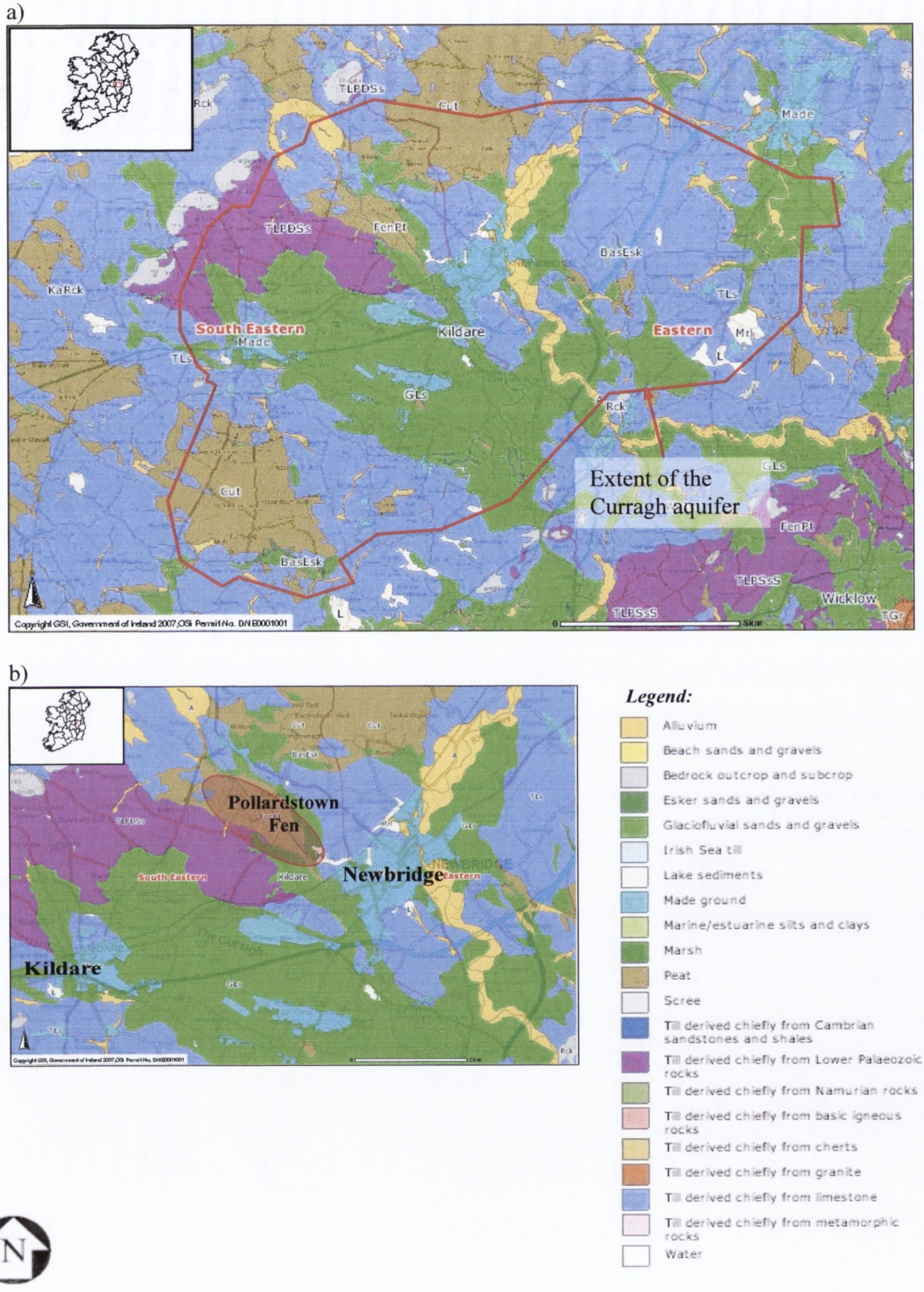



*Figure II-5 Quaternary geological map of the area (a) surrounding the Curragh aquifer; and ( b) Pollardstown Fen. Source: www.gsi.ie*

## II-1.3. Surface Drainage

In terms of surface drainage, there are three major rivers in the area, namely the Barrow, the Liffey, and the Boyne. The closest to the study site is the River Liffey, which runs approximately 3 km to the east of Pollardstown Fen, through Newbridge town, and it drains in a northeasterly direction, Figure II-1. The river rises in the Wicklow Mountains, approximately 30 km southeast of Kildare town and flows west before swinging northwards at Kilcullen. It meanders through Kildare before turning east toward Dublin, where it discharges into the Irish Sea. The northern parts of the county are drained the by River Boyne and its tributaries, including the River Blackwater. The river rises near Edenderry (Co. Offaly) some 30 km northwest of Kildare town, and it flows in a northeasterly direction, entering the Irish Sea at Drogheda. The last large river in the area, the Barrow, rises in Slieve Bloom and the Devil's Bit Mountains, some 50 km west of Kildare; it drains western parts of the county. It drains first into the northeast and east and swings southwards at Monasterevin (10 km west of Kildare town). The river merges with the River Suir, east of Waterford town, where it discharges into the Atlantic Ocean. Regarding the study site, the Barrow runs approximately 18 km southwest of Pollardstown Fen. In addition, the Grand Canal, a man-made surface water channel built in the late 18$^{th}$ century, linking Dublin with the Shannon River, runs through the northern and western parts of the county. The Milltown Feeder, which originates at Pollardstown Fen, connects to the Grand Canal at Huband Bridge, west of Robertstown.

## II-1.4. The Curragh Plain

The dominant landscape in the vicinity of Kildare town comprises the Curragh Plain - an open area of semi-natural grassland and heath, based on a substratum of till. The plain has existed as an uncultivated and unenclosed plain for at least 2,000 years. It is one of Ireland's best known landscapes, probably the largest semi natural grassland in the country. The Curragh is approximately 1,971 hectares in area (4,870 acres) and extends for some 10 km in a northwest/southeast direction and is 5 km across at its widest. The main landscape qualities of the Curragh Plain derive from its geological origins. The very flat, though gently rolling topography of the Curragh has been formed on rocks of the Carboniferous limestone series and a variable covering of boulder clay, sand and gravel that overlies them. The land itself has been mainly uncultivated since prehistoric times, leading to present soil type and topography. Sand and gravel of the Curragh Plain form the Curragh or Mid-Kildare limestone aquifer. Water from the aquifer is rich in calcium carbonate and supplies the needs of the Curragh Camp, the National Stud and the Japanese Gardens. In addition, water emerges naturally from the aquifer around the margins of the gravel plain as a series of springs including those of Pollardstown Fen.

## II-1.5. Characteristics and Properties of the Curragh Aquifer

The properties of the Curragh aquifer have been studied by many, and an extensive geological and hydrogeological description is provided by Wright (1988), K.T. Cullen (1993), White Young Green Ltd. (2001, 2004) and MacCarthy (2008). The latter undertook a detailed investigation of the aquifer in order to assess the potential impact of the proposed construction of a bypass around Kildare town. Substantial amount of information was generated and includes geological coring information and hydrogeological modelling. This

extensive information was reviewed as part of the study but is outside the scope of this thesis, which focuses on the surface of the fen margin.

The Curragh aquifer occurs in an extensive glacial gravel deposition, which extends as far as Nurney and Suncroft in the south, the Hill of Allen in the north and near Kilcullen in the east, Figure II-6. To the east and northwest, the limits of the aquifer are defined by outcrops. Elsewhere, the edge of the aquifer is less clear as the outwash deposits pass laterally into a more till dominated glacial sequence. The central part of the aquifer is underlain by limestone bedrock with more resistant sandstone and volcanic rock forming the edges of a trough like structure. The thickness of the glacial overburden cover is estimated to be less than 20 metres in the area surrounding the Curragh. This increases to between 20 and 40 metres at the edges of the bedrock trough and ultimately extends to greater than 60 metres deep in the centre of the bedrock depression (Figure II-7). This shallow geology is characterised by little vertical or lateral continuity. The overburden sequence is a complex succession of outwash gravel interbedded with till and lake deposits, underlain at depth with outwash gravel. The topography consists of esker and lake features related to the final retreat phase of the last glaciation. Peat and alluvial deposits infill hollows within the overburden surface. Figure II-7 presents characteristics of some local geological features in the Curragh area.

Hydrogeological properties of the Curragh aquifer were first assessed by Aldwell of the Geological Survey of Ireland in the 1960s and 1970s (Wright, 1988). The yields of wells surveyed during the course of this work ranged between 0.0025-0.024 $m^3/s$ and all of them were placed in 'drift', which refers to Quaternary deposits including sand and gravel. A number of drilling and pumping tests performed by K.T. Cullen & Co. Ltd. in 1992/1993 (K.T. Cullen, 1993) indicated two distinct water bearing layers within the aquifer. The upper layer consists of clay and its transmissivity is much lower than the transmissivity of the gravel underlying the clay. The gravel layer was considered the primary aquifer. All wells were screened in gravel at a depth close to 16 metres below ground level. Established yields varied between 0.017 $m^3/s$ (Frenchfurze Road), 0.006 $m^3/s$ (Sewage Treatment Work) and 0.0026 $m^3/s$ (Greyabbey Road) which corresponds with previous findings. The above results indicate that the permeability of the subsoil varies with location, which is related to the complexity of local geology. However, an arithmetical mean for permeability (k) was established at a level of 53 m/day ($6x10^{-4}$ m/sec), (K.T. Cullen, 1993). Surface flow is absent in much of the Curragh area (Figure II-1), as aquifer recharge is considered to be 80-85% (Misstear & Brown, 2007, draft) and run off is taken as low (due to the high permeability of the subsoil and relatively flat topography). The groundwater discharges to the south through springs in the Japanese Gardens and further south into the King's Bog and the Tully Stream. To the north, the groundwater discharges into Pollardstown Fen and into Milltown Stream. To the east, aquifer discharges into the Liffey and on the west to a tributary of the River Barrow.

The nearest Met Eireann synoptic weather station in the area is Casement. The 30 year average (1961-1990) annual total rainfall at this station is 711 mm. Met Eireann calculates the potential evapotranspiration (PE) for the Casement station using the Penman Monteith (1948) equation with an average annual value of 524 mm/yr for the period of 1995-2001. Actual evapotranspiration (AE) is not available from the Met Eireann office, however, results of a recent EPA study evaluating groundwater recharge of the Kildare aquifer (Misstear & Brown, 2007, draft), indicate AE values ranging between 436-474 mm/yr (based on a 30 year observation period 1971-2005), allowing for a seasonal soil moisture deficit. The same study further suggests effective rainfall in the region of

321 mm – 366 mm which is in line with previous GSI estimates (McConnell *et al.*, 1994) suggesting effective rainfall (ER) at a level of 325mm/yr for the gravel aquifer.

The lowest water levels in the aquifer are usually recorded around October-November; however, there was a tendency toward an extended recession running until January during the 2004 and 2005 monitoring period. The highest water levels usually occur at the turn of February/March and annual fluctuations range between 1.25-2.5 metres, indicating high specific yield of the aquifer (porosity c. 30-40%), (Hayes *et al.*, 2001).

Generally, the aquifer is considered to be semi-confined by surface till deposits. At the top of the Curragh Plain, close to the groundwater divide in the aquifer, the groundwater table is unconfined and usually reflects the topographic surface. Close to the discharge points, particularly at the fen margins, where topography is steep and clay and peat overlay gravel, the piezometric surface becomes artesian. The regional groundwater flow towards the fen is generally in a northerly direction. The difference in hydraulic head between the fen margin and the groundwater divide at the top of Curragh is 3 metres maximum (Figures II-8 - II 9).

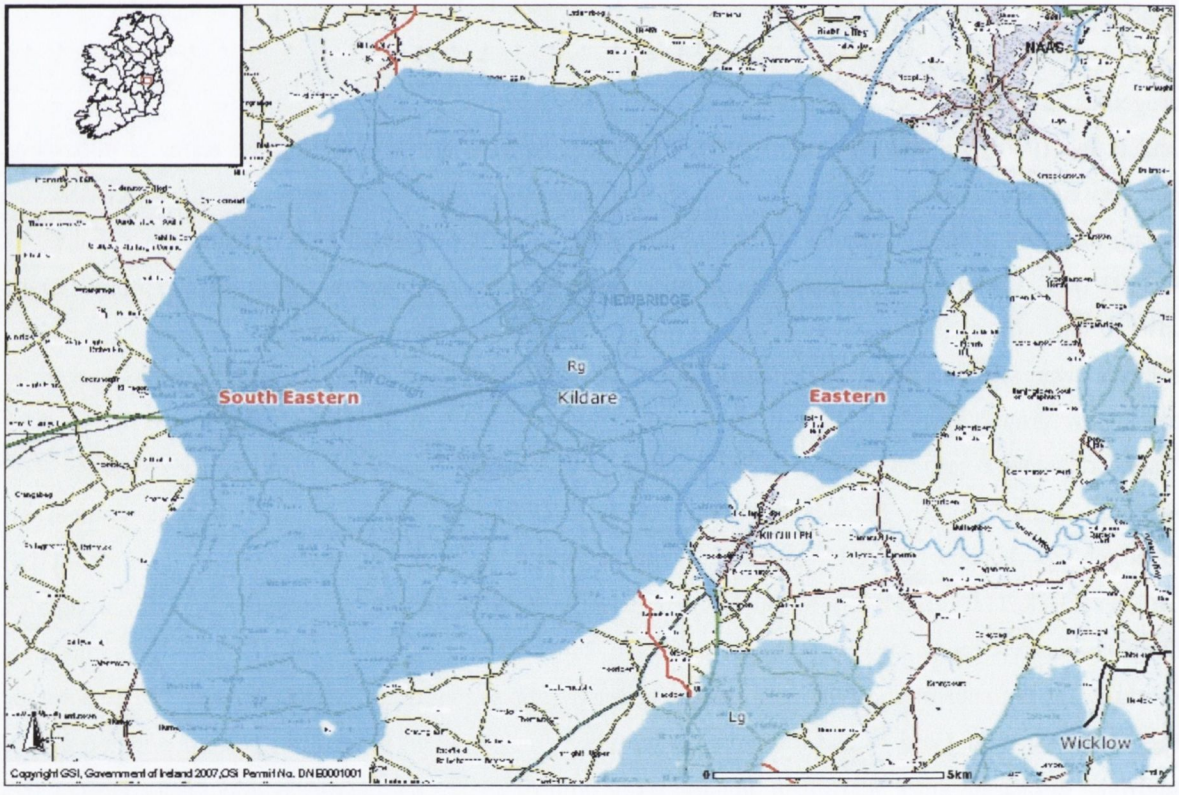
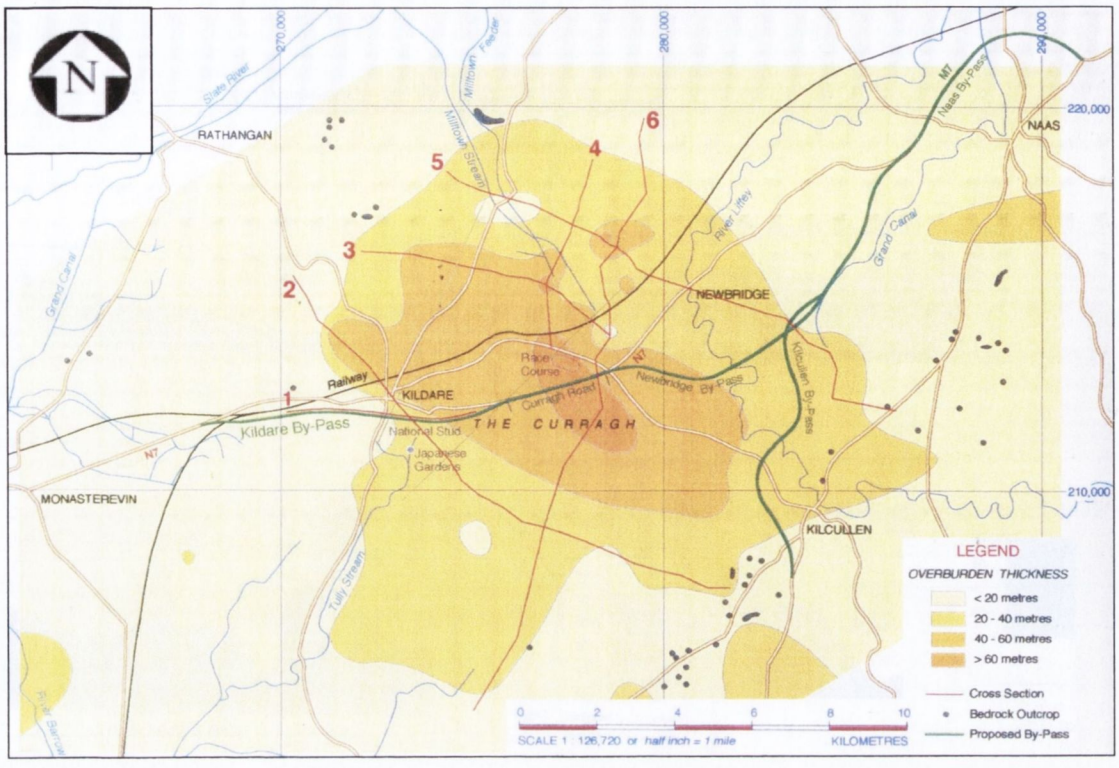



*Figure II-6 Extent of the Curragh aquifer. Source: www.gsi.ie*

a)

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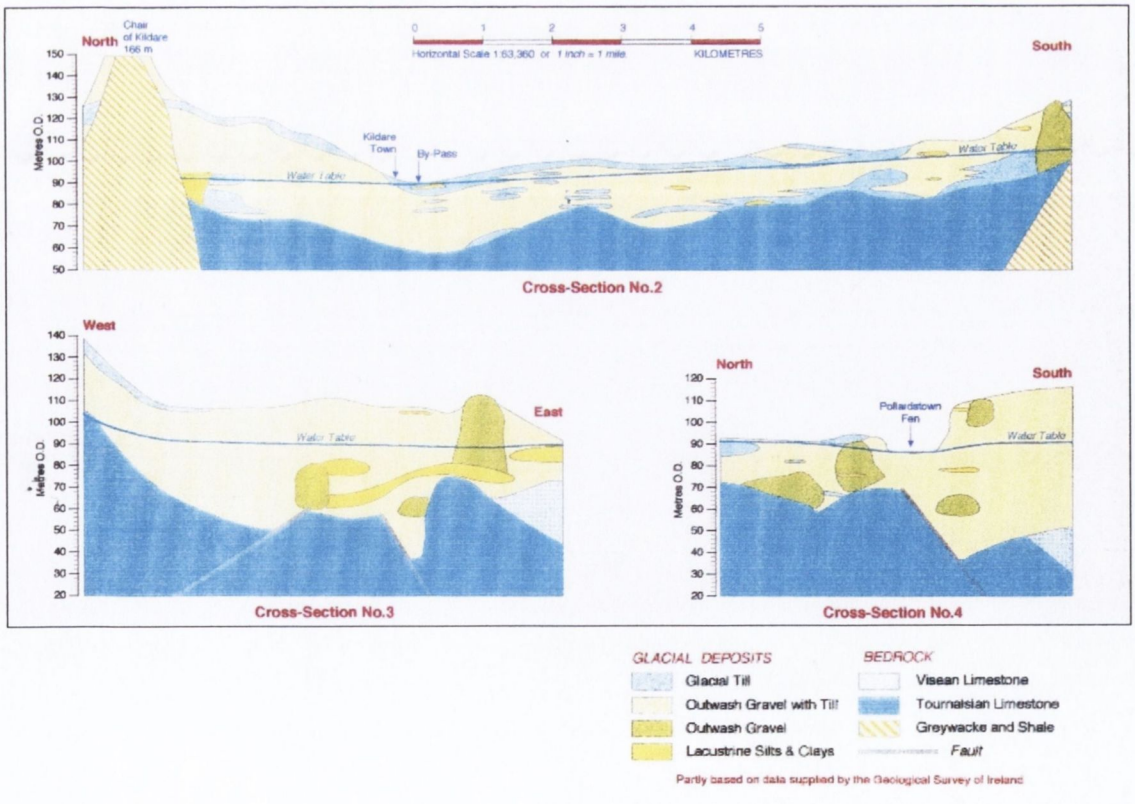



*Figure II-7 (a) Depth of postglacial gravel deposits within the Curragh aquifer; (b) Selected stratigraphical cross sections throughout the study area; after K.T. Cullen (1993).*

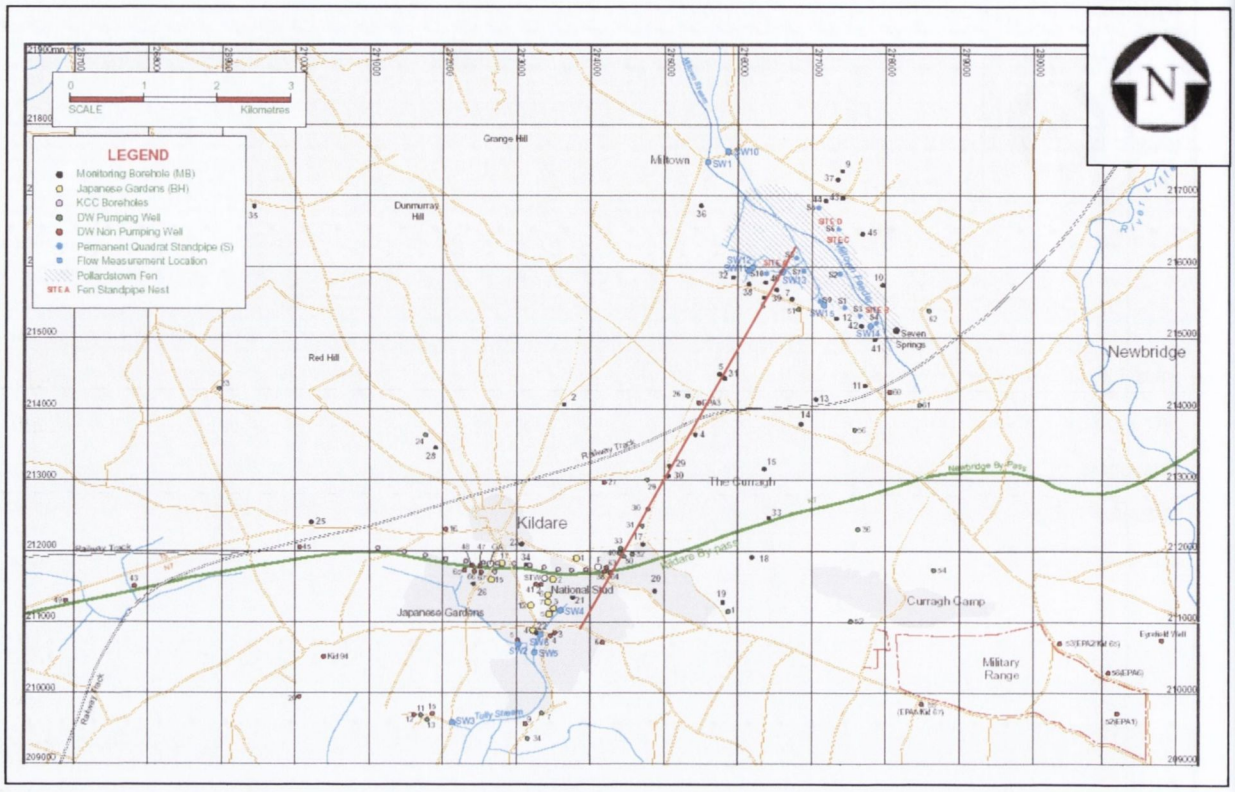



*Figure II-8 Location map of monitoring wells and drilled boreholes within the Curragh aquifer. Courtesy of While, Young & Green Ltd. The red line indicates the location of a cross section presented in the next figure.*

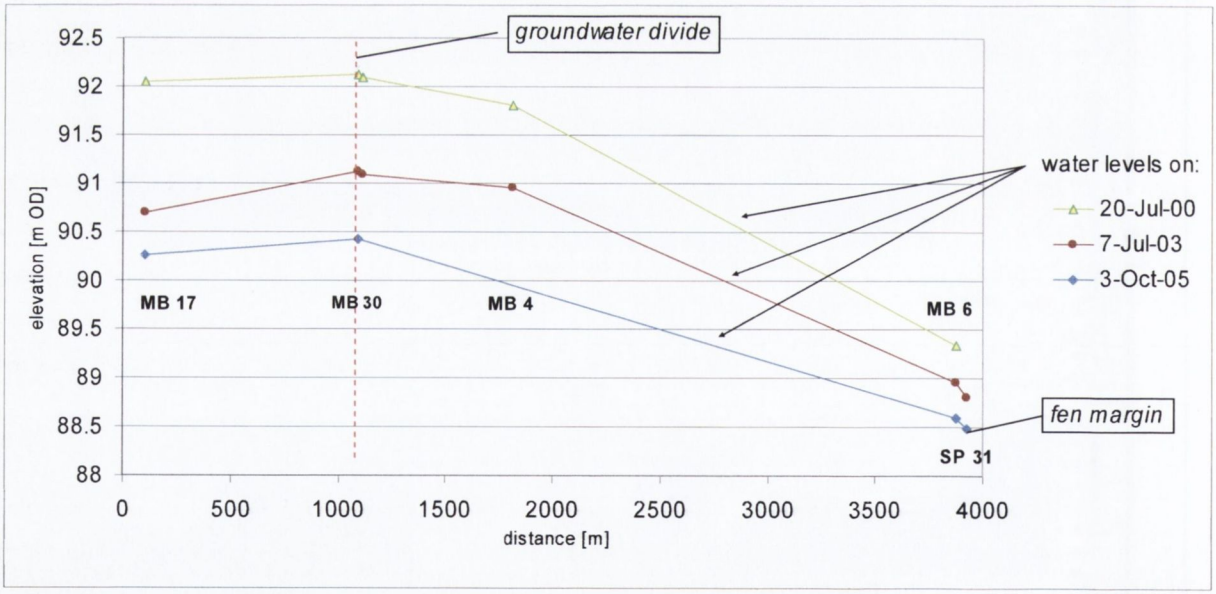



*Figure II-9 Elevation of the water table between the groundwater divide in the Curragh aquifer and the fen margin, various dates, 2000-2005*

## II - 2. Pollardstown Fen Settings

### II-2.1. Introduction

Pollardstown Fen is a wetland located on the northern margin of the Curragh plains. It is roughly elongated in plan running from the northwest to the southeast between Milltown village and Newbridge town in Co. Kildare and is located in a wide flat bottomed basin flanked along either side of its long axis by low ridges under agriculturally improved grassland. The area of wetland fen habitat is around 2.2 $km^2$. Formerly it was larger, but peat has been removed from the area around Milltown to the northwest; the land was reclaimed for agriculture, and coniferous forestry has been unsuccessfully attempted in a further area to the west.

As a fen, Pollardstown fen is a groundwater fed wetland (and a groundwater dependent terrestrial ecosystem GWDTE under the Water Framework Directive), maintained by the continuous groundwater inflow through more than 40 springs and seepage zones. The majority of these springs rise around the margins of the fen depression above the level of the fen and carry groundwater from the Curragh aquifer. This continuous inflow of water to the fen creates waterlogged conditions with limited drainage from the depression, which leads to peat formation. Some layers of calcareous marl in the fen peat, reflecting inundation by calcium rich water or periods during which the present fen was a freshwater lake, have been recorded in previous studies (Daly, 1981). The fen peat marl deposits are believed to reach 6 m thick at its deepest point and are underlain by clay. Outflow from the fen supplies water to the Grand Canal, the existence of which depends on an uninterrupted flow of water from the Curragh aquifer via the fen. The stable quality of water is maintained by its passage through the gravel aquifer and the fen.

To the north of Pollardstown are extensive acid peat bogs. Most ancient Irish fens (similar to Pollardstown) have been transformed into raised bogs by vegetation and peat growing above the influence of groundwater. The constant inflow of calcium rich water to and through the basin at Pollardstown did not allow acid peat to develop (small patches exist on the margins) and the fen, therefore, has remained relatively unchanged for thousands of years. Today, it represents an example of an ancient landscape. The history of the fen can be tracked back to the end of the last glaciation, approximately 12,000 years ago.

It is believed that, over the past 1000 years, the fen has been left relatively undisturbed except for some human intervention within the last 250 years which has caused a diversion of the natural water outflow to power a number of mills and to supply the Grand Canal; turf cutting and an attempt to reclaim the fen for agricultural use in 1960s and 1970s. To redress the effects of the latter, the fen was re-flooded in 1983 and subsequently most of the fen area was purchased by the State. Slow and relatively undisturbed development of the fen has allowed its unique ecology to develop and its many characteristic species to survive.

The morphology of the fen can be best described as a flat bottomed depression with sharply defined edges. These edges are defined by tall ridges to the east and by the edge of the gravel Curragh Plain to the southwest.
A rise in the 'floor' of the fen occurs to the south west, where fen vegetation occurs up to a level of 89.00m OD. The largest inflow of groundwater at Seven Springs occurs to the south east at an elevation of 85.65m OD,

Figure II-10. The northern boundary varies between 86.00-87.00m OD but the main central area of the fen lies between 85.00 - 85.50m OD and is normally flooded.

**Box 1. The history of Pollardstown Fen, after WYG (2004)**

| | |
|---|---|
| 12,000 years ago | Post-glacial lake depositing clay on its bed |
| Intervening period | Accumulation of a marl lake sediment, increasing development of fen peat, transformation to bog peat prevented by drainage conditions and continuous supply of water. |
| 1780 - 1790 | Canalisation of the outflowing streams to feed the Grand Canal. |
| to 1950 | Excavation of peat from local areas of the fen. |
| 1960 - 1970 | Drainage and agricultural land reclamation between the Seven Springs and Grand Canal feeders, notably the excavation in 1964 of a culvert below the Canal Feeder to direct water to Milltown Stream. |
| 1963 | Afforestation of the area south west of the Milltown feeder by An Foras Forbartha. |
| 1970 | Purchase of fen areas by Bord na Mona. |
| 1976 | Inclusion in the list of Areas of Scientific Interest in Kildare |
| 1978 | Kildare County Council's proposal to pass a Special Amenity Area Order covering the fen and all lands between the fen and the nearest road (this proposal failed). |
| 1981 | The Forest and Wildlife Service's purchase of parts of the fen and acquisition of other parts in Bord na Mona ownership |
| 1983 | Blocking of the Culvert under the Canal Feeder and re-wetting of the area between the feeders. |
| 1986 | National Nature Reserve designation |
| 1993 | Threat of drainage effects caused by the Kildare bypass proposal investigated in an EIA. |
| 1994 | Redesignation of the ASI as a Natural Heritage Area. Boundary confirmed by aerial photography and fieldwork and the proposed designation as a Special Area of Conservation under the 'Habitats Directive', including the fen and immediate surface water catchment |

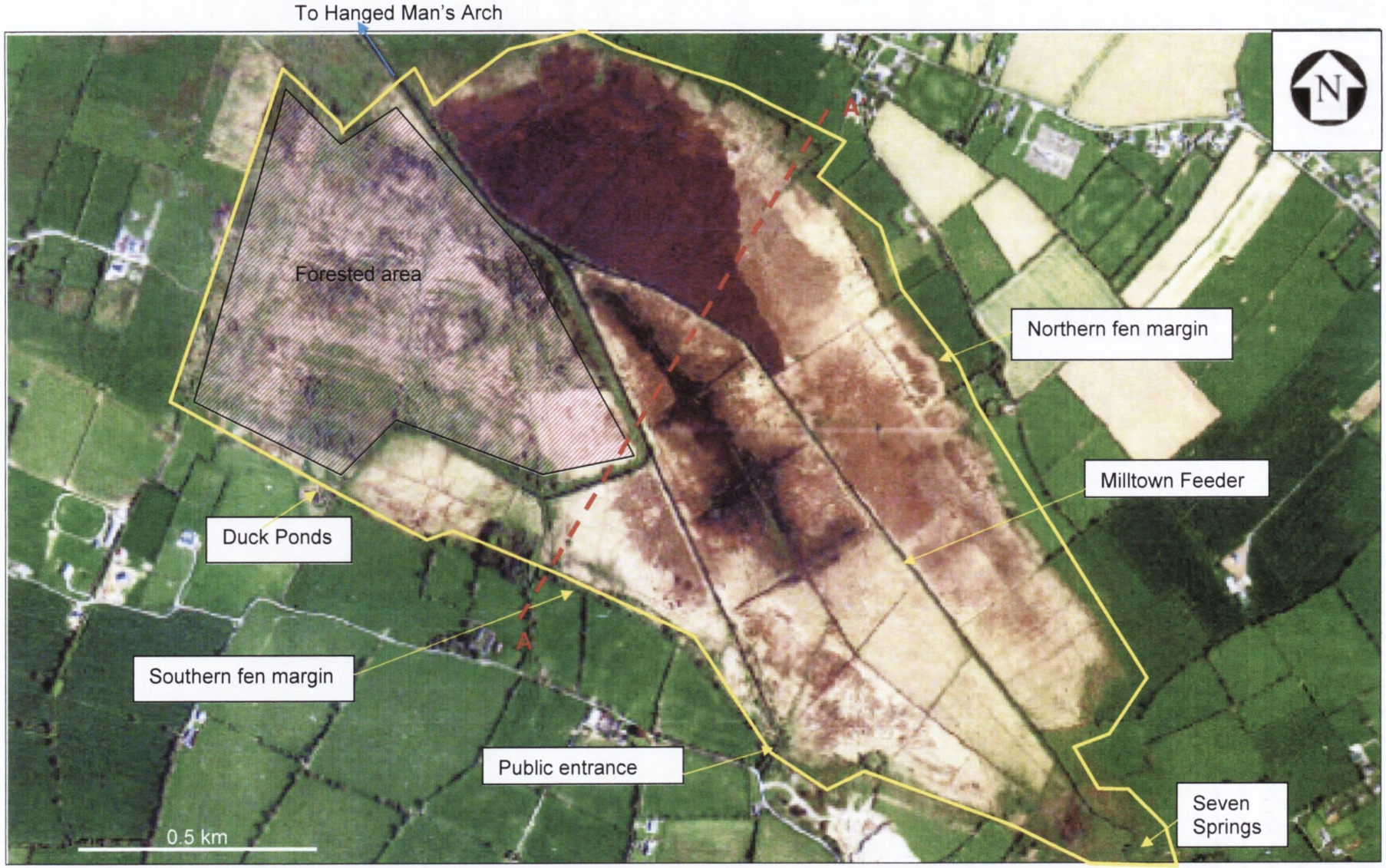



*Figure II-10 Extent of Pollardstown fen, aerial photograph 2002. Geological cross section along A-A' will be discussed in further text and on Figure II-11*

### *II-2.1.1. Quaternary Processes that Led to the Formation of the Fen*

The history of Pleistocene deposits within the study area was investigated and described by Glanville, (1997, 1999) whose model suggests that the fen was formed from meltwater flowing from the south through a narrow channel and depositing materials in a shallow flat bottomed basin. In order to accommodate the formation of a glaciolacustrine fan and delta deposits, a considerable amount of water was required at the margins of the ice. There were a number of ice sheets which played an important role in defining spatial distribution of glaciofluvial and lacustrie deposits within the Curragh area. One ice margin has been located along the western margin of the Pollardstown fen and retreated in a westerly direction; another lay along the Ballysax fan moraine and retreated in a northerly/northwesterly direction (Hayes *et al.*, 2001). The two ice margins are believed to belong to the same ice body. A third margin of a separate ice mass was located to the northeast of Kilcullen which has retreated in a northerly or easterly direction. As these lobes retreated they uncoupled in the area of the present River Liffey basin, opening up an area where water ponded. The surface deposits of gravel in the Curragh may have been deposited as outwash into a shallow lake, which rapidly became sediment filled as the ice margins retreated and the shallow lake drained. Drainage was likely to be southwards along meltwater channels, south from Kilcullen as seen today towards the Barrow and the Slaney basins. As the ice margins retreated, however, lower ground to the north was opened and water could then flow towards the north and the present direction of the River Liffey. It is likely that the meltwater channel to the fen formed at this stage.

The current geological structure shows a ridge of unsorted deposits of sand, silt, cobble and boulders, known as diamicton overlying the extensive sediments of gravel (The Curragh gravels) on the northeastern margin of the Curragh, adjacent to the Pollardstown fen. These diamictons are similar in lithological content and particle size to the gravel, suggesting a local till reworked from previously deposited sand and gravel during a local advance fluctuation in the ice margin. The Curragh gravel appears to continue below the diamicton to the fen, where they are exposed in extensive gravel pits. Vertically, fine sand is overlain by well sorted, cross bedded gravel and these are overlain by a gravel diamicton. At the base of the middle section of sand and gravel, extending towards the fen, sediments become finer and horizontally layered. The middle layer of the section exhibits long, steeply sloping crossbeds of sand and gravel grading into planar beds towards the fen. These crossbeds dip eastwards and northeast towards the fen. The upper subsoil consists of unconsolidated diamicton with a sandy matrix and gravel clasts.

At the fen margin, topsoil changes into a thin deposit of peat that is underlain by grey gravelly clay, in turn underlain by sand and gravel. Daly (1981) suggests that gravels are present around the margin of the fen and probably are present at a depth beneath the clay underlying the peat in the central part; however, drilling performed in the middle of the fen did not reach the gravel, Figure II-11. The upper layer (recent deposit) consists of grey clay rich in organic matter, peat and marl. Vertical sections indicate marl deposition in the deeper central areas and peat deposition around the margins of the fen. In general, marl is more predominant in the central areas (whereas it usually is thin) or is absent around the fen margins. An exception is on the northeast side of the fen where marl was found in the topsoil and at the base of the peat layer.

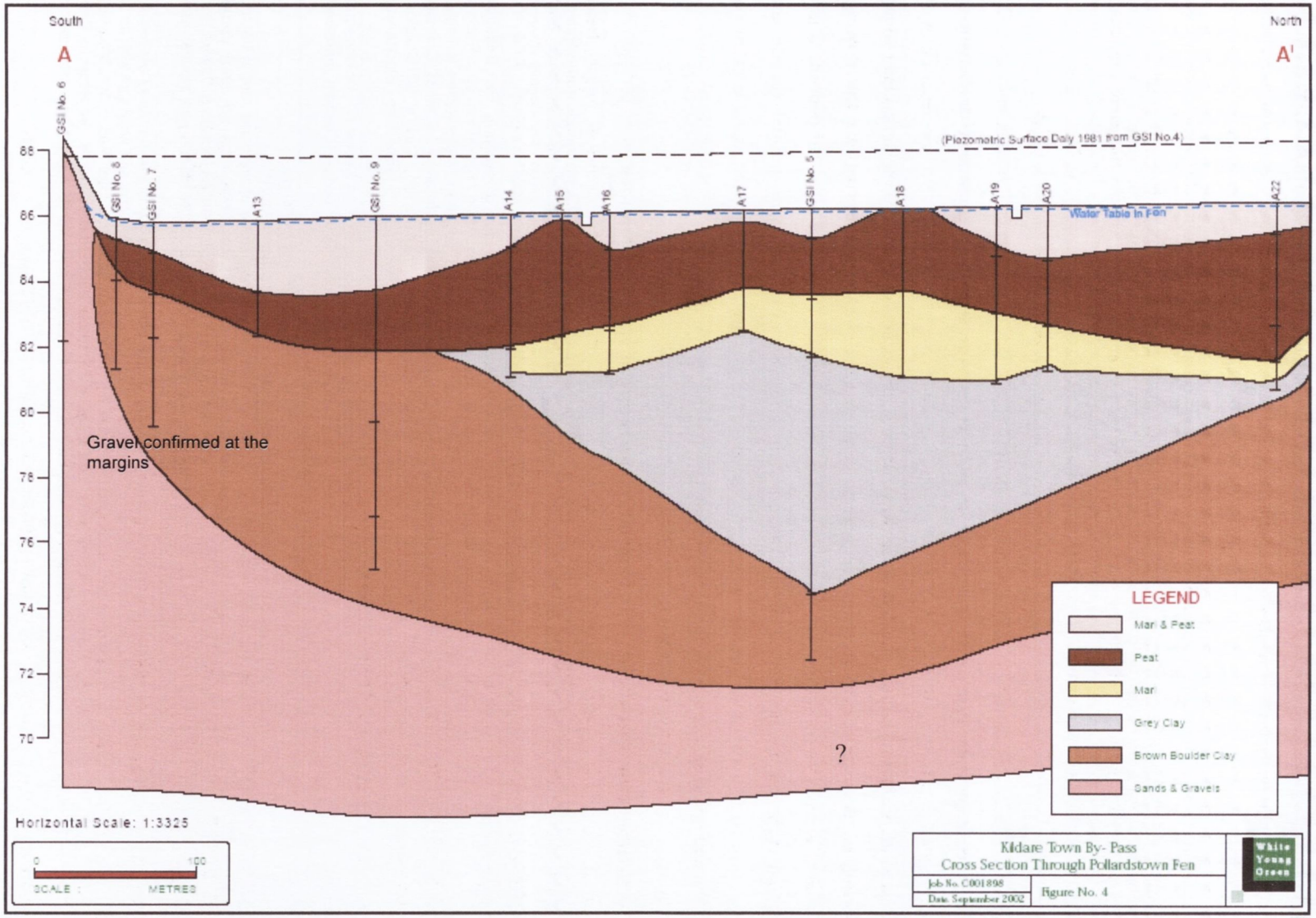



*Figure II-11 Geological cross section of the fen, after Daly (1981). Location of section A-A' presented on an aerial photograph in Figure II-10 . Source: WYG, 2002*

### *II-2.1.2. Ecological Aspects of Pollardstown Fen*

Aspects of the ecology of Pollardstown Fen have been studied by many, including Neff (1980), Doyle (1984), Patton *et al.* (1990), Moorkens (1997), Killeen & Moorkens (2002), WYG Ltd. (2004) and is described as species rich with numerous well defined plant communities and several rare or unusual species (Figure II-12). Distribution of species, their richness and composition structure is dictated by a mixture of physical, geomorphic and hydrological conditions creating various habitats within the fen ecosystem. The dominant plant species at the fen are saw-sedge (*Cladium mariscus*), common reed (*Phragmites australis*), blunt-flowered rush (*Juncus subnodulosus*) and a variety of sedges. Scrub vegetation has hardly developed on the fen but there are small groups of (free standing) shrubs of willow (*Salix sp* and others.).

The central fen area is dominated by more uniform vegetation types such as saw-sedge *Cladium mariscus*. On the margins, where the water first emerges from the ground, there are species and communities characteristic of base-rich conditions (Duff in WYG Ltd., 2004). Damp grasslands on the margins are species rich with particularly good displays of orchids in some areas. Regenerating fen occurs on an area of reclaimed land which was reflooded in 1983 and has reverted to open water, swamp and fen. Some of the springs are free flowing; some are seepage zones where water oozes from the ground. A number of springs have tufaceous deposits where solid calcium carbonate precipitates from the calcium rich water. Some of the more unusual species and communities of the fen are located in the vicinity of tufaceous springs. The list of flora and fauna is extensive and only some of the most noteworthy species are listed in Table II-1 below.

**Table II-1 Selected characteristic plant and animal species recorded at Pollardstown fen.**

| | |
|---|---|
| Orchids | Early Marsh Orchid (*Dactylorhiza incarnata*), Common Spotted Orchid (*D. fuchsii*), Heath Spotted Orchid (*D. maculata*), Narrow Leaved Marsh Orchid (*Dactylorhiza traunsteineri*), Marsh Helleborine (*Epipactis palustris*), Fragrant Orchid (*Gymnadenia conopsea*), Early Purple Orchid (*Orchis mascula*), Common Twayblade (*Listera ovata*), Fly Orchid (*Ophrys insectifera*), Lesser Butterfly Orchid (*Platanthera bifolia*). |
| Other flowering plants | Mountain Everlasting (*Antennaria dioica*), Bog Thistle (*Cirsium dissectum*), Fen Bedstraw (*Galium uliginosum*), Marsh Bedstraw (*G. palustre*), St. John's Wort (*Hypericum sp.*), Ragged Robin (*Lychnis palustris*), Water Mint (*Mentha aquatica*), Bogbean (*Menyanthes trifoliata*), Grass of Parnassus (*Parnassia palustris*), Marsh Lousewort (*Pedicularis palustris*), Common Butterwort (*Pinguicula vulgaris*), Yellow Rattle (*Rhinanthus minor*), Devil's Bit Scabious (*Succisa pratensis*), Marsh Arrowgrass (*Triglochin palustris*), Intermediate Bladderwort (*Utricularia intermedia*). |
| Sedges | Glaucous Sedge (*Carex flacca*), Slender Sedge (*C. lasiocarpa*), Fen Sedge (*C. lepidocarpa*), Carnation Sedge (*C. panicea*), Flea Sedge (*C. pulicaris*), Saw Sedge (*Cladium mariscus*), Broad-Leaved Bog Cotton (*Eriophorum latifolium*). |
| Rushes | *Juncus acutiflorus, J. articulatus, J. subnodulosus, Schoenus nigricans.* |
| Mosses | *Tomentypnum nitens, Cratoneuron commutatum, Scorpidium cossonii* |
| Invertebrates | There are many invertebrate species at Pollardstown Fen; some of them are rare in Ireland. Significant species include the E.U. Annex II molluscs *Vertigo geyeri* and *Vertigo moulinsiana*. A number of internationally important flies and butterflies including *Diptera* (true flies) and the E. U. Annex II species the Marsh Fritillary butterfly (*Eurodryas aurinia*) have been also recorded from the site. |
| Vertebrates | Vertebrates on the fen include the Otter (*Lutra lutra*) (Annex II), Brook Lamprey (Annex II), the Hare and Pygmy Shrew. The fen is an important habitat for frogs and newts as well as for both breeding and wintering birds. Little Grebe, Teal, Mallard, Water Rail, Coot, Moorhen, Snipe, Sedge Warbler and Reed Bunting all breed each year in the fen vegetation. Reed Warbler and Garganey, both rare breeding species in Ireland, have been recorded at Pollardstown. |

### II-2.1.2.1 National and International Importance

The national and international significance of Pollardstown Fen is reflected in its inclusion in various protective legislation and conventions. The list of the statutory designations arrogated to the fen are summarised in the table below.

**Table II-2 Summary table of statutory designations and related protected species and habitats present at Pollardstown Fen**

| Statutory designation | Target species/habitats |
|---|---|
| ***Statutory Nature Reserve*** | |
| Legislation: Wildlife Act, 1976 and the Wildlife (Amendment) Act, 2000. | The whole spring fed fen ecosystem with associated fauna and flora comprising numerous vascular plant species including tufa lowing species and rare invertebrates |
| ***Special Area of Conservation SAC*** | |
| *Rare and endangered species and habitats protected under the E.U. Habitats Directive (92/43/EEC) are listed in annexes to the legislation. Annex I of the 'Habitats Directive' identifies these natural 'priority habitats' which are in danger of disappearing and whose natural range falls mainly within the territory of the E.U. Annex II of the Habitats Directive lists species (other than birds which are catered for in the 'Birds Directive') whose habitats must be protected. It is intended that these species are protected in the E.U.-wide network of sites known as the Natura 2000 network, thus the species may be referred to as Natura 2000 species.*<br><br>Legislation: EU Habitats Directive (92/43/EEC) | <u>E.U. Habitats Directive Annex I habitats:</u><br>– 7210 Calcareous fen with *Cladium mariscus**<br>– 7220 Petryfying spings with tufa formation**<br>– 7230 Alkaline fens***<br><br><u>E.U. Habitats Directive Annex II species:</u><br>Otter (*Lutra lutra*); Brook Lamprey (*Lampetra planer*); White-clawed Crayfish (*Austropotamobius pallipes*); Geyer's Whorl Snail (*Vertigo geyeri*); Des Moulin's Whorl Snail (*Vertigo moulinsiana*); Narrow-Mouthed Whorl Snail (*Vertigo angustior*); Marsh Fritillary (*Euphydryas aurinia*) |
| ***Ramsar Site*** | |
| Legislation: none. Designation under the Convention on Wetlands of International Importance. | The whole spring fed fen wetland ecosystem. Site no 474 |
| ***Biogenetic Reserve*** | |
| Legislation: none. Designation signed by the Council of Europe | The whole spring fed fen ecosystem with associated fauna and flora comprising numerous vascular plant species including tufa lowing species and rare invertebrates. |

****7210 Calcareous fen with Cladium mariscus***

The main bed spreads across the fen predominantly to the north of the confluence between the Seven Springs and the Grand Canal Feeders where they merge to form the Milltown Feeder. This is the largest such stand in Ireland and reputedly also the largest in Europe.

*****7220 Petrifying springs with tufa formation***

This is a habitat of very limited extent in European Union territory and also in Pollardstown Fen. Not all of the springs around the fen fall into this category. Whilst some are marked by vascular plant species, especially *Rorippa nasturtium-aquaticum*, the tufa forming springs are marked by the moss *Cratoneuron commutatum*. Tufa forms beneath the moss carpet. Tufa formation in seepage areas has also been noted and these areas can be

interpreted (for the purposes of the 'Habitats Directive') as fen and petrifying spring complexes. Only a few seepages are classed as tufa spring habitat.

******7230 Alkaline fens***

Alkaline fens extend over much of the seepage and old cutaway areas along both flanks of the fen. This vegetation comprises several different plant communities, including the *Cirsium dissectum/Schoenus nigricans* fen community for which Pollardstown Fen is one of the type localities (WYG, 2004).

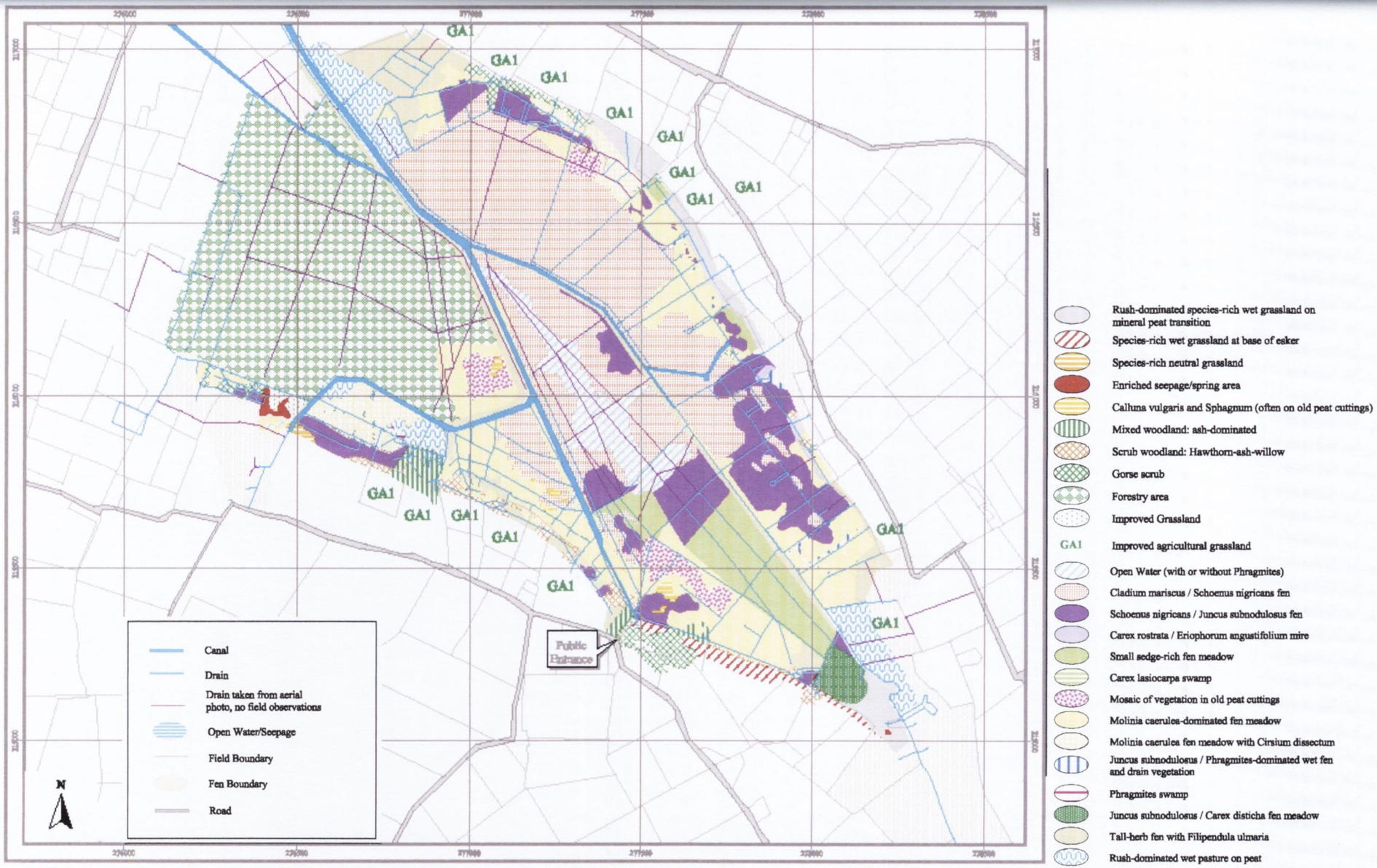



*Figure II-12 Vegetation map of Pollardstown fen, after and courtesy of Natura EnvironmentalConsultants Ltd. (not to scale)*

## II-2.2. Pollardstown Fen Risk Assessment

In hydrogeological studies, a conventional risk assessment analysis is based on a source - pathway – receptor framework (Chapter I - 6.1). A fundamental step in this assessment process is the characterisation of a receptor. Good understanding of what requires protection, how it works, what it is controlled by and how sensitive it is before any damage occurs is essential to provide a comprehensive analysis of risks and establishing an effective risk management strategy. This requires a firm knowledge of a receptor including building a conceptual model, undertaking long term observations and a quantitative analysis. Such an approach allows determining most crucial elements controlling sustainability of the ecosystem and later deciding on potential sources and pathways of various risks. Within one site, a few receptors may be identified, all potentially threatened by the same elements, but with different sensitivity and response mechanisms allied to an individual scale. In the case of Pollardstown Fen, the receptor can be characterised on three basic scales:

1) Pollardstown Fen as a whole area of a wetland of a unique size and floristic composition;
2) Protected habitats listed in Annex I E.U. Habitats Directive, i.e. petrifying tufa springs, *Cladium mariscus* beds and alkaline fen habitat ; and
3) Protected species listed in Annex II E.U. Habitats Directive

No matter the scale, the core for existence of all the above receptors lies in hydrological relationship between the fen basin and the Curragh aquifer. If it wasn't for the water resources gathered within the Curragh outwash sands and gravels, the fen habitat should have transited into a raised bog habitat, as with many other wetland sites in Ireland, with the majority of protected habitats and species being lost during the transformation process. Thus, maintaining the hydrological continuum between the fen and the Curragh should be a major priority in the view of future conservation of the fen.

A schematic Source - Pathway – Receptor framework for the case of Pollardstown Fen is presented in Figure II-13.

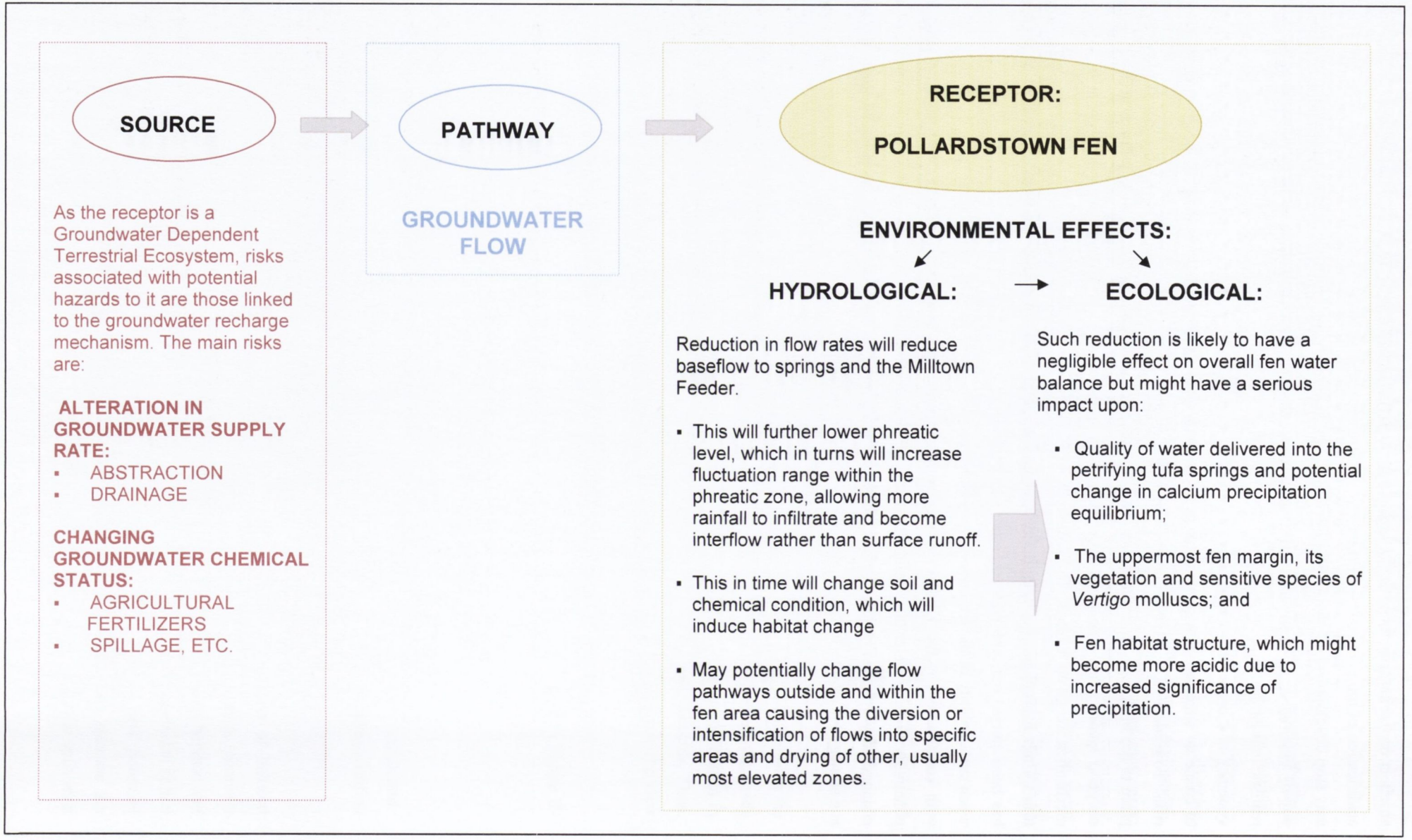
The effects of interference with the water supply mechanism can be grouped as follows:

- Decreased discharge rate (lower flow velocities);
- Changed groundwater and phreatic level regime (lower water table, increased fluctuation range); and
- Potential change of flow pathways outside and within the fen area causing diversion or intensification of flows into specific areas and drying of other, usually most elevated zones.

Ecological effects resulting from the above hydrological changes will be relative to the extent of induced hydrological changes but will also depend on the sensitivity of given receptors. Thus, in the short term, relatively small reductions in groundwater inflow rates might have a negligible effect on the overall fen water balance and the fen as a whole, but may have a significant impact upon the uppermost fen margin and its vegetation (often protected habitats of seepage) and the quality of water delivered into petrifying tufa springs and potential changes in calcium precipitation equilibrium. In the long term, however, such reductions can increase the significance of rainfall in an overall water balance equation and can induce physiochemical changes in soils with

an effect on habitat transformation. Dutch studies (cited in van Wirdum, 1999 a&b) have shown that permanent acidification of top peat can be triggered by a decrease in average water levels as small as 0.05 m and that that may stop development of characteristic fen moss species. Assessing sensitivity of the receptor should be thus of utmost importance in an effective risk management strategy. These strategies further include development of realistic mitigation measures such as (for example) restoration of water levels/flows (temporary irrigation systems), or the creation of alternative habitat sites (temporary or permanent new locations artificially adjusted to create an adequate environment for a given species, to counteract induced hazards and eliminate potential risks. To achieve that, extensive monitoring of the receptor and all those elements that it depends on must be in place to establish baseline information and conditions of habitats and species at risk. Numerical analysis based on good quality and widespread observation data is essential to develop a conceptual model of a working mechanism for given habitats. The sensitivity of Pollardstown Fen and its elements (i.e. *Vertigo geyeri* sp. and tufa springs habitat) has not been defined, as no monitoring of the fen flora and fauna in context of hydrology has been carried out, although some botanical studies exist. Such monitoring was proposed for the first time when sustainability of the fen ecosystem was deemed to be threatened by abstractions carried out in conjunction with construction of the Kildare bypass, which initiated this research. To assess the risk associated with potentially lowered water tables and flow rates, the research focused on monitoring the most sensitive, i.e. most endangered and first to be lost habitats located at the fen margin. The rationale for choosing adequate indicators and strategy for monitoring is outlined in the following paragraph.

*Figure II-13 Schematic of Source-Pathway-Receptor Framework developed for Pollardstown Fen*



## II-2.3. Selection of Ecological Indicators

A list of habitats and species whose habitats must be protected with respect to the E.U. Habitats Directive and that are present on Pollardstown fen is relatively extensive (as shown earlier in Table II-2). Additionally, the exceptional abundance of these species within one site makes Pollardstown fen a unique nature reserve. Currently, there is no other known site in Europe that hosts three species of molluscs from the *Vertigo* family and a part of the *Cladium mariscus* fen is considered to be one of the largest of its kind within the E.U. All of these rare species and habitats qualify as ecological indicator species, based on which the fen is categorised as a priority habitat. These species are further used for monitoring changes in overall wetland health, which can be approached either on a habitat or on a species level. As mentioned in the first part, the use of ecological indicators is related to a risk management framework in which environmental monitoring is triggered by an identified potential risk. The risk assessment process allows the prediction of potential effects resulting from imposed pressures and this shall drive the selection of adequate ecological indicators to ensure choosing the most sensitive species from the wider ecological indicators group. To comply with the Ramsar Risk Assessment Framework (see Chapter One), these most sensitive species shall be referred to as early warning indicators.

The most common species characteristics for fens are hydrophytes which, by definition, are adapted to live in permanently or temporarily waterlogged conditions. Various species and habitats do have, however, varying sensitivities and ranges of acceptable change, which, so far, is understood and quantified for individual species and habitats only (Wheeler *et al.*, 1995a, 2001). Nevertheless, the general concept of utilising the indicator species is to use the most sensitive species to identify environmental changes, if any, at their early stage. In case of Pollardstown fen, there are a number of species and habitats that make the fen an internationally important nature reserve and which could be used as ecological indicators. These were further classified into three following indicator groups (van Wirdum, 1999a):

- Hydrophytes with a particular stress on alkaline fen and calcareous fen communities;
- Tufa springs with an indicator species of *Psychodidae* (Diptera) and *Syrphidae* (Diptera); and
- Annex II Habitat Directive species of the *Vertigo* family.

Out of the three ecological indicators quoted above, mollusc species of the *Vertigo* family were considered the most sensitive to a hydrological regime in both quantitative and qualitative ways, and therefore any changes in their distribution and population sizes were deemed to be the best available early warning indicator of a probable habitat change. The rationale for this was that the *Vertigo* species are small in size (~2mm) and have restricted mobility. They occupy fen margins, which makes them the most vulnerable for even a small change in hydrological regime. The fen receives water from the main sand and gravel aquifer through seepages located at the fen margins; therefore any alteration in groundwater regime causing any stress on the fen habitat is expected to be reflected first in those areas. Although it is not well quantified, the main parameters that mollusc species are known to vary in their needs are vegetation structure and substratum wetness (inclusive of aerial humidity), calcium and major nutrients such as nitrogen and phosphorus. Availability of all of these parameters is dependent on water distribution.

### *II-2.3.1. Facts on Distribution and Vulnerability of the Vertigo Genus*

There are twenty eight species of the mollusc *Vertigo* known from the Tertiary history of Europe, although there were probably many more. These days, only fifteen species of *Vertigo* are known to still exist in Europe (Pokryszko, 2003). Some of them occur in mountains (5 spp.), some in lowlands (3 spp.), but the rest do not have clear preferences and are found at various altitudes. Other classifications associated with preferred habitat indicate that four out of the fifteen species prefer forest ecosystems, and seven others can be associated with wetlands. The *Vertigo* species, however, are not limited to Europe, but are also found in other parts of the world, including America and Siberia.

In terms of their distribution in Europe, the *Vertigo* species cover more or less the whole continent, from the Iberian Peninsula (*V. moulinsiana*) to Scandinavia (*V. genesii*) and from Ireland (*V. geyeri*) to Russia (*V. lilljeborgi*). Distribution and population densities vary and some species are evenly and continuously spread across big areas; but others are limited to very isolated and scattered localities. Some of the species are restricted to a very specific habitat only, like *Vertigo geyeri*, which is associated with calcareous, spring fed wetlands only. These are known as unihabitat species. The multihabitat species are characterised by the fact that two populations of the same *Vertigo* type may be found a few kilometres apart inhabiting different macrohabitats. There are still many uncertainties regarding the life cycle of the *Vertigo* species, their distribution and population densities; more research is needed with regard to their future conservation. Pokryszko (2003) stresses current limited available information on present populations and thus on understanding the threats that the *Vertigo* species face. The *Vertigo* species are very small in size, reaching a couple of millimetres only, hence their movement is limited and preservation of their habitat is essential for the protection of the species. All known losses of the species that have been recorded within historical times have been caused by human activity. The main threats are total physical destruction of habitat through alteration in local hydrology, induced grazing practice, eutrophication of water or the succession of vegetation. Climatic changes combined with anthropogenic activities are blamed for the decline of a species that, as known from Quaternary fossils, was once widespread.

At present, two out of the fifteen European species are considered threatened globally (Pokryszko, 2003). These are *Vertigo moulinsiana* and *Vertigo angustior,* both present on Pollardstown fen. Three or four other species, including *Vertigo geyeri*, are threatened locally and the remaining are not considered threatened. However, due to their very limited distribution, they could still be victims of random events.

### *II-2.3.2. Vertigo Species Found at Pollardstown Fen*

Six different (non-marine) species of the *Vertigo* genus have been recognised on the fen, three of which are protected under Annex II of the European Union Council Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (Habitats Directive). These are:

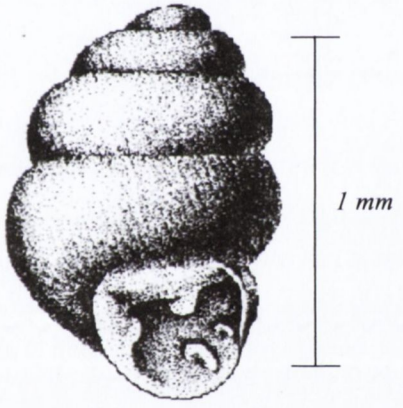
- *Vertigo geyeri* Lindholm, 1925
- *V. moulinsiana* Dupuy, 1849
- *V. angustior* Jeffreys, 1830 (*Stylommatophora : Vertiginidae*)

Their hydrological requirements differ between the species and can be briefly described as:

- *Vertigo geyeri* requires saturated soils in rather open environment;
- *Vertigo moulinsiana* needs saturated soils and strong growth of tall plants;
- *Vertigo angustior* requires humid conditions in a more draining environment – 'contact' zones between wet and dry sites, somewhat variable wetness.

Out of the three, *V. geyeri* is considered the most sensitive to small changes in the water table. It remains a rare animal in Ireland, with relict Postglacial distribution. It is considered to be an indicator of undisturbed ancient habitat and is frequently associated with rare species and high quality habitats that deserve the utmost protection (after Moorkens, WYG, 2004). Also, it lives in the highest part of the Pollardstown fen making it exposed and vulnerable to the slightest change in local hydrology. That is the reason why it was chosen as an indicator species for this study.

### *II-2.3.3. Vertigo geyeri, Lindholm 1925*




*Vertigo geyeri* (Figure II-14) is a mollusc belonging to the class Gastropoda, and the family Vertiginidae. The species has a brown shell with a glossy texture and usually 3-5 whorls. It has four (sometimes less) narrow teeth and its dimensions are 1.7-1.9 mm in height and 1.1 mm in width. The species is hermaphrodite and mainly self fertilising, with more than 80% found to be aphallic, although some cross fertilisation occurs (Cameron *et al.*, 2003). One to 10 uncalcified, separated eggs are produced within a two week development period.

*Figure II-14 Vertigo geyeri Lindholm 1925*

The species reaches reproduction maturity in less than a year. Large juveniles become adults around midsummer (June/July), and a peak of small juveniles occurs usually in September/October. Cameron (*et al.*, 2003) reported also that juveniles are present at all times with peaks occurring in late summer and in autumn (a two month space from two years of observation), the timing associated with differences in climatic conditions in these years. Individuals may live between one and two years. *V. geyeri* grazes on algae or bacteria on vegetation and decaying humic and plant material.



*Photo II-1 Vertigo geyeri crawling on a stem of a dead plant. Photograph made on Pollardtown fen by Dr. E. Moorkens*

#### II-2.3.3.1 Densities and Distribution

Many studies have been carried out on population densities and distribution (von Proschwith, 2003; Falkner, 2003; Killeen, 2003; Valovirta, 2003; Willing, 2003; Holyoak, 2003) and results show rather small population sizes in localised areas. Willing (2003), for example, surveyed a total of 31 calcareous flushes and fen habitats, all very similar and potentially suitable for the snail. However, positive results were found on ten sites only. The theory of 'population explosions' which states high fluctuations in population size varying from one year to another without obvious reason is also broadly discussed. Cameron *et al.* ( 2003) concluded that population dynamics vary in site specific ways and are weather dependent. Willing (2003) stressed the influence of overgrazing, which, in excess, may destroy some flush habitats that support *V.geyeri* habitats. Although grazing has been shown to be destructive and fatal for some mollusc populations (Ausden *et al.,* 2005), it is considered also to be a dispersal mechanism for the species. Transport by birds has also been hypothesised (Cameron *et al.*, 2003).

*Vertigo geyeri* is found at widely scattered localities in Europe between northern Scandinavia, the Swiss and Austrian Alps and Ireland, at a wide range of altitudes. European records of its existence come from eight EU countries (Cameron *et al.*, 2003) including Austria, Denmark, Finland, Germany, Ireland, Italy, Sweden and UK (available data refer to EU before accession of the 10 new member states in 2004). EU conservation regulations, under which *V.geyeri* is protected, (Habitat Directive, Annex II), apply to all member states; therefore, the snail is under strict control in all EU countries. Exceptionally high numbers of the species are found only in Sweden, where the species is recognised as 'not threatened' (von Proschwitz, 2003). In Denmark, the species is vulnerable. There are approximately 400 locations in Scandinavia known for hosting *V. geyeri* with major threats coming from eutrophication caused by leakage from agricultural fertilizers or faeces and urine from cattle. Unfortunately, it is apparent from the literature, populations in the remaining parts of Europe are definitely smaller, seriously vulnerable or even endangered.

#### II-2.3.3.2 Preferred Habitat

The tiny Geyer's whorl snail, *Vertigo geyeri,* is found in relatively exposed, constantly humid calcareous flush fens (including the Annex I E.U. Habitats Directive habitat type 7230 Alkaline fens) that may be fed by tufa

depositing springs (including 7220 Petrifying springs with tufa formation). Colville (1996) and Cameron *et al.* (2003) noticed that *V. geyeri* is especially found on gently sloping sites, which are often present at fen margins along with emerging springs and flushes. On the other hand, Holyoak (2003) reports that the sites are generally level or almost level (less than 15° slope) so that shallow water ponds in dry weather, even where much of calcareous flushing occurred on a steeply sloping hillside. At all sites surveyed, calcareous associations are obvious, although strong botanical relationships are less apparent. For example, Killeen (2003) during his study in Cumbria found that the distribution and abundance of *V. geyeri* is influenced by habitat, with a preference for a short *Carex* dominated sward, rather than *Schoenus nigricans* tussocks, which differs from what was found in Ireland (Holyoak 2003; Moorkens in WYG Ltd., 2004). Cameron *et al.* (2003), who investigated Waun Eurad fen in Wales, showed a local preference for *Schoenus* tussocks and associated sedge rich swards with declining densities of snails in *Molinetum* and in very wet patches dominated by *Juncus subnodulosus*. Observations with regards to preference for tufaceous deposits are also inconclusive. On the Waun Eurad site, *Schoenus* dominated sites were characterised by tufaceous mineral soil, 'suffused by slowly flowing spring water', but on upland sites visited by Holyoak in Co. Leitrim, tufaceous deposits were infrequent.

#### II-2.3.3.3 Conclusions

In summary, most of the data on the molluscs' autecology in the literature is based on botanical associations. These are available on a macrohabitat scale and show rather weak botanical associations which vary from site to site. The fact that there is no clear relationship with species association of plants indicates that *Vertigo geyeri* species rather responds to other factors. In terms of hydrological conditions, it seems that the mollusc shows a preference for calcareous, groundwater-fed seepage areas; however, preferences for tufa deposition which is a characteristic of extremely rich, calcareous fens are inconclusive. Other factors, like site topography, whether it is sloping or flat, allowing for a temporal ponding of water are also not clear. Nonetheless, the studies reviewed above do show that the snail needs rather humid conditions and/or is found in flushing zones. Although these hydrological needs have been often described in a vague, descriptive way, which is very subjective and limits its usefulness for quantitative modelling, it does suggest that water availability either as proximity to water or air content are likely to be important features of the snail microhabitat. And this conclusion led to the formulation of the scope of this investigation. Since botanical associations are not conclusive, it is hypothesised that conditions controlling the existence of the *Vertigo geyeri* species have a rather physical nature and have to be defined locally at Pollardstown fen. Considering the small size of the indicator species, these conditions will be investigated on a microhabitat scale. Specifically microhydrogeology and micrometeorology, understood as characteristics of the phreatic level, soil wetness and moisture conditions just at or above the soil surface, in the closest proximity to the snail. It is believed that an understanding of essential key needs for local survival of the molluscs will lead to establishing controlling factors for sustainability of an important, species rich, habitat of the fen margin. Nonetheless, while microscale changes may indicate problems on the macroscale, it is essential to system's science that microscale "health" is not a sufficient proof of good macroscale conditions.

## II - 3. Monitoring Strategy

Investigation of the hydrogeological conditions supporting the snail habitat necessitated monitoring at two different levels: regional and local. At the regional level, the movement of subsurface water (groundwater) in the Curragh aquifer feeding the fen is closely connected to the movement of water in the springs and seepages supporting the snail habitat. Broadly, in order to define the hydrogeological characteristics of this habitat required monitoring of:

- Groundwater levels;
- Surface water levels, velocities and discharges;
- Meteorological data including temperature, humidity, radiation and wind speed;
- Water chemistry (major ions);
- *Vertigo geyeri* presence; and
- Vegetation structure and type.

All drilling and borehole installation had been done before the research started, and many monitoring points have already been included in an ongoing monitoring programme associated with monitoring the effects of the construction of a road bypass around Kildare town (WYG Ltd., 2002). This programme was reviewed in light of the objectives of the research and, where necessary, additional monitoring locations were chosen and implemented. Only selected monitoring points from existing monitoring schemes were chosen for inclusion in this thesis. Physical collection of data was executed in collaboration with various specialists which included Trinity College Dublin, White Young Green Ltd. (WYG Ltd.), Dr Evelyn Moorkens (mollusc counts) and Natura Environmental Ltd. (botanical studies).

### II-3.1. Groundwater Monitoring

Three types of groundwater monitoring sites were selected depending on objectives and scale. These sites had already been established (WYG Ltd., 2002) when research started and are known as:

**Permanent Quadrats** (abbreviation used: PQ): selected for monitoring of the hydrological regime of the fen as a whole;

**Intensive Quadrats** (abbreviation used: IQ/Site): selected for intensive monitoring of the hydrological regime at the fen margin including the *Vertigo geyeri* microhabitat;

**Monitoring Boreholes** (abbreviation used: MB): selected outside the fen and within the Curragh aquifer to monitor behaviour of the aquifer and its response to impacts arising from construction of the Kildare bypass. For the purposes of this study, only selected boreholes from the MB monitoring network were chosen to relate the fen hydrology to regional hydrology and in defining the sustainability of the fen margin hydrology on the regional groundwater recharge.

### *II-3.1.1. Permanent Quadrats*

Permanent Quadrats are 20 x 20 metre square sites that were originally selected for hydro-botanical monitoring. Ten locations were selected within the fen boundary, mostly along the margins, but some quadrats are also present in the central, flat part of the fen; Figure II-15 shows exact locations of all PQs. These locations were labelled PQ1, PQ2, ..., PQ10. Permanent Quadrats were first selected in 1997 and all, except for one (PQ10), were equipped with two standpipes, one 'shallow' reaching a depth of circa 1 metre and a second – 'deep', reaching approximately 2-3 metres. It is likely therefore, that the shallow standpipes registered phreatic water levels and the deep standpipes had the potential to act as piezometers. Standpipes are small diameter (50 mm) PVC pipes used for monitoring the groundwater level with perforations over the bottom metre of its depth. The standpipes were labelled as in Table II-3. Specific information for each of the pipes within PQ locations such as coordinates and elevations is given in Appendix 1. All standpipes were surveyed using Trimble® RTK GPS surveying equipment and data presented in metres OD (Poolbeg). Descriptions (logs) of the strata in which the pipes are screened in are not available, but a strong similarity between most of the hydrographs from both levels indicates that both of them are probably screened in the same stratographic layer (or are hydrologically connected) but at different depths. The installation was undertaken with a hand auger (WYG, per. com.) and it is unlikely that the underlying clay layer was penetrated. Also, the standpipe S10, located within Permanent Quadrat 10 - the highest site on the fen, where peat is only 0.5 metre deep, was equipped with a shallow pipe only, which indicates that the hydrological focus was water levels in peat only.

Although the pipes were installed in 1997, water level data were not collected on a regular basis until summer 1999 when they started to be collected at one month intervals. However, it was only in June of 2000, when the monitoring started on a regular, biweekly (i.e. every two weeks) basis. This continued until April 2004 when the frequency was reduced back to once a month only and the number of sites was reduced from 10 down to 5, namely PQ 1, PQ5, PQ6, PQ9 and PQ10. The rationale for this reduction was the relative stability of the water levels in most of the PQs.

**Table II-3 Standpipe information within Permanent Quadrats**

| Location name | Abbreviation used | Shallow standpipe name | Deep standpipe name |
|---|---|---|---|
| Permanent Quadrat 1 | PQ1 | S1A | S1B |
| Permanent Quadrat 2 | PQ2 | S2A | S2B |
| Permanent Quadrat 3 | PQ3 | S3A | S3B |
| Permanent Quadrat 4 | PQ4 | S4A | S4B |
| Permanent Quadrat 5 | PQ5 | S5A | S5B |
| Permanent Quadrat 6 | PQ6 | S6A | S6B |
| Permanent Quadrat 7 | PQ7 | S7A | S7B |
| Permanent Quadrat 8 | PQ8 | S8A | S8B |
| Permanent Quadrat 9 | PQ9 | S9A | S9B |
| Permanent Quadrat 10 | PQ10 | S10 | |




*Figure II-15 Location Map of Permanent Quadrats, map drawn using MapInfo*

### *II-3.1.2. Intensive Quadrats*

Intensive Quadrats were established to study the hydrological characteristics of the fen margin, i.e. the microhabitat of the selected indicators, the *Vertigo geyeri* habitat. As such, positioning of these sites was based on snail distribution on the fen and this was established during an extensive survey by Dr. Moorkens, who identified a total of sixteen potential sites within the fen boundary (this was undertaken in 2000/2001 but reported by Moorkens in WYG report in 2004). Further study proved the presence of the snail in five out of sixteen identified locations; all of these were found on the fen margin, in the areas associated with the upwelling springs or ditches. On the southern side, the snail was found in two locations; one at the most elevated southwestern edge of the fen, and secondly in a ditch close to the Permanent Quadrat 9. The three populations found on the north side of the fen were located along the northernmost edge of the fen (these locations will be discussed in more detail in an introduction to the microhabitat result section).

Based on this information, four Intensive Quadrats were selected in 2000 and these were named Sites A, B, C and D (Figure II-16), (WYG Ltd., 2002). Sites A, C and D were chosen in seepage locations where the snail was known to be present. Site B was a dug out, tufaceous spring with a habitat unsuitable for *Vertigo geyeri* and was chosen as a control site to distinguish geological, hydrological and chemical differences from seepages. It was hoped that such site selection would allow the definition of the processes that are responsible for the seepage. All sites were equipped with nine nests of standpipes/piezometers, each nest reaching two or three depths depending on local geology. The detailed description of each site will be given later, but the general idea was to drill a

network of monitoring boreholes reaching 'deep' gravel (7-8 metres depth), 'shallow' gravel (if any, 2-3 metres depth) and phreatic levels in a peat stratum (1 metre depth), which would enable analysis of flow patterns and velocities. In total, 34 nests of standpipes were drilled across four sites. Data are available for all 4 x 9 nests of 2-3 standpipes on a two weekly basis from 2001 until 2004 and later for two nests at each site with the same frequency. The nests of piezometers were aligned roughly parallel to the fen margin. Water levels were measured from the top of the casing, which were surveyed with Trimble® GPS equipment and related to Ordnance Datum (Poolbeg). Each of the sites will be described in detail later and the location map including standpipes together with tables of coordinates and casing elevation for each standpipe are presented in Appendix 2.

For the purpose of describing the hydrological microhabitat of the snail, some standpipes were also equipped with 'Divers' (Van Essen Ltd.), which are self contained pressure transducers with built in loggers and these were measuring water level fluctuations continuously on a 1 or 2 hour basis. Data were later aggregated into daily records.

Within each Intensive Quadrat, 4 to 6 **Botanical Quadrats** were established. These are 1 x 1 metre Quadrats in which intensive study of vegetation patterns and the occurrence of key species such as those of *Vertigo geyeri* was monitored. Some of these sites, which will be later described in a section related to the snail microhabitat, were equipped with additional phreatic tubes (50 mm perforated PVC pipes) with Divers.

One further Intensive Quadrat (E) (Figure II-16) was established in 2003, and this was equipped with a phreatic tube with the Diver. Since no other standpipes/piezometers were drilled on this site, it was not used for hydrological regime evaluation but only for the monitoring of a snail habitat.

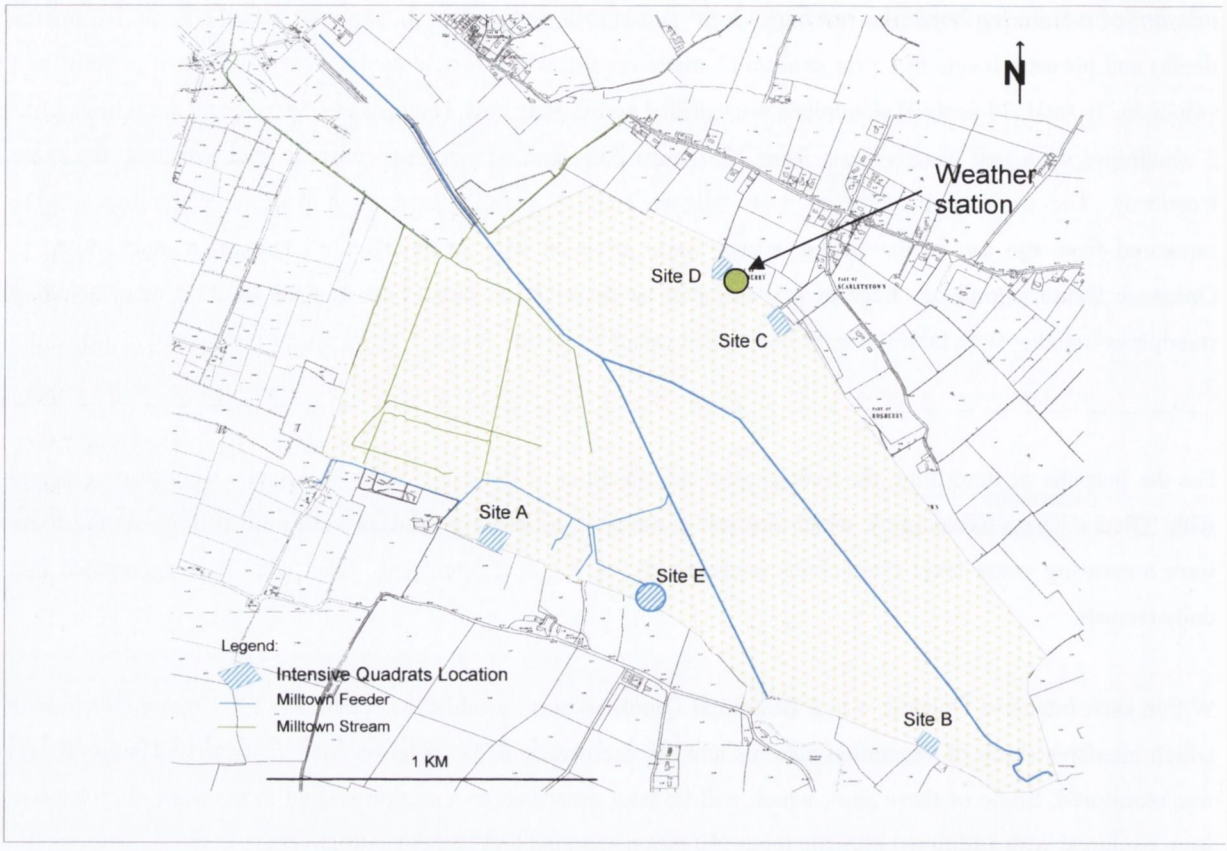



*Figure II-16 Locations of Intensive Quadrats A-E around the Fen margins, map drawn using Map Info*




*Photo II-2 Standpipes nests along the fen margin on site D, north side*

### *II-3.1.3. Monitoring Boreholes*

Regional groundwater level in the Curragh aquifer was monitored in 45 drilled monitoring boreholes placed across the gravel plateau: the Curragh Plains, the Japanese Gardens and around Pollardstown Fen. A location map together with coordinates and screened depths of these boreholes is presented in Appendices 3 and 4 and also in Figure II-8. The depth of these boreholes varied and some of them were equipped with nested piezometers at different depths, although all of theses boreholes reached the level of deeper gravels (Vicky Conlon, WYG, pers. com.). Water level data are available from 1998 for a few monitoring boreholes only, and the majority of boreholes have two weekly data records starting in 1999 running until 2004. In 2004, the number of wells included in regular monitoring was reduced, and the frequency changed to monthly. The monitoring boreholes used in this analysis are those located along the fen margins and at the top of the Curragh aquifer and these are MB 6, MB 7, MB 38, MB 45, MB 29, MB 30, and MB 17. The aim of selecting these boreholes was to be able to monitor groundwater behaviour along a transect more or less along the flow line towards the fen margin and extending beyond the groundwater divide. At the same time, boreholes were selected so as to be able to monitor vertical as well as lateral gradients.

## II-3.2. Surface Water Monitoring

In order to determine inflows and outflows to and from the fen, a number of automatic water level recorders of the Thalimedes type (a float counterweight system with a variable resistance pulley by OTT-Hydrometry Ltd.) were installed in three locations on the drains within the Milltown Feeder system. Two instruments were placed in November 2001, one under Hanged Man's Bridge and one below the Seven Springs. A third instrument, measuring the water level in the canal feeder network was installed in a tributary drain below site A in March 2002 (Figure II-17). As a result, water level fluctuation has been observed and the data used to analyse water fluxes through the fen and their effect on key habitat sites. In parallel with the water level recording, flow discharge measurements (by current meter) were taken irregularly at the same three locations. This work was undertaken many times throughout the study period with the aim of constructing a stage discharge curve for the Milltown Feeder, which with continuous recording of water levels it was hoped could be used for monitoring discharge from the Feeder. The Milltown Feeder, as a part of the Grand Canal System, is regulated by a lock operation, which tends to be intermittent at best, but it is massive seasonal weed growth in the channel that mitigates against a unique rating curve being established. During this study, weed growth and weed cutting were found to impact greatly on the water level during summer time, and this caused an inverse relationship between water level and discharge – higher stages from weed growth relate to lower discharges. The only way to determine the discharge of water from the Milltown Feeder was through direct measurement of velocity – by installing an automatic device which recorded flow velocities and water levels continuously. The device installed was a Starflow Ultrasonic Doppler meter. The meter was centred on the bed of the feeder between fixed channel side walls and in relatively weed free conditions which were established under the Hanged Man's Bridge.



*Photo II-3 Water level monitoring station under the Hanged Man's Arch in Milltown (secured in a PVC pipe)*

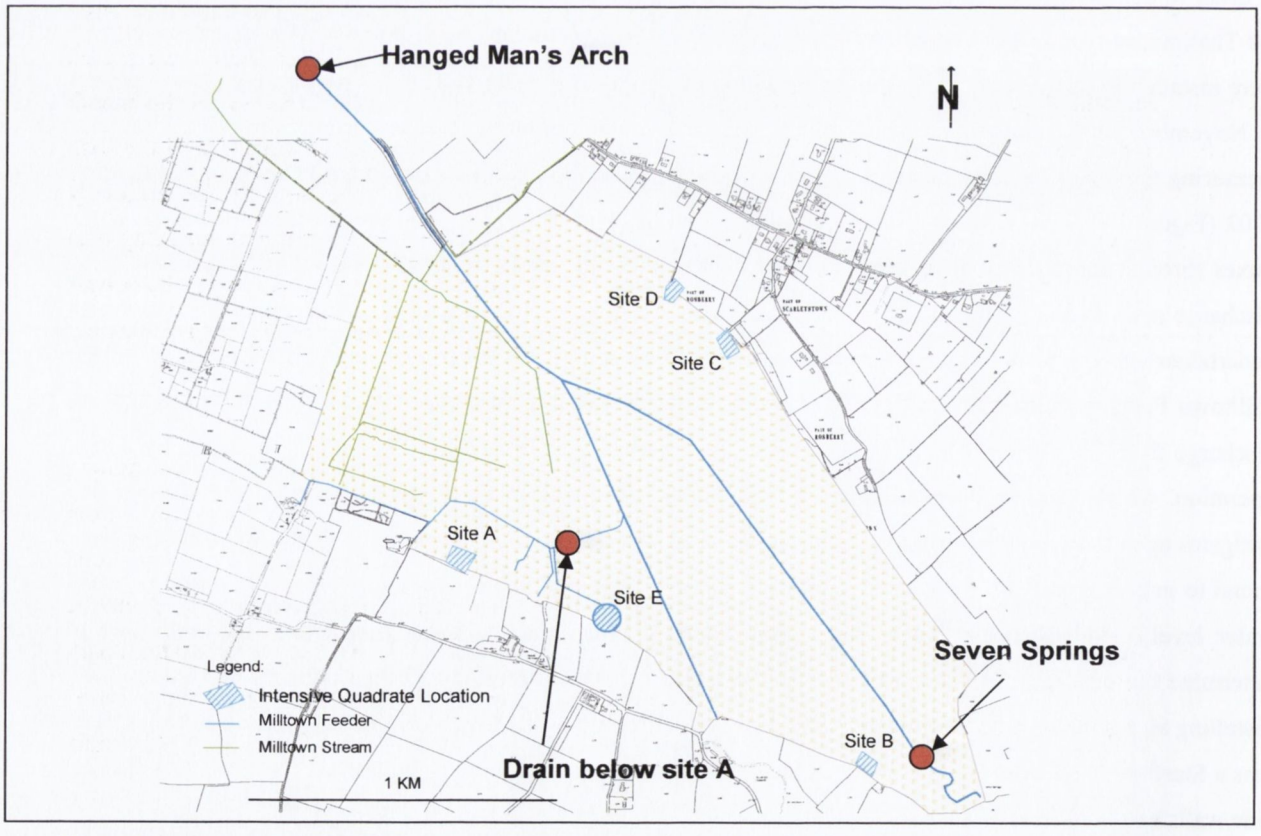



*Figure II-17 Locations of surface water monitoring stations within the Milltown Feeder canal system, map drawn using Map Info*

## II-3.3. Meteorological Station

In order to get a precise measure of regional water balance in the vicinity of the fen, local evaluation of meteorological fluxes was essential. Thus, an automatic weather station was employed on site to monitor various meteorological parameters used for calculation of the fen water balance (mainly evapotranspiration and precipitation). This station was previously operating at Kildare Sewage Treatment Plant and was moved to the northern side of the Fen in November 2001 and data collected since March 2002. The site chosen for placing the weather station is situated on the north side of the fen, in close proximity to site D (Figure II-16). To ensure stability of the monitoring sensors, steel poles were driven through the peat and a triangular framework was constructed. Onto this base, a full meteorological mast was then fixed and sensors connected.

The parameters being monitored at the station were: air temperature, barometric pressure, incoming radiation, net radiation, wind speed, wind direction and rainfall. The sensors were placed at a typical (for a meteorological station) height of 2-3 metres (FAO, 1998). Air temperature, barometric pressure, incoming radiation and net radiation sensors were placed 2 metres above ground level and wind speed and wind direction instruments were placed at 3 metres above the ground surface. Rainfall gauges were placed on a plate mounted just above the surface of the ground, just above surface vegetation level. All sensors were provided by ELE International, except for the net radiometer, which was provided directly by Kipp & Zonen. The sensors' specification and frequency of logging is summarised in Table II-4. The sensors were connected to an ELE logger operated by 'Dialog' software and data were recorded on an hourly basis. The weather station was visited on a monthly basis for data collection and equipment maintenance. Small difficulties occurred sporadically but these were solved promptly. The rainfall gauge (a tipping bucket) was blocked with plant debris in August 2004, so for this month rainfall data were taken from the nearest rainfall station based at Naas CBS School supplying data to the Irish Meteorological Service (Met Éireann), which has well correlated records. A humidity sensor was also originally on site; however data showed evidence of an instrument 'drift' and therefore, it was agreed that humidity data from a synoptic station at Casement Aerodrome (approx. 20 km east from the site) would be used for all analysis (operated by the Irish Meteorological Service). The Naas station, although located closer to the site, does not record humidity or other meteorological data.

For all analyses that considered longer weather records, before the fen weather station was in operation, rainfall data from Naas CBS was used. This is the nearest rainfall station to the fen. Homogeneity between records from the two stations was assessed through statistical analysis covering the period from March 2002 until June 2005 and revealed good correlation. Although the correlation coefficient between daily rainfall data from Naas and the Fen station was calculated to be 0.55, monthly data had a coefficient of 0.82. The two sites are c. 10 km apart; therefore differences in rainfall distribution may account for rather poor correlation on a daily basis. Nevertheless, the double mass curve between two data sets showed an acceptable level of agreement (Appendix 5) and Naas rainfall is 5% higher.

**Table II-4 List of parameters measured at the Pollardstown Fen Weather Station with specification of sensors and recording frequencies**

| Parameters measured | Unit | Range | Resolution | Accuracy | Frequency of scanning | Output |
|---|---|---|---|---|---|---|
| Wind direction | degrees | 0-360 | 1 | 10 degrees | 1 sec | 1- hour mean |
| Incoming radiation | W/m2 | -400 to 1200 | 1 | 5% | 5 sec | 1- hour mean |
| Air Temperature | °C | -20 to +35 | 0.1 | 0.1 | 5 sec | spot reading on the hour |
| Barometric Pressure | hPa (mbar) | 910 to 1050 | 0.1 | 0.3 | 5 sec | spot reading on the hour |
| Net radiation | $W/m^2$ | -2000 to 2000 | 1 | +/-30$W/m^2$ | 5 sec | 1- hour mean |
| Wind Speed | m/sec | 0 to 75 | 0.05 | 0.5 (or 5%) | 1 sec | 1- hour mean |
| Rainfall mm/tip | mm | 0 to 999 | 2 | 2 | | 1 hour totals |



*Photo II-4 Automatic weather station employed on the fen at site D.*

## II-3.4. Botanical and Vertigo Quadrats

With the aim of gaining a better understanding of the hydrological regime and vegetation habitat associated with the snail *Vertigo geyeri*, extensive malacological and botanical surveys were conducted by Dr Evelyn Moorkens and Natura Environmental Ltd., respectively. Assessments were undertaken at the same locations as investigations for conceptualisation of the hydrogeological model of the fen margin. Research areas for this part of the study were located within Intensive Quadrats mentioned earlier and included:

- Botanical Quadrats (1 x 1 metre areas distinguished within each of the Intensive Quadrats) for the purpose of intensive botanical, micrometeorological and microhydrological study, Figure II-18. There were 2-6 Botanical Quadrats within each site located usually along the trackway[5] (Figure II-19). Abbreviations used: BQ1, BQ2, etc.... Each Botanical Quadrat was divided into a grid with 10 x 10 (10cm) squares. The X axis of the grid was numbered 0-9 and the Y axis A-J. The X axis was parallel to the trackway.

- *Vertigo* Quadrats. These were 0.5 x 0.5 metre quadrats that were placed within Botanical Quadrats and in which snail counts were carried out. Similarly to BQs, *Vertigo* Quadrats were divided into a grid with 5 x 5 cm identified squares. Abbreviations used: VQ1, VQ2, etc.

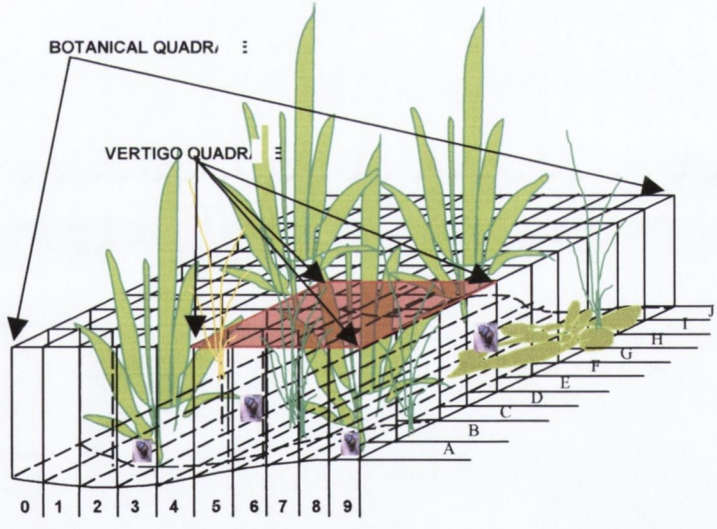



*Figure II-18 Concept of Botanical and Vertigo Quadrats*

[5] A fen surface, as any other very damp/partially waterlogged wetland surface can be easily destroyed by trampling and this, in the long term, can affect habitat structure on a local scale. Considering the frequent monitoring programmes in selected areas of *Vertigo* locations on the fen margin, all Intensive Quadrat A-D were instrumented with a trackway system, which was located at a central point of each site. Trackways were built perpendicular to the fen margin and extended across 20-30 metres and were constructed to facilitate access to Botanical and Vertigo Quadrats. These were chosen either along or in close proximity to trackways. All sampling and monitoring within BQs and VQs were undertaken using small trolleys which slid on trackways and which were built specifically for the project. This strategy was developed purely to avoid walking and the destruction of the ground surface and the habitat of the *Vertigo* snail.

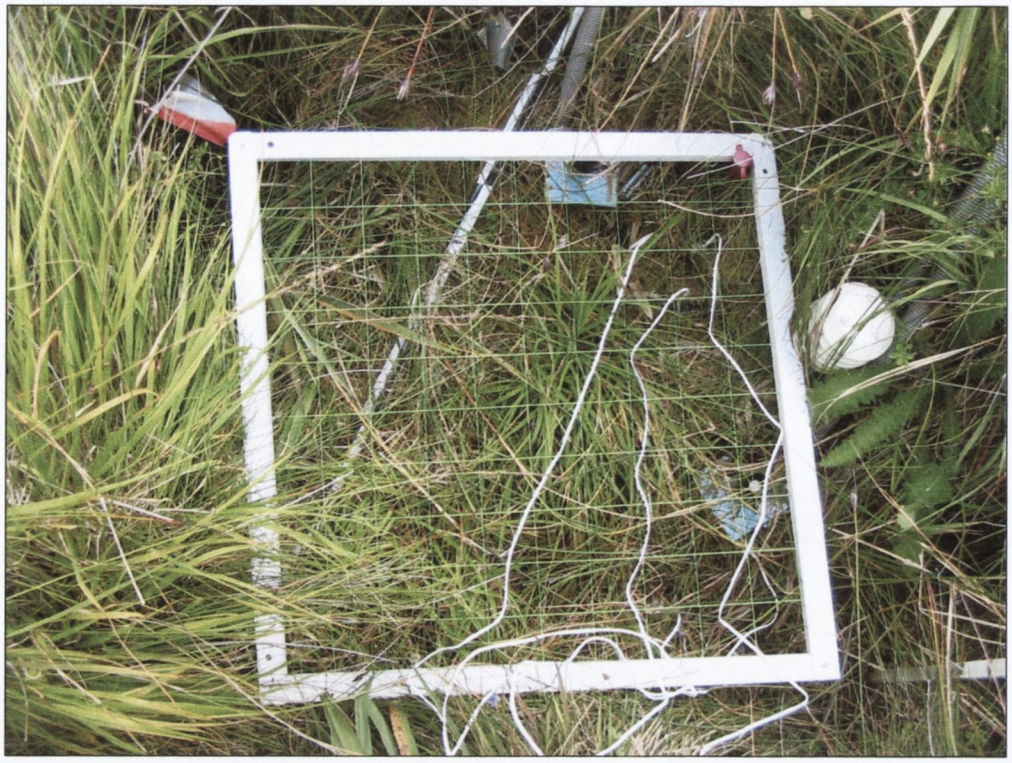


*Photo II-5 Example of a Vertigo Quadrat net in situ*

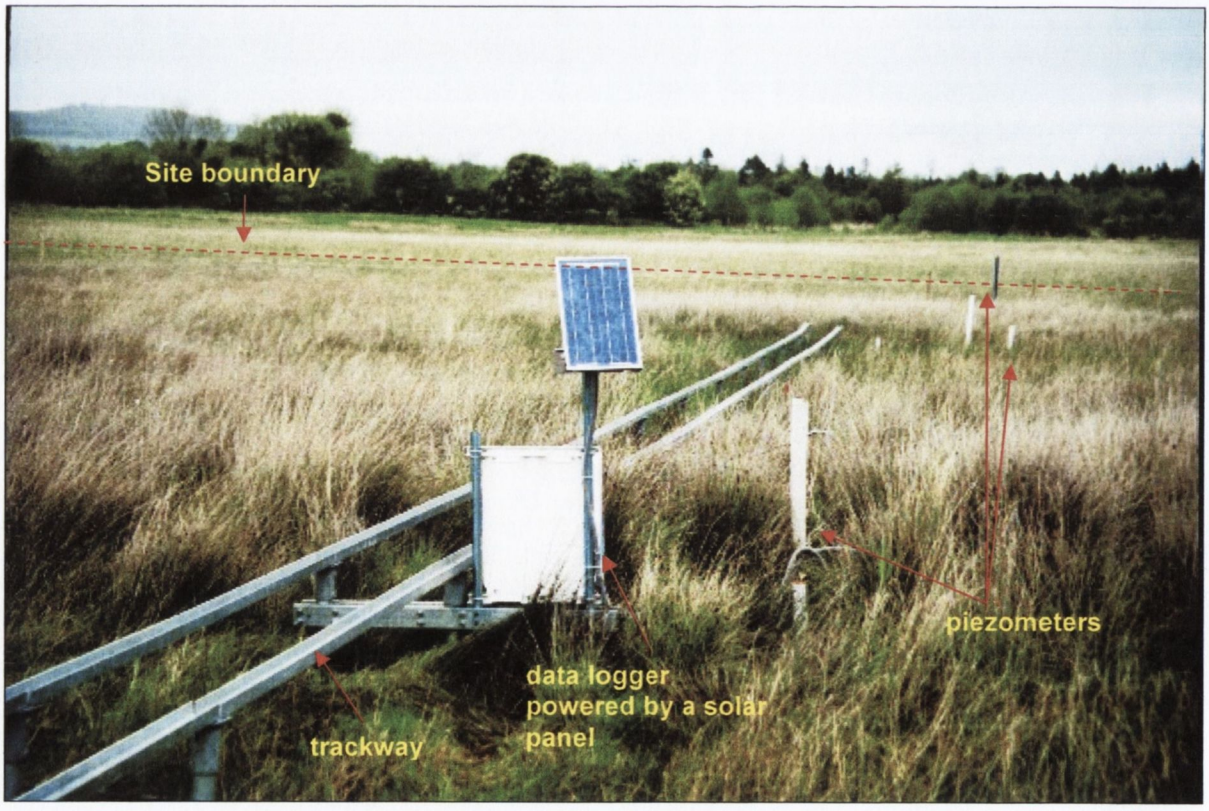



*Photo II-6 Site A – an example of a trackway system with a data logger for monitoring the fen's microhabitat.*

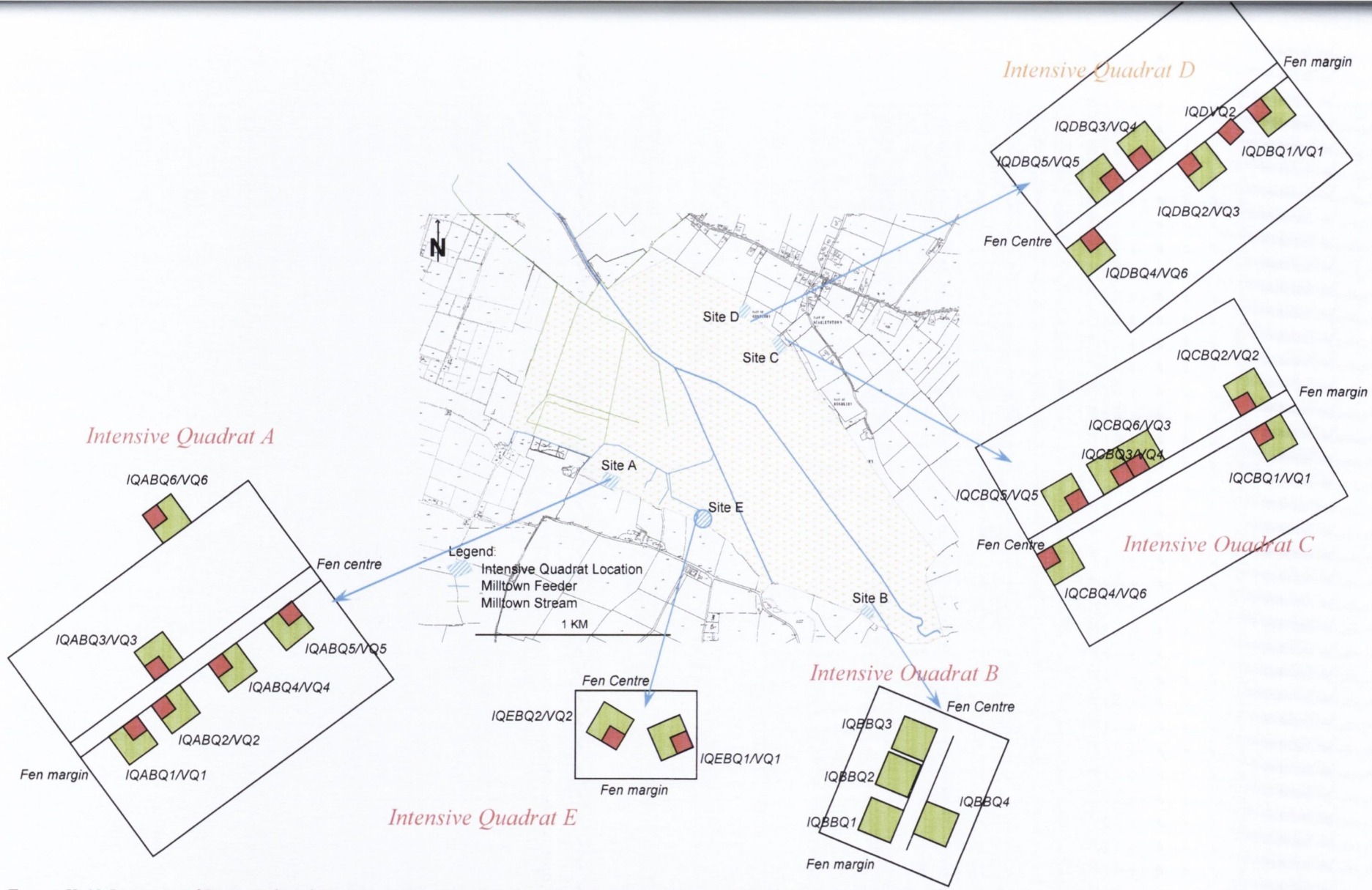



*Figure II-19 Location of Botanical and Vertigo Quadrats within Intensive Quadrats A, B, C, D and E at Pollardstown Fen*

**Table II-5 Georeferences of BQs and VQs locations within site A**

| Corner point | east | north | altitude |
|---|---|---|---|
| BQ1_A | 276426 | 215906 | 88.35 |
| BQ1_B | 276427 | 215907 | 88.66 |
| BQ1_C | 276428 | 215906 | 88.37 |
| BQ1_D | 276427 | 215905 | 88.39 |
| BQ2_A | 276427 | 215907 | 88.31 |
| BQ2_B | 276428 | 215907 | 88.35 |
| BQ2_C | 276428 | 215908 | 88.35 |
| BQ2_D | 276427 | 215908 | 88.32 |
| BQ3_A | 276426 | 215909 | 88.23 |
| BQ3_B | 276427 | 215910 | 88.27 |
| BQ3_C | 276426 | 215910 | 88.33 |
| BQ3_D | 276425 | 215910 | 88.27 |
| BQ4_A | 276429 | 215915 | 88.26 |
| BQ4_B | 276429 | 215916 | 88.22 |
| BQ5_A | 276431 | 215921 | 87.82 |
| BQ5_B | 276431 | 215922 | 87.97 |
| BQ6_A | 276404 | 215941 | 87.82 |
| BQ6_B | 276404 | 215940 | 87.76 |
| BQ6_C | 276404 | 215942 | 87.77 |
| BQ6_D | 276405 | 215941 | 87.70 |
| VQ1_A | 276427 | 215903 | 88.47 |
| VQ2_A | 276427 | 215904 | 88.44 |
| VQ2_B | 276427 | 215905 | 88.49 |
| VQ3_A | 276427 | 215906 | 88.36 |
| VQ3+B | 276427 | 215906 | 88.37 |
| VQ4_A | 276430 | 215913 | 88.37 |
| VQ4_B | 276430 | 215913 | 88.34 |
| VQ5_A | 276431 | 215918 | 87.96 |
| VQ5_B | 276431 | 215918 | 88.00 |

**Table II-6 Georeferences of BQs and VQs locations within site E**

| Corner point | east | north | altitude |
|---|---|---|---|
| BQ1_A | 277030 | 215711 | 86.18 |
| BQ1_B | 277029 | 215712 | 86.21 |
| BQ1_C | 277030 | 215713 | 86.24 |
| BQ1_D | 277030 | 215712 | 86.20 |
| BQ2_A | 277027 | 215715 | 86.21 |
| BQ2_B | 277027 | 215715 | 86.20 |
| BQ2_C | 277028 | 215716 | 86.30 |
| BQ2_D | 277028 | 215715 | 86.23 |

**Table II-7 Georeferences of BQs and VQs locations within site C**

| Corner point | east | north | altitude |
|---|---|---|---|
| BQ1_A | 277315 | 216631 | 85.73 |
| BQ1_B | 277316 | 216631 | 85.72 |
| BQ2_A | 277314 | 216631 | 85.66 |
| BQ2_B | 277315 | 216632 | 85.70 |
| BQ3_A | 277310 | 216629 | 85.67 |
| BQ3_B | 277311 | 216629 | 85.68 |
| BQ4_A | 277306 | 216625 | 85.81 |
| BQ4_B | 277307 | 216626 | 85.75 |
| VQ1_A | 277315 | 216631 | 85.73 |
| VQ1_B | 277315 | 216631 | 85.84 |
| VQ2_A | 277314 | 216631 | 85.66 |
| VQ2_B | 277315 | 216631 | 85.68 |
| VQ3_A | 277311 | 216629 | 85.68 |
| VQ3_B | 277312 | 216630 | 85.73 |
| VQ4_A | 277311 | 216629 | 85.64 |
| VQ4_B | 277311 | 216629 | 85.68 |
| VQ5_A | 277309 | 216628 | 85.68 |
| VQ5_B | 277309 | 216628 | 85.73 |
| VQ6_A | 277306 | 216625 | 85.81 |
| VQ6_B | 277306 | 216625 | 85.72 |

**Table II-8 Georeferences of BQs and VQs locations within site D**

| Corner point | east | north | altitude |
|---|---|---|---|
| BQ1_A | 277145 | 216809 | 85.88 |
| BQ1_B | 277144 | 216808 | 85.91 |
| BQ2_A | 277139 | 216803 | 85.71 |
| BQ2_B | 277139 | 216802 | 85.69 |
| BQ3_A | 277135 | 216799 | 85.60 |
| BQ3_B | 277134 | 216798 | 85.66 |
| BQ4_A | 277131 | 216794 | 85.66 |
| BQ4_B | 277130 | 216794 | 85.67 |
| VQ1_A | 277144 | 216809 | 85.87 |
| VQ1_B | 277144 | 216808 | 85.91 |
| VQ2_A | 277143 | 216806 | 85.89 |
| VQ2_B | 277142 | 216806 | 85.84 |
| VQ3_A | 277139 | 216802 | 85.71 |
| VQ3_B | 277139 | 216802 | 85.69 |
| VQ4_A | 277134 | 216799 | 85.55 |
| VQ4_B | 277134 | 216798 | 85.66 |
| VQ5_A | 277132 | 216797 | 85.65 |
| VQ5_B | 277132 | 216796 | 85.66 |
| VQ6_A | 277131 | 216794 | 85.66 |
| VQ6_B | 277131 | 216794 | 85.68 |

# III Chapter Three: Hydrogeology of Pollardstown Fen

As the ecology of wetlands depends largely on their water regime, the objective of this part is to understand the general workings of the wetlands and to characterise the hydrological conditions of the fen, such as recharge mechanisms, water level elevations, amplitude of fluctuations, seasonality, the duration and frequency of flooding, etc. A particular focus of this investigation was on the fen margin because of the rare species of snail, *Vertigo geyeri,* which lives there. By means of long term observations of fen hydrological inputs and outputs as well the snail microhabitat in terms of proximity to the water table and atmospheric conditions above the ground, valuable information concerning the fen margin hydrological regime was gained, allowing the construction of a broad picture of the conditions necessary to sustain the ecological health of the fen. The adopted methodology included analysis of the fen water balance, characterisation of the water regime of the fen as a whole, and of specific ecological sites located in the marginal zone. Water chemistry analysis was used to define recharge patterns to marginal zones of the fen. The chemical signature of water reflects catchment characteristics, where water is collected, and the pathways that it travels before discharging into the fen. This chemical composition has an important bearing on the fen's ecological characteristics, as it controls peat base richness and fertility status. As such, it defines composition of plant species and controls the fen's sensitive micro fauna (e.g. *Vertigo geyeri*).

First, a broad picture was constructed, in which the fen was analysed in a regional context within the Curragh water body and later the fen margin was analysed in more detail. A conceptual model of water recharge into the fen and flow patterns in the catchment area and specifically at the wetland margins was established.

## III - 1. Water Balance

Water balance is a basic analysis employed in hydrological studies, used for quantitative evaluation of the distribution of total available water among the various components of the hydrological cycle within a given catchment area and this is the primary purpose of this part of the investigation. It solves the continuity equation where the total volume of water entering the catchment area is balanced against the total volume of water leaving, plus the change in volume stored in the catchment over finite time intervals (Cawley, 1994). The investigation focuses on water movement into, out of and through the wetland, where all sources of water are carefully examined in order to quantify specific components. This requires analysis of a catchment area, the quantification of spring flows, analysis of water level elevations as well as assessment of meteorological inputs (Davis & De Wiest, 1966; Freeze and Cherry, 1979; Domenico & Schwartz, 1998). The groundwater catchment area for the fen was delineated using groundwater information from boreholes available within the Curragh aquifer compared with results from intense topographic surveys. A spring survey was undertaken at the fen margins to identify all areas of groundwater discharge. Water chemistry was used to verify the extent of the catchment area and to distinguish local horizontal and vertical flow pathways.

As previously stated, the water balance refers to quantification of all of the inflows and outflows of water throughout the system and as such has been broadly discussed in literature (Leene & Tiebosch 1993; Gilvear *et*

*al.*, 1993; Gilman 1994a, 1994b; Owen, 1995, Johnson, 2000). Factors that can contribute to water balance are precipitation, groundwater recharge, surface water inflow and surface runoff from surrounding fields. At the other end of the scale, water may be lost to the underlying aquifer and open water bodies such as drains or rivers (surface outflows) and through the process of evapotranspiration (Figure III-1).

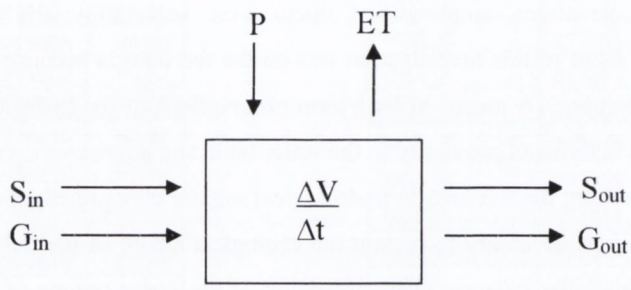



*Figure III-1 Schematic illustration of the wetland water balance with potential input and output. Directions of arrows represent the direction of water movement*

Mitsch and Gosselink (2000) distinguished the three major factors controlling the water budget of the wetland as the water mass balance, the surface contour of the landscape and subsurface soil, and the geological and groundwater conditions. The first of these conditions deals strictly with the inflows and outflows of a wetland. The remaining two conditions describe the field capacity to store water within the wetland.

For any time interval, the full water balance for a wetland can be expressed in the following equation:

$$\frac{\Delta V}{\Delta t} = P_n + S_{in} + G_{in} - ET - S_{out} - G_{out}$$

*Equation III-1*

Where:

$\frac{\Delta V}{\Delta t}$ – change in volume of water storage in wetland per unit time [T]

P – precipitation [$L^3$/T]

$S_{in}$ – surface inflows [$L^3$/T]

$G_{in}$ – groundwater inflows [$L^3$/T]

ET – evapotranspiration [$L^3$/T]

$S_{out}$ – surface outflows [$L^3$/T]

$G_{out}$ – groundwater outflows [$L^3$/T]

In the case of fens, the groundwater contribution to the water balance usually exceeds that given by precipitation, and its magnitude differs between sites depending on local geological and climatic settings. For example, Koerselman (1989), who studied groundwater fed wetlands in The Netherlands attributed 55% of the total inflow to groundwater recharge and only 43% to precipitation. Gilvear *et al.* (1993) recorded groundwater input as high

as 90%. It has also been reported that some wetlands have more complicated interactions with groundwater bodies and may be recharging in one area and discharging in another, which also may vary depending on the seasons (Gilman, 1994b).

## III-1.1. Methods

### *III-1.1.1. Catchment Area*

The catchment area was delineated using hydraulic head information from groundwater boreholes located around the fen. In total, there were 45 monitoring boreholes drilled in the Curragh Plain, the Japanese Gardens and around Pollardstown Fen (Appendix 3). The total depths of these boreholes varied and some of them were instrumented with piezometers at different depths; however, it is certain that all of these boreholes reach a layer of glaciofluvial gravel (Vicky Conlon, WYG, pers. com.). The coordinates and depths of all monitoring boreholes can be found in Appendix 4. The surface catchment area was established by detailed field investigation along the topographic boundary of the catchment area taken from Ordnance Survey Map, Discovery Series 49 (1:50 000). The catchment map was produced in cooperation with Dr. Les Brown, using the Surfer package.

### *III-1.1.2. Spring Survey*

In order to delineate all groundwater discharge areas on the fen and establish their connection with a complex central drainage system which was created to facilitate draining and reflooding activities carried on at the fen in the 1970s and 80s, as well as the supply to the Grand Canal, a walkover survey along the fen margins was initiated. The survey was completed during several site visits throughout 2001-2002 and was carried out:

- along the whole fen margin,
- along all drains accessible from marginal sites.

All springs were levelled and referred to Poolbeg datum to assess the elevation of the groundwater discharge in reference to both regional and local hydrogeological regimes. Physiochemical parameters including electric conductivity (EC [µS/cm]) and temperature (T [°C]) of water were measured to characterise a discharge mechanism and to assess pathways of the groundwater flow. In general, EC is a measure of the ability of water to carry an electric current and refers to the standard temperature of 25°C. The electric current is conducted by movement of charged ions in the water. The higher the concentration of charged ions, the higher the magnitude of conductivity of water (Dojlido & Best, 1993). As electrical conductivity varies with temperature, compensation for temperature differences can be achieved using a formulation given by van Wirdum (1991):

$$EC_{25} = (EC_t) \cdot e^{b(25-t)}$$

*Equation III-2*

where: $EC_{25}$ is the electrical conductivity at 25 [°C],

$EC_t$ is the electrical conductivity at temperature $t$ [°C], and

$b$ is a temperature coefficient.

The value b = 0.02 is correct for most ionic compositions (van Wirdum, 1991).

Groundwater or spring water tends to have a conductivity range of 200-1500 [μS/cm at 20°C] (Kiely, 1997) depending on the amount of ions, which in turn depends on the geology of the stratum which the water travels through and the time it is present there. The longer the pathway, the more dissolved salts in the water. Rainwater has conductivity between 20-100 [μS/cm at 20°C] (Kiely, 1997).

The temperature of groundwater in Ireland tends to be circa 10.5 [°C]. Whether in the soil or after discharge in a spring, the heat exchange between water and the surrounding environment occurs which affects the temperature, especially at shallow depths and on the surface. Surface water tends to have a temperature related to air conditions at the time of a measurement. Spring water will therefore be affected by the air temperature, exposure time and water depth.

### *III-1.1.3. Water Chemistry as a Measure of Groundwater Recharge*

A hydrochemical survey of the fen margin area aimed to extend understanding of the groundwater system as a whole and to build a recharge model of the wetland. A particular interest was focussed on the differences between the northern and southern margins of the fen in order to distinguish the likely mechanism of groundwater recharge. Similar composition of water samples from two sides might indicate that there is a flow route under the fen. Data collected from the fen was compared with historical data provided by WYG Ltd., which was collected for the Kildare By Pass project and encompasses both the Curragh aquifer and the fen. Dowding and Ryan (1990, unpublished) also carried out hydrochemical analysis of the fen shallow water which they related to botanical assemblages and this will be discussed in the results section, where relevant.

Water contains a wide variety of dissolved chemicals depending on pathways in the subsurface and the time present in them. It also depends on what humankind may have introduced to it (external sources or pollution). These substances are found at wide ranges of concentration depending on the origin of the water, soil chemical composition, as well as other physiochemical processes. Normally, the main types found dissolved in water are cations of calcium $Ca^{2+}$, magnesium $Mg^{2+}$, sodium $Na^{+}$ and anions sulphate $SO^{4-}$, chloride $Cl^{-}$ and bicarbonate $HCO_3^{-}$. The content and proportions of the main ions depend greatly on the rock composition in the aquifer or the soil in the drainage area.

The following parameters were chosen for hydrochemical analysis:

- pH,
- Temperature,
- Electric Conductivity,
- Chloride $Cl^{-}$,
- Nitrate $NO_3^{-}$
- Calcium and Magnesium as total hardness $CaCO_3$,
- Sulphate $SO_4^{2-}$,
- Ortho-Phosphate $PO_4^{2-}$,
- Ammonium $NH_4^{+}$,
- Potassium $K^{+}$.

Concentrations of major anions and cations were determined using special field kits - Dr. Lange Cuvette Tests, based on spectrophotometry analysis. The Dr. Lange cuvette system is made up of two components: a photometer and a cuvette. The cuvette contains an accurately measured amount of a reagent that, when a water sample is added, produces a specific colour reaction with a substance that is to be determined. The colour produced depends on a concentration of the substance and it is measured in a photometer as an extinction, which represents the light transmittance of the sample.

**Table III-1 Specification table of hydrochemical cuvette tests used in the analysis. LCK refers to Dr Lange tests, MERC was used for the Sulphate test because of low concentration of sulphate in the samples, which were not covered by Dr Lange tests. The operational principle of both tests remains the same.**

| Parameter | Symbol | Range | Unit | Cuvette Test Name | Accuracy |
|---|---|---|---|---|---|
| Potassium | $K^+$ | 8-50 | mg/l | LCK 328 | +/- 5 |
| Chloride | $Cl^-$ | 1-70 | mg/l | LCK 311 | +/-0.68 |
| Phosphate (ortho) | $PO_4^{2-}$ | 0.05-1.5 | mg/l | LCK 349 | +/-0.006 |
| Ammonium | $NH_4^+$ | 0,02-2,5 | mg/l | LCK 304 | +/-0.012 |
| Ammonium | $NH_4^+$ | 2,5-60 | mg/l | LCK 303 | +/-0.8 |
| Sulphate | $SO_4^{2-}$ | 5-250 | mg/l | MERCK 1.14548.0001 | +/- 2,1 |
| Nitrate | $NO_3^-$ | 1-60 | mg/l | LCK 339 | +/-0.45 |
| Nitrate | $NO_3^-$ | 22-155 | mg/l | LCK 340 | +/-3 |
| Total Water Hardness | | 1-20 | German degree °d | LCK 327 | +/-0.51 |

### III-1.1.3.1 Sampling Protocol

Samples were collected in October 2002 using a Waterra hand pump (a hand operated oscillated tube with a non-returning ball valve at the end). Three volumes of water were removed from a piezometer prior to taking a sample. Water samples were stored in a cool box and were returned to the college, after which samples were analysed. Two samples were taken from each piezometer and analysis done for both samples. An average value was computed for each standpipe.

### III-1.1.3.2 Sampling Locations

The adopted approach included analysis of:

- Water from selected springs along the fen margin on both, the southern and northern sides. These were spring sites: 1, 3, 5, 6, 16, 29, 37 and 39, the locations of which are shown in Figure III-3 in the results section page 87.
- Water from three screen depths (deep 6-8m, middle 5-6m and shallow 1m) was taken from within two Intensive Quadrats, one on the southern fen margin and one the northern fen margin, and these were Sites A and D, respectively. With a view to getting a better understanding of the recharge mechanism throughout the marginal zone of the fen, the investigation was designed to sample water across selected sites and perpendicular to the boundary of the fen with surrounding fields. Therefore, samples were taken from two or three locations, depending on the availability of piezometers. Selected standpipes are listed in Table III-2. For locations please refer to Appendix 2.

**Table III-2 Specification of piezometers chosen for hydrochemical analysis**

| Site A (SOUTH SIDE) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Shallow Screen** | **Depth [m]** | **Geology** | **Middle Screen** | **Depth [m]** | **Geology** | **Deep Screen** | **Depth [m]** | **Geology** |
| S10 (Permanent Quadrat 10) | 1 | Peat | SP 31 | 2 | Gravelly Clay | SP 31 | 7 | Sand |
| SP 35 | 1 | Peat | SP 35 | 3 | Clayey Gravel | SP 33 | 8 | Gravelly Clay |
| SP 36 | 1 | Peat | SP 36 | 4 | Sand/Gravel | SP 38 | 8 | Gravel |
| | | | | | | | | |
| **Site D (NORTH SIDE)** | | | | | | | | |
| **Shallow Screen** | **Depth [m]** | **Geology** | **Middle Screen** | **Depth [m]** | **Geology** | **Deep Screen** | **Depth [m]** | **Geology** |
| SP 24 | 1 | Gravely Clay/Peat | SP 24 | 3 | Sandy Gravel | SP 24 | 9 | Gravel |
| SP 29 | 1 | Peat | SP 29 | 3 | Clay | SP 29 | 12 | Sand |

### III-1.1.3.3 Output Data

From the analysis, concentrations of all parameters were given in milligrams per litre except for hardness, which was given in German degrees. In order to present the reading in mg/l $CaCO_3$, results were multiplied by 17.875 following the manufacturer's guidelines. Phosphates were measured in the form of orthophosphate, which is an inorganic form that is not associated with organic material. Orthophosphate is sometimes referred to as 'reactive phosphorus' and is the form used by plants. Orthophosphate is produced by natural processes. Nitrate was measured as $NO_3^-$.

### III-1.1.3.4 Analysis

#### *III - 1.1.3.4.1. Concentrations of Major Ions*

For the spring sampling, eight spring locations were taken into account, five on the south side (spring 29, 16, 6, 5, 3), two on the north side (37, 39) and the Seven Springs (1), Figure III-3. Numerical results of concentrations are presented in the results section III-1.2.3 in Table III-7. In order to characterise the source of water for selected springs, the analysis compares results with previous studies from the fen and the Curragh aquifer performed by Coxon (1987-1989) (1989., unpublished) and WYG (WYG Ltd., 2002) respectively, and these numerical results can be viewed in Appendices 6 & 7. Six monitoring boreholes were included in this analysis, four on the southern and two on the northern sides of the fen. These were:

- Southern side: MB2, MB6, MB19, MB19a;
- Northern side: MB10, MB43.

MBs: 6, 10, 19, 43 are screened in gravel or a sand and gravel layer; while MBs 2 and MB19A have screens in a deeper, limestone aquifer, which underlines the gravels. MBs 2 and 19/19A are placed at the top of the Curragh Plain and MBs 6, 43 and 10 are located on up gradient fields from the fen with MB 6 being the closest to Site A and MB 43 the closest to Site D.

Further analysis focused on a comparison of concentrations between the southern and northern sides of the fen margin and data for deep, middle and shallow screens were compared between Site A and Site D. Reference to respective deep monitoring boreholes located on upgradient fields from selected sites was made. Conclusions

were drawn regarding a possible groundwater recharge within each of the two sites based on hydrochemistry across horizontal and vertical profiles.

### *III-1.1.4. Meteorological Inputs*

#### III-1.1.4.1 Precipitation (RF)

Rainfall data were collected by a rain gauge connected to the automatic weather station located on the fen margin. The data were recorded on an hourly basis and were later combined into daily and monthly values as presented in Appendix 8.

#### III-1.1.4.2 Evapotranspiration (ET)

Loss of water through the evapotranspiration process is, in most cases, the cause of the most significant water loss in a wetland environment (Gilvear *et al.* 1993, Drexler *et al.* 2004) and has to be estimated for inclusion in the overall water balance. In this study, due to the complexity of the catchment area comprising the wetland and the Curragh Plains area, evapotranspiration needs varied depending on the physical and biological structures of the two zones and this had to be reflected in the computational approach.

Evapotranspiration can be measured directly using instruments such as lysimeters, but the complexity of the measurement makes it a time consuming technique, and therefore other models and micrometeorological methods based on the energy balance equation are more favoured in recent studies. These methods rely on precise measurements of various meteorological parameters including heat components such as different forms of radiation and soil heat fluxes. It must be noted however that empirical models are only estimations of evapotranspiration. The most common micrometeorological methods include: Bowen ratio energy balance (BREB); Eddy covariance (EC); surface renewal (SR) and LIDAR techniques. Empirical equations for estimating evapotranspiration are based on specific relationships determined between measured environmental parameters and ET and various models have been determined depending on the variables used. Among these, temperature based equations such as Blaney-Criddle, Lincare and Thornthwaite are commonly used. More complex models are based on both radiation and aerodynamic contributions of energy for the vaporisation process and are known as combination equations. These include Penman and Penman – Monteith equations. Another common approach, originally developed for agricultural purposes, is the crop coefficient (K) method which relates evapotranspiration to a reference evapotranspiration using a specific crop coefficient derived for particular plant species. A comprehensive comparison of the above methods in the context of wetland research has been presented by Drexler *et al.* (2004) who concluded in his study that none of the existing methods can be deemed best because wetlands vary greatly with respect to plant communities, hydrology and spatial characteristics, and the different approaches, which originally were developed for uniform agricultural fields, have varying degrees of success in dealing with these complexities. However, a cost analysis performed by Drexler proved a majority of the above micrometeorological methods to be very expensive in comparison with empirical equations, which explains why these are most often used in hydrological studies. Nevertheless, site

specific calibration is recommended for all methods. This applies to both micrometeorological models and empirical methods for which relative weighting of parameters for varying surface conditions or establishing site specific factors for different seasons respectively are important for good estimation of evapotranspiration. The crop coefficient method, which is a recommended method by the United Nations Food and Agriculture Organisation FAO (Allen *et al.,* 1998), can also provide accurate estimates if calibrated for the environmental and climatic characteristics of a particular area (Drexler *et al.,* 2004). This method has been very popular in various parts of the world including the Netherlands (Koerselman and Beltman, 1988, Boeye, 1992), the USA (Allen *et al.,* 1992; Allen *et al.,* 1994; Allen, 1998), and Germany (Tiemeyer *et al.*, 2006). A big drawback of this system is that the established crop coefficient is applicable for a particular plant species and therefore its validity for complex systems is questionable, unless some weighting factors, incorporating several crop coefficients according to the vegetation structure is in place (Tiemeyer *et al.*, 2006). This might require more advanced botanical studies and may not be accessible in strict hydrological studies.

In the case of empirical models, the general rule is that more complex models need more meteorological inputs, which can then greatly improve estimates of evapotranspiration (Drexler *et al.,* 2004). Data availability and a time scale shall therefore be considered when choosing an appropriate computation technique (Lee *et al.*, 2004) and these issues are broadly discussed in the literature (Droogers *et al.*, 2002, Alexandris *et al.*, 2003).

#### *III - 1.1.4.2.1. Computation Procedures for Actual Evapotranspiration within the Fen Area ($AE_{Fen}$)*

There is no agreed equation for calculating the evapotranspiration rate on fens. Because the evapotranspiration process is controlled by physical characteristics of plant species which have different rates of water conductance to the atmosphere and hence have varying degrees of control over ET, each site probably has a different ET rate, which restricts giving a uniform equation valid for all sites. A review of the literature reveals that actual evapotranspiration (AE) for wetlands is approximate to the potential evapotranspiration (reference, PE). Bragg (2002) mentions works by Ingram (1983) and Gilman (1994a) who found that for bogs AE/PE $\cong$1.0 or 1.1 and for fens the ratio can even reach 1.4. The reason for AE to exceed the PE is that the PE estimations are based on a uniform grass surface. The annual cycle is also apparent with AE > PE for summer months and AE < PE for winter months and is driven by a combination of factors including albedo change as the vegetation dries out, stomatal control by vascular plants and physical effects in soil.

Establishing the actual evapotranspiration is usually achieved by the application of a relevant crop coefficient, which reflects a plant's ability to transfer water and its transpiration needs. Such a method was also employed on the Pollardstown Fen. Establishing the potential evapotranspiration demands of the region is a primary step in this procedure and this was achieved using meteorological data from the weather station installed within the study site. The modified Penman-Monteith equation, presented by Allen (*et al.,* 1998) has been accepted universally for daily and hourly estimation of reference evapotranspiration (PE). This equation is recommended by the United Nations Food and Agriculture Organisation (FAO) and by the World Meteorological Organisation (WMO). The FAO Penman-Monteith equation (*Equation III-3*) determines the potential evapotranspiration from a reference surface, which is a hypothetical reference crop with an assumed crop height of 0.12 m, with a fixed

surface resistance of 70 s/m and an albedo of 0.23, closely resembling the evapotranspiration of an extensive surface of green grass of uniform height, actively growing and adequately watered.

$$PE = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

*Equation III-3*

where:

$PE$ - reference evapotranspiration, (L/T)

$Rn$ - net radiation at the crop surface, (MJ/L$^2$T)

$G$ - soil heat flux density, (MJ/L$^2$T)

$T$ - air temperature at 2 m height, (°C)

$u_2$ - wind speed at 2 m height, (L/T)

$e_s$ – mean saturation vapour pressure, (kPa)

$e_a$ - actual vapour pressure, (kPa)

$(e_s - e_a)$ - saturation vapour pressure deficit, (kPa)

$\Delta$ - slope of saturation vapour pressure curve, (kPa /°C)

$\gamma$ - psychometric constant, (kPa /°C)

The above formula requires the collection of the following input data:

- wind speed;
- air temperature;
- air humidity;
- net radiation;
- air pressure.

Wind speed is recorded at the station at Pollardstown Fen. Because the sensor is placed at a height of 3 m, a correction was necessary to convert it into the required format i.e. data from a height of 2 m. Where meteorological data were limited, the FAO (Allen *et al.*, 1998) guidelines provide adequate equations to calculate variables from other parameters and this was applied to derive the $u_2$ value.

Air temperature was recorded on the fen on an hourly basis. For the ET calculations, data was required in a format of daily $T_{max}$, $T_{min}$ and $T_{mean}$ (as an arithmetic mean of $T_{max}$ and $T_{min}$) and were determined using an Excel spreadsheet. The temperature was required for computation of the slope of a mean saturation vapour pressure ($e_s$) and a slope of saturation vapour pressure curve ($\Delta$).

Air Humidity was originally recorded on the fen, but a quality assessment showed a drift in data sets and therefore data from Casement Aerodrome, the closest Met Éireann synoptic station to the fen, were used to supplement the fen data. These were required in a format of daily $RH_{max}$ and $RH_{min.}$ and were used for determination of the actual vapour pressure ($e_a$).

Net Radiation was measured on the fen station directly. Data were measured on an hourly basis and daily average values were determined as required.

Air pressure was measured directly on the fen and was required for computation of the psychometric constant ($\gamma$). Data was measured on an hourly basis and was aggregated into daily average values.

Soil heat Flux (G) is assumed zero for daily calculations (Allen *et al.*, 1998).

Calculations were determined on a daily basis using an Excel spreadsheet, which was developed for the project following the FAO guidelines (Allen *et al.,* 1998). Numerical results of this work are presented in Appendix 9.

For any analysis for the period preceding installation of the weather station at the fen, explicitly between 1998 and 2002, the daily potential evapotranspiration data from Casement Aerodrome synoptic station was used. At this station, daily potential evapotranspiration is calculated using Makkink formula, which underestimates evapotranspiration in comparison with Penman and Penman-Monteith by up to 25%. Comparison with Pollardstown fen proved similar discrepancies and Pollardstown data was approximately 20% higher than Casement records. Monthly evapotranspiration data at Casement are calculated using the Penman formula and that shows a better correlation with Pollardstown fen data than daily records. Correlation coefficients between Casement and the fen were found at 0.98 and 0.85 on monthly and daily bases, respectively (Appendix 10).

***Crop coefficient***

To estimate actual evapotranspiration, a relevant crop coefficient ($K_c$) derived for particular crop types should be applied. Evapotranspiration can be then expressed as:

$$AE = PE \cdot K_c$$

*Equation III-4*

where: $AE$ – actual evapotranspiration [L]

$PE$ – potential evapotranspiration [L]

$K_c$ – crop coefficient [-]

Several wetland researches have successfully applied the above method to particular wetland types and species (Koerselman and Beltman, 1988; Boeye, 1992; Allen *et al.*, 1992, 1994); however, Drexler *et al.* (2004) questions the applicability of this method because it requires a relatively uniform canopy surface and highly predictable plant growth and development. To overcome this, some researchers (Tiemeyer *et al.*, 2006) use weighting factors to reflect complexity of vegetation patterns within a given site. Such an approach requires, however, more extensive botanical studies but is probably the most accurate way of estimating the true value.

In this study three different assumptions were made, and the actual evapotranspiration estimates were compared - between one another, and with the actual evapotranspiration from the Curragh Plains. The general perception is that, owing to the density of vegetation on the fen, evapotranspiration is expected to be higher on the fen than on the Curragh ($AE_{Fen} > AE_{Curragh}$). This particularity refers to the growing season from April to October, when evapotranspiration needs are especially high. The first approach was inspired by a study by Koerselman and Beltman (1988) who differentiated between the winter and growing seasons, applying a uniform crop coefficient

during the growing season only. Koerselman and Beltman (1988) studied evapotranspiration needs specifically in fens in the Netherlands, aiming to correlate actual evapotranspiration with free water evaporation. Three different types of fen vegetation were tested and results showed that although the vegetation proved to have an influence on evapotranspiration rates, differences among sites in total evapotranspiration over the entire growing season (April-October) were only small and a single equation was proposed for wetlands in temperate regions:

$$AE = 0.73 \cdot E_0 + 0.16$$

*Equation III-5*

where: $AE$ – actual evapotranspiration [L]
$E_0$ – free water evapotranspiration [L]

This equation shall be used with monthly data sets. Because the rate at which hydrophytes transpire is related to the amount of live plant material and canopy height (Koerselman and Beltman, 1988), it is assumed that in winter months (November – March) actual evapotranspiration is not affected by plant type and its growth; and therefore it will proceed at the rate of potential evapotranspiration. Further modification is necessary to relate $E_0$ (Penman's potential free water evaporation) to PE (modified Penman-Monteith potential evapotranspiration) and this was studied by De Bruin (1981) who found that during the summer months of April – September, PE = $0.8 \cdot E_0$. Incorporating this relationship into the above *Equation III-5*, actual evapotranspiration for the fen in summer months between April and October is calculated from:

$$AE = 0.91 \cdot PE + 0.16$$

*Equation III-6*

where: $AE$ – actual evapotranspiration [L]
$PE$ – potential evapotranspiration [L]

The second approach is based on Tiemeyer's study (Tiemeyer *et al.*, 2006), where crop coefficients are two dimensional and depend on the time of the year and vegetation type. Tiemeyer *et al.* (2006) studied rewetted peatlands in Germany where they applied advanced crop coefficients based on vegetation structure on the fen. A weighted coefficient value, combining a number of dominant vegetation types including grassland, reeds and wet forest (Equation III-7-Equation III-8) was determined for the AE estimations. Crop coefficients were assigned on a monthly basis and were assembled from literature (Table III-3).

$$AE_{crop} = K_c \cdot PE$$

*Equation III-7*

$$AE = f_{crop1} \cdot AE_{crop1} + f_{crop2} \cdot AE_{crop2}$$

*Equation III-8*

where: $AE$ – actual evapotranspiration [L]
$PE$ – potential evapotranspiration [L]
$K_c$ – crop coefficient [-]

**Table III-3 Crop coefficients for various fen vegetation types, after Tiemeyer *et al.*, 2006.**

| Type of Vegetation | April | May | June | July | Aug. | Sept. | Oct. | Nov.-March |
|---|---|---|---|---|---|---|---|---|
| Meadow Grassland / small sedges communities | 1.00 | 1.05 | 1.10 | 1.10 | 1.05 | 1.05 | 1.00 | 1.00 |
| Reeds | 1.20 | 1.40 | 1.45 | 1.60 | 1.80 | 2.15 | 1.35 | 0.70 |
| Wet forest | 0.65 | 0.75 | 0.88 | 1.30 | 1.45 | 2.35 | 1.20 | 0.65 |

On the fen, the dominant vegetation types are sedges, with majority of these being *Cladium mariscus*, common reeds *Phragmites australis* and rushes. Part of the fen is also occupied by a forestry area. Based on the Pollardstown Fen vegetation map (Figure II-12) and in consultation with a botanist (Ms. Katharine Duff of Natura Environmental Consultants Ltd.), it is assumed that sedges and grassland communities occupy approximately 70% of the fen, woodlands – 20%, and the remaining 10% is occupied by mixed tall hydrophytes. As such, the crop coefficients were computed based on Table III-3 and monthly values are presented in Table III-4 below.

**Table III-4 Crop coefficients for mixed vegetation at Pollardstown Fen.**

| April | May | June | July | Aug. | Sept. | Oct. | Nov.-March |
|---|---|---|---|---|---|---|---|
| 0.95 | 1.03 | 1.09 | 1.19 | 1.21 | 1.42 | 1.08 | 0.9 |

The third approach assumes that, taking into account the reduction in AE over the winter, and an increase in the summer, the overall annual AE value is likely to balance with PE, therefore a crop coefficient was set at 1.0. Differences between the three approaches are discussed in the contexts of their impact on the effective rainfall estimates.

### *III - 1.1.4.2.2. Computation Procedures for Actual Evapotranspiration within the Fen Catchment, Outside the Wetland Area ($AE_{Curragh}$)*

Owing to the character of the Curragh Plains area, which is extensive grassland similar to that of the hypothetical reference crop, potential evapotranspiration does not have to be modified by any crop coefficient. However, as the potential evapotranspiration (PE) is a measure of the ability of the atmosphere to remove water from the grassy surface, assuming there to be no control of water supply, in the summer months it may differ from the quantity of water that is actually removed. Actual evapotranspiration depends on the availability of water that can be removed from the soil and is driven by both water recharge and the vegetation being grown in a given area as well as its water needs. In wet months, when precipitation exceeds potential evapotranspiration, actual evapotranspiration is equal to potential evapotranspiration (PE). In dry months, when potential evapotranspiration exceeds precipitation, actual evapotranspiration depends on a delicate soil moisture balance which can be defined using the concept of Soil Moisture Deficit (SMD). This concept is used to define the shortfall of soil moisture below field capacity and is the quantity of rainfall or irrigation needed to return soil to its field capacity. It solely depends on rainfall intensity, soil moisture and PE and is equal to zero when soil is at its field capacity. The field capacity is the maximum amount of water that the unsaturated zone of a soil can hold

against the pull of gravity, (Fetter, 2001). It depends on the length of time the soil has been drained by gravity and decreases in prolonged no rainfall periods and in times with increased evapotranspiration needs (summer).

The methodology employed for SMD determination was as follows:

1) SMD is assumed to be zero after significant rainfall, usually during recharge period (usually in winter).

$$SMD_{(day\ 1)} = 0$$

2) For each following day:

$$SMD_{(day\ 1+1)} = AE_{(day1)} + SMD_{(day1)} - RF_{(day1)}$$

3) And so on for each consecutive day, the calculation is continuous.

*Equation III-9*

A negative result for Equation III-9 indicates a surplus of soil moisture, hence a zero value for SMD. The positive result indicates that SMD has developed and is equal to the value obtained through the calculation.

It also means that there is a shortage of water that plants need for growth and their living functions. When growth of plants is inhibited, so is the respiratory process; hence the decrease in transpiration. Less water in the soil means also less water available for evaporation, therefore actual evapotranspiration is less than potential evapotranspiration. To incorporate this restriction into our ET model, an Aslyng (1965) scale was used (methodology adopted by Met Éireann nationwide), which modifies potential evapotranspiration (PE) depending on the SMD from the previous day. The AE becomes less than PE when SMD reaches 30 mm and proceeds to 120 mm (SMD value for grass wilting point). AE is decreasing linearly for that range and is zero thereafter.

The method employed for determination of AE was as follows:

if $SMD_{(day1-1)} \leq 30$ mm, then $AE_{(day\ 1)}$ is unmodified and equal to PE

however,

if $SMD_{(day\ 1-1)} > 30$ mm, then $AE_{(day\ 1)} = PE_{(day\ 1)} \times [(120\text{-}SMD_{(day\ 1-1)})/90]$

and

if $SMD_{(day1-1)} \geq 120$ mm, then $AE_{(day1)} = 0$

*Equation III-10*

Calculations were determined on daily basis and the numerical results for observation period March 2002-September 2005 are presented in Appendix 9.

#### III-1.1.4.3 Effective Rainfall

Considering the nature of the Curragh landscape with high permeability subsoil, surface runoff and interflow were assumed negligible, therefore effective rainfall is calculated as a difference between gross rainfall (P) and actual evapotranspiration (AE) and this was performed with an annual time scale.

## *III-1.1.5. Surface Water Levels and Flows*

### III-1.1.5.1 Water Levels

As mentioned in Chapter II, water level monitoring of Milltown Feeder was introduced in 2001 in an attempt to quantify the discharge of water from the Pollardstown Fen. Continuous monitoring of water level fluctuations was commenced firstly in November 2001, under the bridge in Milltown village and at 7 Springs (beginning of the Feeder) and later, in March 2002, at an additional point in a drain below site A (southern fen margin), which collects most of the water being discharged through the southern springs. Devices used for monitoring were Thalimedes water recorders and were provided by OTT-Hydrometry. Recorders were set to scan the water table every minute and an average value was recorded on an hourly basis. All loggers were secured inside Ø 0.2 m PVC pipes and surveyed with a GPS to reference them into Poolbeg datum, as were all piezometers and monitoring boreholes. Hydrographs for consecutive hydrometric years 2002-2005 are presented in Appendix 11.

### III-1.1.5.2 Water Velocity and Flows

#### *III - 1.1.5.2.1. Manual Measurements*

Manual measurements of flow velocity were carried out on a number of occasions and flows turned into discharge using Mean and Mid-Section methods (Fetter, 2001). The cross section of the stream flow was divided up into vertical sections in the way that each section has no more than 10% of the total flow (Shaw, 1994) and velocity measured using a portable flow meter (WTW). The number of measurements along the vertical depends on the depth and character of the flow. For small streams and canals it is recommended to measure the flow at 0.6 or at 0.2 and 0.8 of the depth from the water surface. The average velocity is expected at 0.6 depth from the surface, hence it is a common practice to do just only this one measurement along each of the vertical (Brassington, 1998). The number of measurements carried out during the study proved that there is very little difference between these two approaches; therefore, the 0.6 method was adopted in most cases. However, when weeds were obvious obstacles when measuring the flow at a depth of 0.6 (weeds physically interfering with the flow meter), velocities at 0.2 and 0.8 depths were measured and an average flow velocity computed for the vertical.

For the mid-section method, the discharge was then derived from the sum of the product of the stream velocity, depth and distance between imaginary vertical sections:

$$Q_A = \sum V_i \cdot H_i \cdot \left(\frac{B_{i+1} - B_{i-1}}{2}\right)$$

*Equation III-11*

and for the mean-section method, the discharge was computed from:

$$Q_A = \frac{V_i + V_{i+1}}{2} \cdot \frac{H_i + H_{i+1}}{2} \cdot (B_{i+1} - B_i)$$

*Equation III-12*

where:

$Q_A$ – total discharge [$L^3$/T]

$i$ - vertical

$V$ – velocity [L/T]

$H$ – depth at vertical [L]

$B$ – distance from initial point [L]

### *III - 1.1.5.2.2. Automatic Measurements using the Ultrasonic Doppler Flow Meter*

Because of the non-linearity of the discharge from Milltown Feeder, a stage discharge curve was not possible to establish; therefore an Ultrasonic Doppler Meter was used to measure the flow velocity on a continuous basis. Anne-Marie Casey – an MSc student - assisted in installations and calibration of the instrument. A broad description of that work is included in her thesis (Casey, 2003). The Ultrasonic Doppler Flow Meter provides remote velocity sampling and integrated flow measurement based on the Doppler principle. The transducers produce sound pulses of a known frequency along a narrow acoustic beam, which in turn strike particulate matter suspended along the beam in the water. The sound pulse is partially reflected back along the ultrasonic beam to the receiver as an echo. This echo has a frequency or Doppler shift proportional to the velocity of the particulate matter along the acoustic beam, (Unidata, 2000).

In summary, the device was placed under the Hanged Man's Bridge and set to measure velocity and water depth in a canal. According to the manufacturer's recommendations, the instrument should be placed where channel banks and channel beds are stable, i.e. no erosion or deposition would change the profile of the cross section over time. The site should also contain storm discharges within the banks of the river so as not to lose channel control. There should be no boulders or obstacles in the water, which would bias the flow of the river and the UDFM equipment. The location under the bridge was the only location to meet these requirements. It was chosen for its uniform cross section under the bridge, limited access from the boat only and shading provided by the bridge, which limited weed growth. The flow at this site is steady and shows little or no signs of natural turbulence or backflow. There was no known history of the water bursting its banks along this reach and so the canal water stays under channel control. The main consideration in sighting the UDFM flow meter equipment requires laminar flow in the water. The proper position of the sensor is that the flow meter must be horizontally and vertically aligned with the flow as the ultrasonic beam is emitted at 30° to the flow meter, i.e. the horizontal. Any angled flow in the horizontal will reduce the recorded velocity. A 10 degree angle will reduce the recorded velocity by 1.5%, (Unidata, 2000).

Flow velocity and depth was measured in set intervals (1 minute) and an hourly average was automatically obtained. Since the cross section is constant (4.5 metres, flat bottom channel), the following equation was used to calculate the discharge using the data collected from the flow meter:

$$Q_A = V \cdot W \cdot H$$

*Equation III-13*

where:

$V$ - average velocity across the beam length [L/T]

$W$ - width of canal [L]

$H$ - depth of water [L]

$Q_A$ - average discharge [$L^3$/T]

Flows were computed on an hourly basis and were later aggregated into daily records using the average function in Microsoft Excel. These daily results are presented in Appendix 12.

To validate the measurement, manual flow measurements were used to compare the results and calibrate the instrument. For methodology refer to Casey (2003).

## III-1.2. Results

### *III-1.2.1. Catchment Area*

Pollardstown Fen occupies the area of 2.2 $km^2$ and is located in a post glacial valley. The surface runoff from surrounding fields is negligible due to the high permeability of the subsoil in the area, which leaves the fen's water budget with inflows from groundwater and precipitation. The groundwater catchment for Pollardstown fen covers an area of 32.2 $km^2$ and on the south side it follows the line from Red Hill towards north of Kildare, where, after passing the town, it turns southwards and then turns eastwards towards the Curragh Camp. At the Curragh Camp, the divide turns northwards towards Newbridge, parallel to the Liffey River, where it meets the northern line of a divide. On the north side, the groundwater divide runs along the Milltown – Newbridge road R416. About 90% of this area is agricultural land. All of this catchment area drains into the Milltown Feeder with the major spring outflow at 7 Springs and through seepages along the southern fen margin. To the west of the catchment area, another catchment draining towards the Milltown Stream is present. Casey (2003), throughout extensive site investigation established small surface runoff catchment (2.82$km^2$) present in the eastern part of the Pollardstown Fen catchment. This surface runoff originates in the Curragh Camp and follows north-west towards 7 Springs and lies in a valley between Newbridge town and The Curragh Plateau. The investigation of flows and physiochemical parameters (electrical conductivity and temperature) revealed, however, that the upper reach of this drain is a leaking drain with the loss of flow occurring between the Curragh Camp and the railway line, slightly south to 7 Springs. Flows in this part of the drain were extremely small, and impossible to measure. Water in the drain below the railway line showed much higher EC values and temperature close to that of groundwater, which implies a small spring/seepage near the railway bridge.

Nevertheless, the outflow from this spring connects to the main drain below the Seven Springs, which is above the first flow measuring stations, therefore its outflow is measured together with that from 7 Springs.

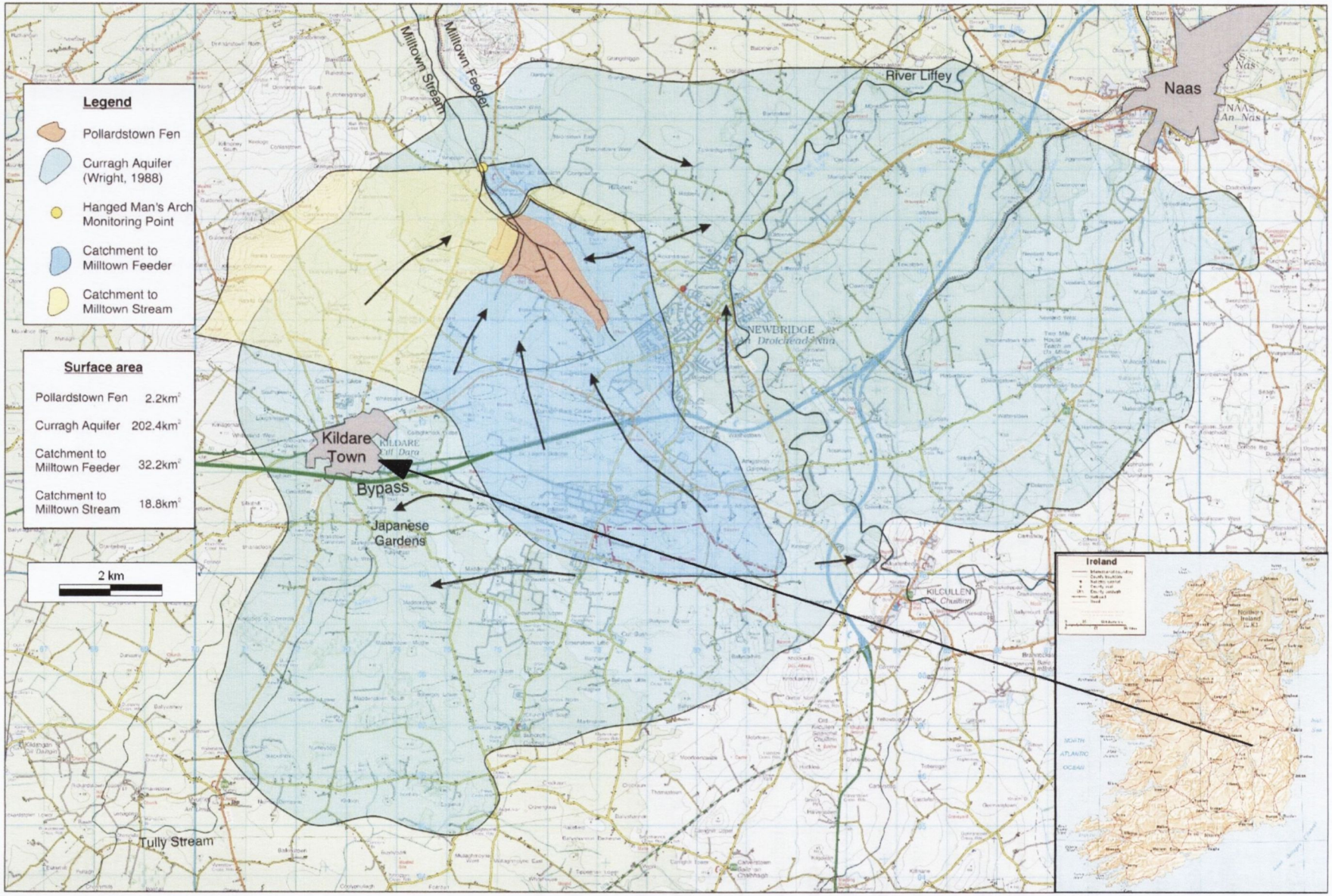



*Figure III-2 Catchment area for Pollardstown Fen with distinguished groundwater flow directions. Courtesy of Dr. Les Brown.*

### *III-1.2.2. Spring Survey*

The majority of springs and seepage areas were identified on the south side of the fen, along the 2 km stretch of the fen margin with an extensive cluster of 23 springs inside the forest below the Spring Bank House, Figure III-3. In general, most of the southern springs gather between the Duck Ponds and the Public Entrance to the Pollardstown Fen Nature Reserve; however, a few more springs are also present further south east towards the Seven Springs. The water from the springs is collected by a system of canal feeders which cross the fen and join to form the Milltown Feeder. The beginning of this canal lies at Seven Springs, which is the biggest groundwater discharge point within the fen boundary.

There are significantly fewer springs and seepages along the northern boundary; nevertheless these are also connected to the Milltown Feeder.

As a result of a drainage scheme developed for the purpose of reclamation of the fen for agricultural purposes (1964), a main drainage channel was excavated in the centre of the fen and an outfall was installed as a culvert under one of the canal feeders and the drained water flew north-westwards as a tributary of the Slate River, via the Milltown Stream (Daly, 1981). This culvert was later blocked in 1983, when a decision was made to re-wet the fen area. The western part of the fen was also drained in 1964 and water was diverted towards the Milltown Stream. This part was afforested and currently the drainage system inside the forest still contributes to the flow in Milltown Stream. Figure III-3 presents a layout of a drainage system and spring/seepage locations based on a field investigation carried out during this research. Measured values of temperature and electrical conductivity are presented in Table III-5.

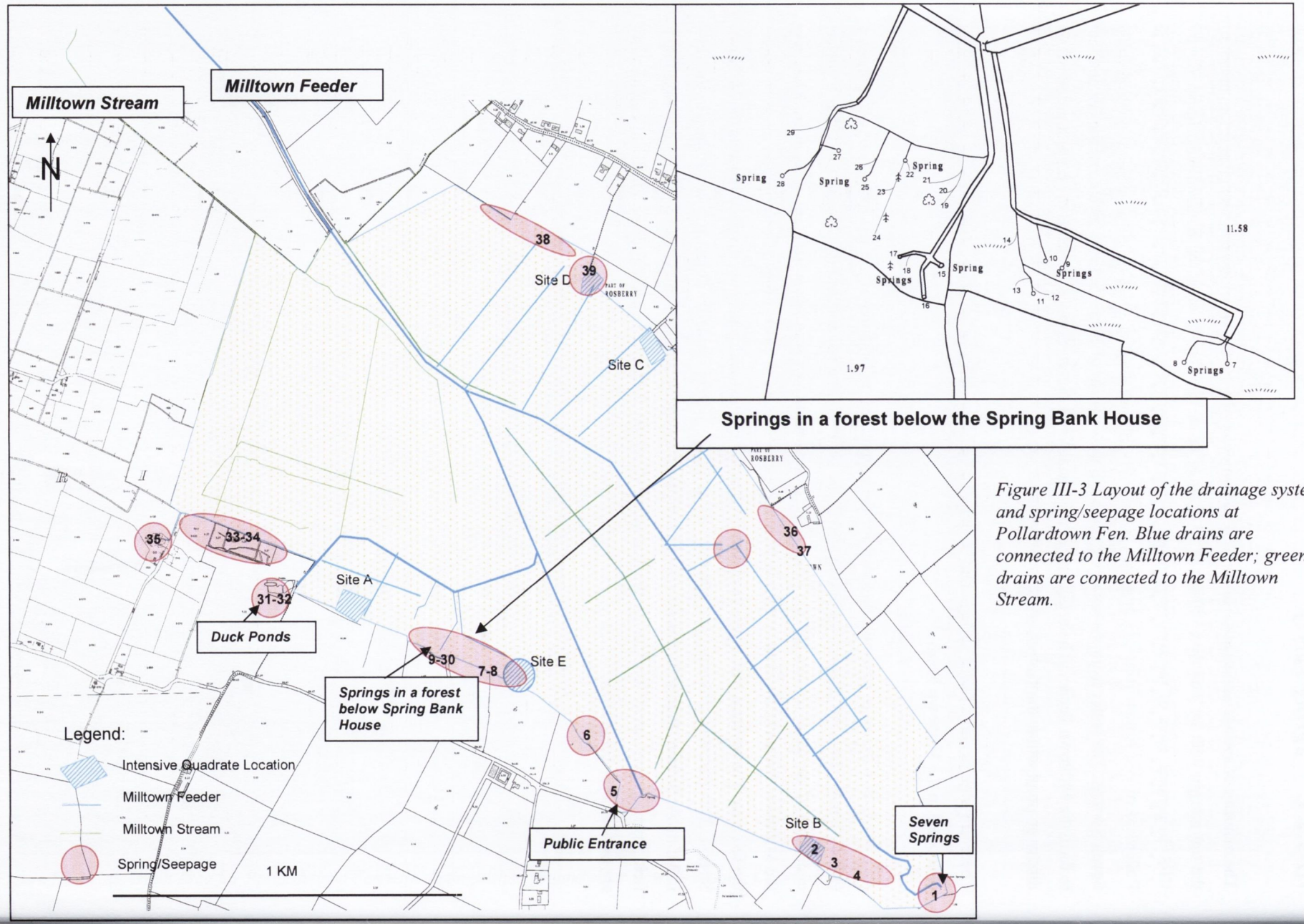



*Figure III-3 Layout of the drainage system and spring/seepage locations at Pollardtown Fen. Blue drains are connected to the Milltown Feeder; green drains are connected to the Milltown Stream.*

**Table III-5 Characteristics of selected major spring outlets along the fen margin. Data collected on 31/09-01/10/2002, air temperature 17.5 °C.**

| Spring | EC | Temp | Location | Elevation | Comment |
|---|---|---|---|---|---|
| | µS/cm | °C | | m OD | |
| 1 | 757 | 10.3 | 7 Springs | 85.55 | Upwelling spring |
| 2 | 733 | 11.3 | Site B | 86.07 | Dug out spring |
| 3 | 811 | 11.1 | Horse pond outside site B | | Upwelling spring |
| 4 | 805 | 11.6 | Seepage next to the horse pond | | seepage |
| 5 | 691 | 10.3 | Public Entrance | | Upwelling spring |
| 6 | 709 | 10.4 | Southern fen margin | | Spring |
| 7 | 744 | 10.3 | Forest below Spring Bank House | 86.00 | Spring |
| 8 | 749 | 10.4 | | 87.21 | Spring |
| 9 | 700 | 10.0 | | | Spring |
| 10 | 686 | 11.6 | | | Spring |
| 11 | 712 | 10.3 | | 87.517 | spring |
| 12 | 646 | 12.8 | | | Tufaceous spring |
| 13 | 705 | 11.8 | | | spring |
| 14 | 600 | 11.2 | | | spring |
| 15 | 729 | 10.4 | | 87.223 | spring |
| 16 | 742 | 10.0 | | 87.292 | spring |
| 17 | 742 | 10.7 | | 87.84 | spring |
| 18 | 732 | 10.7 | | 87.49 | spring |
| 19 | 660 | 10.4 | | 87.233 | Seepage spring |
| 20 | 663 | 10.3 | | 86.43 | Seepage spring |
| 21 | 644 | 10.2 | | 85.99 | Seepage spring |
| 22 | 646 | 11.0 | | | Seepage spring |
| 23 | 672 | 10.7 | | | Seepage spring |
| 24 | 732 | 11.3 | | 87.107 | Seepage spring |
| 25 | 674 | 10.5 | | | Seepage spring |
| 26 | 659 | 10.5 | | | Seepage spring |
| 27 | 658 | 10.5 | | 85.02 | Seepage spring |
| 28 | 646 | 10.6 | | 85.82 | Seepage spring |
| 29 | 637 | 10.2 | | 85.87 | Seepage spring |
| 30 | 666 | 10.6 | | 85.95 | Seepage spring |
| 31 | 711 | 15.3 | Upper Duck Pond | 87.72 | Upwelling springs |
| 32 | 655 | 14.6 | Lower Duck Pond | 87.26 | Upwelling springs |
| 33 | 683 | 12.8 | | 86.03 | Seepage spring |
| 34 | 698 | 12.7 | | 86.96 | seepage |
| 35 | 728 | 11.2 | | 87.17 | Upwelling spring pond |
| 36 | 760 | 11 | Northern fen margin | 87.38 | Upwelling spring |
| 37 | 783 | 15.3 | | 86.6 | seepage |
| 38 | 783 | 15.3 | | 85.55 | seepage |
| 39 | 700 | 16.7 | Site D | 85.68 | Seepage spring |

Because of the high mineral content of groundwater, electrical conductivity was, as expected, high, around 700 µS/cm. Springs located at the highest locations of the southern fen margin (>87.00 m OD) mostly flow laterally and have point outflows with high EC (>700 µS/cm) and temperature of groundwater at c. 10-10.5°C. These

springs emerge directly from the groundwater system, their beds are solid and of a mineral structure; flows are distinctive. Usually there is a strong structure of tufa around the springs.

Springs located at lower elevations are usually of a seeping nature, with soft, peaty beds and oozing outflow over larger areas. Seepage springs show reduced ECs as water loses its mineralisation while upwelling through the peat (values c. 650 µS/cm), following ionic exchange and dilution with rainwater (Almendinger and Leete, 1998). Temperatures are slightly higher (10.2-11.3 °C) than those from upper locations, which is due to heat exchange with surrounding soil. Often the crunchy structure of tufa occurs under the moss cover in the vicinity of these springs. This results from precipitation of calcium carbonate when groundwater, rich in calcium bicarbonate, comes into contact with the air, and the solution equilibrates with the air by releasing $CO_2$ into the atmosphere.

It was noticed that springs 2-4 (Figure III-3) had higher values of both ECs and temperature than other springs located at this stretch of the fen margin, which might result from an external source; most likely from the landfill located above that site. Spring 3, surveyed for the extended hydrochemical suit, showed also an elevated chloride value at a level of 32.5 mg/l, which exceeds a trigger value set by the EPA for unpolluted groundwater in Ireland of 30mg/l, (EPA, 2003). While chloride is a constituent of organic waste (Kiely, 1997), an elevated level in this specific location with respect to other samples from the south side of the fen margin may support the hypothesis of a leakage from the upgradient source; however, there is no other evidence of this. Elevated chloride occurs also in groundwater and spring water on the north side, specifically spring 39 (29.7 mg/l) and MB 43 (32 mg/l).

Springs on the north side show generally higher ECs (up to nearly 800 µS/cm) and temperatures (11.0 - 16.7°C) than springs on the south; however, no tufa formation is present in the immediate vicinity of these springs. Higher water temperature suggests that the water originates from a different, probably shallower source than the deep aquifer supplying water the southern springs.

The highest discharge areas are inside the forest below the Spring Bank House (c.87.00-88.00 m OD) and at the western end, within the Duck Ponds system (88.72 m OD in the upper pond). Lower springs, usually of a seeping nature, are present at c. 85.00-86.00 m OD. The boundary of the northern margin is slightly lower and springs occur at 85.50-86.00 m OD.

### *III-1.2.3. Water Chemistry as an Indicator of Groundwater Recharge*

To understand the differences between the southern and northern fen margin and to discriminate potential mechanisms for changes in concentrations of certain physio-chemical parameters, these sites have to be analysed within the context of underlying geology. To do that, a geological cross-section was drawn based on the borehole logs from piezometers sampled during the analysis. Selecting piezometers at outer and inner horizons (outer – just at the fen margin and inner – slightly closer to the fen centre) allowed differences to be seen in the groundwater and peat water chemistry across the marginal zone and to hypothesise potential zones of groundwater recharge into the fen. This cross section is presented in Figure III-4. Full borehole logs can be

found in Appendix 15 – site A and Appendix 25 – site D. The spatial distribution of piezometers on the fen is presented in Appendix 2.

The major difference between the two sides lies in the layering sequence and thickness of clay deposits underlying the fen peat. On the south side, the general geological profile comprises (from the top) a thin layer of peat (1-2 metres) underlain by a thin clay, underlain with approximately 4 metres of gravel and sand, underlain with a second layer of clay (1-2 m deep) and further down, sand and gravel. These are found at 6-8 m below ground level (bgl). A review of all piezometer logs from site A revealed also that both clay layers are not continuous throughout the site, and the layering sequence is very complex here (intersecting ribbons of sand, gravel and clay). The general pattern is such that clays are thin at the fen margins and thicken towards the fen centre; however some piezometers (SP30, SP31, SP32) show no or very thin deposits of clay underneath the peat. In addition, the presence of man made drainage ditches excavated in the past throughout the site suggest that the upper, relatively thin clay layer may have been cut through or reduced in thickness (in places), which created a pathway for the groundwater and peat water to travel between the peat and upper gravel layers. Log descriptions suggest also that clays present on the south side contain significant amounts of sand and gravel, and are often described as 'sandy, gravely CLAY', which implies they are likely to allow for slow water movement.

In contrast, on the north side, the majority of the deposits are comprised of clay. The peat depth is thin (1-2 m) but increases towards the fen centre, as expected. The fen peat is underlain with a layer of firm grey clay, which is thicker than that found on the south side and its thickness is already 1 m in the outer piezometer (SP24). Gravel that underlies this clay gives artesian conditions. These gravels pinch out between the outer and inner piezometers. Small pockets of sand are also found beneath the upper clay. The second clay layer is described as 'firm, brown, gravely CLAY' and is found beneath the upper gravel. Its thickness varies from 5 to 8 m across the marginal zone (the extent of Site D). This is further underlain by glaciofluvial sands and gravels in which artesian conditions prevail. Yields at depths of 9-11 m bgl were estimated at 1.3 litres per second during drilling (WYG Ltd, 2002). Figure III-4 presents a schematic of a geological cross section on the southern and northern fen margin. The cross section was drawn based on borehole logs from piezometers used during the sampling.

The differences between the southern and northern sides are analysed, firstly with respect to concentrations between the two sides, and later with respect to current legislation and guidelines values.

Spring hydrochemical results were also analysed here as these represent groundwater discharge points and shall be therefore compared with middle and deep screens (Figure III-5).

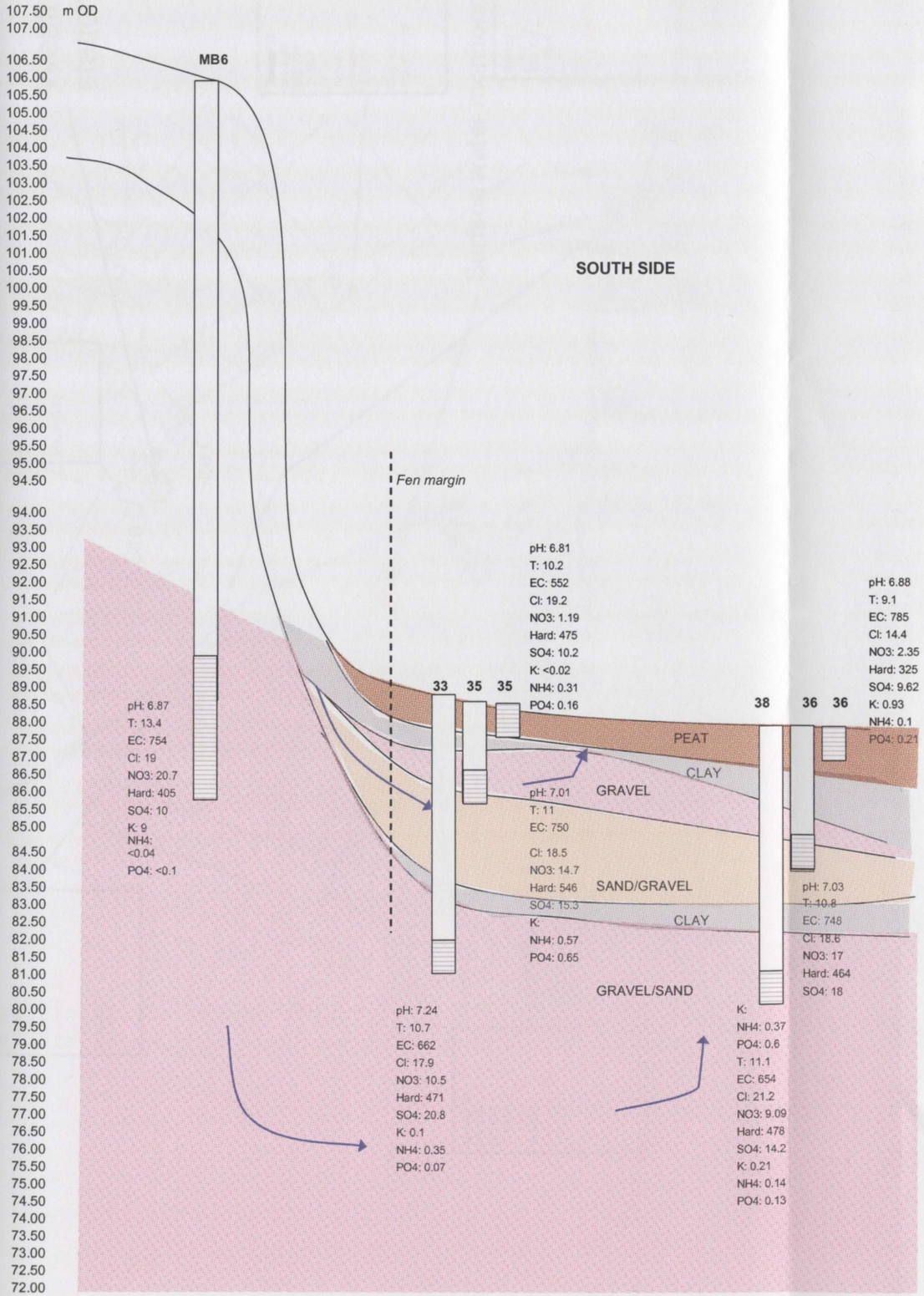



*Figure III-14 Schematic geological cross sections (based on borehole logs from respective hydrochemical sampling locations); potential groundwater flow paths through southern and northern fen margins and the results of chemical analysis.*

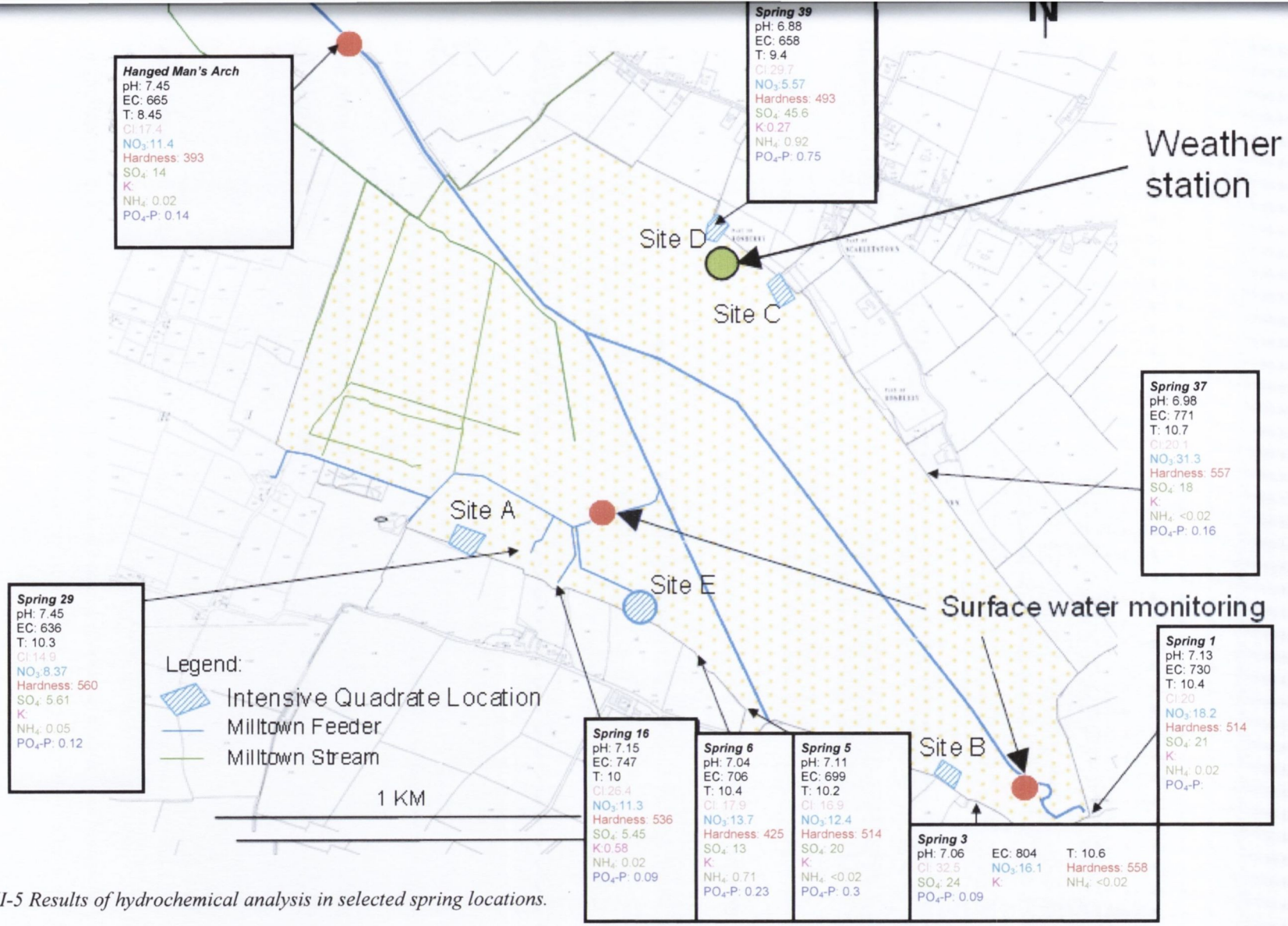



*Figure III-5 Results of hydrochemical analysis in selected spring locations.*

### III-1.2.3.1 Concentrations of Major Ions

#### *III - 1.2.3.1.1. Deep & Middle Screens and Springs*

The major differences between the southern and the northern fen margins within deep screens are:

- Lower temperatures on the north side,
- Higher nitrate and phosphate levels on the north side,
- Higher potassium levels on the south side,
- Elevated chloride concentration on the north side,
- Elevated electric conductivity on the north side.

In the middle screens, differences between the two sites were found in the following:

- Lower temperature on the north side,
- Higher ammonium on the south side,
- Higher phosphate on the south side.

***Temperature, pH and EC***

The temperature of the groundwater in deep screens at site A was found to be between 10.7-11.4 °C while at site D it was found to be at 9.4-9.9 °C. Temperature readings were taken *in situ* but it is unlikely that the ambient temperature, which on the day of sampling was approximately 10-12 °C, affected the readings. All deep piezometers indicated confined conditions with those on the north side being artesian. Screens in these artesian piezometers are placed at deeper depths than deep piezometers on the south side, which is a likely reason for recording lower temperatures here.

A similar pattern was found in the middle screens, where piezometers on the north side were 0.7 °C (approximately), lower than on the south side.

Spring samples showed temperatures ranging from 9.4-10.7°C and the lowest value was found on the north side (Spring 39). In addition, data collected at Seven Springs by Coxon in the late eighties (1987-1989, Appendix 7), showed similar temperatures (ranging from 9.7-11.6°C) to those collected during the TCD study. A seasonal variation with a slight increase in temperature in the summer months is also apparent in this data.

pH (hydrogen ion concentration) values are similar on both sides, and indicate alkaline conditions with values exceeding 7 on Sørensen's 0-14 scale. A lower pH was found in the middle screen in piezometer 29 on the north side. It is likely that this location is separated from the influence of groundwater due to reduced permeability in clay and hence influenced by rainwater, which is expected to have lower pH.

With respect to pH values in springs, all locations showed alkaline conditions (6.88>pH<7.2) although two springs on the northern side (37 & 39) had slightly lower pH values in comparison with remaining springs (6.98

and 6.88 respectively). This possibly indicates an influence of surface water/mixing with rainwater in this location.

Electrical conductivity is found at levels 689-820 µS/cm on the north side and 654-750 µS/cm on the south side. Both sides show highest values in the middle outer screens, which is coincident with increased nutrient levels, as described below. In general, in sand and gravel aquifers, electrical conductivity is expected to be high; however the EPA (2003) sets a threshold for unpolluted water at 1000 µS/cm. Comparing EC values from different sampling locations within the fen, the value recorded in the middle screen in piezometer 24 (north side) seems elevated with respect to the remaining locations and its EC value of 820 µS/cm, matched with high nitrates, phosphates and chloride concentrations found in the same sample, suggests a local pollution point upgradient from the sampling location.

In springs, results show conductivity between 630-810 µS/cm, which is in accordance with results from deep and middle screen values. The lowest EC values were recorded in springs 29 (south east of site A) and 39 (Site D). These were seeping springs, located at relatively low altitudes below 86.00 m OD.

***Total Hardness***

Groundwater becomes saturated with calcium when water containing atmospheric carbon dioxide passes through calcium carbonate containing minerals such as limestone, converting part of the calcium carbonate to bicarbonate, which is very water soluble. Samples from the deep and middle screens showed hardness ranging between 418-546 mg/l $CaCO_3$ which is very high and were classified as very hard, Table III-6. Samples located in the middle outer screens on both sides (24 and 36) showed elevated concentrations with respect to other samples and were measured at 521 and 546 mg/l, respectively, while the remaining samples were all below 500 mg/l. This may reflect closer recharge zones for respective piezeometers where a higher concentration of atmospheric $CO_2$ in groundwater dissolves a higher concentration of calcium carbonate from sandy and gravely deposits. Hardness concentrations at a level above 500 mg/l $CaCO_3$ were frequently recorded in springs. Hardness values found in Monitoring Boreholes located at the fen boundary were 405 mg/l in MB6 and 435mg/l in MB 43. No significant difference was found between the southern and northern fen margin. Typical hardness values of sand and gravel aquifers are usually c. 320 mg/l (EPA, 2003).

**Table III-6 Classification of Water Hardness (after Hammer&Hammer, 1996)**

| Hardness (as mg/l $CaCO_3$) | Hardness Classification |
|---|---|
| <50 | Soft |
| 50-150 | Moderately Hard |
| 151-300 | Hard |
| >300 | Very Hard |

***Nitrate, Ortho-Phosphate, and Potassium***

Nitrates and phosphates are chemicals that may represent pollution introduced to groundwater from external, anthropogenic sources. Therefore, differences between the southern side and the northern side may indicate a pollution source close to the northern sampling locations, likely on the upgradient fields. Both nutrients, nitrates and phosphates, showed higher concentrations in deep screens on the north side, and this relationship is stronger in the case of phosphates. In middle screens, the highest phosphate levels were found on the south side.

In deep screens, concentrations of nitrates ranged between 9.09 mg/l to 17.3 mg/l on the southern side and on the north side they ranged from 17.9 to 28.4 mg/l. Phosphates were found between 0.06 and 0.13 mg/l on the south side and between 0.28 and 0.34 mg/l on the north side. According to the EPA studies (Keegan *et al.*, 2002; EPA, 2003), nitrate occurs in natural water usually in low concentrations, typically in the range of 5-9 mg/l $NO_3$. The EPA states the natural concentration of nitrates ($NO_3$) in sand and gravel aquifers at the level of 2.8 mg/l. Most nitrate found in groundwater comes from organic and inorganic sources such as waste discharges or artificial fertilisers respectively (Keegan *et. al*, 2002). The elevated concentration of nitrates in groundwater is often driven by the agricultural land use and farming practices within the catchment. This could explain elevated values found in the deep gravels at the periphery of the fen, which is surrounded by cattle and sheep grazing fields. The field upgradient from site D was extensively grazed by cattle throughout the study period and occasional slurry spreading was also recorded, which is reflected in higher nutrient levels. Nitrate concentrations in deep screens show a decrease towards the fen centre on this side. Higher nitrate concentrations are also found in a middle screen at the outer horizon (SP24) but not in the inner one (SP29). The inner middle piezometer is screened in clay, and water movement through this layer is impeded due to low permeability of the stratum. Decreased oxygen availability here is likely to impact upon the nitrogen cycle and reduce the nitrate concentration in a process of denitryfication.

On the south side, nitrates in deep screens are found at levels approximating to 10 mg/l and also slightly decrease towards the fen centre.

Nitrate ($NO_3^-$) concentration in springs ranged between 5.57-18.2 mg/l and one spring (37 on the north side) showed an exceptionally high value of 31.3 mg/l. This corresponds with values found in middle and deep screens on the north side and provides further evidence for an organic pollution source within the catchment area on the north side. Slightly elevated nitrate values were also found in spring 3 (16.1 mg/l) and the Seven Springs (18.1 mg/l).

Under the EU Drinking Water Directive (98/83/EC), the maximum nitrate concentration in water intended for human consumption is given as 50 mg/l but a guide level of 25 mg/l is recommended as an indicator of contamination (Keegan *et al.*, 2002). In that respect, water samples from the fen and also from the Curragh aquifer (Table III-8) showed relatively high values. The mid Curragh boreholes had concentrations of c. 20-30 mg/l. The two monitoring boreholes located on the northern side also showed elevated values of 24 and 29.3 mg/l.

With regard to ortho-phosphate (in natural water), concentrations are normally no more than a few tenths of micrograms per litre. Because of its low mobility in soil, phosphorus does not cause much danger to groundwater, but it causes more of a threat to surface water as even in small concentrations it leads to its eutrophication. Concentrations found in fen samples are relatively high. On the north side, a very high ortho-phosphate level is found in deep and shallow screens (0.28-0.9 mg/l), while in middle screens, only the outer piezometer (SP24) shows a comparably high level (0.24 mg/l). In inner piezometers (nest 29), a concentration of ortho-phosphate in the middle screen was found at 0.08 mg/l, which although relatively low in the context of other samples, still stands above the Maximum Allowable Concentration of 0.03 mg/l as P as set by the EU

Drinking Water Directive (98/83/EC). On the contrary, the south side records lower ortho-phosphate concentrations in deep screens (0.07-0.13 mg/l), and higher in middle (0.6-0.65 mg/l) and shallow (0.16-0.9 mg/l) screens. Increased phosphorus and nitrate concentrations in middle screens (higher gravel) on the south side suggest a preferential flow of water into this layer from a closer to the fen pollution source, perhaps infiltration of surface runoff from the upgradient field at the edge of the fen. Increased nutrient levels at this location explain also increased EC values recorded here.

The levels of ortho-phosphates recorded in the springs ranged between 0.09 and 0.75 mg/l, with the maximum value recorded in spring 39. Spring 39 is located few metres below the fen boundary. The upgradient field is utilised for cattle grazing but occasional slurry spreading also occurs. It is most likely that elevated ortho-phosphate value is associated with a leachate from that field. Two other springs, namely 5 and 6, also revealed a higher ortho-phosphate concentration (0.23 and 0.3 mg/l respectively). As these springs are fast flowing and with mineral beds, it is unlikely that phosphates could originate from P mobilisation in these locations; therefore they most likely indicate groundwater pollution, as on site A.

Potassium normally occurs in water only in very small quantities and higher levels may often be associated with usage of agricultural fertilisers (Hermanowicz *et al.*, 1999). Drinking quality standards are set at 12 mg/l, however, the expected value in sand and gravel aquifers is 0.6 mg/l (EPA, 2003). Potassium levels were measured only in selected locations, in deep screens on the south side and in deep and middle screens on the north side. In addition, data from upgradient monitoring boreholes MB6 and MB43 were also available. These were found to be highest on the south side, where the borehole MB6 showed 9 mg/l and concentrations in deep screens at the fen margin ranged from 0.1 to 0.21 mg/l. In comparison, concentrations found on the north side were 2 mg/l in MB43 and less than 0.02 mg/l in deep and middle screen samples at the fen margin. Potassium in soil solution can be lost via three processes; namely potassium fixation, uptake by plants and uptake by micro organisms. Because the above water samples were collected from depths below 7 m from ground level, it is doubtful that the reduction of potassium concentration on the way through the aquifer was promoted by any life forms; therefore, most likely, this reduction occurred due to fixation into clay particles present in the subsoil profile. The higher content of clay particles in subsoil on the north side may have resulted in a faster removal rate of potassium on this side.

Potassium concentrations were determined in two spring locations only, namely 16 and 39, both of which showed normal concentrations (<5 mg/l) of 0.58 and 0.27 mg/l respectively. Due to lack of information from the remaining springs, no major differences can be distinguished between northern and southern sides.

***Ammonia, Chloride and Sulphate levels***

Levels of ammonia concentration in deep screens ranged between 0.14 and 0.35 mg/l on the south side and from 0.25 and 0.3 mg/l on the north side. However upgradient sampling locations (MB6 and MB43) showed concentrations below 0.04 mg/l. As ammonia has low mobility in soil and subsoil, its presence in groundwater at rates of > 0.1 mg/l indicates nearby direct sewage, industrial or agricultural contamination (Keegan *et al.*, 2002). This would provide further evidence for earlier interpretation of high nitrate and phosphorus concentrations. Water containing concentrations higher than 0.3 mg/l $NH_4$ does not meet drinking water quality standards according to EU Directive (98/83/EC).

Concentrations recorded in the springs were mostly small and below given standards; however, two locations showed exceptional values of 0.71 and 0.92 mg/l and these were springs 6 and 39 respectively. Both of these locations have been reported to have higher phosphate and chloride levels (39 only); therefore elevated ammonium is likely to reflect pollution rather than natural processes.

Chloride concentrations in deep and middle screens are at levels typical for unpolluted groundwater in Ireland (EPA threshold level set at 30 mg/l, Keegan *et al.,* 2002; EPA, 2003), except for one location – MB43 on the north side, which exceeded this value by 2 mg/l. The elevated value of chloride in MB43, which strongly stands out from all other groundwater samples collected by WYG, may suggests a local pollution source; however, this should also be reflected in other inorganic parameters ($NO_3^-$, $PO_4^-$) as well as should be verified by a potassium:sodium ratio (i.e. 0.3 threshold employed as an indicator of human or animal waste sources) and all of these remain at levels below which may give rise to concern (Table III-8). Generally, both sides show similar concentration levels and range from 13.1-24.1 mg/l on the south and from 17.9-21.2 mg/l on the north side. The EU drinking water quality standards allow concentrations of up to 250 mg/l.

Chloride concentrations found in the springs ranged between 14.9 and 32.5 mg/l but two locations showed specifically high concentrations and these were Spring 3 (32.5 mg/l) and Spring 39 (29.7 mg/l). While spring 3 is located downhill of a landfill site, the high chloride value found here is likely to reflect pollution leaching from the site. With regard to spring 39; because high levels were identified also in Monitoring Borehole MB43, this elevated chloride concentration provides further evidence for a potential pollution point within the northern extent of the catchment area.

Sulphate levels in deep and middle screens are similar on both sides, although a sample taken from the inner piezometer on the north side (SP29), screened in a clay layer, does show a slightly lower concentration. This again supports the hypothesis that mixing with fresh groundwater is restricted in this location. Sulphate occurs naturally in groundwater in concentrations ranging from a few to a few thousands of mg/l. It dissolves from the soil and geology (pyrite) or, if high values are found, these would indicate pollution (agricultural or atmospheric). In sand and gravel aquifers it is usually expected at low levels, c. 2 mg/l (EPA, 2003); this, however, is not in agreement with the values observed during the fen survey, which in most cases significantly exceeded this value. Values recorded on Pollardstown fen ranged between 14.2-20.8 mg/l on the south side and 13.3 – 23 mg/l on the north side (and 8.08 mg/l in middle clay screen). The upgradient monitoring boreholes MB6 and MB43 showed concentrations of 10 and 19 mg/l respectively.

Springs located on the southern margin tend to show lower concentrations ranging from 5-13 mg/l except for springs 3 (24 mg/l) and Seven Springs (21mg/l). Spring 5 located along the path at the Public Entrance also showed a higher value of 20 mg/l. While mid Curragh wells showed values c. 10 mg/l, monitoring boreholes on the northern side of the fen showed elevated values of 19-21 mg/l.

Although there is a spatial unconformity in sulphate concentrations between various part of the fen and the Curragh, there is some similarity with chloride and nitrate values, suggesting a trend towards higher values found on the northern and south eastern ends of the fen margin.

### *III - 1.2.3.1.2. Shallow Screens*

All shallow screens at both sides were placed in peat substratum. Concentrations of different parameters in peat depend on number of factors, including soil biogeochemical processes such as mineralisation, substrate geology and external inputs (rainwater or groundwater). The major difference between southern and northern sampling locations is that the southern fen peat is underlain by a shallow and not continuous clay layer with a significant depth of gravel beneath the clay. The peat is brown and solid in structure. On the north side, the fen peat is underlain with a thick clay layer, which results in stronger confining conditions found beneath the clay. An area of the peat was cut out between the two sampling locations in SP24 and SP29 and this results in impeded groundwater inflow in this area. The peat is loose and light grey, due to clay sediments being brought to the surface with seeping groundwater.

***Temperature, pH and EC***

The temperature in shallow screens was similar on both sides and to the south it ranged from between 9.1 and 10.2 °C and on the north side it was between 9.03 and 9.6°C. However, a slightly elevated temperature in the outer locations on the south side (SP35) suggests potential ingress of groundwater which is higher in upper gravel. This correlates well with a higher hardness value which could also be driven by upward seepage and mixing of peat water with water saturated with bicarbonate. General lower temperatures in peat, in comparison with temperatures of groundwater in the upper gravel, suggest the influence of rainwater and ambient temperature.

pH values in peat were generally lower in shallow than in deeper screens, which is expected due to the surface being exposed to rainfall (which is naturally acidic due to exposure to atmospheric carbon dioxide) but also due to decomposition of plant litter and peat, which produces organic acids (Ross, 1995). Values recorded ranged between 6.48 and 7.27 and one value, in the shallow screen in piezometer SP24, showed an elevated level in contrast with other locations suggesting mixing with a more alkaline water source or may have resulted from ammonium build up, which is often observed in waterlogged anaerobic conditions (Ross, 1995). This occurs during decomposition of organic matter, which in waterlogged, anaerobic conditions proceeds at a slower rate than in aerobic conditions, due to a lower number of anaerobic decomposers (bacteria). However, since anaerobic decomposers have a lower immobilisation requirement than aerobic decomposers, a more rapid release of $NH_4^+$-N is often observed and this results in a build up of $NH_4^+$-N, which is accompanied by a small increase in pH levels. Ammonium concentrations in location SP24 were observed at 0.44 mg/l and were higher than concentrations observed in gravel and other peat locations. Nevertheless, elevated hardness in underlying gravel in this location (with known strong hydraulic pressure) suggests also an influence of a more alkaline water source, or both processes combined together.

EC levels are normally lower in peat than in groundwater due to a higher mineral content in groundwater and the diluting effect of rainwater. Results from the fen were similar, except for one location (SP36) on the south side, where EC values were exceptionally high (785 µS/cm) in comparison with other locations (463-552 µS/cm). Such a level is typical for a mineral rich groundwater (Kiely, 1997) and corresponds with EC found in underlying gravel deposits, which further implies potential groundwater seepage in close proximity to this sampling location.

***Total Hardness***

Hardness values in peat are significantly reduced from groundwater samples and this is controlled by lower pH (rainwater contribution, acid formation during plant decomposition) at the surface. Hence, values recorded from shallow piezometers were 350 mg/l $CaCO_3$ on the north side and 325-475 mg/l $CaCO_3$ on the south side. The latter value was measured in outer piezometer SP35 and may indicate a potential groundwater seepage in this location (a higher temperature was also found in this location).

***Nitrates, Ortho-Phosphates and Sulphates***

The processes controlling the distribution of nitrates, phosphates and sulphides in peatland substrates are controlled by complex chemical mechanisms in which redox potential plays a key role. These transformations are beyond the scope of this study and will not be analysed in detail. On the most basic level, studies show (Ross, 1995) that P and N naturally accumulate in peat soil through uptake by plants and microbes, and immobilisation occurring during chemical transformation. These are very dependent on oxygen availability in the peat substrate; therefore release and retention rates are dependent on water level fluctuations, soil permeability (and related flow rates), the temperature and quality of water percolating through peat (Koerselman *et al.*, 1993).

Nitrates are lost in peat soil in the process of denitrification. This is facilitated by a special type of heterotrophic bacteria which, in the absence of a readily available oxygen source, utilises oxygen available in the $NO_3$ for its cell synthesis. Because of the large amount of soluble organic carbon in peat, which is a necessary food source for the above bacteria, denitrification in wetlands is rarely energy limited and proceeds at a fast rate. This was also found at Pollardstown fen, where much smaller concentrations of nitrates in peat, in comparison with concentrations determined in gravel layers, suggest fast denitrification rates here. It is also expected that if the fen surface was recharged at the fen margin, nitrate levels shall reduce towards the fen centre. Therefore, higher concentrations of $NO_3$ in location SP36 (closer to the fen centre) than in location SP35 (closer to the fen margin) suggest an inflow of groundwater between the two locations. This can also be supported by higher phosphate, sulphates and EC values found here.

Phosphorus can be fixed or retained in peat substrates in the sediments or taken up by plants. Ross (1995) mentions also the ferrous phosphate precipitation mechanism and phosphate adsorption as important P reduction processes. While there is a common agreement that wetlands play an important role in $PO_4$ removal, some authors, including Lucassen *et al.* (2004) and Surridge *et al.* (2005) proved that phosphorus can be also released from peat soil into peat water, particularly through mobilisation of sediment and a reduction of ferric oxyhydroxides. Ross (1995) explains also rapid release of $PO_4$ from decaying vegetation and stresses seasonal fluctuations of $PO_4$ in peat related to the seasonality of plant growth, which results in particularity high $PO_4$ uptake in spring, and high $PO_4$ leaching in autumn. On the Pollardstown fen, phosphate concentrations in peat were found at levels varying from 0.16 to 0.9 mg/l (as ortho-P) and were higher on the north side. Taking into account the time of the sampling (samples taken in October), elevated ortho-phosphate levels in peat may reflect a $PO_4$ release from decaying vegetation. A significantly higher $PO_4$ concentration was found in one sample on the north side, in the outer piezometer SP24. In addition, a similarly high concentration of ortho-phosphate was found in adjacent spring 39, which strengthens the credibility of the measurement and suggests likely organic

pollution located in proximity to sampling locations. Lower concentrations of ortho-phosphate in peat substrate than in the underlying gravel on the south side is likely to be controlled by phosphate adsorption on clay, assuming water seeping upwards from upper gravels into the peat layer. A recent study by Lucassen *et al.* (2004) also revealed a complex relationship between nitrate, sulphate and phosphate concentrations in groundwater fed wetlands, according to which sulphate anions in wetlands can also induce P release. This happens due to reactions between $SO_4^{2-}$ with Fe-$PO_4^{3-}$ complexes, which are common in peat soil, and which can cause mobilisation of $PO_4^{3-}$ and $SO_4^{2-}$ and reductions in reactions with Fe-$PO_4^{3-}$ during which $FeS_x$ is produced and $PO_4^{3-}$ is freed. This suggests that high phosphate levels can be found along with high sulphate levels. Pollardstown fen results conform to this hypothesis as phosphate levels were found higher on the north side where sulphide concentrations were also elevated. This relationship is presented on the graph below (Figure III-6). Ross (1995) also highlights that the presence of sulphides in anaerobic soil inhibits denitryfication rates, and this relationship was also found in the Pollardstown fen data (Figure III-7).

***Potassium, Chloride and Ammonium***

Potasium concentrations were found to be higher on the south side, and that conforms to levels found in gravel (in MB6 potassium was at 9 mg/l, while in MB43 it was 2 mg/l). Specifically a high K value was found in the inner piezometer SP36, which again suggests a groundwater discharge into the fen between piezometers SP35 and SP36; however, potassium concentrations were not determined in the middle screens; therefore full interpretation is limited. Big differences between potassium in MB6 and in peat substrate can be attributed to potassium adsorption on clay minerals (potassium fixation).

Chloride levels were found to be similar on both sides and ranged between 14.4-19.2 mg/l on the south side and between 15.9-23 mg/l on the north side. In both cases the values decreased towards the fen centre due to dilution and dispersion processes.

With regard to ammonium; as said earlier, owing to anaerobic conditions, ammonium levels are expected to be high in peatlands and Pollardstown fen confirms this with values ranging between 0.1 to 0.44 mg/l and greater values are found on the north side. These elevated concentrations correspond well with generally high nitrogen loads on this side and are more likely to reflect organic pollution than the purely chemical characteristics of peat. Lower values at the fen centre are likely to reflect a dilution of peat water (flowing laterally from the fen margins) with both rainwater and groundwater seeping from deeper levels.

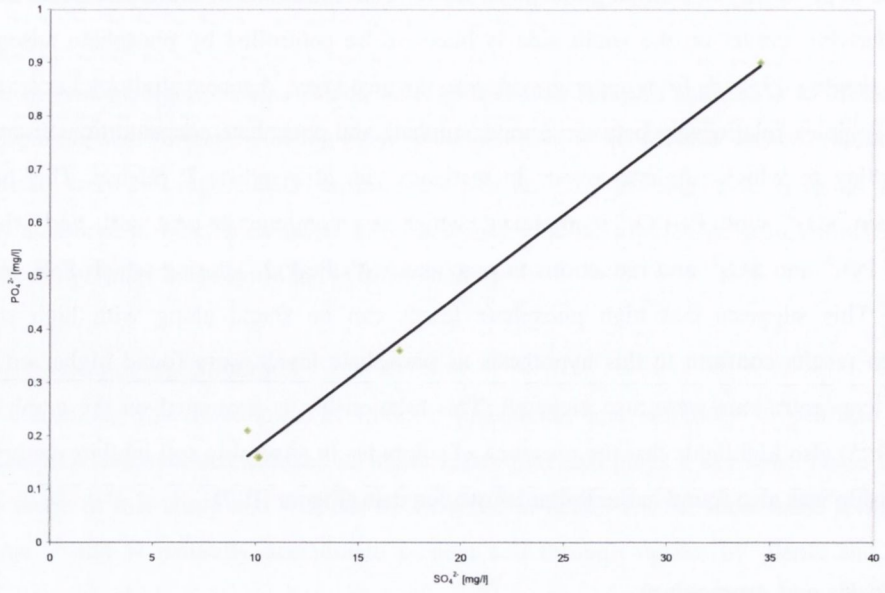



*Figure III-6 Relationship between sulphate and ortho-phosphate concentrations determined in peat substratum, Pollardstown Fen*

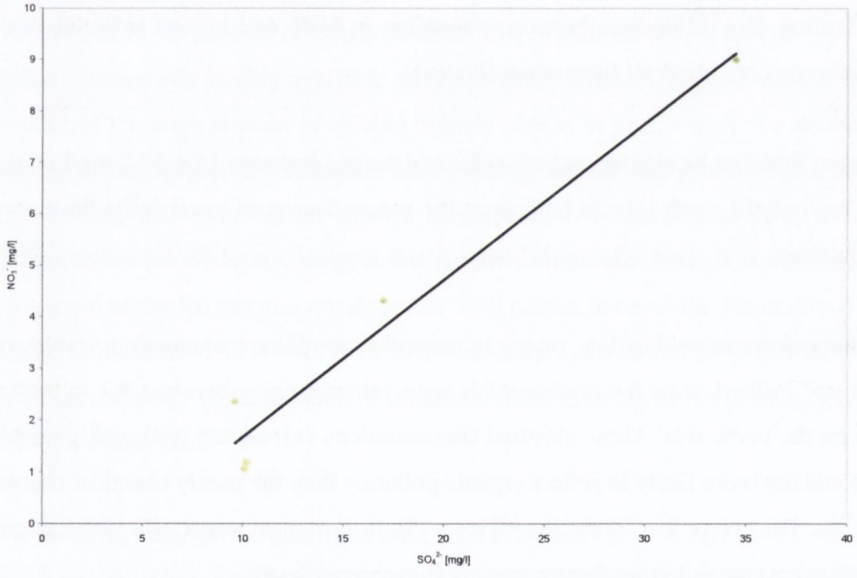



*Figure III-7 Relationship between sulphate and nitrate concentrations determined in peat substratum, Pollardstown Fen*

### III-1.2.3.2 Conclusions

The results of hydrochemistry analysis of both spring and groundwater revealed significant differences between southern and northern margins of the fen and confirmed the hypothesis of separate recharge mechanisms supporting each side.

Differences in groundwater signatures found on the south and north side at two distinct depths (middle and deep) suggest that on the north side both depths receive relatively local recharge, while on the south side it is the middle depth that is recharged locally. This is based on nutrient concentration levels found in deep screens which were much higher on the north side than on the south side. Nevertheless, high nutrient levels found in middle screens on the south side indicate the influence of local land use (hence local recharge) on the chemical signature at this depth. Lower nutrient loadings in the deeper depth on the south side suggest that water at this depth is likely to come from further parts of the catchment area.

The shallow screens proved to be prone to mixing with surface water on either side of the fen. The fen surface is also affected by the biodegradation of organics in the overlying peat and this is reflected in lower pH and hardness values. Nevertheless, variations in nutrient levels, hardness and electrical conductivity between inner and outer shallow piezometers on the south side suggests an ingress of mineral rich groundwater (i.e. seepage) between the sampling locations. This could be facilitated by reduced thickness and/or discontinuity of clay located below the peat which provides a window for water to move upwards from the upper gravels.

Groundwater is of calcium carbonate composition which results in abundant tufa deposition within the discharge zones. Based on the above observations, the following flow pathways are assumed:

- ***South side:***

Upper gravels receive local recharge and the groundwater flow is in a south easterly direction. The confining layer of clay is not continuous; therefore water seeps upward into peat wherever permeability of the confining layer is reduced. Non uniformity of clay deposits beneath peat controls the distribution of seepage zones and seepage rates throughout the site, which is reflected on the fen surfaces with patches of separate seepage zones having distinct ecological characteristics (abundance of black bog rush - *Schoenus nigricans* – an indicator of seepage). Deeper layers receive recharge from more distant locations and upward flow, although restricted by confining deposits of clay, is dominant in more central locations.

- ***North side:***

The groundwater flow is in a south westerly direction, and is found at two depths, namely in upper and lower gravels, both of which are recharged by the same, relatively close catchment. The upper gravels pinch out close to the fen margin and water flow is inhibited by a low permeability clay layer. High hydraulic pressure builds up in upper gravels which results in upward seepage wherever permeability of the confining clay layer allows. A peat cut over area located between piezometer SP24 and SP29 provides a reduction in the thickness of the confining material and hence increases upward seepage rates in this location. The thickness of clay increases significantly towards the fen centre, which separates the gravels from the fen surface, reducing the influence of

the alkaline groundwater on peat characteristics and associated flora and fauna. Therefore; seepage zone on the north side is relatively narrow in comparison with the south side.

An additional observation was also made with regard to the effect of land use and potential pollution sources during this study. Elevated concentrations of nitrates, phosphates, chlorides, ammonium, sulphates and potassium in numerous samples suggested groundwater pollution from local external sources, most likely effluent from upgradient cattle and sheep grazing fields, but also possibly from leaking septic tanks. This is strongly seen on the north side, within site D and around Springs 39 and 37, where nitrates and phosphates were found at levels above current legislative standards, and chloride and sulphate levels were also elevated. If such concentrations of nutrients leaked into surface water, this could induce a serious eutrophication. High nutrient levels were also recorded on the south side and phosphates are dominant pollutants on this side. Other locations indicating water pollution are springs 5&6 (high phosphates) and spring 3 (high chloride and sulphates).

12.5°C.

| | sample | Elevation | pH | EC | T | Chloride | Nitrate as $NO_3$ | Hardness | Sulphate | Potassium | Ammonium | Ortho -Phosphates as P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [m OD] | | [uS/cm] | [C] | [mg/l] | [mg/l] | [mg/l $CaCO_3$] | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| Springs | 29 | 85.87 | 7,2 | 636 | 10,3 | 14,9 | 8,37 | 560 | 5,61 | | 0,05 | 0,12 |
| | 16 | 87.29 | 7,15 | 745 | 10 | 26,4 | 11,3 | 536 | 5,45 | 0,58 | 0,02 | 0,09 |
| | 6 | | 7,04 | 706 | 10,4 | 17,9 | 13,7 | 425 | 13 | | 0,71 | 0,23 |
| | 5 | | 7,11 | 699 | 10,2 | 16,9 | 12,4 | 514 | 20 | | <0.02 | 0,3 |
| | 3 | 87.17 | 7,06 | 804 | 10,6 | 32,5 | 16,1 | 568 | 24 | | 0 | 0,09 |
| | 1 | 85.55 | 7,13 | 730 | 10,4 | 20 | 18,2 | 514 | 21 | | 0,02 | |
| | 37 | 86.6 | 6,98 | 771 | 10,7 | 20,1 | 31,3 | 557 | 18 | | <0.02 | 0,16 |
| | 39 | 85.98 | 6.88 | 658 | 9.4 | 29.7 | 5.57 | 493 | 45.6 | 0,27 | 0.92 | 0,75 |
| Hanged Man's Arch | | | 7,46 | 665 | 8,45 | 17,4 | 11,4 | 393 | 14 | | 0,02 | 0,14 |
| | sample | Screen Location | pH | EC | T | Chloride | Nitrate as $NO_3$ | Hardness | Sulphate | Potassium | Ammonium | Ortho -Phosphates as P |
| | | [m OD] | | [uS/cm] | [C] | [mg/l] | [mg/l] | [mg/l $CaCO_3$] | [mg/l] | [mg/l] | [mg/l] | [mg/l] |
| Site A | DEEP | | | | | | | | | | | |
| | SP 31 | 82.08-83.08 | 7,09 | 743 | 11,4 | 20,8 | 17,3 | 560 | 5,7 | 0,24 | 0,3 | 0,06 |
| | SP 33 | 80.16-81.06 | 7,24 | 662 | 10,7 | 17,9 | 10,5 | 471 | 20,8 | 0,10 | 0,35 | 0,07 |
| | SP 38 | 79.35-80.35 | 7,24 | 654 | 11,1 | 21,2 | 9,09 | 478 | 14,2 | 0,21 | 0,14 | 0,13 |
| | MIDDLE | | | | | | | | | | | |
| | SP 31 | 87.08-88.08 | 6,93 | 756 | 11,6 | 11,6 | 0,42 | 489 | 4,68 | 0,02 | 0,07 | 0,12 |
| | SP 35 | 85.16-86.16 | 7,01 | 750 | 11 | 18,5 | 14,7 | 546 | 15,3 | | 0,57 | 0,65 |
| | SP 36 | 83.35-84.35 | 7,03 | 748 | 10,8 | 18,6 | 17 | 464 | 18 | | 0,37 | 0,6 |
| | SHALLOW | | | | | | | | | | | |
| | S 10 | 84.55-85.55 | 7,65 | 715 | 10,5 | 17,8 | 1,06 | 528 | 10,1 | 0,12 | 0,21 | 0,16 |
| | SP 35 | 85.06-86.06 | 6,81 | 552 | 10,2 | 19,2 | 1,19 | 475 | 10,2 | <0.02 | 0,31 | 0,16 |
| | SP 36 | 86.44-87.44 | 6,88 | 785 | 9,1 | 14,4 | 2,35 | 325 | 9,62 | 0,93 | 0,1 | 0,21 |
| Site D | DEEP | | | | | | | | | | | |
| | SP 24 | 77.72-78.82 | 7,11 | 751 | 9,9 | 21,8 | 28,4 | 489 | 13,3 | <0.02 | 0,25 | 0,34 |
| | SP 29 | 73.61-74.61 | 7,18 | 689 | 9,4 | 24,1 | 17,9 | 418 | 23 | <0.02 | 0,3 | 0,28 |
| | MIDDLE | | | | | | | | | | | |
| | SP 24 | 83.71-84.71 | 7,07 | 820 | 10,4 | 24 | 31,5 | 521 | 16,5 | 0,01 | 0,22 | 0,24 |
| | SP 29 | 83.17-84.17 | 6,73 | 704 | 10,8 | 13,1 | 0,92 | 478 | 8,06 | <0.02 | 0,21 | 0,08 |
| | SHALLOW | | | | | | | | | | | |
| | SP 24 | 85.73-86.73 | 7,27 | 463 | 9,3 | 23 | 8,99 | 350 | 34,5 | <0.02 | 0,44 | 0,9 |
| | SP 29 | 85.19-86.19 | 6,48 | 479 | 9,6 | 15,9 | 4,31 | 350 | 17 | <0.02 | 0,19 | 0,36 |

**Table III-8 Results of a chemical analysis of water samples collected from the Curragh aquifer by WYG Ltd. May 2002, after WYG, 2002.**

| Sample Reference | Units | MB 2 | MB 6 | MB 10 | MB 19 | MB 19a | MB 43 | Sp 23 | Sp 22 | Sp 34 | MB 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Location | | mid-Curragh | South of the fen | NE of the fen | South Currgah | South Curragh | upgradient from site D | Site D | Site B | Site A | Public Entrance |
| Sample Date | | 14/5/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 14/05/2002 | 01/02/2002 |
| Screen Location | m OD | 62.27-68.27 | 85.28-89.28 | 76.11-87.11 | 76.39-82.39 | 52.88-58.88 | 84.8-88.8 | 77.68-78.68 | 78.2-79.2 | 82.03-83.03 | 75.0-81.0 |
| Aquifer | | Limestone | Gravel | Gravel | Sand and Gravel | Limestone | Gravel | Gravel | Gravel | Gravel | Gravel |
| | | | | | | | | | | | |
| Temperature | deg C | 11,8 | 13,4 | 12,7 | | | | 10 | 9,8 | 10 | |
| pH Value Field | | 7,71 | 6,87 | 7,14 | 7,21 | | | 7,58 | 7,5 | 8,21 | |
| pH Value - Laboratoty | | 7,58 | 7,32 | 7,47 | 7,44 | 7,46 | 7,16 | 7,61 | 7,49 | 7,44 | 7,4 |
| Conductivity - Field | µS/cm | 718 | 754 | 725 | 642 | | | 769 | 750 | 660 | |
| Conductivity - Laboratory | µS/cm | 667 | 696 | 688 | 602 | 534 | 777 | 733 | 731 | 626 | 625 |
| Bicarbonate | mg/l | 416 | 452 | 484 | 406 | 408 | 512 | 420 | 416 | 408 | |
| Alkalinity | mg/l | 416 | 452 | 484 | 406 | 408 | 512 | 420 | 416 | 408 | 335 |
| Total Hardness as $CaCO_3$ | mg/l | 399 | 405 | 383 | 361 | 365 | 435 | 431 | 416 | 363 | 349 |
| Nitrite as NO2 | mg/l | <0,01 | 0,01 | 0,06 | <0,01 | 0,02 | 0,03 | <0,01 | <0,01 | <0,01 | <0,01 |
| Nitrate as NO3 | mg/l | 27,1 | 20,7 | 24 | 6,1 | 6,2 | 29,3 | 40,8 | 40,8 | 15,5 | 12 |
| Sulphate as $SO_4$ | mg/l | 13 | 10 | 21 | 9 | 9 | 19 | 23 | 24 | 13 | 17 |
| Chloride as Cl | mg/l | 19 | 19 | 16 | <10 | <10 | 32 | 21 | 21 | 12 | 18 |
| Calcium, total as Ca | mg/l | 131 | 149 | 186 | 124 | 126 | 252 | 145 | 147 | 142 | 110 |
| Magnesium total as Mg | mg/l | 18 | 10 | 12 | 13 | 14 | 13 | 19 | 18 | 10 | 18 |
| Potassium, total as K | mg/l | 1 | 9 | 2 | <1 | <1 | 2 | 2 | 2 | <1 | 1,2 |
| Sodium, total as Na | mg/l | 8 | 9 | 11 | 7 | 7 | 16 | 9 | 9 | 9 | 11 |
| Fluoride as F | mg/l | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | |
| Iron, total as Fe | mg/l | 0,165 | 3,445 | 2,01 | 0,101 | 0,115 | 7,67 | 0,025 | 0,055 | 0,246 | 0,09 |
| Monganese, total as Mn | mg/l | 0,018 | 0,725 | 0,49 | 0,016 | 0,017 | 0,68 | 0,006 | 0,008 | 0,058 | <0,01 |
| Aluminium, total as Al | mg/l | 0,09 | 2,56 | 0,752 | 0,027 | 0,039 | 8,3 | 0,023 | 0,052 | 0,177 | 0,12 |
| Selenium, total as Se | mg/l | <0,001 | <0,001 | <0,001 | <0,001 | <0,001 | <0,001 | <0,001 | <0,001 | <0,001 | |
| Lead, total as Pb | mg/l | 0,002 | 0,033 | 0,03 | <0,001 | <0,001 | 0,029 | <0,001 | <0,001 | 0,002 | <0,05 |
| Copper, total as Cu | mg/l | <0,005 | 0,01 | 0,011 | 0,008 | 0,009 | 0,01 | <0,005 | <0,005 | <0,005 | <0,01 |
| Zinc, total Zn | mg/l | 0,019 | 0,072 | 0,062 | 0,024 | 0,024 | 0,127 | <0,01 | <0,01 | 0,014 | 0,2 |
| Barium, total as B | mg/l | 0,115 | 0,276 | 0,122 | 0,059 | 0,059 | 0,141 | 0,058 | 0,057 | 0,076 | 0,31 |
| Baron, total as B | mg/l | 0,032 | 0,03 | 0,064 | <0,02 | <0,02 | 0,074 | 0,045 | 0,041 | 0,027 | 0,17 |
| Sollids, Dissolved 180 deg C | mg/l | 474 | 520 | 486 | 324 | 388 | 588 | 512 | 528 | 428 | |
| Stontium, total as Sr | mg/l | 0,19 | 0,169 | 0,238 | 0,171 | 0,172 | 0,282 | 0,207 | 0,212 | 0,186 | 0,19 |
| Ammonical Nitrogen as $NH_4$ | mg/l | <0,04 | <0,04 | <0,04 | <0,04 | <0,04 | 0,04 | 0,04 | 0,04 | 0,04 | <0,05 |
| Total Phosphorus as P | mg/l | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,1 | <0,05 |
| Saturation Index | | + 0,96 | + 0,22 | + 0,59 | | | 0,86 | + 0,83 | + 0,75 | + 0,75 | |

## *III-1.2.4. Meteorological Input*

### III-1.2.4.1 Precipitation

In terms of rainfall patterns throughout the study period, the year 2002 (analysed from March) was a considerably wet year, with six out of ten months with rainfall in excess of the 30 year average and with two months with nearly double the 30 year average (October – November). 2003 was in turn much drier, with eight months below the 30 year average, of which four months fell into important recharge months (January-April). The value recorded in August was far below the long term average with only 7.8 mm of rain; however May and June were nearly 200% of the norm (Table III-9). In 2004, there were seven months above the 30 year average, with the three winter months of January, March, October circa 1.5 higher than average, which is the important recharge period of the year. There was a significant shortage of rainfall in May with only 58.5% of a 30 year average. Until the end of September, 2005 can be considered as wet, with the first five months being either above or close to the 30 year average and with a considerably wet July (Figure III-8). In hydrological terms, the annual rainfall in 2003-2005, was recorded as 848.5, 773.5 and 771.0 mm respectively.

**Table III-9 Monthly rainfall data recorded at Pollardstown Fen weather station, 2002-2005 (results in millimetres)**

| | JAN | FEB | MAR | APR | MAY | JUN |
|---|---|---|---|---|---|---|
| **2002** | | | 34.6 | 101.2 | 94.2 | 63.8 |
| % of 30-year average | | | 68.8% | 199.2% | 162.1% | 121.3% |
| **2003** | 62.0 | 41.6 | 37.4 | 36.5 | 117.4 | 103.8 |
| % of 30-year average | 97.03% | 85.60% | 74.31% | 71.93% | 202.07% | 197.34% |
| **2004** | 102.4 | 30.0 | 68.8 | 64.0 | 34.0 | 54.8 |
| % of30-year average | 160.3% | 61.7% | 136.8% | 126.0% | 58.5% | 104.2% |
| **2005** | 83.6 | 44.6 | 50.8 | 78.8 | 70.4 | 32.0 |
| % of 30-year average | 130.8% | 91.8% | 101.0% | 155.1% | 121.2% | 60.8% |
| **30-year average (Casement, 1961-1990)** | **63.9** | **48.6** | **50.3** | **50.8** | **58.1** | **52.6** |
| | | | | | | |
| | **JUL** | **AUG** | **SEP** | **OCT** | **NOV** | **DEC** |
| **2002** | 67.2 | 33.0 | 14.8 | 131.2 | 130.4 | 63.0 |
| % of 30-year average | 143.3% | 48.2% | 23.4% | 191.3% | 197.9% | 85.6% |
| **2003** | 81.0 | 7.8 | 38.2 | 67.4 | 50.8 | 64.6 |
| % of 30-year average | 172.71% | 11.39% | 60.35% | 98.25% | 77.09% | 87.77% |
| **2004** | 44.0 | 112.9 | 69.0 | 116.2 | 46.8 | 59.8 |
| % of30-year average | 93.8% | 164.8% | 109.0% | 169.4% | 71.0% | 81.3% |
| **2005** | 69.8 | 51.0 | 67.0 | | | |
| % of 30-year average | 148.8% | 74.5% | 105.8% | | | |
| **30-year average (Casement, 1961-1990)** | **46.9** | **68.5** | **63.3** | **68.6** | **65.9** | **73.6** |

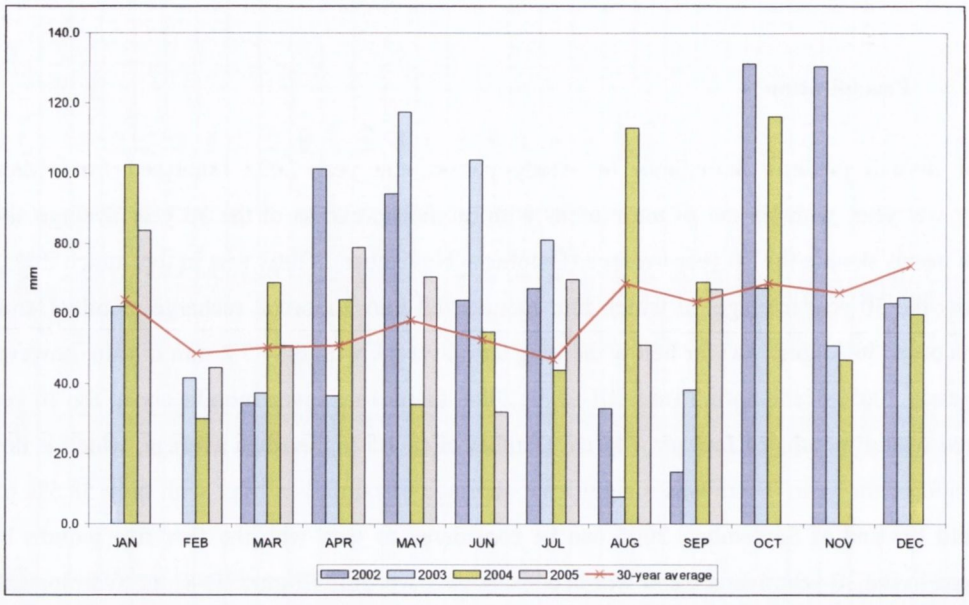



*Figure III-8 Monthly rainfall data recorded at Pollardstown Fen, 2002-2005*

A comparison with the nearest synoptic station in Naas (13 km northeast of the study site) showed a high similarity in rainfall patterns; however Pollardstown Fen recorded slightly lower values, which may be due to differences in daily rainfall distribution or instrumental error and installation. The fen rain gauge is placed on the fen's surface and is surrounded by relatively high reeds, potentially shading the instrument. During the period from March 2002 - June 2005, cumulative rainfall from Pollardstown Fen was 96% of that recorded at Naas station. Correlation analysis between data from the two stations revealed a good relationship with a correlation coefficient at r = 0.82 (based on monthly data, Appendix 5). Daily data does not show a good correlation (r = 0.55); however, this is expected due to differences in daily rainfall distribution patterns. Comparison with data from another Met Éireann synoptic station in Casement (approximately 20 km north east of the study site) also shows a good fit with the monthly data from Pollardstown Fen (correlation coefficient r = 0.84), however, daily data is correlated at r = 0.78 only. In addition, cumulative rainfall at Casement was 4% lower than on the Fen for the observation period March 2002 – June 2005. The correlation between cumulative daily rainfall at the fen and the two stations in Naas and Casement was found to be very high (0.997 and 0.998 respectively) and is graphically presented in Figure III-9. Monthly rainfall distribution at the three stations can be seen on Figure III-10.

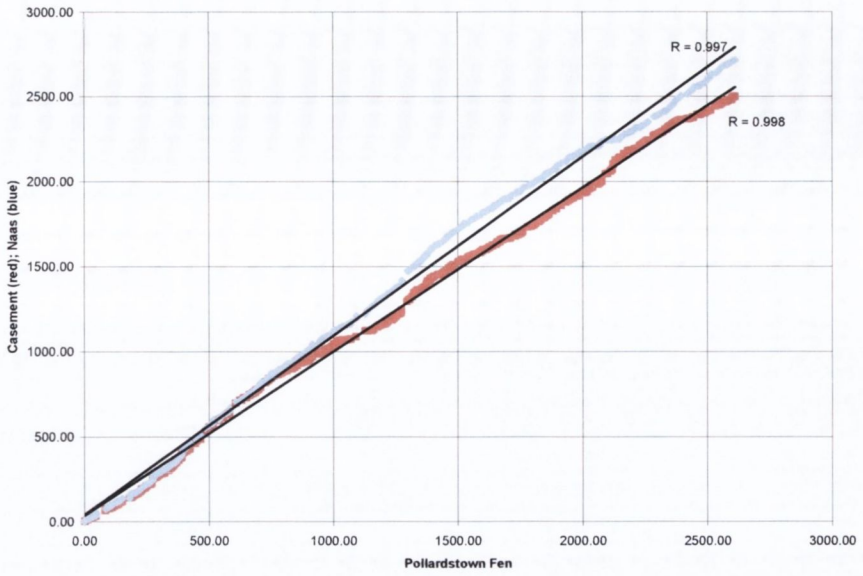



*Figure III-9 Comparison between cumulative daily rainfall at Pollardstown Fen vs. Casement and Naas stations, March 2002-June 2005*

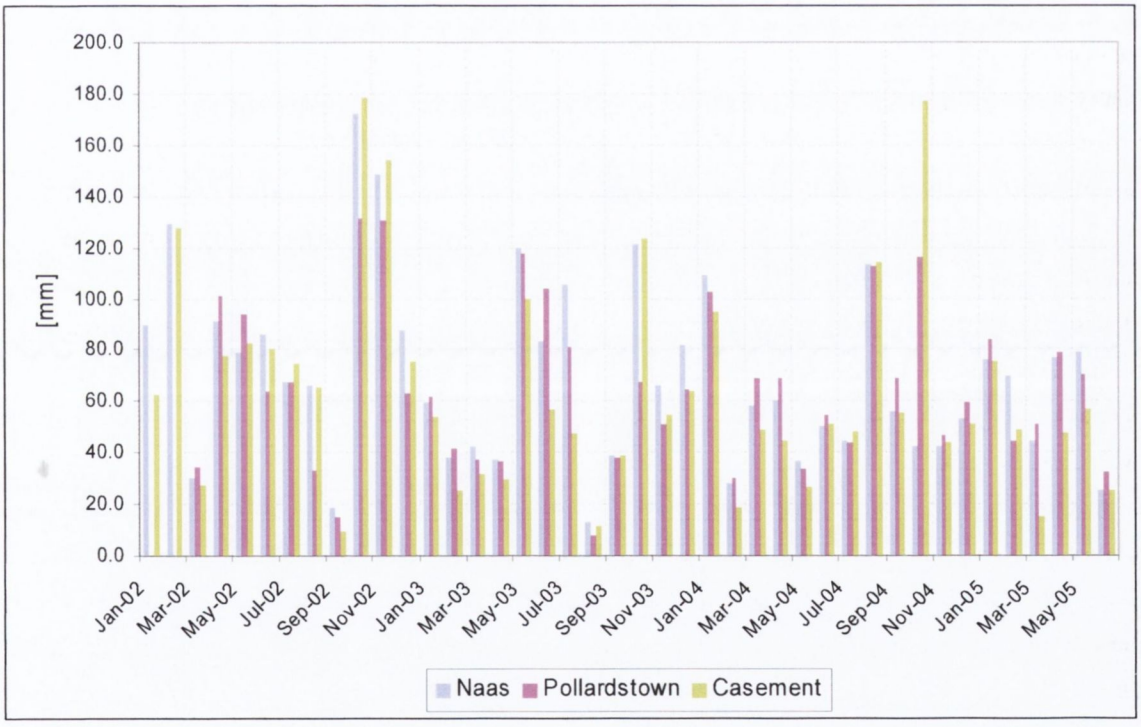



*Figure III-10 Distribution of monthly rainfall data from weather stations in Naas, Casement and Pollardstown Fen, 2002-2005*

### III-1.2.4.2 Potential Evapotranspiration (PE)

The annual pattern of potential evapotranspiration (PE for reference vegetation i.e. grass) is such that maximum values are usually reached in May-June, when solar radiation, air temperature and vegetation growth are at their highest and the lowest values are recorded in December-January. Winter values are very low and reach less than 10 mm per month, while in summer evapotranspiration reaches a few mm/day (and c.80-90 mm/month) depending on ambient conditions such as cloud cover, air temperature, humidity and wind speed.

Over the observation period, from March 2002 until September 2005, the highest values were recorded in summer 2004 with a maximum of 97.2 mm reached in June. Over the hydrological year (measured from October to September), total potential evapotranspiration in 2005 was considerably lower than in the two previous years and reached only 494 mm. The records for 2003 and 2004 were 529 mm and 538 mm respectively, which means that evapotranspiration of 2005 was recorded at a level of 93% and 92% in comparison to previous years. This was driven by considerably colder and wetter conditions compared to the two previous years; however, it was accepted within a natural variation level and no significant trend suggesting any change in climatic condition over the observation time was distinguished, Figure III-11.

Daily potential evapotranspiration data are available in Appendix 9.

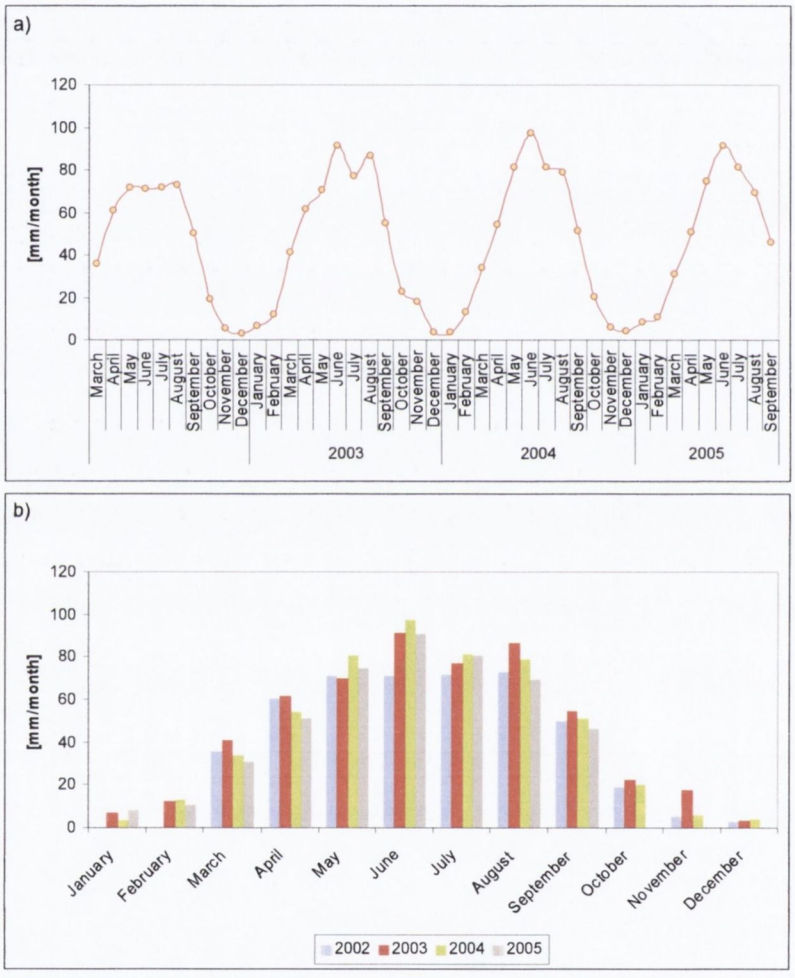



*Figure III-11 a & b. Monthly distribution of potential evapotranspiration (PE) records from Pollardstown Fen, 2002-2005*

### III-1.2.4.3 Actual Evapotranspiration (AE)

#### *III - 1.2.4.3.1. Wetland Area*

The three approaches for computing the actual evapotranspiration for the fen area resulted in the annual evapotranspiration range of 456-626 mm. It is apparent (Figure III-12, Table III-10) that the equation proposed by Koerselman and Beltman (AE Fen [1]) reduces the AE compared to the PE. On an annual scale, the reduction

is of approximately 8%. This contradicts the general perception that actual evapotranspiration on fens is higher than potential evapotranspiration, especially in the growing season. Also, assuming that actual evapotranspiration in Ireland is at approximately 90 % - 95% of PE (Bruce Misstear, pers. comm.), the ratio AE Fen [1] / PE of 92% seem rather low for an ecosystem, in which the soil moisture deficit does not develop due to a constant supply of groundwater. Using this method, the annual actual evapotranspiration rates ranged from 456-497 mm over the hydrological years 2003-2005.

The second method used in this study applied crop coefficients developed for a mixture of vegetation types present on the fen, and with monthly adjustments to accommodate physiological changes that plants undergo during their annual cycles. This accounts for increased transpiration needs in summer and reduced water needs in winter. As such, actual evapotranspiration is higher with respect to potential evapotranspiration during the growing season (May – October) and lower in winter. Using this model, the annual actual evapotranspiration ranged from 547-595 mm over the hydrological years 2003-2005 and AE/PE ratio is 1.2, which is a more likely scenario for the fen ecosystem.

The third approach assumed that actual evapotranspiration is equal to potential evapotranspiration.

Numerical results of the above calculations are presented in Table III-10. A comparison of the three models gives a range of AE/PE ratio (annual) from 0.92 (Koerselman and Beltman, 1988) to 1.11 (Tiemeyer *el al.*, 2006); however, it is deemed unlikely that, on an annual scale, the actual evapotranspiration on the fen will be less than potential evapotranspiration and hence the first model was rejected for further water balance study. Considering the approach by Tiemeyer *et al.*, as most precise for the given site conditions, with its probable AE/PE ratio of 1.11, this model was used for further assessment of effective rainfall and water budget calculations.

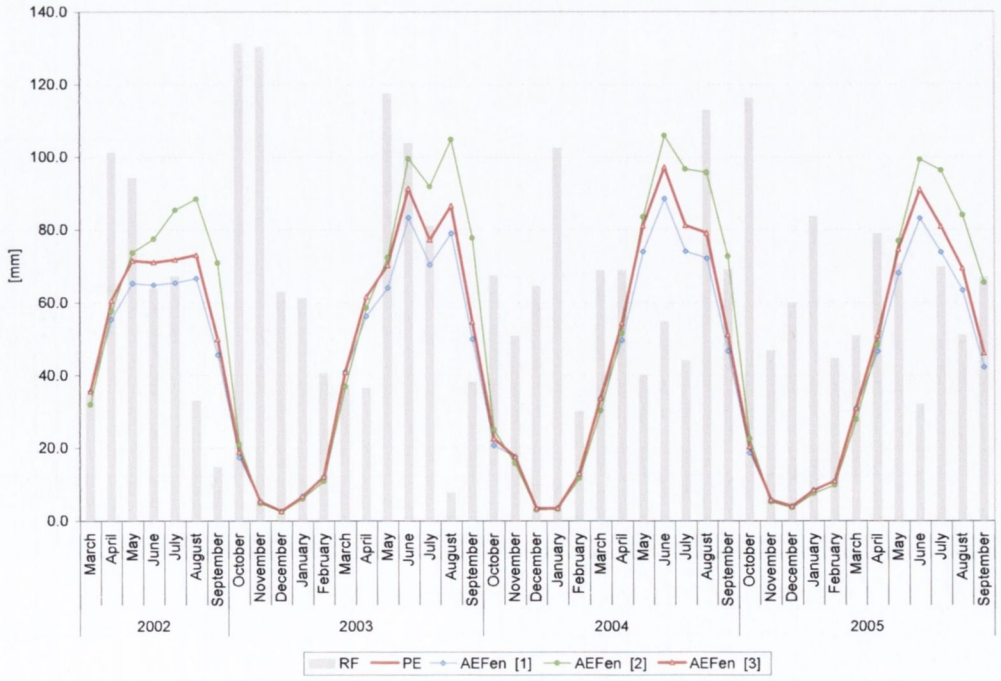



*Figure III-12 Comparison of different methods for computing actual evapotranspiration for the fen area: AE Fen [1] was computed using the Koerselman & Beltman (1988) approach; AE Fen [2] - using monthly crop coefficients derived after Tiemeyer et al. (2006) and AE Fen [3] = PE.*

**Table III-10 Monthly meteorological balance calculations including different methods for computing actual evapotranspiration for the fen. All data presented in millimetres.**

| Meteorological Balance Calculations | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gross rainfall | Potential Evapotranspiration | Actual Evapotranspiration FEN | Actual Evapotranspiration FEN | Actual Evapotranspiration FEN | Actuall Evapotranspiration Curragh | Effective Rainfall (Fen) | Effective Rainfall (Fen) | Effective Rainfall (Fen) | Effective Rainfall (Curragh) |
| | | | | $AE_{Fen}$ [mm] after Koerselman & Boltman (1988) | $AE_{Fen}$ [mm] after Tiemeyer *et al*. (2006) | $AE_{Fen}$ = PE | | $AE_{Fen}$ [mm] after Koerselman & Boltman (1988) | $AE_{Fen}$ [mm] after Tiemeyer *et al*. (2006) | $AE_{Fen}$ = PE | |
| | | RF | PE | $AE_{Fen}$ [1] | $AE_{Fen}$ [2] | $AE_{Fen}$ [3] | $AE_{Curragh}$ | RF-AE[1] | RF-AE[2] | RF-AE[3] | RF-$AE_{Curragh}$ |
| | March | 34.6 | 35.6 | 35.6 | 32.1 | 35.6 | 35.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| | April | 101.2 | 60.7 | 55.4 | 57.6 | 60.7 | 60.6 | 45.8 | 43.6 | 40.5 | 40.6 |
| | May | 94.2 | 71.6 | 65.3 | 73.7 | 71.6 | 71.6 | 28.9 | 20.5 | 22.6 | 22.6 |
| | June | 63.8 | 71.0 | 64.8 | 77.4 | 71.0 | 71.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | July | 67.2 | 71.7 | 65.4 | 85.4 | 71.7 | 71.4 | 1.8 | 0.0 | 0.0 | 0.0 |
| | August | 33.0 | 73.1 | 66.7 | 88.4 | 73.1 | 65.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2002 | September | 14.8 | 49.94 | 45.6 | 70.9 | 49.9 | 27.03 | 0.0 | 0.0 | 0.0 | 0.0 |
| | October | 131.2 | 18.9 | 17.4 | 21.0 | 18.9 | 12.8 | 113.8 | 110.2 | 112.3 | 118.4 |
| | November | 130.4 | 5.4 | 5.4 | 4.8 | 5.4 | 5.4 | 125.0 | 125.6 | 125.0 | 125.0 |
| | December | 63.0 | 2.8 | 2.8 | 2.5 | 2.8 | 2.8 | 60.2 | 60.5 | 60.2 | 60.2 |
| | January | 61.2 | 6.8 | 6.8 | 6.2 | 6.8 | 6.8 | 54.4 | 55.0 | 54.4 | 54.4 |
| | February | 40.6 | 12.2 | 12.2 | 11.0 | 12.2 | 12.2 | 28.4 | 29.6 | 28.4 | 28.4 |
| | March | 37.4 | 41.0 | 41.0 | 36.9 | 41.0 | 41.0 | 0.0 | 0.5 | 0.0 | 0.0 |
| | April | 36.5 | 61.7 | 56.3 | 58.6 | 61.7 | 52.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| | May | 117.4 | 70.3 | 64.1 | 72.4 | 70.3 | 69.0 | 53.3 | 45.0 | 47.1 | 48.4 |
| | June | 103.8 | 91.4 | 83.3 | 99.6 | 91.4 | 88.4 | 20.5 | 4.2 | 12.4 | 15.4 |
| | July | 81.0 | 77.2 | 70.4 | 91.9 | 77.2 | 77.1 | 10.6 | 0.0 | 3.8 | 3.9 |
| | August | 7.8 | 86.6 | 79.0 | 104.8 | 86.6 | 74.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2003 | September | 38.2 | 54.8 | 50.0 | 77.7 | 54.8 | 32.6 | 0.0 | 0.0 | 0.0 | 5.6 |
| | October | 67.4 | 22.6 | 20.8 | 25.1 | 22.6 | 16.0 | 46.6 | 42.3 | 44.8 | 51.4 |
| | November | 50.8 | 17.7 | 17.7 | 15.9 | 17.7 | 17.7 | 33.1 | 34.9 | 33.1 | 33.1 |
| | December | 64.6 | 3.4 | 3.4 | 3.1 | 3.4 | 3.4 | 61.2 | 61.5 | 61.2 | 61.2 |
| | January | 102.4 | 3.6 | 3.6 | 3.2 | 3.6 | 3.6 | 98.8 | 99.2 | 98.8 | 98.8 |
| | February | 30.0 | 13.0 | 13.0 | 11.7 | 13.0 | 13.0 | 17.0 | 18.3 | 17.0 | 17.0 |
| | March | 68.8 | 33.8 | 33.8 | 30.4 | 33.8 | 33.8 | 35.0 | 38.4 | 35.0 | 35.0 |
| | April | 68.8 | 54.3 | 49.6 | 51.6 | 54.3 | 54.3 | 19.2 | 17.2 | 14.5 | 14.5 |
| | May | 40.0 | 81.1 | 73.9 | 83.5 | 81.1 | 73.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| | June | 54.8 | 97.2 | 88.6 | 105.9 | 97.2 | 58.6 | 0.0 | 0.0 | 0.0 | 0.0 |
| | July | 44.0 | 81.2 | 74.0 | 96.6 | 81.2 | 58.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| | August | 112.9 | 79.1 | 72.1 | 95.7 | 79.1 | 56.2 | 40.8 | 17.2 | 33.8 | 56.7 |
| 2004 | September | 69.0 | 51.1 | 46.7 | 72.6 | 51.1 | 50.9 | 22.3 | 0.0 | 17.9 | 18.1 |
| | October | 116.2 | 20.3 | 18.7 | 22.5 | 20.3 | 20.3 | 97.5 | 93.7 | 95.9 | 95.9 |
| | November | 46.8 | 5.8 | 5.8 | 5.3 | 5.8 | 5.8 | 41.0 | 41.5 | 41.0 | 41.0 |
| | December | 59.8 | 4.1 | 4.1 | 3.7 | 4.1 | 4.1 | 55.7 | 56.1 | 55.7 | 55.7 |
| | January | 83.6 | 8.4 | 8.4 | 7.6 | 8.4 | 8.4 | 75.2 | 76.0 | 75.2 | 75.2 |
| | February | 44.6 | 11.0 | 11.0 | 9.9 | 11.0 | 11.0 | 33.6 | 34.7 | 33.6 | 33.6 |
| | March | 50.8 | 30.9 | 30.9 | 27.8 | 30.9 | 30.9 | 19.9 | 23.0 | 19.9 | 19.9 |
| | April | 78.8 | 51.0 | 46.5 | 48.4 | 51.0 | 51.0 | 32.3 | 30.4 | 27.8 | 27.8 |
| | May | 70.6 | 74.6 | 68.0 | 76.8 | 74.6 | 74.4 | 2.6 | 0.0 | 0.0 | 0.0 |
| | June | 32.0 | 91.1 | 83.0 | 99.3 | 91.1 | 74.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | July | 69.8 | 80.9 | 73.8 | 96.3 | 80.9 | 48.5 | 0.0 | 0.0 | 0.0 | 21.3 |
| | August | 51.0 | 69.4 | 63.3 | 84.0 | 69.4 | 57.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2005 | September | 67.0 | 46.1 | 42.1 | 65.5 | 46.1 | 36.9 | 24.9 | 1.5 | 20.9 | 30.1 |

### *III - 1.2.4.3.2. The Curragh Area*

Soil moisture deficit at a level exceeding 30 mm develops regularly at Curragh during summer months. Shorter, few day long periods of SMD can also develop in spring and late autumn depending on the amount of rainfall and air temperatures. During the observation period, SMD exceeding 30 mm occurred in April 2002, July 2002, August-October 2002, April 2003, June 2003, August-October 2003, May-August 2004, September 2004, May 2005 and in June-September 2005. During these periods, actual evapotranspiration was reduced with respect to the potential evapotranspiration at a rate dependent on the soil moisture deficit (Equation III-10). The total actual evapotranspiration in hydrological years 2003-2005 was computed at 475 mm, 439 mm and 423 mm, Figure III-14, which constitutes 90%, 82% and 87% of PE in respective years.

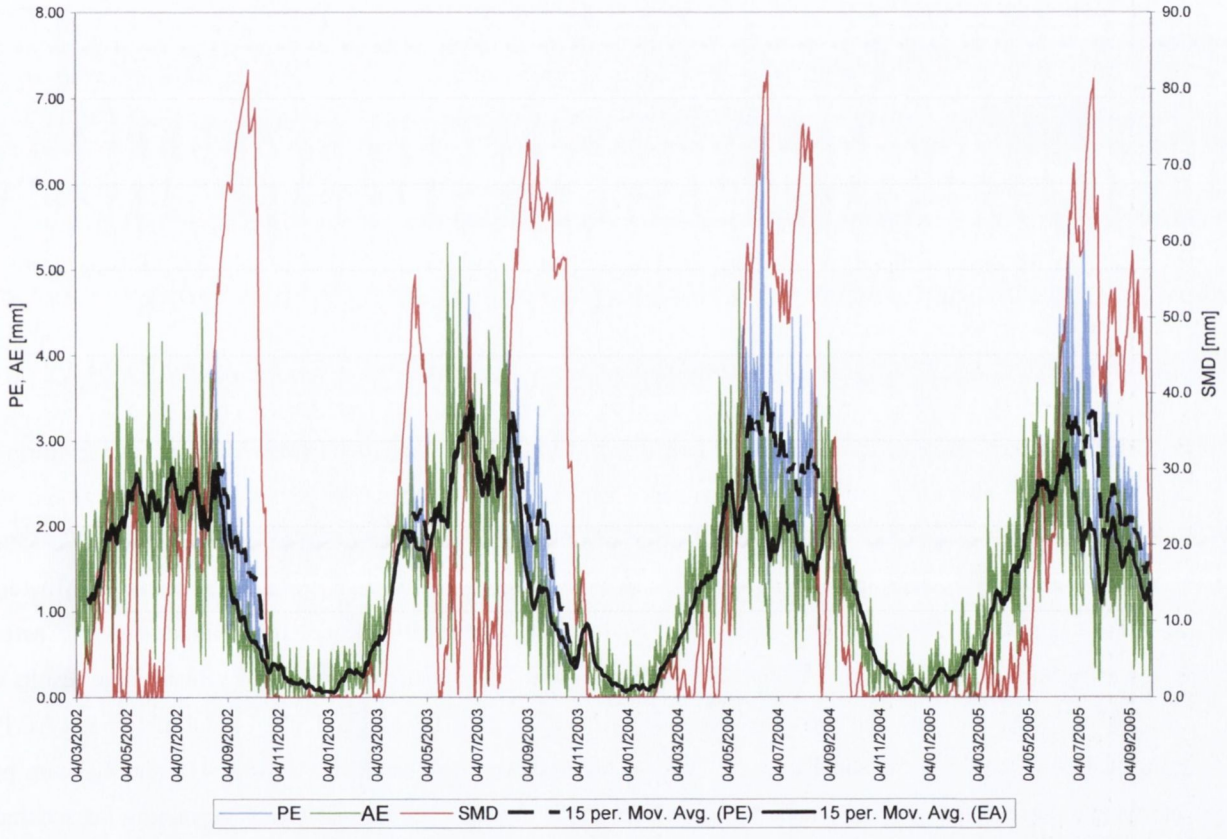



*Figure III-13 Distribution of daily potential evapotranspiration (PE), actual evapotranspiration (AE) and soil moisture deficit (SMD) at the Curragh Plains, 2002-2005*

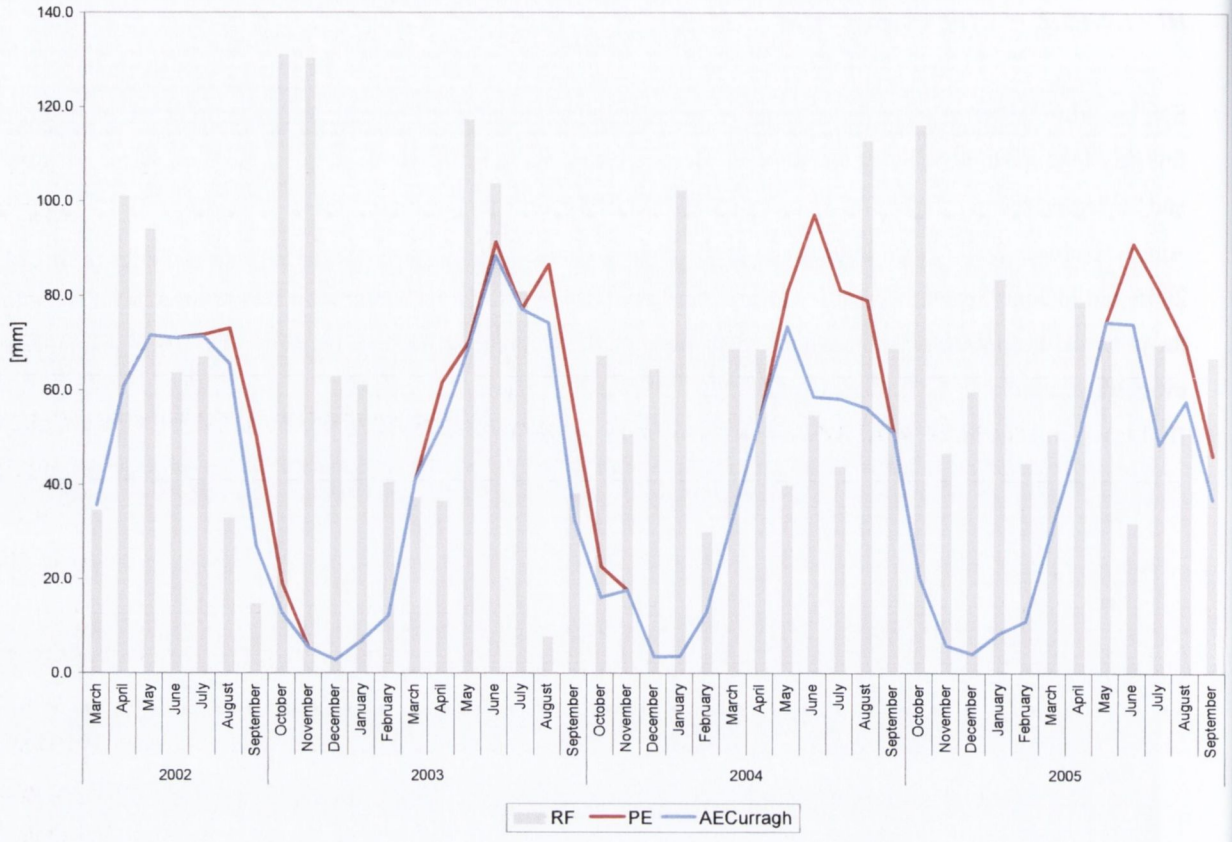



*Figure III-14 Monthly distribution of gross rainfall vs. evapotranspiration, Curragh Plains, 2002-2005*

A recent, comprehensive study by Misstear and Brown (draft, 2007) on groundwater recharge for the Curragh aquifer provides some information for comparison with the above estimates. The actual evapotranspiration in the above study was calculated using Casement Aerodrome data and followed the FAO method (Allen *at al.*, 1998) using a water stress factor applied to the PE, which was determined using a modified Penman – Monteith equation. Similarily to the Aslyng scale, this model is based on a soil moisture budget and the actual evapotranspiration is a function of a daily PE, soil moisture deficit and rainfall. Thirty year average results of this study suggest annual actual evapotranspiration for the Curragh in the range of 393 - 474.4 mm/yr and AE/PE ratio of 82% - 90%. For the specific years 2003 - 2005 the AE was established at 465, 415 and 423 mm per annum and these differ from the fen study by -10, -25 and 0 mm per annum respectively. Assuming the accuracy of sensors at the Pollardstown Fen weather station of 5%, 1-7% the difference in AE estimates between the Pollardstown Fen and Misstear's and Brown's study may be attributed to either measuring or instrumental errors and/or differences in spatial distribution of rainfall, incoming radiation, humidity and other parameters contributing to the AE estimations. It should be remembered that both AE estimates are based on different sets of synoptic data originating from two different weather stations located approximately 20 km apart.

#### III-1.2.4.4 Effective Rainfall

Effective rainfall was determined on an annual basis as the difference between gross annual rainfall and actual evapotranspiration. Over the observation period, the annual effective rainfall for the fen was established at the level of 262, 179 and 224 mm/yr for the respective hydrological years 2003, 2004 and 2005. For the rest of the

catchment, the effective rainfall was 374, 335 and 348 mm/yr respectively. This shows that effective rainfall on the fen is reduced by approximately 30 – 50 % compared to that on the Curragh Plains.

**Table III-11 Annual meteorological balance at the fen and the Curragh area in hydrological years 2003-2005. All data presented in millimetres.**

| | Fen Area | | | Curragh Area | | |
|---|---|---|---|---|---|---|
| | RF | AE | $RF_{eff}$ | RF | AE | $RF_{eff}$ |
| **2002-2003** | 849 | 587 | **262** | 849 | 475 | **374** |
| **2003-2004** | 774 | 595 | **179** | 774 | 439 | **335** |
| **2004-2005** | 771 | 547 | **224** | 771 | 423 | **348** |

The study by Misstear and Brown (draft, 2007) suggests a 30 year average effective rainfall for the Curragh in a range of 321.4-366.4 mm/yr, which is in line with the above findings. However, estimates for the specific hydrological years 2003-2005 give effective rainfall values of 480, 409 and 259 mm/yr which are higher than ours by approximately 106 and 75 mm in the years 2003-2004 and lower by 89 mm in the year 2005 respectively. However, soil moisture budgeting and effective rainfall calculations by Misstear and Brown are based on rainfall from the Naas station and meteorological parameters from Casement Aerodrome, as this was assumed to be the most representative for the entire Curragh aquifer. The earlier rainfall analysis showed that rainfall records for Naas exceed Pollardstown Fen data by 4%. In addition, there were significant differences between rainfall distribution and annual totals between the hydrometric years for which the meteorological budgeting was undertaken. These can be viewed in Figure III-10 and in Table III-12. Annual rainfall totals for the hydrological years 2003-2005 were 848.5, 773.5, 771 mm on Pollardstown Fen and 945, 824, 682.5 mm in Naas, which accounts for a difference of +96.5 mm in 2003, +50.5 mm in 2004 and -88.4 mm in 2005 between Naas and Pollardstown Fen. This and the differences in AE estimates between the fen and the Casement data explain inconsistencies in effective rainfall estimates between the two data sets.

**Table III-12 Monthly Rainfall Data from recording stations at Pollardstown Fen, in Naas and in Casement**

| | | Pollardstown Fen | Naas | Casement |
|---|---|---|---|---|
| 2002 | March | 34.6 | 30.2 | 27.5 |
| | April | 101.2 | 91.3 | 77.2 |
| | May | 94.2 | 91.2 | 82.5 |
| | June | 63.8 | 86.1 | 80.1 |
| | July | 67.2 | 67.4 | 74.4 |
| | August | 33.0 | 65.7 | 65.4 |
| | September | 14.8 | 18.4 | 9.3 |
| Hydrometric year 2003 | October | 131.2 | 172.4 | 178.7 |
| | November | 130.4 | 148.7 | 154.2 |
| | December | 63.0 | 87.7 | 75.4 |
| | January | 61.2 | 59.3 | 53.5 |
| | February | 40.6 | 38.2 | 24.8 |
| | March | 37.4 | 42.2 | 31.7 |
| | April | 36.5 | 37.0 | 29.5 |
| | May | 117.4 | 119.4 | 99.9 |
| | June | 103.8 | 83.0 | 56.8 |
| | July | 81.0 | 105.1 | 47.4 |
| | August | 7.8 | 13.2 | 11.2 |
| | September | 38.2 | 38.8 | 38.4 |
| Hydrometric year 2004 | October | 67.4 | 120.0 | 123.5 |
| | November | 50.8 | 65.9 | 54.3 |
| | December | 64.6 | 81.8 | 63.8 |
| | January | 102.4 | 109.2 | 94.4 |
| | February | 30.0 | 27.9 | 18.4 |
| | March | 68.8 | 58.4 | 48.5 |
| | April | 68.8 | 60.0 | 44.4 |
| | May | 40.0 | 36.4 | 26.4 |
| | June | 54.8 | 50.2 | 50.7 |
| | July | 44.0 | 44.5 | 48.2 |
| | August | 112.9 | 113.6 | 113.9 |
| | September | 69.0 | 56.1 | 55.3 |
| Hydrometric year 2005 | October | 116.2 | 42.2 | 177.4 |
| | November | 46.8 | 42.2 | 43.8 |
| | December | 59.8 | 53.3 | 51.1 |
| | January | 83.6 | 76.3 | 75.1 |
| | February | 44.6 | 69.7 | 48.4 |
| | March | 50.8 | 44.5 | 15.4 |
| | April | 78.8 | 76.9 | 47.2 |
| | May | 70.6 | 78.9 | 56.8 |
| | June | 32.0 | 25.4 | 25.4 |
| | July | 69.8 | 65.8 | 78.5 |
| | August | 51.0 | 42.9 | 31.2 |
| | September | 67.0 | 64.5 | 55.6 |
| | | | | |
| **2003** | | 848.5 | 945.0 | 801.5 |
| **2004** | | 773.5 | 824.0 | 741.8 |
| **2005** | | 771.0 | 682.6 | 705.9 |

## *III-1.2.5. Surface Water Levels and Flows*

### III-1.2.5.1 Water Levels

Water levels in Milltown Feeder are in general very stable, with a nominal difference between the groundwater discharge point at Seven Springs and the feeder discharge at Hanged Man's Arch of as little as 0.16-0.35 m over the 3000 metre distance (based on average annual water levels).

The lowest levels are usually recorded in the winter months (December - February) and highest during the summer (July – August).

There are two major factors controlling annual water table fluctuations. Firstly, as a part of the Grand Canal, the Milltown Feeder joins the Barrow Line downstream of the 19$^{th}$ Lock. This hydraulic connection implies that the water level in Milltown Feeder is regulated by the Lock operation to accommodate the needs for water supply to the Grand Canal and also occasional activities due to traffic control. This results in a stable water level with occasional but significant drops of water of 15-20 cm over a very short time.

The second important feature is the weed growth on the bed of the canal. This is a seasonal characteristic, which starts at the end of March and continues until the end of August, with a maximum reached in June and July. These weeds are dense, thick and high, often reach the water surface and result in retardation of water flow. Weed height is regulated by Waterways Ireland, which undertakes cutting usually 2-4 times during the summer. This results in a significant lowering of the water level from 10 to 30 cm in places (the highest drops of water are recorded at 7 Springs). Throughout the study, this was recorded between 4-20 June 2002, 1-20 August 2002, 20 June - 5 July 2003, 14 August – 3 September 2003, 25 May – 16 June 2004, 7-28 July 2004, 8-24 October 2004. There was no weed cutting undertaken in the section from Hanged Man's Bridge to Seven Springs in 2005, which resulted in elevated water levels especially in the northern branch on the Feeder, upstream of Point of Gibraltar and in Seven Spring. The weed cutting executed downstream from the Hanged Man's Bridge during the first two weeks of July 2005 was reflected in lowered levels recorded under the bridge and at the drain below site A (N276775; E215978). Hydrographs of water level fluctuations in Milltown Feeder are presented in Appendix 11.

Since fluctuation in surface water level is controlled by external factors, the pattern is poorly correlated with seasonal variations of groundwater discharge so the numerical comparison of the fluctuations throughout the years is of limited value. The annual minima are more likely to result from opening the lock rather than reflecting decreased groundwater discharge, however basic statistics are presented in Table III-13.

**Table III-13 Maximum, minimum and average annual water level in Milltown Feeder, 2001-2005**

| Hydrological Year | Seven Springs N277995; E215251 | | | Drain below site A N276775; E215978 | | | Hanged Man's Arch N275916; E217543 | | |
|---|---|---|---|---|---|---|---|---|---|
| | maximum | minimum | average | maximum | minimum | average | maximum | minimum | average |
| | m OD | m OD | M OD | m OD | m OD | m OD | m OD | m OD | m OD |
| 2001-2002 | 85.69 | 85.27 | 85.37 | 85.47 | 85.20 | 85.32 | 85.35 | 85.07 | 85.19 |
| 2002-2003 | 85.52 | 85.22 | 85.38 | 85.43 | 85.14 | 85.30 | 85.34 | 85.06 | 85.22 |
| 2003-2004 | 85.62 | 85.21 | 85.39 | 85.44 | 85.05 | 85.24 | 85.30 | 84.95 | 85.15 |
| 2004-2005 | 85.67 | 85.29 | 85.49 | 85.50 | 85.05 | 85.29 | 85.32 | 84.97 | 85.14 |

### III-1.2.5.2 Water Velocity and Flows

#### *III - 1.2.5.2.1. Manual Measurements*

The intention of this campaign was to establish a stage discharge relationship, which would be used later for establishing flow rates (and outflow from Milltown Feeder) from continuous water level records. The shape of the rating curve depends on factors such as the shape of the channel and the gradient of the water surface. Storms cause occasional overflows, which with other natural phenomena like weed growth or the freezing of a riverbed, restrict the validity of a rating curve for specific hydraulic conditions. These limitations, and methods for estimation of rating curves in given settings are broadly discussed in literature (De Gagne *et al.* 1996; Ozga-Zielinska *et al.*, 1997; Bajkiewicz-Grabowska & Mikulski, 1999; Viessman & Lewis, 2003).

There were 27 measurements taken under the bridge over the course of a study, the majority of which were taken in summer 2002 when they were carried out on a biweekly basis. These were plotted against the water level but no relationship could be established, Figure III-15. This was attributed mainly to the two factors stated above, which are control of the lock downstream of the canal and weed growth.

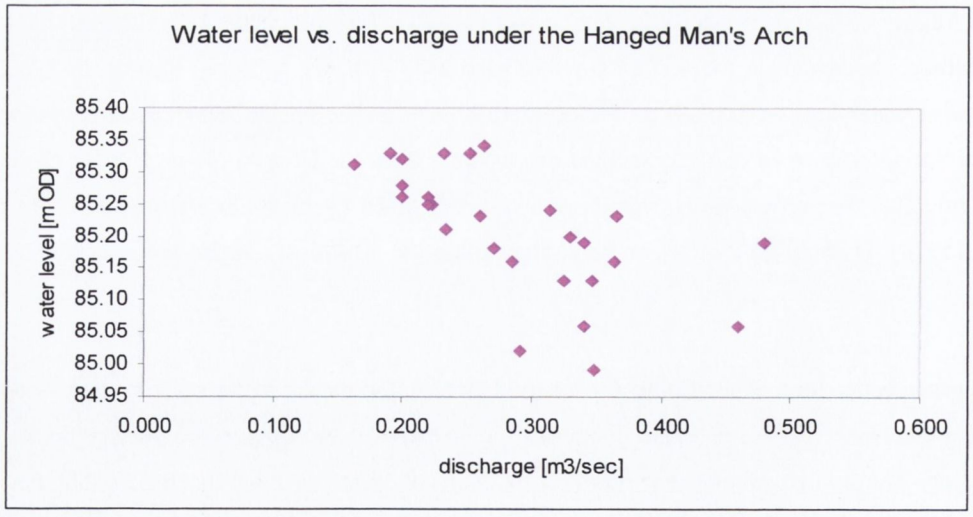



*Figure III-15 Relation between water level in Milltown Feeder under the Hanged Man's Arch and measured discharge*

Although constructing a stage discharge curve was impossible, the available information gives a very good idea of discharge from the fen. Additionally, 35 records of discharge from the Milltown Feeder under the Hanged Man's Bridge covering years 1973-1998 and executed by OPW were available from Kildare County Council

(Water Strategy for County Kildare, www.kildarecountycouncil.ie). These data correspond very well with results obtained during the study, Table III-14, Figure III-16.

**Table III-14 Discharge data from Milltown Feeder, manual measurements performed between 1973-2005. Data between 1993-1999 was collected by OPW, later data was obtained during the research.**

| | | DISCHARGE | | | | | |
|---|---|---|---|---|---|---|---|
| | Date | 7Springs | | Drain below site A | | Hanged Man's Arch | |
| | | $m^3$/sec | $m^3$/day | $m^3$/sec | $m^3$/day | $m^3$/sec | $m^3$/day |
| 1 | 09-May-73 | | | | | 0.250 | 21600 |
| 2 | 07-Jun-73 | | | | | 0.210 | 18144 |
| 3 | 10-Jul-73 | | | | | 0.160 | 13824 |
| 4 | 31-Jul-73 | | | | | 0.260 | 22464 |
| 5 | 05-Sep-73 | | | | | 0.350 | 30240 |
| 6 | 11-Nov-86 | | | | | 0.451 | 38966 |
| 7 | 26-Nov-86 | | | | | 0.394 | 34042 |
| 8 | 12-Jan-87 | | | | | 0.297 | 25661 |
| 9 | 03-Mar-87 | | | | | 0.468 | 40435 |
| 10 | 08-Jul-87 | | | | | 0.266 | 22982 |
| 11 | 17-Dec-87 | | | | | 0.417 | 36029 |
| 12 | 04-Mar-88 | | | | | 0.370 | 31968 |
| 13 | 06-Feb-96 | | | | | 0.395 | 34128 |
| 14 | 07-Mar-96 | | | | | 0.431 | 37238 |
| 15 | 16-Oct-96 | | | | | 0.298 | 25747 |
| 16 | 07-Nov-96 | | | | | 0.335 | 28944 |
| 17 | 06-Dec-96 | | | | | 0.315 | 27216 |
| 18 | 06-Dec-96 | | | | | 0.315 | 27216 |
| 19 | 08-Apr-97 | | | | | 0.302 | 26093 |
| 20 | 23-Jul-97 | | | | | 0.252 | 21773 |
| 21 | 14-Nov-97 | | | | | 0.265 | 22896 |
| 22 | 09-Dec-97 | | | | | 0.252 | 21773 |
| 23 | 21-Jan-98 | | | | | 0.382 | 33005 |
| 24 | 27-Jan-98 | | | | | 0.314 | 27130 |
| 25 | 06-Feb-98 | | | | | 0.319 | 27562 |
| 26 | 16-Feb-98 | | | | | 0.316 | 27302 |
| 27 | 06-Mar-98 | | | | | 0.417 | 36029 |
| 28 | 31-Mar-98 | | | | | 0.308 | 26611 |
| 29 | 28-Apr-98 | | | | | 0.358 | 30931 |
| 30 | 01-Sep-98 | | | | | 0.340 | 29376 |
| 31 | 14/10/1998 | | | | | 0.2818 | 24348 |
| 32 | 04/11/1998 | | | | | 0.411 | 35493 |
| 33 | 04/12/1998 | | | | | 0.453 | 39131 |
| 34 | 26/01/1999 | | | | | 0.446 | 38534 |
| 35 | 20/04/1999 | | | | | 0.4371 | 37765 |
| 36 | 20-Mar-02 | 0.223 | 19595 | 0.040 | 3486 | 0.325 | 28041 |
| 37 | 01-May-02 | 0.171 | 14980 | 0.108 | 9329 | 0.365 | 31547 |
| 38 | 05-Jun-02 | 0.092 | 8069 | 0.052 | 4511 | 0.232 | 20003 |
| 39 | 19-Jun-02 | 0.193 | 16953 | 0.072 | 6195 | 0.222 | 19181 |
| 40 | 03-Jul-02 | 0.206 | 18128 | 0.106 | 9135 | 0.200 | 17273 |
| 41 | 15-Jul-02 | 0.151 | 13266 | 0.063 | 5417 | 0.200 | 17280 |
| 42 | 01-Aug-02 | | | 0.077 | 6653 | 0.252 | 21773 |
| 43 | 21-Aug-02 | 0.173 | 15196 | 0.080 | 6912 | 0.263 | 22723 |
| 44 | 03-Sep-02 | 0.135 | 11858 | 0.091 | 7862 | 0.270 | 23328 |
| 45 | 18-Sep-02 | 0.134 | 11727 | 0.087 | 7517 | 0.233 | 20131 |
| 46 | 24-Oct-02 | 0.149 | 13115 | 0.080 | 6912 | 0.220 | 19008 |
| 47 | 25-Mar-03 | 0.200 | 17568 | 0.108 | 9331 | 0.480 | 41472 |
| 48 | 01-Apr-03 | 0.170 | 14933 | 0.100 | 8640 | 0.340 | 29376 |
| 49 | 07-Jul-03 | 0.204 | 17919 | 0.108 | 9331 | 0.260 | 22464 |
| 50 | 01-Aug-03 | 0.092 | 8081 | 0.052 | 4493 | 0.163 | 14083 |
| 51 | 06-Aug-03 | | | | | 0.190 | 16416 |
| 52 | 03-Sep-03 | 0.134 | 11771 | 0.106 | 9158 | 0.200 | 17280 |

| | | DISCHARGE | | | | | |
|---|---|---|---|---|---|---|---|
| | Date | 7Springs | | Drain below site A | | Hanged Man's Arch | |
| | | $m^3$/sec | $m^3$/day | $m^3$/sec | $m^3$/day | $m^3$/sec | $m^3$/day |
| 53 | 28-Jan-04 | | | | | 0.340 | 29376 |
| 54 | 17-Feb-04 | | | | | 0.285 | 24624 |
| 55 | 03-Mar-04 | | | | | 0.460 | 39744 |
| 56 | 07-Apr-04 | | | | | 0.364 | 31450 |
| 57 | 10-May-04 | | | | | 0.329 | 28426 |
| 58 | 02-Jun-04 | | | | | 0.314 | 27130 |
| 59 | 10-Jan-05 | | | | | 0.346 | 29868 |
| 60 | 31-Jan-05 | | | | | 0.348 | 30076 |
| 61 | 11-Feb-05 | | | | | 0.291 | 25168 |
| 62 | 26-May-05 | | | | | 0.220 | 19017 |
| | | | | | | | |
| | | | | | **Average [$m^3$/yr]:** | | **$9.94 \times 10^6$** |
| | | | | | **Maximum [$m^3$/yr]:** | | **$15.2 \times 10^6$** |
| | | | | | **Minimum [$m^3$/yr]:** | | **$5.1 \times 10^6$** |

From results gained manually during the study, the average discharge from Milltown Feeder was calculated at the level of 0.265 $m^3$/sec (22879 $m^3$/day = $8.35 \times 10^6$ $m^3$/yr). The average discharge from Seven Springs was 0.16 $m^3$/sec (14211 $m^3$/day and 61% of the total outflow) and for the drain below site A 0.08 $m^3$/sec (7180 $m^3$/day, and 31% of the outflow). The remaining difference between discharge from under the bridge and the sum of 7 Springs and the drain below site A is attributed to input from springs located in the vicinity of the Public Entrance and the north side. This accounts for 0.02 $m^3$/sec (1686 $m^3$/day) and is about 8% of the total outflow from the canal. These calculations are based on 15 measuring episodes undertaken in 2002-2003 when data was collected in all three locations simultaneously.

Comparison with historical data collected in the 70s and 80s does not indicate a dramatic change in discharge from the fen (Figure III-16); however due to the random nature of the data, conclusions regarding seasonal patterns or long term trends may not be given. When including this data, the average discharge from Milltown Feeder was determined as $9.94 \times 10^6$ $m^3$/yr and values ranged between $5.1 \times 10^6$ $m^3$/yr to $15.2 \times 10^6$ $m^3$/yr with the minimum value measured in July 1973 and the maximum in March 2003.

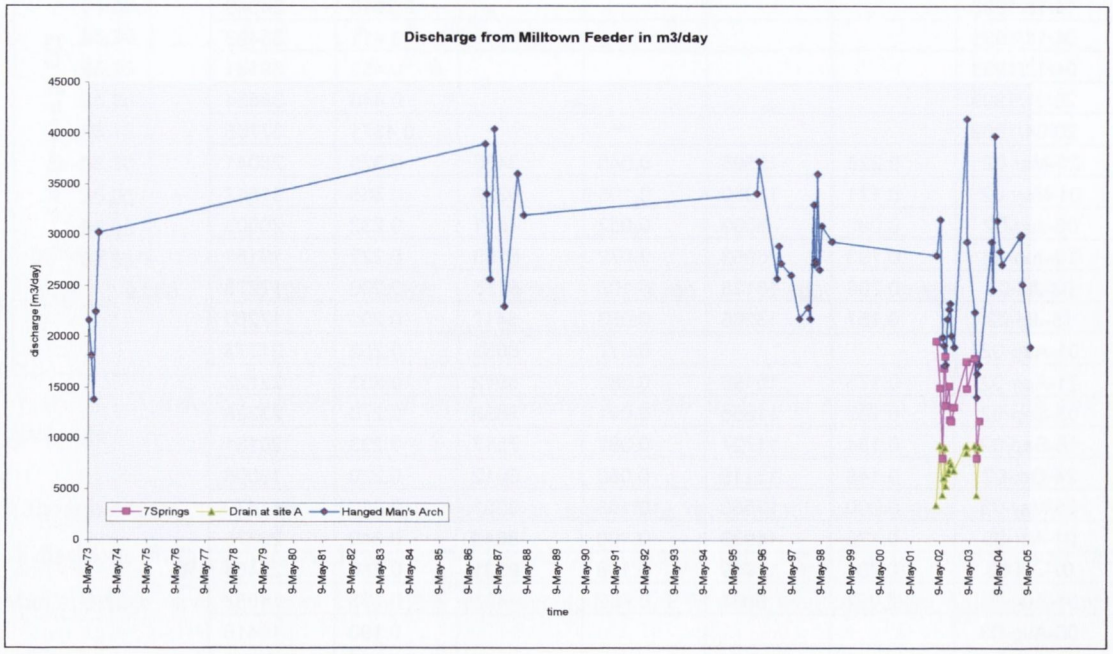



*Figure III-16 Discharge from Milltown Feeder based on manual velocity measurements over 1973-2005*

### *III - 1.2.5.2.2. Automatic Measurements using the Ultrasonic Doppler Flow Meter*

The ultrasonic Doppler flow meter (UDFM), a continuous velocity recorder, was first tried at the turn of March and April 2003. A feasibility study and calibration against manual measurements was performed by Casey (Casey 2003). This work resulted in the conclusion that the UDFM overestimates the velocity of flow; however, the application of a correction factor did resolve this problem and the device was recommended for use for continuous monitoring of flow velocity and depth of water, which was then turned into a discharge. A correction factor for winter conditions was established at 0.79. Due to the changing condition of the canal bed, it was recommended that the correction factor should be revised for the summer months, when more weeds occur and inhibit the flow rate. Following the trial and recommendations the flow meter was installed in July 2003; however operational periods were limited to the following times: 07 July 2003 – 04 September 2003, 17 February 2004 – 22 September 2004 and 10 January 2005 – 9 March 2005. Despite many efforts at prevention, the logger was subject to human interference, which three times resulted in its termination.

The summer calibration was undertaken in July and August 2003 and was based on five manual measurements, and the summer correction factor was established at 0.48 (Casey, 2003). Since weed growth occurs in the canal between May and September, it was agreed to use this correction factor for those months. For the remaining months, when the flow is hardly affected by any obstacles, the value of 0.79 was adopted. Spot manual flow measurements were later undertaken to check the validity of the implemented factors and these were satisfactory (Table III-15).

**Table III-15 Comparison between flow in Milltown Feeder measured with standard method using a portable flow meter and flow recorded by the Ultrasonic Doppler Flow Meter (UDFM)**

| Date | Time | Q [$m^3$/sec] Manual | Q [$m^3$/sec] UDFM | Ratio |
|---|---|---|---|---|
| 17.02.2004 | 4 pm | 0.285 | 0.52 | 0.55 |
| 03.03.2004 | 3 pm | 0.460 | 0.52 | 0.88 |
| 07.04.2004 | 12 pm | 0.364 | 0.45 | 0.81 |
| 11.05.2004 | 4 pm | 0.329 | 0.64 | 0.52 |
| 02.06.2004 | 1 pm | 0.314 | 0.64 | 0.49 |
| 10.01.2005 | 2 pm | 0.346 | 0.45 | 0.78 |
| 31.01.2005 | 3 pm | 0.348 | 0.49 | 0.71 |
| 11.02.2005 | 12 pm | 0.291 | 0.37 | 0.78 |

The application of appropriate correction factors resulted in discharge values for the months of July-August 2003, February-September 2004, and January-February 2005, which are presented in Appendix 12. Data were collected on an hourly basis; however, scanning was set for 60 seconds and automatically aggregated into hourly records. This data were later aggregated into daily data sets.

### *III - 1.2.5.2.3. Estimation of Annual Outflow from Milltown Feeder*

Analysis of daily records revealed that discharge values may vary significantly and ambient conditions such as wind, or objects immersed in the canal such as boats can either inhibit or enhance the flow. These records showed also that the range of daily discharge is more variable in winter months than in the summer; for example, the range of daily discharge recorded in March 2004 was 0.77 and for August 2003 it was 0.3; for June 2004 it

was 0.31 and for August 2004 it was 0.18. High fluctuations suggest that spot measurements may not represent the outflow from Milltown Feeder well; therefore a better estimation of outflow can be obtained by using the UDMF records. This data were therefore aggregated into monthly averages and results are presented in Table III-16.

Unfortunately, due to instrument failure, the full hydrological year was not covered for the purposes of water balance; therefore further investigations of the relationship between discharge and groundwater level in the vicinity of the Feeder were undertaken. Three deep wells from the southern, south eastern and northern fen margin were chosen and monthly records for the period covering UDMF data were selected. These were MB6, SP16 and SP4 respectively (map in Appendix 2 & 3). Hydrographs of these water levels vs. the discharge are presented in Figure III-17. In 2003, the discharge measured in the Feeder was better related to the levels presented by hydrographs on the south side, picking up in March 2004. However, later in 2004, when an extended recession was recorded on the south side (minimum in December 2004), the discharge showed a better fit with hydrographs from the northern side, with both reaching the minimum in September 2004 and maximum in January 2005. It is important to notice that September – October 2004 were wet months, all of which had a rainfall higher than the 30 year average. As discussed earlier, the northern margin shows evidence for different recharge than the southern side with a much smaller and closer recharge area. This is reflected in the quick response in hydraulic heads to intensive rainfalls such as at the end of the summer. The fact that the measured discharge showed a similar response to that of the SP4 indicates that the northern side contributes significantly to discharge and because of the closeness of the catchment area, intensity of rainfall and rainfall distribution seems to be an important issue for discharge patterns. Because we do not have good information about discharge from the canal before 2003, it is difficult to assess the contribution of both sides of the fen catchment into the Milltown Feeder. It is an original belief that the base flow in Milltown Feeder is largely fed from the south (the Curragh Aquifer) and it is likely that this only varies slightly seasonally. The base flow from the south side is superimposed by peak flow discharges, mainly coming from the north side. It is possible, then, that because of decreasing discharge from the southern fen margin, the contribution from the northern margin becomes more significant than in previous years. It is recommended that this matter is further investigated.

Because of the lack of measured values as well the lack of correlation with deep groundwater levels from around the fen margin, missing values were fitted in using visual interpolation. Computation of the outflow from the system was possible for one hydrometric year only (2004), when UDFM was installed and that was $8.6 \times 10^6$ $m^3/yr$. When spot measurements were used for the determination of outflow, the value yielded $11 \times 10^6$ $m^3/yr$. Taking into account difficulties that occurred during the measuring period, which resulted in periods of missing data, it is suggested the outflow be estimated as a range of $8.6 - 11 \times 10^6$ $m^3/yr$ rather than as a single value. For comparison, previous works by Daly (1981) and Collins (2002) established outflow from the Milltown Feeder at the level of $9.1 \times 10^6$ $m^3/yr$ and $10.1 \times 10^6$ $m^3/yr$ respectively.

**Table III-16 Monthly discharge from Milltown Feeder based on UDFM data, 2003-2005; * data sets do not cover a whole month; [1]data interpolated visually.**

| | Q | | | | |
|---|---|---|---|---|---|
| | $m^3$/sec | max | min | range | SD |
| | | | | | |
| Jul-03 | 0.35* | 0.52 | 0.17 | 0.35 | 0.09 |
| Aug-03 | 0.28 | 0.40 | 0.10 | 0.30 | 0.07 |
| Sep-03 | 0.19* | 0.24 | 0.12 | 0.12 | 0.05 |
| Oct-03 | *0.18*[1] | | | | |
| Nov-03 | *0.20*[1] | | | | |
| Dec-03 | *0.24*[1] | | | | |
| Jan-04 | *0.29*[1] | | | | |
| Feb-04 | 0.34* | 0.60 | 0.23 | 0.37 | 0.10 |
| Mar-04 | 0.52 | 1.01 | 0.24 | 0.77 | 0.20 |
| Apr-04 | 0.49 | 0.90 | 0.26 | 0.63 | 0.17 |
| May-04 | 0.33 | 0.48 | 0.22 | 0.25 | 0.07 |
| Jun-04 | 0.21 | 0.40 | 0.10 | 0.31 | 0.09 |
| Jul-04 | 0.15 | 0.38 | 0.08 | 0.31 | 0.07 |
| Aug-04 | 0.14 | 0.25 | 0.07 | 0.18 | 0.03 |
| Sep-04 | 0.11* | 0.14 | 0.09 | 0.05 | 0.01 |
| Oct-04 | *0.15*[1] | | | | |
| Nov-04 | *0.24*[1] | | | | |
| Dec-04 | *0.32*[1] | | | | |
| Jan-05 | 0.38* | 1.11 | 0.21 | 0.90 | 0.21 |
| Feb-05 | 0.36 | 1.25 | 0.20 | 1.05 | 0.23 |
| Mar-05 | 0.24* | 0.40 | 0.18 | 0.22 | 0.07 |

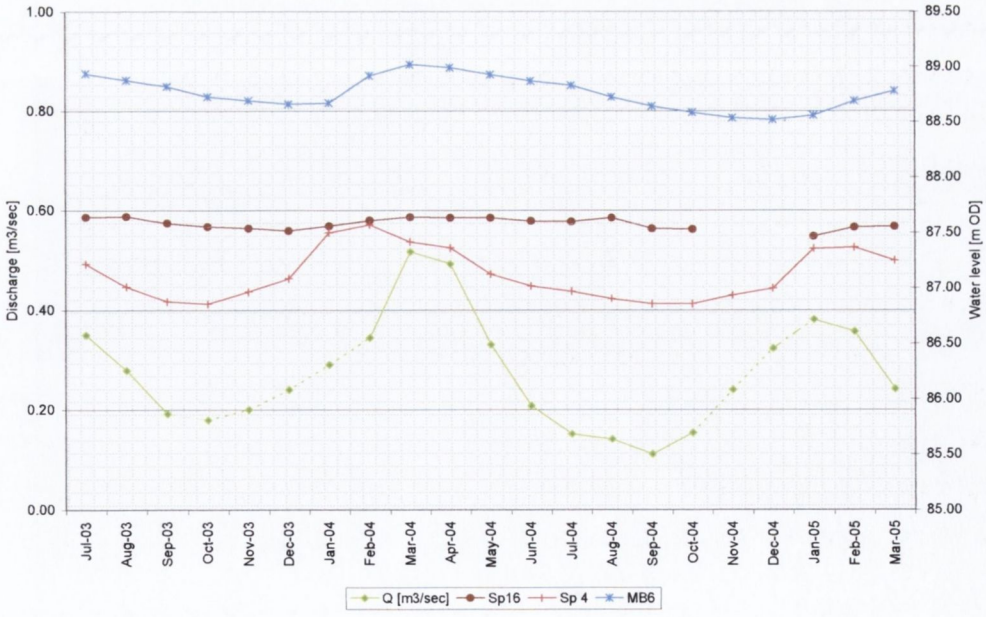



*Figure III-17 Fluctuations of discharge from Milltown Feeder and groundwater levels in deep wells around the fen, 2003-2005. Dotted line indicates points for which discharge data were fitted, not measured.*



*Photo III-1 Example of weed growth in the drain below site A, September 2005*



*Photo III-2 Example of weed growth in the drain below site A, September 2005*



*Photo III-3 Example of weed growth at Seven Springs location, September 2005*

### III-1.2.5.3 Conclusions

In summary, due to small velocities, extensive weed growth and operations on the lock gates, a rating curve on discharge from the Milltown Feeder was not established. Nevertheless, the study revealed the following:

- The annual water level fluctuation under the Hanged Man's Arch is expected to oscillate between 84.95-85.35 m OD.
- The gradient between the Seven Springs and the Hanged Man's Arch is very small within the range of 0.16-0.35 m (annual averages) difference over the 3 km distance.
- Flow rates are highly dependent on ambient conditions such as wind speed as the majority of the flow occurs close to the surface due to extensive weed growth.
- Weed cutting and lock operations have a significant influence on water level gradients.
- Peak flow discharges show a correlation with peaks in groundwater level on the north side of the fen rather than on the south side.
- Approximately 61% of the total outflow from the Milltown Feeder comes from Seven Springs and 31% from springs located along the southern fen margin, which drain into the drain below site A. Springs around the Public Entrance and along the northern fen margin contribute to approximately 8% of the total outflow from the canal.
- Total discharge from Milltown Feeder for hydrological year 2004 was in a range **of 8.6 – 11 x $10^6$ $m^3$/yr.**

## III-1.3. Estimation of the Water Balance

The above study allows establishing major elements of the water balance. It is now known that the fen is recharged by both groundwater and precipitation, with the majority having groundwater origin. Most of the groundwater discharge outlets occur on the southern fen margin and the end of the catchment area for this water lies as far as three kilometres away towards the west, north west and south west. The northern springs have much smaller catchment area which occupies a short stretch between the fen margin and the local road R 416. This area constitutes only 15% of the catchment. The total catchment area for the fen is c. 32.2 $km^2$. Cattle and sheep grazing is common. The rest of area is urban. Discrepancies between the southern and northern catchment area are clearly expressed in dissimilarity of the water chemistry from representative samples, which depends on the residence time of water in the soil and on land use within the catchment boundary.

The only discharge point from the fen is through the Milltown Feeder which was measured under the Hanged Man's Bridge in Milltown village. There are two tributary drains which supply the Milltown Feeder with water, one of which starts at Seven Springs and the second is the drain below site A. Approximately 92% of the total Milltown Feeder discharge runs from these two points. The remaining 8% comes from the collection of northern springs, the Public Entrance spring and direct precipitation.

To evaluate results established in previous analysis we used the water balance equation as presented in Equation III-1. Because of difficulties with data quality, due to reasons described previously, only one hydrological year was chosen for this evaluation. This was 2004 (October 2003 – September 2004).
The elements of the fen water balance consisited of:

***Recharge to the fen:***

- Springs and seepages discharging into the fen expressed as a product of effective rainfall from the catchment area and the area of the catchment (surface runoff is negligible) = ($RF\text{-}AE_{Curragh}$) x area

$$\mathbf{0.335 \times 32.2 \times 10^6 = 10.79 \times 10^6\ m^3/yr}$$

- Recharge over the fen area expressed as a product of the fen effective rainfall and the fen area = ($RF\text{-}AE_{Fen}$) x area

$$\mathbf{0.179 \times 2.2 \times 10^6 = 0.39 \times 10^6\ m^3/yr}$$

**Total recharge: (10.79+0.39) x $10^6$ $m^3$/yr = 11.18 x $10^6$ $m^3$/yr**

***Discharge from the fen:***

- Based on the manual and automatic flow measurement, the outflow from the Milltown Feeder in hydrometric year 2004 was determined as **8.6 -11 x $10^6$ $m^3$/yr**

From the above values it seems that the recharge estimates are higher than the discharge values. However, a study by Misstear and Brown (draft, 2007) suggests that not all effective rainfall that falls over the Curragh aquifer contributes to the groundwater recharge, and based on the well hydrograph analysis, the proposed recharge coefficients range between 72-100%.

A ratio between lower and higher estimates of the discharge from the fen to the recharge estimation gives a range of 77-98%, well within the Misstear's and Brown's proposed recharge coefficient range. Flow measurement errors resulting from low flow velocities in the canal, at a limit of detection by conventional measuring devices, should also be borne in mind.

## III - 2. Water Regime

In the previous chapter the water inputs into Pollardstown Fen, as determined from the climatic characteristics of the region, appeared to be balanced by a measured discharge through the Milltown Feeder. This chapter aims to describe the water regime of the fen, and specifically the mechanism of water delivery into the fen.

It is known at this stage that groundwater is the major input into the overall water balance and this can occur through either springs or seepage zones, the latter being important habitats for protected species. As such, in this part, the work focuses on identification of the working mechanism of seepage, factors that control the rate of water delivery and its importance in satisfying stable and long term sustainable conditions. It is hypothesised here that water flow in these zones can occur either in lateral or vertical directions and the rate of delivery will depend on the following components:

- Site elevation,
- Groundwater pressure in the underlying aquifer,
- The site's geomorphology,
- Substrate properties.

These components are considered to be most the important seepage control factors and therefore the intention here is to identify their roles in the occurrence of seepage at the fen margin. To do that, four known seepage sites were selected for an in depth analysis of local hydrological regimes. This will include analysis of the sites' geomorphology, monitoring of water levels at different depths and undertaking *in situ* permeability tests to study properties of the substrate. Such an approach aims to distinguish geological differences (or similarities) between selected seepage sites, and by comparison of the associated local water regimes within these sites, to arrive at a conclusion concerning their importance on the quality of the habitat above. Data used for this analysis were collected from Intensive Quadrats A, B, C and D (Figure II-16), for which habitat quality data also exist.

But first, a broad approach will be taken to characterise general flow patterns throughout the fen and seasonal variations of groundwater flows. This will include analysis of vertical groundwater discharge rates based on conventional flow equations using Darcy's law. This work intends to verify dominant flow patterns within the peat substrate, i.e. whether it is lateral or vertical. This work will be based on data collected from Permanent Quadrats (Figure II-15) because these are available for longer periods and as such represent the hydrological regime of the fen better.

### III-2.1. Methods

#### *III-2.1.1. Groundwater Flow Patterns*

The information used for this analysis comprised of groundwater level data from 10 Permanent Quadrats 1-10. Data were collected from two depths, 1 and 3 metres below ground level (bgl) and covered the period from 1997

until 2005; however, frequency of measurements is rather irregular in some periods; therefore it was necessary to select a shorter period for some parts of the analysis. Until the summer of 1999, the frequency of measurement was very irregular. From July 1999 until June 2000 data was collected on a monthly basis. From June 2000 until April 2004 water levels were measured on a biweekly basis. In April 2004 the frequency was reduced to once a month and the number of sites was reduced from 10 down to 5 (PQ 1, PQ5, PQ6, PQ9 and PQ10). The data were analysed as follows:

a) To determine long-term trends, the water table was graphically presented in the form of hydrographs. Monthly rainfall was calculated from hourly data recorded at Pollardstown Fen weather station (from March 2002) and earlier data for January 1997- January 2002 were computed from daily records from Naas CBS Station and were also presented on charts.

b) To describe the water regime in terms of seasonal variations:
   - Descriptive statistics were distinguished using SPSS statistical software. This was performed for 2000-2003, when data was collected on a biweekly basis;
   - Frequencies of a given water table were analysed in the form of histograms;
   - Empirical probability distribution was constructed on the basis of observed data.

   The idea of empirical distribution lies in the interpretation of a frequency of a given probability (Dowdy & Wearden, 1985; Jóźwiak & Podgórski., 1992; Ozga-Zielinska *et al.*, 1997; Linsley *et al.*, 1998; Manly 2000) and is often referred to as a duration curve or probability of exceedence. Probability of exceedence is usually used for stream flows analysis (Fetter, 2001), however because it is water availability/fluctuation in peatlands that controls the botanical patterns, duration curves have been proved to be a useful tool in relation to wetlands studies on hydro-ecological interactions, (Tynan *et al.*, 2005). There are several equations given for probability of exceedence in literature (Chow *et. al* 1988; Ozga-Zielinska *et. al*, 1997); for hydrological data of unknown theoretical distribution, Ozga - Zielinska (1997) suggest using the Weibull formula, also recommended by WMO[6]:

$$\hat{p}_m = \frac{m}{n+1} \cdot 100\%$$

*Equation III-14*

where:

$\hat{p}_m$ - empirical probability of occurrence

m – rank

n – number of cases

The methodology is presented in Fetter (2001), but briefly, to construct a frequency duration curve, the data set must be ordered in decreasing order, and then all cases ranked from 1 to n, where n is a total number of cases. Probability of occurrence is calculated according to Equation III-14 for each case. A plot $\hat{p}_m$ as a function of water level is called a frequency duration curve, showing percentage of time, when a given water table is equalled or exceeded.

[6] World Meteorological Organisation

c) In order to evaluate the vertical gradients, for those Permanent Quadrats where two standpipes were available, the difference between hydraulic heads in these two standpipes was computed. Some standpipes were shown to be strongly upwelling, others were clearly infiltrating; however, several wells were less conclusive, with the changing direction of a vertical flow. For these locations, frequency duration curves were established with a $\hat{p}_m$ being a function of a vertical gradient.

### *III-2.1.2. Hydrological Regime of the Fen Margin*

Water level monitoring within Intensive Quadrats was carried out biweekly. Data was analysed on the basis of the hydrometric year and covered the period from 2002-2005. The aim of the work was to build a conceptual model of a possible groundwater recharge mechanism; therefore the study incorporated all available information such as local topography, geology and water level data.

In order to determine flow rates within the selected sites, properties of the soils were established experimentally in situ prior to the investigation of the water regime.

Two bail tests were carried out on site, one in a peat layer (in Permanent Quadrat 10 (S10)) and one in a deep gravel layer (in standpipe SP31D). For both, the Hvorslev (1951) formula was used to calculate hydraulic conductivity (after Fetter 2001):

$$k = \frac{r^2 \ln\left(L_e / R\right)}{2 L_e t_{37}}$$

*Equation III-15*

where:

$k$ – hydraulic conductivity [L/T]

$r$ – radius of the well casing [L]

$R$ – radius of the well screen [L]

$L_e$ – length of the well screen [L]

$t_{37}$ – time it takes for the water level to fall to 37% of the initial change [T]

Three volumes of water were pumped out prior to the test. The rise in the water level was recorded with 30 second spacing in the gravel well and every minute during the first 10 minutes, and later every 5 minutes until full recovery in the peat well. The numerical results of these tests are presented in Appendix 13 and the summary will be discussed in the result section.

When permeability of the soil was known, the analysis was continued as follows:

a) A topographical survey was undertaken using Trimble® GPS equipment and maps produced using Surfer software for each site.

b) Geological profiles across the fen margin were drawn from borehole logs for each of the sites by WYG Ltd. (used with permission).

c) For each standpipe, descriptive statistics were computed using Excel software and hydrographs were drawn for records from 2002-2005 (hydrometric).

d) The lateral direction of groundwater flow in three layers that were monitored was established by comparison of hydraulic heads and gradients between all nests within each Intensive Quadrat.

e) The assumption of steady state conditions was made for the confined gravel layer and Darcy's law (Equation III-16) was used to calculate the groundwater flow rate and was expressed as specific discharge[7] (or Darcy's velocity, i.e. volumetric flow rate per unit cross-sectional area):

$$q = k \cdot \frac{dh}{dl}$$

*Equation III-16*

where:

$q$ – specific discharge [L/T]

$k$ – hydraulic conductivity [L/T]

$\frac{dh}{dl}$ - hydraulic gradient [-]

For the peat layer, as for an unconfined aquifer, Dupuit (1863) assumptions were applied and flow calculated according to:

$$q' = \frac{1}{2} \cdot k \cdot \left( \frac{h_1^2 - h_2^2}{L} \right)$$

*Equation III-17*

where:

$q'$ – flow per unit width [$L^2$/T]

$k$ – hydraulic conductivity [L/T]

$h_1$, $h_2$ – hydraulic head in piezometers 1 and 2; assumption: reference point measured at the peat base in a deeper peat profile, usually in more central piezometer [L]

$L$ – distance between piezometers 1 and 2 [L]

[7] Considering morphological complexity of the fen margin, i.e. sloping layers of clay and the peat base, the computed flow rates should be taken as approximations only.

f) To distinguish potential seepage areas and help to develop the conceptual model of hydrological gradients and flow rates, a prickstocking survey was undertaken across sites A, C and D (Table III-17). These rates were compared with vertical seepage calculated from Darcy's law (Equation III-16). For the vertical flow calculations, hydraulic conductivity was modified to reflect permeabilities of all strata through which the groundwater flows, i.e. gravel, clay and peat:

$$k = \frac{D}{\sum_{i=0}^{i=n} \frac{d_i}{k_i}}$$

*Equation III-18*

where:

$k$ – mean hydraulic conductivity [L/T]

$d_i$ – thickness of layer $i$ [L]

$k_i$ – hydraulic conductivity for layer $i$ [L/T]

$D$ – total thickness [L]

$i$ – a geological stratographic layer [-]

$n$ – total number of layers [-]

A table with computed vertical permeabilities for all sites can be viewed in Appendix 33.

A prickstock is a stainless steel probing rod with a temperature sensor and electrodes for the measurement of electric conductance at different depths of soft soil (peat). Temperature and electric conductivity (measured as conductance) data is collected by pushing the instrument into the peat layer and relevant values recorded at 10 cm intervals. The data is collected from ground level downwards. If standing water is present on site, the water table is regarded as the surface. The last reading is taken at the base of the peat layer. Electrical conductance is used to estimate the variation of the electrical conductivity of peat water. The temperature data is used for quantitative estimation of seepage rates. During the study on Pollardstown Fen, six transects of approximately 30 metre length were surveyed. These are listed in a table below:

**Table III-17 Prickstocking transect description**

| Transect ID | Date of a survey | Location |
|---|---|---|
| A-middle | 06.06.2002 | In the central section of site A, in the middle of a trackway installed to facilitate the study, direction SW-NE |
| A-left | 06.06.2002 | 16 metres left from and parallel to A-middle |
| A-right | 06.06.2002 | 16 metres right from and parallel to A-middle |
| C | 13.06.2002 | In the central section of site C, in the middle of a trackway installed to facilitate the study, direction NE-SW |
| D | 14.06.2002 | In the central section of site D, in the middle of a trackway installed to facilitate the study, direction NE-SW |
| A-middle | 08.10.2003 | In the central section of site A, in the middle of a trackway installed to facilitate the study, direction SW-NE |

All transects were surveyed with one metre spacing. At site A, there were three parallel transects, each starting at the fen margin, at a line marked by the beginning of the trackway and all extended

towards the fen centre. Exactly thirty verticals were surveyed along each transect. The middle transect at site A was surveyed twice, in June 2002 and in October 2003, in order to detect potential seasonal changes in the recharge mechanism on site.

Only one transect was surveyed at sites C and D. At site C, the first reading was taken at a line marked by standpipes SP7/8- SP5/6- SP4 and measurements followed the trackway towards the fen centre. The last reading was taken 10 metres below the end of the trackway, at a line marked by Standpipes SP9/10-11/12-13/14. At site D, measurements were taken along the length of the trackway only. The analysis was performed in two steps:

- First of all, results were aggregated in an Excel spreadsheet and diagrams of vertical and spatial variability were drawn for both parameters. The interpretation of these diagrams is such that patterns of spatial distribution of conductance or temperature lead to detection of predominant vertical gradients. Vertical gradients are expected especially for temperature. The difference in lateral transects may reflect either a water flow with vertical component or differences in peat density and silt content or differences in vegetation structure (van Wirdum, 1998). These vertical temperature gradients can be further investigated with quantitative analysis to consider for vertical flow, which forms the second part of the analysis.

- The estimate of vertical water movement with a prickstock was performed using TC-Taureg.xls spreadsheet (van Wirdum, 1991). This programme comprises a numerical solution of the temperature depth gradient for the temperature regime at the surface, taking account of the thermal properties of peat and an assumed gross velocity of vertical flow. As this solution is based on the temperature at three different depths, and as the temperature at all other depths can then be computed, the 'goodness' of a solution can be statistically evaluated. By repeating this for several sets of these observed temperatures, a 'best solution' for the whole gradient can be determined. This procedure is automatically repeated for different assumed flow velocities. A 'most probable' flow velocity can be determined by comparing the regime properties thus far found with known values for the temperature regime at the nearby surface. There are two elements of heat transport to be considered here: the first is conduction of heat within the body of wet peat and second is convection of heat with water moving through the peat. Heat transport in the soil is driven by varying temperatures at the surface, characterised by sinusoidal fluctuations on a daily and annual basis. These fluctuations are highest at depths close to the surface and decrease with increased depth in the soil. At a depth where variations are close to zero, the soil temperature almost equals an annual mean surface temperature. The temperature 'wave' at each depth reflects the results of the heat flow. The deeper the peat depth, the amplitude of the wave is smaller and the phase lag is greater. Vertical movement of water can either promote (if infiltrating) or impede (if seeping upwards) the natural downwards distribution of the temperature wave. The damping and lagging effect at depth depends on the physical

characteristics of the soil, the periods of the driving waves at the surface and the possible convection of heat with moving water.

***Procedures using TC-Taureg.xls programme:***

1) Select a temperature depth gradient (with potential vertical movement of water).
2) Select a layer of interest (can be a complete vertical or only a part of it) to be tested.
3) Adjust soil composition (volumetric %) including water, air, peat and mineral content.
4) Select a range of velocities that will be tested. The spreadsheet automatically returns the best fit velocity and various graphs for further interpretation.
5) Compare modelled[8] with observed graphs of temperature. If both graphs correspond well with each other and the differences between modelled and observed (Model - Observation) is near to zero, then automatically aggregated best fit velocity (and its flow direction) may be consider a good solution; however, other parameters must be checked before selecting the final result.
6) Check the following parameters for conformity with expected values at ground level:
   - $T_{mean}$ = between 9.0 –10.3 [°C]
   - Amplitude = 7+/-0.3 [°C]
   - Lag[9] = c.25 [days]
   - Error < 10

A short explanation is needed here regarding the selection of the criteria for best results. Preferably, a locally measured regime should be used for establishing the 'good fit' criteria. These were available for the fen as part of an extensive monitoring of micrometeorological regime for *Vertigo geyeri*. These are discussed in detail in Chapter IV. Since the methodology used here is not common, and limited information is provided on the subject, the criteria for a best fit solution were agreed by consultation with the author of the model based on his own experience. $T_{mean}$ represents the annual mean temperature at the soil surface, which is assumed to be similar to an annual air temperature, and for Ireland is circa 10°C. A micrometerological study carried out within Site A shows that the average temperature in the soil, at 10 cm depth, for the months June 2002-May 2003 was 9.1°C and at the surface it was 9.3 °C (Appendix 30). The value of the phase lag of the temperature wave should probably not be less than 15 days. According to van Wirdum (1998), who performed detailed Fourier analysis on above-ground temperature data from various meteorological stations, the value should vary between 25 and 40 days for the northern hemisphere. At the Pollardstown fen the values ranged from between 19 at the surface to 30 at 10 cm depth in the soil at site A. The amplitude of the wave and error values were arbitrarily agreed on the basis of the author's previous experience. If the error value exceeds 10, the result should be rejected and values

[8] The model describes the temperature at the intermediate depth **z** as a reflection of temperature fluctuations at the surface with decreased amplitude and phase lag. It assumes that the soil temperature at the soil surface (depth $\mathbf{z_0}$) varies depending on ambient conditions; where else it is constant at an infinite depth of $\mathbf{z_\infty}$.

The temperature at the intermediate depth **z** is described as: $T_{t,z} = T_m - A_0 e^{-az} \cos(\varphi - bz)$

where: $T_{t,z}$ – temperature at depth $z$, at time $t$ [°C], $T_m$ – mean annual temperature [°C], $A_0$ – temperature amplitude at depth z=0 [C], b – phase-shift coefficient [$L^{-1}$], a – damping coefficient [$L^{-1}$]; $b = (\pi/(\tau\kappa))^{1/2}$, τ - period of the wave [T], κ - thermal diffusivity [$L^2/T$], z – depth [L], φ - phase, relative to the wave minimum [rad]; $\varphi = 2\pi t/\tau$. For more information please refer to Van Wirdum (1991).

[9] The lag is the number of days between the 1st of January and the annual minimum at ground level.

around 5 can be considered as a very good result, provided that the other parameters fulfil the criteria. It is assumed that the reading and instrumental accuracy of the measurement is 0.01 k, hence observation error being +/- 0.05 k; the average deviation should be 0.05, which is expressed as 5. Hence, an error of '0' would be 'too good' to expect.

Sometimes a good solution can be found for some parts of a vertical only which will be due to complexity of the soil properties and flow characteristics. In this situation, a partition of a vertical shall be made and different solutions found for separate layers.

## III-2.2. Results

### *III-2.2.1. Groundwater Flow Patterns*

Ten Permanent Quadrats were established within the fen area, seven of which were at the fen margin, and three inside the fen, in the area often referred to as a fen flat (location map Figure II-15). The fluctuations of water level from these locations were analysed using hydrographs. The results of this analysis are presented in Figures III-26 – III-29. Generally, the phreatic level on Pollardstown Fen was expected to be less variable than in deep standpipes and to be maintained at or near the surface, with very little variation. If higher variation occurred, this would be due to the proximity of drains with varying water levels, or later inflow from up-slope peat (or other land), or because there was not enough hydraulic potential in the underlying aquifer to compensate for evapotranspiration loses and hence the phreatic level fell below the surface.

The elevation of water levels is a function of the distance from the valley margin, so the highest water levels (data presented in OD Poolbeg) were recorded at the highest Permanent Quadrat PQ10, located on the south westerly edge of the fen. The topography of this site lies approximately 2 metres higher than the levels of the remaining Permanent Quadrats which decrease in the following order: PQ 3, PQ4, PQ9, PQ1, PQ6, PQ5, PQ7, PQ2, PQ8. The topography of the fen is generally higher on the southern fen margin than on the northern. The general flow direction was towards the drains into the fen centre.

Among all the sites, Permanent Quadrats 1 and 8 showed the most stable water table fluctuations. As for PQ 8, this is the lowest site topographically, and is located in the middle of the fen. The stability of the water table here is closely controlled by the water level maintained in the Milltown Feeder. The site is located approximately 50-80 metres from the Feeder. PQ 1 shows high stability at both the shallow and deep levels and the close proximity of both levels to ground level indicates potential seepage in the surrounding area. The highest fluctuations were recorded at PQ 4, PQ5, and PQ9, which can be attributed to the proximity of drains. Permanent Quadrat 10 also demonstrated a similar pattern; however, this was changed in mid 2003.

A summary of a statistical analysis on water level fluctuation done in the SPSS package is presented in Table III-18.

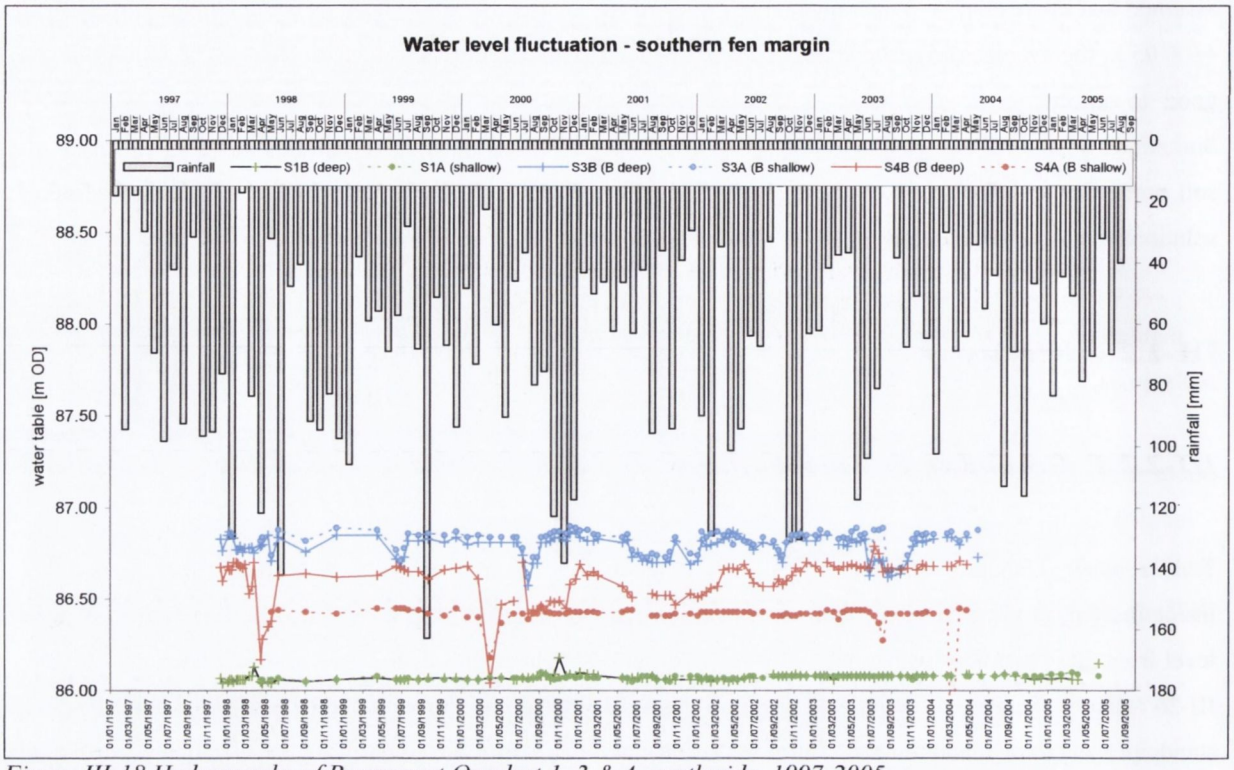



*Figure III-18 Hydrographs of Permanent Quadrat 1, 3 & 4, south side, 1997-2005*

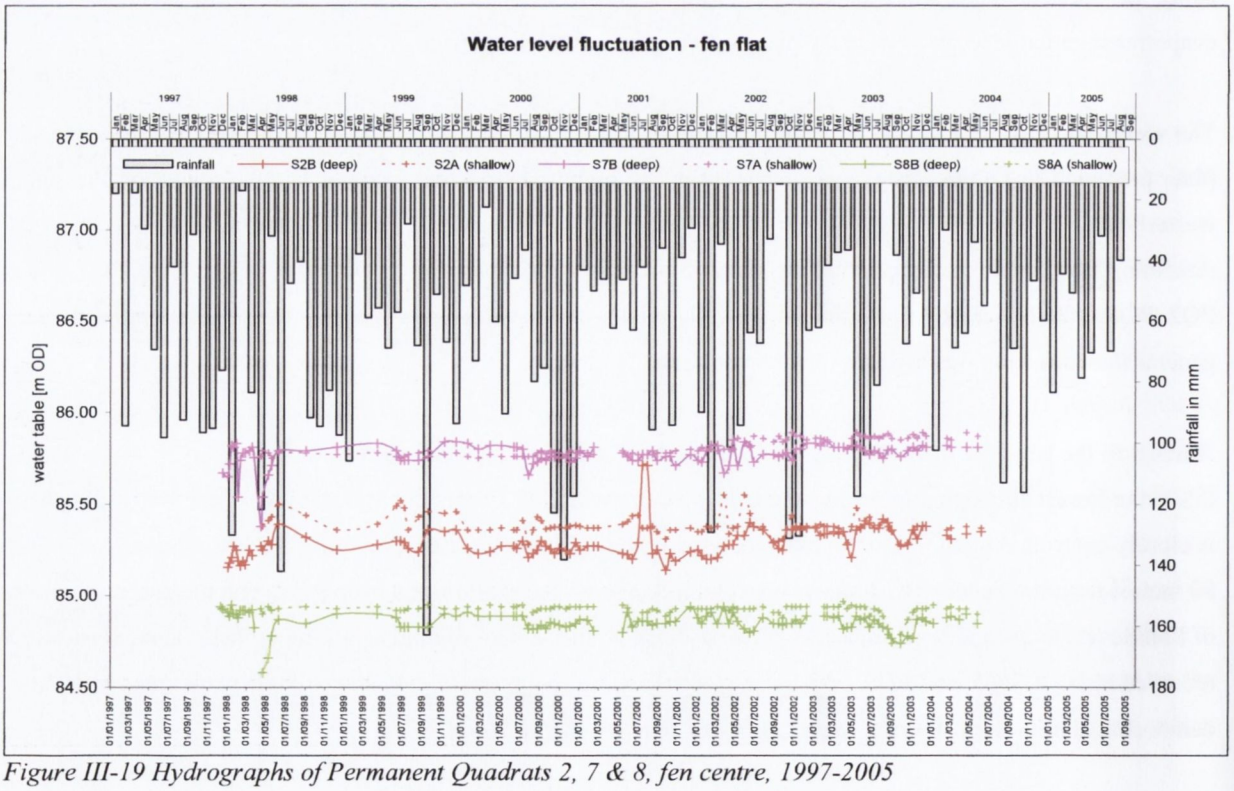



*Figure III-19 Hydrographs of Permanent Quadrats 2, 7 & 8, fen centre, 1997-2005*

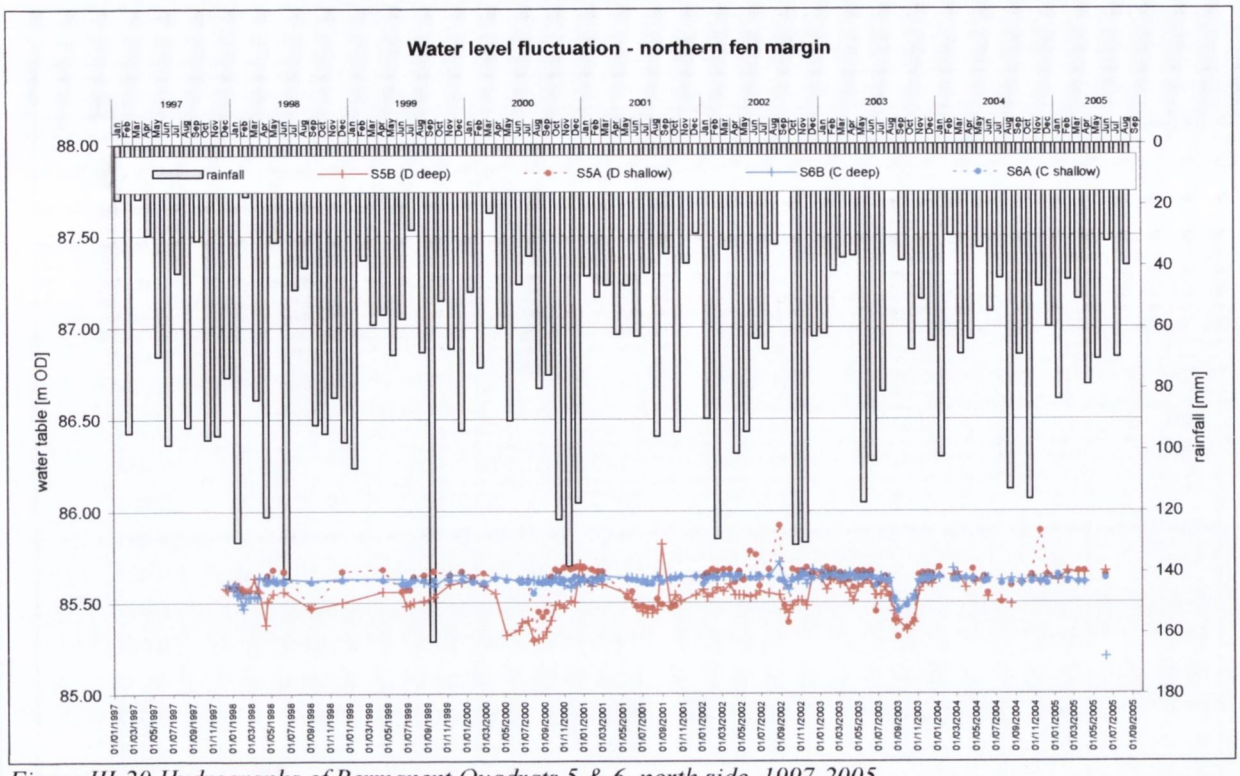



*Figure III-20 Hydrographs of Permanent Quadrats 5 & 6, north side, 1997-2005*

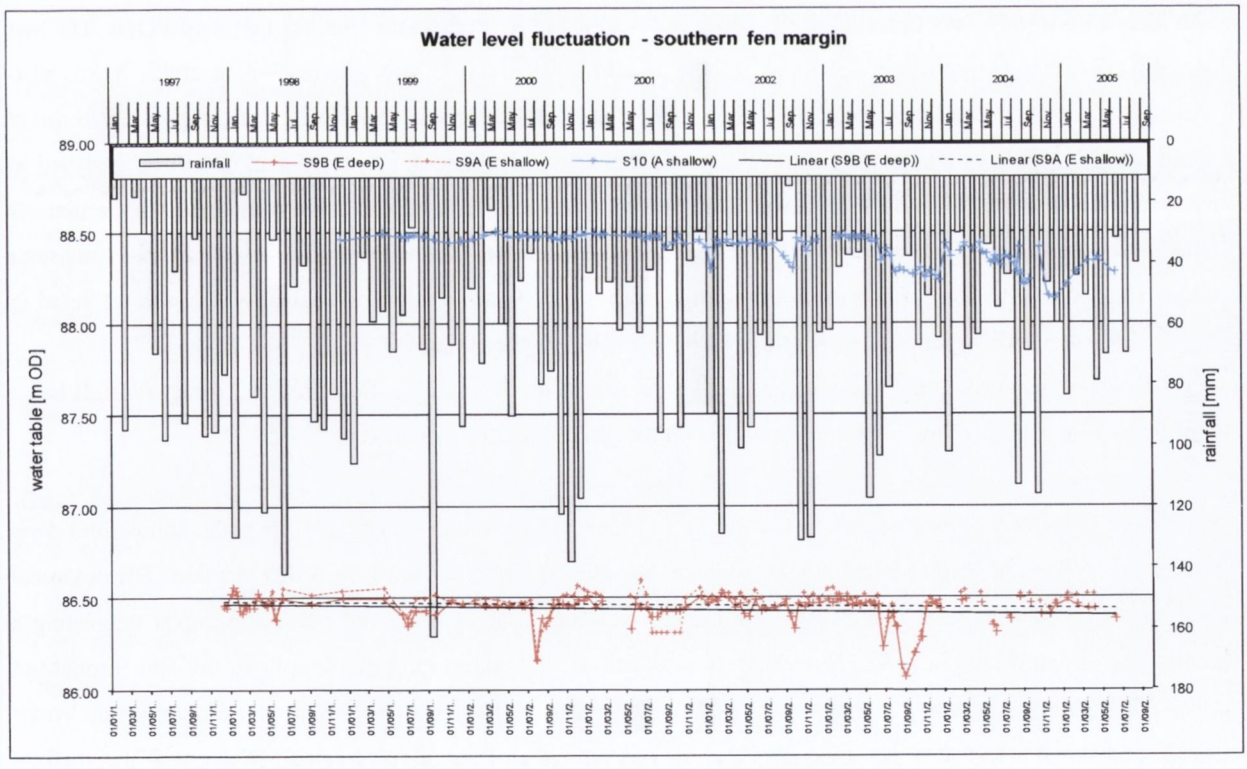



*Figure III-21 Hydrographs of Permanent Quadrats 9 & 10, south side, 1997-2005*

**Table III-18 Permanent Quadrats - Descriptive statistics of water level fluctuations during 2002-2005. 'B' refers to deep and 'A' refers to shallow piezometers.**

| | N | Range [m] | Minimum [m OD] | Maximum [m OD] | Mean [m OD] | Std. Deviation [-] | Variance [-] |
|---|---|---|---|---|---|---|---|
| S1B | 78 | 0.13 | 86.05 | 86.18 | 86.0751 | 0.01601 | 0.000 |
| S1A | 79 | 0.05 | 86.05 | 86.10 | 86.0738 | 0.00896 | 0.000 |
| S2B | 79 | 0.57 | 85.14 | 85.71 | 85.3037 | 0.09132 | 0.008 |
| S2A | 79 | 0.28 | 85.27 | 85.55 | 85.3771 | 0.04611 | 0.002 |
| S3B | 77 | 0.29 | 86.58 | 86.87 | 86.7816 | 0.06633 | 0.004 |
| S3A | 76 | 0.28 | 86.62 | 86.90 | 86.8180 | 0.06466 | 0.004 |
| S4B | 73 | 0.75 | 86.04 | 86.79 | 86.5955 | 0.10909 | 0.012 |
| S4A | 73 | 0.28 | 86.18 | 86.46 | 86.4166 | 0.03579 | 0.001 |
| S5B | 79 | 0.53 | 85.29 | 85.82 | 85.5225 | 0.09683 | 0.009 |
| S5A | 79 | 0.62 | 85.30 | 85.92 | 85.6052 | 0.11105 | 0.012 |
| S6B | 77 | 0.26 | 85.46 | 85.72 | 85.6266 | 0.03633 | 0.001 |
| S6A | 77 | 0.21 | 85.45 | 85.66 | 85.6170 | 0.03438 | 0.001 |
| S7B | 78 | 0.19 | 85.66 | 85.85 | 85.7791 | 0.03971 | 0.002 |
| S7A | 75 | 0.14 | 85.75 | 85.89 | 85.8160 | 0.04402 | 0.002 |
| S8B | 76 | 0.20 | 84.74 | 84.94 | 84.8546 | 0.03707 | 0.001 |
| S8A | 76 | 0.23 | 84.74 | 84.97 | 84.9203 | 0.03816 | 0.001 |
| S9B | 78 | 0.46 | 86.07 | 86.53 | 86.4297 | 0.08497 | 0.007 |
| S9A | 78 | 0.52 | 86.08 | 86.60 | 86.4537 | 0.10492 | 0.011 |
| S10 | 76 | 0.27 | 88.24 | 88.51 | 88.4341 | 0.07223 | 0.005 |

The long term trends were detected in the cases of two sites only, Permanent Quadrat PQ9 and PQ10. The last one shows a strong decreasing trend that started in mid 2001 and was still progressing in 2005. It was also apparent that with a decreased water table, the range of fluctuation increased and was more responsive to direct precipitation input. As Permanent Quadrat PQ10 is part of Intensive Quadrat A, this location will be analysed in more detail in Chapter IV. The second site that showed a decrease in the water table over time was Permanent Quadrat 9. The site lies at an elevation of approximately 86.60 metres OD and shows a very slight, but consistent trend. The summer of 2003 was a very dry summer with only 7.8 mm rainfall in August, which was reflected in a very low water level at this site with a fall of 0.5 metres below the surface.
The drought of summer 2003 was noticed in all PQs except for PQ 1. This illustrates that direct rainfall has a significant role in controlling phreatic conditions on the fen during dry conditions.

Permanent Quadrat 1 is located east to the Public Entrance. The average water table for both shallow and deep standpipes was established at 86.07 m OD, which is also the topographic elevation at this location. The botanical associations present indicate a seepage environment, which is in agreement with flat hydrographs suggesting a continuous groundwater inflow. There was no evidence of a shortage in water supply to the site throughout 1997-2005, even during the dry summer of 2003, which suggests that the site lies below minimum groundwater levels, and is not affected by its seasonal patterns. The presence of precipitated calcite ($CaCO_3$) at the surface, between vegetation tussocks, also supports the thesis that this site is a seepage zone.

Permanent Quadrats PQ2, PQ7 and PQ8 lie on the fen flat, in the central parts of the fen where topography is uniform and peat depth reaches circa 2-3 metres. The fluctuations found in these standpipes follow similar patterns, especially in PQ7 and PQ8 with amplitudes for both deep and shallow levels at circa 0.2 m. The phreatic level in Permanent Quadrat PQ2 did not change throughout the observation period and the mean value

was calculated at 85.37 m OD. The close proximity of drains also controls the phreatic level at this site. With regard to the deeper standpipe, the fluctuation pattern was very similar to the shallow piezometer; however, up until 2002 the deep level was approximately 0.1 m lower than the shallow level and since September 2002 both levels show very close values. Such sudden change suggests a possible malfunction of the installation, e.g. leakage between two levels triggered in 2002. Hydrographs from PQ7 demonstrated an overall increasing trend over 1997-2005, showing upwelling conditions between 1997 and 2000 and, later, the downwards gradient was dominant. Also, comparisons with a hydrograph from monitoring borehole MB6 revealed similarities in distribution of hydraulic heads, which suggests a strong connection between water levels in the peat and the groundwater body in this location. A moving average trendline was used to smooth the data for PQ7 and that showed clearly that between 1997 and the end of 2000, and from October 2002 until 2005, the water level changes in PQ7 followed the same seasonal pattern as groundwater levels in the aquifer (Figure III-22), as observed in the monitoring borehole MB6. In 2001, a decrease in the deep water level of approximately 5-10cm occurred, and that was followed by a slight increase in water levels in 2002. That shift was recorded in both shallow and deep levels simultaneously and since then (2002) both water levels remained relatively stable. No changes in ground or surface conditions, drainage system or rainfall pattern were observed at that time. This suggests that a likely reason for these changes lies possibly in groundwater recharge, i.e. temporal reduction of the groundwater recharge component. Permanent Quadrat PQ8 is controlled by a drainage system which surrounds the site on all sides. The pattern of changes was uniform at both shallow and deep levels; however, a higher amplitude was recorded in a deeper screen, which is a characteristic of sites with land drainage influence. No long-term trend was observed at this site.

Permanent Quadrats PQ3 and PQ4 are located at the south east end of the fen and are close to Seven Springs – the major groundwater discharge point into Pollardstown Fen. In 1998, a dug out spring was created next to PQ4, which resulted in a considerable lowering of the water table at both depths. The levels quickly returned to pre-digging elevations. The deep level was significantly higher than the shallow one (circa 0.2 metres in 1999) suggesting a strong groundwater gradient in an upward direction. The phreatic has remained stable throughout the observation period with only one temporal decrease (April 2000). The fact that it was seen in both levels, with a higher significance in the deeper one suggests a local abstraction, or work on nearby drainage system; such as, for example, cleaning of the dug out spring. With regard to the deep level, the high hydraulic head and the fluctuations that correspond with those found in MB6 (Figure III-23), especially an extended recession of 2001, indicate hydraulic connection with the water in the underlying gravel layer. Similarly to the situation of PQ2 and PQ7, the deep water level at PQ4 slightly increased in 2002 and became more stable than before.

In Permanent Quadrat PQ3 both levels remained very close to each other with a phreatic level being always a little bit higher – 0.04 metres. Small annual fluctuations did not exceed 0.3 metres for both levels, and high sensitivity to evapotranspiration losses in the summer months was apparent. The deep standpipe did not follow the trend of PQ2, PQ4 & PQ7.

Permanent Quadrats PQ5 & PQ6, located on the northern side of the fen, did not show any long term trends. Water level fluctuations recorded at PQ6 (north-east of the fen) during 1997-2005 were as little as 0.26 metres, but there was only one episode, the drought in summer 2003 when the water table dropped by 0.2 metres. Most of the time, the fluctuations were within 10 cm range and the dominant direction of flow was upward. Higher

fluctuations within Permanent Quadrat PQ5 (west from PQ6) indicate different controlling factors, which is most likely due to the close proximity to a drain on its north western boundary.

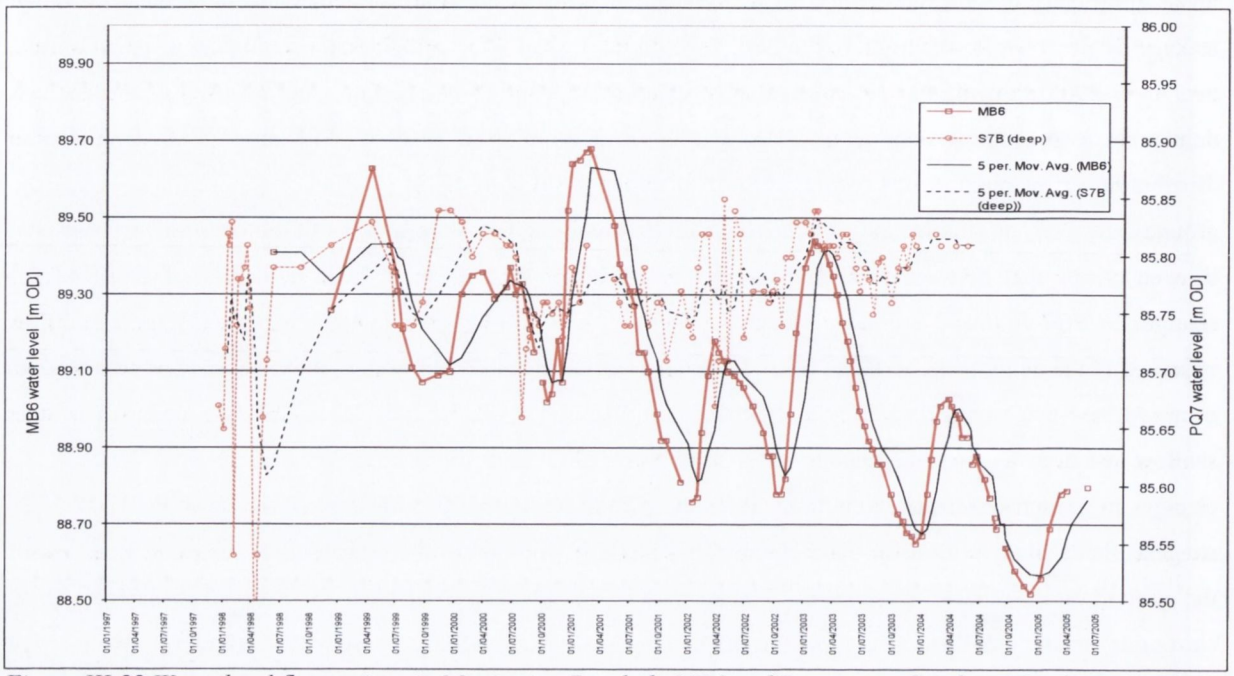



*Figure III-22 Water level fluctuations in Monitoring Borehole MB6 and Permanent Quadrat PQ7 (Deep pipe)*

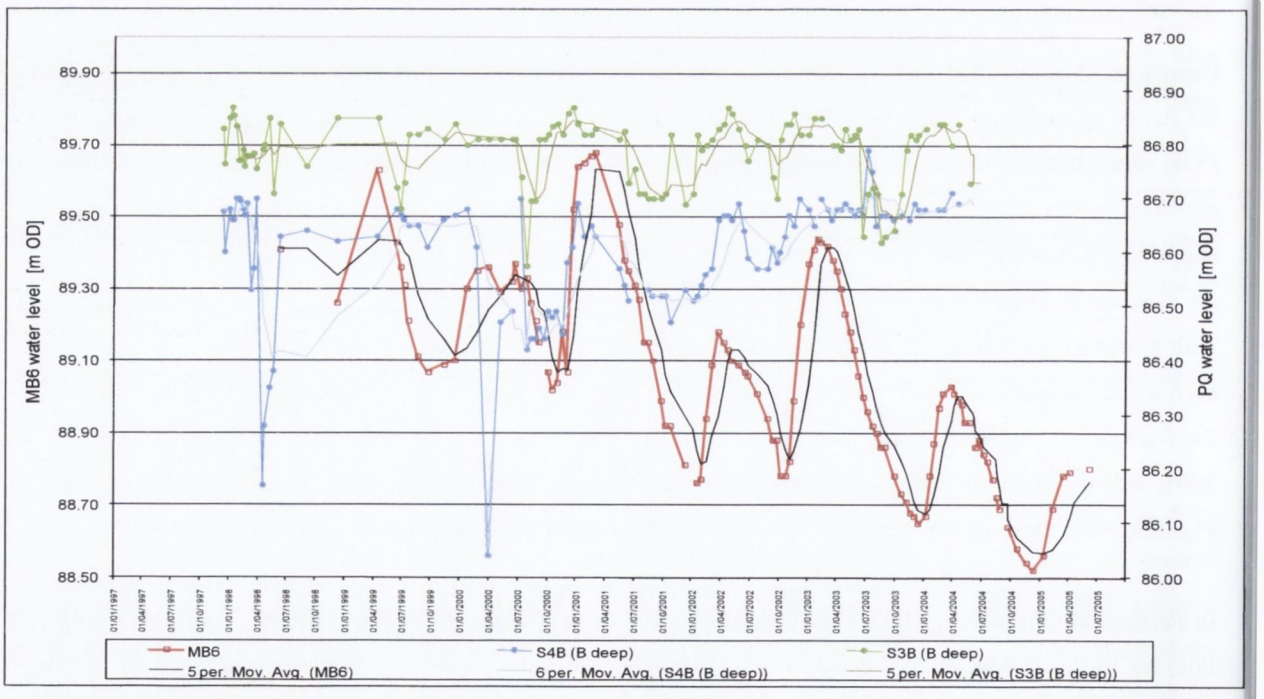



*Figure III-23 Water level fluctuations in Monitoring Borehole MB6 and deep standpipes in Permanent Quadrats PQ3 (S3B) and PQ4 (S4B).*

Histograms for all standpipes included in Permanent Quadrat monitoring are attached in Appendix 14. In most cases, the data did not fit normal distribution, and were most often skewed toward the upper limit, which implies that higher water levels were dominant within their fluctuation range.

Empirical probability and frequency duration curves were constructed for all standpipes, and the graphs are presented also in Appendix 14. All analysed standpipes showed very flat and smooth gradients, which indicate rather small changes in water levels. However, standpipes S9, S6, S5 and S10 showed some higher decreases at about 80%, the probability being that this was due to higher sensitivity of those sites resulting from their specific, higher locations (margin of the fen). For S9 shallow and S10 standpipes, the simple trend analysis using the moving average with a 10 period value revealed a tendency to decreasing water levels over the last few years, which is especially visible at the highest location of standpipe S10. At this location, the phreatic water table started decreasing in 2001 and was still ongoing in 2005 (Figure III-21).

The difference between the hydraulic head in deep and phreatic standpipes located in the same nest (Table III-19) indicated that for Permanent Quadrat PQ2, PQ3, PQ5, PQ7, PQ8 and PQ9 there can not be a direct inflow from the deeper level or drains. The strongest upward seepage was possible in PQ4 (average for 2000-2003) and it was 2.07E-07 m/sec with assumed *k* value for peat of k = 1.19E-06 m/sec (value established *in situ*). The other Quadrats that showed upward gradients were: PQ1 and PQ6.

**Table III-19 Difference between hydraulic heads in deep and shallow standpipes in Permanent Quadrats 1-9. PQs 2, 3, 5, 7, 8 and 9 show the dominance of downward movement and PQs 1, 4 & 6, upward movement.**

| | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|
| Average [m] | 0.001 | -0.08 | -0.04 | 0.18 | -0.44 | 0.36 | -0.03 | -0.07 | -0.03 |
| Max [m] | 0.12 | 0.34 | 0.07 | 0.38 | 0.01 | 0.46 | 0.57 | 0.03 | 0.12 |
| Min [m] | -0.02 | -0.28 | -0.18 | -0.14 | -0.74 | -0.09 | -0.38 | -0.32 | -0.67 |
| Range [m] | 0.14 | 0.62 | 0.25 | 0.52 | 0.75 | 0.55 | 0.95 | 0.35 | 0.79 |
| SD | 0.02 | 0.09 | 0.03 | 0.10 | 0.11 | 0.05 | 0.09 | 0.05 | 0.08 |
| *Vertical seepage* [m/s]* | ***3.02E-9*** | *-1.18E-7* | *-9.59E-8* | ***2.07E-07*** | *-8.49E-8* | ***6.8E-9*** | *-4.72E-8* | *-7.12E-8* | *-3.17E-8* |
| *Vertical seepage* [m/day]* | ***0.0003*** | *-0.01* | *-0.008* | ***0.02*** | *-0.007* | ***0.0006*** | *-0.004* | *-0.006* | *-0.003* |

**specific discharge*

For all upwelling locations, including PQ1, PQ4 and PQ 6, probabilities of exceedence were calculated for established seepage velocities and frequency duration curves of seepage/infiltration occurrence were constructed. These are presented in Figures III-32 - III-34. While it is apparent that in locations PQ4 and PQ6 the upward gradient is dominant, in PQ1 upward flow was possible in as little as 22% of the time during the observation period 1997-2005. The greatest and strongest seepage occurred in PQ4, where the upward gradient was dominant in 96% cases. In PQ6, the upward gradient was recorded with 67% probability of exceedence.

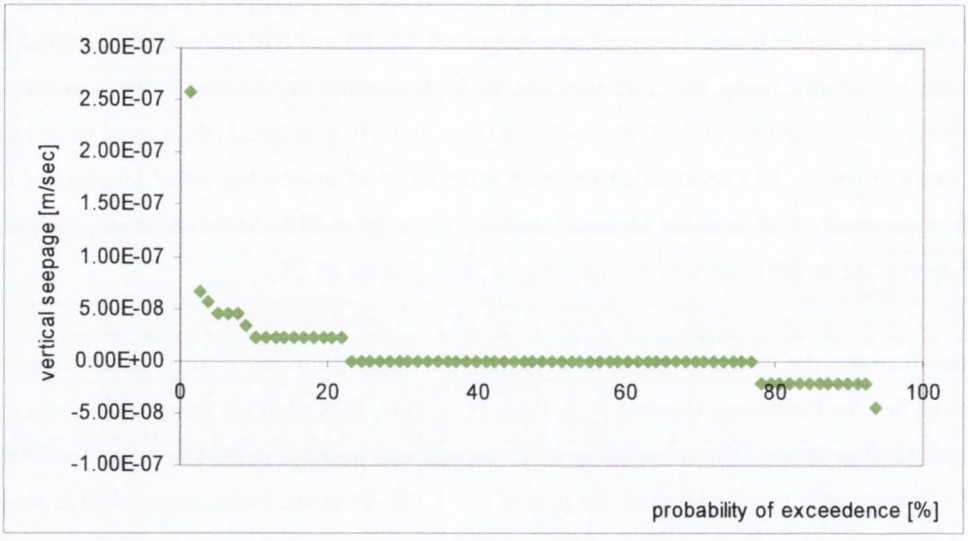



*Figure III-24 Vertical seepage frequency duration curve for Permanent Quadrat 1*

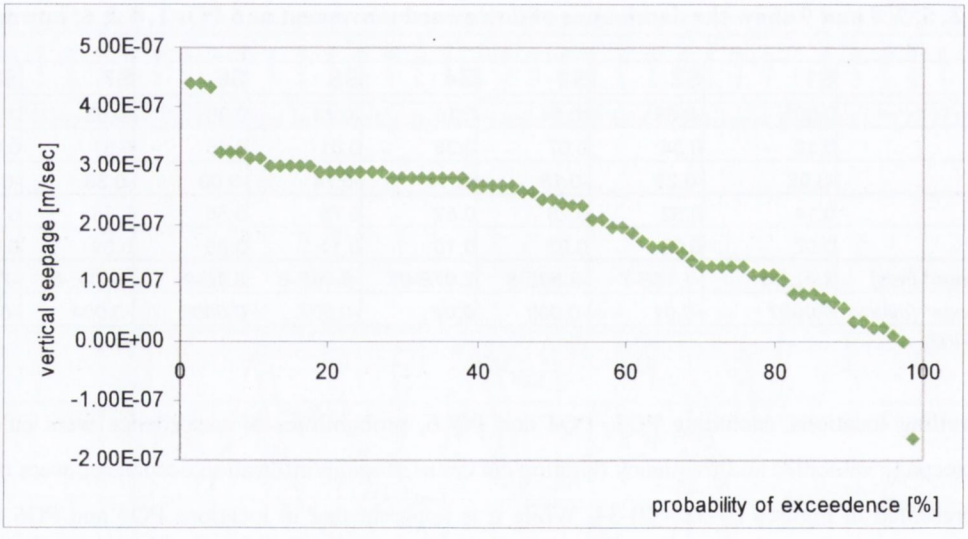



*Figure III-25 Vertical seepage frequency duration curve for Permanent Quadrat 4*

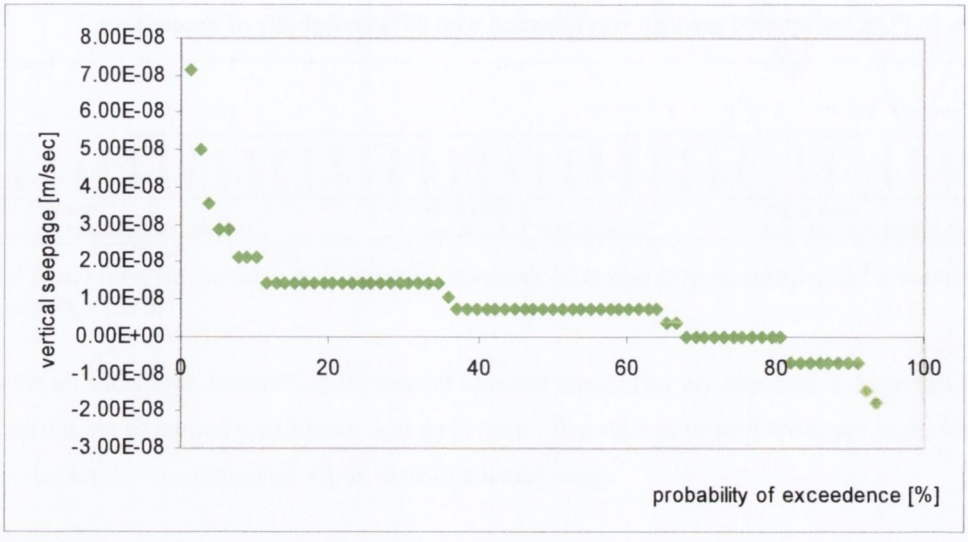



*Figure III-26Vertical seepage frequency duration curve for Permanent Quadrat 6*

#### III-2.2.1.1 Conclusions

- In conclusion, the analysis performed on data collected in the Permanent Quadrats revealed that the hydrology of the fen is very complex and several locations analysed indicated different hydrogeological characteristics. Topography is definitely one of the controlling factors of the local regime, as for example in Permanent Quadrat PQ10.

- The Permanent Quadrats can be divided into three groups, because of the vertical movement of water. This is upwards in PQ1, PQ4, PQ6 and PQ10, downwards in PQ3, PQ5, PQ8 and PQ9, and with changing gradients, as in the cases of PQ2 and PQ7; however, these classes do not follow a clear spatial pattern. Upward seepages are apparent at the fen margin, however Permanent Quadrats PQ2 & PQ7, located at the fen flat, provide evidence for upward seepage in more inner locations, which indicates that this recharge mechanism may also occur in central parts of the fen. In addition, similar patterns on hydrographs from deep borehole MB6 and deep piezometer in PQ7 suggests a strong hydraulic connection between groundwater and the phreatic level in some more central areas of the fen. The underlying geology must therefore be another factor controlling flow mechanism.

- In the absence of upward seepage as in Permanent Quadrats PQ3, PQ5, PQ8 and PQ9, lateral flow is likely to be a dominant recharge mechanism in these locations. Taking into account the small percentage of the fen examined during this study, it is possible that the lateral flow through the fen is very important in sustaining a stable and high phreatic surface.

- The drought of summer 2003 was reflected in phreatic levels in nearly all locations, except for Permanent Quadrat PQ1. This illustrates that direct rainfall has a significant role in controlling phreatic conditions.

- Two sites showed an evident decrease in water levels during the long term observation (1997-2005); these were PQ10 and PQ9, suggesting an ongoing decrease in the groundwater recharge.

- Comparison of water level data at different PQ locations suggests that the dominant flow direction is from south east to north west.

### *III-2.2.2. Hydrological Regime of the Fen Margin*

All four Intensive Quadrats, Sites A-D, were chosen on the fen margin, where the peat layer is thin and underlying gravels lie relatively close to the surface. The geology of the fen margin is very complex and inconsistent in a spatial sense, which creates an opportunity for water to seep through the surface in discrete locations. All four of the selected sites are known to be seepage areas, and remain well saturated or waterlogged throughout the year.

Each of the sites was analysed separately according to the methodology presented earlier. Comparison between all of the sites will be presented at the end.

Because of its highest topography and closeness to the catchment divide, site A was treated as the most sensitive site; hence this site was studied in the most detail and a conceptual model of groundwater recharge of the fen margin was built on an example of this site.

#### III-2.2.2.1 Permeability Tests

In order to estimate groundwater flow rates within the soil, accurate hydraulic conductivity must be known and that was found by conducting bail tests. Two tests were performed, one for deep gravel and one for the peat layer using the Hvorslev (1951) formula. Numerical results of these tests are presented in Appendix 13 and the summary is as follows:

- The gravel recovery was very fast, the water level raised to its pre-test elevation within 8 minutes; however, 90% of the water was recovered during the first 3 minutes. This implies high permeability within this strata and the ability to transfer into the strata overlying the gravel. Tests revealed that *k* value for gravel was **$1.21 \times 10^{-5}$ m/s**, which is equal to c. 1 m/d and for peat **$1.19 \times 10^{-6}$ m/s**, (0.1m/d). Previous pumping tests performed by K.T. Cullen Ltd. (Hayes *et al.*, 2001) in the Curragh aquifer (testing locations at the top of the Curragh, some 4-6 km away from the fen) revealed a horizontal hydraulic conductivity value of 30 m/d; however, big discrepancies were apparent between the tested locations. The KAM model that was built to model groundwater levels around the road cutting used a *k* value of 100 m/d. Daly (1981), in his report distinguished a big difference between the deep gravel that surround the fen and clayey gravels present around the fen margin. Permeabilities stated in this report were as high as 200 m/d for the deep gravel and in the range 1 - $10^{-1}$ m/d for the clayey gravels. The permeability of lacustrine clay between shallow and deep gravel was reported at $10^{-3}$ m/d. The value of $1.21 \times 10^{-5}$ m/s was well correlated to Daly's findings, therefore this was used for calculations of the groundwater flow within the fen margin area.

- Recovery of the peat layer took 45 minutes and was very linear. Perhaps the value of $1.19 \times 10^{-6}$ m/s seems to be quite high, but it must be remembered that the depth of peat at this site is shallow and the predominant vegetation is *Schoenus nigricans* and *Juncus subnodulosus,* hence high fibre content in peat.

### III-2.2.2.2 Water Regime at site A

*1. Location and Topography*

Site A is located at the south side of the Fen in the direct neighbourhood of the Curragh Plateau. The site undulates due to peat cutting carried out in the past and a complex drainage system that is present both within and outside the site. Many flowing and seeping springs are present in the forest, approximately 300m to the east of site A, and in the vicinity of Duck Ponds, 200m west of the site.

The site lies on gently sloping ground, with a topographic gradient of i = 0.03 towards the main drain (circa 200 metres towards north east), Figure III-35. At the beginning of the site, the elevation is at 89.10 m OD, at the end of the trackway at 88.00 m OD, and at the end of the site A 87.00 m OD, Figure III-36.

*2. Geology*

Geological cross sections of the site were drawn on the basis of the drilling logs, and these are presented in Appendix 15 (WYG Ltd., 2002). In addition, three parallel prickstock surveys – temperature and conductivity probing - were accomplished along the site, starting at the margin toward the fen centre. This data provided information on peat depths across the site and showed high spatial variability in peat depth (changes of 1 m) across small distances (1-2 m). The peat stratum was rather solid in structure at site A, the only exception being a drain located at the middle of the site, between standpipe nests SP31 and SP34, where very loose material was recorded.

In general, the vertical profile showed very complex geology with gravel domination. The profile showed a relatively steep slope from the up gradient field, which suddenly flattens at the fen's margin. The field is characterised by a relatively shallow layer of topsoil consisting of boulder clay, underlain by an almost 9 m thick layer of gravel. Geological cross sections and well logs are presented in Appendix 15.

At the fen margin topsoil changes into a thin deposit of peat, that is underlain by grey gravelly clay underlain by sand and gravel. The layer of clay is not uniform across site A, and for example has not formed at location SP38 and SP30. For well log locations, please view Figure III-36.

Clay was found to be very thin in a few other places (e.g. SP31, SP32, SP33, SP35), which creates seepage potential for water flowing within the deep gravel, which is confined by clay and/or peat and its hydraulic head becomes artesian toward the fen centre. This theory was confirmed by conductivity probing, which showed high EC values in the peat and also increasing temperature profiles indicating upward seepage (Appendix 16). According to the well logs, a thin (0.2-0.4) grey, sandy clay lies below the peat along the trackway, but the peat depth is relatively shallow, increasing from 0.4 m to 1 m throughout the length of the trackway. Therefore, a drainage ditch located at the 25$^{th}$ metre might have cut through the clay layer and created a discharge area.



*Photo III-4 Photograph of a geological cross section captured at the field up gradient from site A reveals layers of gravel and sandy gravel mixed with layers of boulder clay*

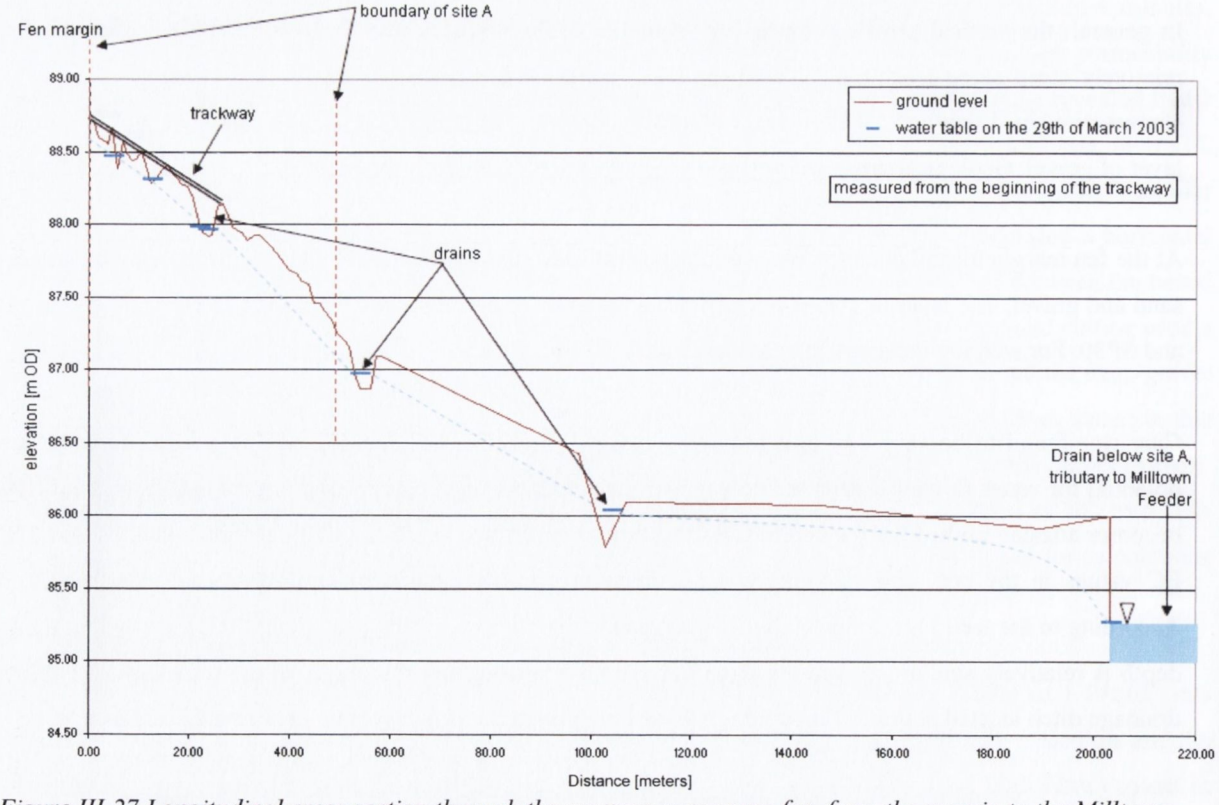



*Figure III-27 Longitudinal cross section through the southern side of the fen, from the margin to the Milltown Feeder*

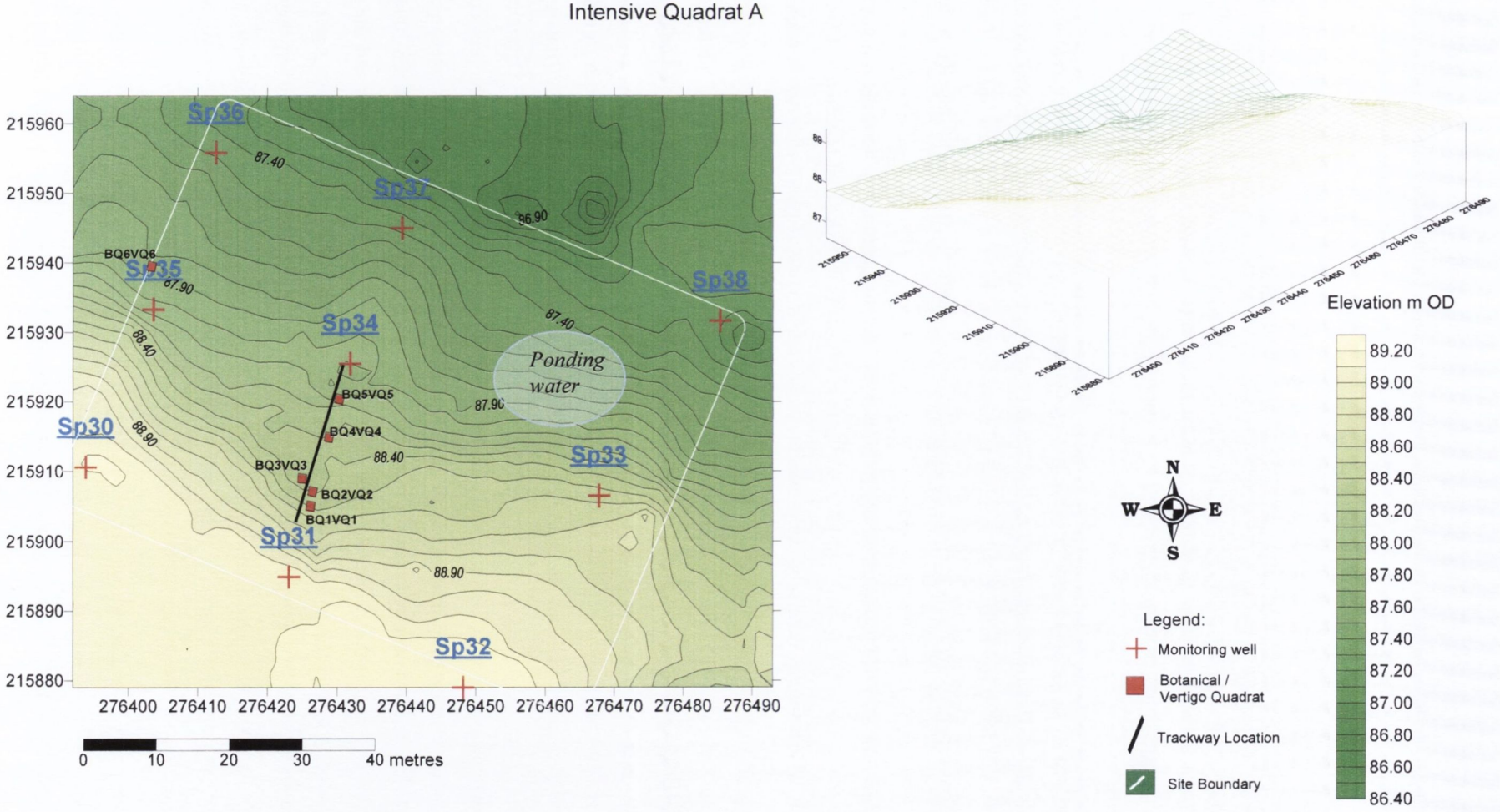



*Figure III-28 Topography and situation plan of Intensive Quadrat A*

## 3. Hydrogeology

The direction of deep groundwater flow at site A follows the regional northerly pattern. The middle water level (shallow gravel) shows a slightly more north eastern direction. The phreatic water level follows the local topography but is also controlled by a network of drains which cross the site. Considerable differences between the surface water level at site A and the water level in the drain below site A are apparent. Spot measurements of the water table were undertaken using GPS and these revealed nearly 3 metres' decrease in the water level along a 220 metre distance. Nevertheless, no correlation was found between the water level in the drain and any of the levels at site A. This is likely to be due to the canal being heavily regulated by locks and the extensive weed growth in the canal (and weed management) resulting in disturbances in natural water fluctuations. Hydrographs of all standpipes are presented in Figure III-29 - Figure III-31. Full groundwater level data are provided in Appendix 17.

The annual fluctuations observed at different depths in monitoring wells at site A, in the period October 2001-September 2005 are summarised in Table III-20. It was clear that all levels followed seasonal recharge patterns with lowest levels being recorded at the end of the summer season and highest in early spring. These seasonal fluctuations corresponded very well with the groundwater levels recorded in the Curragh aquifer, which indicates a strong hydraulic connection with the aquifer. The correlation coefficient between SP34 deep and MB6 (the upgradient borehole screened in the gravel aquifer) was 0.96. The same monitoring borehole was correlated with SP34A (shallow gravel, middle layer) at 0.84. No lag time between the upgradient borehole and fen standpipes was evident, which implies relatively rapid horizontal movement (conductivity) of water through the gravel layer.

In the hydrometric year 2002, groundwater started to rise very late (in early February) and the recharge period for that year was very short – it lasted only two months until the end of March, which could explain the significantly lower maximum that year. The following recession was slow with a hydraulic gradient being flat until July, when it started to steep downwards. Levels started to rise again in October 2002, which is an expected pattern in Irish climatic conditions. In 2003, the recharge period lasted 3 months (November-January) and was followed by an extended recession which started in February and continued until the end of December 2003. At the end of the recession period, water levels were 0.2 m below the minimum level from the previous year and this steep fall in water level was reflected in all three - deep, middle and shallow levels. The recharge period for the hydrometric year 2004 occurred between the end of December 2003 and the end of March 2004; however, despite a relatively long recharge period, water levels rose only for approximately 20cm and the subsequent recession started at a level 0.3 m lower than in a previous year. In hydrometric year 2005, water levels rose between December 2004 and February 2005, and remained flat until the end of April, when they started to recede. They were still recessing at the end of the hydrometric year. Overall, annual fluctuations for the deep gravel layer ranged between 0.17 – 0.88 metres throughout hydrometric years 2002-2005, with higher fluctuations recorded in standpipes located closer to the fen centre, which are artesian wells.

In the middle gravel layer, fluctuations varied between 0.12 and 0.63 metres, and in general, higher amplitudes were recorded in wells placed at the immediate fen margin. The only exception was SP37A, for which the amplitude in 2002 was 0.67 m; however, lack of information for the following years restricts further statements.

The shallow standpipes, which are screened in peat (a phreatic surface), showed relatively uniform spatial distribution of fluctuation ranges throughout the site, mostly within a 0.2-0.3 metre range with one exception of SP35B, which ranged up to 0.77 m in 2002.

It was noticed that all water levels decreased throughout the course of the study, with the biggest fall recorded in deep standpipes. Table III-21 presents differences between maximum and minimum levels in two subsequent years, 2001-2005. Negative values indicate a decrease in water levels with regard to levels recorded in a previous year. This comparison revealed that groundwater levels decreased significantly throughout the study period, and a difference between maximum/minimum levels in Sp31 deep and Sp34 deep during 2002 and 2005 was approximately 0.2 m. Falls in middle and phreatic water levels were less pronounced, c. 0.1-0.15 m, however decreasing trends were evident.

Comparison with hydraulic heads in upgradient Monitoring Boreholes MB6 and MB38, both screened in gravel, showed that water moves towards the fen from the Curragh with a hydraulic gradient of c. $i = 0.0003$ in July – October and $i = 0.0014$ in January – June. The average values of 0.0007 gives a nominal difference of 16 cm between the water table measured in MB38 and the fen's margin (230 metres).

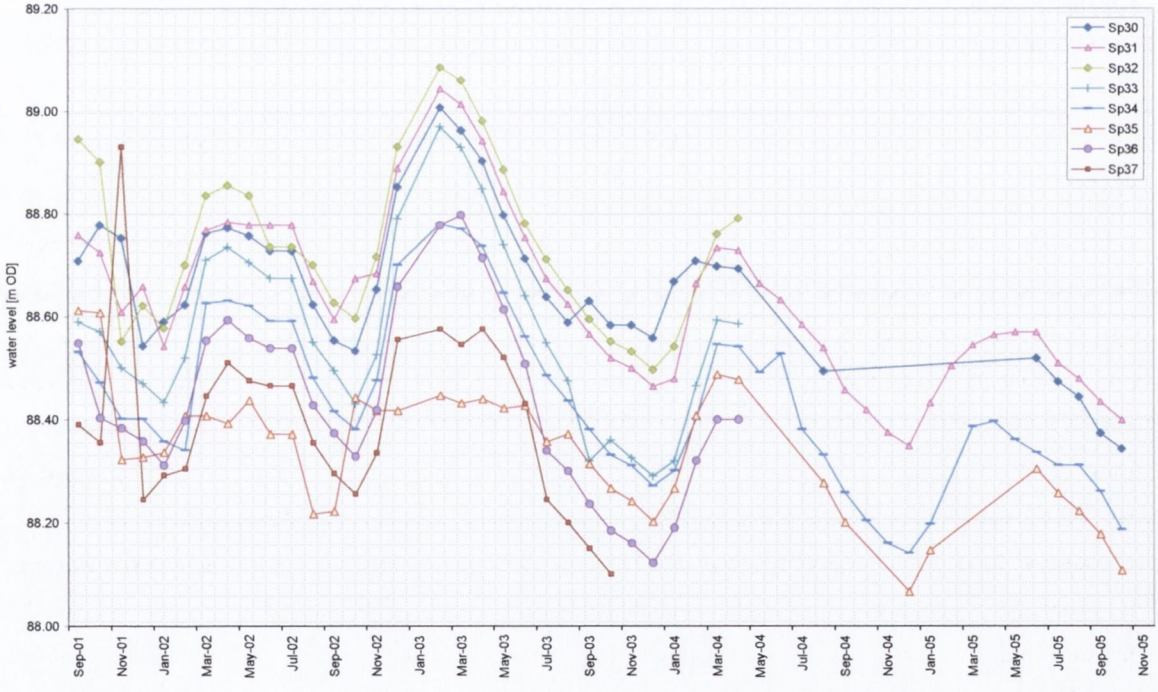



*Figure III-29 Monthly distribution of groundwater levels in deep standpipes at site A, southern fen margin, 2002-2005*

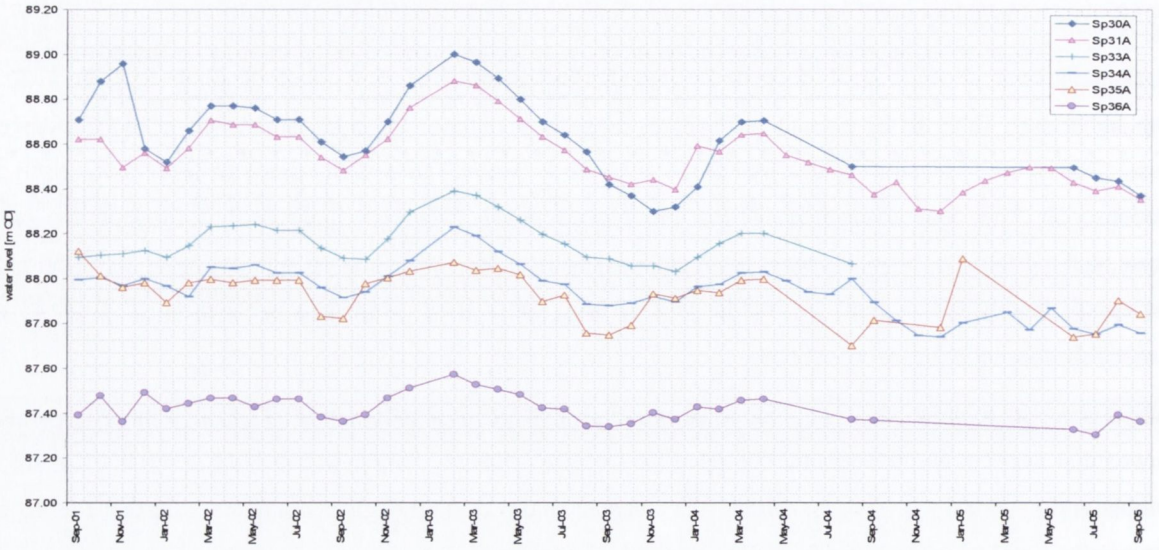



*Figure III-30 Monthly distribution of groundwater levels in middle standpipes at site A, southern fen margin, 2002-2005*

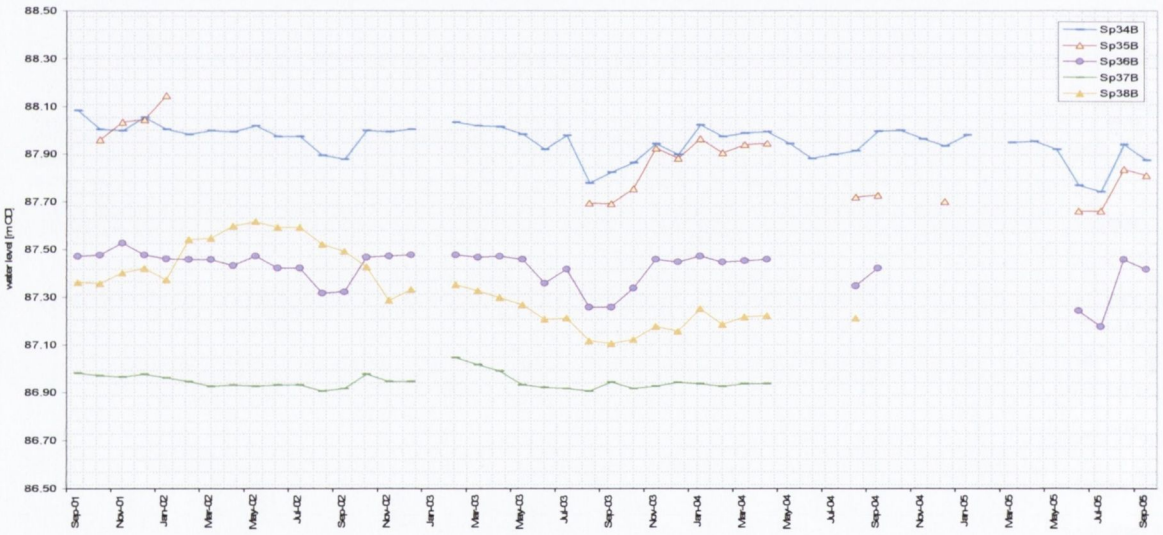



*Figure III-31 Monthly distribution of groundwater levels in shallow standpipes at site A, southern fen margin, 2002-2005*

**Table III-20 Summary of groundwater levels (m OD) at site A in hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| | | DEEP | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SP30 | SP31 | SP32 | SP33 | SP34 | SP35 | SP36 | SP37 |
| 2002 | max | 88.82 | 88.83 | 89.20 | 88.74 | 88.66 | 88.67 | 88.63 | 89.10 |
| | min | 88.49 | 88.50 | 88.51 | 88.42 | 88.34 | 88.17 | 88.18 | 88.22 |
| | average | 88.69 | 88.68 | 88.72 | 88.59 | 88.51 | 88.38 | 88.45 | 88.44 |
| | amplitude | 0.33 | 0.33 | 0.69 | 0.32 | 0.32 | 0.50 | 0.45 | 0.88 |
| | SD | 0.10 | 0.10 | 0.16 | 0.11 | 0.12 | 0.11 | 0.12 | 0.19 |
| 2003 | max | 89.01 | 89.05 | 89.09 | 88.97 | 88.78 | 88.47 | 88.82 | 88.59 |
| | min | 88.51 | 88.55 | 88.58 | 88.31 | 88.36 | 88.30 | 88.22 | 88.13 |
| | average | 88.75 | 88.79 | 88.81 | 88.64 | 88.58 | 88.40 | 88.52 | 88.40 |
| | amplitude | 0.50 | 0.50 | 0.51 | 0.66 | 0.42 | 0.17 | 0.60 | 0.45 |
| | SD | 0.16 | 0.17 | 0.18 | 0.22 | 0.16 | 0.05 | 0.21 | 0.17 |

*(continued)*

**DEEP**

| | | SP30 | SP31 | SP32 | SP33 | SP34 | SP35 | SP36 | SP37 |
|---|---|---|---|---|---|---|---|---|---|
| 2004 | max | 88.71 | 88.74 | 88.81 | 88.60 | 88.55 | 88.49 | 88.40 | 88.10 |
| | min | 88.49 | 88.45 | 88.49 | 88.29 | 88.26 | 88.20 | 88.12 | 87.35 |
| | average | 88.64 | 88.60 | 88.61 | 88.42 | 88.39 | 88.34 | 88.25 | 87.95 |
| | amplitude | 0.22 | 0.29 | 0.32 | 0.30 | 0.29 | 0.29 | 0.29 | 0.75 |
| | SD | 0.07 | 0.09 | 0.13 | 0.13 | 0.10 | 0.12 | 0.11 | 0.29 |
| 2005 | max | | 88.61 | | | 88.44 | | | |
| | min | | 88.35 | | | 88.14 | | | |
| | average | | 88.48 | | | 88.27 | | | |
| | amplitude | | 0.26 | | | 0.30 | | | |
| | SD | | 0.07 | | | 0.09 | | | |

**MIDDLE**

| | | SP30A | SP31A | SP33A | SP34A | SP35A | SP36A | SP37A | SP38A |
|---|---|---|---|---|---|---|---|---|---|
| 2002 | max | 89.05 | 88.72 | 88.25 | 88.06 | 88.03 | 87.50 | 87.10 | |
| | min | 88.48 | 88.44 | 88.06 | 87.89 | 87.77 | 87.27 | 86.47 | |
| | average | 88.70 | 88.59 | 88.16 | 88.00 | 87.95 | 87.43 | 86.93 | |
| | amplitude | 0.57 | 0.28 | 0.19 | 0.17 | 0.26 | 0.23 | 0.63 | |
| | SD | 0.14 | 0.09 | 0.06 | 0.05 | 0.07 | 0.06 | 0.31 | |
| 2003 | max | 89.00 | 88.89 | 88.40 | 88.23 | 88.07 | 87.60 | 87.11 | |
| | min | 88.40 | 88.44 | 88.06 | 87.87 | 87.71 | 87.32 | 87.10 | |
| | average | 88.72 | 88.66 | 88.22 | 88.03 | 87.95 | 87.45 | 87.11 | |
| | amplitude | 0.60 | 0.45 | 0.34 | 0.36 | 0.36 | 0.28 | 0.01 | |
| | SD | 0.19 | 0.15 | 0.11 | 0.12 | 0.12 | 0.08 | 0.00 | |
| 2004 | max | 88.71 | 88.67 | 88.21 | 88.05 | 88.03 | 87.47 | | 87.49 |
| | min | 88.24 | 88.38 | 88.02 | 87.81 | 87.70 | 87.35 | | 87.34 |
| | average | 88.50 | 88.52 | 88.11 | 87.96 | 87.92 | 87.42 | | 87.42 |
| | amplitude | 0.47 | 0.29 | 0.19 | 0.24 | 0.33 | 0.12 | | 0.15 |
| | SD | 0.17 | 0.09 | 0.07 | 0.06 | 0.08 | 0.04 | | 0.06 |
| 2005 | max | | 88.56 | | 87.89 | | | | |
| | min | | 88.29 | | 87.65 | | | | |
| | average | | 88.41 | | 87.79 | | | | |
| | amplitude | | 0.27 | | 0.24 | | | | |
| | SD | | 0.07 | | 0.06 | | | | |

**SHALLOW**

| | | SP34B | SP35B | SP36B | SP37B | SP38B |
|---|---|---|---|---|---|---|
| 2002 | max | 88.05 | 88.71 | 87.58 | 87.13 | 87.62 |
| | min | 87.85 | 87.94 | 87.27 | 86.91 | 87.34 |
| | average | 87.98 | 88.13 | 87.44 | 86.95 | 87.50 |
| | amplitude | 0.20 | 0.77 | 0.31 | 0.22 | 0.28 |
| | SD | 0.05 | 0.25 | 0.06 | 0.05 | 0.10 |
| 2003 | max | 88.04 | 87.74 | 87.49 | 87.10 | 87.51 |
| | min | 87.75 | 87.64 | 87.20 | 86.91 | 87.09 |
| | average | 87.95 | 87.69 | 87.41 | 86.96 | 87.26 |
| | amplitude | 0.29 | 0.10 | 0.29 | 0.19 | 0.42 |
| | SD | 0.09 | 0.05 | 0.10 | 0.06 | 0.11 |
| 2004 | max | 88.04 | 87.99 | 87.48 | 86.95 | 87.30 |
| | min | 87.85 | 87.75 | 87.34 | 86.91 | 87.12 |
| | average | 87.94 | 87.90 | 87.44 | 86.93 | 87.20 |
| | amplitude | 0.19 | 0.24 | 0.14 | 0.04 | 0.18 |
| | SD | 0.06 | 0.07 | 0.04 | 0.01 | 0.05 |
| 2005 | max | 88.06 | | | | |
| | min | 87.72 | | | | |
| | average | 87.93 | | | | |
| | amplitude | 0.34 | | | | |
| | SD | 0.08 | | | | |

**Table III-21 Differences between maximum and minimum groundwater levels in the consecutive hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| DEEP | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SP30 | SP31 | SP32 | SP33 | SP34 | SP35 | SP36 | SP37 |
| 2003-2002 | Max | 0.19 | 0.22 | -0.11 | 0.23 | 0.12 | -0.20 | 0.19 | -0.51 |
| | Min | 0.02 | 0.05 | 0.07 | -0.11 | 0.02 | 0.13 | 0.04 | -0.09 |
| 2004-2003 | Max | -0.30 | -0.31 | -0.28 | -0.38 | -0.23 | 0.02 | -0.42 | -0.48 |
| | Min | -0.02 | -0.10 | -0.09 | -0.02 | -0.10 | -0.10 | -0.11 | -0.78 |
| 2005-2004 | Max | | -0.09 | | | -0.11 | | | |
| | Min | | -0.05 | | | -0.08 | | | |
| 2005-2002 | Max | | -0.22 | | | -0.22 | | | |
| | Min | | -0.15 | | | -0.20 | | | |
| **MIDDLE** | | | | | | | | | |
| | | SP30A | SP31A | SP33A | SP34A | SP35A | SP36A | SP37A | |
| 2003-2002 | Max | -0.05 | 0.17 | 0.15 | 0.17 | 0.04 | 0.10 | 0.01 | |
| | Min | -0.08 | 0.00 | 0.00 | -0.02 | -0.06 | 0.05 | 0.63 | |
| 2004-2003 | Max | -0.29 | -0.22 | -0.19 | -0.18 | -0.04 | -0.13 | | |
| | Min | -0.16 | -0.06 | -0.04 | -0.06 | -0.01 | 0.03 | | |
| 2005-2004 | Max | | -0.11 | | -0.16 | | | | |
| | Min | | -0.09 | | -0.16 | | | | |
| 2005-2002 | Max | | -0.16 | | -0.17 | | | | |
| | Min | | -0.15 | | -0.24 | | | | |
| **SHALLOW** | | | | | | | | | |
| | | SP34B | SP35B | SP36B | SP37B | SP38B | | | |
| 2003-2002 | Max | -0.01 | -0.97 | -0.09 | -0.03 | -0.11 | | | |
| | Min | -0.10 | -0.30 | -0.07 | 0.00 | -0.25 | | | |
| 2004-2003 | Max | 0.00 | 0.25 | -0.01 | -0.15 | -0.21 | | | |
| | Min | 0.10 | 0.11 | 0.14 | 0.00 | 0.03 | | | |
| 2005-2004 | Max | 0.02 | | | | | | | |
| | Min | -0.13 | | | | | | | |
| 2005-2002 | Max | 0.01 | | | | | | | |
| | Min | -0.13 | | | | | | | |

## 4. Estimation of groundwater flow velocities

Groundwater flow rates expressed as specific discharge were calculated using Darcy's equation for groundwater flow in a confined medium and were computed between standpipes placed along the profiles perpendicular to the fen margin (SP32-SP33; SP31-SP34-SP37 and SP30-SP35-SP36). Results are presented in units of m/s. An assumption was made that the medium was homogenous and isotropic. Flows in peat layers were computed using the Dupuit (1863) equation. Numerical results are presented in Appendix 18.

A summary of flow rates is presented in Table III-22 -Table III-24. The flow velocities at the fen margin ranged from 0.005 to 0.013 m/day for deep gravel, which are equivalent to 1.8-4.7m/yr. The highest rates were determined between standpipes SP30 and SP35. A fall in hydraulic pressure in SP35 suggests a potential discharge zone in close proximity to the nest and this is reflected in situ by the presence of *Vertigo geyeri* species in a botanical quadrat BQ6, located approximately 5 m north of SP35.

**Table III-22 Summary of groundwater flow rates (lateral), expressed as specific discharge, in deep gravel layer within Site A**

*k* = 1.21E-05 [m/s]

| | dl | gradient | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | | m/s | m/day |
| 32-33 | 35.10 | 0.004 | 0.0000001 | 0.005 |
| 31-34 | 32.50 | 0.006 | 0.0000001 | 0.006 |
| 30-35 | 27.11 | 0.013 | 0.00000014 | 0.013 |
| 35-36 | 24.11 | -0.003 | 0.00000003 | -0.003 |
| 34-37 | 21.70 | 0.009 | 0.0000001 | 0.009 |

Velocities calculated in middle gravels showed higher values of c.0.02-0.03 m/day, and, in places, where clay deposits are not present (SP38), much higher velocities were computed of 0.13 m/day. Lack of a confining layer provides a pathway for groundwater discharge in this location and this is reflected *in situ* in a permanent pool of water and the presence of rushes *Schoenus nigricans,* known to be a seepage indicator.

**Table III-23 Summary of groundwater flow rates (lateral), expressed as specific discharge, in shallow gravel layers (middle standpipes) within Site A**

*k* = 1.21E-05 [m/s]

| | dl | gradient | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | | m/s | m/day |
| 31-34 | 32.5 | 0.018 | 0.0000002 | 0.019 |
| 30-35 | 27.11 | 0.027 | 0.0000003 | 0.027 |
| 35-36 | 24.11 | 0.021 | 0.0000003 | 0.022 |
| 33-38 | 31.91 | 0.120 | 0.0000015 | 0.126 |

Flow rates in the peat layer were established at a level of c. 0.002-0.007 $m^2$/day with increasing values towards the fen centre. This is likely to be influenced by the presence of a drain behind the last row of standpipes (SP36-SP37-SP38), but also suggests a potential groundwater discharge, and upward seepage into the peat occurring between the first and the second row of piezometers, which gives rise to increased flow velocities in peat.

**Table III-24 Summary of groundwater flow rates (lateral) in peat layer within Site A**

*k*= 1.19E-06 [m/s]

| | dl | gradient | Groundwater flow per unit width | |
|---|---|---|---|---|
| Standpipe | m | | $m^2$/s | $m^2$/day |
| S10-34 | 22.20 | 0.019 | 0.00000003 | 0.002 |
| 35-36 | 24.11 | 0.021 | 0.00000003 | 0.003 |
| 34-37 | 21.70 | 0.047 | 0.00000008 | 0.007 |

Computation of vertical flow rates, expressed as specific discharge, was possible in four locations only. The highest specific discharge rate was determined at the most marginal location, between SP31 and S10 and the average value for 2002-2005 was established at 0.002 m/d, which is equivalent to 0.7 m/yr. Toward the fen centre Darcy's velocities are reduced owing to increased depths of confining deposits and hence decreased vertical permeabilities (0.04-0.05 m/yr). Table III-25 provides a summary of vertical specific discharge rates determined for site A. Upward directions of flow were determined in SP31-S10 and in the nest SP35, while downward flows were found in nests SP34 and SP36. These findings conform to previous suggestions based on geological assessment and determination of lateral flow velocities, which suggested a discharge zone in the vicinity of SP35. Determined flow velocities varied across the site due to changing geomorphology of the fen subsurface. Nevertheless, highest specific discharge rates at marginal locations suggest a preference for

groundwater discharge in areas with thin or minimal clay deposits (which restrict groundwater movement). Based on the above flow velocity estimates and geological information, groundwater seepage within Site A is likely to occur between piezometers SP30-SP35, SP31-SP34, around SP33 and SP38. This conceptual model is presented in a sketch map (Figure III-32) and will be verified using the prickstocking survey.

**Table III-25 Summary of vertical groundwater flow rates, expressed as specific discharge, between upper gravels and peat in selected standpipes within Site A, positive values denote upward flow.**

| | dl | *K* | specific discharge | |
|---|---|---|---|---|
| **Standpipe** | m | [m/s] | m/s | m/day |
| **31-S10** | 6.10 | 4.71E-07 | 0.00000002 | 0.002 |
| **34A-34B** | 2.00 | 5.44E-07 | -0.000000001 | -0.0001 |
| **35A-35B** | 2.00 | 3.00E-07 | 0.000000001 | 0.0001 |
| **36A-36B** | 3.00 | 2.82E-07 | -0.000000002 | -0.0001 |

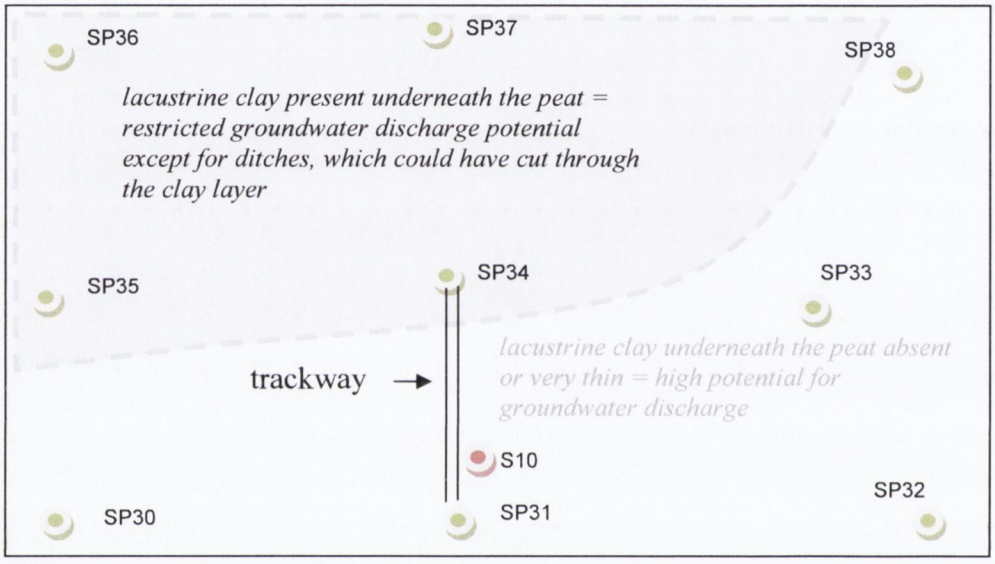



*Figure III-32 Conceptual model of potential groundwater discharge area within site A based on piezometry and geology*

5. Vertical flow modelling using temperature profiles

The prickstocking survey was undertaken to verify the hypothesis of an upward flow and to compare it with numerical flow rates determined using the standard Darcy's equation. It also aimed to distinguish seepage locations within site A. The results revealed the following:

- In general, the electric conductivity at the site varied between 200 and 700 μS/cm with the average around 500 μS/cm. Values from close to the surface locations were usually slightly lower than those in deeper layers, indicating the influence of rainwater.
- Two repetitive surveys carried out along the trackway, one in June 2002 and one in October 2003, revealed the same EC patterns within peat (Appendix 16) and indicated an upward flow in two locations along the trackway. The first was between 3-4 metres from the beginning of a trackway, which was close to IQABQ1[10], where snails *Vertigo geyeri* were present in 2002-2003. The second location was at 18-19 metres from the beginning of the trackway. Few verticals presented increased EC values at some

[10] Intensive Quadrat A Botanic Quadrat 1

depths which were significantly higher than the values at adjacent depths, which possibly indicate the presence of some more mineral soil material, e.g. marl.

- The temperature results showed that summer heating caused an increase in temperature up to 12.8°C, even at a depth of 30 cm below the surface. Nevertheless, there were few places where the temperature at that depth reached only 10-10.5°C (June 2002), which indicated an influence of groundwater flow. Some calcite deposition formation in the vicinity of those places was also found, which supported the idea of upward groundwater seepage at these locations.

The two repetitive surveys along the middle transect (along the trackway) of site A were subject to detailed analysis using the TC-Taureg.xls spreadsheet provided by Dr G. van Wirdum. The use of that tool was sometimes limited due to shallow peat verticals; however, some good results from both downward flow and upward seepage zones were identified and confirmed by two measuring processes.

The conductivity and temperature probing carried out along the trackway revealed that there was seepage at the fourth metre from the beginning, next to IQABQ1. Good parameters were found for flow velocities between -1.5 m/yr (upwards) to 1.5 m/yr (downwards); however, quite high and stable conductivity values recorded across the vertical suggested a somewhat upward flow. Vertical seepage velocity was calculated from manual measurements of water levels in the deep standpipe SP31 and the phreatic standpipe S10, both at the fen margin and in the immediate vicinity of the seepage area that was established with the prickstocking survey. At the time of the prickstock sampling, an upward flow velocity (specific discharge) between SP31 and S10 was determined at c. 0.002-0.001 m/d for respective surveys in June 2002 and October 2003, which was equal to the flow of 0.53-0.84 m/yr, which is within the range found by the prickstock (Appendix 18).

It was impossible to establish good results of flow pattern for next couple of verticals (A5-A16), for which either shallow peat or perhaps strong lateral flow were to blame; however, it was more likely that downward flow was a dominating mechanism. Interesting results started to come at 16$^{th}$ metre from the beginning of the trackway, where peat depth reached one metre. On a few occasions, it was necessary to split the model into layers, as there was no solution for the complete vertical. This happens when there is a change in substrate material, e.g. when deposits of more humified peat or marl lie under the thin top stratum, of brown peat, rich in organic matter. The difference in the hydraulic properties of the strata might create some preferential pathways that allow for increased velocities of flow. This was found at the A-17 (middle cross-section – between the trackways, 17 metres from the beginning of a trackway), for the layer of 0.5-0.9 with a strong upward seepage at v = -3.0 m/yr. The upper layer was difficult to interpret. Similarly, in the same vicinity at A-18, on the 8$^{th}$ of October 2003, the lower part shows strong upward seepage at –10.5 m/yr; however, results for the upper part gave a little downward flow at v = 0.8 m/yr.

There is evidence of a drainage channel on site A, between 20 and 25 metres from the beginning of the trackway with very loose material and high, stable EC values. The modelling confirmed strong upward flow in the drainage ditch with velocities ranging from v = - 4.5 to –8 m/yr at A-22 and A-23. These values suggest, therefore, that in areas with no clay deposits (or where they have been possibly removed), flow velocity rates are relatively high, and may reach up to a few metres per annum - and this is in line with results determined for SP31-S10 using water level data. Strong upward seepage was also found at other locations along that drain as

well as at the end of the trackway. Results of the vertical modelling are summarised in Table III-26 and seepage locations within the site distinguished by the probing are presented in Figure III-33-Figure III-34.

**Table III-26 Results of vertical flow modelling along the three parallel profiles along site A. Green colour highlights these rows for which downward velocity was determined, blue – upward velocity and orange – no good solution was found. Negative values denote upward flow.**

| date | profile | location | layer | | V [m/annum] | Mean Temp [C] | Amplitude | Lag | Error | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | beginning | end | | | | | | |
| 06/06/2002 | A-1 to A-15 | middle | | | | | | | | no solution, various reasons |
| 06/06/2002 | A-16 | middle | 0.3 | 0.9 | 3.5 | 10.1 | 5.5 | 26.6 | 5.3 | good fit for downward flow |
| 06/06/2002 | A-17 | middle | 0.5 | 0.9 | -3.0 | 10.0 | 9.0 | 26.2 | 4.8 | very good fit for lower layer, however no good solution for upper |
| 06/06/2002 | A-18 | middle | 0.6 | 1.1 | 8.0 | 9.8 | 4.5 | 27.0 | 5.8 | very strong downward flow in lower part, no good fit found for upper layer |
| 06/06/2002 | A-19 | middle | 0.3 | 0.8 | 2.0 | 10.4 | 4.0 | 27.0 | 2.8 | |
| 06/06/2002 | A-20 | middle | 0.3 | 1.2 | 2.0 | 10.5 | 4.5 | 26.6 | 5.5 | very good fit for lower layer, however no good solution for upper |
| 06/06/2002 | A-22 | middle | 0.3 | 0.8 | -4.5 | 10.3 | 6.6 | 27.2 | 6.3 | very good fit, strong seepage |
| 06/06/2002 | A-23 | middle | 0.3 | 0.8 | -8.0 | 9.7 | 6.5 | 25.3 | 6.7 | very good fit, strong seepage |
| 06/06/2002 | A-24 | middle | 0.3 | 0.8 | 4.0 | 9.8 | 5.8 | 27.7 | 4.1 | very good fit |
| 06/06/2002 | A-25 | middle | 0.4 | 0.9 | -1.0 | 10.3 | 4.2 | 31.9 | 10.7 | very good fit |
| 08/10/2003 | A1-A3 | middle | | | | | | | | no solution |
| 08/10/2003 | A-4 | middle | 0.3 | 0.6 | 0.0 | 10.0 | 5.0 | 23.3 | 3.5 | good fit |
| 08/10/2003 | A-4 | middle | 0.3 | 0.6 | -1.5 | 10.5 | 4.7 | 17.5 | 3.5 | good fit |
| 08/10/2003 | A-4 | middle | 0.3 | 0.6 | 0.5 | 9.8 | 5.1 | 25.3 | 3.5 | good fit |
| 08/10/2003 | A-4 | middle | 0.3 | 0.6 | 1.5 | 9.3 | 5.4 | 29.5 | 3.4 | good fit |
| 08/10/2003 | A-5 to A-13 | middle | | | | | | | | no solution, very stable temeratures along whole verticals |
| 08/10/2003 | A-14 | middle | 0.3 | 0.5 | -2.0 | 9.9 | 2.0 | 7.0 | | not acceptable, lag time too short |
| 08/10/2003 | A-18 | middle | 0.3 | 0.8 | 0.8 | 10.8 | 2.6 | 24.6 | 7.6 | |
| 08/10/2003 | A-18 | middle | 0.8 | 1.1 | -10.5 | 11.7 | 2.7 | 26.9 | 9.4 | the lower layer indicates substantial seepage at a high rate of 10.5 meters per annum. The upper layer shows slightly downwards flow . |
| 08/10/2003 | A-19 | middle | 0.9 | 1.6 | -8.3 | 11.4 | 5.2 | 24.7 | | very strong seepage in the lower layer and no solution for the upper layer might indicate strong lateral flow in the upper part |
| 08/10/2003 | A-20 | middle | 0.8 | 1.2 | 4.5 | 10.4 | 2.2 | 25.4 | | no solution, amplitude too low |
| 08/10/2003 | A-21 | middle | 0.4 | 0.8 | -1.0 | 9.7 | 4.9 | 25.9 | 9.2 | good fit |
| 08/10/2003 | A-26 | middle | 0.3 | 1.2 | 0.0 | 8.7 | 8.3 | 9.8 | | not acceptable, lag time too short |
| 06/06/2002 | A-18 | right | 0.3 | 1.3 | -3.3 | 9.4 | 4.3 | 25.5 | 4.6 | good fit also for velocities from -4 to -1 m/a |
| 06/06/2002 | A-19 | right | 0.3 | 0.6 | -3.5 | 9.8 | 6.8 | 43.5 | 5.0 | very good fit |
| 06/06/2002 | A-19 | right | 0.3 | 0.8 | -8.5 | 9.5 | 11.7 | 45.0 | 4.6 | very good fit |
| 06/06/2002 | A-21 | right | 0.3 | 1.0 | -11.0 | 9.3 | 4.7 | 28.0 | 6.2 | very good fit |
| 06/06/2002 | A-3.7 | left | 0.3 | 0.7 | -10.5 | 9.5 | 4.4 | 27.5 | 6.2 | very good fit |
| 06/06/2002 | A-16.7 | left | 0.3 | 0.7 | -19.8 | 9.5 | 6.5 | 26.4 | 3.6 | very good fit |
| 06/06/2002 | A-18.7 | left | 0.3 | 1.2 | -3.5 | 9.7 | 4.7 | 27.5 | 6.5 | good fit also for velocities from -5 to -0.5 m/a |
| 06/06/2002 | A-29.5 | left | 0.3 | 1.6 | -2.3 | 9.3 | 3.9 | 25.1 | 8.5 | good fit also for velocities from -2.3 to 1 m/a |

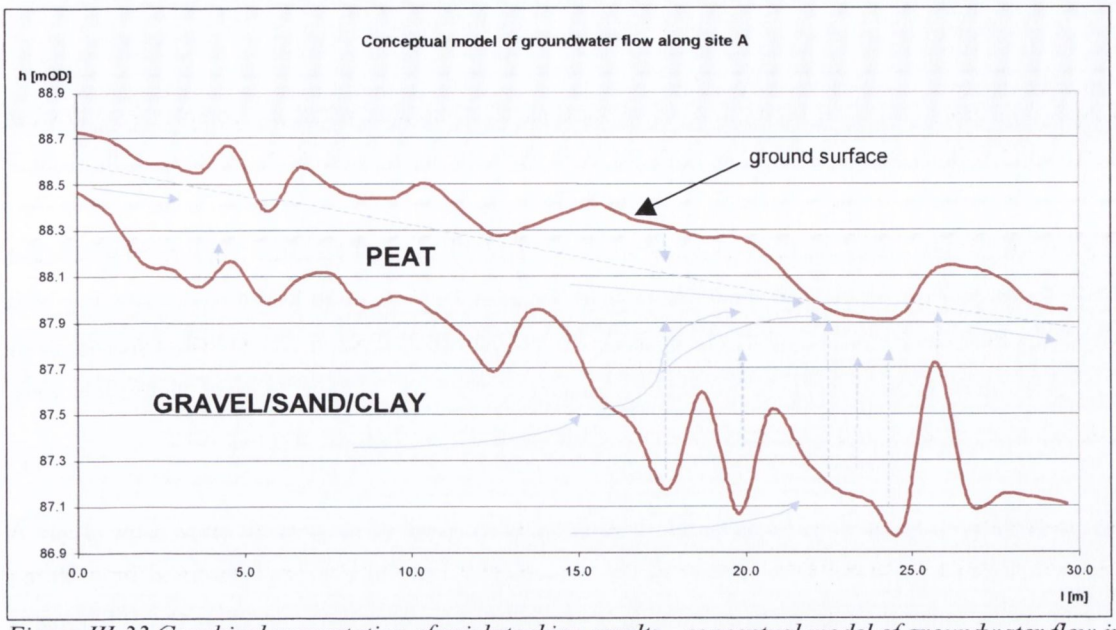



*Figure III-33 Graphical presentation of prickstocking results - conceptual model of groundwater flow in peat stratum at the fen margin, middle transect, site A*

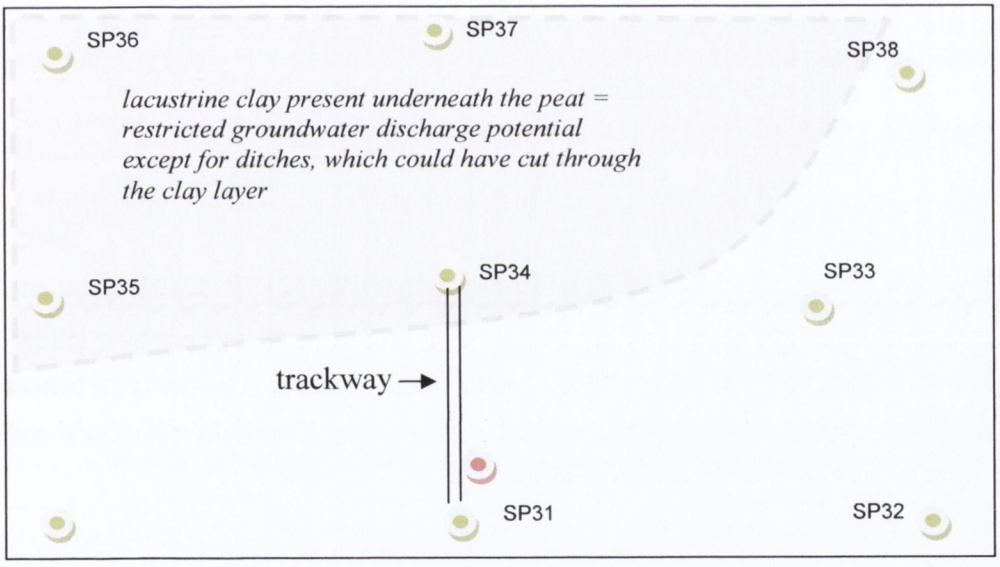



*Figure III-34 Seepage areas within site A determined during the prickstocking survey (blue ovals) and original conceptual model for potential seepage location*

## 6. Conclusions

From the available data it may be concluded that the south side of the fen is fed by water coming from a large and distant recharge area – the Curragh aquifer. Deep groundwater flows from south to north towards the drain and the Milltown Feeder. At the fen margin, water flow is split between two layers of gravel and becomes confined by layers of clay and peat. The clay layer is not consistent, and the peat depth is thin, which creates windows through which groundwater oozes out and later flows laterally towards the fen centre. A number of seepage locations were determined within the site and this was based on piezometry and prickstock profiling. These seepages were found in places where peat depth was shallow with no or thin deposits of clay beneath. The

location of clay seems to be therefore a dominant factor determining spatial distribution and strength of seepage zones.

The geological complexity of the subsurface soil, as well as a number of drains, result in a complex groundwater system with local flow diversions as well as upwelling fluxes. This was recognised in six locations within site A (Figure III-34); in the middle, at the beginning ($5^{th}$ metre) and between the $18^{th}$ - $25^{th}$ metre of the trackway as well as on both sides of the trackway; in three locations between SP30 and SP35 (on the left side) and between SP33 and SP34 (on the right side). The employment of the prickstock was found useful in determining both spatial distribution of seepage zones and also in quantitative analysis of specific discharge. The latter suggests discharge at approximate rates of 0.5-1 m/yr (specific discharge) at the edge of fen. In more central locations, seepage rates are much smaller (0.04-0.05 m/yr) owing to thicker depths of peat and clay deposits.

In summary, according to the presented results, the dominating mechanism of the phreatic water flow at site A (southern fen's margin) is a lateral flow driven by the groundwater head in Curragh, amplified by a strong upward flow in places where the geology is favourable (thin peat, lacking clay layer) or where the old drainage system facilitates seepage.

#### III-2.2.2.3 Water Regime at Site B

1. Location and Topography

Site B is located at the south east of the fen, close to the main recharge area, known as Seven Springs.

The site is a man made, dug out spring, discharging straight into the Milltown Feeder. The topography of the site is very uniform and flat with a gradient of 0.04 (Figure III-43). Similar to site A, the site is located at the bottom of a steep field, of which the topsoil combines mainly brown clay underlain by a thick deposit of sand and gravel. The elevation of the fen margin in this location is at 87.5 m OD.

2. Geology

The geology of an area uphill of the site shows large deposits of sand and gravel (see cross section (Appendix 19) covered with approximately 1-2 m of brown clay. This clay extends towards the fen margin, where its depth varies between 2-3 m (SP15, SP16, SP17). This clay is described in the geological cross sections as gravely, sandy clay with varying degrees of firmness; however, pockets of sand or gravel have also been reported within this clay layer. At the fen margin, the clay or gravel deposits become overlain with fen peat deposits, which start below piezometer line SP15-SP16-SP17 (Figure III-43). The peat depth quickly rises up to about 1.5 metres and is evenly distributed throughout the site. In the majority of the fen margin, peat is underlain by wet gravely brown clay (SP18, SP22), however, in some places (SP19), peat occurs directly above gravel, which suggests that clay deposits at the fen margin thin out and/or mix with gravel. Further down towards the fen centre (SP20, SP21) clay deposits beneath the peat become tighter and grey in colour, suggesting a lacustrine origin and as

such low permeability of the strata. It is apparent that at the fen margin clay is more gravely, hence its permeability is likely to allow for some water movement in both horizontal and vertical directions. Toward the fen centre, tight grey deposits are likely to restrict water movement. Such geological composition will provide confinement for water gathered in underlying sand and gravel deposits and this is reflected in strong artesian heads occurring in the most centred nests SP20-SP22. Lack of lacustrine deposits at the most marginal locations provide good conditions for groundwater seepage. Cross sectional diagrams and well logs are presented in Appendix 19.

## 3. Hydrogeology

The general direction of flow was determined from south west to the north east and follows the regional pattern. The water table in the dug out spring was recorded at an approximate level of 86.00 m OD.

The amplitude of fluctuations at all monitoring levels was highly variable over the observation period, and did not indicate a significant change over time, Table III-27. Deep water levels showed annual variations ranging from 0.09 m to 0.7 m over the monitoring period 2002-2005 and there was only a slight decrease in water levels Figure III-36. Also, the highest annual fluctuations were found in the most marginal standpipes, i.e. SP17, SP15 and SP16. In middle screens, the annual variations ranged from 0.11 m to 1.35 m but no significant trend in fluctuation ranges over the observation period is evident. Nevertheless, Figure III-36 - Figure III-38 and Table III-27 - Table III-28 suggest that minimum levels were falling throughout 2002-2005. A similar trend is also noticeable in the phreatic level, where the decrease in minimum levels in SP20 was 0.22 m between 2002 and 2005. Seasonal variations in groundwater levels follow the same annual patterns recorded at site A suggesting the same recharge area. All deep standpipes showed confined conditions and the following wells: SP15, SP18, SP19, SP19A, SP20, SP21, SP22 were artesian.

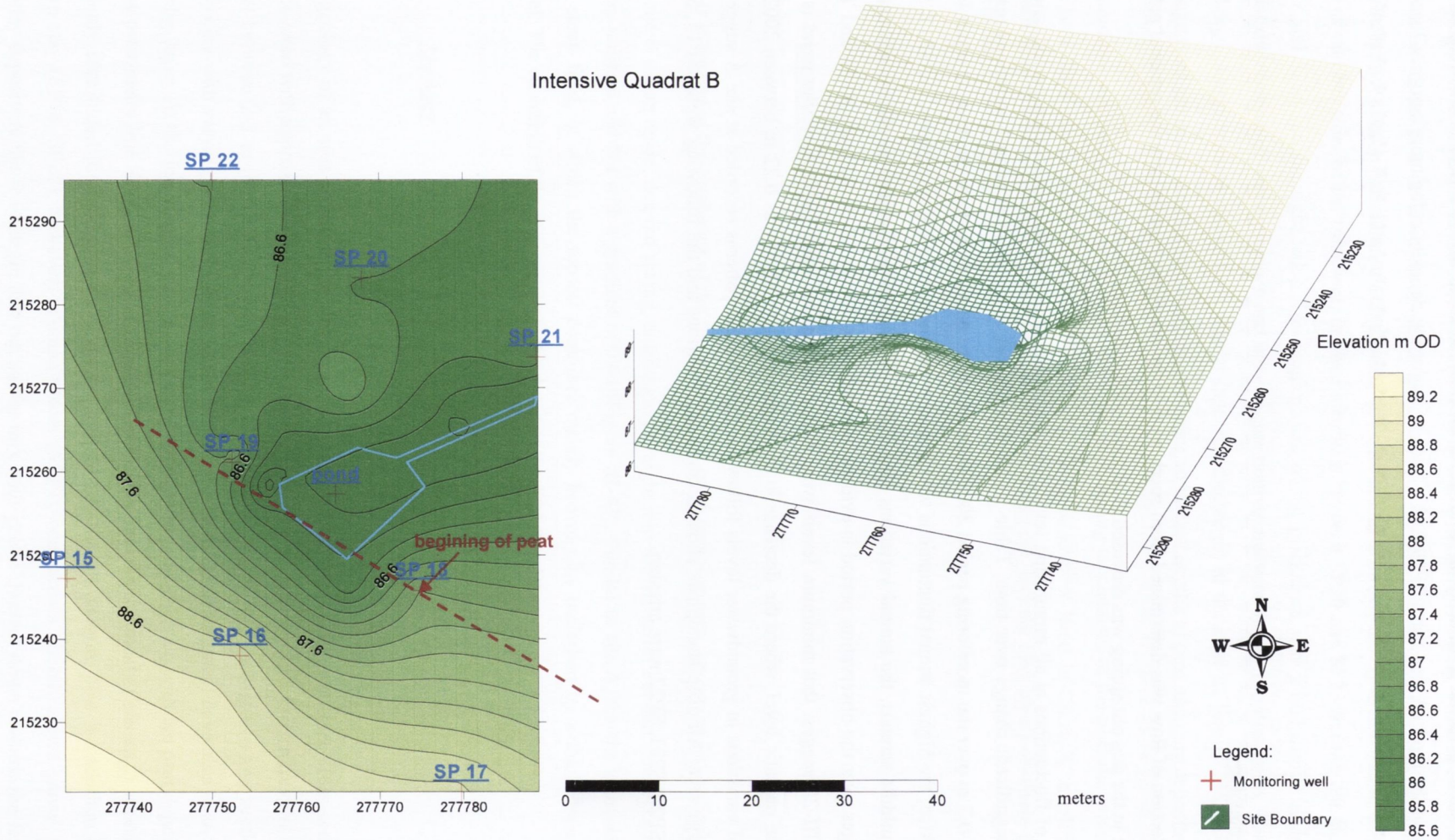



*Figure III-35 Topography and situation plan of Intensive Quadrat B*

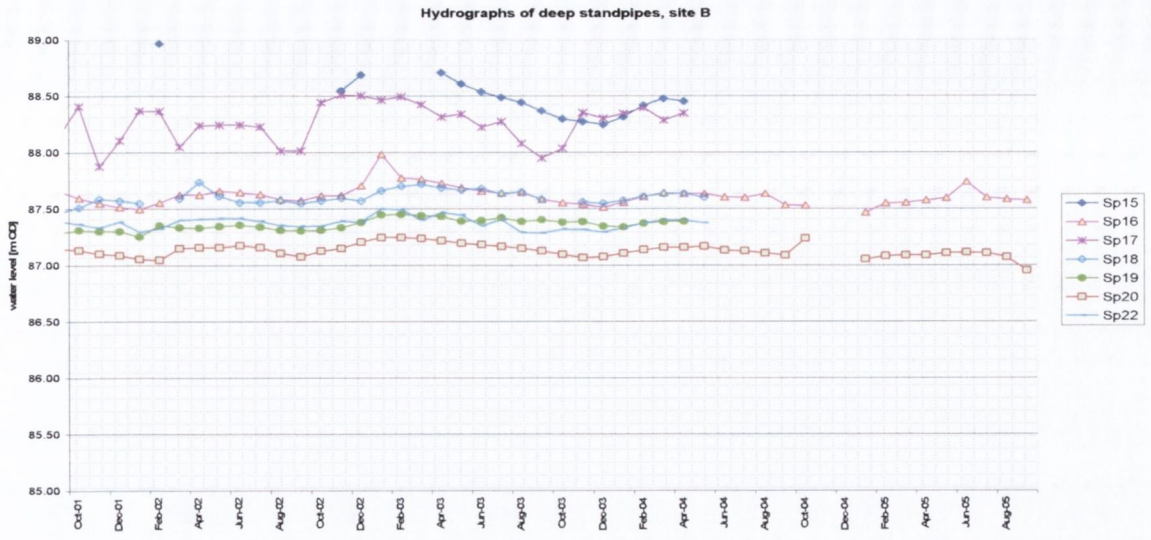



*Figure III-36 Monthly distribution of groundwater levels in deep standpipes at site B, southern fen margin, 2002-2005*

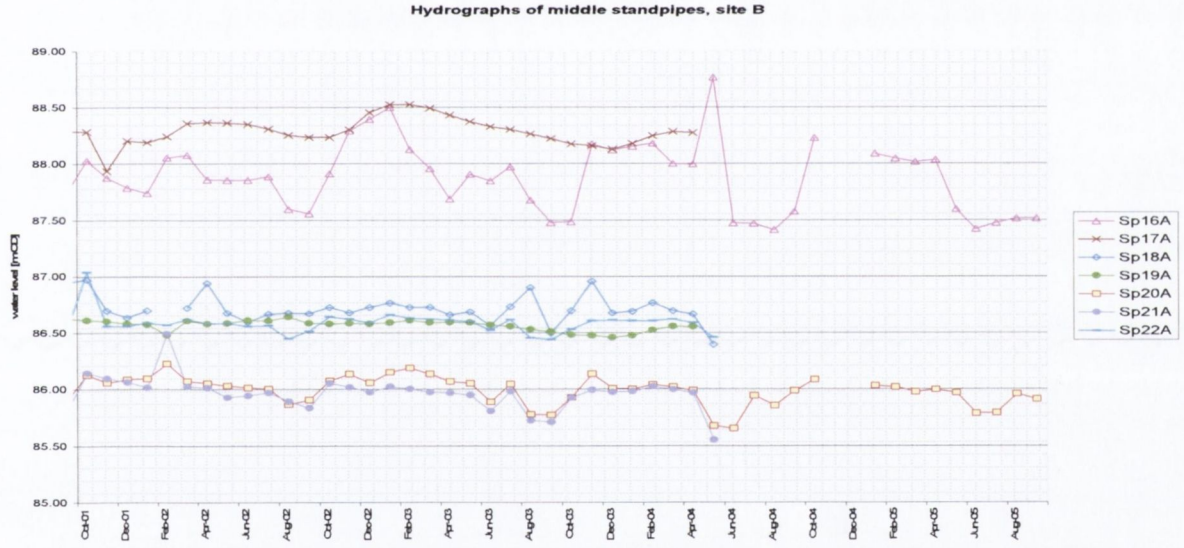



*Figure III-37 Monthly distribution of groundwater levels in middle standpipes at site B, southern fen margin, 2002-2005*

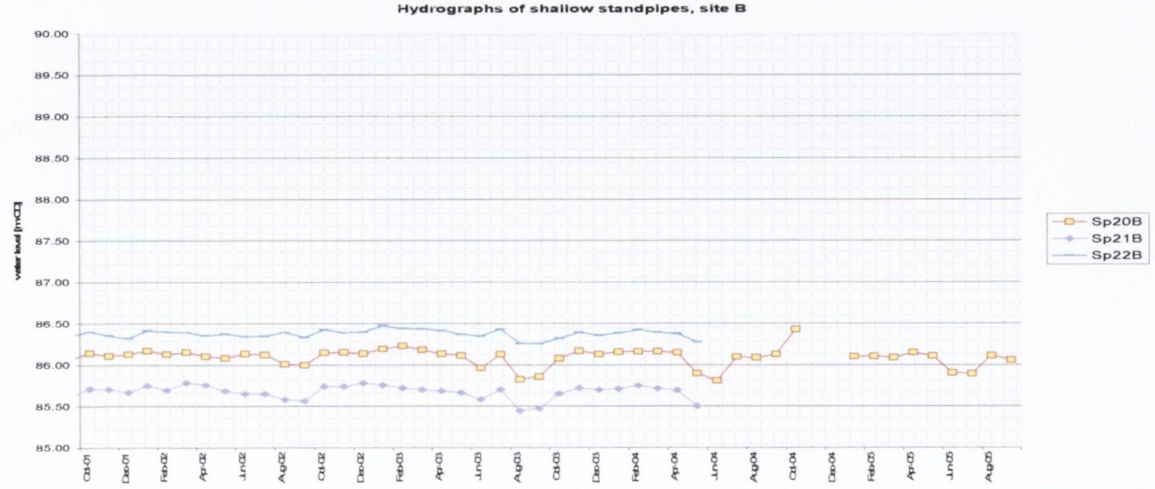



*Figure III-38 Monthly distribution of groundwater levels in shallow standpipes at site B, southern fen margin, 2002-2005*

**Table III-27 Summary of groundwater levels (m OD) at site B in hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| DEEP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | SP15 | SP16 | SP17 | SP18 | SP19 | SP20 | SP22 |
| 2002 | max | | 87.66 | 88.48 | 87.87 | 87.36 | 87.19 | 87.41 |
| | min | | 87.49 | 87.78 | 87.51 | 87.25 | 87.03 | 87.28 |
| | average | | 87.59 | 88.19 | 87.58 | 87.32 | 87.12 | 87.37 |
| | amplitude | | 0.17 | 0.70 | 0.36 | 0.11 | 0.16 | 0.13 |
| | SD | | 0.06 | 0.19 | 0.07 | 0.03 | 0.05 | 0.04 |
| 2003 | max | 88.75 | 88.19 | 88.56 | 87.73 | 87.45 | 87.25 | 87.52 |
| | min | 88.34 | 87.56 | 87.93 | 87.56 | 87.30 | 87.12 | 87.18 |
| | average | 88.54 | 87.69 | 88.31 | 87.64 | 87.40 | 87.18 | 87.39 |
| | amplitude | 0.41 | 0.63 | 0.63 | 0.17 | 0.15 | 0.13 | 0.34 |
| | SD | 0.13 | 0.12 | 0.20 | 0.05 | 0.04 | 0.04 | 0.09 |
| 2004 | max | | 87.64 | | | | 87.17 | |
| | min | | 87.51 | | | | 87.03 | |
| | average | | 87.59 | | | | 87.12 | |
| | amplitude | | 0.13 | | | | 0.14 | |
| | SD | | 0.04 | | | | 0.04 | |
| 2005 | max | | 87.88 | | | | 87.12 | |
| | min | | 87.39 | | | | 86.83 | |
| | average | | 87.57 | | | | 87.07 | |
| | amplitude | | 0.49 | | | | 0.29 | |
| | SD | | 0.10 | | | | 0.07 | |

| MIDDLE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | SP16A | SP17A | SP18A | SP19A | SP20A | SP21A | SP22A |
| 2002 | max | 88.37 | 88.37 | 87.30 | 86.64 | 86.23 | 86.49 | 87.41 |
| | min | 87.53 | 87.61 | 86.57 | 86.48 | 85.86 | 85.75 | 86.45 |
| | average | 87.85 | 88.26 | 86.73 | 86.59 | 86.04 | 86.02 | 86.61 |
| | amplitude | 0.84 | 0.76 | 0.73 | 0.16 | 0.37 | 0.74 | 0.96 |
| | SD | 0.20 | 0.16 | 0.19 | 0.03 | 0.09 | 0.14 | 0.19 |
| 2003 | max | 88.52 | 88.53 | 87.31 | 86.61 | 86.19 | 86.06 | 86.71 |
| | min | 87.47 | 88.20 | 86.40 | 86.50 | 85.60 | 85.48 | 86.38 |
| | average | 87.92 | 88.36 | 86.69 | 86.57 | 86.01 | 85.92 | 86.58 |
| | amplitude | 1.05 | 0.33 | 0.91 | 0.11 | 0.59 | 0.58 | 0.33 |
| | SD | 0.33 | 0.11 | 0.17 | 0.03 | 0.17 | 0.15 | 0.09 |
| 2004 | max | 88.76 | | | | 86.28 | | |
| | min | 87.42 | | | | 85.55 | | |
| | average | 87.92 | | | | 85.95 | | |
| | amplitude | 1.35 | | | | 0.73 | | |
| | SD | 0.39 | | | | 0.15 | | |
| 2005 | max | 88.31 | | | | 86.06 | | |
| | min | 87.35 | | | | 85.64 | | |
| | average | 87.77 | | | | 85.94 | | |
| | amplitude | 0.96 | | | | 0.42 | | |
| | SD | 0.32 | | | | 0.11 | | |

| SHALLOW *(continued)* | | | | |
|---|---|---|---|---|
| | | **SP20B** | **SP21B** | **SP22B** |
| **2002** | max | 86.22 | 85.85 | 86.49 |
| | min | 85.93 | 85.49 | 86.31 |
| | average | 86.11 | 85.69 | 86.37 |
| | amplitude | 0.29 | 0.36 | 0.18 |
| | SD | 0.06 | 0.08 | 0.04 |
| **2003** | max | 86.26 | 85.81 | 86.52 |
| | min | 85.68 | 85.31 | 86.19 |
| | average | 86.08 | 85.65 | 86.38 |
| | amplitude | 0.58 | 0.50 | 0.33 |
| | SD | 0.17 | 0.13 | 0.08 |
| **2004** | max | 86.22 | | |
| | min | 85.73 | | |
| | average | 86.09 | | |
| | amplitude | 0.49 | | |
| | SD | 0.12 | | |
| **2005** | max | 86.55 | | |
| | min | 85.71 | | |
| | average | 86.08 | | |
| | amplitude | 0.84 | | |
| | SD | 0.17 | | |

**Table III-28 Differences between maximum and minimum levels in the consecutive hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| DEEP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **SP15** | **SP16** | **SP17** | **SP18** | **SP19** | **SP20** | **SP22** |
| 2003-2002 | Max | | 0.53 | 0.08 | -0.14 | 0.09 | 0.06 | 0.11 |
| | Min | | 0.07 | 0.15 | 0.05 | 0.05 | 0.09 | -0.10 |
| 2004-2003 | Max | | -0.55 | | | | -0.08 | |
| | Min | | -0.05 | | | | -0.09 | |
| 2005-2004 | Max | | 0.24 | | | | -0.05 | |
| | Min | | -0.12 | | | | -0.20 | |
| 2005-2002 | Max | | 0.22 | | | | -0.07 | |
| | Min | | -0.10 | | | | -0.20 | |
| **MIDDLE** | | | | | | | | |
| | | **SP16A** | **SP17A** | **SP18A** | **SP19A** | **SP20A** | **SP21A** | **SP22A** |
| 2003-2002 | Max | 0.15 | 0.16 | 0.01 | -0.03 | -0.04 | -0.43 | -0.70 |
| | Min | -0.06 | 0.59 | -0.17 | 0.02 | -0.26 | -0.27 | -0.07 |
| 2004-2003 | Max | 0.25 | | | | 0.09 | | |
| | Min | -0.05 | | | | -0.05 | | |
| 2005-2004 | Max | -0.46 | | | | -0.22 | | |
| | Min | -0.07 | | | | 0.09 | | |
| 2005-2002 | Max | -0.06 | | | | -0.17 | | |
| | Min | -0.18 | | | | -0.22 | | |
| **SHALLOW** | | | | | | | | |
| | | **SP20B** | **SP21B** | **SP22B** | | | | |
| 2003-2002 | Max | 0.04 | -0.04 | 0.03 | | | | |
| | Min | -0.25 | -0.18 | -0.12 | | | | |
| 2004-2003 | Max | -0.04 | | | | | | |
| | Min | 0.05 | | | | | | |
| 2005-2004 | Max | 0.33 | | | | | | |
| | Min | -0.02 | | | | | | |
| 2005-2002 | Max | 0.33 | | | | | | |
| | Min | -0.22 | | | | | | |

## 4. Estimation of groundwater flow velocities

Similarly to site A, groundwater flow velocities, expressed as specific discharge, between wells within middle and deep screens were higher in middle screens where they ranged between 0.003-0.067 m/day (Table III-30). In deeper gravel, these velocities were found between 0.005-0.048 m/day (Table III-29). Both levels showed higher flow velocities in locations closer to the fen margin, i.e. where the hydraulic gradient is higher (SP15-SP19, SP17-SP18 and SP16-SP21). Full water level data and monthly Darcy's velocities are available in Appendices 20 and 21.

Only three standpipes within site B targeted the peat layer, therefore computation of a horizontal flow rate was not possible here.

Calculations of vertical flow velocities confirmed that at this site, similarly as at site A, the upward seepage occurs in localised zones only and its presence depends on local geological settings. The upward flow was distinguished in nests SP21 and SP22, which are underlain by either wet, brown, gravely clay or a mixture of sand and grey gravely clay but not in SP20, where peat lies on 3 metres of tight, grey, gravely, sandy clay (Appendix 19). The upward Darcy's velocities were found at levels of 0.002-0.004 m/day, equal to approximately 0.7-1.5 m per annum – values corresponding to that from site A at the most marginal locations. The prickstocking survey was not undertaken at this site because of the absence of *Vertigo geyeri*. Thus, establishing the seepage zones was not as critical at this site as it was at site A. Based on piezometry, the conceptual model of groundwater flow is similar to that on site A; the dominant flow mechanism is a lateral flow driven by the hydraulic head in the Curragh aquifer. The groundwater discharge occurs both laterally and vertically and this is controlled by hydraulic pressure in the underlying fen gravel. Upward flow can only occur where there is enough pressure to drive upward seepage and in places where geology provides favourable conditions.

**Table III-29 Summary of groundwater flow rates (lateral), expressed as specific discharge, in the deep gravel layer within Site B**

| | k = | 1.21E-05 | [m/s] | |
|---|---|---|---|---|
| | dl | gradient | Specific discharge | |
| Standpipe | m | | m/s | m/day |
| 15-19 | 24.20 | 0.0458 | 0.0000006 | 0.048 |
| 17-18 | 24.72 | 0.027 | 0.0000003 | 0.028 |
| 16-21 | 50.00 | 0.005 | 0.0000001 | 0.005 |
| 18-22 | 50.72 | 0.005 | 0.0000001 | 0.005 |
| 19-20 | 27.00 | 0.008 | 0.0000001 | 0.008 |

**Table III-30 Summary of groundwater flow rates (lateral), expressed as specific discharge, in shallow gravel layer (middle standpipes) within Site B**

| | k = | 1.21E-05 | [m/s] | |
|---|---|---|---|---|
| | dl | gradient | Specific discharge | |
| Standpipe | m | | m/s | m/day |
| 17-18 | 24.72 | 0.064 | 0.0000008 | 0.067 |
| 16-21 | 50.00 | 0.0399 | 0.0000005 | 0.042 |
| 18-22 | 50.72 | 0.003 | 0.0000000 | 0.003 |
| 19-20 | 27.00 | 0.020 | 0.0000002 | 0.021 |

**Table III-31 Summary of groundwater flow rates (vertical), expressed as specific discharge, between upper gravels and the peat within Site B. Positive values denote upward flow.**

| | dl | *k* | Specific discharge | |
|---|---|---|---|---|
| **Standpipe** | m | m/s | m/s | m/day |
| **20A-20B** | 2.00 | 1.73E-07 | -0.00000001 | -0.001 |
| **21A-21B** | 2.00 | 2.89E-07 | 0.00000004 | 0.004 |
| **22A-22B** | 2.50 | 1.8E-07 | 0.00000002 | 0.002 |

5. Conclusion

From the available data, it may be concluded that the water recharge mechanism at site B is similar to that at site A; water originates from the Curragh aquifer and follows its north eastern direction of flow. Water discharge at site B is controlled by a dug out spring which is located between SP18 and SP19, however, strong upward seepage is also present in places further down from the spring. Gravely beds in the spring as well as borehole logs from standpipes SP15-SP19 reveal that lacustrine clay deposits do not extend to the fen margin but start between the second and the third row of piezometers (between SP19-SP20 and SP18-SP21), which facilitates groundwater discharge in the most up gradient areas. This lacustrine clay, described in borehole logs as tight grey clay, provides confinement for water gathered in the gravel layer.

### III-2.2.2.4 Water Regime at Site C

1. Location

Site C is located on the north eastern margin of the fen. The site lies in a small depression between two shallow drains connecting water from springs emerging at the fen margin to the Milltown Feeder. These are seepage springs, which become active only in the wetter months and high water heads and usually remain dry in the summer. The average altitude of the site is a little below 86.0 m OD (Figure III-47).

2. Geology

The geology of the site was established on the basis of the drilling logs (WYG Ltd., 2002) from the following wells: MB45 (Monitoring Borehole located at the top of an upgradient field), SP2, SP5/6, SP11/12, auger hole A10 (Daly, 1981) and the prickstock survey.

Generally, the vertical profile shows a domination of clay and gravel with a relatively steep slope from the upgradient grass field, which flattens sharply at the fen margin. The field is characterised by a shallow layer of topsoil, underlain by an almost 2 m thick layer of boulder clay and 5 m thickness of gravel. According to the maps of the Quaternary deposits of Co. Kildare (Glanville, 1999) the top layer of boulder clay is not continuous and gravel crops out in many places. Beneath this gravel, there is another layer of boulder clay. Towards the fen, the topsoil gives way to a thin deposit of peat. At the fen margin, a layer of sand and gravel (max. 2 metres thick) lies under the peat and, in turn, is underlain by a thick deposit of boulder clay, which is a continuation of an up

gradient sediment. This cover confines the deep gravel deposits. At the fen margin, the peat dips steeply, the upper gravels pinch out into a thin layer of gravely, clayey sand underlain by grey clay over the deep gravel. This gravely/sandy grey clay does not reach the upmost fen margin. Thick grey clay deposits start only along the line between SP1-SP13; however, thinner (0.2 m) depths are found also in SP4 and SP6. Lack of grey clay in SP5 suggests that sediment is not continuous in its upper extent, i.e. north of a line between SP1 and SP13. The presence of thick lacustrine deposits is likely to restrict water movement between gravel and boulder clay, transferring water from the upgradient fields and the peat layer. Therefore, seepage will be likely to occur uphill from this clay edge (Figure III-47). The cross section graphs and well logs can be found in Appendix 22.

3. Hydrogeology

Water level within site C is monitored at two levels, deep (6-7 metres deep) and shallow (2-4 m deep), and the monitoring network consists of 9 nests of piezometres within and outside the Intensive Quatrat C. These are located along three vertical profiles, the first profile consisting of SP1, SP7, SP8, SP9 and SP10; the second, central profile: SP2, SP5, SP6, SP11, SPp12 and the third: SP14, SP13 (Figure III-47). Deep standpipes reach the deeper gravel layer and all showed confined conditions, which were highest at the fen margin and decrease towards the centre.

Shallow standpipes are located only in five nests and these reflect water level in combination of upper gravels, sands, grey clay and peat.

Within deep screens, the seasonal patterns at site C throughout the observation period was such that in hydrometric year 2002, the maximum water level was recorded at the beginning of March 2002 following 5 month recharge period (Figure III-40). The recession proceeded until the end of September; however, between 10$^{th}$ April and 4$^{th}$ July, the water levels were stable. The next recharge period occurred between the end of September 2002 and the third week of November with deep water levels rising 2 metres over the two months (see Figure III-40). A recession lasted until the end of October 2003 and was followed by a three month recharge period; however the maximum heads in 2004 were approximately 0.2m lower than those from 2003. The following minimum occurred at the end of October 2004 and minimum levels were similar to those from 2003; however, the maximum of 2005, which was measured at the end of February 2005, was again approximately 0.2m lower with regard to the previous year. The levels were still in recession at the end of hydrometric year 2005. The above demonstrates that annual fluctuations are different here than at sites A and B, and maximum levels occur even 2-3 months earlier than on the south side, which suggests a closer and smaller catchment area and subsequently limited storage in the aquifer reflected in faster response in water level fluctuations. Also, it is apparent from the above analysis that water levels measured in deep screens were steadily decreasing throughout the observation period (Table III-33) with a drop of 0.13m measured in SP11 between 2002-2005. Hydrographs of deep water levels as a monthly average are presented in Figure III-40. A comparison between hydraulic heads and rainfall distribution showed that groundwater response is almost immediate to rainfall, which confirms previous findings (hydrochemistry) and delineation of the groundwater catchment boundary at the top of an upgradient field.

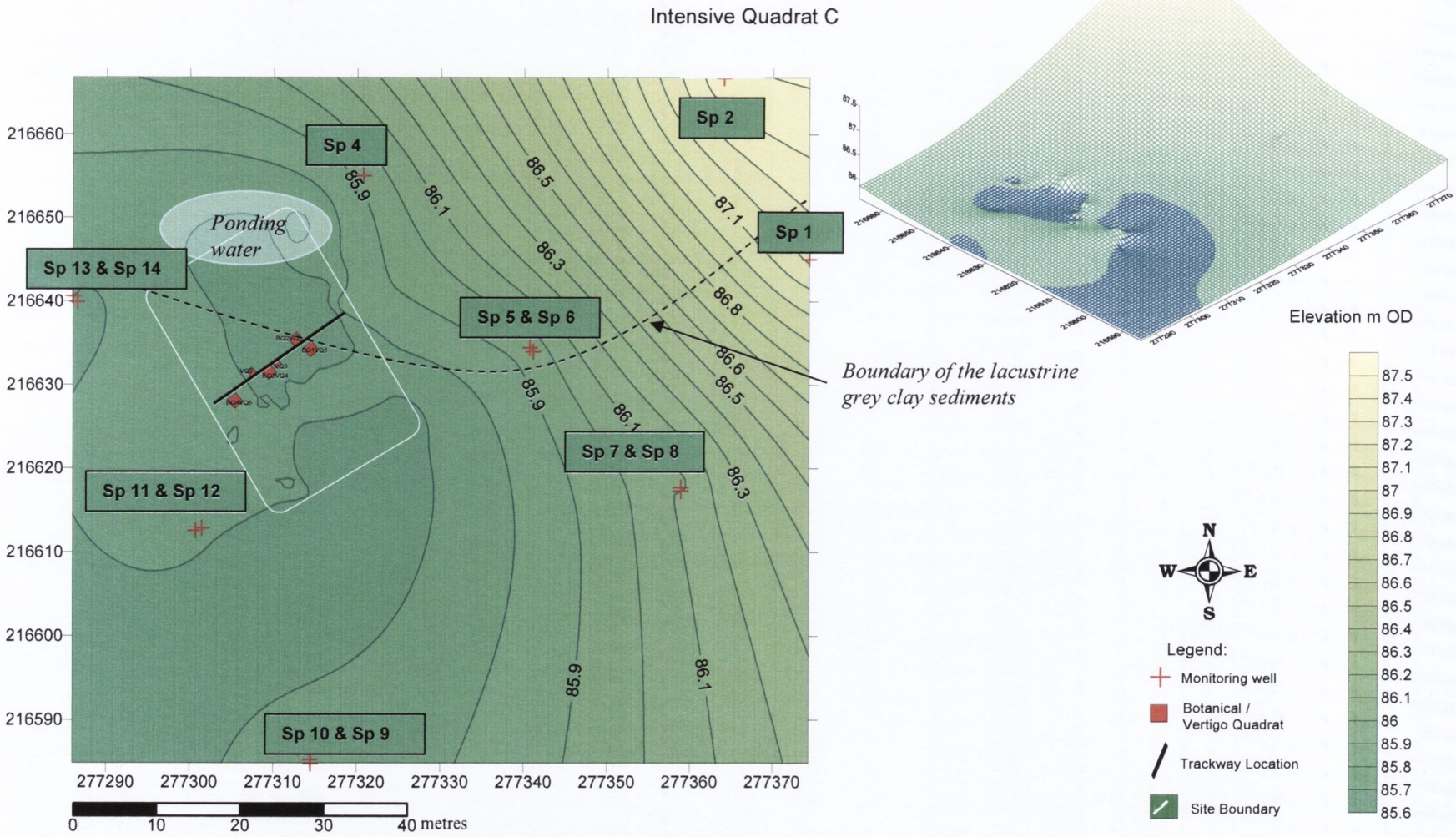



*Figure III-39 Topography and situation plan of Intensive Quadrat C*

With respect to the phreatic level, the analysis showed quite stable water levels throughout the observation period with draw downs recorded only during summer months; hydrographs presented in Figure III-41. That implies that for the phreatic level at site C, evapotranspiration losses and rainfall patterns are important factors controlling the water level. This was especially apparent in summer 2003, when after an exceptionally dry August, the phreatic level in September decreased by up to 0.65 metre (SP14). All water level data are presented in Appendix 23.

The analysis of groundwater elevations and gradients between heads in adjacent wells showed a south-western direction of flow, from the margin towards the Milltown Feeder drain. Significantly lower piezometric heads in standpipe SP5 indicates possible outflow i.e. seepage from groundwater in close proximity to this well. This conforms to the lack of a clay layer in this location which allows groundwater to seep into and through a relatively thin (<0.5 m) peat stratum. Well logs from SP6, SP11 and SP12 show a thin layer of sand underneath the peat, but above the clay which is likely to transmit water into the peat from upper sands and gravels.

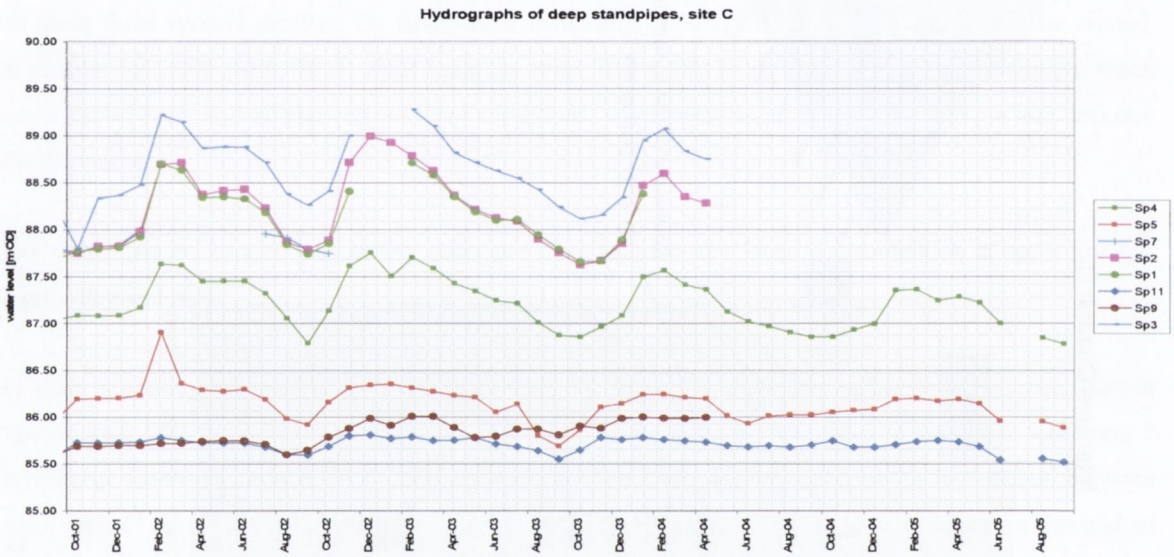



*Figure III-40 Monthly distribution of groundwater levels in deep standpipes at site C, northern side, 2002-2005*

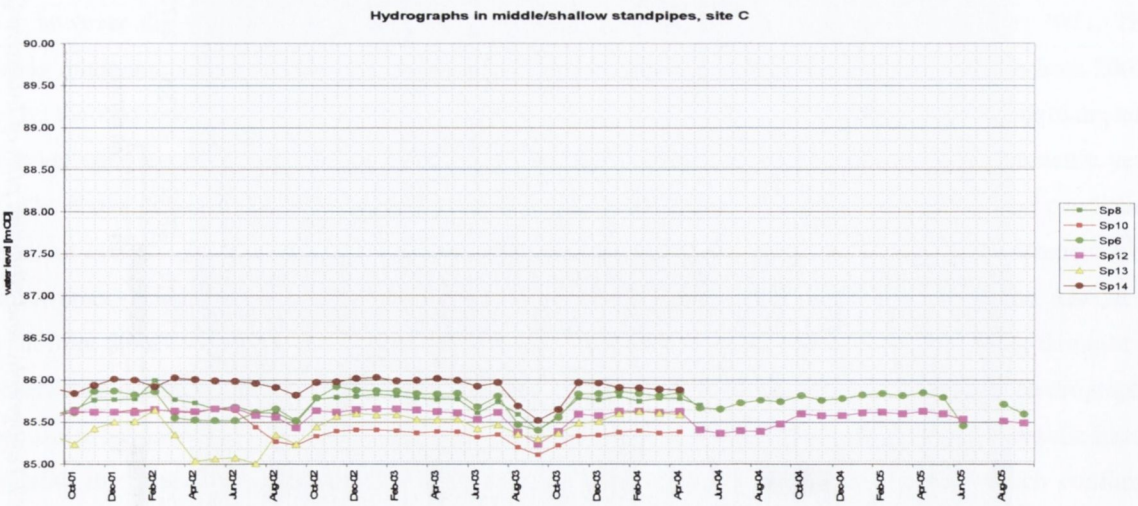



*Figure III-41 Monthly distribution of groundwater levels in middle & shallow standpipes at site C, northern side, 2005*

The correlation coefficient between hydraulic heads in SP5 and SP6 (deep and shallow gravels) was found at 0.94 for the period from July 2002 – September 2005, which emphasises the hydraulic connectivity between the two layers. Deep groundwater at the fen margin is strongly artesian with heads being even more than 1 m above the ground.

**Table III-32 Summary of groundwater levels (m OD) at site C in hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| DEEP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | SP1 | SP2 | SP3 | SP4 | SP5 | SP9 | SP11 |
| 2002 | max | 88.74 | 88.84 | 89.26 | 87.70 | 86.90 | 85.76 | 85.78 |
| | min | 87.70 | 87.74 | 87.80 | 86.79 | 85.79 | 85.60 | 85.56 |
| | average | 88.13 | 88.17 | 88.63 | 87.30 | 86.24 | 85.70 | 85.71 |
| | amplitude | 1.04 | 1.10 | 1.46 | 0.91 | 1.11 | 0.16 | 0.22 |
| | SD | 0.33 | 0.34 | 0.37 | 0.24 | 0.20 | 0.04 | 0.06 |
| 2003 | max | 88.71 | 88.99 | 89.28 | 87.76 | 86.36 | 86.01 | 85.81 |
| | min | 87.67 | 87.68 | 88.19 | 86.87 | 85.61 | 85.60 | 85.54 |
| | average | 88.15 | 88.26 | 88.65 | 87.31 | 86.12 | 85.87 | 85.71 |
| | amplitude | 1.04 | 1.31 | 1.09 | 0.89 | 0.75 | 0.41 | 0.27 |
| | SD | 0.29 | 0.40 | 0.31 | 0.28 | 0.23 | 0.10 | 0.08 |
| 2004 | max | | | | 87.59 | 86.25 | | 85.80 |
| | min | | | | 86.86 | 85.83 | | 85.65 |
| | average | | | | 87.16 | 86.10 | | 85.73 |
| | amplitude | | | | 0.73 | 0.42 | | 0.15 |
| | SD | | | | 0.25 | 0.13 | | 0.04 |
| 2005 | max | | | | 87.76 | 87.35 | | 86.45 |
| | min | | | | 86.78 | 85.84 | | 85.43 |
| | average | | | | 87.13 | 86.15 | | 85.70 |
| | amplitude | | | | 0.98 | 1.51 | | 1.02 |
| | SD | | | | 0.26 | 0.30 | | 0.20 |

| MIDDLE/SHALLOW | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | SP6 | SP8 | SP10 | SP12 | SP13 | SP14 |
| 2002 | max | 85.87 | 85.99 | 85.68 | 85.67 | 85.66 | 86.03 |
| | min | 85.45 | 85.49 | 85.19 | 85.31 | 84.95 | 85.77 |
| | average | 85.65 | 85.70 | 85.56 | 85.60 | 85.27 | 85.96 |
| | amplitude | 0.42 | 0.50 | 0.49 | 0.36 | 0.71 | 0.26 |
| | SD | 0.15 | 0.11 | 0.16 | 0.08 | 0.23 | 0.07 |
| 2003 | max | 85.96 | 85.85 | 85.41 | 85.67 | 85.60 | 86.09 |
| | min | 85.38 | 85.32 | 85.09 | 85.20 | 85.28 | 85.44 |
| | average | 85.74 | 85.69 | 85.33 | 85.55 | 85.48 | 85.91 |
| | amplitude | 0.58 | 0.53 | 0.32 | 0.47 | 0.32 | 0.65 |
| | SD | 0.18 | 0.15 | 0.10 | 0.15 | 0.10 | 0.18 |
| 2004 | max | 85.87 | | | 85.65 | | |
| | min | 85.56 | | | 85.32 | | |
| | average | 85.77 | | | 85.52 | | |
| | amplitude | 0.31 | | | 0.33 | | |
| | SD | 0.09 | | | 0.11 | | |
| 2005 | max | 86.47 | | | 86.31 | | |
| | min | 85.46 | | | 85.48 | | |
| | average | 85.79 | | | 85.61 | | |
| | amplitude | 1.01 | | | 0.83 | | |
| | SD | 0.19 | | | 0.17 | | |

**Table III-33 Differences between maximum and minimum levels in the consecutive hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| DEEP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | SP1 | SP2 | SP3 | SP4 | SP5 | SP9 | SP11 |
| 2003-2002 | Max | -0.03 | 0.15 | 0.02 | 0.06 | -0.54 | 0.25 | 0.03 |
| | Min | -0.03 | -0.06 | 0.39 | 0.08 | -0.18 | 0.00 | -0.02 |
| 2004-2003 | Max | | | | -0.17 | -0.11 | | -0.01 |
| | Min | | | | -0.01 | 0.22 | | 0.11 |
| 2005-2004 | Max | | | | 0.17 | 1.10 | | 0.65 |
| | Min | | | | -0.08 | 0.01 | | -0.22 |
| 2005-2002 | Max | | | | 0.06 | 0.45 | | 0.67 |
| | Min | | | | -0.01 | 0.05 | | -0.13 |
| **MIDDLE/SHALLOW** | | | | | | | | |
| | | SP6 | SP8 | SP10 | SP12 | SP13 | SP14 | |
| 2003-2002 | Max | 0.09 | -0.14 | -0.27 | 0.00 | -0.06 | 0.06 | |
| | Min | -0.07 | -0.17 | -0.10 | -0.11 | 0.33 | -0.33 | |
| 2004-2003 | Max | -0.09 | | | -0.02 | | | |
| | Min | 0.18 | | | 0.12 | | | |
| 2005-2004 | Max | 0.60 | | | 0.66 | | | |
| | Min | -0.10 | | | 0.16 | | | |
| 2005-2002 | Max | 0.60 | | | 0.64 | | | |
| | Min | 0.01 | | | 0.17 | | | |

4. Estimation of groundwater flow velocities

Groundwater flow velocities (specific discharge) in deep screens, calculated using Darcy's law (Table III-34, Appendix 24), revealed higher values than those found at sites A and B, but comparable with values found in middle screens from these sites (Figure III-46) and ranged from 0.01 to 0.07 m/day. The highest velocities were determined between SP4 and SP13. High Darcy's velocities were also found between SP2 and SP5 which is just before an extensive seepage zone with *Schoenus nigricans* stands and a permanent pool of standing water. This correlates well with distribution of the grey clay, which starts approximately south of SP5. This layer of clay provides a restriction for the groundwater flow and causes the groundwater to discharge, seep upwards wherever geomorphology allows for such movement and such conditions seem to be found between piezometers SP4-SP13.

Groundwater flow rates in peat layers were established at a level of c. 0.002-0.003 $m^2$/day (per unit width), which are similar to that from Sites A and B. Results are summarised in Table III-35.

Vertical Darcy's velocity was found to be similar to that at site B and the most marginal location at site A. The highest velocities in upwards direction were determined for SP9 and SP10 at 0.003 m/day (0.98 m/yr) and in nests SP5-SP6 and SP11-SP12 they were determined at 0.002 m/day (0.73 m/yr). In a nest SP13-SP14 downward flow was found with a specific discharge of 0.014m/day (4.9 m/yr), which is most likely controlled by close proximity of a drainage channel to the west.

**Table III-34 Summary of groundwater flow rates (lateral), expressed as specific discharge, in the deep gravel layer within Site C**

k = 1.21E-05 [m/s]

| | dl | gradient | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | | m/s | m/day |
| 3-4 | 39.80 | 0.034 | 0.0000004 | 0.036 |
| 2-5 | 39.80 | 0.051 | 0.0000006 | 0.054 |
| 7-9 | 55.11 | 0.039 | 0.0000005 | 0.041 |
| 5-11 | 44.83 | 0.010 | 0.0000001 | 0.010 |
| 4-13 | 30.50 | 0.009 | 0.0000007 | 0.064 |

**Table III-35 Summary of groundwater flow rates (lateral), in peat layer within Site C**

*k*= 1.19E-06 [m/s]

| | dl | gradient | Groundwater flow per unit width | |
|---|---|---|---|---|
| Standpipe | m | | $m^2/s$ | $m^2/day$ |
| 6-12 | 45.75 | 0.004 | 0.00000002 | 0.002 |
| 8-10 | 58.48 | 0.005 | 0.00000003 | 0.003 |

**Table III-36 Summary of vertical flow rates (expressed as specific discharge) between upper gravels and the peat in selected standpipes within Site C. Positive values denote upward flow.**

| | dl | *k* | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | [m/s] | m/s | m/day |
| 5-6 | 3.00 | 1.77E-07 | 0.00000002 | 0.002 |
| 11-12 | 1.00 | 2.81E-07 | 0.00000002 | 0.002 |
| 9-10 | 3.00 | 3.05E-07 | 0.00000002 | 0.003 |
| 13-14 | 1.00 | 3.13E-07 | -0.00000016 | -0.014 |

To conclude; based on piezometry, the conceptual model of groundwater flow at site C is such that water recharges at up gradient fields, and is quickly transferred into the fen edge, where it discharges laterally and vertically, depending on layering of boulder clay and gravel sediments and their contact with peat. The presence of grey lacustrine clay plays an important role in controlling seepage distribution, which seems to occur uphill of the grey clay sediment.

## 5. Vertical flow modelling using temperature profiles

The average EC values vary between 600 and 800 µS/cm with a few patches of higher values reaching more than 900 µS/cm. Generally, the values at the surface were lower, but quickly increased to around 700µS/cm and decreased to 500µS/cm at the very bottom. The closer to the fen centre, the lower the values of conductance in the upper layer. The base values were still around 700 µS/cm. The temperature chart showed decreasing values with the depth of peat and did not indicate any upward flow along the profile. Certainly, summer air temperatures influenced the surface layer of soil as the temperatures were close to 12°C or more. For the first metre depth of the peat, the temperature decreased almost linearly reaching 10°C at that depth, then 9°C at 1.6 metres and finally remained stable below that point (8.8-8.9°C). The only exception was the last vertical where temperatures decreased faster with depth and the minimum value of 8.6°C was reached at 2.7m. Numerical modelling of flow velocities, using TC-Taureg.xls programme, did not give clear results for this site. This is likely due to rather soft structure of peat within the site and likely significant lateral water movement.

6. Conclusion

The collected data suggests that the hydrogeology of site C depends on a local, likely smaller recharge area located close to the discharge points. The geological information suggest two layers of gravel separated by boulder clay, the upper being mixed with sand; however, its extent is not continuous throughout the site. Both layers present similar fluctuations, suggesting hydraulic connectivity between the layers. Water in deep gravel demonstrated strongly artesian conditions. A comparison between water levels in shallow standpipes and the Milltown Feeder does not show much correlation.

Water recharges at the upgradient fields and then travels into the fen through boulder and gravel sediments. Discharge at the fen margin can be either lateral, onto the fen surface, or vertical, wherever boulder clay and gravel sediments are in direct contact with peat. The grey lacustrine clay also occurs under the fen peat; however it does not underlie the whole extent of the fen margin. The presence of this clay plays an important role in controlling seepage distribution as seepages tend to occure in places outside and upgradient to (i.e. at the northern edge of the margin) the zone where this tight grey clay occurs.

Vertical hydraulic conductivity controls the discharge rate and, as this depends on the morphology of the soil matrix and the depth of subsequent deposits through which water travels, high spatial complexity of geological deposits leads to many separate discharge outlets.

The predominant direction of flow within the site is to the south west, from the fen margin towards Milltown Feeder.

### III-2.2.2.5 Water Regime at Site D

1. Location

Site D is the second experimental site on the northern fen margin and it is located north of site C. The site lies in a shallow depression, a remnant of peat cutting, with very loose, very humified peat strata in the middle section of the site. This makes the ground slightly higher at the site's edges and results in a permanent pool of water in the middle of the site. The actual elevation at the beginning of the trackway (from the fen margin to the centre) is 86.0 m OD, in the middle 85.5 m OD and 85.7 m OD at the end. The same pattern is found horizontally; on the west side the ground level is at 85.9 m OD, in the middle at 85.5 m OD and at the east border at 85.7 m OD, Figure III-42.

2. Geology

The geology of the site seems to have a more uniform structure than at site C, but similarly contains two distinct layers of gravel deposits. The geology of the site has been already discussed in the hydrochemistry section. However, the geological cross sections, well logs (Appendix 25) and the prickstock survey showed

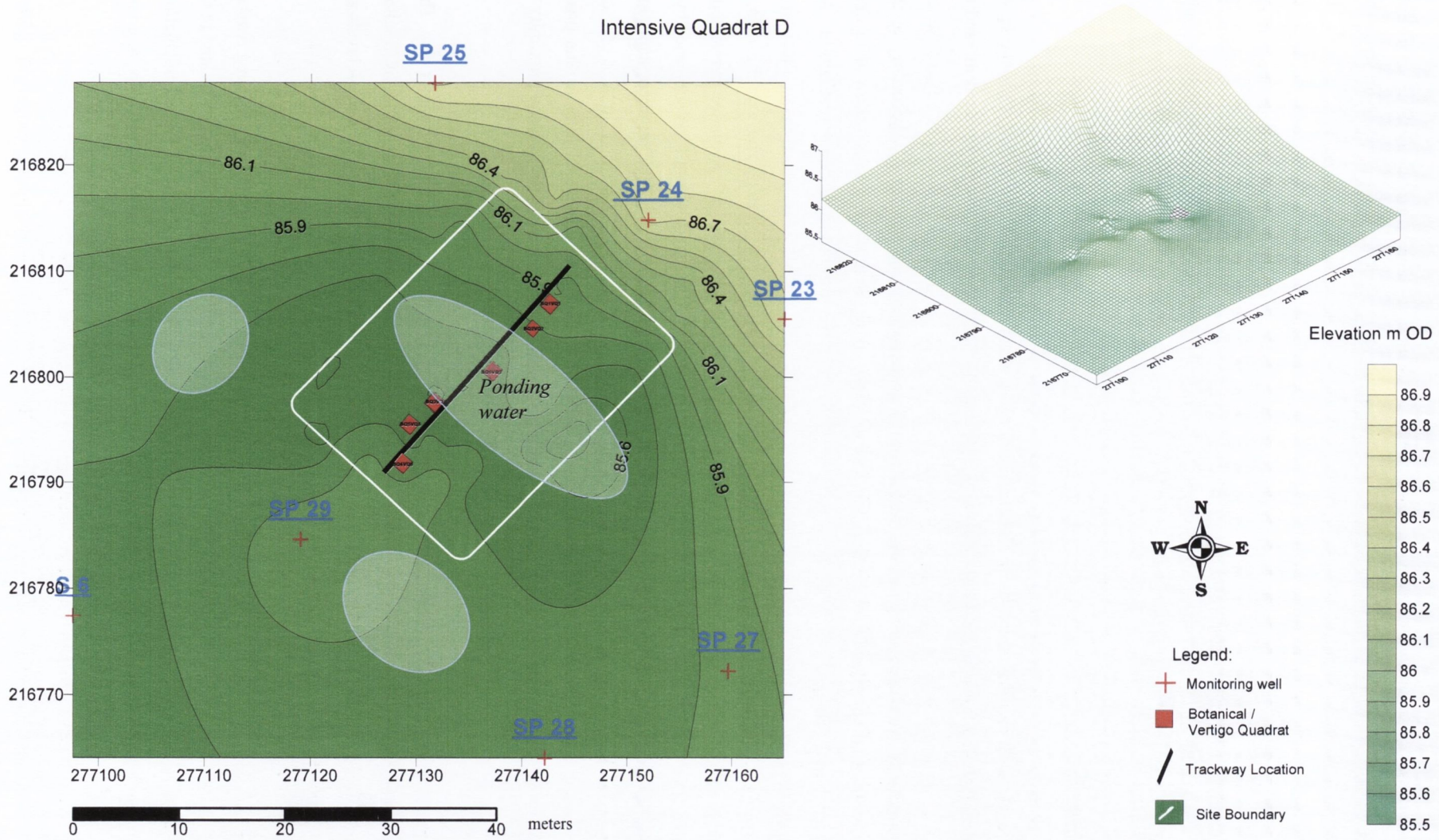



*Figure III-42 Topography and situational plan of site D, northern fen margin*

that the subsurface soil (peat) is relatively thin (<1-2m across the site) and irregular, i.e. the depth of peat may vary greatly across short distances. However, the general pattern is such that across the first 12 metres (from the beginning of the trackway) the peat depth only reaches 0.4m and later the depth steadily increases, reaching 1.2m at the end of the trackway. A thin layer of clay appears underneath the peat, which is underlain by gravel and sand deposits and further down by another clay layer (blue, lacustrine clay) and then again by gravel. The upper gravel layer is thin and probably pinches out at the up gradient field. This layer thins out between standpipes SP24 and SP29 and also between SP28 and SP29, and is a likely source of water in the middle, waterlogged section of the site. Water reported in the upper gravel layer shows confined conditions. The deep gravel appears at a depth of 11 metres and more (at site C at 8-9m) and water in this layer is under high hydraulic pressure resulting in artesian conditions.

## 3. Hydrogeology

Three water levels were monitored at site D. The deep standpipes reach depths of 11-12 m below ground level; all of them demonstrated artesian conditions but only two, namely SP24 and SP28, were screened in sand or gravel deposits. All others were reported to be screened in boulder clay; however hydrographs suggest strong hydraulic connectivity with underlying gravel, and a similar pattern was found at site C. According to the borehole log information provided by WYG from the time of well drilling, there was no water inflow at 11 m in SP27, but water 'burst' through, which indicates very high hydraulic pressure in the deeper gravel aquifer. All deep standpipes were artesian with heads extending nearly 2m above the ground. This caused data collection to be very difficult and available information is very limited at this site. However, using the existing data, a correlation analysis was performed between sites C and D, and this revealed a very good correlation between the two sites, Table III-37. Thus, it is accepted that a deep groundwater level at site D, as at site C, is supported by a local recharge from an up gradient field. Water level data is available in Appendix 26. One deep standpipe, SP28, did not follow the annual groundwater pattern as found in deep wells at Site C. Decreases in head pressure in both deep and middle screens in this location indicate a possible discharge in close vicinity to this point. Abundance of a well developed, wet loving species of common reed *Phragmites australis* in close proximity to SP28 and a pool of standing water between SP27 and SP28 supports this hypothesis.

Middle standpipes were screened between 2-3m below the surface and reached gravel, sand or boulder clay. This water layer was confined by the layer of clay and peat, and hence water levels have confined conditions. Shallow standpipes refer to the phreatic surface as placed in peat or peat and grey clay only. Hydrographs of all levels are presented in Figure III-43-Figure III-45.

The seasonal variations in all levels were similar to these recorded at site C, with minimum values being reached at the end of September - October and maximum values occurring usually in January. Standpipes located at the fen margin showed more pronounced groundwater fluctuations than those in the fen centre. Annual fluctuations within middle screens range from 0.18-1.19 m and these were highest in hydrometric year 2003. No long term trends are evident within this layer over the observation period 2002-2005.

Fluctuations within shallow water levels ranged between 0.08 to 0.77 m and the fluctuation range was uniform across the site. The range remained unchanged through the observation period (Table III-38), however, as

presented in Table III-39, some data suggests that minimum water levels were steadily decreasing throughout 2002-2005 and the minimum water table in SP28 was 0.22 m lower in 2005 with respect to 2002 data. It is also apparent that the phreatic level at site D is sensitive to prolonged drought periods that occur in the summer months. A similar pattern was found at site C.

From the information available, the water direction is from the north east to the south west; however, the phreatic level is highly controlled by local topography, artificial drainage and effects of peat cutting. The dominant flow is towards the site centre and further, towards the fen centre and the Milltown Feeder (i.e. in a south westerly direction). A very small difference was found between the phreatic level on the site and in the Milltown Feeder, with only a 0.3 m decline over 400 metres.

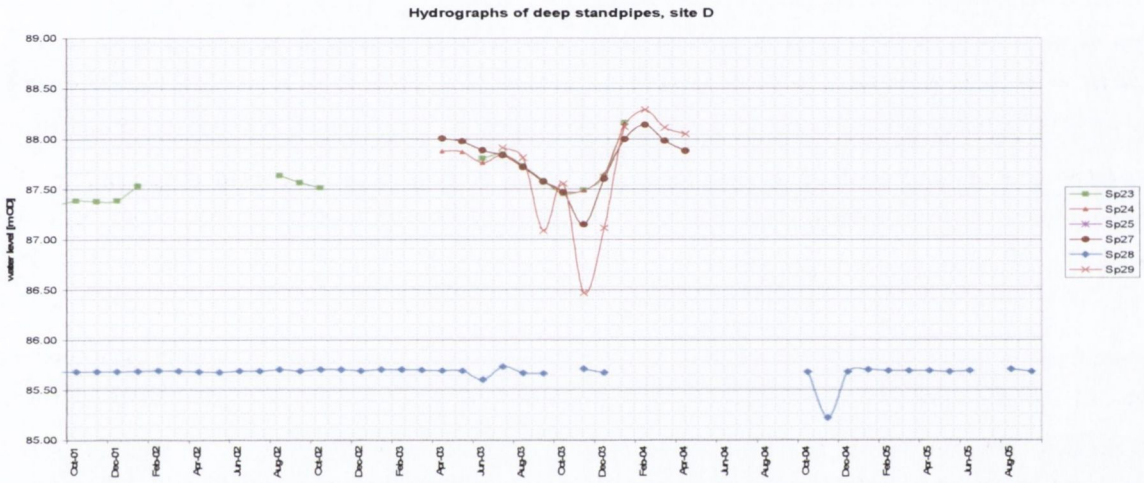



*Figure III-43 Monthly distribution of groundwater levels in deep standpipes at site D, northern side, 2002 -2005*

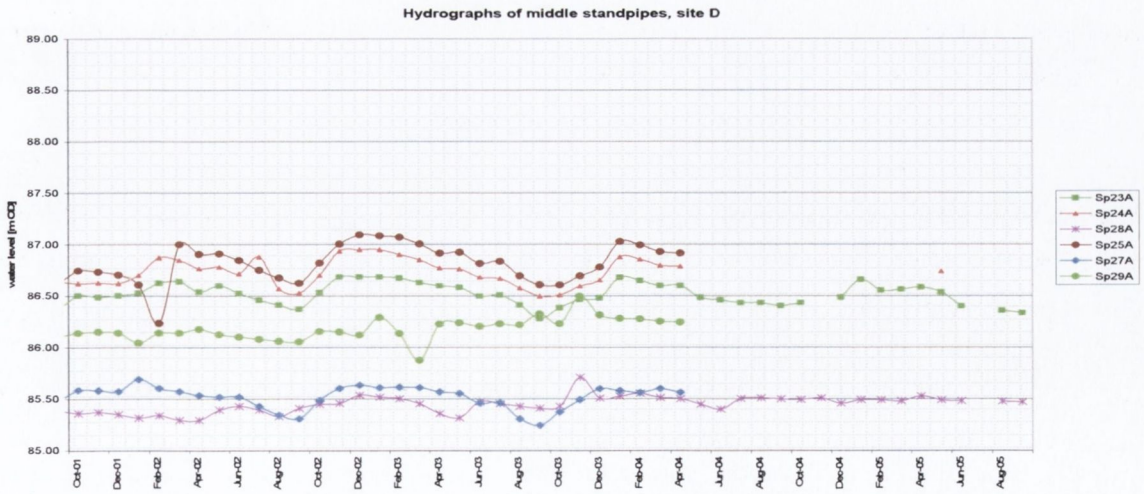



*Figure III-44 Monthly distribution of groundwater levels in middle standpipes at site D, northern side, 2002 – 2005*

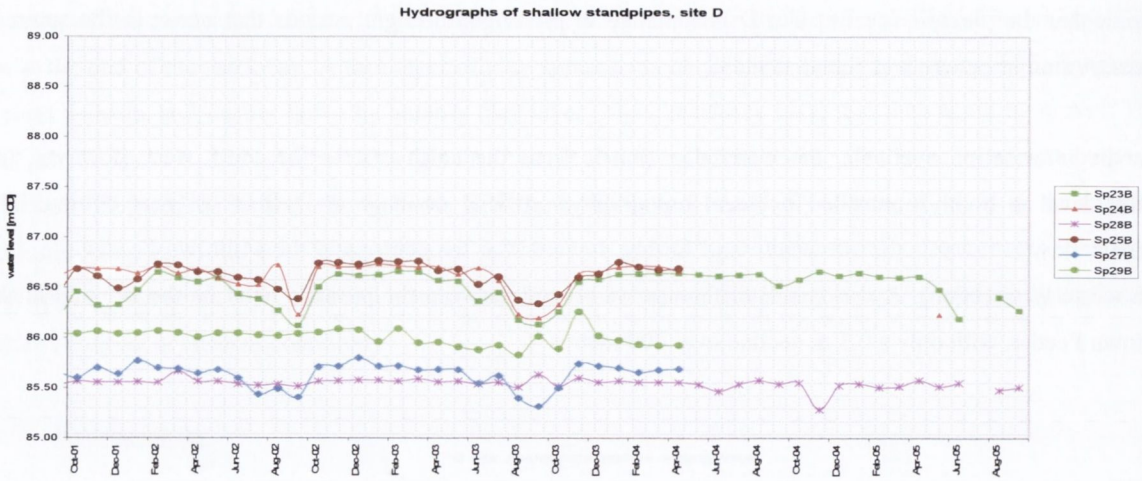



*Figure III-45 Monthly distribution of groundwater levels in shallow standpipes at site D, northern side, 2002 – 2005*

**Table III-37 Correlation coefficient between hydraulic heads in deep standpipes at site C and site D**

| | | Site D | |
|---|---|---|---|
| | SP | 24 | 27 |
| Site C | 1 | 0.87 | 0.87 |
| | 2 | 0.92 | 0.84 |
| | 3 | 0.92 | 0.82 |
| | 4 | 0.97 | 0.74 |

**Table III-38 Summary of groundwater levels (m OD) at site D (based on biweekly data, only full hydrometric year data included). Deep water levels were excluded due to limited data, see Figure III-43.**

| | | MIDDLE | | | | | |
|---|---|---|---|---|---|---|---|
| | | SP23A | SP24A | SP25A | SP27A | SP28A | SP29A |
| 2002 | max | 86.67 | 87.12 | 87.05 | 85.90 | 85.47 | 86.20 |
| | min | 86.35 | 86.51 | 86.23 | 85.28 | 85.29 | 85.83 |
| | average | 86.52 | 86.72 | 86.75 | 85.53 | 85.36 | 86.11 |
| | amplitude | 0.32 | 0.61 | 0.82 | 0.62 | 0.18 | 0.37 |
| | SD | 0.08 | 0.14 | 0.19 | 0.13 | 0.05 | 0.07 |
| 2003 | max | 86.73 | 87.02 | 87.09 | 85.63 | 85.54 | 86.68 |
| | min | 86.13 | 86.49 | 86.59 | 85.14 | 85.32 | 85.49 |
| | average | 86.54 | 86.75 | 86.86 | 85.49 | 85.44 | 86.19 |
| | amplitude | 0.60 | 0.53 | 0.50 | 0.49 | 0.22 | 1.19 |
| | SD | 0.14 | 0.16 | 0.16 | 0.15 | 0.06 | 0.18 |
| 2004 | max | 86.68 | | | | 86.03 | |
| | min | 86.38 | | | | 85.36 | |
| | average | 86.52 | | | | 85.51 | |
| | amplitude | 0.30 | | | | 0.67 | |
| | SD | 0.10 | | | | 0.13 | |
| 2005 | max | 86.68 | | | | 85.53 | |
| | min | 86.32 | | | | 85.44 | |
| | average | 86.49 | | | | 85.49 | |
| | amplitude | 0.36 | | | | 0.09 | |
| | SD | 0.12 | | | | 0.02 | |

| SHALLOW (*continued*) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | SP23B | SP24B | SP25B | SP27B | SP28B | SP29B |
| 2002 | max | 86.65 | 86.73 | 86.77 | 85.82 | 85.77 | 86.08 |
| | min | 86.12 | 86.19 | 86.35 | 85.36 | 85.51 | 86.00 |
| | average | 86.43 | 86.60 | 86.60 | 85.62 | 85.56 | 86.04 |
| | amplitude | 0.53 | 0.54 | 0.42 | 0.46 | 0.26 | 0.08 |
| | SD | 0.17 | 0.15 | 0.11 | 0.13 | 0.05 | 0.02 |
| 2003 | max | 86.70 | 86.75 | 86.82 | 85.80 | 86.03 | 86.50 |
| | min | 86.05 | 86.17 | 86.31 | 85.21 | 85.42 | 85.73 |
| | average | 86.46 | 86.57 | 86.61 | 85.60 | 85.57 | 85.97 |
| | amplitude | 0.65 | 0.58 | 0.51 | 0.59 | 0.61 | 0.77 |
| | SD | 0.21 | 0.22 | 0.17 | 0.17 | 0.10 | 0.15 |
| 2004 | max | 86.65 | | | | 85.65 | |
| | min | 86.26 | | | | 85.47 | |
| | average | 86.59 | | | | 85.54 | |
| | amplitude | 0.39 | | | | 0.18 | |
| | SD | 0.08 | | | | 0.04 | |
| 2005 | max | 86.66 | | | | 85.62 | |
| | min | 86.09 | | | | 85.29 | |
| | average | 86.50 | | | | 85.52 | |
| | amplitude | 0.57 | | | | 0.33 | |
| | SD | 0.17 | | | | 0.07 | |

**Table III-39 Difference between maximum and minimum levels in the consecutive hydrometric years 2002-2005, (based on biweekly data, only full hydrometric year data included)**

| MIDDLE | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | SP23A | SP24A | SP25A | SP27A | SP28A | SP29A |
| 2003-2002 | Max | 0.06 | -0.10 | 0.04 | -0.27 | 0.07 | 0.48 |
| | Min | -0.22 | -0.02 | 0.36 | -0.14 | 0.03 | -0.34 |
| 2004-2003 | Max | -0.05 | | | | 0.49 | |
| | Min | 0.25 | | | | 0.04 | |
| 2005-2004 | Max | 0.00 | | | | -0.50 | |
| | Min | -0.06 | | | | 0.08 | |
| 2005-2002 | Max | 0.01 | | | | 0.06 | |
| | Min | -0.03 | | | | 0.15 | |
| **SHALLOW** | | | | | | | |
| | | SP23B | SP24B | SP25B | SP27B | SP28B | SP29B |
| 2003-2002 | Max | 0.05 | 0.02 | 0.05 | -0.02 | 0.26 | 0.42 |
| | Min | -0.07 | -0.02 | -0.04 | -0.15 | -0.09 | -0.27 |
| 2004-2003 | Max | -0.05 | | | | -0.38 | |
| | Min | 0.21 | | | | 0.05 | |
| 2005-2004 | Max | 0.01 | | | | -0.03 | |
| | Min | -0.17 | | | | -0.18 | |
| 2005-2002 | Max | 0.01 | | | | -0.15 | |
| | Min | -0.03 | | | | -0.22 | |

## 4. Estimation of groundwater flow velocities

Data restriction allowed for computing Darcy's velocities along two profiles only, namely between SP23 and SP28 and between SP24 and SP29. Determined velocities were lower than values found on site C and ranged from 0.006-0.017 m/day. Higher values were established along SP23-SP28 profiles and confirmed the hypothesis of a discharge zone in close vicinity to the SP28, Table III-40, and Appendix 27.

**Table III-40 Summary of groundwater flow rates (lateral), expressed as specific discharge, in the deep gravel layer within site D**

k = 1.21E-05 [m/s]

| | dL | gradient | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | | m/s | m/day |
| 24-29 | 44.83 | 0.0059 | 0.0000001 | 0.006 |
| 23-28 | 52.00 | 0.016 | 0.0000002 | 0.017 |

In middle screens (upper gravels), established flow velocities were higher than in deeper gravels, suggesting that the majority of the groundwater flow occurs in the upper horizon. Again, higher values were found in proximity to SP28.

Flow rates in the peat layer were established at a level of c. 0.002-0.003 $m^2$/day (per unit width) and conformed to groundwater flow rates found elsewhere in the peat stratum. Results are summarised in Table III-42.

**Table III-41 Summary of groundwater flow rates (lateral), expressed as specific discharge, in the upper gravel layer within site D**

k = 1.21E-05 [m/s]

| | dl | gradient | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | | m/s | m/day |
| 24-29 | 44.83 | 0.012 | 0.0000002 | 0.013 |
| 23-28 | 52.00 | 0.021 | 0.0000002 | 0.022 |

**Table III-42 Summary of groundwater flow rates (lateral), in peat layer within Site D**

*k*= 1.19E-06 [m/s]

| | dl | gradient | Groundwater flow per unit width | |
|---|---|---|---|---|
| Standpipe | m | | $m^2$/s | $m^2$/day |
| 24-29 | 44.83 | 0.02 | 0.00000002 | 0.002 |
| 23-28 | 52.00 | 0.01 | 0.00000003 | 0.003 |

Analysis of the vertical specific discharge between the upper gravel and a peat layer showed upward flow for the following nests: SP23 (0.0002 m/day or 0.73 m/yr), SP24 (0.0018 m/day or 0.66 m/yr), SP25 (0.0018 m/day or 0.66 m/yr), SP29 (0.0017 m/day or 0.62 m/yr); however, nests SP27 and SP28 accounted for a downward flow of 0.0012-0.0014 m/day (0.44 - 0.51 m/yr, Table III-43). That confirms again that upward seepage is localised and occurs in places where geology provides a window for upward flow and that is highly variable around the whole fen margin. Darcy's flow velocities of the upward flow within site A conform to velocities found at other sites B and C.

**Table III-43 Summary of vertical flow rates (expressed as specific discharge) between upper gravels and the peat in selected standpipes within Site D. Positive values denote upward flow.**

| | dl | *k* | Specific discharge | |
|---|---|---|---|---|
| Standpipe | m | [m/s] | m/s | m/day |
| 23A-23B | 2.00 | 1.96E-07 | 0.000000002 | 0.0002 |
| 24A-24B | 2.00 | 3.43E-07 | 0.00000002 | 0.0018 |
| 25A-25B | 2.00 | 2.12E-07 | 0.00000002 | 0.0018 |
| 27A-27B | 2.00 | 2.42E-07 | -0.00000001 | -0.0012 |
| 28A-28B | 2.00 | 3.38E-07 | -0.00000002 | -0.0014 |
| 29A-29B | 2.00 | 2.19E-07 | 0.00000002 | 0.0017 |

5. Vertical flow modelling using temperature profiles

The use of the prickstock was very limited at site D due to the very thin peat depth; however, the conductivity chart presented in Appendix 16 indicates a potential for seepage around 13th and 26th -27th metre points of the trackway.

Nevertheless, the survey revealed that site D has a much different geomorphology than site C, with a shallower peat depth of about 40-50cm and EC values of 500-600μS/cm. This increased gradually towards the fen centre but at the end of the site reached only 1.2 metres. Low EC values at the bottom of the peat layer were most likely caused by the influence of the clay underlying the peat. There were a few patches of higher conductivity values that could have been caused by different, more mineralised material within the peat. The peat temperatures remained above 11°C up to 50 cm below the surface and decreased steadily down to 9.7°C. Temperatures at the same depths at site C were somewhat lower. As the site is underlain by clay, and there are lower conductivity and higher temperature values, it seems likely that, along the trackway, the site is more affected by surface derived water than directly by groundwater.

6. Conclusions

Generally, the deep water aquifer showed the direction of flow towards the south west. The middle and shallow water levels, however, showed a more southerly flow direction, which is controlled by the seepage zone located between standpipes SP28 and SP27, where the upper gravel pinches out.

The conceptual model of groundwater recharge is similar to that at site C. Groundwater recharges relatively close by and travels with relatively high flow velocities towards the fen margin where it discharges into the peat. Lateral flows are dominant; however, vertical movement is also apparent and is controlled by the presence of lacustrine clay across the site.

Horizontal and vertical water profiles and groundwater level were done by using Trimble® GPS and show a very small gradient in surface water levels between the margins of the fen and the Milltown Feeder – for both sites C and D $i = 0.00075$, which is a decrease of 0.3 m over 400 metres. At the same time, the fluctuations in the Milltown Feeder are c. 0.3 m throughout the year. As the main recharge for the north side of the Fen comes from the up gradient fields, the water changes in the drain do not seem to be a controlling factor of the phreatic level at the fen margin.

## *III-2.2.3. Summary of the Hydrological Regime*

In essence, the results of the above analysis, which are based on piezometry, electrical and temperature probing, borehole logs and detailed topographic surveys, indicate a significant difference in the behaviour of the northern and southern fen margins, although springs and seepages are the main mechanisms for water supply to the fen on both sides. On all intensively investigated sites, there is a complex intercalation of beds of unconsolidated material: gravel, sand, clay and peat, which, in some senses makes each site unique. However, the fen is a

shallow depression in thick gravel at the edge of the Curragh plateau, lined with low permeability clay or marl and filled with a relatively thin bed of peat. The complexity of the hydrogeology arises particularly at the margin of the wetland where the peat and clay feather out.

According to the results as presented, the dominant mechanism of the phreatic water flow at each studied site is a lateral flow driven by a groundwater head in the Curragh aquifer, amplified by a strong upward flow in places where the geology is favourable (shallow peat, lacking a clay layer) or where an old drainage system or peat cutover zone facilitates seepage, and these usually occur on a sloping fen margin. Water discharges through the different locations and later flows laterally toward the fen centre and eventually discharges into the Milltown Feeder. As such, the hydraulic head in underlying gravel is important to sustain all discharge points, as a reduction in head below the elevation of a discharge point will imply deactivation of the discharge location, causing a drying up of the most marginal zones and reducing net water inflow into the fen.

While the general regional groundwater flow is in a roughly northerly direction in the vicinity of the fen, it was important to establish local variations in that flow. The local directions of flow would particularly affect the supply to each of the two sides of the fen, the northern margin along the Milltown Road and the southern margin on the Curragh side. Detailed analysis of the borehole water levels, and earlier the hydrochemistry have indicated that the supply to the springs and seepages on the northern margin of the fen come from relatively local recharge. A consequence of the northern sites being recharged relatively locally is that they respond comparatively quickly to rainfall, often within a day. The southern sites may take longer (a few days) to respond to heavy rainfall, but in all cases the speed of response depends on the season (soil moisture deficit) as well as the scale of the site itself (phreatic levels at small scale sites can be seen to respond to direct rainfall input). The implications are that the sites on the northern margins are less likely to be impacted by abstraction within the main Curragh Plateau. Conversely, any risky activities occurring within the northern extent of the catchment area are likely to have a local effect, mainly on this side of the fen.

Both water quantity and quality shall be considered potentially at risk on both sides as a high content of organic pollution was found in the fen water at both sides.

Determined vertical flow velocities (determined as specific discharge) showed an important difference between site A and the other study sites. Specific discharge values determined for sites B-D showed were similar falling within a range of 0.5-1.5 m/yr. At site A, however, velocities of a similar order of magnitude were found in one location only, specifically between SP31/S10, which is the most marginal location. In all other places where estimates of vertical water movement were possible, seepage velocities were in a range of a few centimetres per annum only. At the same time, vertical permeabilities at site A did not differ much from that determined for other sites; all were within the same order of magnitude (Appendix 33). In fact, permeabilities at site A were slightly higher than at sites B-D. Lower seepage velocities determined within site A suggest much lower volumes of water delivered into this site in comparison with other sites, but this was expected due to topographical differences across the fen, with site A being the most elevated of all sites. The meteorological analysis outlined in an earlier section of this chapter (III-1.2.4) revealed that actual evapotranspiration losses on the fen are approximately 0.55-0.6 m/yr and this balances neatly with water delivery rates found at sites B-D. To keep the fen peat surface moist, evapotranspiration losses must balance water delivery rates, otherwise the fen

surface would have dried up. Quantitative analysis on vertical specific discharge rates indicates, therefore, that hydraulic vertical gradients within site A are not strong enough to support upward seepage at the required rates (except for the most marginal zone) and therefore this seepage zone plays an important role in keeping the entire site A wet. The reduction in seepage velocity in this location that would cause delivery rates to fall below the rate of evapotranspiration losses may affect, then, a more extensive area of the fen, and not only the immediate surroundings on the discharge zone. As proven by the prickstock survey, it is likely that there are a large number of much more localised, separate discharge points within the seepage zone, the extent of which is defined by local geology, and occurs in places where there is either no layer or a thin clay layer beneath the peat. As water delivery throughout the marginal locations within site A is likely to be key discharge zone for this site and also lower parts of the fen below site A, further works should focus on assessing sustainability of the delivery rates and this is undertaken in later parts of this thesis.

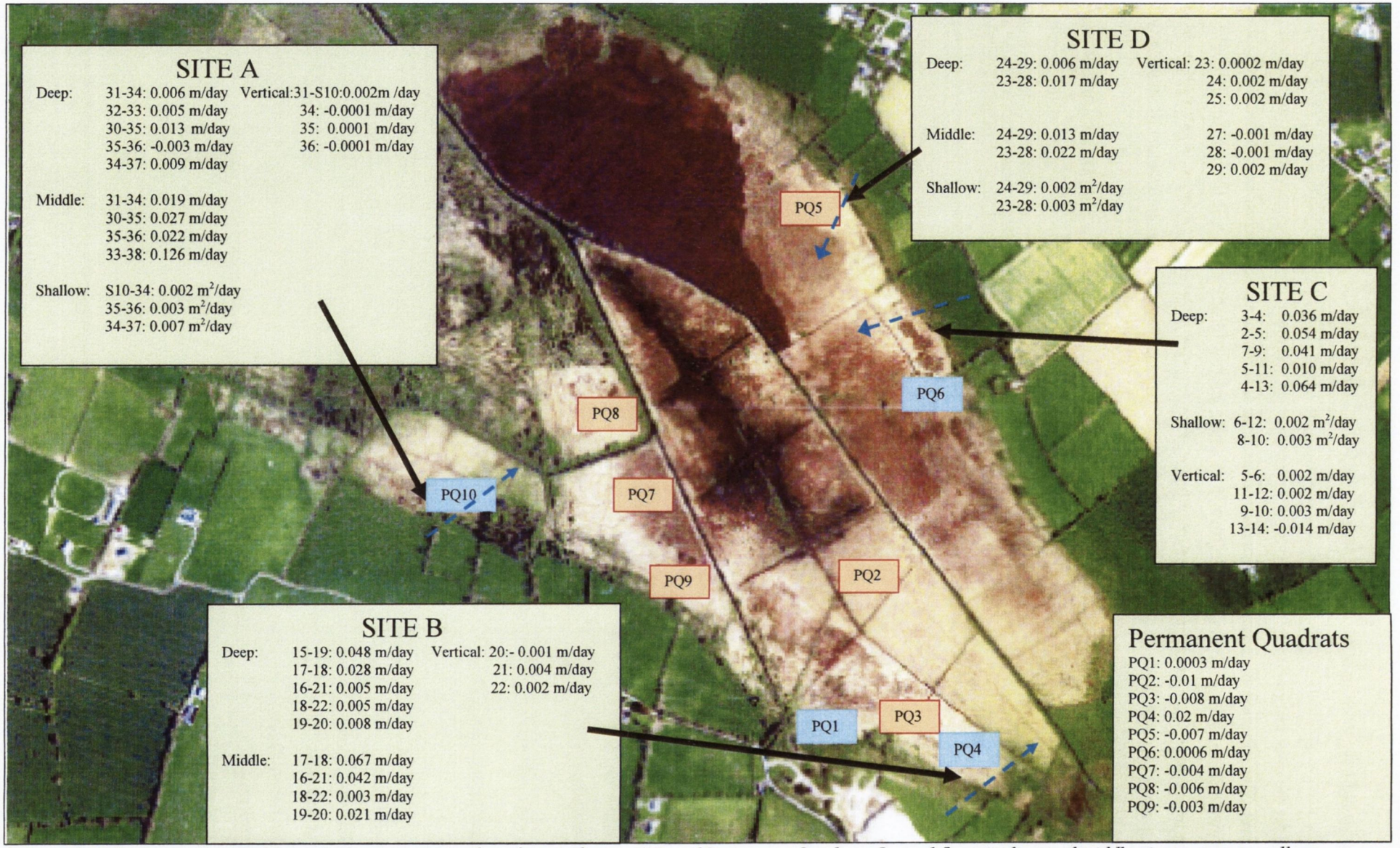



*Figure III-46 Summary of groundwater discharge estimates from four study sites A-D and Permanent Quadrats. Lateral flows in deep and middle piezometers as well as vertical flows are expressed as specific discharge [m/day]; flows in shallow piezometres are expressed as q per unit width [$m^2$/day]; blue arrows indicate direction of the [illegible] positive values denote upward flow. Blue squares denote dominating upward seepage and orange – downward.*

## III - 3. Conceptual Model of the Recharge Mechanism at the Fen Margin

The above analysis allowed the establishment of the conceptual model of the fen margin. The samples of evidence presented above indicate that groundwater discharge is a principal source of water and it occurs in two forms – seepage (vertical and horizontal depending on local geology) and the spring - although one could be said to merge into the other. However, the difference in their hydrological characteristics does give rise to different habitats. The spring has typically higher velocities of flow than seepage, although the driving head may be similar for both. It is the resistance to flow provided by peat and clay which can make a difference. Thus, a relatively thin layer of resistant material can have a strong influence on the habitat which may exist on the surface. The mechanism of seepage delivery is dependent on the layering of peat, clay and gravel at a given site. Giving that there is a significant driving head in the regional gravel, the rate of delivery (discharge) is essentially controlled partly by the elevation of the site and partly by the hydraulic resistance offered by the overlying layers.

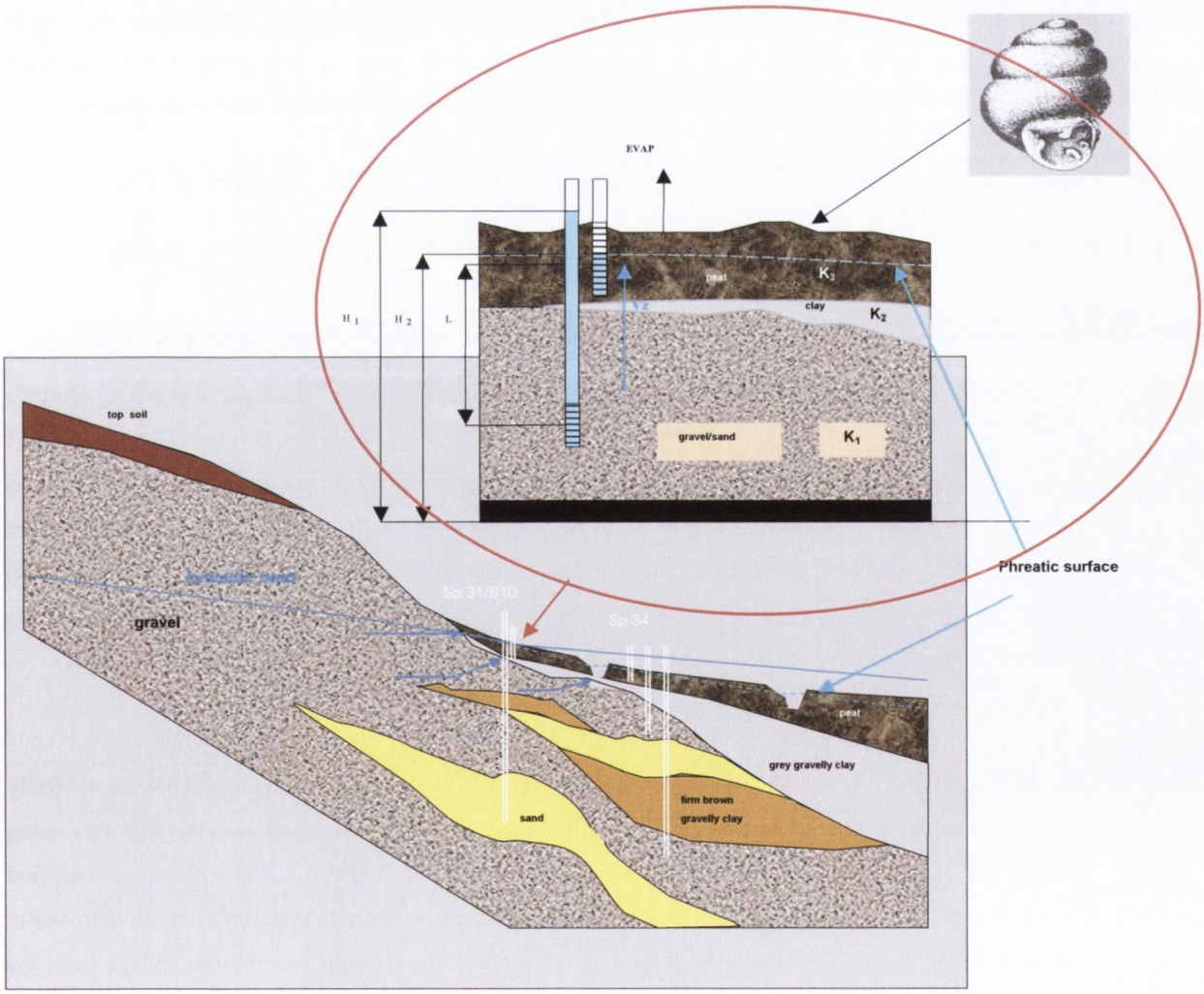



*Figure III-47 Conceptual model of the recharge mechanism through seepage at the fen margin.*

The conceptual model of the seepage mechanism presented here assumes that there are three layers of different permeabilities within the vertical profile. The upper two layers of peat and clay are much less permeable and act

as a confining layer for the lower, much more porous gravel layer. The confining layer of peat and clay results in an artesian head in gravels, causing upward vertical flow whenever the driving head forces are stronger than the resistance caused by the confining layer. The rate of that flow is controlled by:

- Permeability of the soil in the vertical profile through which the water movement occurs – this is a mean vertical permeability depended on thickness and permeability of each geological strata within the profile,
- Hydraulic head of water in a confined layer,
- Evapotranspiration rate.

In order to keep the peat layer wet, the volume of water that is supplied to that layer must be delivered at a rate that is higher than the evapotranspiration rate, otherwise more water will be depleted than supplied to the stratum.

$$EVAP \leq q_z$$

*Equation III-19*

What controls the stability of the phreatic level is therefore the balance between the two constituents. To validate this model, the three variables, of seepage flow velocity (specific discharge), evapotranspiration and fluctuation of water table in the phreatic zone were studied from 2002-2005. The adopted approach is presented below:

## III-3.1. Methods

To establish parameters of the model, the following analyses were undertaken:

1. The upward seepage velocity (expressed as specific discharge) $q_z$ [m/sec] was calculated using Darcy's law (Equation III-16). Water level data were available on a biweekly basis and were collected in SP31 (deep gravel) and S10 (peat layer). An understanding of the working mechanism of that model requires a good knowledge of physical parameters of the soil profile. Depth and geomorphology across the studied vertical were determined based on geological information (geological logs from SP31 and S10) and hydraulic conductivity for each strata was established based on *in situ* tests (chapter III-2.2.2.1, Appendix 13), and review of previous reports on Pollardstown Fen (Daly, 1981; Hayes *et al.*, 2001).

2. Evapotranspiration was calculated according to the methodology presented in chapter III-1.1.4. Daily actual evapotranspiration (AE) was computed based on Potential Evapotranspiration (PE) data using mixed crop coefficients from Table III-4. Potential evapotranspiration was computed using a modified Penman-Monteith equation (Allen *et al.*, 1998) and was based on climatic data from the weather station installed on the fen. Both PE and AE data were presented on the graph against the seepage velocity. Data was smoothed using a 14 day moving average trendline. Frequency duration curves (methodology in chapter III-2.1.1) were produced for the months May to October[11] (when evapotranspiration is at its

[11] Months May-October were selected to match with the *Vertigo geyeri* habitat study and due to the fact that the snail is most active in these months.

maximum) to evaluate long term changes and to assess its contribution to climatic changes into potential trends in the hydrological regime.

3. Net seepage was established by deducting actual evapotranspiration from the seepage velocity and that was compared with fluctuations of the water table within the phreatic zone. Rainfall was included in soil moisture budgeting of the actual evapotranspiration computation.

4. The water table in peat was observed in two locations, in standpipe S10 – which was used for calculating the seepage velocity and in a phreatic tube, which was installed for monitoring the microhydrological regime of the *Vertigo geyeri* site. This phreatic tube was placed one metre down the slope from S10 with an 11 cm decrease in elevation. Data from the S10 standpipe was collected on a biweekly basis and data in the phreatic tube was collected automatically using a pressure transducer and data was recorded in hourly intervals. These were later aggregated in average daily water levels. (More information about this instrument will be given in the next chapter regarding the microhabitat of *Vertigo geyeri sp.*).

## III-3.2. Results

1. The specific discharge between SP31 and S10 vs. evapotranspiration rates are presented in Figure III-48. Both parameters presented strong seasonal variations. The Darcy's velocity followed the same annual pattern of groundwater levels, which is due to 'head-fixed' phreatic levels until the head on the base drops. The strongest seepage velocities (and subsequently seepage rates) occurred at the end of a recharge period, February - March, where water levels in deep gravel were at their highest, and the lowest at the end of the summer, or mid autumn. In terms of evapotranspiration, the phenomenon depends on many meteorological parameters but mainly radiation and air temperature; therefore the lowest values were recorded, as expected, in winter and the highest in summer months. Over the four years of the observation period, there has been a clearly decreasing trend in the specific discharge, which was expected due to decreased water levels in deeper gravel. It is also apparent that evapotranspiration rates tend to exceed seepage velocities during the summer months and this has an immediate reflection in the stability of water levels in peat.

2. The highest seepage velocities (specific discharge) were recorded during the winters of 2001 and 2003 and were at 0.005 and 0.004 m/day respectively. In 2004, seepage rates hardly exceeded 0.002 m/day and the maximum in winter that year was at 0.0022 m/day and in the following year 2005 – 0.0024 m/day. In both 2002 and 2003, no less than 0.0019 m/day was recorded until the end of September with values exceeding 0.002 m/day throughout most of the summer (May-October). In 2004 and 2005, the seepage velocity at c. 0.0018 m/day remained only until the end of June and at the end of October in 2004 and 2005, groundwater flow velocities were at approximate 0 m/day and 0.0014 m/day respectively. The summary of the summer flow velocities presented in Table III-44 shows a significant fall in minimum and average Darcy's velocities between 2003-2005, Figure III-48.

3. The average actual evapotranspiration for months May - October 2002-2005 was at 0.0023, 0.0026, 0.0026 and 0.0024 m/day respectively with maximum values recorded usually in June. In 2002, the AE values were more evenly distributed throughout the summer than in the following years (Table III-44) which suggests more stable climatic conditions i.e. lesser air temperature fluctuations. High temperatures and prolonged droughts in September 2003 and May 2004 have increased actual evapotranspiration during those years, and this is reflected in the frequency duration curves presented in Figure III-49, which in approximately 75%-80% of data show higher values in 2003 and 2004 with respect to 2002 data. The difference is approximately 0.4 - 0.5 mm per day which over the 6 month summer period accounts for 55 and 60 mm increases in 2003 and 2004 compared to 2002 and constitutes a rise of approximately 13 -14% in total AE during months from May to October. Over May - October 2005, total summer actual evapotranspiration was 445 mm and approximately 7% higher than in 2002 for given months. The analysis is based on a relatively short observation period and therefore is not indicative of long term changes; nevertheless it can be stated that evapotranspiration losses were increasing between 2002 and 2005.

**Table III-44 Summary of daily summer evapotranspiration and seepage velocity rates [mm/day], June-September 2002-2005**

| | | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|
| **Summer specific discharge** | average | 1.93 | 2.16 | 1.52 | 1.62 |
| | maximum | 2.37 | 2.64 | 2.17 | 2.38 |
| | minimum | 0.94 | 1.49 | 0.00 | 0.68 |
| | amplitude | 1.43 | 1.15 | 2.17 | 1.70 |
| | SD | 0.45 | 0.36 | 0.57 | 0.63 |
| **Summer Potential Evapotranspiration (PE)** | average | 1.94 | 2.19 | 2.23 | 2.08 |
| | maximum | 4.51 | 5.32 | 6.75 | 5.52 |
| | minimum | 0.00 | 0.00 | 0.00 | 0.00 |
| | amplitude | 4.51 | 5.32 | 6.75 | 5.52 |
| | SD | 1.02 | 1.17 | 1.23 | 1.18 |
| **Summer Actual Evapotranspiration (AE)** | average | 2.26 | 2.56 | 2.59 | 2.42 |
| | maximum | 5.45 | 6.14 | 7.36 | 6.50 |
| | minimum | 0.00 | 0.00 | 0.00 | 0.00 |
| | amplitude | 5.45 | 6.14 | 7.36 | 6.50 |
| | SD | 1.19 | 1.37 | 1.38 | 1.35 |

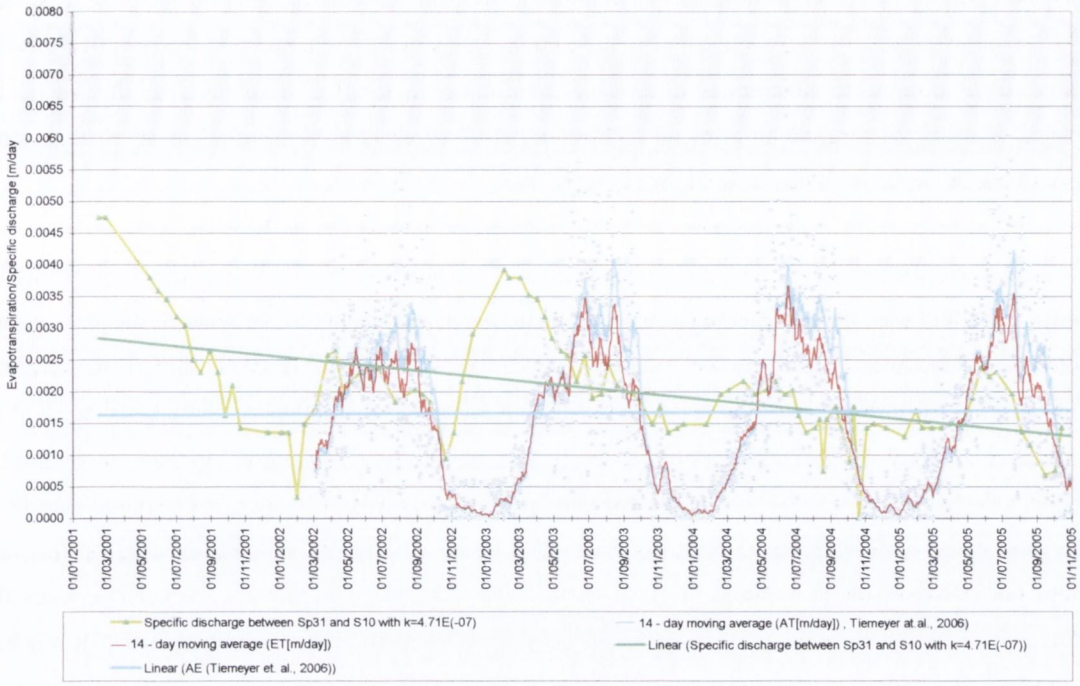



*Figure III-48 Distribution of seepage velocity and evapotranspiration rates at the fen margin, Site A, over 2001-2005*

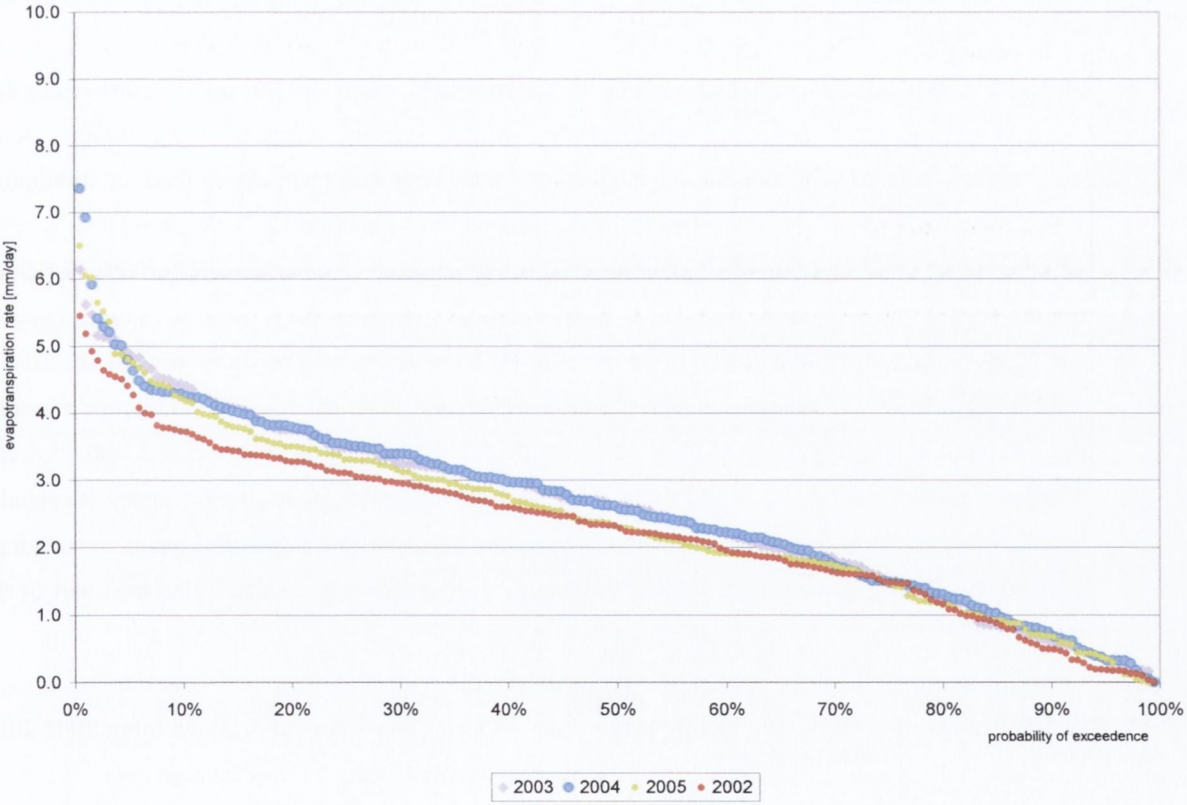



*Figure III-49Frequency duration curves of daily actual evapotranspiration rates measured over six month observation periods (May-October) between 2002-2005*

4. Net seepage was determined by deducting actual evapotranspiration from specific discharge. Average summer net seepage as well as the nominal range for the subsequent summers 2002-2005 are presented in Figure III-50. The graph shows an increase in net seepage range and a decrease in its average value over time. Figure III-51 presents distribution of net seepage, actual evapotranstion vs. water level fluctuations in peat between January 2001 and November 2005. It is apparent from this graph that

negative net seepage occurs during summer months and this pattern has been repeated each summer throughout the entire observation period 2002-2005. It should also be noted that the negative gradient has been increasing throughout 2002-2005 (Table III-45, Figure III-50) similarly to the fluctuation range, which may suggest that the groundwater delivery rate was not sufficient to sustain stable conditions and induced a lowering of the phreatic level.

5. A comparison of net seepage with the phreatic level, Figure III-51, shows that the 'seepage deficit' leads to instability of the phreatic level. As presented in Figure III-51, whenever the net seepage velocity is negative, i.e. there is less water delivered, the phreatic level recedes. Some water deficit is however accepted during the summer months, provided that subsequent re-wetting takes place and the peat is returned to its field capacity during the winter months, as for example happened in summer of 2002 and the winter of 2003. It is apparent that such re-wetting is necessary and requires significant seepage with velocities probably not less than 0.004 m/day (1.5 m/yr). When re-wetting (at this rate) does not occur, as for example in the winters of 2004 and 2005, the phreatic level remains unstable during the winter and carries on throughout the summer. Observations suggest, therefore, that it is both summer and winter seepage velocities which need to be sustained at certain levels in order to sustain the stability of the phreatic surface at a fixed head and that this head should reflect the desired hydrological conditions required by the fen's margin fauna and flora. Seepage velocities are proportional to a hydraulic gradient and this is related to a nominal difference between hydraulic heads in two piezometers between which the groundwater flow is computed. Subsequently, if the required minimum summer water level in peat is known and the seepage velocity is equal to the summer actual evapotranspiration rate, the minimum hydraulic head in the underlying aquifer required for sustaining a stable water level in the phreatic zone can be determined from Equation III-16. Such analysis requires definite information regarding the desired phreatic conditions at the fen margin and current information (Figure III-51) suggests that this level is at 88.45 m OD (0.1 m below the ground surface) in standpipe S10. This is supported by hydrograph for the phreatic level in a nearby sensitive site (Figure III-51). Such a water level was maintained in S10 between February 2001 and May 2003 (average measured water level), although occasional falls to 88.30 m OD did also occur and are associated with a lowered hydraulic head in underlying gravel (January 2002) and high evapotranspiration losses (September 2002). A definite hydrological regime within the marginal zone will be established based on studying a microhabitat of the selected indicator species *Vertigo geyeri*, which is a focus of the next part of this thesis.

**Table III-45 Summary of vertical specific discharge rates vs. water levels in peat, May-October 2002-2005**

| Year | Water Table Level | | | | Specific Discharge | | Net Seepage Rate | |
|---|---|---|---|---|---|---|---|---|
| | S 10 | | Phreatic tube | | | | | |
| | Average | Range | Average | Range | Average | Range | Average | Range |
| | m OD | m | m OD | m | m/day | m/day | m/day | m/day |
| **2002** | 88.40 | 0.16 | 88.35 | 0.17 | 0.0019 | 0.0014 | -0.0005 | 0.0048 |
| **2003** | 88.36 | 0.20 | 88.33 | 0.12 | 0.0022 | 0.0012 | -0.0003 | 0.0051 |
| **2004** | 88.32 | 0.26 | 88.25 | 0.31 | 0.0015 | 0.0022 | -0.0008 | 0.0067 |
| **2005** | 88.26 | 0.14 | 88.22* | 0.30* | 0.0016 | 0.0017 | -0.0011 | 0.0049 |

** data available until 11th September2005*

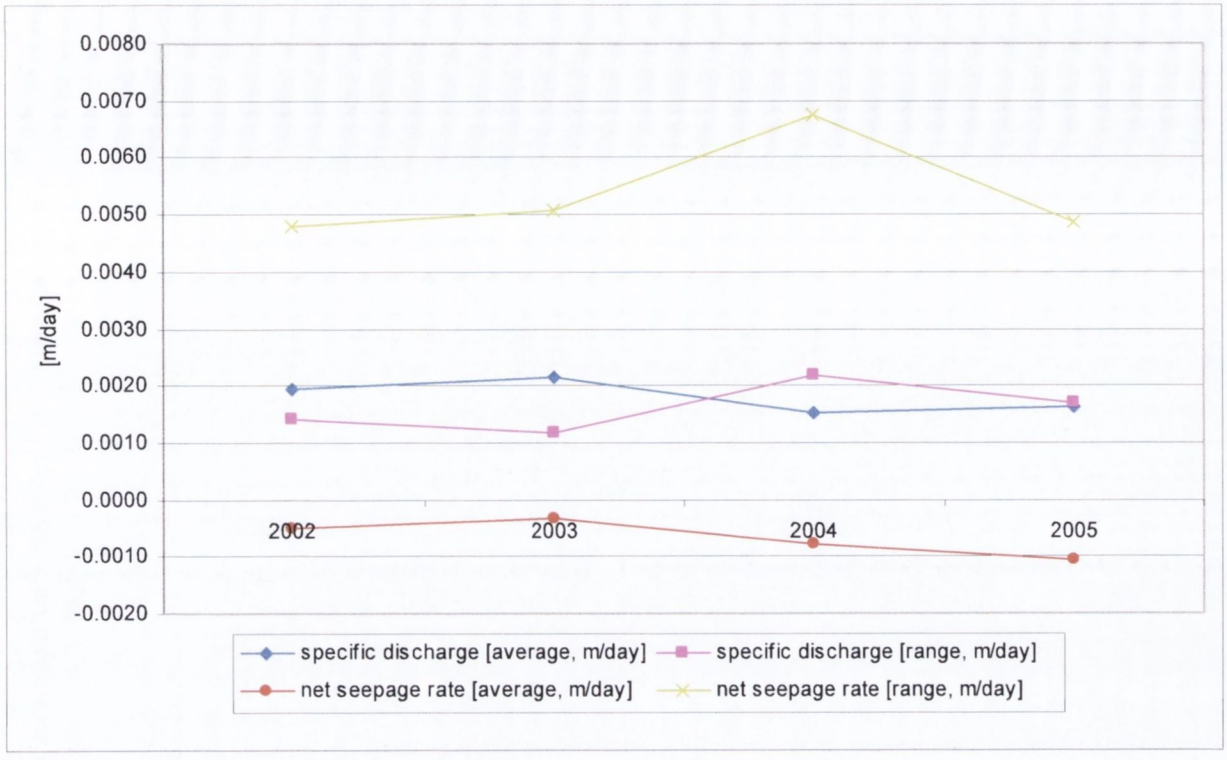



*Figure III-50 Distribution of vertical specific discharge and net seepage rates at site A, 2002-2005*

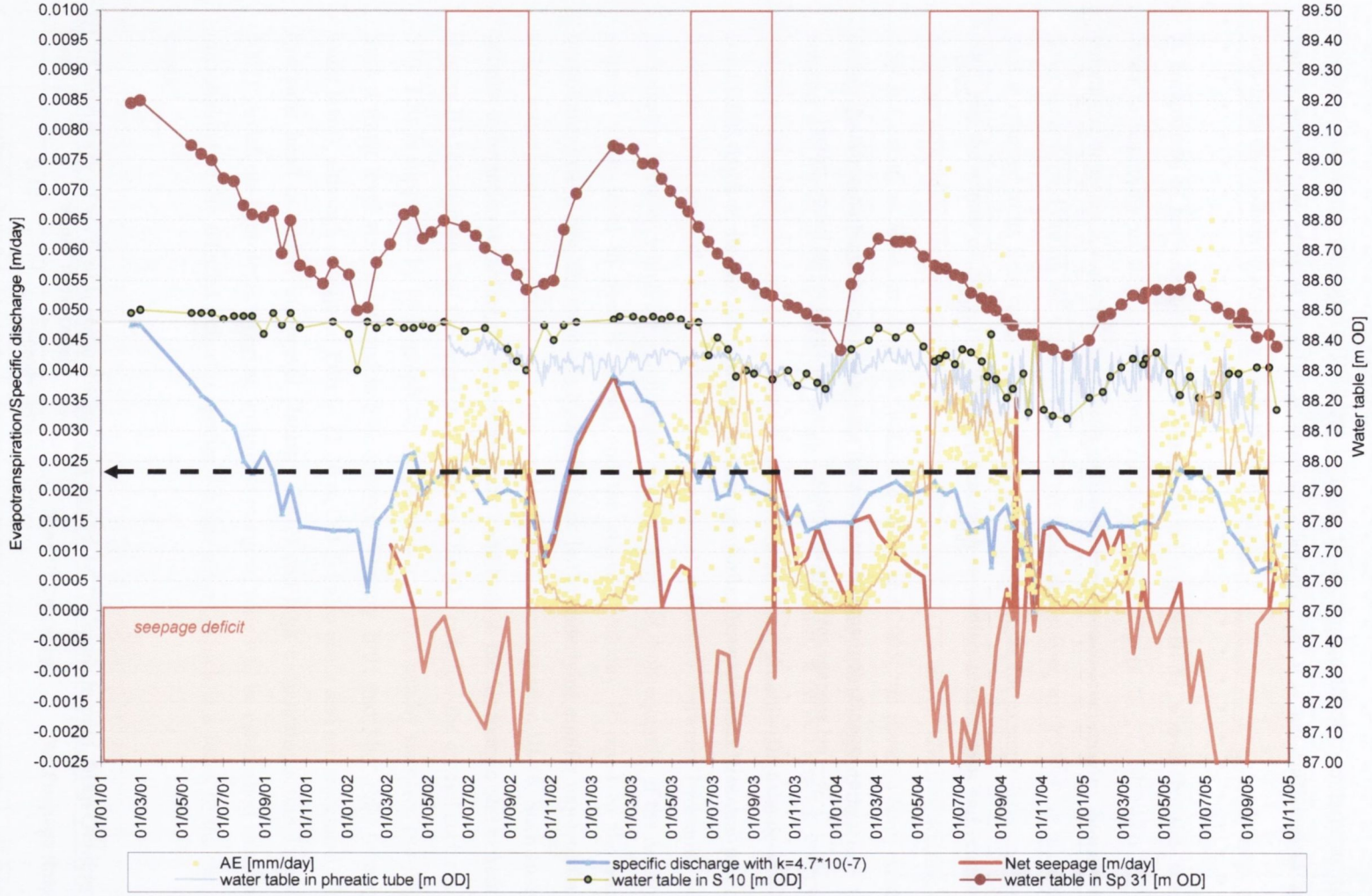



*Figure III-51 Distribution of water table levels vs.actual evapotranspiration and specific discharge, Site A, 2002-2005. Net seepage rate is constructed from subtraction of actual evapotranspiration from specific discharge rates. It is apparent that in summer months net seepage rates are negative and this results in lowering the phreatic surface.*

## III-3.3. Sensitivity of the Model

To assess the importance of the determination of the estimated values, a short discussion over the sensitivity of the model to different parameters will be given here.

As outlined before, the model is based on an assumption that the specific discharge is equal to the actual evapotranspiration rate. According to Darcy's law, the parameters controlling the seepage rate are: differences in hydraulic heads between the two layers ($h_1$-$h_2$), the distance between the two screens ($L$) and soil permeability ($k$). Since $L$ is constant, the sensitive variables of the model are only the differences in the hydraulic heads and soil permeability.

With constant permeability of the soil at the $k$ value estimated to be $4.72 \times 10^{-7}$ m/sec, changes in the hydraulic gradient cause linear changes in the seepage rate at a rate of 0.00068 metres per day (~0.7 mm/day) per 0.1 metre change in hydraulic gradient. This may be considered significant if compared with total monthly evapotranspiration for the winter months of c. 5-7 mm/month; however, evapotranspiration in winter is very inaccurately estimated by most calculations (van Wirdum, pers. comm.). The average daily summer evapotranspiration was approximately 2.5 mm/day over 2002-2005. The accuracy of a dip meter is usually 0.01 m, which allows for a total margin of error, while collecting the data, of 0.02 m. That is equal to a difference in specific discharge at c. 0.00014 m/day (0.14 mm/day).

Regarding the second variable of hydraulic conductivity, the adapted value was established based on geological information of the subsurface profile and hydrogeological information based on two *in situ* tests, one for gravel ($1.21 \times 10^{-5}$ m/s) and one for peat stratum ($1.19 \times 10^{-6}$ m/s). The hydraulic conductivity value for the clay layer was taken from Daly (1981; $1.1 \times 10^{-7}$ m/s) as there weren't any standpipes (screened in clay only) available for testing. Peat depth was also tested *in situ* using a steel rod and a confirmed peat depth of 1 m in the location of S10. The mean hydraulic conductivity reflects, therefore, physical properties in the soil matrix along the entire profile along which vertical water movement occurs.

Physical differences between the three subsequent strata are reflected in their ability to transfer water and differ between one another with a range of two orders of magnitude. As such, the depth of each stratum will have a significant effect on mean vertical permeability and this is disproportional to its relative permeability, i.e. the depth of low permeability will have a bigger effect on the mean permeability value than the depth of high permeability strata. A number of combinations were examined to see their effects on the mean permeability value and this is presented in Table III-46. The results show that reducing depth of the clay layer in favour of peat increases mean hydraulic conductivity by 1.38 when clay depth is reduced from 1.5 to 1 m and by 2.25 when clay depth is reduced from 1.5 to 0.5 m. Also, when only confining deposits of clay and peat are used for mean permeability estimates (as reducing and controlling flow velocities) these would cause an underestimation of discharge rates by 0.4. This suggests the high importance of clay deposits in controlling the vertical flow velocities.

It can be concluded that hydraulic conductivity is a parameter that is very sensitive to the geophysical structure of the profile and a good understanding of local geology and the physical properties of deposits within a vertical

profile is essential for proper estimates of vertical flow velocities. Depths of the fen deposits were read from geological borehole logs provided by WYG Ltd. (2002), therefore an assessment of error is not feasible.

**Table III-46 Summary table of different mean vertical hydraulic conductivities depending on a relative depth of gravel, clay and peat stratum**

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 4.5 | 371900.8264 | | |
| peat | 0.00000119 | 1 | 840336.1345 | | |
| clay | 0.00000011 | 1.5 | 13636363.64 | | |
| | | | | 14848600.6 | **4.71E-07** |

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 0 | 0 | | |
| peat | 0.00000119 | 1 | 840336.1345 | | |
| clay | 0.00000011 | 1.5 | 13636363.64 | | |
| | | | | 14476699.77 | **1.73E-07** |

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 4.5 | 371900.8264 | | |
| peat | 0.00000119 | 1.5 | 1260504.202 | | |
| clay | 0.00000011 | 1 | 9090909.091 | | |
| | | | | 10723314.12 | **6.53E-07** |

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 0 | 0 | | |
| peat | 0.00000119 | 1.5 | 1260504.202 | | |
| clay | 0.00000011 | 1 | 9090909.091 | | |
| | | | | 10351413.29 | **2.42E-07** |

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 4.5 | 371900.8264 | | |
| peat | 0.00000119 | 2 | 1680672.269 | | |
| clay | 0.00000011 | 0.5 | 4545454.545 | | |
| | | | | 6598027.641 | **1.06E-06** |

| *SP31/S10* | | | | | |
|---|---|---|---|---|---|
| | hydraulic conductivity | layer depth | | sum of di/ki | mean vertical hydraulic conductivity |
| | ki | di | di/ki | | sum of di/sum of di/ki |
| | [m/s] | [m] | [s] | [s] | [m/s] |
| gravel | 0.0000121 | 0 | 0 | | |
| peat | 0.00000119 | 2 | 1680672.269 | | |
| clay | 0.00000011 | 0.5 | 4545454.545 | | |
| | | | | 6226126.814 | **4.02E-07** |

## III-3.4. Conclusions

In summary; analysis of the water balance and the fen margin's water regime allowed the creation of a conceptual model of the mechanism for water delivery to the fen margin, which was outlined in the above section. The basis of this model lies in the moisture balance in the upper layer of peat, which is controlled by the amount of an upwelling flow and the evapotranspiration from the peat surface. The complex geology of the fen margin seems to be a leading factor controlling seepage. It is the intercalation of beds of unconsolidated gravel, sand, clay and peat that causes different spatial resistance. From information extracted from the borehole logs and the prickstocking survey, seepage tends to occur in places of either very shallow or absent clay layers, often in overgrown old drains; and its rate is controlled by the height of the driving head in the deep gravel layer and the permeability of the confining layer. Although the model shows high sensitivity to both parameters it is especially important to determine accurately the properties of the resisting layer. The numerical analysis based on Darcy's law allowed establishing the minimum specific discharge rates required to counterbalance the depleting force and the mechanism of evapotranspiration. Assuming permeability of the vertical profile at the level of $4.72 \times 10^{-7}$ m/sec, stable phreatic level at an approximate level of 88.45 m OD is sustained at S10 when the upward seepage between SP31 and S10, expressed in units of specific discharge, equals to 0.0025 m/day approximately (Figure III-51) during the summer time and this is equal to average daily summer actual evapotranspiration (Table III-44). An agreement between vertical gradients determined using Darcy's law and soil temperature gradients suggests similar order of magnitude of vertical flow. Although the numerical analysis was based on a fairly generic $k$ value and the prickstocking survey had a very localised extent, similar results of the two analyses give the model some confidence and demonstrate its potential.

# IV Chapter Four: Microhabitat of *Vertigo geyeri* sp. on Pollardstown Fen

The general hydrology of the sites supporting the selected protected habitats was described in the previous section. The complex routing of the groundwater flows as they emerge at the margin of the fen is now well understood and was proven to be site specific. It is apparent that stability of phreatic level at the fen margin, particularly on the southern site, i. e. site A depends on a balance between supplied seepage rates vs. evapotranspiration and is a function of differences between water levels in the phreatic zone and in the underlying aquifer. In this section, a linkage between the ecology and the hydrological regime will be investigated. To establish required Darcy's velocities that will sustain stable phreatic levels at the fen margin, these levels have to be known, and they will depend upon microhydrological conditions defined for a specific indicator species i.e. the *Vertigo geyeri* mollusc. The investigation of the snail's microhabitat is therefore focused on establishing microhydrological and micrometeorological characteristics of the key habitats of the species concerned. By studying an acceptable range of hydrological conditions including fluctuations in phreatic water levels, proximity to the water table, surface wetness, soil moisture content as well as meteorological conditions above the surface that the snail needs for living, it is hoped to identify conclusive and quantitative local thresholds that could feed into a regional scale model.

Extensive botanical and malacological surveys were undertaken by others, at the same locations as hydrological investigations, with the aim of gaining a better understanding of the vegetation habitat associated with the snail. The results of that study have been broadly discussed in 'Pollardstown Fen Interpretive Report (Review of 1997-2003 Work Progress)' prepared by White Young Green Ltd. (2004) and will be summarised briefly in this section prior to the results of the microhydrological and micrometeorological study in order to give a better overview of the snail and the habitat in which it is found. Three types of study areas will be mentioned in this chapter. These were explained in chapter two and are:

- Intensive Quadrats (these are sites A-E). Abbreviations used: (IQA, IQB, IQC, IQD, IQE)
- Botanical Quadrats (Abbreviations used: BQ1, BQ2, etc.)
- *Vertigo* Quadrats (Abbreviations used: VQ1, VQ2, etc.)

## IV - 1. Status of Vertigo geyeri on Pollardstown Fen and Botanical Associates of its Habitat

### IV-1.1. Distribution

In 2001, the entire fen margin has been the subject of a detailed survey of *V.geyeri* (Moorkens in WYG Ltd., 2004). Sixteen potential sites were identified, but only five locations had snails, which indicated little abundance of the snail on the fen site (Figure IV-1). The snail was found only on the fen margins, in areas associated with upwelling springs or ditches, on both the southern and northern sides of the fen. The southern populations were found in two locations, and these were later chosen for detailed hydrological and ecological study and were

named as Intensive Quadrats A and E. There were three extensive populations found on the north side of the fen, two of which were chosen for an in depth study; these were Intensive Quadrats C and D. The remaining snail location was found on the north east fen margin approximating to Mr Farrell's farm at East Rosberry and Scarlettstown. Other areas of less ideal habitat for *V. geyeri* were also identified with occasional species found around the tufa mounds to the east of the public entrance, but any suitable habitat was very sparse here. All populations of *V. geyeri* were found to be on peat based soils, and usually on sloping ground. Moorkens noticed that groundwater availability appears to be a significant factor indicating the species' presence. Constantly upwelling groundwater at the top of a slope helps to maintain wet, cool, humid conditions throughout the year but sloping topography prevents the habitat from flooding during wet conditions. Stable and shallow phreatic levels in peat substrate allows for continued humidity during dry conditions. The topography of the microhabitat in these conditions varies, with tussock forming vegetation being interspersed with low lying pools of standing water. This appears to be another important factor for *V. geyeri* as it allows for small variations in humidity, suitable refuge from cold and heat, and digestible food over a relatively small area, i.e. within the potential for short term movements of such a small animal.

In terms of water chemistry, Moorkens reports (after Dowding and Ryan, 1990, unpublished report) that present populations of *V. geyeri* have been associated with neutral pH levels; however, lower calcium levels were found in the *Schoenus* zone of Pollardstown fen compared with the *Phragmites* and flat fen areas. While very high Ca levels may be detrimental to *V. geyeri* (Moorkens, per.comm.) it is possible that its association with lower calcium levels is indirectly due to its requirements for a sloping habitat.

### IV-1.2. Population Estimate

Population estimates of *Vertigo geyeri* were first made in 1998 and 1999 (WYG Ltd., 2004). The aim of that work was to determine a quantitative baseline for *Vertigo* species to assess the properties of populations for which a level of acceptable change (LAC) could be determined. The adoted methodology was that two sites, one at each side of the fen were chosen (Permanent Quadrat 6 – off Intensive Quadrat C at the northern side and Permanent Quadrat 10 - within Intensive Quadrat A, on the southern side) and population counts within six randomly chosen 20 x 20 cm Quadrats were made. The results were then multiplied by the area that was distinguished as a 'suitable micro - habitat for the snail'. The results of the 1998 and 1999 counts are given in Table IV-1.

As is concluded in the table, the estimated population of *V.geyeri* in 1998 on the northern margin was 15,000 and on the southern margin 1,875. The results from 1999 show a significant decrease on both sides. This change in the population size was not understood. During the course of the population survey, microhydrology and micrometerology was not monitored. There was no visual evidence of external causes, and thus this may be a normal variation, potentially related to meteorological factors and/or with variations in grazing. A significant difference in population size over years is not unusual for *Vertigo* species. (Moorkens, pers. com.); therefore the area of occupancy is a better estimation of *Vertigo* status.

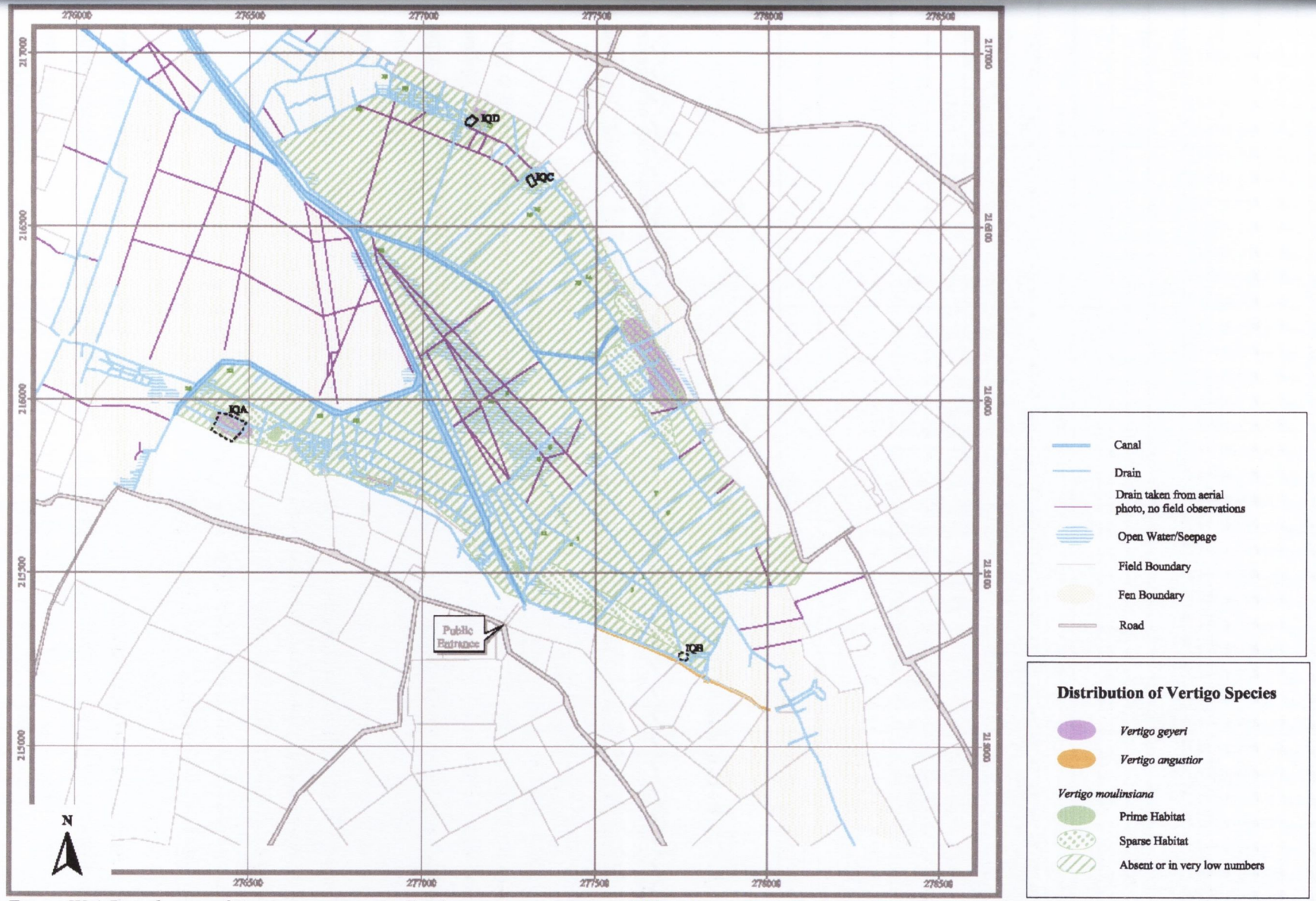



*Figure IV-1 Distribution of Vertigo species in Pollardstown Fen. Courtesy of White Young Green Ltd. (not to scale)*

**Table IV-1 Results and extrapolations from *Vertigo* population counts in 1998 and 1999 (after Moorkens in WYG Ltd., 2004).**

| Population estimated | *Vertigo geyeri* at PQ6 (Northern Side) | | *Vertigo geyeri* at PQ10 (Southern Side) | |
|---|---|---|---|---|
| | 1998 | 1999 | 1998 | 1999 |
| Count 1 | 14 | 3 | 0 | 1 |
| Count 2 | 6 | 4 | 2 | 2 |
| Count 3 | 5 | 0 | 3 | 0 |
| Count 4 | 14 | 4 | 0 | 2 |
| Count 5 | 0 | 3 | 1 | 1 |
| Count 6 | 1 | 4 | 3 | 0 |
| Total Count (0.24 m2) (A) | 40 | 18 | 9 | 6 |
| Width of population macro habitat | 20m | 20m | 5m | 5m |
| Length of population macro habitat | 45m | 45m | 10m | 10m |
| Area of macro habitat | 900$m^2$ | 900 $m^2$ | 50 $m^2$ | 50 $m^2$ |
| % suitable micro habitat | 10% | 10% | 100% | 100% |
| Area of suitable micro habitat (B) | 90 $m^2$ | 90 $m^2$ | 50 $m^2$ | 50 $m^2$ |
| Estimated numbers of individuals ((A x B) / 0.24) | 15,000 | 6,750 | 1,875 | 1,250 |
| % of 1998 result in 1999 | | 45% | | 67% |

## IV-1.3. Botanical Associations

The botanical survey carried out on the fen margin aimed to provide the botanical characteristics of *V.geyeri* preferred habitats and attempted to classify vegetation to the nearest community of National Vegetation Classification (NVC), (WYG Ltd., 2004).

The majority of the Quadrats that were surveyed within selected sites at Pollardstown Fen were linked to NVC category M13 the *Schoenus nigricans-Juncus subnodulosus* mire. Tussocks were often mixed with *Molinia caerulea, Juncus subnodulosus* and a range of sedges, notably *Carex panicea* and *C. viridula*. The moss carpet was often abundant and diverse in species with frequent presence of *Calliergonella cuspidata, Campylium stellatum*, and *Scorpidium cossoni.* The latter is indicative of calcium rich conditions and *V.geyeri* is often seen in its vicinity. In some places a calcite deposition on the peat was observed. More profound formations known as tufa were also recorded in some areas. Botanical Quadrats linked to this category are:

- At site A: BQ1, BQ2, BQ3, BQ6
- At site C: BQ1, BQ2, BQ3, BQ4, BQ6
- At site D: BQ2, BQ6
- At site E: BQ2

Of the remaining Quadrats, the majority were linked to community M22 *Juncus subnodulosus-Cirsium palustre* fen meadow where blunt flowered rush was dominant with a good diversity of sedges and other species. In the wettest sites, *Carex panicea* and *C. viridula* sedges were dominant. *Schoenus nigricans* was also often present but scattered and not in dense tussocks. Carpets of moss were abundant, particularly *Calliergonella cuspidata.*

This tends to occur in the wetter parts of the seepage areas where there is more likely to be some standing water. Botanical Quadrats linked to this category are:

- At site A: BQ5
- At site C: BQ5
- At site D: BQ3, BQ4
- At site E: BQ1

Only one Quadrat within Site A – BQ4 was linked to NVC M24 *Molinia Caerulea-Cirsium dissectum* fen meadow. This Quadrat was located on a slightly elevated plateau. *Molinia* was the main species as well as rushes, sedges and mosses with the rare *Tomentypnum nitens,* which was very abundant and is associated with base rich fen margins.

All quadrats surveyed at site B were linked with community M37 *Cratoneuron commutatum-Festuca rubra* spring. All of these Quadrats were located in an upwelling spring area with deposits of tufa being colonised by the characteristic moss *Cratoneuron commutatum*. *Nasturtum officinale* was also abundant and growing over the moss.

## IV - 2. Micrometeorology and Microhydrology

A microhabitat study was the second objective of this project and was undertaken on Pollardstown fen in the summer of 2002 and continued in the summer of 2003. Based on regional hydrogeological considerations, the study was carried out on two sides of the fen (South and North). Through long term observations and data collection, the aim was to define the hydrogeological regime, which also gives rise to the micrometeorology that is a feature of certain habitats. There were four key study areas around the fen where botanical and zoological research were carried out, in parallel with the hydrogeological study and these were Intensive Quadrats A (south side), E (south side), C (north side), D (north side). Physical and hydrogeological descriptions of sites A, C and D were given in detail in Chapter III. The last site, Site E, is located on the southern fen margin (277028; 215714) and is situated in a ditch. The main objective of this work was to gain a better understanding of the habitat that *V.geyeri* lives in. At present it is understood that the snail prefers wet or damp conditions and is associated with seepage zones. It is also anticipated that the snail is sensitive to alterations in phreatic levels; however, the range of these changes, annual cycles, distances to the water table and micrometeorology above the ground have not been analysed before. Thermal variations in air and soil, as well as humidity, surface wetness and solar radiation availability are components of this microhabitat and thus were recorded and analysed. The specific objectives of this part of the study were:

1. To characterise the nature and dynamics of physical micrometeorological and microhydrological characteristics of the fen margin in space and time.
2. To assess the role of these parameters in the control of snail distribution.
3. To define the snail preferred micro-hydrological habitat, which can be used for further assessment of sustainability of the fen margin.

### IV-2.1. Methodology

The experimental design was to study both micrometeorology and microhydrology. Micrometeorology concerns the study of atmospheric conditions close to the ground. Microhydrology concerns the study of groundwater (phreatic) level changes within the topsoil of this site, which was peat. These characteristics were studied in various locations around the fen margin to discriminate their spatial distribution and to find out if they correlate with the snail's occurrence. Long term observation within known snail locations were analysed to define its preferred microhabitat.

#### *IV-2.1.1. The Micrometeorological Regime*

In this part, the investigation was focused on meteorological conditions above and within the fen surface. Both snail positive and snail negative locations were investigated and data compared with meteorological inputs from a weather station located on the fen. The work strategy was planned to address the following:

- Analysis of micrometeorological spatial variability;
- Establishment of annual micrometeorological cycle on the fen margin;
- Analysis of soil moisture condition.

#### IV-2.1.1.1 Micrometeorological Spatial Variability

Firstly, the spatial uniformity of micrometeorological conditions required assessment and characterisation. Three characteristic sites were chosen for an in depth study. These sites (A, C, E) were typical for the fen margin habitat, therefore were instrumented and continuous records were collected. Both positive and negative sites of *Vertigo geyeri* were studied. Datasets were then randomly chosen for comparison with meteorological data collected from the conventional weather station. Chosen locations are presented in Table IV-2. Instrument locations within these sites are presented in Appendix 28.

**Table IV-2 Microhabitat monitoring locations, summer 2002**

| Site A | | | | |
|---|---|---|---|---|
| No. | Beginning | End | Location | Vertigo presence in 2000 or 2001 |
| 1. | 27.05.2002 | 11.07.2002 | BQ2/VQ2 | No |
| 2. | 11.07.2002 | 16.07.2002 | BQ3/VQ3 | No |
| 3. | 16.07.2002 | 18.07.2002 | Outside VQ4 | No |
| 4. | 18.07.2002 | 21.07.2002 | PQ10 | Yes |
| 5. | 21.07.2002 | 14.05.2003 | BQ1/VQ1 | Yes |
| **Site C** | | | | |
| 1. | 27.05.2002 | 09.07.2002 | BQ6/VQ3 | Yes |
| 2. | 09.07.2002 | 12.07.2002 | BQ5/VQ5 | No |
| 3. | 12.07.2002 | 16.07.2002 | BQ4/VQ6 | No |
| 4. | 16.07.2002 | 18.07.2002 | BQ3/VQ4 | Yes |
| 5. | 18.07.2002 | 25.07.2002 | Invertebrate trap | No |
| 6. | 24.09.2002 | 14.05.2003 | BQ3/VQ4 | Yes |
| **Site E** | | | | |
| 1. | 22.07.2002 | 14.05.2003 | BQ2 | Yes |

In total, 25 datasets were analysed, 10 each for sites A and C and five for site E, and parameters compared with the weather station as follows:

- air temperature;
- humidity[12];
- irradiance (an average of all sensors was computed).

Humidity, air temperature and solar radiation are major parameters controlling the evapotranspiration process, which dictates atmospheric moisture conditions just above ground level; therefore these parameters were chosen for analysis of *Vertigo's* microhabitat. *Vertigo geyeri* is known to be found in humid conditions, with a preference for wet surfaces, but warm temperatures. If the conditions are right, it climbs up and rests on the wet moss *Scorpidium cossoni* cover. But in a stress situation, when there isn't enough moisture, and conditions are too hot and dry, molluscs tend to retreat into a refuge, into shaded areas under the canopy or litter; or they bury themselves in gaps in the soil (after Moorkens, pers. com.).

[12] The humidity sensor at the weather station was not operating correctly and therefore data from the closest synoptic station at Casement Aerodrome were used.

As a tool for comparison, statistical analysis was used. This employed:

- descriptive statistics;
- scatter diagrams;
- correlation analysis.

These are basic techniques, which are broadly described by Dowdy & Wearden (1985) and Barnett & Turkman (1994). All datasets were prepared and calculations made using Excel software.

#### IV-2.1.1.2 Annual Micrometeorological Cycle on the Fen Margin

The second part of the micrometeorological study was to establish the meteorological regime of the fen margin, just above the ground on the basis of long term observations. The results of spatial variability will be discussed later; however, the main output of that study was that there was very little spatial variability in temperature and humidity between sample locations; therefore the assumption was made that the micrometeorology of the fen margin is uniform. Radiation was not as well defined as the other two parameters, which is due to differences in vegetation distribution throughout the sites. To establish an annual cycle of the micrometeorological regime, measurements of the following parameters were selected from site A dated from June 2002 until May 2003:

- air temperature,
- relative humidity,
- radiation,
- soil temperature at 10 cm depth.

Data were analysed in depth. Day and night hours were differentiated to increase the sensitivity of the measurements (low radiation values in the night might have damped daily averages). The data were analysed using descriptive statistics and graphical interpretation made using Excel.

#### IV-2.1.1.3 Soil Moisture Conditions

The final part concerned assessment of soil moisture conditions in locations where the snail was present, and this was investigated in three ways by measuring wetness, moisture and water content within the topsoil or at ground level. Definitions used in these investigations are:

- surface wetness, which refers to humidity within surface vegetation, just above the ground, within moss and on the peat surface;
- soil moisture, which is water that is held in the spaces between soil particles; and
- soil water content – a volumetric measurement of water stored in soil.

As surface/soil wetness and moisture conditions were expected to be an important factor controlling the existence of the rare species of snail *Vertigo geyeri*, three experiments were conducted in order to establish soil and surface conditions with respect to available water. The work was undertaken in summer 2003, within three *Vertigo* Quadrats of IQVQ1, IQAVQ3 and IQDVQ5. These three experiments were:

- Surface wetness measured by clay balls,
- Soil moisture measured by gypsum blocks,
- Soil water content measured by an oven drying method.

### *IV - 2.1.1.3.1. Surface Wetness Measured by Clay Balls*

Surface wetness usually refers to percentage of wetted area over some specific surface, for example a leaf. Standard instruments for this parameter are designed to detect free water on any exposed surface, which is then turned into a proportion of the sensing area. These types of instruments were not suitable for experiments on Pollardstown fen as it was not the area but the saturation of the ground surface within moss and plant debris that needed to be investigated. This investigation aimed to assess the risk of dessication or overheating for a snail sitting on the surface, and no standard instruments were suitable for that. The level of saturation may be expressed as the moisture content of the soil (BS 1377); however, that applies to the soil conditions, which with high phreatic levels will remain very moist because of capillary rise. Despite a high soil moisture content, the ground may continue to dry as it stays under the influence of solar radiation and air temperature. On the other hand, the drying process will be inhibited by shading and high humidity very close to the surface, which in turn is controlled by soil moisture conditions. Water is also kept in vegetation stems and leaves.

This is a very complicated inter-related system, and there is not any standard procedure to accommodate given requirements; therefore the first experiment was invented especially for the specific conditions of the study. It involved measurements of change in weight of small clay balls, which imitated snails, after exposing them in a few different locations within botanical quadrats. The investigation was designed to measure the 'moisture stress' that the snail is likely to experience under dry conditions. The reason for using the clay balls was that they are small in diameter (c.5 mm) and very light, which enabled them to be left in very close proximity to a snail. The absorption characteristics of clay allowed changing saturation conditions to be measured within the plant cover at ground level.

The balls were made of Hortag clay material, which is half of the weight of sand and gravel and is commonly used in gardening, crocking or as watering frequency indicator. They are small in diameter and each weighs from 0.2 – 0.6 mg. The balls can absorb up to 30% of their own weight in water and were used in an experiment for assessment of surface wetness.

The experimental protocol was as follows:

1) Dry balls were weighed on a micro scale (Mettler H33) in a laboratory.

2) Each ball was numbered and placed in a separate sterile container with a lid.

3) The balls were taken to the site immediately after being weighed and placed in cells within *Vertigo* Quadrats IQAVQ1, IQAVQ3, and IQDVQ5 for seven days to reach equilibrium with the surrounding environment. One ball, as a control sample, was left in the car in an open container. The positioning of the clay balls on site was that some of them were resting within the moss cover and some were left on the peat soil, depending on the nature of the surface. The idea was to measure the wetness of the environment that the snail is sitting on. The environment varies depending on ambient conditions; therefore a comparison with air humidity, rainfall and air temperature was also undertaken over the week of exposure to incorporate these factors. It is

important to mention that all three botanical quadrats chosen for monitoring were underlain by a thin peat layer (40-50 cm depth). In addition, IQDVQ5 at site D is located on the edge of a permanent pool created by peat abstraction.

4) After seven days of exposure, all of the balls were gently removed and placed in individual plastic containers, transported to the laboratory, where they were immediately weighed on the micro scale.

5) Each ball was then placed in a metal container and left in an oven at 105°C overnight for 12 hours. After that time, the balls were weighted every hour until their weight stabilised.

6) Water was added to each container for balls to absorb it. After seven days, each ball was weighed twice within a five hour interval to confirm that they were fully saturated.

To express surface wetness, the following formula was used:

$$sw = \frac{m_w - m_d}{m_s - m_d} \cdot 100\%$$

*Equation IV-1*

where: $sw$ – surface wetness [%]

$m_w$- is a mass of a wet ball, after exposure in a habitat [M]

$m_d$ – is a mass of an oven dried ball [M]

$m_s$ – is a mass of a saturated ball [M]

This is not a standard formula; however, it is analogous to the moisture content concept provided by British Standards (BSS 1377)[13], where soil moisture content is expressed as a percentage of the dry soil mass.

The surface wetness (*sw)* in *Equation IV-1* represents the percentage of absorption capacity of a clay ball, so the value in the numerator reflects the mass of water that is held in the studied environment and available for absorption by the ball and the value in the denumerator reflects the capacity of a clay ball to absorb water. The ratio of these two gives surface wetness.

[13] The soil moisture content of the soil specimen (*w*) is calculated from the formula: $w = (\frac{m_2 - m_3}{m_3 - m_1}) \cdot 100\%$, where $m_1$ is the mass of container [g], $m_2$ is the mass of container and wet soil [g], and $m_3$ is the mass of container and dry soil [g]

### *IV - 2.1.1.3.2. Soil Moisture Measured by Gypsum Blocks*

Parallel to the clay ball experiment, soil moisture was measured using gypsum soil moisture blocks (14.22.05 type of Eijkelkamp), which were buried in the ground just below the surface and readings were taken for 5 continuous days.

The gypsum block is a cylindrical block of gypsum ($CaSO_4$) into which two electrodes are inserted. The operational principle of soil moisture blocks is that they are porous and allow water to move in and out as soil wets (under irrigation or rainfall) and dries (as plants and evaporation draw water away). In the presence of moisture, the $CaSO_4$ goes into solution allowing ion movement between the two electrodes. When the block is excited electrically, ions move to the respective electrodes establishing an effective block resistance. A greater amount of water in the block equals more ions and a lower resistance to electrical current flow.

The blocks were inserted into the cells in which the snails were found earlier that year (the same as the clay balls). Diamentions of gypsum blocks were: length - 3 cm; radius - 1 cm. The installation procedure was that a thin wall, sharply ended PVC tube of 2 cm diameter (the same as the blocks) was pushed into the ground down to a depth of 3.5 cm and the soil removed gently. According to the manufacturer's recommendations, before inserting, the soil moisture blocks were kept in water to reach a state of full saturation. Saturated soil moisture blocks were left on site for five days before taking measurements to absorb/give off water from surrounding soil and to reach equilibrium with that environment. After that time, readings with a 14.22 Soil Moisture Meter were taken. The meter has a range of 1-100% with 1 indicating drought conditions and 100 full saturation. Since gypsum blocks are in direct contact with the soil under study, the measurement is a straight assessment of soil moisture conditions.

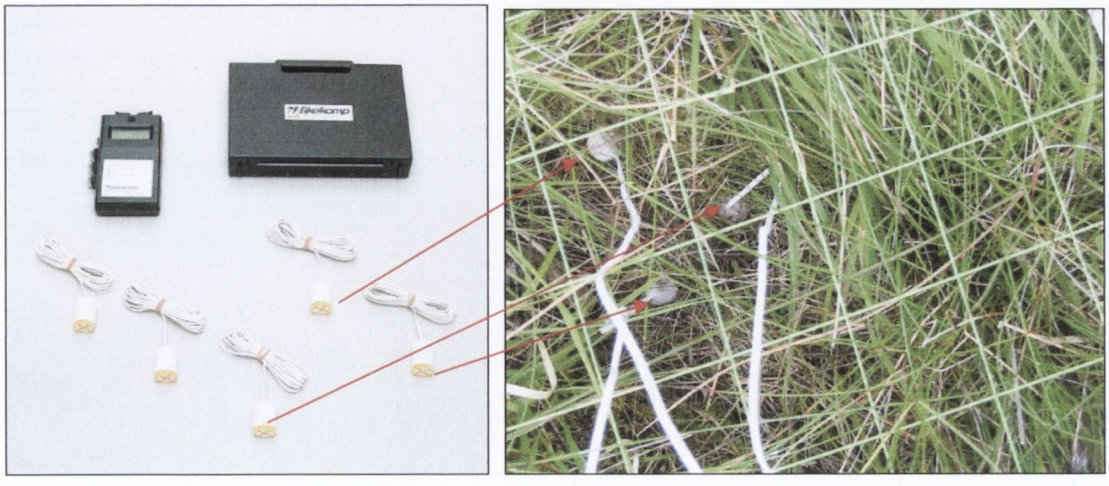



*Photo IV-1 Soil moisture blocks in the laboratory and on site*

Fifteen soil moisture blocks were employed on site, five within site D (IQDBQ5), and ten within site A, six in IQABQ1 and four in IQABQ3.

### *IV - 2.1.1.3.3. Soil Water Content Measured by the Oven Drying Method*

In addition to the above experiments, four samples of soil removed during insertion of the soil moisture blocks were evaluated for dry mass content using an over dry method. The dry mass of peat is a mixture of organic and non organic material that is obtained by total removal of water from a sample. The dry mass of peaty soils depends on the nature of a given site and can vary from 5 to 80% (Maciak & Liwski, 1996).

Samples were collected from the following cells IQABQ3/VQ3 – F5, IQABQ1/VQ1 – J2, IQABQ3/VQ3 – D6 and IQABQ3/VQ3 – F7. They were removed using a thin wall, sharply ended PVC tube of 2 cm diameter that was gently pushed into the ground down to a depth of 3.5 cm and soil was removed.

All soil samples were weighed in a laboratory, then placed in metal containers and oven dried in 105°C. The mass of each sample was measured again after 8, 12, 16, 17, and 18 hours until each sample was measured to have a constant mass.

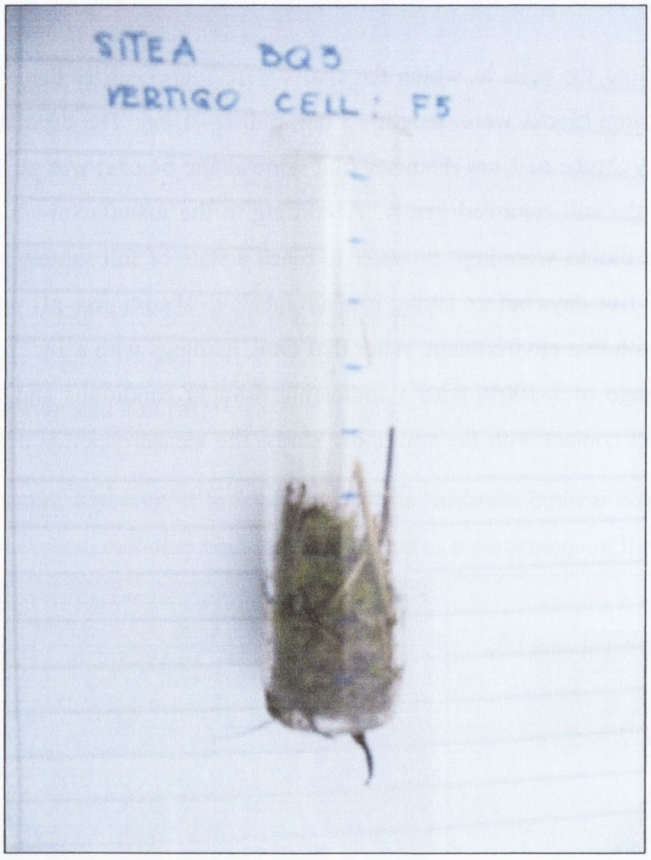



*Photo IV-2 A sample of soil for examination of soil water content*

The amount of dry mass in a given sample was calculated from (after Maciak & Liwski, 1996):

$$dm = \frac{100 \cdot b}{a}$$

*Equation IV-2*

per 100 g of peat, where:

$dm$ – is dry matter [%]

$a$ – is a mass of a wet sample [M]

$b$ – is a mass of a sample after drying [M]

The difference between the calculated percentage of a dry mass and 100 is the percentage of water content in a sample (Maciak & Liwski, 1996):

$$wc = 100 - (d.m.)$$

*Equation IV-3*

where:

$wc$ – is water content [%]

$dm$ – is a dry matter [%]

### *IV-2.1.2. The Microhydrological Regime*

Review of literature on *Vertigo geyeri* snails revealed that the species could be potentially sensitive to changes in hydrological regime on a micro scale. Therefore, this investigation was focused on determination of the water regime that is characteristic of areas where the snail lives. On average, the phreatic level on fens is very stable due to continuous water supply from deep groundwater, which sustains soil at its field capacity despite ambient conditions. To monitor the movement of the phreatic level, three sensitive water level recorders (Pressure Transducers PDCR 1830 by Campbell Scientific Ltd.) were installed at site A, C and E.

Initially, it was planned to monitor the phreatic level for two years. However, three years' data has now been collected (May 2002 - May 2005) and analysed for this study. The phreatic water level has been monitored continuously on site A since May 2002, on Site E since July 2002, on site C from May 2002 until May 2003 and on site D from June 2003 until May 2005 (Table IV-3). Phreatic tubes were placed in close proximity to *Vertigo* quadrats in order to reflect conditions of the phreatic level within these areas. At site A, a phreatic tube was placed at the edge of IQA BQ2/VQ2, at site E – at the boundary with IQEBQ1/VQ1, and at site D - at the boundary with IQDVQ5/VQ5.

**Table IV-3 Time of phreatic level monitoring around various locations at the fen margin.**

| Location | Monitoring period |
|---|---|
| Site A | May 2002 - May 2005 |
| Site B | None due to lack of *Vertigo sp.* |
| Site C | May 2002-May 2003 |
| Site D | June 2003 – May 2005 |
| Site E | July 2002- May 2005 |

Since the mollusc count study was carried out during summer months only, three continuous summer seasons between May – October 2002-2004 were distinguished and compared with snail occurrence.

Data was collected on an hourly basis and aggregated into daily averages.

Graphical presentation in the form of hydrographs and descriptive statistics were used to describe annual cycles in water levels. Rainfall from the weather station was also used to assess the response in phreatic level change to precipitation.

Trimble® GPS equipment was used to survey and produce detailed maps of Botanical Quadrats. The survey was done only for those quadrats where the snail was known to be present. These were:

- IQABQ1, IQABQ2, IQABQ3
- IQEBQ1, IQEBQ2
- IQDVQ5.

The maps were produced with a 10 cm grid, with measurements taken inside each 10 x 10 cm cell of botanical quadrat (Figure IV-2). Vertical resolution was set at 0.01 metre.

Topographic maps were made using Surfer ver.6.04 software. Data from malacological studies were plotted over the topographic surface and so that a contour of the phreatic level was produced for the specific days when the snail count was taken. This provided information about the spatial relationship of snails with regard to the phreatic level.

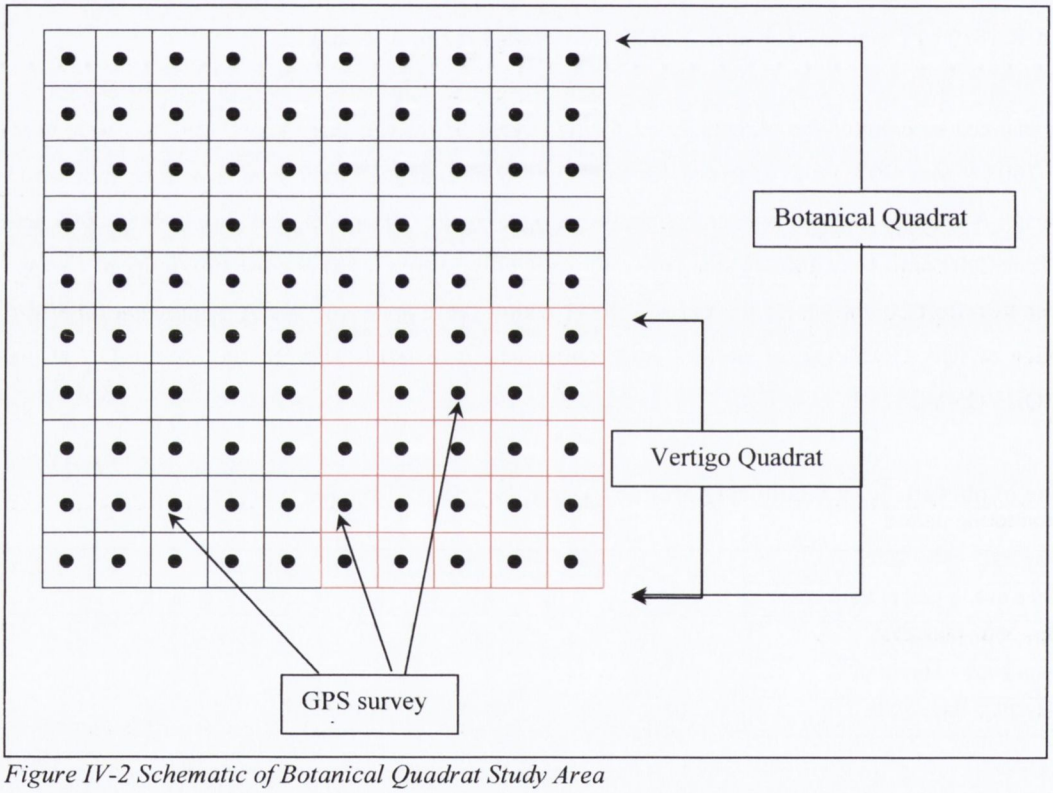



*Figure IV-2 Schematic of Botanical Quadrat Study Area*

The depth of the phreatic level to the topographic surface was calculated for each day of the snail count to investigate preferences of snails to the range of vertical distance to water table.

The following figure presents the schematic of a monitoring site for microhydrological regime (Figure IV-3).

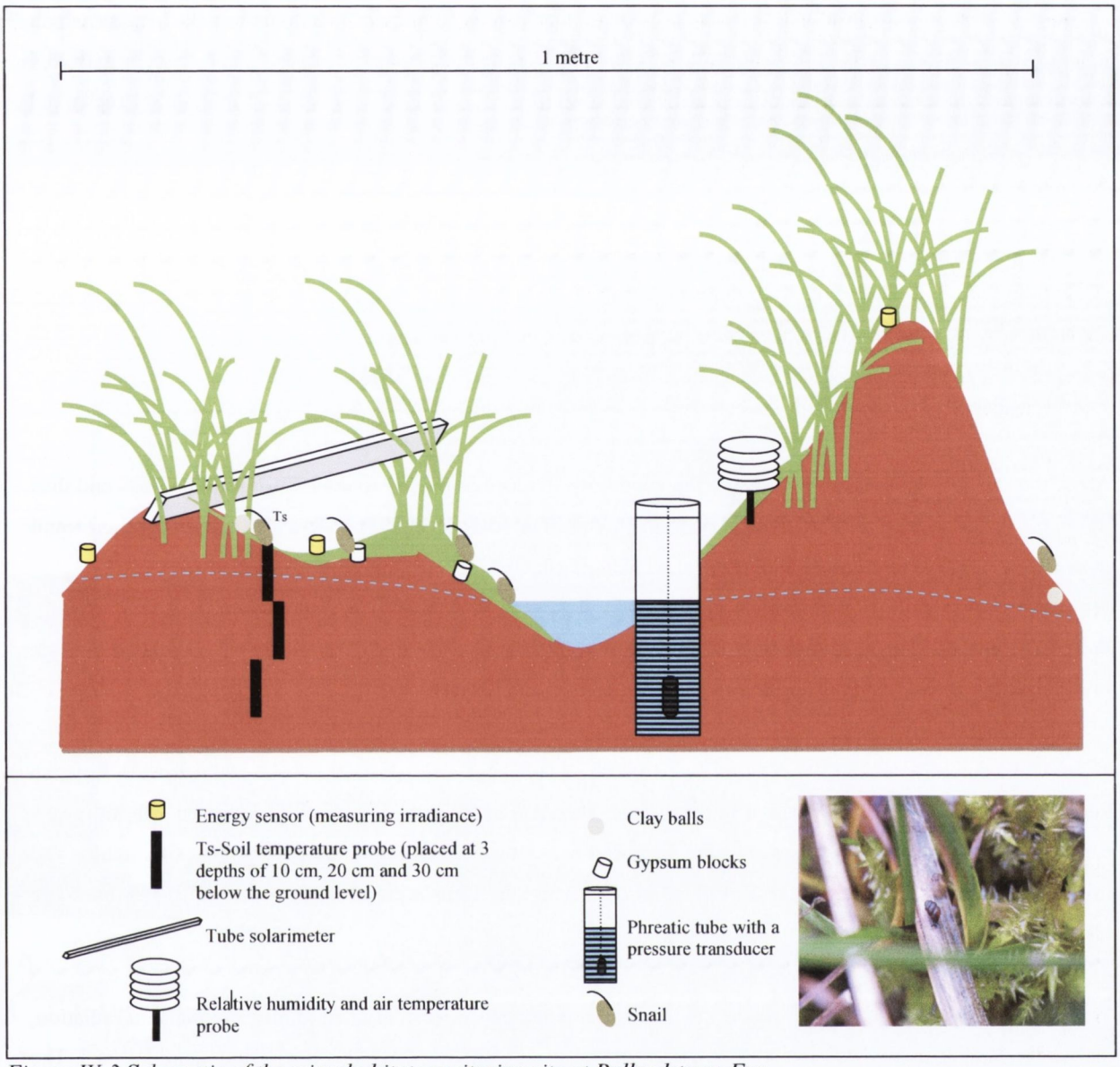



*Figure IV-3 Schematic of the microhabitat monitoring site at Pollardstown Fen*

## IV-2.2. Instrumentation

The work was planned for two summer seasons (May - October) in 2002 and 2003. The reason for that time frame was that snails are supposed to be most active in those months with the highest reproduction taking place in September, depending on weather conditions.

Within these sites, three sets of instruments were employed to measure the characteristics of the following micrometeorological and microhydrological parameters:

- Air Temperature,
- Relative Humidity,
- Soil temperature at 10 cm depth,
- Incoming solar radiation,
- Phreatic surface,
- Surface Wetness.

In total, 8 sensors were installed at each site. All of them were connected to automatic data loggers which scanned the sensors every 60 seconds and recorded the average hourly values. Data loggers (CR23X Micrologger® from Campbell Scientific Ltd.) were powered by a 12 V lead acid battery continuously recharged by a solar panel. The sensors installed were as follows:

- soil temperature probe,
- relative humidity,
- air temperature,
- 3 x point energy sensors,
- tube solarimeter (incoming radiation sensor over the length of 1 metre,
- water level transducers.

All of the sensors were placed to measure the conditions in close proximity to the known snail habitats and thus were installed as low as possible to be close to the ground/fen water level. They were also chosen for their small dimensions so as not to interfere with the regime being evaluated.

In order to prevent the site from being trampled during measuring campaigns, trackways were installed on each of the sites A - D to assist transfer of sensors and access to data loggers.

The relative humidity and air temperature probes were installed approximately 10 cm above the ground. Relative humidity is a measurement of relative water vapour saturation in the atmosphere. It is expressed as a ratio, as a percentage of the quantity of vapour in the air compared with the maximum amount the air can contain. The instruments employed were SKH 2040/I Mini Humidity & Temperature Sensors manufactured by Skye Instruments Ltd.

Point energy sensors type ES2 as well as the tube solarimeter are devices designed to measure incident radiation, that is, the radiant energy flux incident on a unit surface area. Units were in watts per square metre [$W/m^2$]. The Tube solarimeters are designed to measure average irradiance in situations where distribution of radiant energy is not uniform e.g. under the canopy. It is a 1 metre long, narrow plate with thermopile sensors covered with a glass tube. As a result of its geometry, the integrated average from the 1 metre length is taken and expressed in watts per square metre. The Point Energy Sensors each took the readings from one location only. Both point energy sensors and the tube solarimeter were provided by Delta -T Devices Ltd.

Phreatic water level recorders (PDCR 1830 Pressure Transducers, provided by Campbell Scientific Ltd.) were installed in 100 mm diameter perforated plastic pipes pushed into the peat layer. The operational principle is that changes in water level correspond to pressure changes on a strain gauge bonded to a pressure sensitive diaphragm. When a precision excitation voltage is applied, the electrical resistance varies with changing liquid pressure. The excitation voltage is supplied by a datalogger that also measures resistance, which is converted to desired units (i.e., pressure, depth, or level). The sensor features a titanium body, 0.69" outer diameter, isolated diaphragm, and a vented cable. The vented cable eliminates the need to compensate for changes in barometric pressure.

The instruments record the variation in water levels with reference to the top of the pipe and that reference height was measured with the Trimble® GPS equipment so as to relate it to Ordnance Datum (Poolbeg). As a result, the data was presented in terms of metres OD. Detailed information of sensors positioning is listed in Table IV-4. On the north side, the phreatic level was firstly monitored at site C, however because the site became flooded over time and the snail population disappeared from the site, the sensor was relocated to site D.

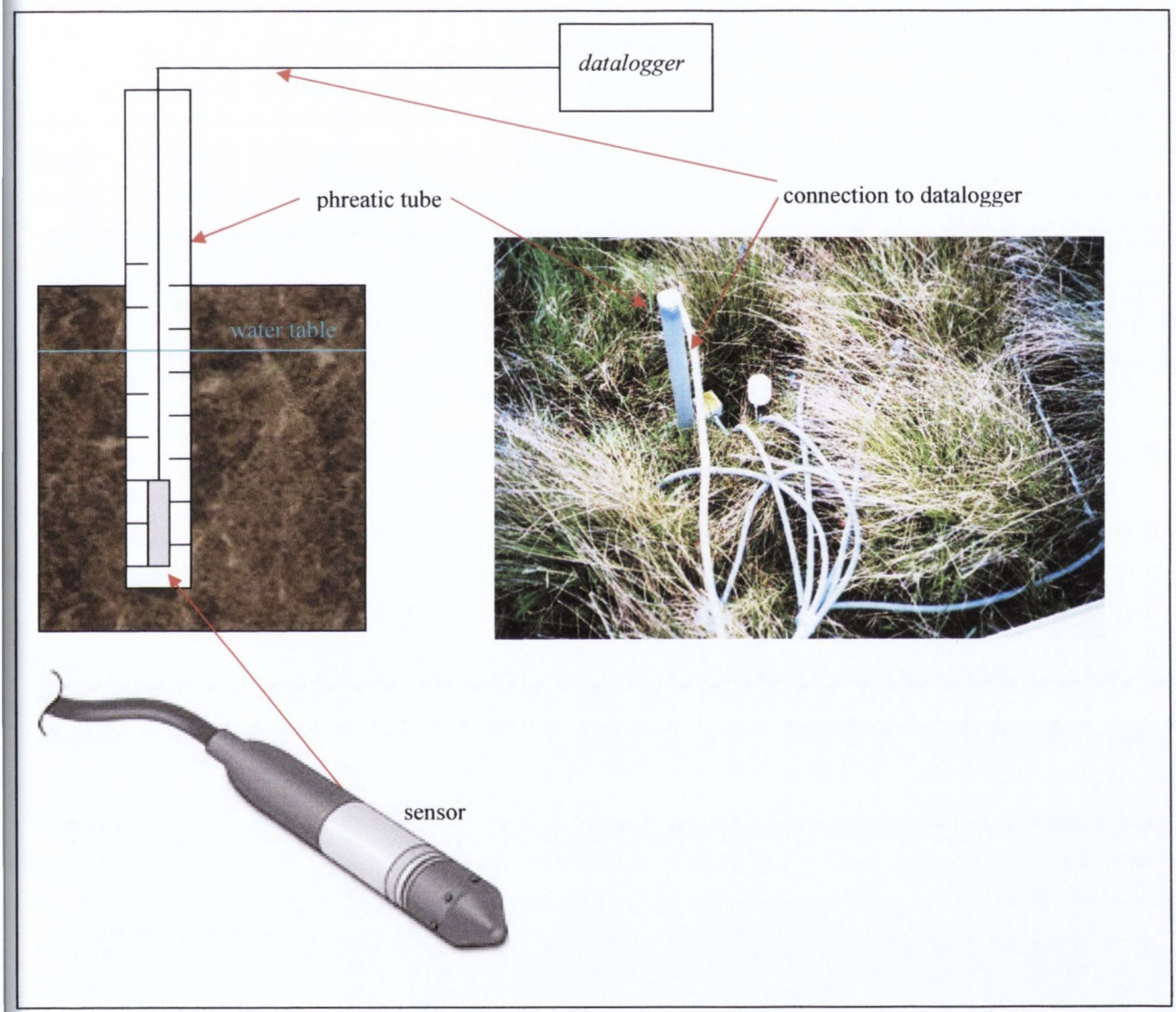



*Figure IV-4 Design for water table monitoring*

**Table IV-4 Summary information about positioning and elevations of phreatic tubes within Intensive Quadrats**

| Location | | Site A | | Site E | | | Site C | | Site D |
|---|---|---|---|---|---|---|---|---|---|
| ground level [m OD] | | 88.44 | | 86.37 | | | 85.73 | | 85.68 |
| coordinates | east | 276427.591 | | 277027.741 | | | 277309.565 | | 277131.982 |
| | north | 215907.704 | | 215713.753 | | | 216633.043 | | 216796.864 |
| duration | | from 28.05.2002 until 29.04.2004 | from 29.04.2004 on | from 22.07.2002 until 17.11.2003 | from 17.11.2003 until 17.02.2004 | from 17.02.2004 on | from 28.05.2002 until 25.07.2002 | from 24.09.2002 until 13.05.2003 | from 11.06.2003 on |
| Top of the casing [m OD] | | 89.11 | 89.03 | 86.64 | 86.57 | 86.6 | 86.07 | 86.13 | 86.27 |
| Depth [m] | | 1.1 | 1.1 | 0.84 | 0.84 | 0.84 | 1.0 | 1.0 | 1.0 |
| below GL [m] | | 0.43 | 0.51 | 0.57 | 0.64 | 0.61 | 0.66 | 0.6 | 0.41 |
| above GL [m] | | 0.67 | 0.59 | 0.27 | 0.2 | 0.23 | 0.34 | 0.4 | 0.59 |




*Photo IV-3 Sensors for micrometeorological monitoring at site C, summer 2002*

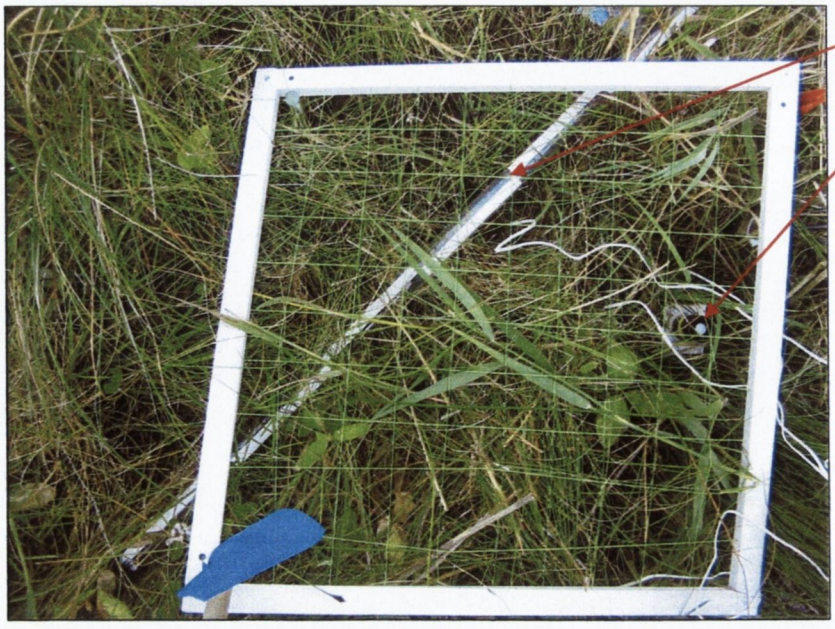



*Photo IV-4 Sensors for micrometeorological monitoring within a botanical quadrat, site A, summer 2002*

## IV-2.3. Results

### *IV-2.3.1. The Micrometeorological Regime*

#### IV-2.3.1.1 Micrometeorological Spatial Variability

As previously stated in the methodology section, humidity and air temperature sensors plus a number of solar radiation instruments were installed on Pollardstown Fen in summer 2002 to evaluate spatial distribution of these parameters along the fen margin. The main weather station was placed on the northern side of the fen and a further three sites A, C and E chosen on three different locations along the margin, all of which were hosting *Vertigo* sp. Twenty four hour data sets from individual locations were compared with the data recorded at the same day at the weather station. Malfunctioning of the humidity sensor at the weather station required substituting humidity data with the Casement Aerodrome records. The dates for comparisons were chosen randomly and descriptive statistics calculated using Excel spreadsheet. Full numerical results are presented in Appendix 29. Scatter diagrams were drawn to present the relationship between data obtained from different locations under different botanical and soil conditions and are also presented in Appendix 29.

In total, twenty five different data sets (of atmospheric conditions just above the ground surface) from various dates were compared between the fen margin and the weather station data. The results show very high correlations of all three parameters (air temperature, humidity and solar radiation). Each pair was positively correlated with 88% of all pairs having a correlation coefficient higher than 0.7 (in most cases, the correlation coefficient was higher than 0.8). A major significant difference between the fen margin conditions and the weather station was the maximum air temperature, which at all sites was higher than the temperature at the fen's weather station. On average, at site A the maximum temperatures were higher by 4 degrees, at site E – by 5.5 degrees and at site C – by 3 degrees. This pattern is not unexpected since there is less wind above ground level than at a height of 2 metres at the weather station, hence a less cooling effect and warmer conditions above the ground. Also advective heating of the soil surface influences conditions just above it. The higher temperatures on the south side reflect more exposure to the sun compared to the northern site C. Over the twelve month observation period, the actual monthly maximum values ranged from 12.15°C to 26.02°C at site A; from 12.10°C to 26.71°C at site C and from 11.30°C to 24.20°C at the fen's weather station. The minimum values were more similar and the difference rarely exceeded 1.0 degree. The minimum monthly temperatures varied from -8.02°C to 4.32°C at site A; from -5.89°C to 4.36°C at site C and at the fen's weather station they ranged from -7.70°C to 3.70°C.

More surprising is the fact that the range of humidity recorded just above the ground is similar to that at Casement Aerodrome. There is relatively little difference between these locations and 70% of the data treated showed good correlation with 17% at $r^2>0.9$. Nevertheless, some 30% of compared records was poorly correlated with a correlation coefficient falling below $r^2<0.1$. Original expectations that wet, warm and windless conditions close to the ground at the fen will result in higher humidity values here than in an open space at the airport station were proved wrong. In fact, for the three month period of June 2002 - August 2002, the maximum daily average humidity at Casement Aerodrome and site A were 98.96% and 92.7% respectively, the minimum

daily averages were 71.21% and 70.05% at Casement and site A, respectively, and the daily averages were 84.23% and 82.44% at Casement and the site A, respectively. This suggests a drier atmosphere at the fen margin (and subsequently an increased potential for evapotranspiration). It is noticeable, however, that the difference between the maximum and the minimum daily average humidities was lower on the fen (RH range of 22.65%) than at the airport site (RH range of 27.05%) which suggests more stable conditions at the fen.

A big difference was found between solar radiation on the ground and at 2 metres height which was expected according to differences in vegetation density at these two heights. On average, only 28% of the incoming irradiance gets through the vegetation and reaches the soil (based on maximum values). While the maximum monthly incoming radiation at the weather station was recorded between 315 – 1558 $W/m^2$, at the fen margin monthly maximum radiation levels ranged from 17 $W/m^2$ to 495 $W/m^2$ (site A) and from 49 $W/m^2$ to 337 $W/m^2$ (site C).

In summary, the comparison between particular sample locations and the weather stations shows very good correlation and great similarity despite topographic and botanical differences between sampling locations (Table IV-5-Table IV-7).

Data for the southern and northern margins also show very little difference between each other, with all data being correlated at a very high level (Table IV-8). The lowest correlation was computed for irradiance parameters and was equal to 0.86. As measured irradiance is mainly controlled by positioning of the sensor with respect to the vegetation structure, results can have high variations even if placed within the same site. Nevertheless, the correlation coefficient for 29 out of 30 samples was higher than 0.95.

**Table IV-5 Correlation coefficients of temperature, humidity and solar radiation between site A and the fen weather station**

| Date | Location | NVC Category | Temperature | Humidity | Irradiance |
|---|---|---|---|---|---|
| 29.05.02 | BQ2/VQ2 | M13 | 0.97 | 0.78 | 0.50 |
| 15.06.02 | BQ2/VQ2 | M13 | 0.98 | 0.89 | 0.89 |
| 28.06.02 | BQ2/VQ2 | M13 | 0.97 | 0.89 | 0.89 |
| 13.07.02 | BQ3/VQ3 | M13 | 0.95 | 0.88 | 0.95 |
| 15.07.02 | BQ3/VQ3 | M13 | 0.97 | 0.11 | 0.88 |
| 17.07.02 | Outside BQ4 | M24 | 0.97 | 0.91 | 0.83 |
| 19.07.02 | PQ10 | M13 | 0.95 | 0.17 | 0.89 |
| 20.07.02 | PQ10 | M13 | 0.98 | 0.80 | 0.73 |
| 27.07.02 | BQ1/VQ1 | M13 | 0.98 | 0.87 | 0.97 |
| 22.08.02 | BQ1/VQ1 | M13 | 0.99 | 0.60 | 0.98 |

**Table IV-6 Correlation coefficients of temperature, humidity and solar radiation between site C and the fen weather station**

| Date | Location | NVC Category | Temperature | Humidity | Irradiance |
|---|---|---|---|---|---|
| 29.05.02 | BQ6/VQ3 | M13 | 0.94 | 0.79 | 0.70 |
| 15.06.02 | BQ6/VQ3 | M13 | 0.99 | 0.91 | 0.87 |
| 07.07.02 | BQ6/VQ3 | M13 | 0.97 | 0.91 | 0.95 |
| 10.07.02 | BQ5/VQ5 | M22 | 0.99 | 0.77 | 0.79 |
| 11.07.02 | BQ5/VQ5 | M22 | 0.97 | 0.63 | 0.50 |
| 13.07.02 | BQ4/VQ6 | M13 | 0.96 | 0.86 | 0.92 |
| 15.07.02 | BQ4/VQ6 | M13 | 0.97 | 0.09 | 0.88 |
| 17.07.02 | BQ3/VQ4 | M13 | 0.90 | 0.90 | 0.85 |
| 20.07.02 | Invertebrate Trap | | 0.98 | 0.85 | 0.77 |
| 23.07.02 | Invertebrate Trap | | 0.97 | 0.93 | 0.90 |

**Table IV-7 Correlation coefficients of temperature, humidity and solar radiation between site E and the fen weather station**

| Date | Location | NVC Category | Temperature | Humidity | Irradiance |
|---|---|---|---|---|---|
| 23.07.02 | BQ2/VQ2 | M13 | 0.96 | 0.93 | 0.90 |
| 27.07.02 | BQ2/VQ2 | M13 | 0.98 | 0.84 | 0.99 |
| 22.08.02 | BQ2/VQ2 | M13 | 0.98 | 0.63 | 0.99 |
| 26.08.02 | BQ2/VQ2 | M13 | 0.97 | 0.82 | 0.81 |
| 01.09.02 | BQ2/VQ2 | M13 | 0.97 | 0.57 | 0.88 |

**Table IV-8 Correlation coefficients of temperature, humidity and solar radiation between site A and site C. Blue cells indicate *Vertigo* negative locations and orange – *Vertigo* positive locations**

| Date | Site A Location | Site C Location | Temperature | Humidity | Irradiance |
|---|---|---|---|---|---|
| 29.05.02 | BQ2/VQ2 | BQ6/VQ3 | 1.0 | 0.99 | 1.0 |
| 15.06.02 | BQ2/VQ2 | BQ6/VQ3 | 0.99 | 0.99 | 0.99 |
| 07.07.02 | BQ2/VQ2 | BQ6/VQ3 | 1.0 | 0.99 | 1.0 |
| 10.07.02 | BQ2/VQ2 | BQ5/VQ5 | 0.98 | 0.96 | 0.96 |
| 13.07.02 | BQ3/VQ3 | BQ4/VQ6 | 0.99 | 0.98 | 0.99 |
| 15.07.02 | BQ3/VQ3 | BQ4/VQ6 | 0.99 | 0.97 | 1.0 |
| 17.07.02 | Outside BQ4 | BQ3/VQ4 | 0.96 | 0.96 | 0.98 |
| 19.07.02 | PQ10 | Invertebrate trap | 0.99 | 0.97 | 1.0 |
| 20.07.02 | PQ10 | Invertebrate trap | 1.0 | 0.98 | 0.99 |
| 23.07.02 | BQ1/VQ1 | Invertebrate trap | 1.0 | 1.0 | 0.86 |

The annual characteristics of the micrometeorological conditions will be treated in more detail in the next section; however, data presented in Table IV-9 and Figure IV-5-Figure IV-7 demonstrates that all sites closely follow the same annual pattern. The biggest differences between the sites occur in maximum air temperatures (Temp) and minimum air humidity (RH) values, and these differences are bigger during summer in the case of temperatures and for humidity they are higher in winter. It is apparent also that RH amplitudes are lowest at site E (Figure IV-8) but similar at sites A and C. The relative humidity above the fen surface is a function of air temperature, which controls also the evapotranspiration process during which water is evaporated from the ground and vegetation surfaces into the air. There also have to be sufficient water resources in the soil or within plant cover for the evapotranspiration to occur. As the ambient conditions were shown to be relatively stable across the fen, differences in humidity amplitudes between the three sites are likely to be controlled by local

water availability for the evapotranspiration process to occur. This finding implies that there are likely to be differences in microhydrological conditions between the three sites; nevertheless this does not provide evidence that the existence of the snail in given locations depends on relative humidity. This is because firstly the snail was found on all three sites, and secondly comparison of daily datasets from sites A and C for both *Vertigo* positive and *Vertigo* negative locations show very good correlation and the similar humidity levels.

**Table IV-9 Summary of monthly temperature, relative humidity and incoming radiation at the fen's surface in location: Site A, C and E and at the weather station over the observation period 2002-2003.**

| | | Air Temperature [°C] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Jun-02 | Jul-02 | Aug-02 | Sep-02 | Oct-02 | Nov-02 | Dec-02 | Jan-03 | Feb-03 | Mar-03 | Apr-03 |
| A | max | 24.47 | 28.55 | 28.58 | 26.02 | 20.42 | 14.49 | 12.15 | 13.90 | 12.28 | 21.54 | 29.06 |
| | min | 2.52 | 1.89 | 4.32 | -0.53 | -4.17 | 0.60 | -5.32 | -8.02 | -7.72 | -6.29 | -6.09 |
| | average | 13.65 | 15.29 | 15.70 | 12.07 | 8.37 | 7.78 | 5.34 | 3.85 | 3.88 | 6.30 | 9.19 |
| E | max | | | 30.49 | 27.57 | 19.44 | 13.99 | 11.66 | 12.82 | 12.65 | 21.85 | 27.08 |
| | min | | | 5.01 | -0.34 | -2.31 | 1.87 | -2.72 | -4.79 | -4.76 | -3.63 | -2.60 |
| | average | | | 16.15 | 12.31 | 8.52 | 7.82 | 5.38 | 3.94 | 4.06 | 6.62 | 9.58 |
| C | max | 23.95 | 24.37 | 22.08 | 26.71 | 24.38 | 14.49 | 12.10 | 13.89 | 13.96 | 19.62 | 25.23 |
| | min | 3.32 | 3.87 | 4.36 | -0.91 | -4.03 | 1.24 | -3.53 | -5.82 | -5.89 | -4.29 | -4.03 |
| | average | 13.78 | 14.82 | 14.41 | 11.81 | 8.68 | 8.02 | 5.47 | 4.15 | 4.29 | 6.62 | 9.22 |
| Weather station | max | 20.10 | 22.00 | 23.90 | 21.00 | 18.80 | 14.60 | 12.10 | 13.60 | 11.30 | 16.80 | |
| | min | 3.60 | 3.20 | 3.70 | -1.10 | -4.20 | 0.20 | -5.20 | -7.50 | -7.70 | -6.00 | |
| | average | 12.25 | 13.66 | 14.54 | 11.62 | 8.33 | 7.93 | 5.48 | 4.18 | 4.14 | 5.93 | |
| | | Incoming Radiation W/m2 | | | | | | | | | | |
| | | Jun-02 | Jul-02 | Aug-02 | Sep-02 | Oct-02 | Nov-02 | Dec-02 | Jan-03 | Feb-03 | Mar-03 | Apr-03 |
| A | max | | 193 | 200 | 144 | 76 | 25 | 17 | 18 | 39 | 99 | 133 |
| | min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | average | | 24 | 23 | 16 | 7 | 3 | 2 | 3 | 6 | 14 | 21 |
| E | max | | | 249 | 153 | | | | | 97 | 300 | 354 |
| | min | | | 0 | 0 | | | | | 0 | 0 | 0 |
| | average | | | 36 | 28 | | | | | 11 | 39 | 57 |
| C | max | | 336 | 140 | 157 | 130 | 132 | 49 | 115 | 188 | 266 | 337 |
| | min | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | average | | 46 | 18 | 12 | 4 | 9 | 6 | 8 | 17 | 34 | 50 |
| Weather station | max | 1558 | 1412 | 923 | 852 | 675 | 466 | 329 | 315 | 546 | 772 | |
| | min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | average | 225 | 195 | 179 | 136 | 75 | 42 | 24 | 36 | 63 | 131 | |
| | | Relative Humidity [%] | | | | | | | | | | |
| | | Jun-02 | Jul-02 | Aug-02 | Sep-02 | Oct-02 | Nov-02 | Dec-02 | Jan-03 | Feb-03 | Mar-03 | Apr-03 |
| A | max | 93.2 | 94.0 | 95.4 | 96.4 | 95.9 | 96.2 | 96.1 | 95.7 | 96.7 | 96.3 | 96.9 |
| | min | 44.0 | 40.9 | 41.1 | 51.9 | 64.9 | 78.0 | 71.6 | 70.4 | 64.6 | 37.4 | 29.4 |
| | average | 80.8 | 82.5 | 84.0 | 84.7 | 90.7 | 93.1 | 91.4 | 90.0 | 88.5 | 82.8 | 79.1 |
| E | max | | | 99.8 | 99.8 | 99.8 | 99.8 | 99.8 | 99.8 | 99.8 | 99.8 | 99.8 |
| | min | | | 54.2 | 56.6 | 78.6 | 94.7 | 88.9 | 83.4 | 73.3 | 51.7 | 45.1 |
| | average | | | 91.5 | 90.1 | 97.0 | 99.2 | 98.1 | 96.9 | 94.8 | 90.3 | 86.5 |
| C | max | 94.8 | 99.9 | 99.9 | 99.8 | 99.9 | 99.8 | 99.8 | 99.8 | 99.8 | 99.7 | 99.8 |
| | min | 45.2 | 50.1 | 82.4 | 46.7 | 62.7 | 72.4 | 75.4 | 69.4 | 52.3 | 43.1 | 41.7 |
| | average | 81.1 | 85.7 | 95.9 | 92.7 | 93.1 | 95.2 | 95.0 | 92.5 | 88.5 | 85.6 | 82.4 |
| Casement Aerodrome | max | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | min | 41.0 | 54.0 | 55.0 | 48.0 | 60.0 | 66.0 | 56.0 | 58.0 | 48.0 | 42.0 | 39.0 |
| | average | 82.5 | 84.1 | 86.1 | 84.1 | 87.4 | 87.9 | 88.5 | 86.0 | 83.6 | 81.1 | 78.4 |

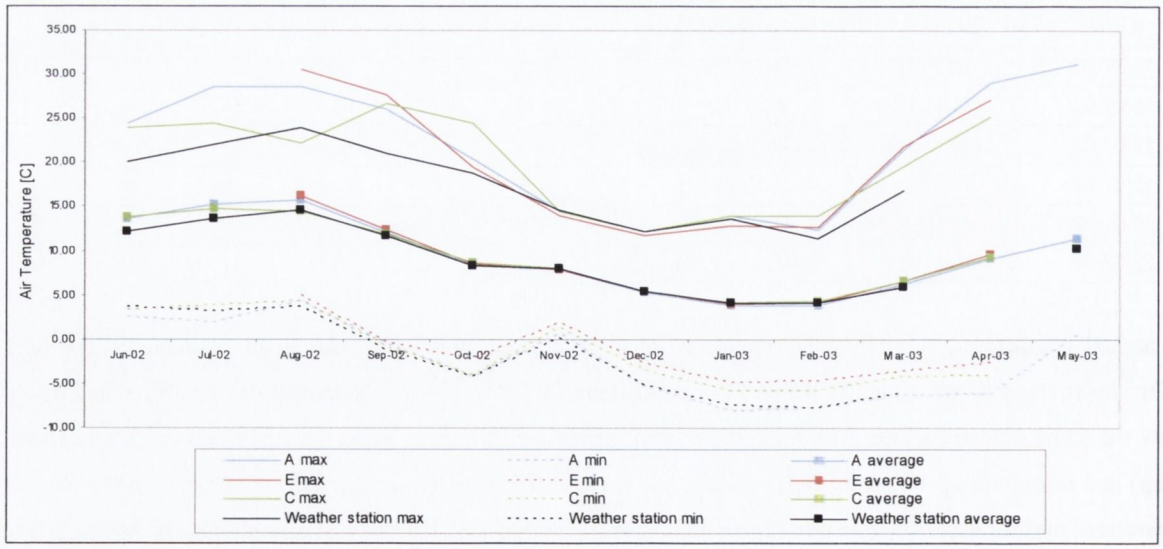



*Figure IV-5 Monthly distribution of air temperature within Intensive Quadrats A, C, E and the weather station at Pollardstown Fen, June 2002-May 2003*

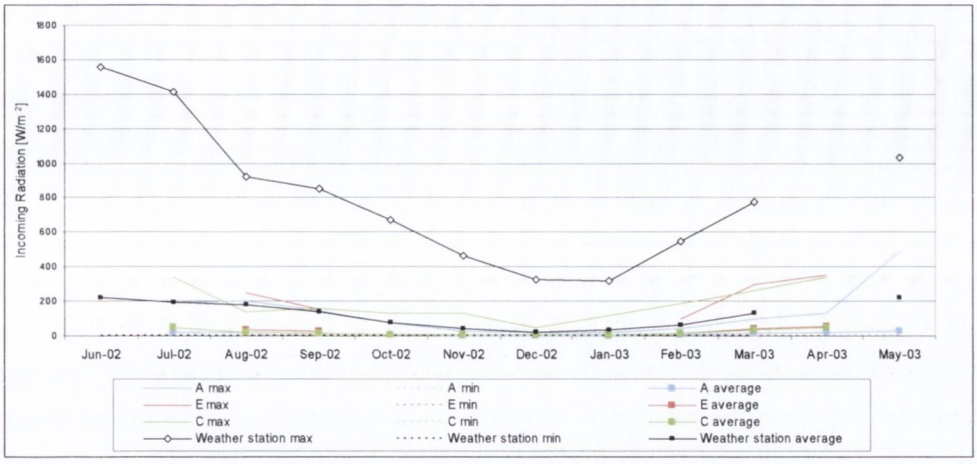



*Figure IV-6 Monthly distribution of incoming radiation within Intensive Quadrats A, C, E and the weather station at Pollardstown Fen, June 2002-May 2003*

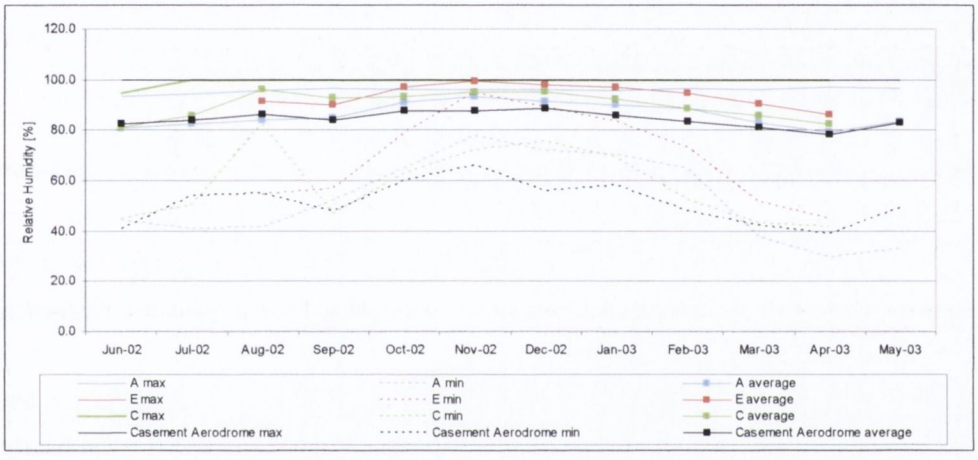



*Figure IV-7 Monthly distribution of relative humidity within Intensive Quadrats A, C, E at Pollardstown Fen and the Casement Aerodrome weather station, June 2002-May 2003*

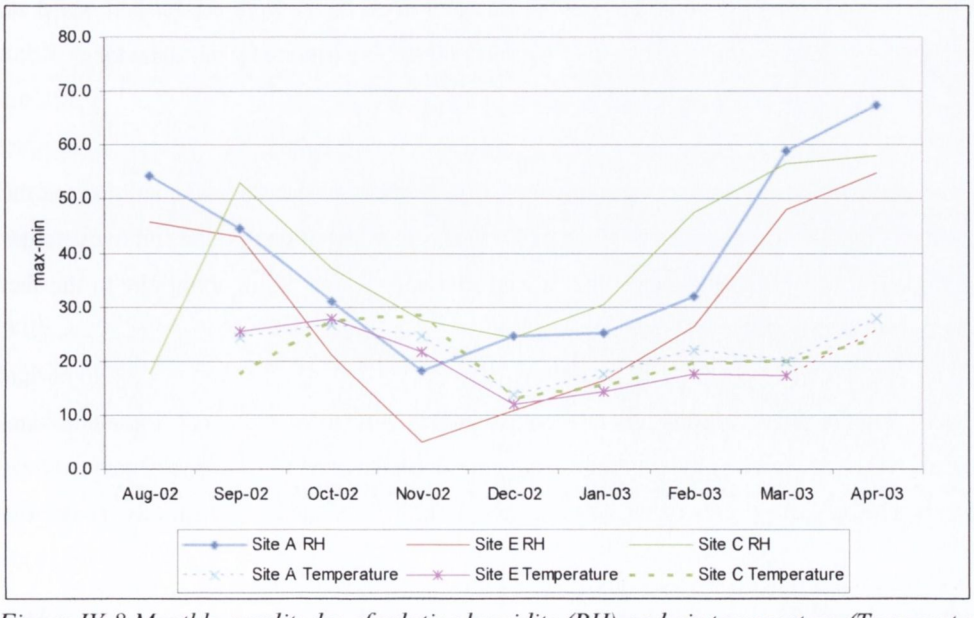



*Figure IV-8 Monthly amplitudes of relative humidity (RH) and air temperature (Temperature) within three Intensive Quadrats A, C and E, 2002-2003*

*Conclusions*

The final finding of this analysis was that there is very high uniformity in spatial distribution of humidity, air temperature and solar radiation along the fen margin and no differences between *Vertigo* positive and *Vertigo* negative sites were found. This implies that although these parameters are part of the microhabitat that *Vertigo geyeri* lives in, they are not controlling parameters.

An important discovery is that there is high similarity between humidity at the fen site and the Casement Aerodrome, which are located approximately 20 km apart and in different environmental settings. Nevertheless, humidity conditions at the fen were found to be slightly more stable, i.e. have smaller fluctuation ranges. Stable humidity conditions seem to be also more characteristic for site E than for sites A and C.

These conclusions suggest that microhydrological aspects of the fen margin will be of much greater importance than micrometeorology.

#### IV-2.3.1.2 Annual Micrometeorological Cycle on the Fen Margin

Previous analysis proved the stability of the pattern of micrometeorological parameters within three key study areas, therefore for this micrometeorological analysis, data from site A were selected as representative for the fen margin and the regime was established based upon them.

The analysis was performed using data for the period June 2002 - May 2003. Data was recorded on an hourly basis and aggregated into daily and monthly records. Day and night hours were separated to increase the sensibility of measurements and minimise the 'damping' effect caused by low night time values, especially important with regard to radiation during the summer months. Day and night hours were established based on 'Sun or Moon Rise/Set Table' provided by the U.S. Naval Observatory (http://aa.usno.navy.mil/data/docs/RS_OneYear.html). Full numerical results are presented in tables in Appendix 30.

When referring to the micrometeorological regime, we imply annual patterns in meteorological conditions of the atmosphere just above the ground, i.e. at the nearest position to *Vertigo geyeri*. Additionally, the soil temperature at 10 cm depth was monitored to establish tendencies in soil characteristics which is important due to the fact that the *Vertigo* hide themselves during inactive[14] periods.

Previous analysis showed that the most variable monitored parameter was solar radiation. Radiation data summaries were based on mean data recorded by the tube solarimeter that measured the average irradiance over a 1 metre long area and three point energy sensors placed into the ground in three different locations. There was

[14] According to Moorkens (pers. comm.), snail inactivity depends on extremes of both dry heat and cold, and may occur some years on a few occasions and in other years may not happen at all. There is no exact temperature at which this happens; it is a combination of conditions that limit humidity. If it is very humid, they will be very active, less humid = less active. If there is low humidity and low temperature, they will become completely inactive until conditions improve. In cold and drought conditions, it hides in a suitable refuge and becomes inactive. An example of a refuge is a small hole in the soil - it will follow a snail sized crack and crawl into it, out of any wind or extreme temperature fluctuation.

a big difference between data recorded by the tube solarimeter and the point energy sensors due to big differences in vegetation structure across small areas. The point energy sensors showed that the highest radiation occurred in June and reached the average day maximum of 580 - 600 W/m$^2$, Figure IV-9. The average values recorded by the tube solarimeter did not, however, reach values higher than 336 W/m$^2$.

Two main seasons can be distinguished, summer and winter. In the monitored period, the winter months covered October to February and maximum daily values were as low as less than 100 W/m$^2$. In comparison, the highest summer values reached the level of nearly 600 W/m$^2$ under the canopy (Figure IV-9). A substantial increase in incoming radiation was apparent in March, when values doubled in comparison to February. This trend continued throughout April and May. May and June were the sunniest of all monitored months with the maximum values reached in June, which corresponds to extended daytime hours. In July and August, a slow decrease was noticed, however in September the reduction was more pronounced with highest values being less than 200 W/m$^2$. The minimum irradiance occurred in December 2003 with average values ranging between 5 and 30 W/m$^2$.

Variation in air temperature, as related to solar radiation, in general shows a similar annual pattern with minimum values recorded in December and maximum in July, Figure IV-9. The average air temperature recorded at the fen during the monitoring period never dropped below zero degrees; however the absolute minimum was recorded below (–8) degrees. The smallest variations over day and night time appeare in November. During months from November to January, the average temperatures for day and night were at the same level of 5°C. From March, the amplitude of variation started to increase. The range between maximum and minimum was the highest in April 2003 with the value of 35 degrees. The air temperature just above the ground is not only affected by the amount of solar energy but also by the temperature of the ground and vice versa. Soil temperature at 10 cm depth shows circa two months' lag with regard to air temperature and solar radiation. The coldest month was February and the warmest August. In terms of amplitude, the temperature of the soil, even at shallow depths, does follow a daily pattern of ambient conditions; however it is much more stable with the difference between monthly daily maximum and minimum not higher than 6 degrees. The minimum daily fluctuation was recorded in August and was only 2 degrees. On average, minimum air temperatures were recorded in January. The increasing trend started in March and continued until August. Similarly, patterns in irradiance during summer months differed quite significantly between day and night. From September onwards, the temperature gradually decreased, which was followed by decreasing soil temperature.

With regard to humidity, average humidity for all except for one month (April – 79%) was above 80% with higher values during the night than during the day, which fits in with the higher water levels recorded during the nights and also usually calmer conditions, Figure IV-9. Similarly to all other parameters, two major seasons can be distinguished by the increased amplitude of the minimum of day time observations. Increased temperature and reduced soil moisture due to increased need for water for vegetation growth contribute in lower humidity during summer months. From March until August, the minimum daily values were recorded at a level below 50%; however, the daily average still remained at a significantly high level, above 80%.

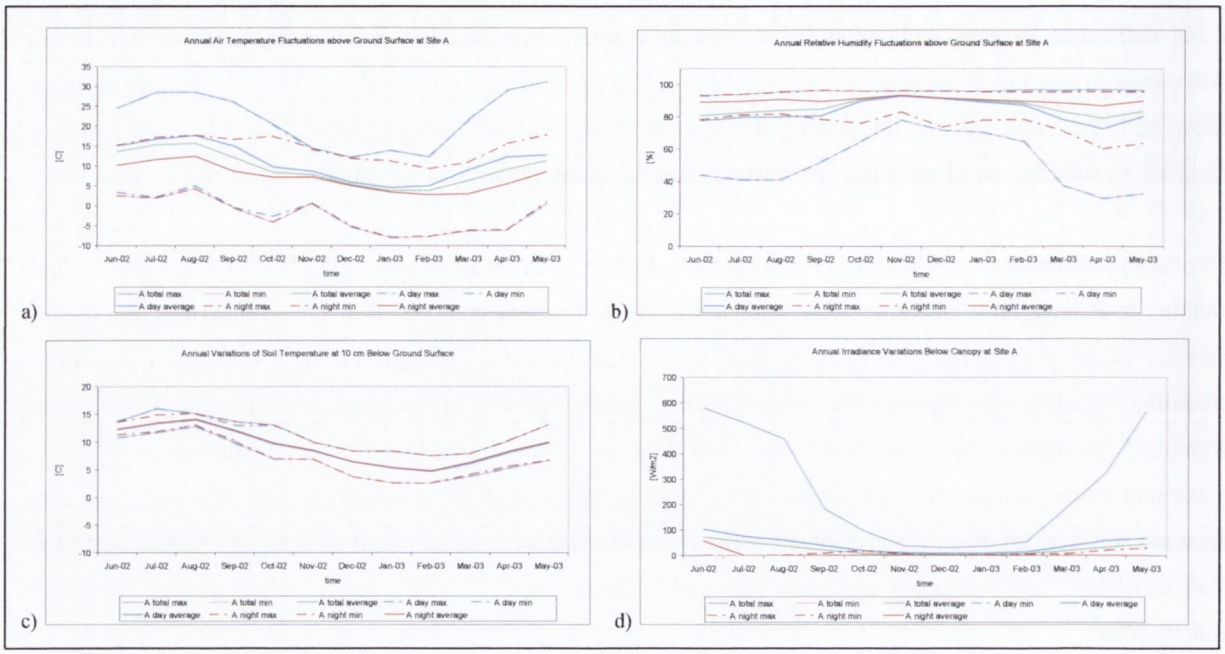



*Figure IV-9 Monthly distribution of key microhabitat elements observed at site A between June 2002 and May 2003. Numerical values are provided in Appendix 30; a) air temperature, c) relative humidity, d) soil temperature at 10cm depth below ground surface, e) incoming radiation*

*Conclusions*

From analysed variables, there is a strong difference in recorded values due to seasonal changes. Two main periods can be distinguished; first from November to February, when the variation between maximum and minimum values and differences between values recorded during the day and night reach their minimum and remain unchanged within a small range. The summer season starts in March, lasts until October, and is characterised by increased amplitudes for all parameters in these months. The stability of parameters during winter months suggests that these fluctuations are not important, or at least are not controlling the habitat of *Vertigo geyeri*. The most significant of all findings is the very stable and high mean humidity value, which remains over 80% throughout the whole year.

### IV-2.3.1.3 Soil Moisture Conditions

#### *IV - 2.3.1.3.1. Surface Wetness Measured by Clay Balls*

Surface wetness was believed to one of the most important factors controlling the presence of the snails. The parameter could not be measured on a continuous basis due to lack of suitable instrumentation; therefore some experiments were undertaken to quantify the amount of water being held in soil pores. These were described in the methodology section. Eight sampling locations were selected at site A and eight at site D to cover a wide range of surface conditions and these are stated in Table IV-10. In addition one sample was kept in a car as a control sample. Depending on surface conditions, balls were either left inside moss cover or on the peat where moss was not present. Two major location types can be distinguished, one in an open area, where very little or no shading was provided by surrounding vegetation. Such conditions often are present on small mounds. The second type was in less exposed areas, where moss and overhanging vegetation cover were denser. These areas

were often wetter. All locations were chosen within *Vertigo* positive quadrats. The results of the experiment are presented in Table IV-11.

**Table IV-10 Locations of clay balls for surface wetness assessment, site A and D, summer 2003. The light red rows indicate more open conditions and the blue where more shading was provided.**

| No. | Location SITE A | Surface conditions | No. | Location SITE D | Surface conditions |
|---|---|---|---|---|---|
| 1 | IQAVQ1-B10 | moss, open space | 9 | IQDVQ5-A10 | moss, open |
| 2 | IQAVQ1-B3 | moss on a mound | 10 | IQDVQ5-D6 | moss, wetter |
| 3 | IQAVQ1-C5 | moss | 11 | IQDVQ5-G10 | moss on a mound of *Molinia* grass |
| 4 | IQAVQ1-E3 | wet moss | 12 | IQDVQ5-G6 | open moss |
| 5 | IQAVQ1-F10 | peat | 13 | IQDVQ5-H2 | moss |
| 6 | IQAVQ3-A4 | moss | 14 | IQDVQ5-H4 | moss |
| 7 | IQAVQ3-B10 | peat/moss | 15 | IQDVQ5-J1 | very wet moss |
| 8 | IQAVQ3-E8 | moss, no shade | 16 | IQDVQ5-J8 | moss |
| 17 | car | No capillary supply to surface and soil humidity | | | |

**Table IV-11 Results of clay balls mass increase and soil wetness results**

| No. | mass at the beginning of the experiment (26.08.03) | mass at the end of the experiment (02.09.03) | mass after 12 hours in oven at 105°C | mass after 13 hours in oven at 105°C | mass after 14 hours in oven at 105°C | mass of saturated clay ball | surface wetness |
|---|---|---|---|---|---|---|---|
| | mg | mg | mg | mg | mg | mg | % |
| 1 | 0.186 | 0.2168 | 0.1819 | 0.1817 | 0.1817 | 0.236 | 65 |
| 2 | 0.3066 | 0.3371 | 0.3092 | 0.300 | 0.300 | 0.3585 | 63 |
| 3 | 0.5118 | 0.5900 | 0.5089 | 0.5087 | 0.5087 | 0.6000 | 89 |
| 4 | 0.2900 | 0.3269 | 0.2823 | 0.2823 | 0.2823 | 0.3436 | 73 |
| 5 | 0.3237 | 0.3718 | 0.3200 | 0.3200 | 0.3200 | 0.3817 | 84 |
| 6 | 0.2760 | 0.3446 | 0.2785 | 0.2785 | 0.2785 | 0.3600 | 81 |
| 7 | 0.4836 | 0.5653 | 0.4843 | 0.4835 | 0.4835 | 0.5723 | 92 |
| 8 | 0.3638 | 0.4208 | 0.3721 | 0.363 | 0.363 | 0.4739 | 52 |
| 9 | 0.3591 | 0.4200 | 0.3625 | 0.3527 | 0.3527 | 0.4277 | 90 |
| 10 | 0.3355 | 0.4124 | 0.3398 | 0.3312 | 0.3312 | 0.4127 | 99 |
| 11 | 0.3207 | 0.3694 | 0.3147 | 0.3147 | 0.3147 | 0.3748 | 91 |
| 12 | 0.2139 | 0.256 | 0.2109 | 0.2109 | 0.2109 | 0.2833 | 62 |
| 13 | 0.2231 | 0.2658 | 0.2215 | 0.2215 | 0.2215 | 0.2754 | 82 |
| 14 | 0.6000 | 0.6971 | 0.6000 | 0.5874 | 0.5874 | 0.7051 | 93 |
| 15 | 0.4061 | 0.4710 | 0.3999 | 0.3997 | 0.3997 | 0.4800 | 89 |
| 16 | 0.4065 | 0.4826 | 0.4235 | 0.3986 | 0.3986 | 0.4826 | 100 |
| 17 | 0.2273 | 0.2658 | 0.2233 | 0.2233 | 0.2233 | 0.2925 | 62 |

The results presented in the above table indicate very high saturation of the ground (as measured by clay balls) across sampling locations with 69% of samples being saturated at a rate of over 80%. These samples represent conditions with moss cover. Only 2 out of 16 samples were stored on peat soil and these received saturation levels of 84% and 92% respectively. Six balls were left in open moss with no shading, or on a mossy mound. Four of these showed much lower saturation (below 65%) however, the remaining two balls (samples 9 and 11) increased their wetness by 90 - 91%. One sample that was placed in the wet moss (sample 4) showed saturation of only 73%. The control sample that was left in a car received saturation of 62% over the course of the experiment. This sample was not exposed to the capillary rise but equilibrated with atmospheric conditions. The atmospheric conditions during that period were warm and humid with average daily humidity above 80% and an average daily temperature of between 12-16 degrees Celsius (Figure IV-11). Only 1.8 mm of rain was recorded in these 7 days against 14.9 mm of evapotranspiration. This implies that without additional water supply, the soil

would be exposed to a soil moisture deficit; however, results of the experiment do not indicate such conditions. It is likely, however, that clay balls were exposed to a combination of wetness coming from the air and from the surface that they were placed on (inclusive of the capillary rise). Nevertheless, it is apparent that balls placed in more shaded conditions or with a more dense moss cover that was less exposed to air flow and direct radiation showed higher saturation levels, which stresses the importance of vegetation structure in sustaining wetter surface conditions, if indeed such are needed by the snail. This investigation was aimed as an initial recognition of likely factors sustaining the snail habitat. Hence it was designed to provide an inside view on the snail habitat on a fen scale rather than detailed transect analysis; therefore this was not analysed statistically.

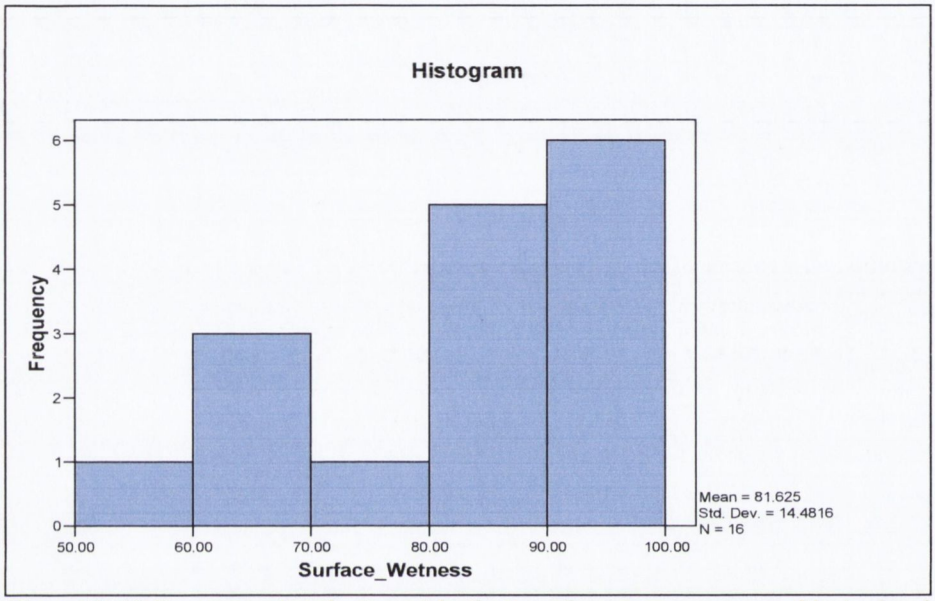



*Figure IV-10 Frequency distribution of the fen's surface wetness measured by in the clay balls experiment*

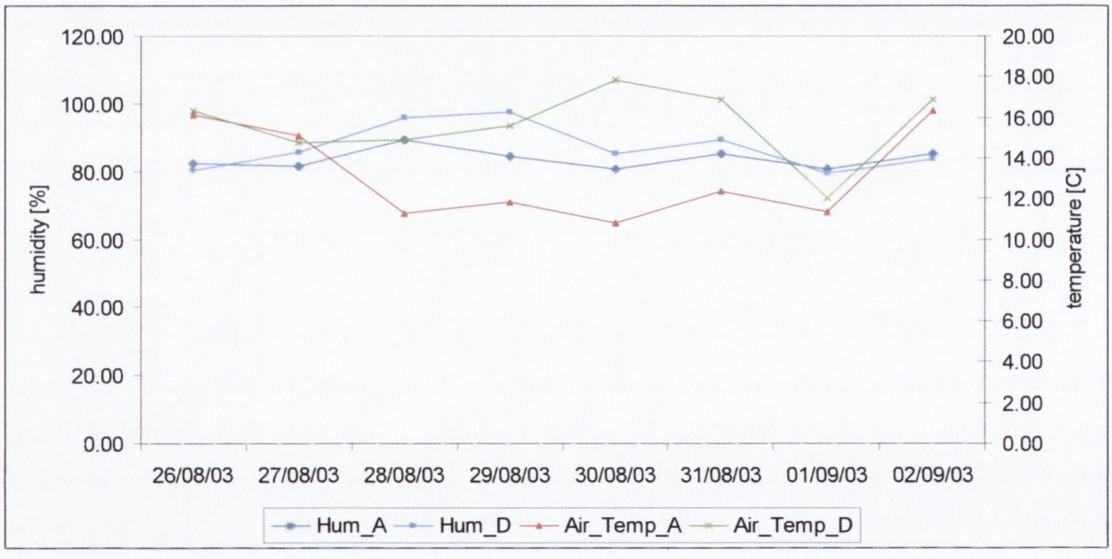



*Figure IV-11 Climatic conditions recorded on sites A and D during the clay ball experiment.*

*Conclusions*

In conclusion, the majority of clay balls used in the test reached high saturation levels despite dry and warm ambient conditions. The stability of these conditions may play an important role in sustaining a preferable habitat for the *Vertigo geyeri* snail.

### *IV - 2.3.1.3.2. Soil Moisture Measured by Gypsum Blocks*

As previously stated, parallel to the clay balls experiment, all three Intensive Quadrats of IQAVQ1, IQAVQ3 and IQDVQ5 were equipped with gypsum soil moisture blocks. In total there were 15 soil moisture blocks installed; six went to IQAVQ1, four to IQAVQ3 and five to IQDVQ5. Although installation was carried out on the 26th of August 2003, in order to allow the blocks to equilibrate with the surrounding soil the readings started on 1st September, and were carried out for five continuous days until the 5th September. The ambient conditions throughout this period were hot and dry with no rainfall between 1st – 4th and 1.4 mm precipitation recorded on the 5th September. The readings from the soil moisture meter are presented in Table IV-12.

**Table IV-12 Results of soil moisture measurement using gypsum blocks, Pollardstown Fen, summer 2003**

| | Readings | | | | | |
|---|---|---|---|---|---|---|
| Location | 26/08/2003 | 1/9/2003 | 2/9/2003 | 3/9/2003 | 4/9/2003 | 5/9/2003 |
| IQDVQ5-G10 | 90 | 89 | 90 | 91 | 91 | 91 |
| IQDVQ5-H5 | 89 | 90 | 90 | 91 | 90 | 91 |
| IQDVQ5-J4 | 91 | 90 | 90 | 91 | 90 | 91 |
| IQDVQ5-E3 | 86 | 88 | 89 | 90 | 90 | 90 |
| IQDVQ5-B2 | 90 | 90 | 90 | 91 | 91 | 90 |
| IQAVQ1-H2 | 92 | 86 | 86 | 86 | 86 | 83 |
| IQAVQ1-I3 | 91 | 88 | 88 | 88 | 89 | 86 |
| IQAVQ1-J2 | 91 | 88 | 89 | 88 | 89 | 90 |
| IQAVQ1-H9 | 94 | 88 | 87 | 87 | 87 | 87 |
| IQAVQ1-I10 | 91 | 88 | 89 | 90 | 90 | 88 |
| IQAVQ1-J8 | 92 | 88 | 89 | 90 | 90 | 90 |
| IQAVQ3-D6 | 89 | 86 | 87 | 88 | 88 | 87 |
| IQAVQ3-F5 | 92 | 87 | 89 | 90 | 89 | 88 |
| IQAVQ3-F7 | 93 | 88 | 90 | 90 | 90 | 90 |
| IQAVQ3-G6 | 92 | 88 | 90 | 90 | 90 | 90 |

The results were similar to that of clay balls with even stronger saturation, which can be explained by the fact that blocks were buried in the ground (peaty soil). The range of readings remained very small during the experiment and varied between 83% and 94% which confirms the very high stability of soil moisture conditions within the *Vertigo* habitat. The majority of readings showed 90% saturation; however, the mean value was computed at a level of 88.9%. Overall, there was no sample below 80% of saturation, which was the lower limit for surface wetness in shaded (or not exposed) areas tested with clay balls. An additional finding of that study was the partial destruction of all soil moisture blocks used at site D (northern fen margin) by acidic corrosion. The recharge mechanism for both sides differs and that on the northern side is much closer and more dependent on precipitation; while the southern fen margin is more reliant to the discharge from the Curragh aquifer. Lower pH has been previously recorded on the northern side; however such strong acidic corrosion of the blocks suggests that the northern fen margin hydrogeology is strongly supported by surface runoff. A question in relation to the water chemistry required by *Vertigo geyeri* has to be asked here. As given in the introduction, *Vertigo geyeri* is known to have a strong association with alkaline, calcium rich fens, where pH values range between 6.0-7.5 and calcium concentration being between 25-80 mg/l (after Johnson, 2000). It is believed that the snail builds its shell from calcium that it draws from the water. The chemical analysis carried out on the fen revealed pH concentrations along all transects sites at the level higher than 6.5, which classified the fen into that category. The incidence of corrosion of the gypsum blocks indicates, however, that the site gets temporarily flooded with surface runoff, which affects its hydrochemistry. There is no published exact pH range for *V. geyeri* but it is broadly accepted that it can tolerate a range from neutral to base rich (Speight *et al.*, 2002), however this

is based on studies of habitat phytoassociations, not direct water chemistry. Within a habitat of lower pH values (transition mires, which Site D is an example of) *V. geyeri* tends to be very sparsely distributed, which perhaps can be attributed to low pH values (after Moorkens, per. comm.). Nevertheless, Moorkens suggests that lower snail densities at site D are more likely to be attributed to relatively high water levels limiting habitable zones.

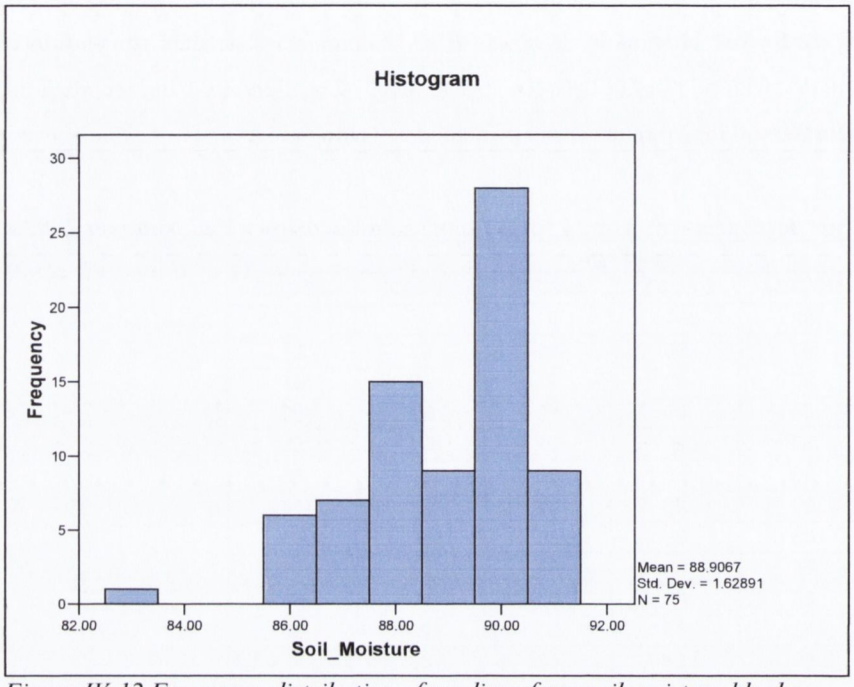



*Figure IV-12 Frequency distribution of readings from soil moisture blocks*

### *IV - 2.3.1.3.3. Soil Water Content Measured by the Oven Drying Method*

The final examination of soil moisture conditions consisted of establishing the soil water content using an oven drying method. Four samples were taken, these were IQAVQ3 – F5, IQAVQ1 – J2, IQAVQ3 – D6 and IQAVQ3 – F7. The results of this test are presented in Table IV-13.

**Table IV-13 Results of soil water content test using oven-drying method**

| | mass of a wet sample | mass after 8 hours on 105°C | mass after 12 hours on 105°C | mass after 16 hours on 105°C | mass after 17 hours on 105°C | mass after 18 hours on 105°C | water content in sample |
|---|---|---|---|---|---|---|---|
| | mg | mg | mg | mg | mg | mg | % |
| **IQABQ3-F5** *(open hollow)* | 4.85 | 1.69 | 1.68 | 1.66 | 1.66 | 1.66 | 66 |
| **IQABQ1-J2** *(lower elevation under tussock)* | 7.12 | 2.30 | 1.92 | 1.73 | 1.7 | 1.7 | 76 |
| **IQABQ3-D6** *(lower elevation under tussock)* | 3.11 | 1.21 | 0.68 | 0.62 | 0.6 | 0.6 | 81 |
| **IQABQ3-F7** *(under tussock)* | 5.25 | 2.35 | 1.97 | 1.6 | 1.6 | 1.6 | 70 |

In general, the results showed lower values than the two previous experiments and also higher variability between the four samples. As expected, topographic arrangements such as altitude (tussocks or hollow) and the presence of shading by vegetation contributed to these important differences.

Out of four samples, one sample (IQABQ3 – F5) showed a significantly lower water content of 66%, and this was taken from an open hollow accessible to direct radiation. Samples from locations placed under the tussock, where more shading was provided showed slightly higher values ranging from 70 - 81%.

*Conclusions*

In summary, despite the fact there was very little rain in August 2003, it hardly affected surface moisture conditions. Both experiments (the clay balls and the gypsum blocks), indicated relatively high surface wetness and soil moisture, the latter at the level of c. 90%. Nevertheless, samples from some more exposed sites showed the saturation level of a clay ball decreased down to 52%. This was confirmed by visual inspection (very dry moss cover). During hot, sunny days, the moss cover was very dry but the soil underneath remained wet with water content ranging between 66 - 81%. In such conditions, snails, which require a wet environment, could possibly not survive exposure on the moss carpet and are likely to hide in lower areas, underneath plant debris or bury themselves in gaps in the wetter soil.

Acidic corrosion of gypsum blocks at site D might support earlier findings of the more direct influence of rainfall at this site and this could potentially decrease the suitability of the site for snails. However, the relationship between snail distribution and pH is not yet well understood.

## *IV-2.3.2. The Microhydrological Regime*

### IV-2.3.2.1 Summary of Phreatic Levels

The description of flow mechanism of the fen margin was given in Chapter III; therefore here only the relationship between mollusc counts and the water table will be discussed. Summer months were distinguished and were agreed for months of May until October. This was chosen to correspond with the mollusc study, which was carried out during these months. As *Vertigo geyeri* hibernates for winter, May to October were considered best for monitoring snail dynamics. Loggers were set to record data on an hourly basis, which was later aggregated into daily values. This data is presented in Table IV-14.

Fluctuations within the phreatic zone of the fen margin remained relatively stable, with the maximum range of 32 cm recorded at site E. It is apparent that fluctuation ranges were higher on the southern fen margin than on the northern fen margin, which is most likely to be controlled by the elevations of these sites. On the north side, records showed the maximum of 12 cm difference between the maximum and minimum levels over 12 months (site D in June 2003 - May 2004) and throughout whole observation period (site D, 2002 - 2005). Also, both sites of C and D remained flooded most of the time with an average water table being recorded above the surface which may explain lower and patchier snail distribution as extensive flooding significantly reduced habitable ground surface. Figure IV-13-Figure IV-15 present hydrographs of the phreatic level within Intensive Quadrats A, E and D over the time of observation. More analysis was performed on data covering summer months.

There was an evident trend of increasing fluctuations, in line with decreasing average annual water table on site A. This was especially apparent from October 2003. The reason for these increased fluctuations will be

discussed later. A comparison with continuous years showed a decrease in the average water table by 9 cm over three years and increase in fluctuation range from 17 to 31 cm. On the north side, long term trends in the phreatic water table are difficult to assess because of limitations of the data; however data from 2004 showed slightly higher levels that in 2003. Visual observations from 2005 confirmed high water levels and flooding. Therefore there wasn't any indication that the phreatic level dropped over time on these sites.

**Table IV-14 Annual water table fluctuations (meter OD) within Intensive Quadrats A-E**

| | Site A, BQ1 & BQ2 (ground level at 88.44 m OD) | | | | | |
|---|---|---|---|---|---|---|
| | **max** | **min** | **Average** | **range** | **SD** | **VAR** |
| Jun02-May03 | 88.42 | 88.25 | 88.34 | 0.17 | 0.03 | 0.001 |
| Jun03-May04 | 88.38 | 88.17 | 88.32 | 0.21 | 0.04 | 0.002 |
| Jun04-May05 | 88.42 | 88.11 | 88.25 | 0.31 | 0.07 | 0.005 |
| | **Site E, BQ1 & BQ2 (ground level at 86.37 m OD)** | | | | | |
| | **max** | **min** | **Average** | **range** | **SD** | **VAR** |
| Jul02-May03 | 86.32 | 86.19 | 86.26 | 0.12 | 0.03 | 0.001 |
| Jun03-May04 | 86.37 | 86.05 | 86.30 | 0.32 | 0.08 | 0.006 |
| Jun04-May05 | 86.40 | 86.16 | 86.32 | 0.24 | 0.04 | 0.002 |
| | **Site C (ground level at 85.73 m OD)** | | | | | |
| | **max** | **min** | **Average** | **range** | **SD** | **VAR** |
| Jun02-May03 | 85.81 | 85.74 | 85.77 | 0.07 | 0.02 | 0.0004 |
| Jun03-May04 | | | | | | |
| Jun04-May05 | | | | | | |
| | **Site D, BQ3, BQ4 & BQ5 (ground level at 85.68 m OD)** | | | | | |
| | **max** | **min** | **Average** | **range** | **SD** | **VAR** |
| Jun02-May03 | | | | | | |
| Jun03-May04 | 85.74 | 85.62 | 85.69 | 0.12 | 0.02 | 0.0004 |
| Jun04-May05 | 85.74 | 85.68 | 85.71 | 0.06 | 0.01 | 0.0001 |

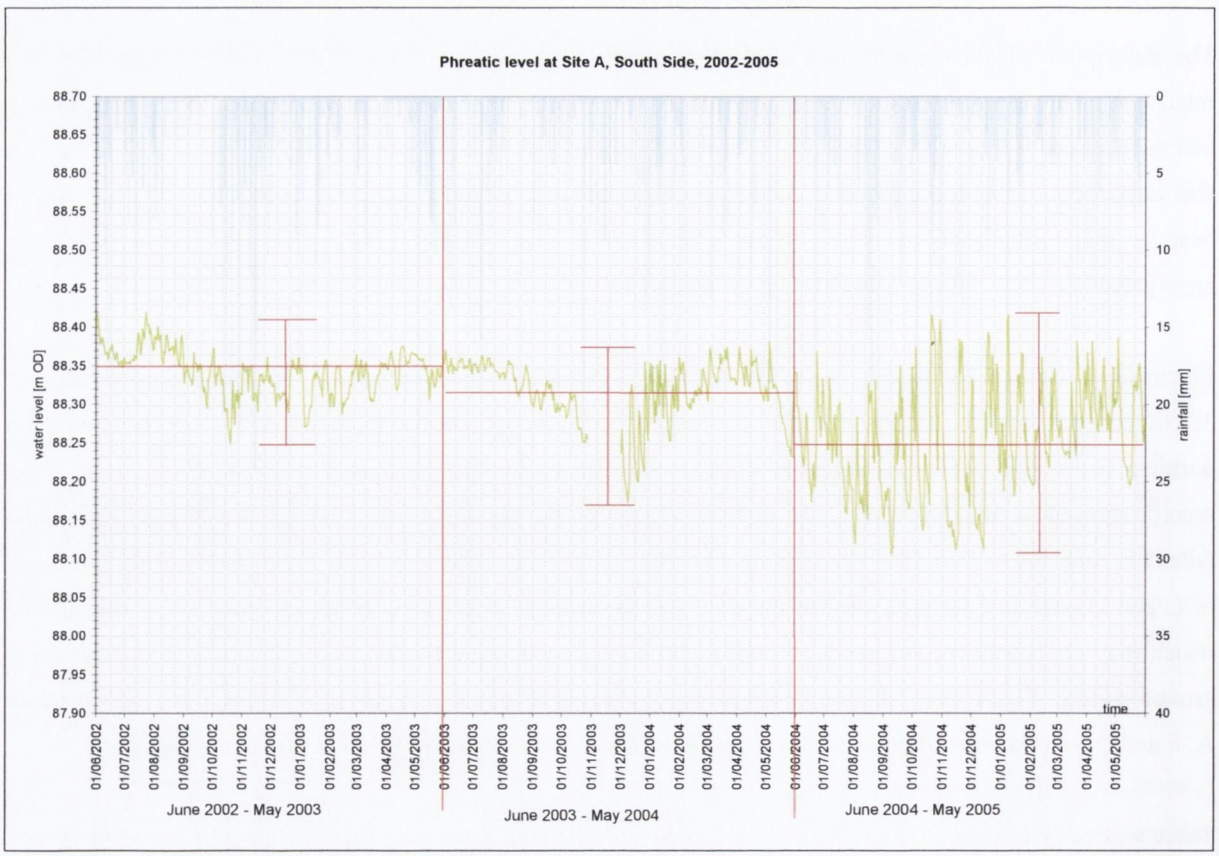



*Figure IV-13 Phreatic level fluctuations in Intensive Quadrat A (Site A), 2002-2005.*

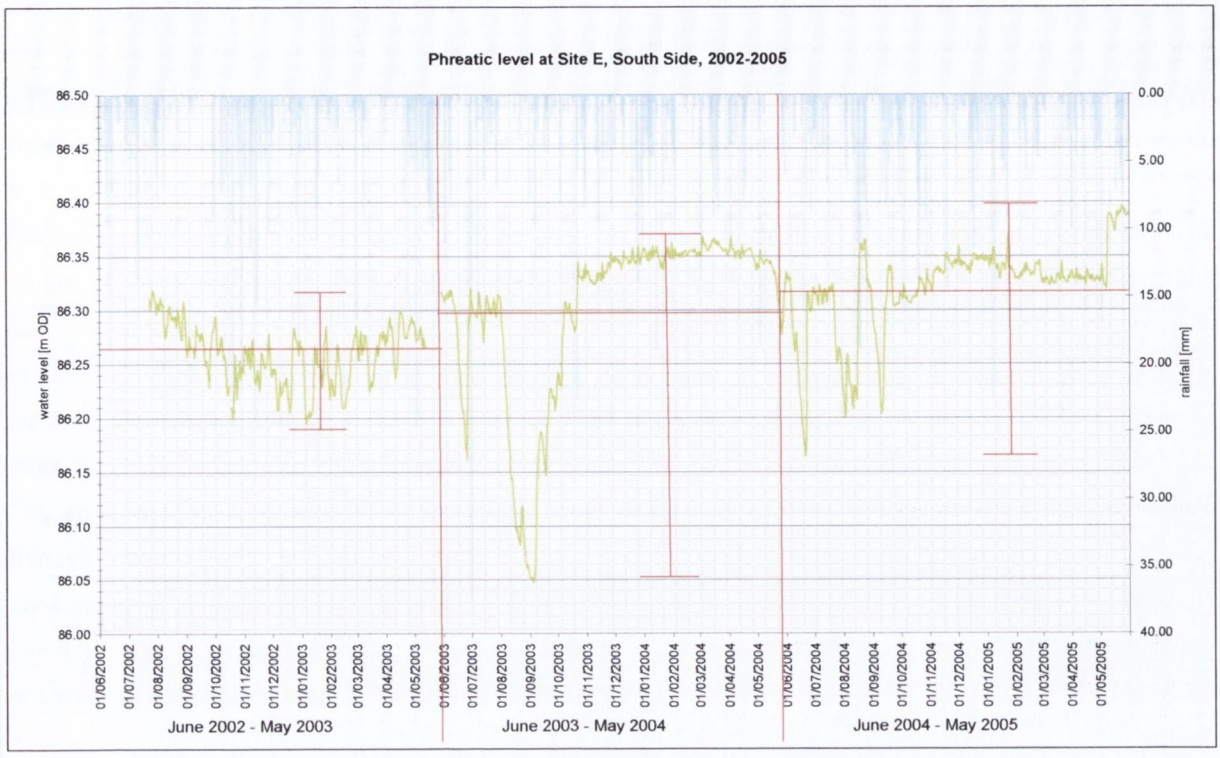



*Figure IV-14 Phreatic level fluctuations in Intensive Quadrat E (Site E), 2002-2005.*

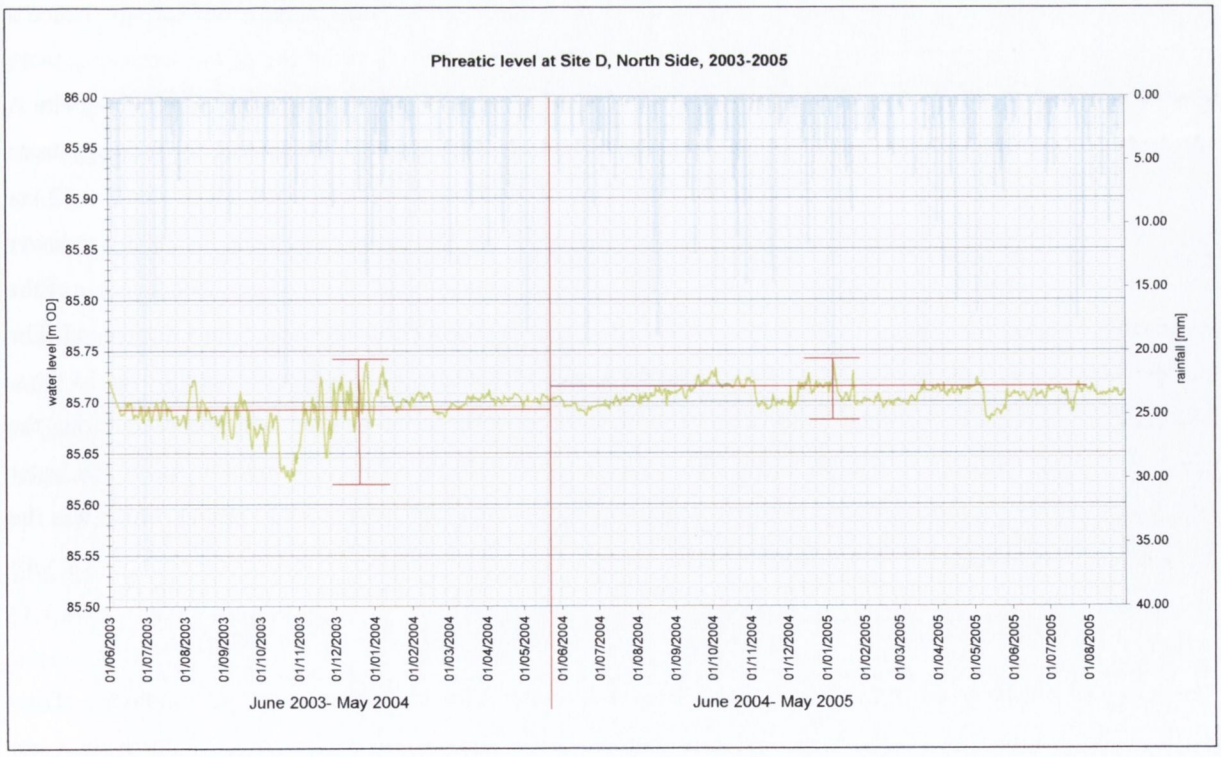



*Figure IV-15 Phreatic level fluctuations in Intensive Quadrat D (Site D), 2003-2005.*

### *IV - 2.3.2.1.1. Comparison of the Summer Water Table (May-October) over 2002-2004*

**Site A**

Observations showed a very stable water table on site A (Intensive Quadrat A) in 2002 and 2003, with slightly lower levels in 2003. The pattern was that the highest water table was usually in May and it slowly decreased throughout the summer. The mean summer water table for 2002 was recorded at 88.35 m OD, in 2003 it was at 88.33 m OD and in 2004 it decreased to 88.25 m OD. The range of fluctuations between the daily maximum and minimum values over the six month period was 17 cm in 2002, and in the following two years it was 12 and 31 cm respectively. The big change in 2004 in the range corresponds with significantly decreased mean level and an increased depth of the minimum level. The results also showed a more direct response to rainfall in 2004 in comparison with previous years with higher changes in the water table over short periods. For example, between 21st and 23rd June the water table increased by 18 cm in response to 19.6 mm of rain recorded on 22/06/04; there was a 7 cm increase between 27th and 29th June and 0.6 mm of rain on the 27th June plus 8.8 mm on the 28th June; 15.6 mm fell on the 15th August, which resulted in an 18 cm rise within the next 24 hours. Rainfall response in the phreatic level has not been seen to such an extent in previous years because the minimum level which is controlled by seepage from deep groundwater was at a higher level of 88.25 m OD in both 2002 and 2003, and 88.11 m OD in 2004. Ground surface is at 88.44 m OD. A summary of water level data is presented in Table IV-15.

**Site E**

Although located on the southern fen margin and not far away from site A, site E showed an entirely different regime. The site lies in a ditch along the fen margin and is controlled by a discharge from springs, hence a seasonal cycle with highest water levels in the winter, and lower water levels at the end of the summer is more evident here than at site A. The site was also more responsive to rainfall and prolonged droughts than at site A (Figure IV-14) which indicates some surface recharge from surrounding fields contributing to discharge from these springs. In 2002, the mean water table was at 86.27 m OD and range of fluctuations was as small as 12 cm only. A declining trend towards the end of the summer was apparent. The mean water table for 2003 was lower and was at 86.24 m OD. A drought that occurred in the area that summer resulted in a significant decrease of the water table with the minimum daily value recorded at 86.05 metres OD, which was 32 cm below the ground. The site showed a very quick recovery during the first two weeks of September (26.6 mm of rainfall over 14 days, leading to an increase in the water table from 86.05 to 86.19 m OD). A similar event was recorded during the summer of 2004; however, to a lesser extent (minimum water table recorded at 86.16 m OD). Again, the water table recovered within two days after a rainfall event. The mean water table was at 86.30 m OD, which was the highest of all three years.

**Sites C & D**

Sites C & D will be discussed together, as both lie at a similar altitude and represent the conditions of the northern fen margin. Both sites showed extreme stability in the water table, with a range of fluctuations not exceeding 10 cm throughout the study period and minimum levels being only 6 cm below the surface (site D, summer 2003). A comparison between records from two continuous summers of 2003 and 2004 from site D showed wetter conditions in 2004, which is similar to site E. In 2003 the mean summer water table was established at 85.68 m OD with fluctuations of 10 cm and a drying trend towards the end of the summer. 2004

was definitely wetter with a range of fluctuations as small as 5 cm, and increasing water table level throughout summer months Figure IV-29. This coincided also with negative *Vertigo* counts. The occurrence of snails was generally quite random at these sites, which have a rather flat topography with little vertical variations. Dr Moorkens (per. com.) has indicated that frequent flooding was the most likely cause of the disappearance of snails from site C in 2002 and could also affect the snails' presence at site D in 2004.

**Table IV-15 Summer water table fluctuations (m OD) at sites A, C, D and E over years 2002-2004**

| | Site A, BQ1 & BQ2 | | | | | |
|---|---|---|---|---|---|---|
| | max | min | Average | range | SD | VAR |
| 2002 | 88.42 | 88.25 | 88.35 | 0.17 | 0.03 | 0.001 |
| 2003 | 88.37 | 88.25 | 88.33 | 0.12 | 0.03 | 0.001 |
| 2004 | 88.42 | 88.11 | 88.25 | 0.31 | 0.07 | 0.005 |
| | Site E, BQ1 & BQ2 | | | | | |
| | max | min | average | range | SD | VAR |
| 2002 | 86.32 | 86.20 | 86.27 | 0.12 | 0.03 | 0.001 |
| 2003 | 86.35 | 86.05 | 86.24 | 0.30 | 0.08 | 0.007 |
| 2004 | 86.36 | 86.16 | 86.30 | 0.20 | 0.04 | 0.002 |
| | Site C | | | | | |
| | max | min | average | range | SD | VAR |
| 2002 | 85.81 | 85.74 | 85.76 | 0.07 | 0.02 | 0.0004 |
| 2003 | | | | | | |
| 2004 | | | | | | |
| | Site D, BQ3, BQ4 & BQ5 | | | | | |
| | max | min | average | range | SD | VAR |
| 2002 | | | | | | |
| 2003 | 85.72 | 85.62 | 85.68 | 0.10 | 0.02 | 0.0004 |
| 2004 | 85.73 | 85.69 | 85.71 | 0.05 | 0.01 | 0.0001 |

### *IV - 2.3.2.1.2. Snail Presence vs. Depth of Phreatic Level Fluctuations*

The snail can relocate within small areas depending on water availability; however a prolonged or irreversible change in the hydrological regime might in the long term cause stress and extinction from a given location (Moorkens, pers. comm.). Proximity of the water table to the surface and spatial distribution of snails with reference to surface water seems to be a good indication of acceptable fluctuations. Average daily water table was therefore compared against snail presence on site. Figure IV-16, Figure IV-21 and Figure IV-29 present daily water table fluctuations within summer months May – October over 2002-2004. Red and black dots indicate days when snail counts were carried out. Red dots point towards positive count result and black towards negative.

**Site A**

Out of 15 snail surveys undertaken on site A within IQABQ1 during May – October 2002-2004, seven were positive and eight negative. Water table levels recorded on site during positive surveys ranged between 88.29 m OD to 88.38 m OD. All negative snail counts matched with a water table of between 88.15 m OD and 88.32 m OD. The last sighting of the snail within IQABQ1 was in early May 2004 with a corresponding water table at 88.32 m OD; however no snail was found throughout the remaining months of the 2004 monitoring season when a significant decrease in the water table was observed (Table IV-15).

A frequency duration analysis was used to assess water availability throughout 2002 - 2004 summer periods. This revealed a change in water level distribution between the three continuous summers. Specifically the 2004 curve shows much bigger fluctuation range with a rather even distribution throughout the range. The 2002 and 2003 curves have similar, flatter shapes which indicate more stable conditions with relatively small fluctuation ranges. It is apparent also that the proportion of water levels exceeding the arithmetic average from 2002 (88.35 m OD, Table IV-15) decreased throughout the observation period. In 2002, about 70% of the phreatic surface was measured at a level equal or higher to 88.35 m OD. In the consecutive years 2003 and 2004 this value was exceeded by approximately 32% and 7% respectively. The minimum summer level of 2002 (85.25 m OD) did not change in 2003 but was exceeded by as little as 50% only in 2004 indicating a significant decrease in water levels in 2004. The fact that snails were present on site in 2002 and 2003 but have not been recorded in 2004 (except for the first counting in early May with water levels still relatively high) suggests therefore that the minimum water level may be more important in controlling presence of the snail on site rather than the average summer level. When water table is below a certain threshold, the capillary rise may not reach the surface to allow for suitably wet or moist conditions to develop. Also, a higher fluctuation range may force the snail to travel to lower locations to reach adequately moist conditions. These zones, as topographically lower, may be prone to flash flooding after rainfall and endanger the species by drowning. As presented in Figure IV-18 to Figure IV-20 which demonstrate a change in percentage of the area that floods under a maximum, minimum and average water table within Botanical Quadrat 1 over 2002-2004. An extent of the flooding is controlled by maximum water levels and these were the same in 2002 and 2004. Therefore, the most likely trigger controlling the snail presence within site A is the minimum water table and an associated capillary rise, which controls surface wetness and soil moisture conditions. Based on this three year observation the suggested minimum summer water table at site A is therefore 88.25 m OD (i.e. 0.19 m below the surface).

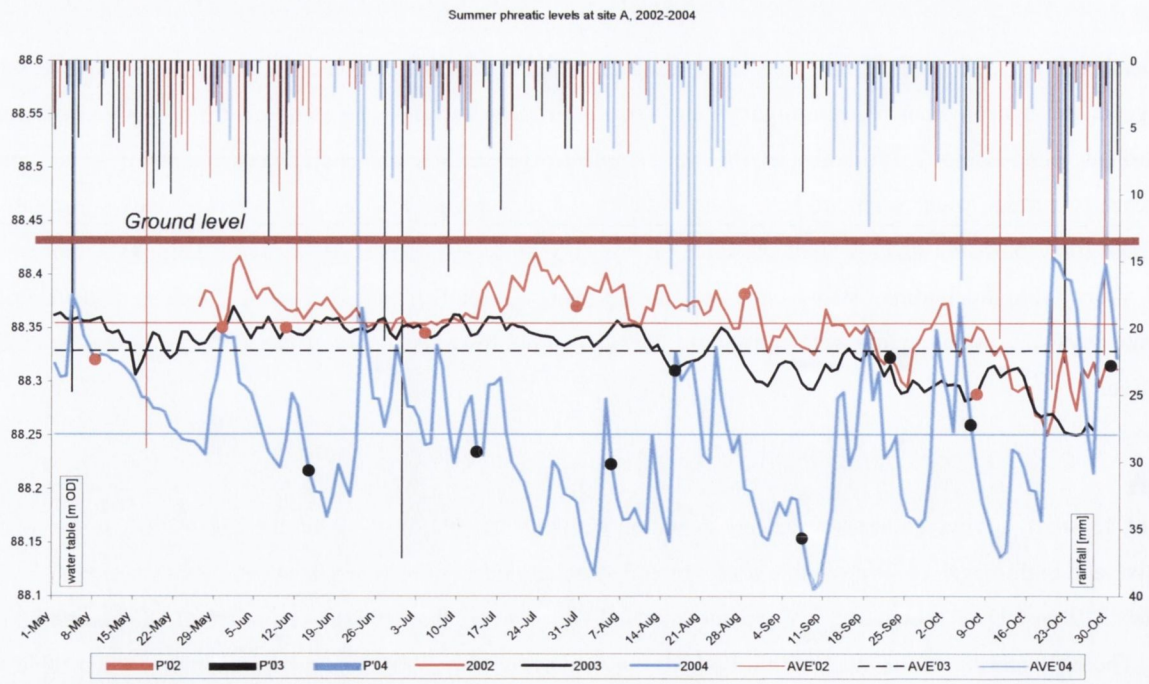



*Figure IV-16 Summer water table fluctuations on site A, 2002-2004; P- rainfall, AVE – average water level over the observation period. Red and black dots indicate days when snail counts were carried out. Red dots indicate a positive count result and black negative.*

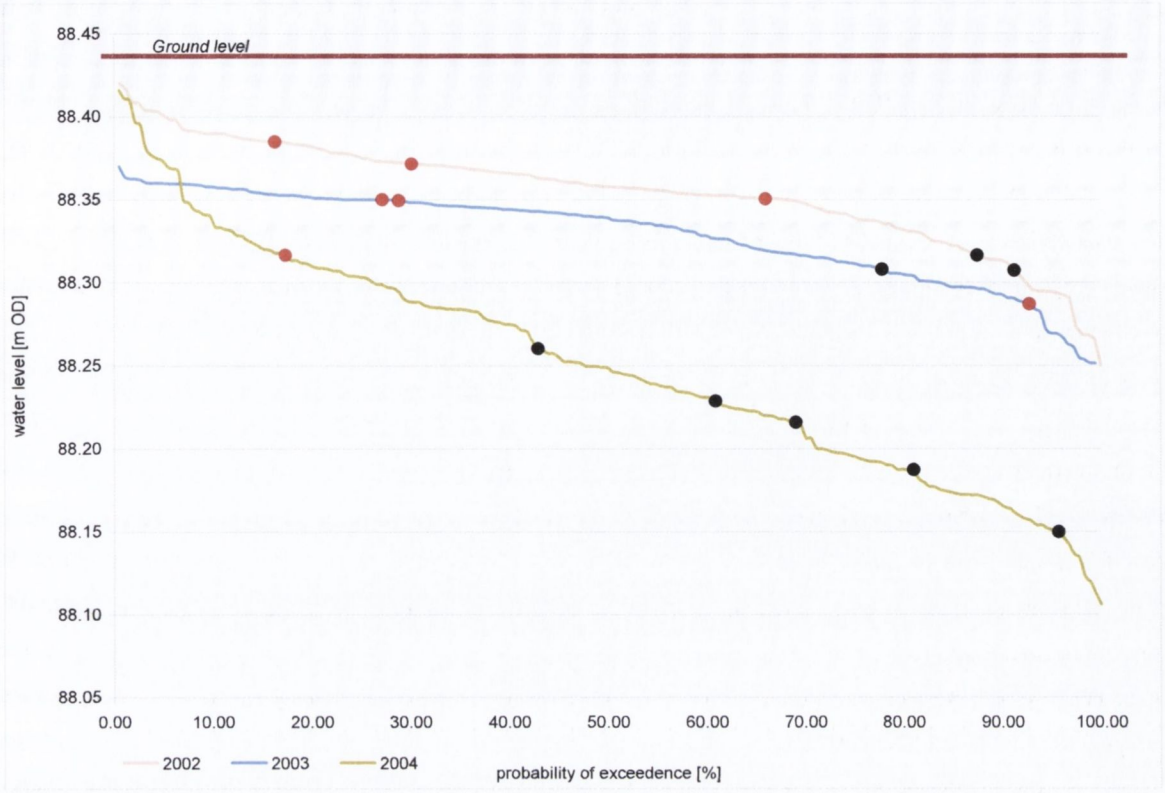



*Figure IV-17 Frequency duration curves of the summer phreatic level at site A, 2002-2004*

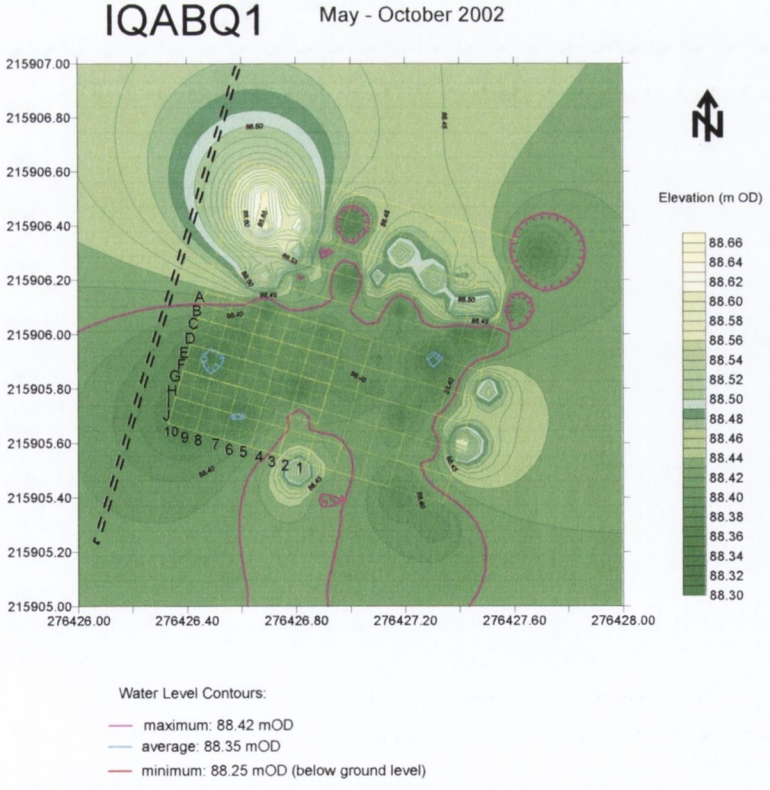



*Figure IV-18 Spatial distribution of the maximum, minimum and average summer water table, Site A, Botanical Quadrat 1, 2002*

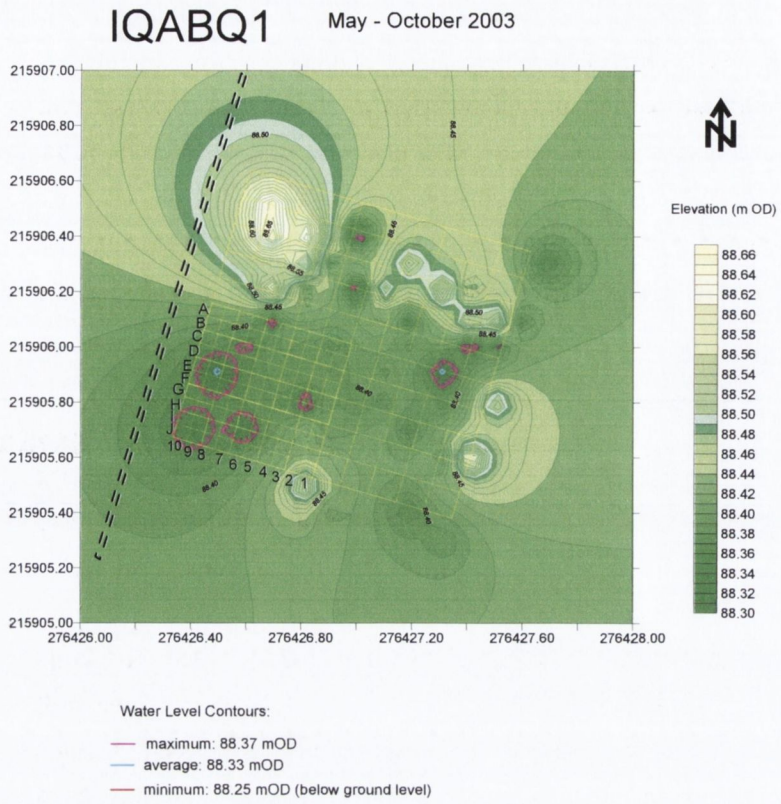



*Figure IV-19 Spatial distribution of the maximum, minimum and average summer water table, Site A, Botanical Quadrat 1, 2003*

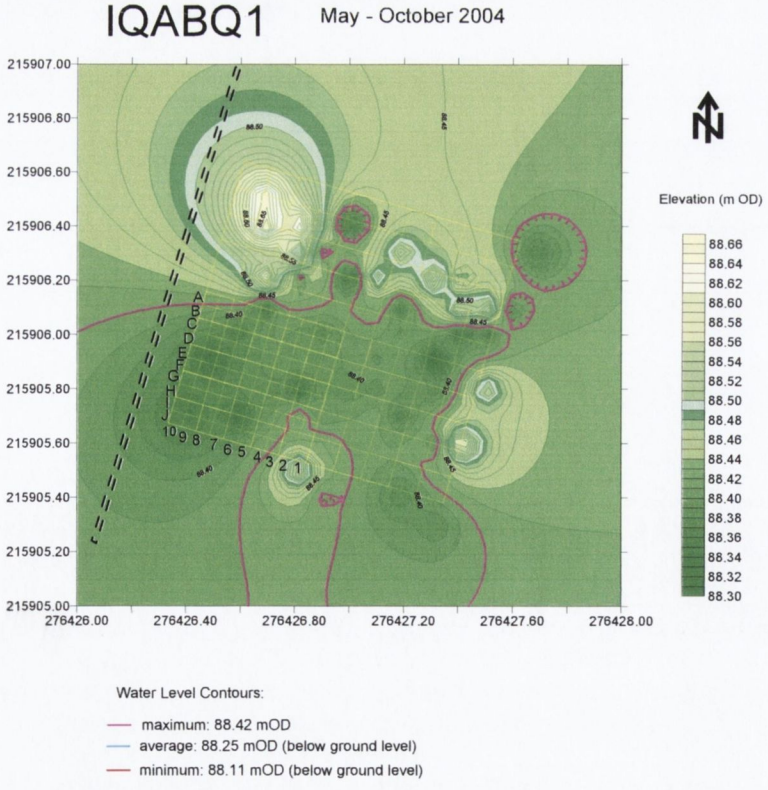



*Figure IV-20 Spatial distribution of the maximum, minimum and average summer water table, Site A, Botanical Quadrat 1, 2004*

**Site E**

The presence of snails with respect to water table fluctuations was very uneven and not conclusive on this site. The snails happened to be seen on site in both situations of high and low water levels and three data sets show different scenarios. In 2002, the snail was seen until the end of July. After that time, water levels indicated a decreasing trend and there are no records of snails being present on the site until the end of the summer. That suggests that conditions became probably too dry toward the end of the season; however, they were still above levels recorded in the following year when the snail was found. In 2003, snails were found in four sampling campaigns with the latest record of snail occurrence from August 15th, when the water table was much lower.

The lack of snails on site afterwards can be attributed to either too dry conditions that continued after that event or that the snails moved towards too low altitudes during their search for water and were washed out when the water table suddenly increased due to higher precipitation at the beginning of September. The year 2004 was generally wetter and was very poor in positive snail counts, which implies that the site was probably too wet to host the species. Changing patterns of spatial water distribution within Botanical Quadrats 1 and 2 are presented in Figure IV-23 - Figure IV-28 and demonstrate the clear reduction of dry areas in 2004. Since there is no obvious pattern in snail occurrence, it was very difficult to establish a threshold level that controls the snail presence. Water table is clearly correlated with rainfall events therefore data sets do not have a good fit with a normal distribution and probability of exceedence seems not to be a good indication of water availability. Even though impeding statistical analysis, the graph may still be useful and as such is presented in Figure IV-22

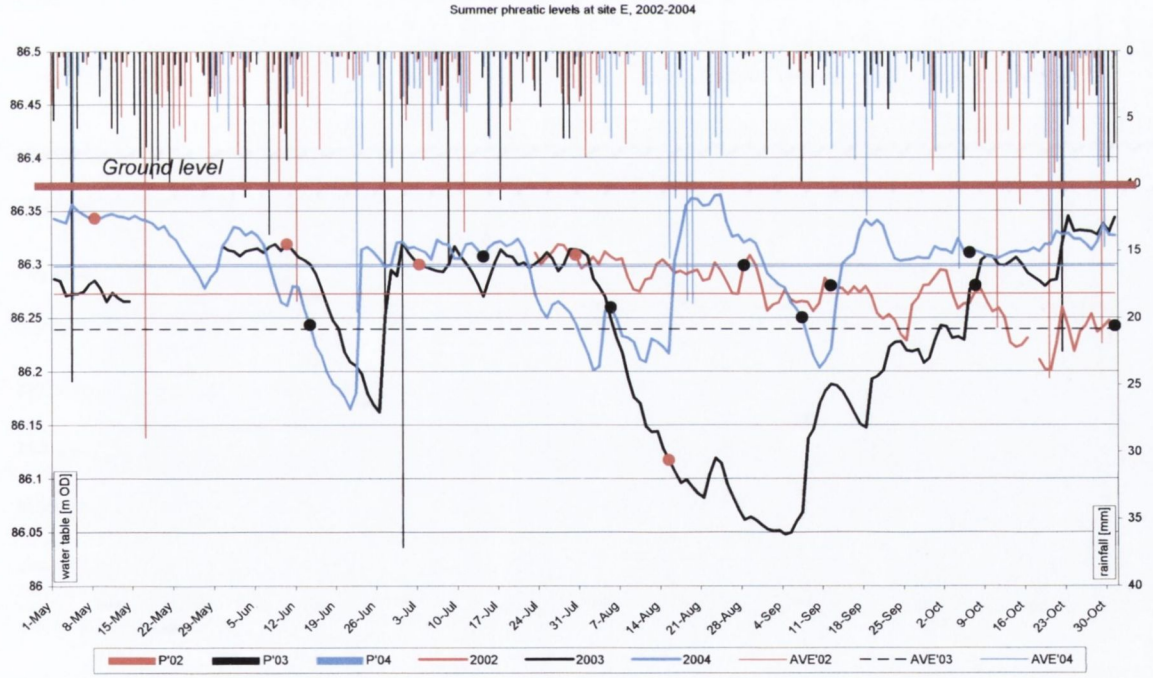



*Figure IV-21 Summer water table fluctuations on site E, 2002-2004; P- rainfall, AVE – average water level over observation period. Red and black dots indicate days when snail counts were carried out. Red dots indicate a positive count result and black negative.*

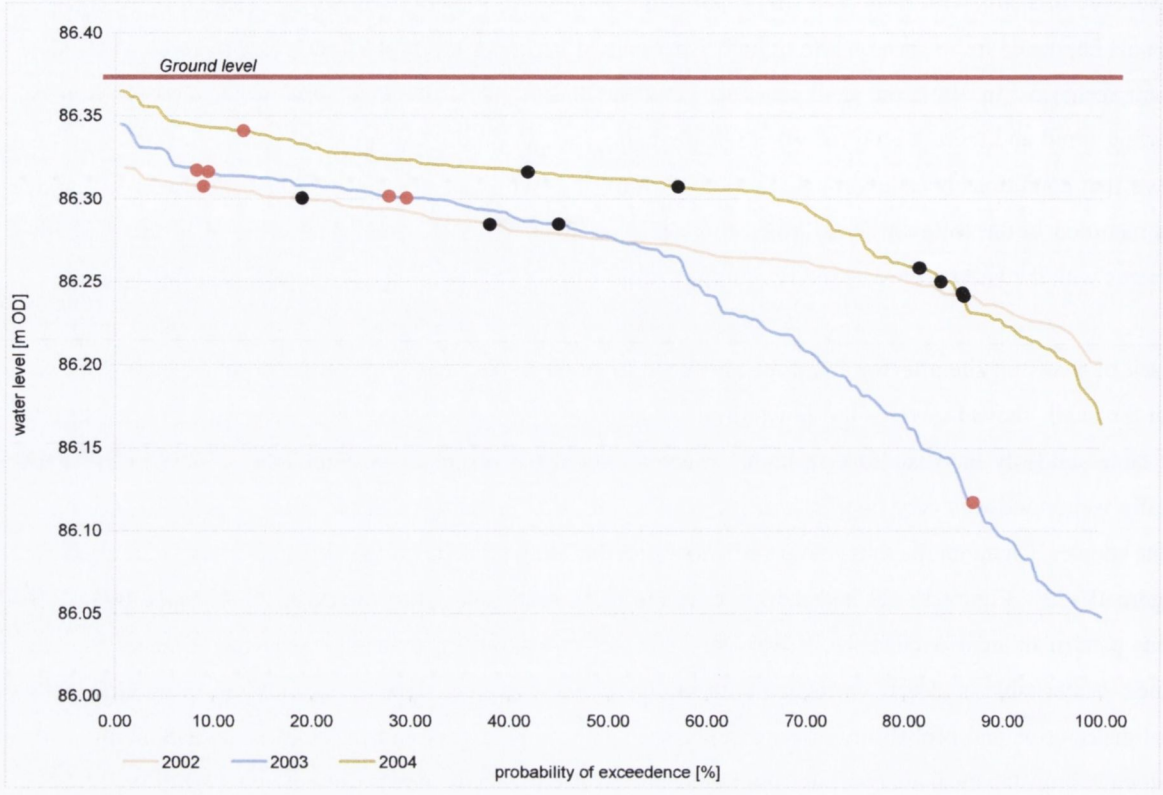



*Figure IV-22 Frequency duration curves of the summer phreatic level at site E, 2002-2004*

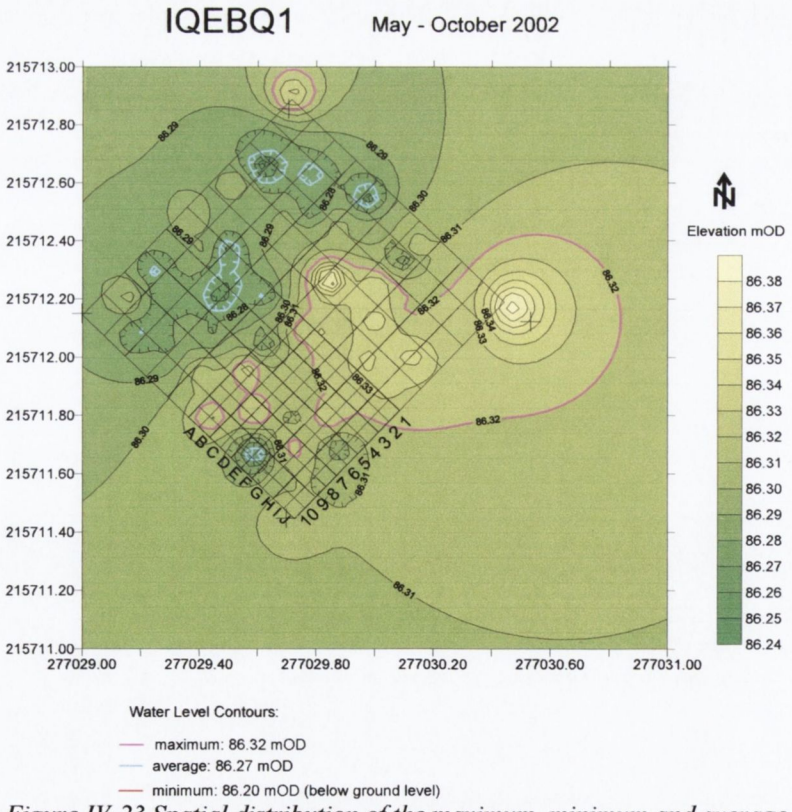



*Figure IV-23 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 1, 2002*

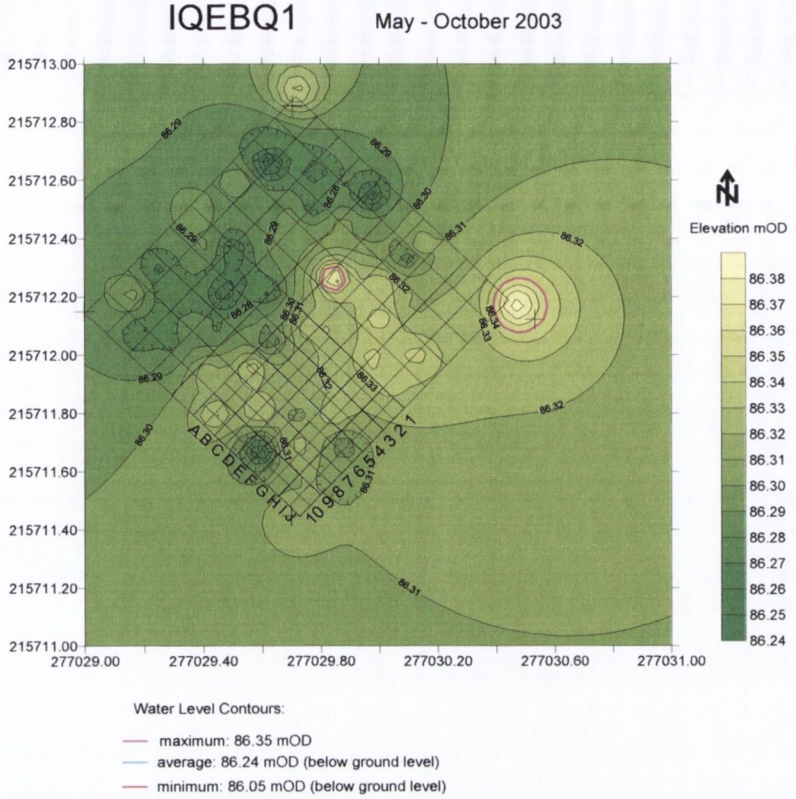



*Figure IV-24 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 1, 2003*

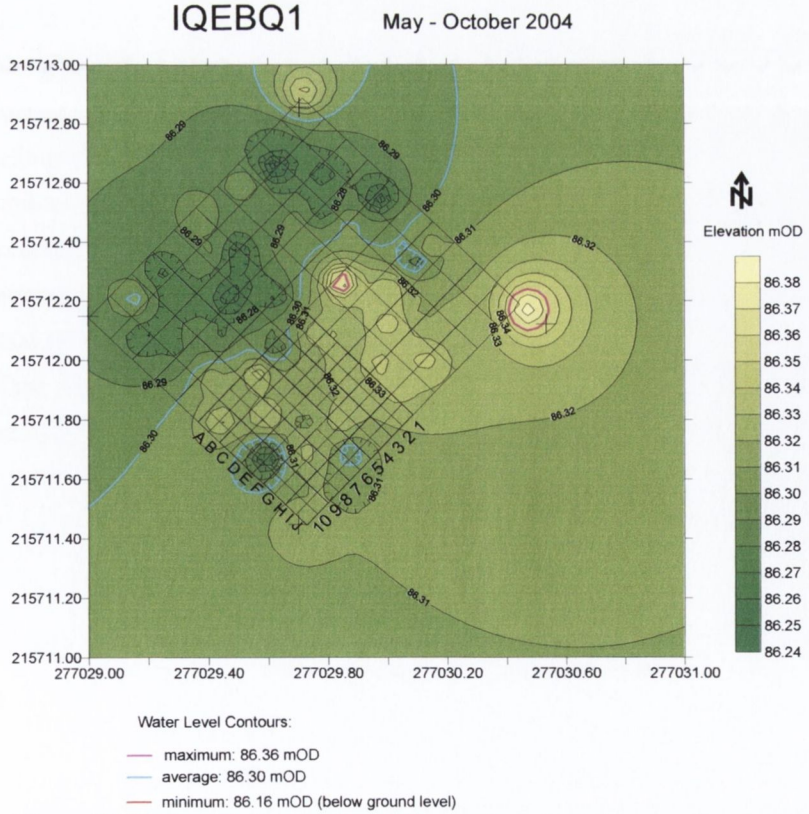



*Figure IV-25 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 1, 2004*

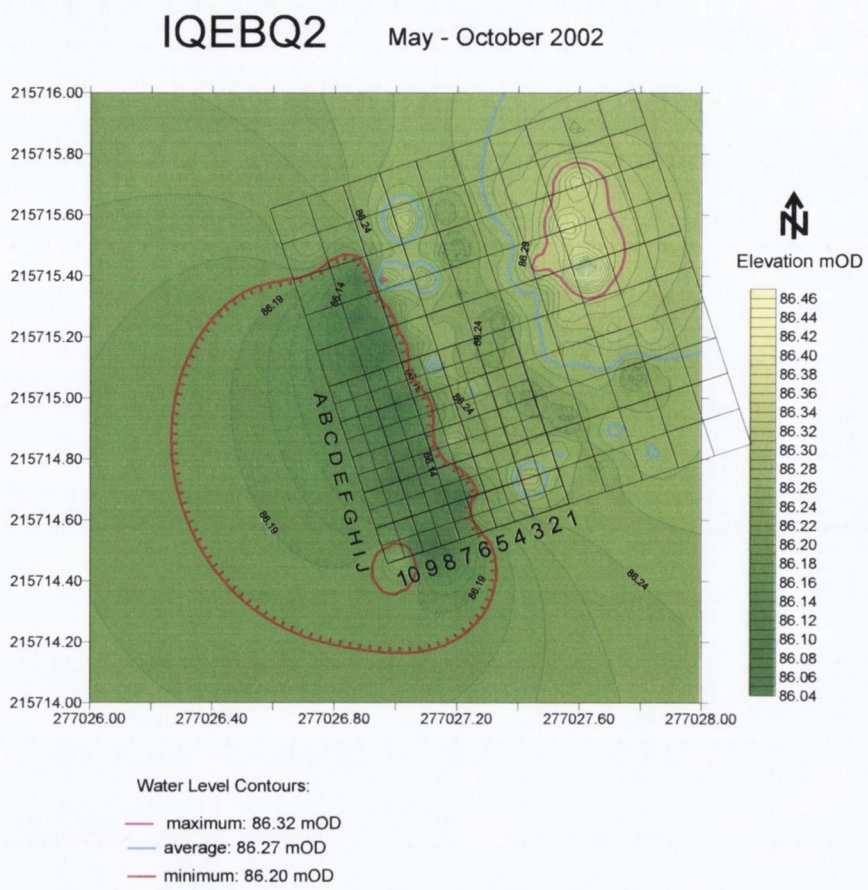



*Figure IV-26 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 2, 2002*

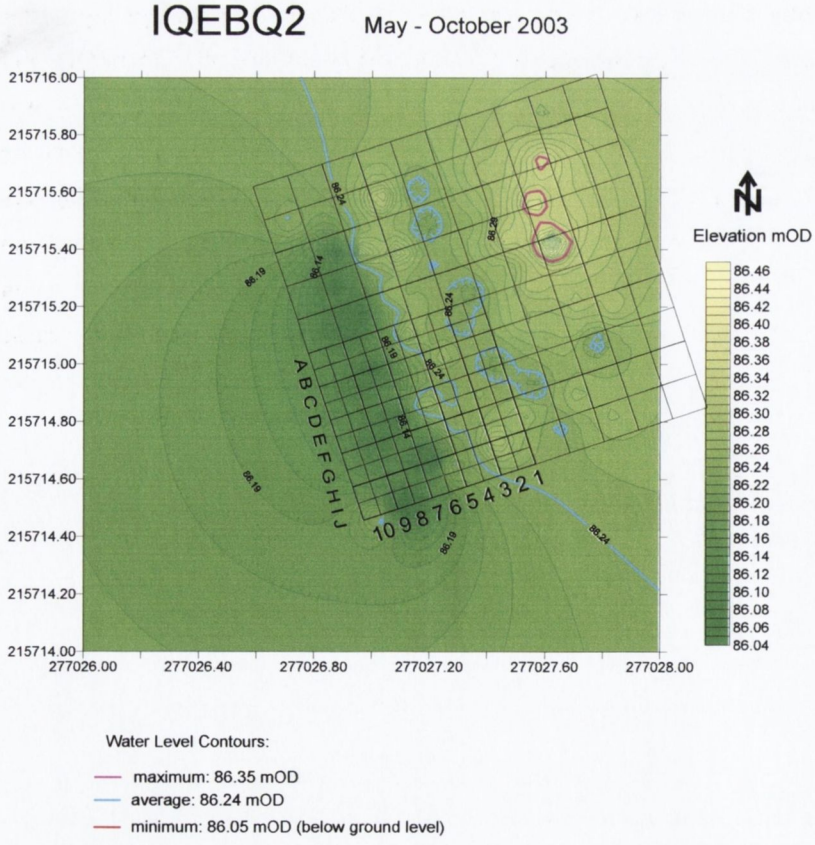



*Figure IV-27 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 2, 2003*

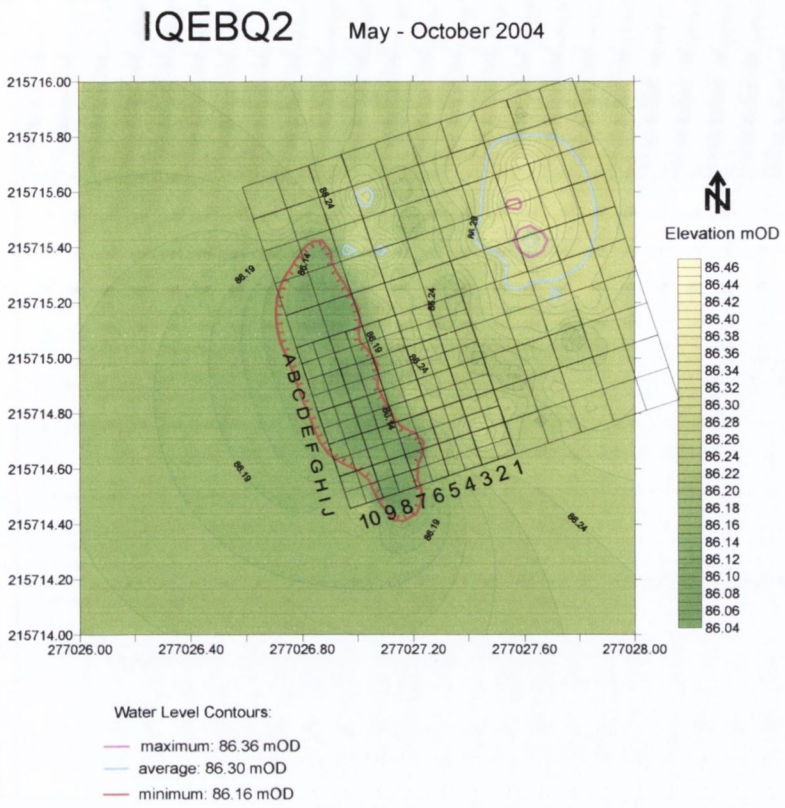



*Figure IV-28 Spatial distribution of the maximum, minimum and average summer water table, Site E, Botanical Quadrat 2, 2004*

**Site D**

Site D was the most stable of all of the sites, and observations indicated that the site was getting wetter throughout the observation period. In 2003 the mean summer water table was established at 85.68 m OD with fluctuations of 10 cm over a six month period and a drying trend toward the end of the summer. 2004 was definitely wetter with a range of fluctuations as small as 5 cm and an increasing water table throughout the summer months, Figure IV-29. Similarly to site E, the occurrence of the snail was quite random, but taking into account the flat topography of the quadrat, an increased water table might have caused frequent flooding with no space (higher elevation) for the snail to escape, which might be a reason for the snail not being present on site in 2004 (Figure IV-31 and Figure IV-32). Moorkens (per.com.) has indicated that flooding was most likely a cause of the disappearance of snails from site C in 2002, therefore this hypothesis is a highly probable explanation for the 2004 results at site D.

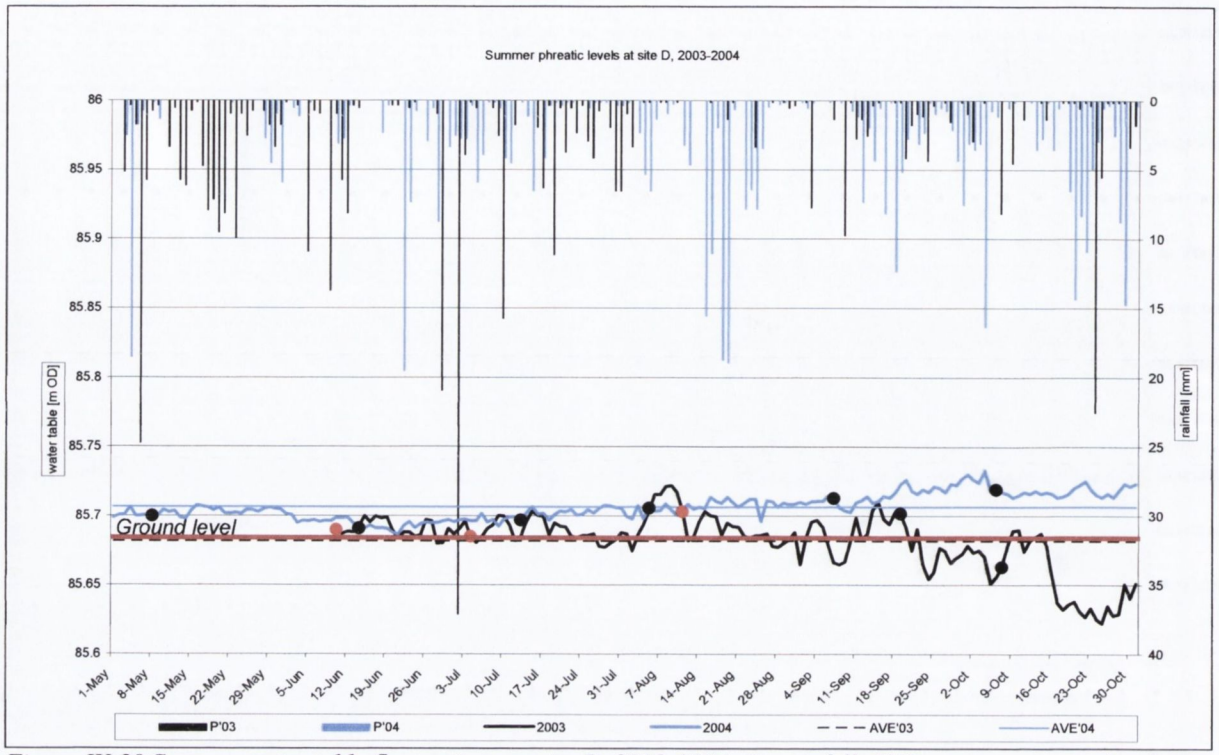



*Figure IV-29 Summer water table fluctuations on site D, 2003-2004; P- rainfall, AVE – average water level over observation period. Red and black dots indicate days when snail counts were carried out. Red dots indicate a positive count result and black negative.*

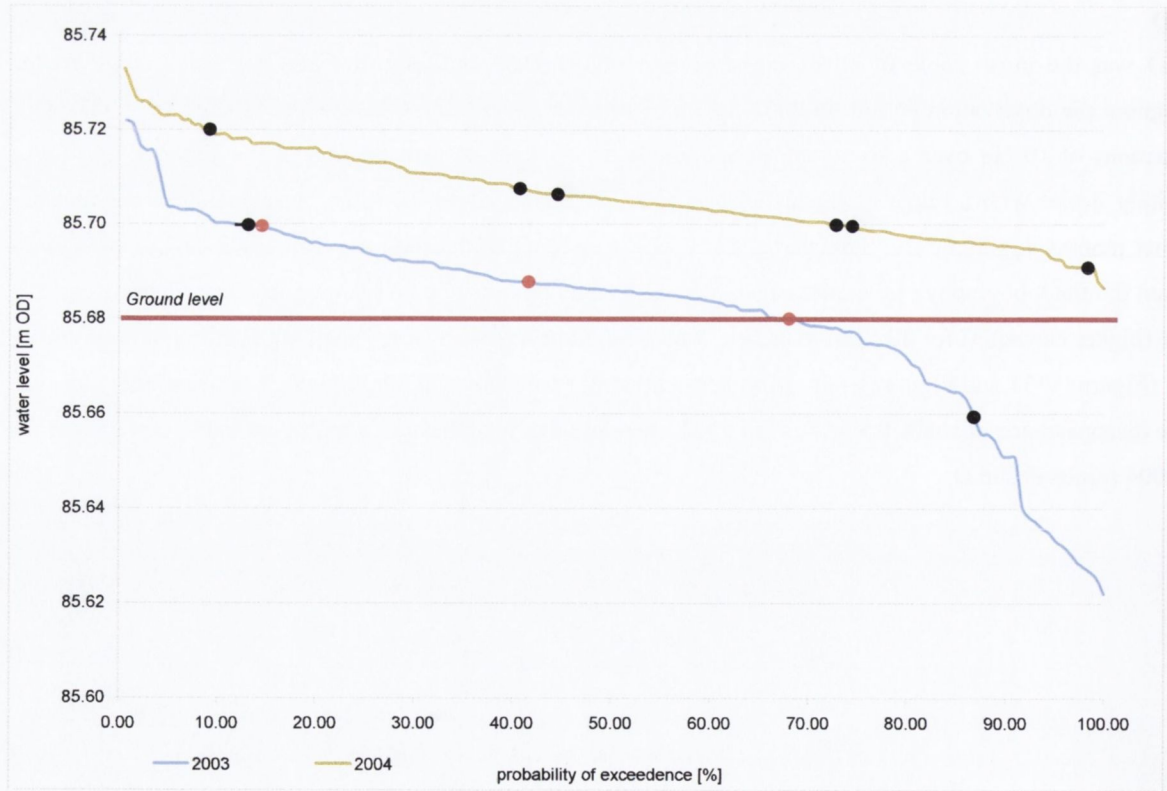



*Figure IV-30 Frequency duration curves of the summer phreatic level at site D, 2002-2004*

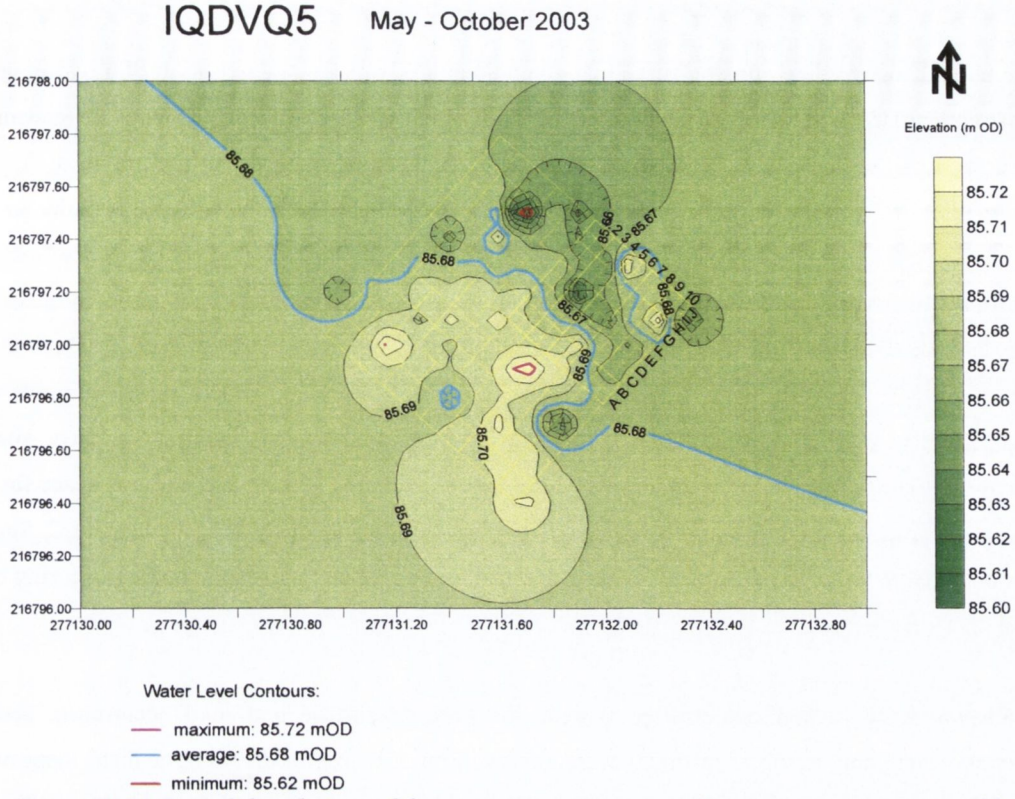



*Figure IV-31 Spatial distribution of the maximum, minimum and average summer water table, Site D, Botanical Quadrat 5, 2003*

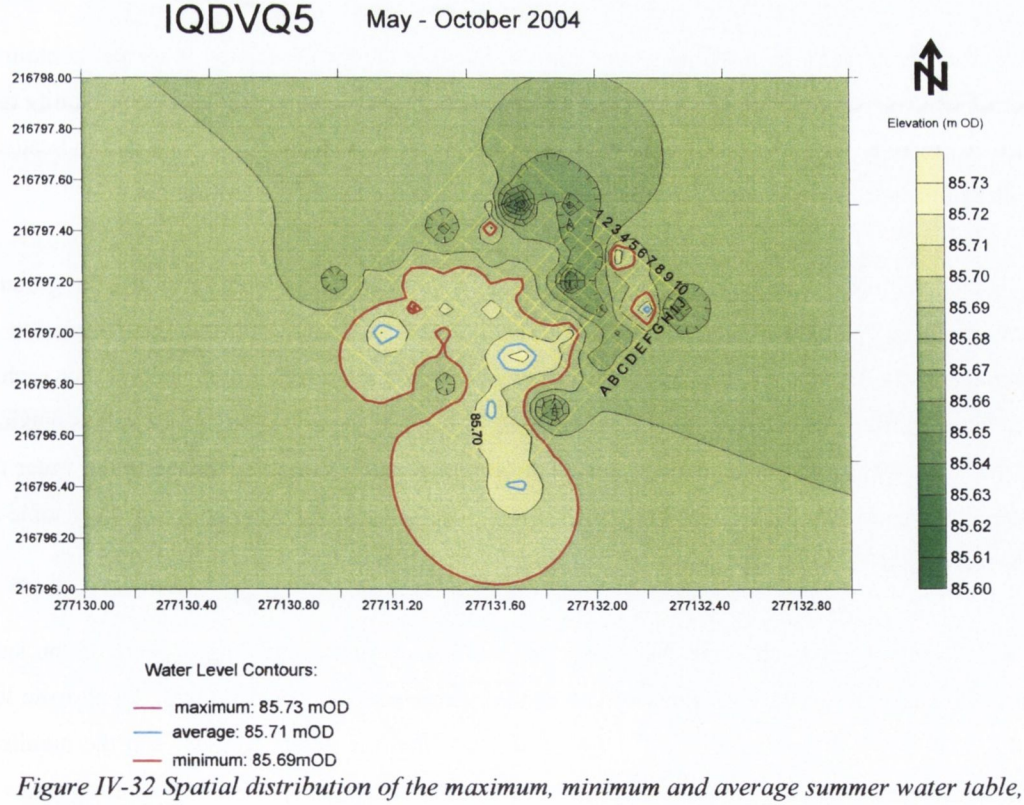



*Figure IV-32 Spatial distribution of the maximum, minimum and average summer water table, Site D, Botanical Quadrat 5, 2004*

### *IV - 2.3.2.1.3. Spatial Distribution of Vertigo geyeri with Reference to Depth of Phreatic Surface*

Seasonal and annual changes in the phreatic surface are commonplace in the characterisation of a hydrological regime; however comparison with other variables, as for example the presence of snails, which is dependent on the water table, requires long term observations to draw some conclusions. As given in the previous chapter, three year observations of sites A, E and D, only in case of site A suggested a numerical threshold for the phreatic level that is likely to control snail occurrence on the site and this was suggested as the summer minimum water table of 2002 - 2003 monitoring period of 88.25 m OD. Topography seems to be an important factor affecting the occurrence of the species. This is especially obvious in the case of sites E, where a flat landscape with a vertical range of only 15 cm is particularity prone to flooding, which in turn suggests that perhaps an upper limit would be more important at this site for conservation of the species. Similarly, site D, whose stable, but increasing, water table gradually increased the flooded area leaving less and less space for the snail within the study area and forcing it to relocate into higher ground as previously happened at site C. Site A, in contrast, lies on a gentle but definite slope of i = 0.03 that facilitates surface runoff and ponding occuring only temporarily and on a small scale.

In order to understand this spatial relationship between the phreatic surface and snail occurrence, several Botanical Quadrats (including *Vertigo* Quadrats) were surveyed on a 10 cm grid. Topographical maps were produced with 0.01 m vertical resolution and the actual water table contoured for a day of a positive *Vertigo* count. As an interpolation method, a Kriging technique was used. Results are presented in Figure IV-33 - Figure IV-39.

As is noticeable from these maps, in most cases the snail was found in the direct vicinity of a water contour and the maximum distance was approximately 20 cm on a horizontal axis. This finding stresses that proximity to the phreatic surface is probably the most of all important factors controlling snail presence and also indicates the high vulnerability of the species to events like prolonged droughts and sudden heavy downpours.

Further analysis included the determination of a vertical distance between the phreatic level and the ground in the exact location where the snail occurred. For each *Vertigo* cell a minimum and maximum elevation was established from the maps. These were drawn with 0.01 m resolution using the GIS Surfer package. For each day of a positive count, the difference between minimum elevation and a daily mean water table as well as maximum elevation and the water table was calculated. As a result, a minimum and maximum distance to the water table within a *Vertigo* cell was found. Only those *Vertigo* Quadrats were selected for which precise water table data exist, and these were IQABQ1VQ1, IQABQ3VQ3, IQDBQ5VQ5, IQEBQ1VQ1 and IQEBQ2VQ2.

All negative cases were disregarded since there was too much uncertainty regarding aspects of the snails' dynamics that could cause the absence of snails on site that is not necessarily connected with the phreatic level. Considering the relatively low distribution of *Vertigo* molluscs within the whole fen site, and the monitoring strategy based on monthly intervals, the probability that the snail is not found is relatively high; therefore this investigation is aimed at defining microhydrological conditions in places where the snail is found. Also, in the case of negative events, the topographical boundary within the *Vertigo* quadrat (i.e. difference between maximum and minimum elevation) would have to cover the entire quadrat, i.e. 100 cells of 5 x 5 cm which

would lead to much bigger topographic ranges than in *Vertigo* positive counts, which were analysed on a single cell size (i.e. 5 x 5 cm) and as such give much more precise measurement that cannot be compared with negative episodes.

Throughout three years of observations, there were only 35 cases of a positive count within all these sites together. Individual cases being instances of monitoring a 5x5 $cm^2$ cell. A total of 6800 cell searches were analysed for the snail presence vs. water level over the 2002-2004 observation period. Results of this ivestigation are presented in Table IV-16.

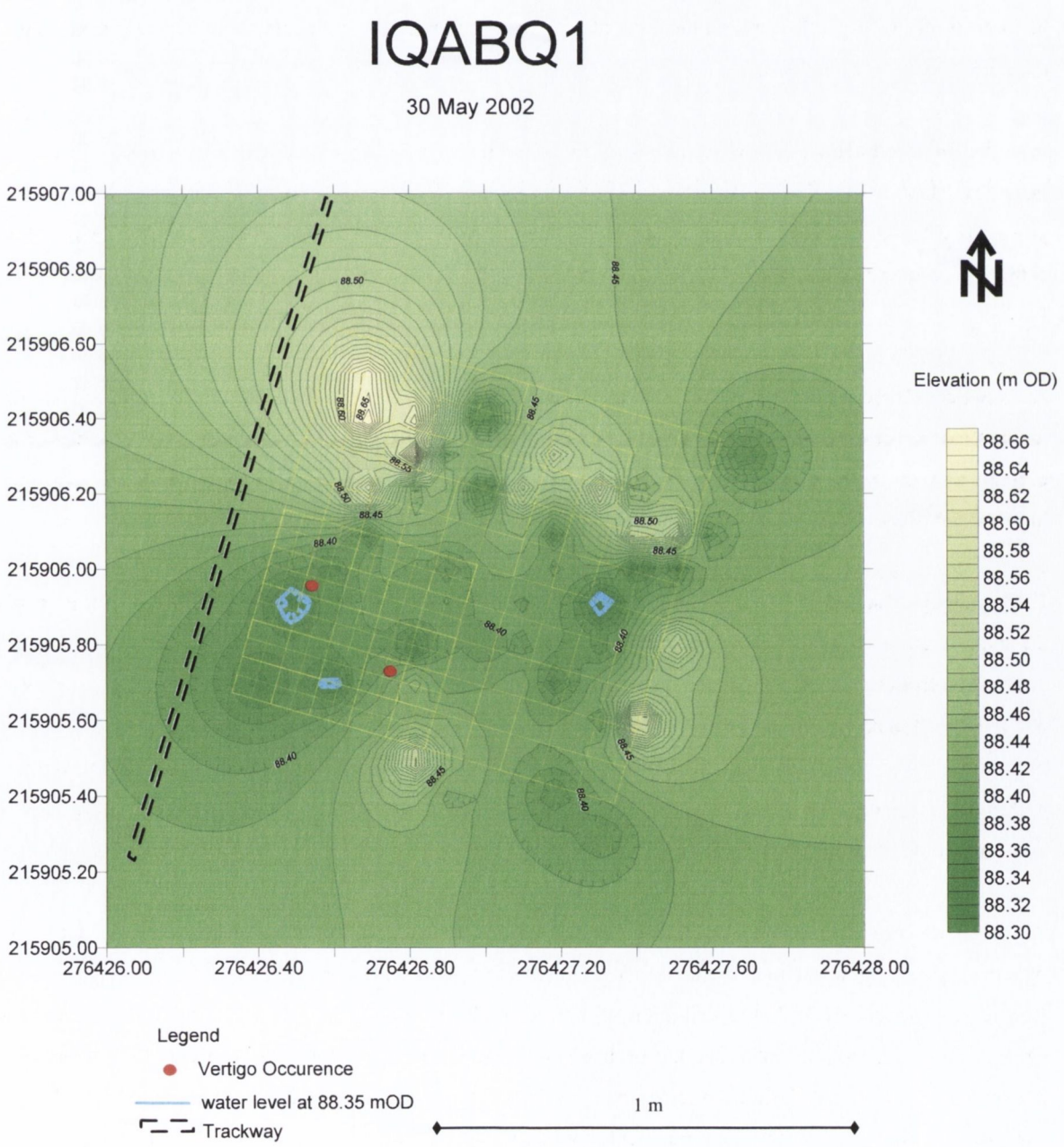



*Figure IV-33 Water table contours and Vertigo occurrence within IQABQ1 on 30th May 2002*

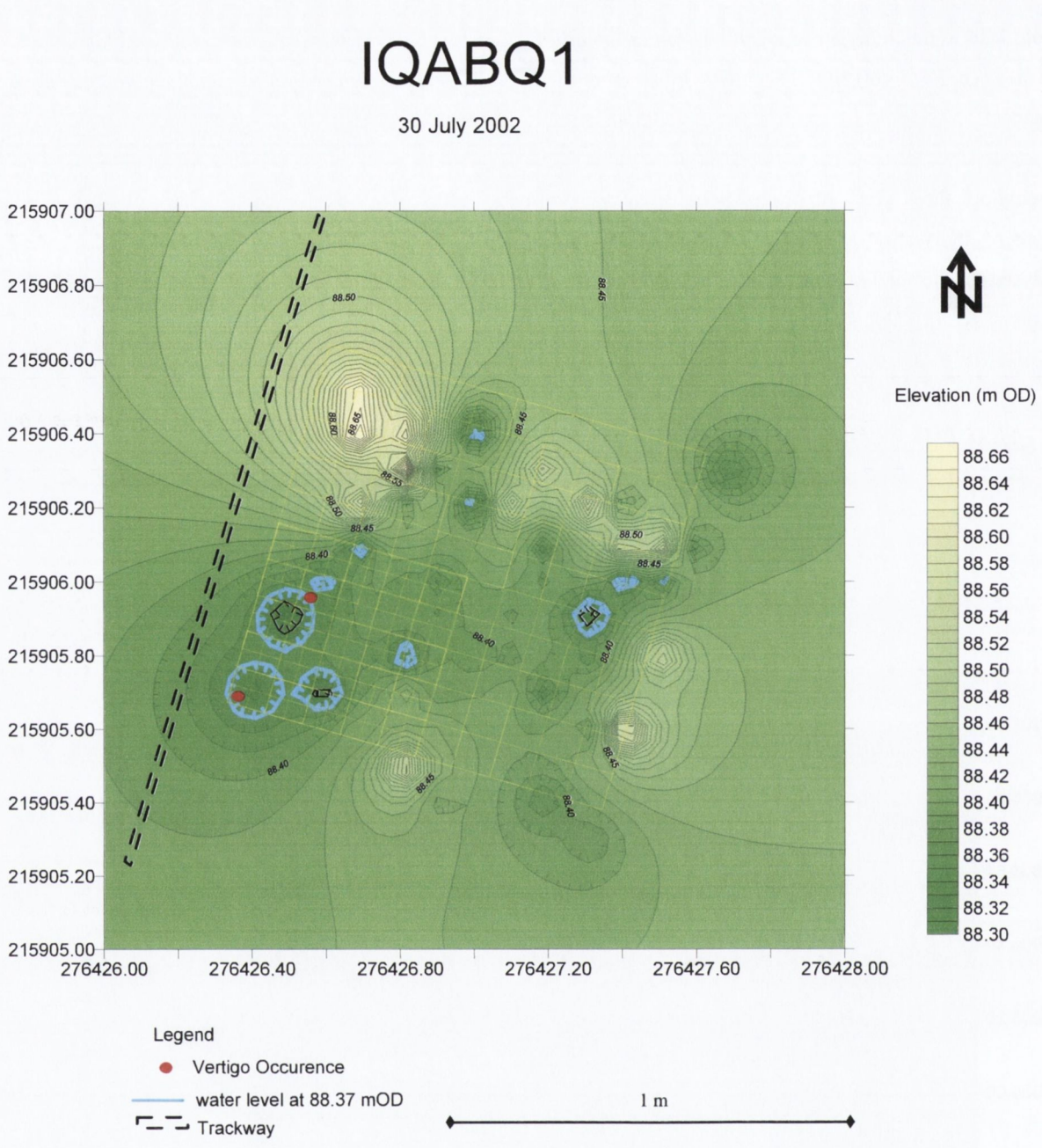



*Figure IV-34 Water table contours and Vertigo occurrence within IQABQ1 on 30th July 2002*

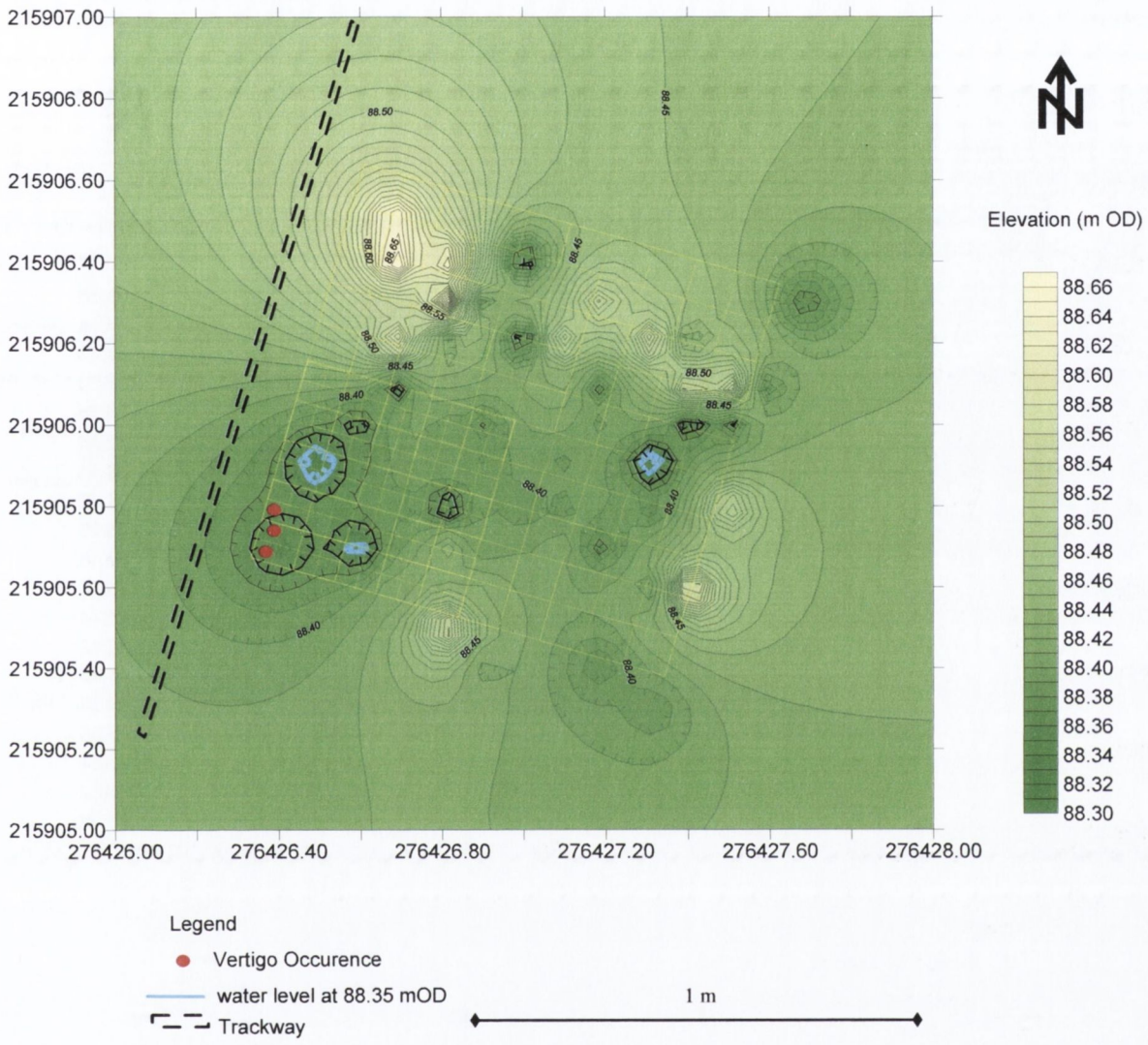



*Figure IV-35 Water table contours and Vertigo occurrence within IQABQ1 on 10th June 2003*

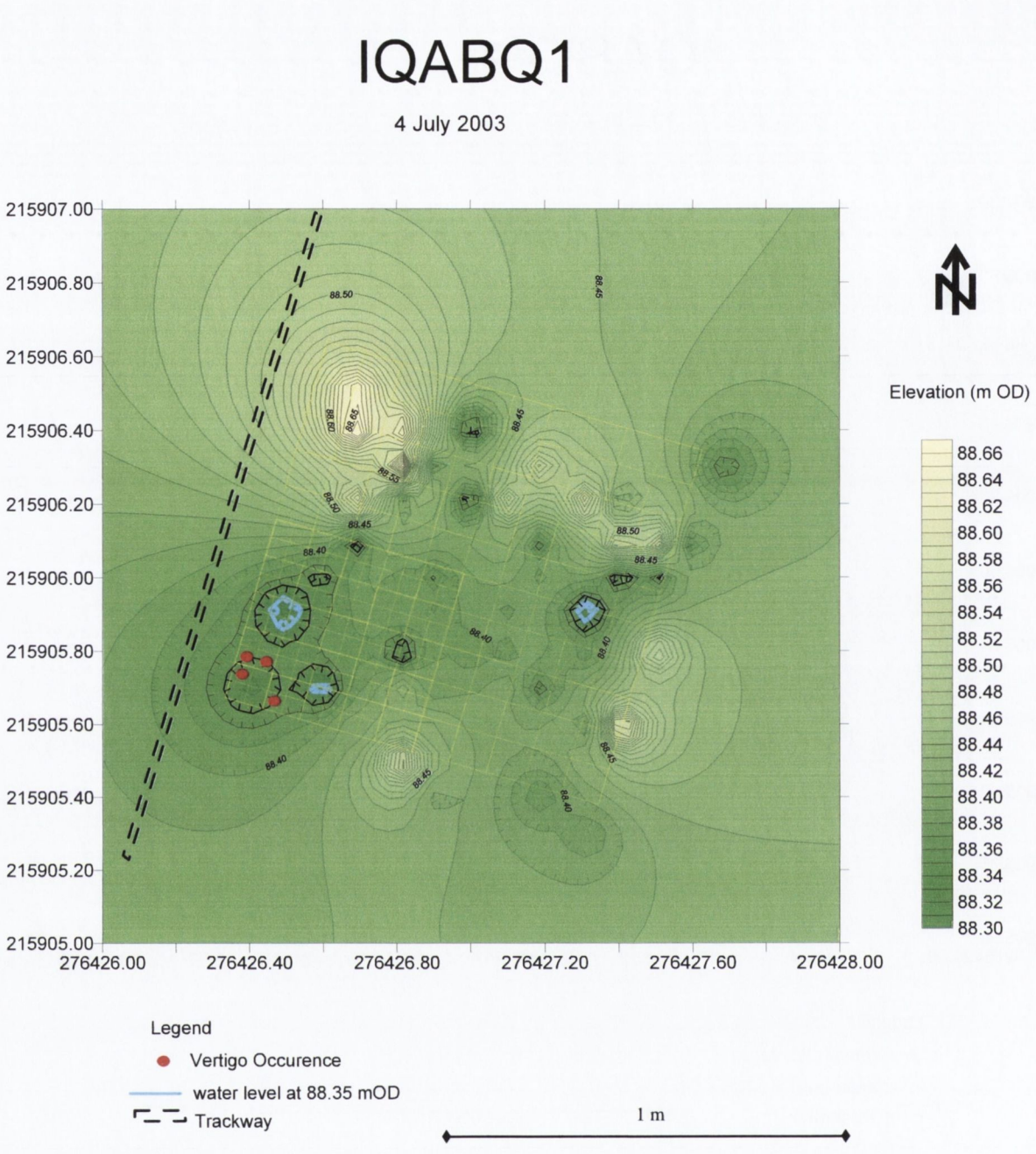



*Figure IV-36 Water table contours and Vertigo occurrence within IQABQ1 on 4th July 2003*

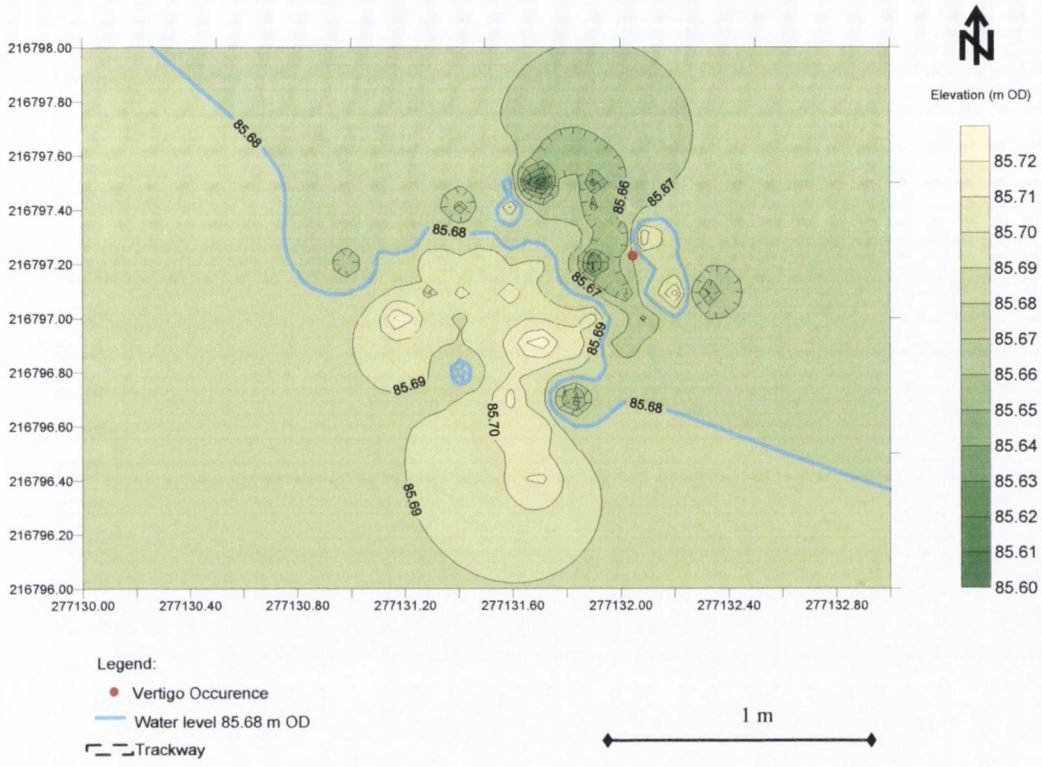



*Figure IV-37 Water table contours and Vertigo occurrence within IQDVQ5 on 4th July 2003*

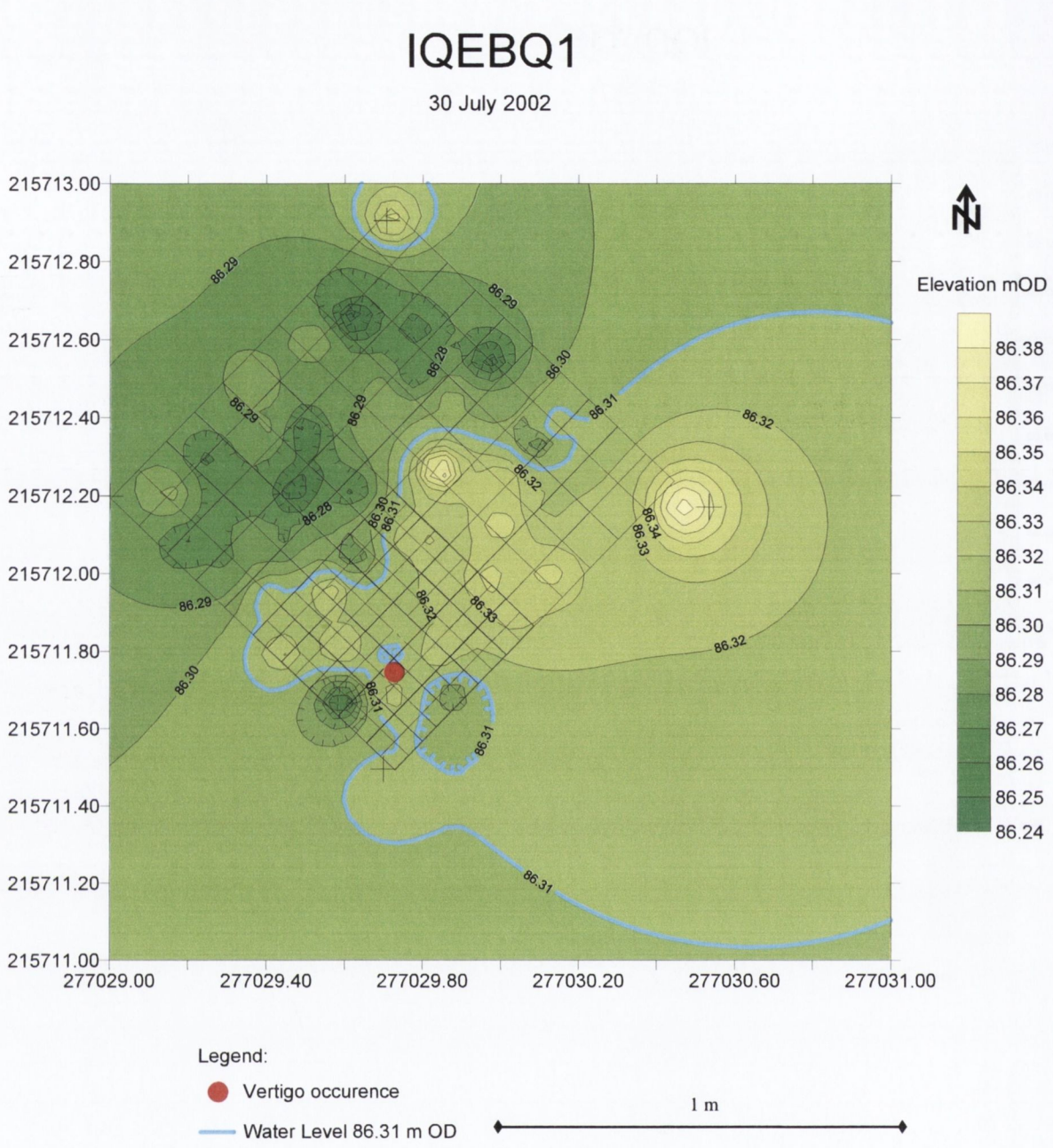



*Figure IV-38 Water table contours and Vertigo occurrence within IQEBQ1 on 30th July 2002*

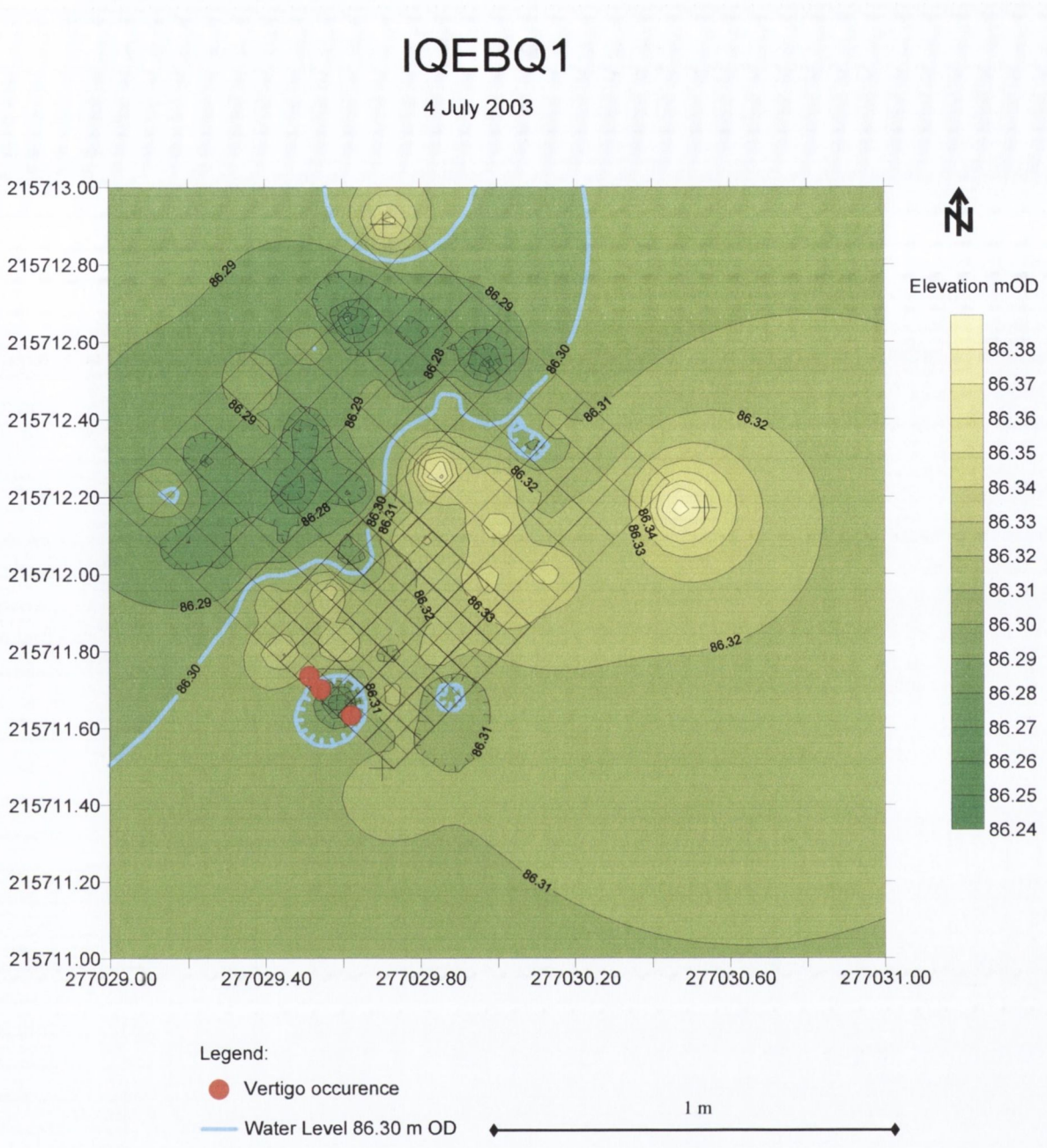



*Figure IV-39 Water table contours and Vertigo occurrence within IQEBQ1 on 4th July 2003*

**Table IV-16 Summary of water table, topography and *Vertigo* counts 2002-2004 within IQABQ1, IQABQ3, IQABQ2, IQDBQ5, IQEBQ1, IQEBQ1.**

| | | | | | Elevation of a cell where snail was found | | | |
|---|---|---|---|---|---|---|---|---|
| Snail location | | Year | Date | Exact water table [m OD] | min [m OD] | max [m OD] | min elevation-water table [m] | max elevation-water table [m] |
| IQABQ1VQ1 | D8 | 2002 | 30-May | 88.35 | 88.36 | 88.37 | 0.01 | 0.02 |
| IQABQ1VQ1 | G3 | 2002 | 30-May | 88.35 | 88.40 | 88.41 | 0.05 | 0.06 |
| IQABQ1VQ1 | D8 | 2002 | 30-Jul | 88.37 | 88.36 | 88.37 | -0.01 | 0 |
| IQABQ1VQ1 | J10 | 2002 | 30-Jul | 88.37 | 88.36 | 88.38 | -0.01 | 0.01 |
| IQABQ1VQ1* | D8 | 2002 | 28-Aug | 88.38 | 88.36 | 88.37 | -0.02 | -0.01 |
| IQABQ1VQ1 | Not found | 2002 | 22-Sep | 88.32 | 88.31 | | -0.01 | |
| IQABQ1VQ1 | Not found | 2002 | 30-Oct | 88.31 | 88.31 | | 0 | |
| IQABQ1VQ1 | H10 | 2003 | 10-Jun | 88.35 | 88.37 | 88.38 | 0.02 | 0.03 |
| IQABQ1VQ1 | I10 | 2003 | 10-Jun | 88.35 | 88.36 | 88.37 | 0.01 | 0.02 |
| IQABQ1VQ1 | J10 | 2003 | 10-Jun | 88.35 | 88.36 | 88.37 | 0.01 | 0.02 |
| IQABQ1VQ1 | H9 | 2003 | 04-Jul | 88.35 | 88.37 | 88.38 | 0.02 | 0.03 |
| IQABQ1VQ1 | H10 | 2003 | 04-Jul | 88.35 | 88.37 | 88.38 | 0.02 | 0.03 |
| IQABQ1VQ1 | I10 | 2003 | 04-Jul | 88.35 | 88.36 | 88.37 | 0.01 | 0.02 |
| IQABQ1VQ1 | J8 | 2003 | 04-Jul | 88.35 | 88.37 | 88.38 | 0.02 | 0.03 |
| IQABQ1VQ1 | Not found | 2003 | 16-Aug | 88.31 | 88.31 | | 0 | |
| IQABQ1VQ1 | D5 | 2003 | 07-Oct | 88.29 | 88.39 | 88.40 | 0.1 | 0.11 |
| IQABQ1VQ1 | H10 | 2004 | 08-May | 88.32 | 88.37 | 88.38 | 0.05 | 0.06 |
| IQABQ1VQ1 | Not found | 2004 | 14-June | 88.22 | 88.31 | | 0.09 | |
| IQABQ1VQ1 | Not found | 2004 | 13-July | 88.23 | 88.31 | | 0.08 | |
| IQABQ1VQ1 | Not found | 2004 | 05-Aug | 88.19 | 88.31 | | 0.12 | |
| IQABQ1VQ1 | Not found | 2004 | 07-Sept | 88.15 | 88.31 | | 0.13 | |
| IQABQ1VQ1 | Not found | 2004 | 06-Oct | 88.26 | 88.31 | | 0.05 | |
| IQABQ3VQ3 | Not found | 2002 | 30-May | 88.24 | 88.24 | | 0 | |
| IQABQ3VQ3 | Not found | 2002 | 30-Jul | 88.26 | 88.24 | | -0.02 | |
| IQABQ3VQ3 | Not found | 2002 | 28-Aug | 88.27 | 88.24 | | -0.03 | |
| IQABQ3VQ3 | Not found | 2002 | 22-Sep | 88.21 | 88.24 | | 0.03 | |
| IQABQ3VQ3 | Not found | 2002 | 30-Oct | 88.2 | 88.24 | | 0.04 | |
| IQABQ3VQ3 | F8 | 2003 | 10-Jun | 88.24 | 88.30 | 88.31 | 0.06 | 0.07 |
| IQABQ3VQ3 | F9 | 2003 | 10-Jun | 88.24 | 88.29 | 88.31 | 0.05 | 0.06 |
| IQABQ3VQ3 | G8 | 2003 | 10-Jun | 88.24 | 88.30 | 88.31 | 0.06 | 0.07 |
| IQABQ3VQ3 | F7 | 2003 | 04-Jul | 88.24 | 88.30 | 88.31 | 0.06 | 0.07 |
| IQABQ3VQ3 | Not found | 2003 | 16-Aug | 88.2 | 88.24 | | 0.04 | |
| IQABQ3VQ3 | Not found | 2003 | 07-Oct | 88.18 | 88.24 | | 0.06 | |
| IQABQ3VQ3 | Not found | 2004 | 08-May | 88.21 | 88.24 | | 0.03 | |
| IQABQ3VQ3 | Not found | 2004 | 14-June | 88.11 | 88.24 | | 0.13 | |
| IQABQ3VQ3 | Not found | 2004 | 13-July | 88.12 | 88.24 | | 0.12 | |
| IQABQ3VQ3 | Not found | 2004 | 05-Aug | 88.08 | 88.24 | | 0.16 | |
| IQABQ3VQ3 | Not found | 2004 | 07-Sept | 88.04 | 88.24 | | 0.20 | |
| IQABQ3VQ3 | Not found | 2004 | 06-Oct | 88.15 | 88.24 | | 0.09 | |
| IQDBQ5VQ5 | H7 | 2003 | 10-Jun | 85.69 | 85.68 | 85.69 | -0.01 | 0 |
| IQDBQ5VQ5 | H5 | 2003 | 04-Jul | 85.68 | 85.67 | 85.68 | -0.01 | 0 |
| IQDBQ5VQ5* | G1 | 2003 | 11-Aug | 85.7 | 85.66 | 85.68 | -0.04 | -0.02 |
| IQDBQ5VQ5 | Not found | 2003 | 19-Sep | 85.7 | 85.61 | | -0.09 | |
| IQDBQ5VQ5 | Not found | 2003 | 07-Oct | 85.66 | 85.61 | | -0.05 | |
| IQDBQ5VQ5 | Not found | 2004 | 08-May | 85.7 | 85.61 | | -0.09 | |
| IQDBQ5VQ5 | Not found | 2004 | 14-June | 85.69 | 85.61 | | -0.08 | |

| | | | | | Elevation of a cell where snail was found | | | |
|---|---|---|---|---|---|---|---|---|
| Snail location | | Year | Date | Exact water table [m OD] | min [m OD] | max [m OD] | min elevation-water table [m] | max elevation-water table [m] |
| IQDBQ5VQ5 | Not found | 2004 | 13-July | 85.7 | 85.61 | | -0.09 | |
| IQDBQ5VQ5 | Not found | 2004 | 05-Aug | 85.71 | 85.61 | | -0.1 | |
| IQDBQ5VQ5 | Not found | 2004 | 07-Sept | 85.71 | 85.61 | | -0.1 | |
| IQDBQ5VQ5 | Not found | 2004 | 06-Oct | 85.72 | 85.61 | | -0.11 | |
| IQEBQ1VQ1** | G7 | 2002 | 30-Jul | 86.31 | 86.31 | 86.32 | 0 | 0.01 |
| IQEBQ1VQ1** | Not found | 2002 | 28-Aug | 86.3 | 86.27 | | -0.03 | |
| IQEBQ1VQ1** | Not found | 2002 | 12-Sep | 86.28 | 86.27 | | -0.01 | |
| IQEBQ1VQ1** | Not found | 2002 | 31-Oct | 86.24 | 86.27 | | 0.03 | |
| IQEBQ1VQ1** | G10 | 2003 | 10-Jun | 86.32 | 86.27 | 86.30 | -0.05 | -0.02 |
| QEBQ1VQ1** | H10 | 2003 | 10-Jun | 86.32 | 86.30 | 86.31 | -0.02 | -0.01 |
| QEBQ1VQ1** | I10 | 2003 | 10-Jun | 86.32 | 86.31 | 86.31 | -0.01 | -0.01 |
| IQEBQ1VQ1** | D10 | 2003 | 04-Jul | 86.30 | 86.31 | 86.32 | 0.01 | 0.02 |
| QEBQ1VQ1** | E10 | 2003 | 04-Jul | 86.30 | 86.28 | 86.30 | -0.02 | 0 |
| QEBQ1VQ1** | G10 | 2003 | 04-Jul | 86.30 | 86.27 | 86.30 | -0.03 | 0 |
| QEBQ1VQ1** | Not found | 2003 | 15-Aug | 86.12 | 86.27 | | 0.15 | |
| QEBQ1VQ1** | Not found | 2003 | 07-Oct | 86.28 | 86.27 | | -0.01 | |
| IQEBQ1VQ1** | F5 | 2004 | 08-May | 86.34 | 86.31 | 86.32 | -0.03 | -0.02 |
| IQEBQ1VQ1** | F6 | 2004 | 08-May | 86.34 | 86.31 | 86.32 | -0.03 | -0.02 |
| QEBQ1VQ1** | Not found | 2004 | 14-June | 86.24 | 86.27 | | 0.03 | |
| QEBQ1VQ1** | Not found | 2004 | 14-July | 86.32 | 86.27 | | -0.05 | |
| QEBQ1VQ1** | Not found | 2004 | 05-Aug | 86.26 | 86.27 | | 0.01 | |
| QEBQ1VQ1** | Not found | 2004 | 07-Sept | 86.25 | 86.27 | | 0.02 | |
| QEBQ1VQ1** | Not found | 2004 | 6-Oct | 86.31 | 86.27 | | -0.04 | |
| IQEBQ2VQ2** | F5 | 2002 | 30-Jul | 86.31 | 86.31 | 86.36 | 0 | 0.05 |
| IQEBQ2VQ2** | Not found | 2002 | 28-Aug | 86.3 | 86.31 | | 0.01 | |
| IQEBQ2VQ2** | Not found | 2002 | 12-Sep | 86.28 | 86.31 | | 0.03 | |
| IQEBQ2VQ2** | Not found | 2002 | 31-Oct | 86.24 | 86.31 | | 0.07 | |
| IQEBQ2VQ2** | A3 | 2003 | 10-Jun | 86.32 | 86.24 | 86.25 | -0.08 | -0.07 |
| IQEBQ2VQ2** | A6 | 2003 | 04-Jul | 86.30 | 86.18 | 86.24 | -0.12 | -0.06 |
| IQEBQ2VQ2** | F1 | 2003 | 15-Aug | 86.12 | 86.23 | 86.25 | 0.11 | 0.13 |
| IQEBQ2VQ2** | H2 | 2003 | 15-Aug | 86.12 | 86.25 | 86.29 | 0.13 | 0.17 |
| IQEBQ2VQ2** | Not found | 2003 | 07-Oct | 86.28 | 86.31 | | 0.03 | |
| IQEBQ2VQ2** | Not found | 2004 | 14-June | 86.24 | 86.31 | | 0.07 | |
| IQEBQ2VQ2** | Not found | 2004 | 14-July | 86.32 | 86.31 | | 0.01 | |
| IQEBQ2VQ2** | Not found | 2004 | 05-Aug | 86.26 | 86.31 | | 0.05 | |
| IQEBQ2VQ2** | Not found | 2004 | 07-Sept | 86.25 | 86.31 | | 0.06 | |
| IQEBQ2VQ2** | Not found | 2004 | 6-Oct | 86.31 | 86.31 | | 0 | |

* - *empirical errors*
** - *excluded from analysis*

The results from Table IV-16 were then plotted using a bar chart, which is presented in Figure IV-40. The bars represent the topography of a specific cell, within which a snail had been found. The lower and upper limits of the bar stand for the difference between the minimum or the maximum elevation and a specific water table on the survey day, which appears on the Y axis at '0' level. Positive values occur when the phreatic surface was below ground level, negative when the water table was above the surface (local flooding). Comparison of microhydrological and malacological results returned six cases (out of 35) where the snail was found within a cell that, based on hydrological data, should be flooded, i.e. water table > 0 level. The experiment was designed

on a very small scale and much attention was given to the accuracy of measurements. Nevertheless, considering the accuracy of the GPS equipment of +/-0.02 m and water levels measurements at +/-0.01 m some errors were unavoidable and are very difficult to detect. Nevertheless, four out of the six flooded cells were recorded at site E in 2003 and 2004 and the remaining two included site A and site D. The fact that a majority of flooded cells were found within one site only suggests that perhaps the site underwent some topographical changes on a local scale. This could have happened because the site was accessed by foot (in contrary to other sites accessed from the trackway system) and therefore the site was trampled by visiting scientists during each monitoring visit. This could have resulted in small changes in altitude, which might have affected monitoring results. As such, results from site E were deemed unreliable and therefore were removed from this analysis. The remaining two flooded positive cells included one monitoring event from site A and one from site D with the water table rising above the surface by 1-2 cm only. These results were treated as empirical errors. In summary 21 positive cells were analysed.

All positive *Vertigo* counts showed extreme closeness to the phreatic surface.

In 71% of cases the water table was found below ground level and in 19% the water table was either at ground level (but without flooding the cell) or the water table intersected the surface within the given cell. The maximum distance between the water table and the surface was found at 0.11 metres, 57% of all cases were found within +/- 0.03 m range and 71% within +/-0.05 m range. The two flooded cells account for 9% and therefore error of the analysis is estimated at approximately 10%.

This analysis demonstrates very strongly that whenever the snail was found, it was found in extreme proximity to the water table, within a 0 - 0.11 m range. Nevertheless, considering the random nature of *Vertigo* counting, which was carried out once a month, and the dynamic nature of the species under investigation it is likely that the snail was present just by a chance within the given *Vertigo* Quadrat on selected surveying dates. Therefore, although the above figures suggest that the snail likes the close proximity of water, a different schedule of the experiment might have given different statistics. Figures Figure IV-41 and Figure IV-42, where both positive and negative episodes occur within the same water level ranges during the years 2002-2003, demonstrate this effect. The increased distance between the site ground surface and the phreatic level in 2004 with no positive count suggests, however, that these conditions were not suitable for the snail.

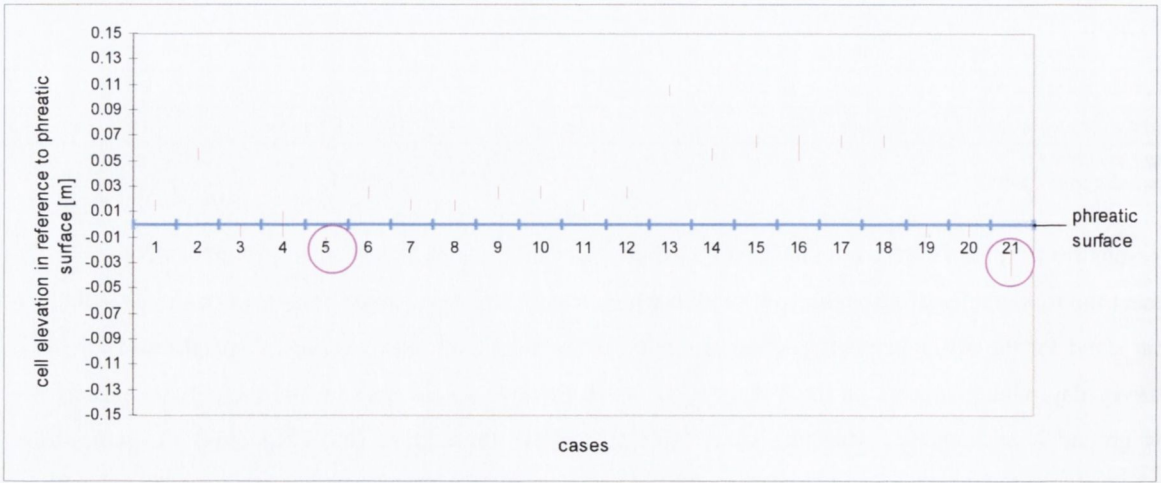



*Figure IV-40 Range of cell elevation with reference to the phreatic surface during the positive snail counts at sites A and D. Circled cases were treated as empirical errors.*

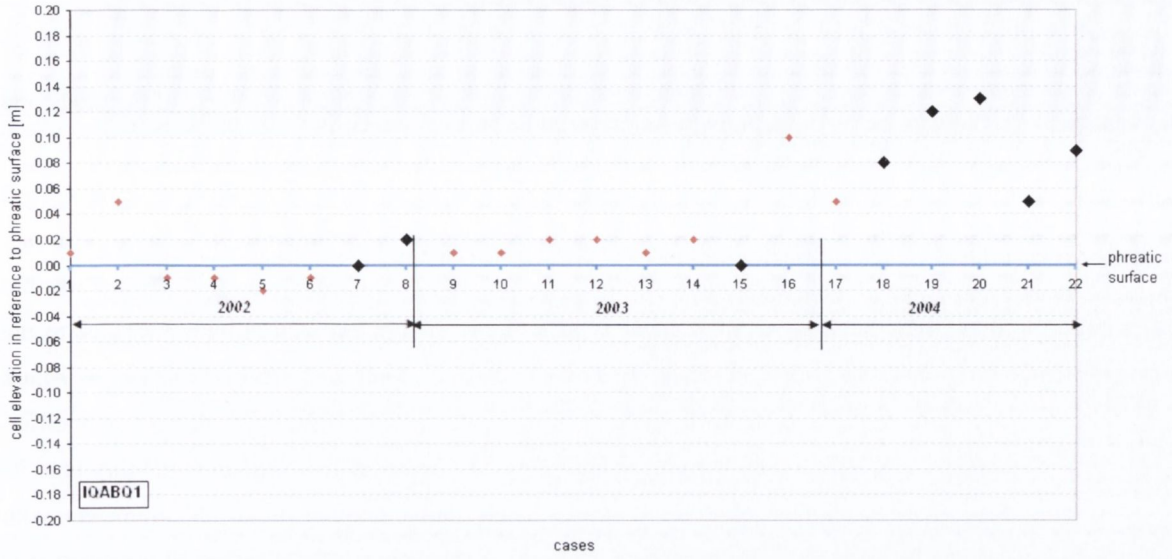



*Figure IV-41 Distribution of the water table with respect to the ground level, IQABQ1, 2002-2004. Red dots indicate events when the snail was found and black dots indicate events when the snail was not found. In positive events, differences between the water level and the ground surface were based on a minimum topographic level within a given 5 x 5 cm Vertigo cell; and in negative episodes, the minimum elevation within an entire Vertigo Quadrat, i.e. 50 x 50 cm was taken.*

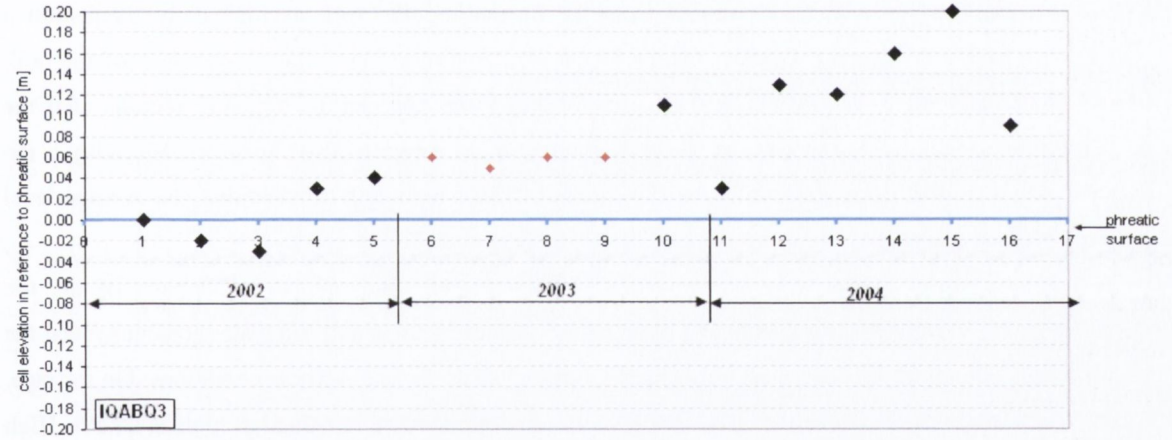



*Figure IV-42 Distribution of the water table with respect to the ground level, IQABQ3, 2002-2004. Red dots indicate events when the snail was found and black dots indicate events when the snail was not found. In positive events, difference between the water level and the ground surface were based on a minimum topographic level within a given 5 x 5 cm Vertigo cell; and in negative episodes, the minimum elevation within an entire Vertigo Quadrat, i.e. 50 x 50 cm was taken.*

## IV-2.4. Summary of the Snail's Microhabitat

The microhabitat of the snail *Vertigo geyeri* has been broadly examined throughout the course of the study and the summary of the findings are as follows:

- Micrometeorology was found to be uniform across the whole fen. No major differences were found between various locations on the fen margin on both sides of the fen and the weather station. The only exception was that incoming radiation was circa 50% less under the canopy than it was at the weather station. Surprisingly, humidity did not change much above the ground surface with reference to the weather station data, but remained above 80% nearly all year round with increased values in winter months. Two main periods can be distinguished during which meteorological parameters vastly differ. Winter months can be timed from November until February, when meteorological variability is at its lowest. These stable conditions are characterised by small diurnal amplitudes for all parameters, with humidity ranging between 65 - 95% but the daily average being above 90%. Average air temperature is below 10 degrees in this period but values as low as –9°C were also recorded. Soil temperature is at its lowest in these months with a minimum in the middle of February but the temperature never dropped below zero degrees. Radiation is significantly decreased during winter. Summer months are considered from March - October and all parameters increase in both values and diurnal amplitudes with maximum values occurring in July. June -August were the hottest months with average daily temperatures reaching nearly 20 degrees Celsius. Increased air temperature affected the temperature of the soil, which similarly increased. However, the highest values were recorded in August (2 months after the highest air temperature). The summer soil temperature ranges between 10 - 15 degrees. Humidity is the only parameter that decreases during the summer but despite high daily fluctuations, the average level remained above 80%.
- Soil moisture was found to be an important element of the snail habitat in all parts of the fen investigated. Various measurements of soil moisture, surface wetness and soil water content proved the very high saturation of subsurface soil, which in turn controls surface wetness conditions. On average, the soil water content was between 70 - 80%; however, soil moisture remained as high as 88.6%. High soil moisture has a direct effect on surface wetness conditions. The clay balls experiment showed that fen surface wetness ranges from between 52-90%; however 69% of samples showed saturation exceeding 80%. Shading provided by vegetation greatly affects the surface wetness level.
- The final and most important output of the study is direct relationship between snail occurrence and the phreatic surface. The overall fluctuation in the phreatic level varied between different sites with a broad range of 5 - 30 cm over the summer observation period (May - October). The range of fluctuations is controlled by a minimum water level at the bottom and the topography at the top. The minimum water level in turn depends on the amount of the groundwater discharged through either seepage as at site A and C/D, or spring flow at site E. Decreased minimum levels imply a deeper unsaturated zone, which, as data shows, can quickly become fully saturated after intensive rainfall resulting in relatively high water level changes over short periods. Site A is a very good example here. In both years 2002 and 2003, the minimum water table was recorded at a level of 88.25 m OD with an average phreatic surface at 88.35 and 88.33 m OD respectively. The range of fluctuation was as small as 17 cm in 2002 and 12 cm in 2003. In 2004, the minimum level was at 88.11 m OD and the range of fluctuation doubled,

reaching 31 cm during that summer. The topography of the IQABQ1 is circa 88.44 m OD, which with the minimum level at 88.25 m OD gives 19 cm of acceptable drawdown that the snail is able to accept. Comparison between snail occurrence and the elevation of the phreatic water table demonstrated that the snail was only found when water was within 0 – 0.11 m zone below the ground surface and this coincides with an approximate average summer water table of 2002-2003. Since the snail was not seen on site when the levels decreased in 2004 (minimum at 88.11 m OD = c. 30 cm below ground level and mean summer level at 88.24 m OD = c. 20 cm below g.l.), these conditions are assumed to be already unsuitable for the snail. To conclude then, the snail appears to accept the range of fluctuations between -20 – 0 cm below ground level with the average water table being c. 10 cm below the ground surface. It should be noted that, while results from both sides of the fen were examined in this analysis (Site A and Site D), the majority of results originate from the southern Site A.

# V Chapter five: Modelling of Hydrological Controls for Sustainability of the Microhabitat on the Fen Margin

The two previous chapters summarised the findings of a three year measuring campaign which was set out to characterise the flow mechanism on the fen margin and the micrometeorological and microhydrological conditions that are needed to sustain the habitat of the *Vertigo geyeri* snail. Results confirm the hypothesis that the investigated microhabitat has a relatively small range of acceptable hydrological changes. Therefore, the fen margin is likely to be very receptive to relatively small changes introduced into the system. As seen in the example of site A, relatively small alterations in the phreatic surface, i.e. lowering the average summer water table by 0.1 m, were reflected by the absence of indicator species within that area. Therefore, in order to protect this habitat, it is necessary to specify hydrological indicators or threshold values that will indicate potential risks and will trigger the implementation of mitigation measures when necessary. As the habitat in question is dependent on regional hydrogeology, these threshold values must be specified for the local scale, i.e. the fen margin and regional scales i.e. the Curragh aquifer, for both spatial and temporal scales. Although the snail habitat was studied at four locations, namely sites A, C, D and E, and conclusions on their preferred conditions were made based on observations from each of these sites, the hydrological controls will be different for each site as topography and morphology vary locally. Trigger values for the fen will depend on a type of the threat and its location within the fen's catchment; therefore, they should really be based on case by case basis. In this study, the threat to the fen arose from constructing the Kildare By-Pass which was located to the west of the southern fen margin. Subsequently, the most sensitive part of the fen that was prone to be potentially disturbed was Site A, and that is why it was this site for which trigger values needed to be established.

Detailed analysis of the fen margin revealed that the morphology of this zone is very complex, can change significantly across small distances and can give rise to the creation of slightly different ecological responses, leading to rather patchy distribution of the snail. Snail distribution will also be limited by limited movement capability; therefore, the most efficient approach to conserve the species is by conserving the habitat in which it lives. The disappearance of the snail from upper locations of the fen margin, i.e. site IQABQ1 suggested a change of habitat in this location; this, however, should not be taken to indicate an alteration in the entire fen margin - rather a limitation of suitable habitat in a spatial sense, i.e. a decrease in the area that used to be regarded as a suitable habitat for the snail. Therefore, to meet the conservation requirements of the species, the maximum suitable habitat area must be provided, and subsequently the critical levels shall be established for the highest locations at the fen margin. For this study, the location of piezometer nests SP31 and S10 are most relevant.

Based on the results of the analysis of local hydrogeology (Chapter III) and the requirements for *Vertigo geyeri* species (Chapter IV), the following can be specified for the habitat of the fen margin of Pollardstown Fen, at the key site:

1. In order to sustain stable phreatic conditions at the fen margin, groundwater seepage (measured as specific discharge) must be supplied at a rate equal to the actual evapotranspiration rate during the summer months May - October and this was established at an approximate level of ~2.5 mm/day (range of 2.26 – 2.59 mm/day), based on four years of observation data (2002-2005).

2. The snail habitat remains unaffected and in a good state of ecological health if the water table fluctuates within a range of not more than 20 cm depth from the ground level with a mean value c. 10 cm bgl. The maximum distance between ground level and the water table (in places where the snail was found) was 0.11 m.

These are conditions that are required (at least at the time being considered) by the key species, and hence are needed to support the sustainability of the fen margin habitat. As such, these conditions will now be referred to as the '**acceptable conditions**'. It is assumed that the water table would remain at a mean depth of 0.1 m bgl for most of the time, and a maximum depth of 0.2 m bgl would be reached as a result of prolonged dry periods. Although a water table at 0.2 m depth bgl is acceptable as a minimum summer water level, it is not acceptable in the long term; for example as an average summer water table. As such, this lower boundary of acceptable conditions should be termed as '**critical condition**' that requires the implementation of mitigating measures. To ensure the sustainability of ecological values of the fen margin a precautionary principle should be applied, and the critical conditions should be preceded by some more conservative threshold levels that will warn in advance of the potential of the critical situation occurring at the fen margin. This will allow for the early preparation of a mitigation plan or more specific measures; for example the preparation of a surface irrigation system. Therefore, this work proposes establishment of local and regional **mitigation threshold levels** that will be treated as triggers to prepare for critical conditions, *i.e.* those conditions which will trigger the preparation of mitigation measures. In summary, two sets of threshold levels will be specified here for the local and regional scales. The local scale specifications will include conditions in the phreatic zone as indicated by our observations at locations in standpipe S10 and in the underlying gravels in piezometer SP31. The regional scale conditions will be represented by monitoring boreholes MB29 and MB6, which are located outside the fen, in the southern fen catchment. The following threshold will be determined:

- **Critical levels** – groundwater levels at which mitigation action is implemented at the fen
- **Mitigation threshold levels** – groundwater levels, which signal the requirement to plan mitigation measures (for example a surface irrigation system)

Correctly timed, mitigation threshold levels will arrive before critical levels, and should issue a warning that critical levels are being approached. It is recommended that the mitigation threshold levels trigger a more frequent groundwater monitoring regime to ensure a prompt response to the arrival of critical conditions. Also, the use of mitigation measures will have to be adjusted according to conditions at the fen surface and this, as was proven earlier, depends on changing weather conditions and subsequent evapotranspiration rates. As such, responses to changing water level conditions at the fen surface should be quick.

## V - 1. Establishing Local Critical and Mitigation Threshold Water Levels

In this part critical and mitigation threshold levels will be established based on observations and the monitoring data and will be validated using groundwater flow equations.

### V-1.1. Methods

Local critical water levels were established based on hydrograph analysis, by comparing the behaviour of the phreatic level and groundwater levels measured in locations S10 and SP31 respectively (Figure V-1). Lowering the phreatic surface below the critical level of 88.35 m OD was related to a range of hydraulic head in SP31, which were read from hydrographs. A conservative approach was adopted and the upper limit of this range was taken as the local critical water level in the underlying gravel.

The local mitigation threshold levels have to be established more conservatively. It is proposed to use summer statistics of the phreatic level (May - October, Chapter IV) as characteristics of the summer water regime to define these thresholds. Firstly, a local mitigation threshold level in the phreatic zone was chosen. This was selected based on established requirements for the *Vertigo geyeri* snail and was chosen as a difference of:

- the preferable mean summer water table of 0.1 m below ground level,
- a standard deviation of summer water table fluctuations during the period when the snail was seen within the studied habitat (SD = 0.03m).

As such, the local mitigation threshold water level in the phreatic zone in standpipe S10 was set at a level of 88.48 m OD. The corresponding groundwater levels in the underlying gravel medium were read from hydrographs and the upper limit of the range was chosen to be the threshold level (Figure V-2).

### V-1.2. Results

Analysis of hydrographs of deep and shallow piezometers SP31 and S10 at the uppermost fen margin (Figure V-1) allowed the following observations:

- The phreatic level was relatively stable between March 2001 and June 2003 and this stable condition was at approximately 88.45 m OD (i.e. 0.1 m bgl). The range of fluctuation within that period was 0.25m.
- After June 2003, the phreatic level showed a definite decrease and the fluctuation range increased. The instability or lowering of the phreatic level was in all cases associated with receding groundwater levels in SP31.
- Comparison of the two hydrographs suggests that the fall in the phreatic surface below 88.45 m OD at location S10 is associated with groundwater levels falling below levels of 88.67 -88.78 m OD in location SP31 and the exact level is a function of the evapotranspiration rate for a given year. So, in

years when evapotranspiration was higher, as it was in 2003 and 2004, instability of the phreatic surface started at higher groundwater levels in SP 31 than in 2002.

- In 2005, the groundwater level in piezometer SP31 was so low that the phreatic level in standpipe S10 was unstable throughout the whole year.
- It is also clear that whenever the phreatic level decreases below 88.35 m OD, hydrograph of S10 followed the seasonal patterns of the groundwater level in SP31, which signifies dependence of the phreatic level on the hydraulic head in the underlying aquifer.

The **local critical water level** in the underlying gravel for the given location at site A (as measured in SP31) was determined by hydrograph analysis. The minimum summer water table that defines a critical phreatic level for the snail (88.35 m OD, S10) corresponds with a range of groundwater level in the underlying gravel of 88.57-88.67 m OD. Triggering these levels should be regarded as prompting unsafe conditions for the snail to survive. As such, the upper limit of this range will be treated as the local critical groundwater level and is therefore specified as **88.67 m OD** (Figure V-2).

The **local mitigation threshold levels** in the phreatic zone is specified as 88.48 m OD in the standpipe S10 and the corresponding groundwater levels in the underlying gravel layer fall between ranges of 88.75 -88.87 m OD. Therefore the local mitigation threshold level in the underlying gravel can be specified as **88.87 m OD** (Figure V-3).

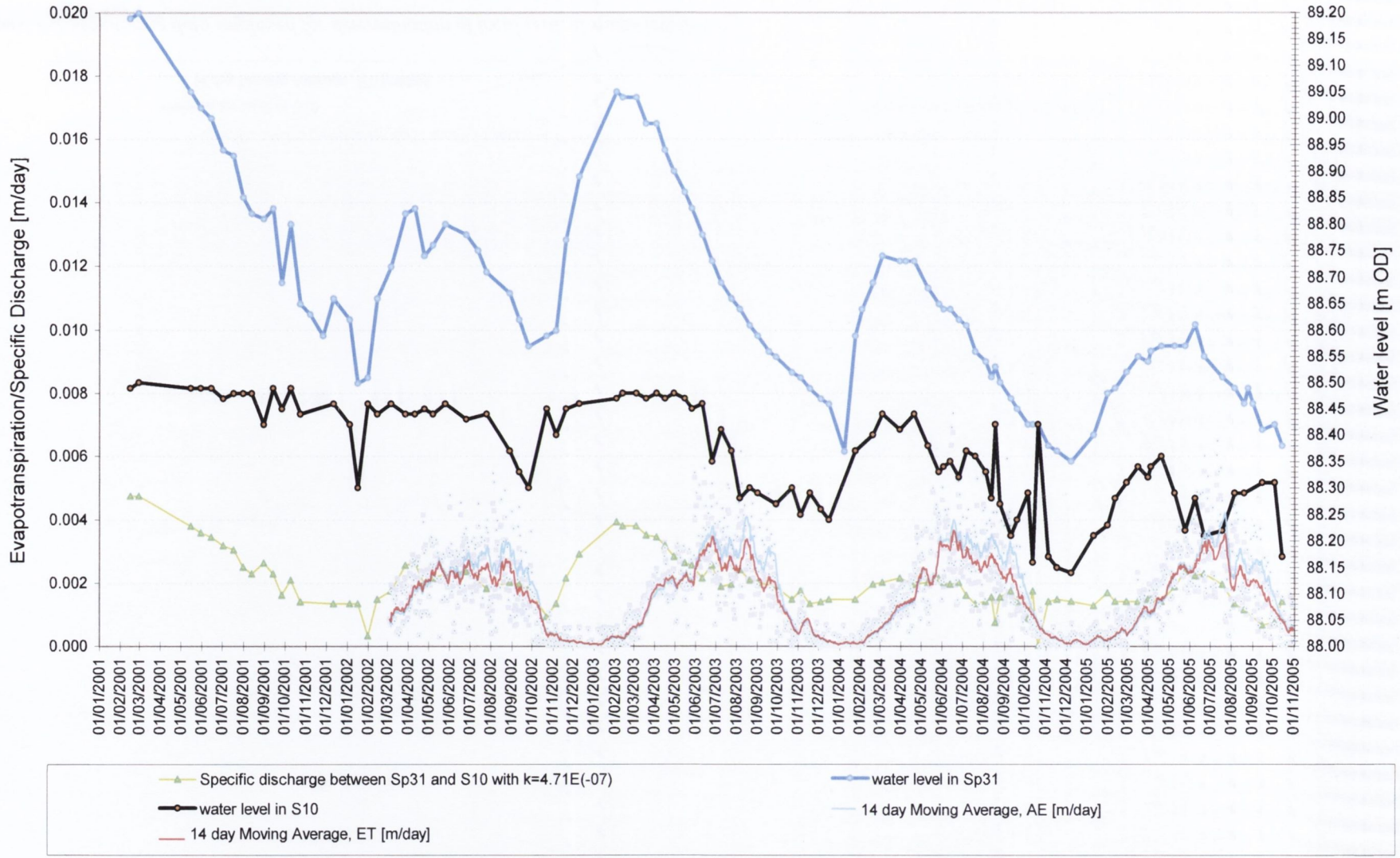



*Figure V-1 Monitoring data showing distribution of water levels in peat (S10) and in the underlying gravel layer (SP 31) over 2001-2005 observation period.*

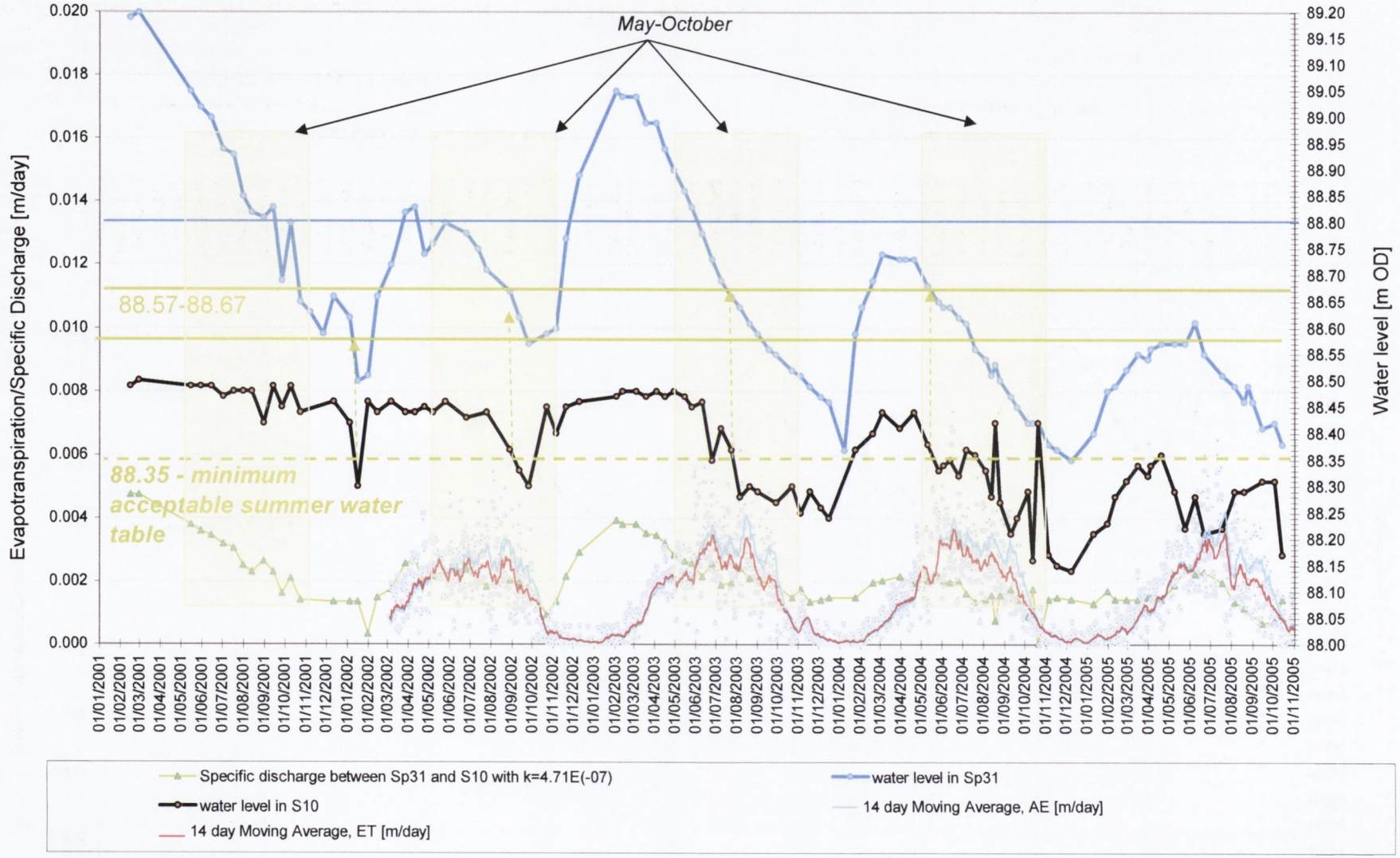



*Figure V-2 Monitoring data employed for determination of local critical water levels*

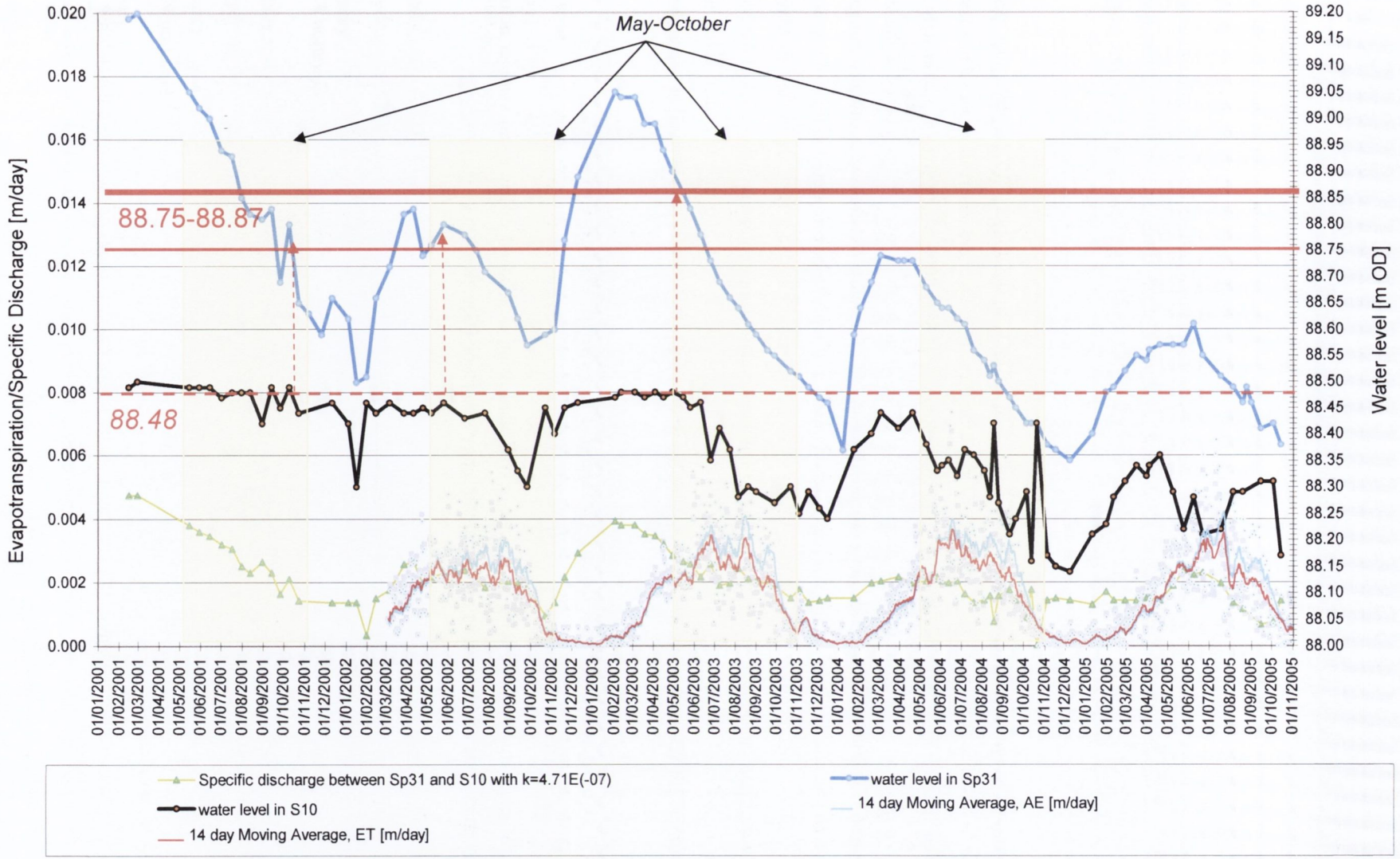



*Figure V-3 Monitoring data employed for determination of local mitigation threshold levels*

Monitoring data (presented in Figure V-1 to Figure V-3) demonstrated that the critical water level was reached in piezometer SP31 during the summers of 2002 and 2003. However, in 2002 this level was reached for a short period starting at the beginning of September and quickly recovered to the acceptable condition before the end of October. In 2003 the critical water levels were reached in August, and persisted until the end of October. It is apparent that the critical water level is reached earlier in each consecutive year of monitoring, i.e. in 2001 it was reached in December; in 2002 in September; in 2003 in August and in 2004 in May. This suggests that the mitigation measures should probably have been implemented in 2002, and definitely in 2003. A caveat regarding the snail habitat is needed here. The snail presence at site A was observed in IQABQ1 which is approximately 1 m down slope of standpipe S10, in a location where the topography is 0.1m lower than in S10 and therefore, although S10 seemed already to be too dry a habitat for the snail in 2003, this remained acceptable within IQABQ1.

With regard to the mitigation thresholds, a value of 88.48 m OD in standpipes S10 suggests that deep groundwater levels should be sustained at 88.87m OD in piezometer SP31. Over the observation period this level was observed in September 2001 and May 2002, and consistently since May 2003 which gives approximately 3-4 months to prepare adequate mitigation measures. Nevertheless, when the threshold level is reached at the end of the summer, it is unlikely that mitigation is required (as in 2001) because recharge will naturally mitigate against lowered phreatic levels. Activation of the mitigation measures needs to be considered in light of seasonal climatic conditions, specifically the distribution of the evapotranspiration rates and these are highest in May - June but reduce significantly in September - October, when they constitute approximately 50% - 25% of the May evapotranspiration rates respectively. Therefore, mitigation measures need to be implemented when levels are observed in May. However, these are not necessary needed when the threshold levels are observed in September.

### V-1.3. Validation of the Local Critical Threshold Water Levels

These critical and mitigation threshold levels can be validated using established earlier mean summer actual evapotranspirations rates, which can be applied to the Darcy's equation (Equation V-1):

$$q_z = \frac{h_1 - h_2}{L} \cdot k$$

*Equation V-1*

then:

$$h_1 = \frac{q_z \cdot L}{k} + h_2$$

*Equation V-2*

where: $q_z$ – vertical specific discharge [L/T] i.e. the minimum bulk velocity necessary to sustain the stability of the water table, equal to the average summer actual evapotranspiration rate. Based on a four year observation, $q_z = 2.26\text{-}2.59 \times 10^{-3}$ [m/day]

$h_1$ – water level in gravel layer [L]

$h_2$ – water level in the phreatic zone [L],

$k$ – permeability of the vertical profile [L/T], $k \sim 4.72 \times 10^{-7}$ [m/sec] (equal to $40.6 \times 10^{-3}$ [m/day])

$L$ – distance between screens in the gravel layer and in the phreatic standpipe: 6.1 [L]

hence:

for the local critical level in the phreatic zone set at $h_2 = 88.35$ m OD

$$if: q_z = 2.26 \cdot 10^{-3} [m/day]$$
$$then: h_1 = \frac{2.26 \cdot 10^{-3} \cdot 6.1}{40.6 \cdot 10^{-3}} + 88.35 = 0.34 + 88.35 = 88.69..[mOD]$$

$$if: q_z = 2.59 \cdot 10^{-3} [m/day]$$
$$then: h_1 = \frac{2.59 \cdot 10^{-3} \cdot 6.1}{40.6 \cdot 10^{-3}} + 88.35 = 0.39 + 88.35 = 88.74..[mOD]$$

for the local mitigation level in the phreatic zone set at $h_2 = 88.48$ m OD

$$if: q_z = 2.26 \cdot 10^{-3} [m/day]$$
$$then: h_1 = \frac{2.26 \cdot 10^{-3} \cdot 6.1}{40.6 \cdot 10^{-3}} + 88.48 = 0.34 + 88.48 = 88.82..[mOD]$$

$$if: q_z = 2.59 \cdot 10^{-3} [m/day]$$
$$then: h_1 = \frac{2.59 \cdot 10^{-3} \cdot 6.1}{40.6 \cdot 10^{-3}} + 88.48 = 0.39 + 88.48 = 88.87..[mOD]$$

The above analysis revealed only a slightly different range of the minimum groundwater level in the location SP31 required to sustain the stable phreatic level at selected trigger levels from those established from the hydrograph analysis. To be precise, the established local threshold levels in piezometer SP31 are:

*Local critical levels*

Hydrographs analysis: 88.57 - 88.67 m OD

Darcy's approach: 88.69 – 88.74 m OD

*Local mitigation threshold levels*

Hydrographs analysis: 88.75 - 88.87 m OD

Darcy's approach: 88.82 – 88.87 m OD

However, analysis based on Darcy's approach is susceptible to errors arising from both the actual evapotranspiration estimates and the vertical permeability estimates. With respect to actual evapotranspiration, the value cannot be established *in situ* and as such relies on the accuracy of the empirical model used as well as the accuracy of the meteorological inputs. The example above shows that a difference in evapotranspiration value of 0.33 mm/day gives a change in the required groundwater hydraulic head of 0.05 m, which suggests that this model is very sensitive to applied evapotranspiration rates. In turn, 0.33 mm/day constitutes as little as 13-

15% of the average summer daily evapotranspiration rate (which is probably within the acceptable error range). Also, determination of the actual evapotranspiration requires the application of a crop coefficient which was established for the entire fen area, and it is likely that the specific location of the SP31-S10 nest would have slightly different coefficients. Precise determination of the crop coefficient would require a very detailed study focused on this particular subject only. Although this was outside the scope of this work, the high degree of sensitivity of the model to the exactitude of the evapotranspiration estimates suggests that future studies should perhaps incorporate such a detailed approach.

With respect to the permeability estimates, the sensitivity analysis was previously provided in Chapter III and it showed that small changes in the depth of clay deposits have important bearings on specific discharge estimates.

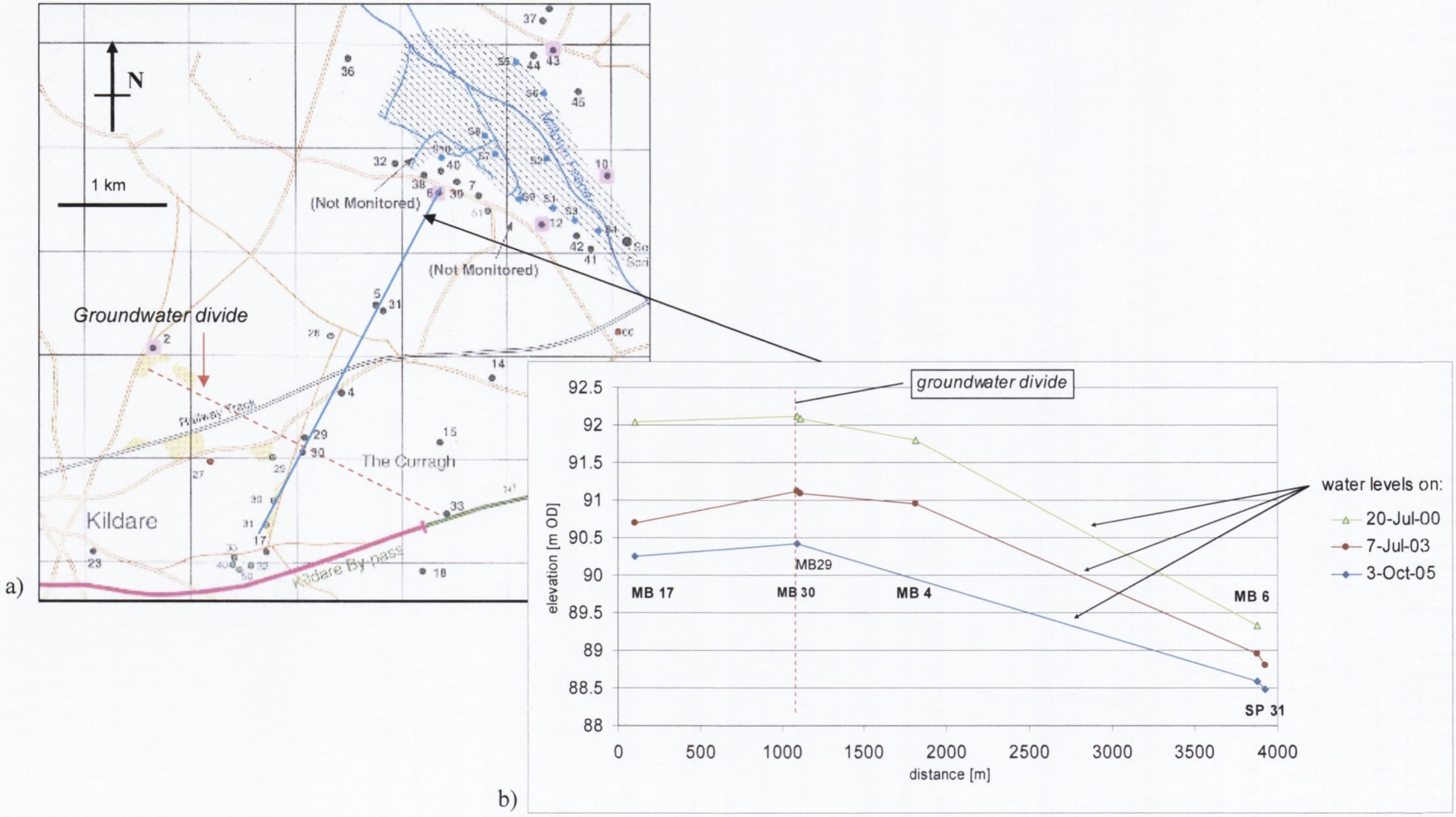
### V-1.4. Conclusions

In summary, taking into consideration the imperfections of the evapotranspiration and permeability estimates, differences between the numerical analysis applied and observations made *in situ* can be considered as minimal and this suggests that the conceptual model applied is correct and therefore validates the established threshold values. Nevertheless, as it is probably more reliable, the hydrograph analysis (i.e. actual field observations) should be used to determine conservation trigger levels. The minimum groundwater level in location SP31 which indicates approaching risk conditions at the fen margin should be set at 88.87 m OD (the local mitigation threshold level) and mitigation action should be initiated when this level approaches 88.67 m OD (the local critical level).

## V - 2. Establishing Regional Critical and Mitigation Threshold Water Levels

As local critical and mitigation levels have been now established, in this part a comparison between groundwater patterns in the fen gravel and the Curragh aquifer will be undertaken to verify hydrological links between the two points and to assess sensitivity of the fen to recharge from the Curragh aquifer and to establish critical levels at distance. The terminology used in this chapter is similar to that used previously, i.e. regional mitigation threshold levels are those that indicate that conditions at the fen are approaching critical levels (defined by the summer minimum groundwater level at the fen margin) and regional critical levels are those when groundwater seepage velocity (expressed as specific discharge) at the fen margin is not sufficient to sustain stable conditions within the 0.2 m bgl range. We have previously established that mitigating action needs to be initiated at the fen margin to sustain the conditions required by the *Vertigo* snail when water level drops to 0.2 m bgl. The regional trigger values will be established from hydrographs, similar to the methodology proven for local critical threshold levels. However, prior to this, an analysis of the characteristics of distribution of groundwater heads across the aquifer between the groundwater divide and the fen margin will be presented to verify the reliability of monitoring locations. The analysis focused on the interface between the Curragh aquifer and the fen margin with a view to investigating the relationship between the two. It is assumed that the Curragh aquifer is unconfined along the analysed transects. Three wells targeting the gravel layer along the transect between the groundwater divide and the fen margin were selected for this study. These were monitoring boreholes MB29, MB6 and SP31 (location map in Figure V-4 and Appendix 3). Standpipe S10 (Appendix 3) was used to represent phreatic conditions at the fen margin. Groundwater level data for monitoring boreholes MB29, MB6, SP31 and S10 were available on a biweekly basis. Data for MB29 were available from 1998 until 2004; for MB6 from 1998 until 2005 and for SP31 from 2001 until 2005. Because of the shortness of the data record for MB29, another borehole (MB30) was also compared with MB29 and MB6 data with a view to using it as a means of extrapolating MB29 records until 2005. The monitoring borehole MB30 is located approximately 125 m south of MB29, is deeper than MB29 and targets a depth of 24 m bgl. A borehole log for this borehole (Appendix 4) shows that depth of overburden deposits in this location is only 19.5 m and therefore the screen of the borehole, placed between 12-24 m bgl, targets both gravel deposits and limestone bedrock. Nevertheless, as presented on the hydrographs below (Figure V-5), groundwater responses in both boreholes MB29 and MB30 are very similar, especially from the year 2000 onwards.

*Figure V-4 Location map of studied monitoring boreholes along the transect from the groundwater divide and the fen margin, and b) distribution of groundwater elevations across transect between monitoring boreholes MB 17- MB6*



## V-2.1. Methods

Establishment of the regional critical and mitigation threshold levels was determined in the following steps:

### *V-2.1.1. Analysis of Spatial Distribution of Groundwater Levels Between the Groundwater Divide and the Fen*

This analysis was based on groundwater monitoring data from the following locations: MB6, MB29, MB30 and SP31 (Table V-1) and included:

1) Comparison of annual changes in groundwater levels in the four selected monitoring boreholes across the Curragh Plains-Pollardstown Fen transect over the period 1998-2005. Correlation and double mass curve analysis, based on biweekly water level data. This was determined using SPSS and an Excel spreadsheet respectively. Data were analysed for the Pearson's correlation coefficient for linear relationship and were tested at a significance level of 0.01.

2) Investigations of water level response to the winter effective rainfall (October-March). Daily effective rainfall data for the Curragh were provided by Dr Les Brown, who undertook a study on the recharge coefficient for the Curragh aquifer (Misstear and Brown, 2007). These data were used because long term records are required for this analysis, which was not available from the fen data. The long term data were based on rainfall data from the Naas CBS station and meteorological inputs from the Casement Aerodrome. The actual evapotranspiration was calculated by applying a water stress factor to Penman - Monteith Potential Evapotranspiration. Data were provided for the daily time scale and were later converted into 6 month totals, covering the months October - March, for the consecutive hydrometric years 1999-2005. (Full effective rainfall data is presented in Appendix 31). Changes in groundwater levels in response to effective winter rainfall were computed as the difference between the maximum water level and the preceding minimum. The data are summarised in Table V-5 and in Figure V-7 and Figure V-8.

### *V-2.1.2. Determination of Regional Critical and Mitigation Threshold Water Levels*

The regional threshold levels were established from the hydrographs based on selected local critical and mitigation thresholds. Again, following the more conservative approach, when the local threshold corresponded with a range of levels in the regional monitoring boreholes, the most conservative value was adopted as the threshold value to attempt to ensure that the local critical and mitigation levels were valid for all conditions.

## V-2.2. Results

### *V-2.2.1. Analysis of Spatial Distribution of Groundwater Levels Between the Groundwater Divide and the Fen*

1) Comparison between deep groundwater boreholes MB29, MB30, MB6 and SP31.

The three boreholes MB29, MB6 and SP31, selected for the analysis, were screened in the gravel layer with base screens reaching from 82.0 to 86.0 m OD, approximately, Table V-1. Data for MB29 and MB6 were available from 1998 and for SP31 from 2001. Hydrographs of all three wells (Figure V-5) show very similar inphase seasonal variations suggesting strong hydraulic connectivity. However, there were some differences between the maximum and minimum levels in the investigated boreholes, but they did not follow a clear pattern and as such do not suggest any firm time lag in groundwater response between the selected locations (Table V-2). Possibly more frequent monitoring would provide this information. Approximate distances between selected wells were:

- MB29 – MB6 : 3000 metres
- MB6 – SP31: 400 metres
- MB29 – SP31: 3050 metres

The monitoring borehole MB30, screened in a deeper horizon intersecting both drift and bedrock lithologies, showed exactly the same patterns as the remaining boreholes MB29, MB6 and SP31. The greatest groundwater level amplitude fluctuations were recorded in MB29 and MB30, which are located closest to the groundwater divide and at the top of the recharge area. The smallest groundwater level changes were observed at the fen margin in piezometer SP31. Fluctuations in monitoring boreholes MB29 and MB30 showed an annual range of ~ 2 metres, while those at the fen margin did not exceed 0.5 metre.

**Table V-1 Monitoring wells information: MB29, MB30, MB6 and SP31**

| Well | MB 29 | MB 30 | MB 6 | SP 31 |
|---|---|---|---|---|
| Top of the casing [m OD] | 99.84 | 99.96 | 105.78 | 89.53 |
| Ground level [m OD] | 99.84 | 99.96 | 105.78 | 89.08 |
| Depth [m] | 13.5 | 24 | 20.5 | 7 |
| Screen level [m OD] | 86.54 - 90.54 | 75.96-87.96 | 85.28 - 89.28 | 82.53 - 83.53 |

Groundwater monitoring data (Figure V-5) show a clear downward trend in water levels for the 1998-2005 observation period. These minimum levels were recorded in October - November 1998, September 1999, October 2000, January 2001, October 2002 and in December of 2003 and 2004. It is apparent that minimum levels started to occur at later months while monitoring progressed; maximum levels were measured between February and May and there was no distinct change in their annual distribution. The extended recessions resulted in continuously shorter recharge periods for the fen.

When connecting the minimum points from consecutive years 1998 - 2000 and 2001 - 2005 (Figure V-5), it is noticeable that there is a definitive step shift in all boreholes (MB29, MB30 and MB6). However, while trendlines for periods 1998 - 2000 and 2001 - 2005 are parallel in the case of monitoring borehole MB30; in the case of MB29 and MB6 gradients of the 2001 - 2005 lines are steeper than for the 1998 - 2000 data, (Figure V-5, monitoring borehole MB30); in case of MB29 and MB6 gradients of the 2001 - 2005 lines are steeper than for the 1998 - 2000 data, see Figure V-5. This figure also shows that the 1998 - 2000 gradient for MB30 is much steeper than for the remaining boreholes MB29 and MB6. As the general water table slopes from monitoring borehole MB30 towards MB6 (toward the Pollardstown fen), a smaller gradient in the minimum groundwater levels trendline is expected in MB6 than in MB30. However, the big difference in slope of the 1998 - 2000 minimum groundwater levels trendline between MB29 and MB30 reflects differences in borehole construction between the two points and may suggest different recharge patterns for the two overlying water bearing layers. The step shift was not noted in SP31 as data do not cover the period before 2001; however, closeness in water level distribution between piezometer SP31 and monitoring boreholes MB29, MB30 and MB6 suggests that this location was probably similarly affected, although to a relatively smaller degree. A correlation analysis was performed on the four boreholes, using SPSS software, and that revealed a very high similarity between the four data sets at levels of 0.96-0.99, (Table V-4). All four datasets showed a very good correlation. The Pearson's correlation coefficients exceeded 0.9 value in all cases, which indicates a strong, positive linear relationship between the variables tested. This is presented as double mass curves presented in Figure V-6. The significance of the correlation coefficient was tested at a level of 0.01 and was proved high for all pairs of piezometers.

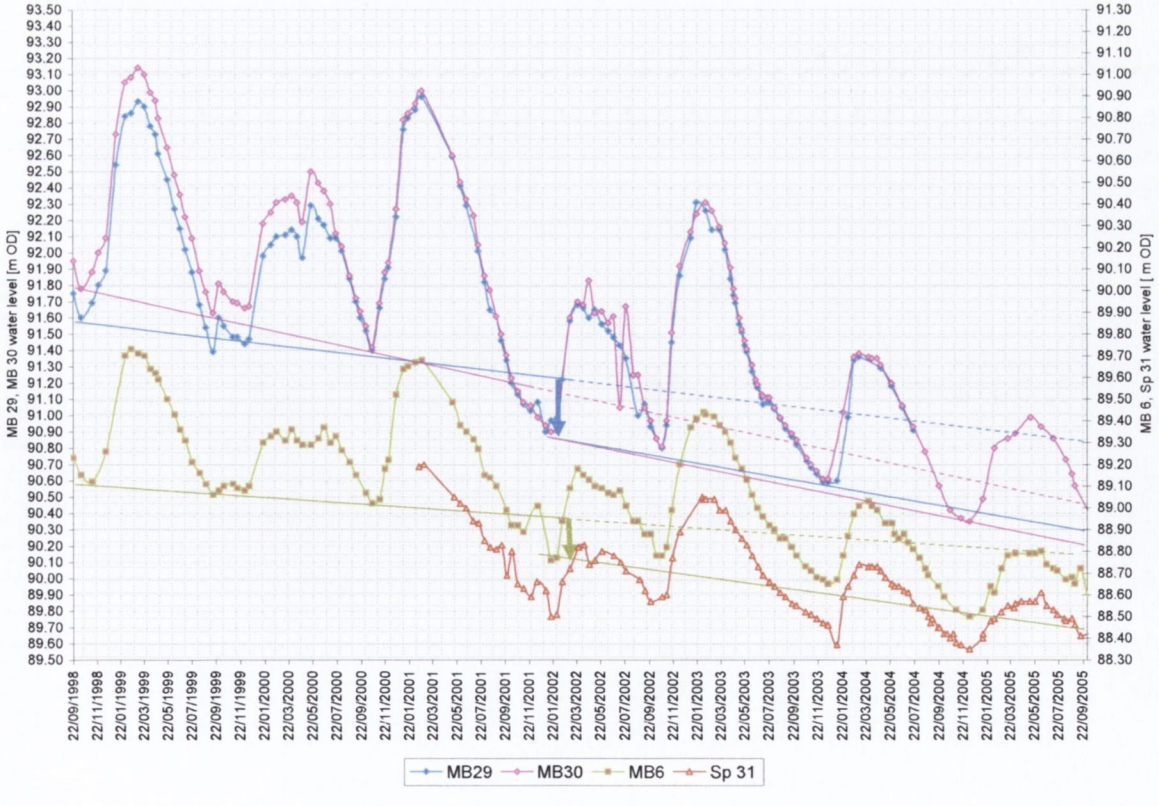



*Figure V-5 Hydrographs for monitoring boreholes MB29, MB30, MB6 and piezometer SP31, 1998-2005*

**Table V-2 Annual maximum and minimum water levels in monitoring boreholes MB29, MB30, MB6 and piezometer SP31 over 1998-2005**

| Date | MB 29 | | MB 30 | | MB 6 | | SP 31 | |
|---|---|---|---|---|---|---|---|---|
| | minimum | maximum | minimum | maximum | minimum | maximum | Minimum | maximum |
| 12/10/98 | 91.60 | | 91.78 | | | | | |
| 10/11/98 | | | | | 89.12 | | | |
| 18/02/99 | | | | | | 89.73 | | |
| 08/03/99 | | 92.93 | | 93.14 | | | | |
| 15/09/99 | 91.39 | | 91.63 | | 89.06 | | | |
| 18/05/00 | | 92.29 | | 92.50 | | | | |
| 20/06/00 | | | | | | 89.37 | | |
| 20/10/00 | 91.40 | | 91.42 | | 89.02 | | | |
| 23/02/01 | | 92.96 | | 93.00 | | 89.68 | | |
| 28/02/01 | | | | | | | | 89.20 |
| 03/01/02 | 90.90 | | | | | | | |
| 16/01/02 | | | 90.90 | | 88.76 | | 88.50 | |
| 25/03/02 | | 91.68 | | | | 89.18 | | |
| 10/04/02 | | | | | | | | 88.83 |
| 23/04/02 | | | | 91.83 | | | | |
| 25/09/02 | | | | | | | 88.57 | |
| 24/10/02 | 90.80 | | 90.81 | | 88.78 | | | |
| 20/01/03 | | 92.31 | | | | | | |
| 7/02/03 | | | | | | 89.44 | | 89.04 |
| 12/02/03 | | | | 92.31 | | | | |
| 4/12/03 | 90.59 | | 90.61 | | | | | |
| 16/12/03 | | | | | 88.65 | | | |
| 7/01/04 | | | | | | | 88.37 | |
| 4/03/04 | | 91.36 | | 91.38 | | | | 88.74 |
| 29/03/04 | | | | | | 89.03 | | |
| 8/12/04 | | | 90.35 | | 88.50 | | 88.35 | |
| 12/05/05 | | | | 90.99 | | | | |
| 8/06/05 | | | | | | 88.80 | | 88.61 |

**Table V-3 Descriptive statistics for water level data from monitoring boreholes MB6, MB29 and MB30, 2001-2005**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| **MB29** | 91.68 | 0.59 | 134 |
| **MB30** | 91.62 | 0.69 | 147 |
| **MB6** | 89.07 | 0.31 | 156 |
| **SP31** | 88.65 | 0.19 | 114 |

**Table V-4 Correlation coefficients between monitoring boreholes MB29, MB30, MB6 and SP31**

| | | MB29 | MB30 | MB6 | SP31 |
|---|---|---|---|---|---|
| **MB29** | Pearson Correlation | 1 | 0.989(**) | 0.986(**) | 0.961(**) |
| | Sig. (2-tailed) | | 0.000 | 0.000 | 0.000 |
| | N | 134 | 125 | 117 | 36 |
| **MB30** | Pearson Correlation | 0.989(**) | 1 | 0.980(**) | 0.976(**) |
| | Sig. (2-tailed) | 0.000 | | 0.000 | 0.000 |
| | N | 125 | 147 | 124 | 50 |
| **MB6** | Pearson Correlation | 0.986(**) | 0.980(**) | 1 | 0.987(**) |
| | Sig. (2-tailed) | 0.000 | 0.000 | | 0.000 |
| | N | 117 | 124 | 156 | 71 |
| **SP31** | Pearson Correlation | 0.961(**) | 0.976(**) | 0.987(**) | 1 |
| | Sig. (2-tailed) | 0.000 | 0.000 | 0.000 | |
| | N | 36 | 50 | 71 | 114 |

** *Correlation is significant at the 0.01 level (2-tailed).*

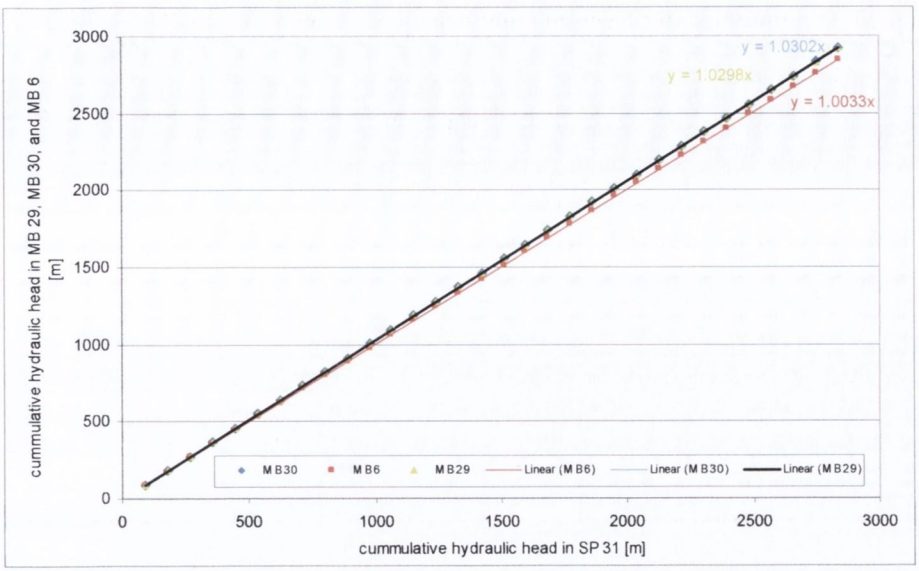



*Figure V-6 Double mass curve between fen piezometer SP31 and monitoring boreholes MB29, MB30 and MB6*

2) Groundwater level response to winter effective rainfall

The effective rainfall data from the Naas CBS station were compared with changes in groundwater levels to assess the influence of change in rainfall patterns on trends in groundwater level response. These data are summarised in Table V-5 and in Figure V-7 - Figure V-8. It was noted that changes in groundwater levels for all four wells closely followed a pattern of winter effective rainfall, indicating the same immediate response across the transect, although head responses were highest for monitoring boreholes MB29 and MB30. This similarity emphasises the importance of relatively recent rainfall in sustaining water levels across the transect. Decreasing trends in both effective rainfall and the change between the maximum and minimum head levels is also clear throughout 1999-2005, although a higher drop in groundwater level amplitude was recorded for 2004 and 2005 than for the respective effective rainfall data. As presented in Figure V-8, none of the water level data correlated linearly with the effective rainfall data and this might suggest some water losses within the system. This specifically applies to 2004, which was a relatively wet year but there was a limited response in the groundwater levels.

**Table V-5 Characteristics of winter effective rainfall patterns (October - March) vs. change in groundwater levels, MB29, MB30, MB6, and SP31 over 1999-2005**

| Year | Effective Rainfall at Naas CBS station | % of '99-'05 Average | Response in water level in MB 29 | Response in water level in MB 30 | Response in water level in MB 6 | Response in water level in SP 31 |
|---|---|---|---|---|---|---|
| | mm | % | m | m | M | m |
| 1999 | 370.0 | 121.09% | 1.33 | 1.36 | 0.61 | |
| 2000 | 265.0 | 86.46% | 0.9 | 0.87 | 0.31 | |
| 2001 | 378.3 | 123.43% | 1.56 | 1.58 | 0.66 | |
| 2002 | 155.3 | 50.67% | 0.78 | 0.93 | 0.42 | 0.33 |
| 2003 | 421.1 | 137.39% | 1.51 | 1.5 | 0.66 | 0.53 |
| 2004 | 328.0 | 107.01% | 0.77 | 0.77 | 0.36 | 0.37 |
| 2005 | 227.5 | 74.23% | | 0.64 | 0.3 | 0.26 |
| **Average '99-'05** | **306.5** | | | | | |

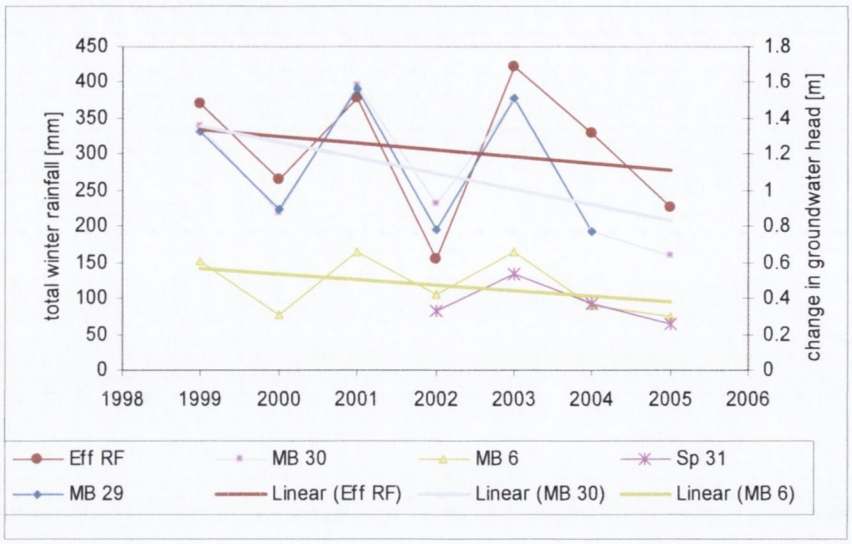



*Figure V-7 Winter effective rainfall (from Naas CBS weather station) and changes in groundwater levels in MB29, MB30, MB6 and SP31, 1999-2005*

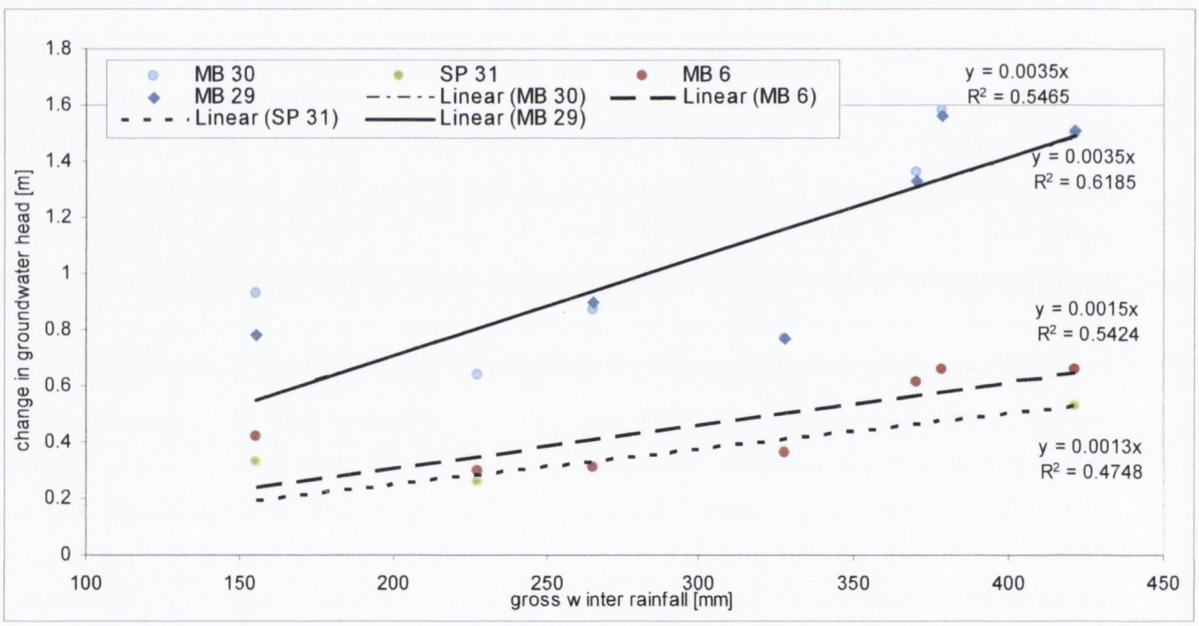



*Figure V-8 Response in groundwater head to winter effective rainfall (October-March), 1999-2005, including linear trendlines*

### *V-2.2.2. Determination of Regional Critical and Mitigation Threshold Water Levels*

Figure V-9 presents hydrographs of monitoring boreholes MB29 and monitoring borehole MB6 and the established local critical and mitigation threshold levels for the piezometer SP31. The regional critical and mitigation threshold values were determined by numerical comparison of the observed values. Specifically, local critical and mitigation water levels in SP31 were found on hydrographs and then corresponding water levels in MB6 and MB29 for given dates were read from the hydrograph. This comparison suggest that for the local critical level in the SP31 of 88.67 m OD, the regional critical levels are (Table V-6):

*Regional critical levels:*

MB6: 88.92 m OD

MB29: 91.20 m OD

The same comparison reveals the following, corresponding to the local mitigation level of 88.87 m OD (SP31), regional mitigation thresholds:

*Regional mitigation threshold levels:*

MB6: 89.20 m OD

MB29: 91.82 m OD

However, as presented in Figure V-9, if these levels were adopted the regional mitigation threshold level would have been triggered every summer (starting in 1998) and as such, this value is probably too conservative. The fact that the fen surface remained wet throughout 2002-2003, when deep groundwater levels at the fen margin were likely to be reduced with respect to 1998-2000 levels, indicates that conditions prior to 2001 must have been sufficiently wet to sustain a stable water table at the fen margin. Therefore, setting triggers at levels that would have activated mitigation actions during 1998 - 2000 is unrealistic. It is proposed, then, to reduce the local mitigation threshold level from 88.48 m OD to 88.45 m OD in standpipe S10, which is the summer mean water table at 0.1 m bgl. When this level is used, the corresponding local mitigation threshold level in standpipes SP31 is 88.75 m OD and this further corresponds with a range of 91.20 - 91.44 m OD in monitoring borehole MB29 and a range of 88.92 - 89.06 m OD in monitoring borehole MB6, Table V-6. Trigger values chosen at the upper limit of these ranges give the following regional threshold values (Figure V-10-Figure V-11):

***Revised Regional Critical Levels:***

MB6: 88.92 m OD

MB29: 91.20 m OD

***Revised Regional Mitigation Threshold Levels:***

MB6: 89.06 m OD

MB29: 91.44 m OD

Implementation of the above threshold levels suggests that mitigation alerts should have been issued in July 2002, June 2003 and May 2004 (or earlier before the summer started) allowing for a 2 month mobilisation period.

To conclude; in order to sustain seepage at the fen margin at sufficient rates to counteract water depletion caused by evapotranspiration, the groundwater level within the Curragh aquifer will have to be maintained at minimum levels of 91.20 m OD in monitoring borehole MB29 and 88.92 m OD in monitoring borehole MB6; however, levels of 91.44 m OD in MB29 and 89.06 m OD in MB6 should be treated as risk situations and should initiate preparations for adequate mitigation.

**Table V-6 Summary table of local and regional critical and mitigation threshold levels.**

| S10 | SP31 | MB6 | MB6 | MB29 | MB29 |
|---|---|---|---|---|---|
| Local | | Regional | | | |
| | | Range | Trigger value | range | Trigger value |
| **Mitigation threshold** level of 88.48 m OD | **Mitigation threshold** level of 88.87 m OD | 89.14 – 89.20 m OD | 89.20 m OD | 91.56 – 91.82 m OD | 91. 82 m OD |
| **Critical water level** at 88.35 m OD | **Critical water level** at 88.67 m OD | - | 88.92 m OD | 91.08-91.20 m OD | 91.20 m OD |
| **Revised trigger levels** | | | | | |
| **S10** | **SP31** | **MB6** | **MB6** | **MB29** | **MB29** |
| Local | | Regional | | | |
| | | Range | Trigger value | range | Trigger value |
| **Mitigation threshold** level of 88.45 m OD | **Mitigation threshold** level of 88.75 m OD | 88.92 – 89.06 m OD | 89.06 m OD | 91.20 - 91.44 m OD | 91.44 m OD |
| **Critical water level** at 88.35 m OD | **Critical water level** at 88.67 m OD | - | 88.92 m OD | 91.08-91.20 m OD | 91.20 m OD |

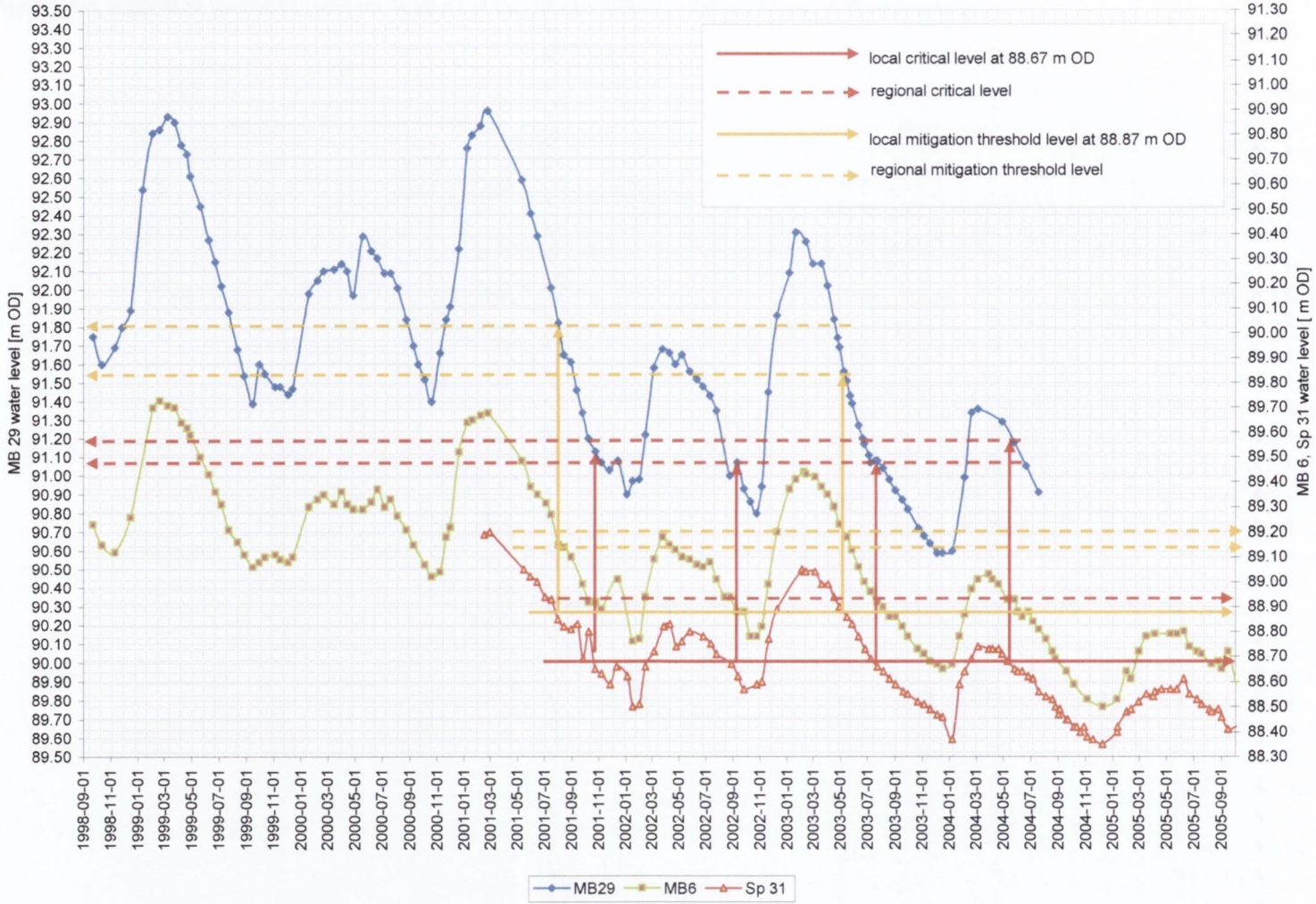



*Figure V-9 Monitoring data showing summer regional critical and mitigation threshold levels in MB29, MB6 and SP31 corresponding with the local critical level in SP31 at 88.67 m OD and in S10 at 88.35 m OD; and the local mitigation threshold level in SP31at 88.87m OD and in S10 at 88.48 m OD.*

*Figure V-10 Revised local mitigation threshold level set at 88.45 m OD in S10 and corresponding 88.75 m OD in SP31*

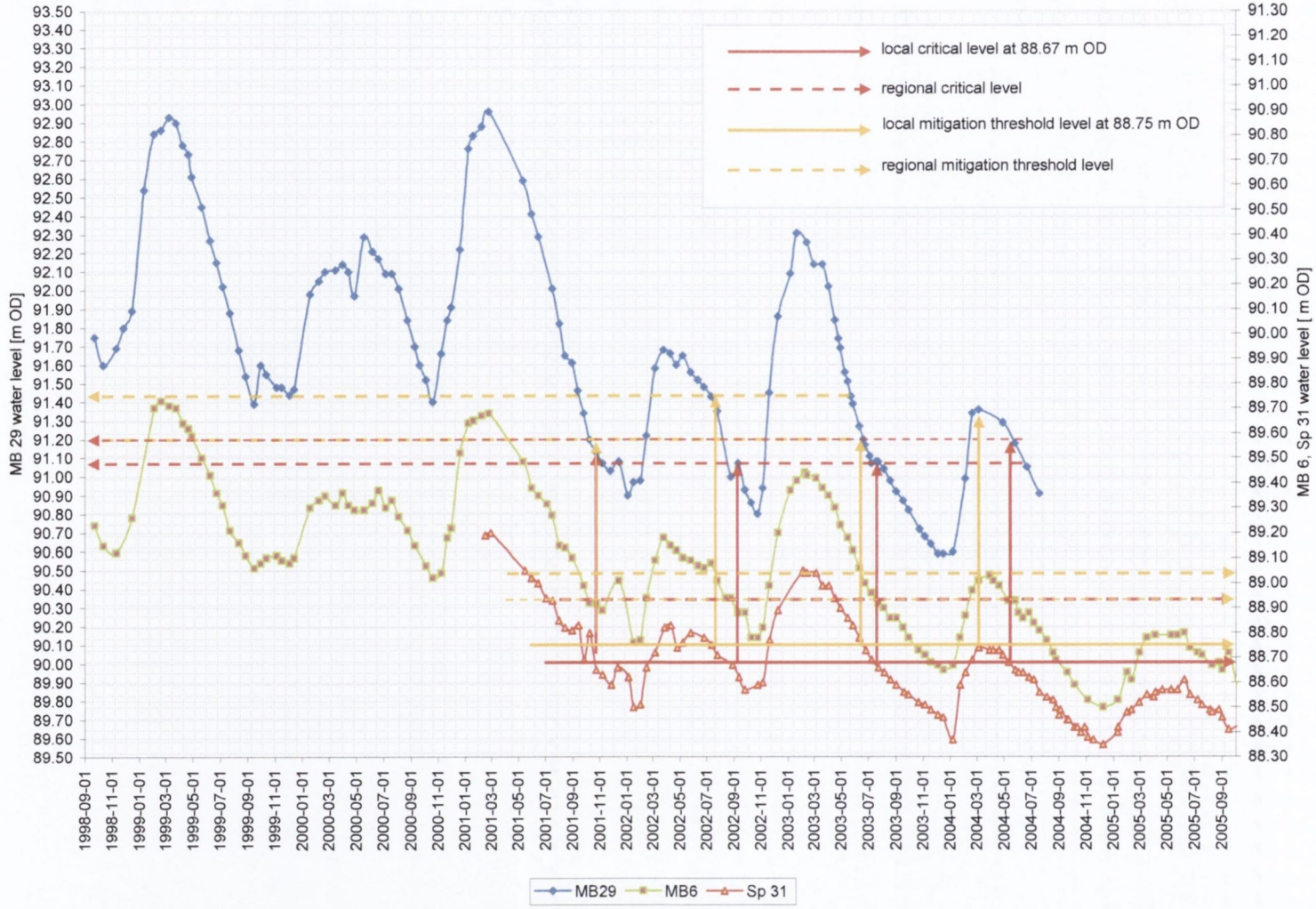



*Figure V-11 Summer regional critical and mitigation threshold levels in MB29, MB6 and SP31 corresponding with the local critical level in SP31 at 88.67 m OD and in S10 at 88.35 m OD; and the local mitigation threshold level in SP31 at 88.75m OD and in S10 at 88.45 m OD.*

## V-2.3. Conclusions

In summary, all four monitoring locations MB29, MB30, MB6 and SP31 show high correlation in their water levels (Table V-4) and synchronity. The comparison with winter effective rainfall confirmed that all locations simultaneously react very quickly to the winter recharge which indicates high transmissivity in the gravel medium. This immediate response to rainfall that was observed across the region, and lack of a phase shift between the top of the Curragh and the fen margin makes it very difficult to establish distant time - based triggers which could be used in advance as a warning of possible risk to the fen margin. Also, because the system reacts fairly rapidly to rainfall, effective rainfall must therefore have an important role in sustaining water levels at given depths, which implies that alterations in the components of a recharge such as an increase or decrease of the catchment area may show relatively quick responses at the fen margin.

A strong positive relationship between the fen standpipe SP31 and Curragh monitoring boreholes MB29, MB30 and MB6, for which longer term records exist, suggests that water levels measured in SP31 also experienced the step shift that was noted in MB29, MB30 and MB6 in 2001. That means that water levels at the fen margin were probably already reduced with respect to previous years at the beginning of the study in 2001. High correlation between fen piezometer SP31 and monitoring boreholes at the Curragh Plains allows the assumption that results of any analysis regarding the groundwater regime of the Curragh aquifer before 2001 would have been mirrored at the fen margin in the vicinity of site A (SP 31) if this data were available. However, taking into account the non linearity of the water table in an unconfined aquifer, which is governed by the Dupuit (1863) approximation, further assessment of flow rates along the profile between the groundwater divide and the fen margin may further support the representativeness of monitoring boreholes MB29 and MB6 as trigger indicators for the fen margin conditions.

Finally, based on the hydrograph analysis it is concluded that maintenance of sufficient hydraulic head at the fen margin to counteract a local water depletion caused by evapotranspiration depends on the groundwater levels within the Curragh aquifer and these have to be maintained at minimum levels of 91.20 m OD in MB29 and 88.92 m OD in MB6. However, levels of 91.44 m OD in MB29 and 89.06 m OD in MB6 should be treated as a risk situation and should initiate preparations for adequate mitigation.

## V - 3. Verification of Established Threshold Water Levels by Assessment of Groundwater Flow Rates

In an unconfined aquifer, the water table determines the upper boundary of the saturated zone within which the groundwater flow occurs. Under steady flow conditions, the same volume of water flow passes any two monitoring locations in the direction of flow and, according to Darcy's law, changes in cross-sectional areas, which are controlled by the height of the water table, must be reflected in hydraulic gradients. The gradient of the water table in unconfined flow conditions is not constant, and increases in the direction of flow and therefore the reliability of established threshold levels should be checked against corresponding flow rates. Therefore, to verify the established threshold levels further analysis will focus on groundwater flow rates that are delivered into the fen margin at different hydraulic head conditions. The flow through an unconfined aquifer is described by the Dupuit (1863) approximation:

$$q' = \frac{1}{2} k \cdot \left( \frac{h^2_1 - h^2_2}{L} \right)$$

*Equation V-3*

where:

$q'$ – flow per unit width [$L^2$/T]

$k$ – hydraulic conductivity [L/T]

$h_1$, $h_2$ – water elevations in monitoring wells 1 and 2 above the base level [L]

$L$ – distance between monitoring wells 1 and 2 [L]

As reported earlier (Section II-1.4 and III-2.2.2.1) the hydraulic conductivity across the Curragh aquifer varies and was measured between 53 -200 m/d. However, a mean value of 100 m/day has been adopted for groundwater modelling along the road cutting using the KAM model and this value was also used in this analysis. It is assumed therefore that the aquifer is isotropic across the transect beetwen the groundwater divide and the southern fen margin, Site A specifically, for which threshold levels were established.

An impermeable base was assumed at the base of the gravel deposits and this was established from the overburden depth map (refer: Figure II-7, gravel depth of 40-60 metres) supplemented by information from borehole logs from selected monitoring boreholes aligned along the investigated transect (Appendix 4). This included monitoring boreholes MB5, MB6, MB7, MB17, MB29, MB30 and MB31. The only boreholes that provide definite information on the entire depth of the gravel layer are MB30 and MB7 and these show depths of 19.5 and 51.0 m respectively. Comparison with the topographic elevations relative to the Ordnance Datum suggests the base level varies between 56-80 m OD. Therefore, for computation purposes, the base level was set at 65 m OD to reflect spatial differences in depth of the gravel strata. Subsequently, all groundwater levels were reduced by 65 metres prior to the analysis and are termed as water elevations above the base level.

The following analysis aims to investigate temporal changes of the groundwater flow rates rather than the quantitative values. Limitation of data restrict establishing the real hydraulic conductivity for these transect and the precise base of gravels is also difficult to assess. Therefore, determined flow discharges shall be treated as '*indicative flows*' rather than quantitative ones.

## V-3.1. Methods

Three sets of '*indicative flow*' were analysed here; between monitoring borehole MB29 and piezometer SP31, between monitoring borehole MB6 and piezometer SP31, and between monitoring borehole MB29 and MB6. However, because data for monitoring borehole MB29 finished in 2004, and for other boreholes these are available until 2005, data for MB29 were extrapolated using linear regression. Data sets from monitoring boreholes MB6 and MB30 were tested as adequate independents. This was carried out according to the following schedule:

1) Monthly water level data from monitoring boreholes MB6, MB29 and MB30 was transferred into SPSS software for correlation analysis. Pearson's correlation coefficient for a linear relationship was tested at 0.01 significance level. Four sets of data were tested, MB29 vs. MB30 between 1998 and 2004, MB29 vs. MB6 between 1998 and 2004, MB29 vs. MB30 between 2001 and 2004; and MB29 vs. MB6 between 2001 and 2004. Such a selection was used to test the reliability of MB30 and MB6 as independent variables. As presented on an earlier graph (Figure V-5), the difference in the hydraulic head distribution between monitoring boreholes MB30 and MB29 was bigger between 1998 and 2000 than in the following period and this could have had an influence on the regression equation.

2) The data set that showed the best correlation with the MB29 data set was then used to extrapolate MB29 data until September 2005.

3) '*Indicative flow*' was then computed according to Equation V-3 between two selected pair of monitoring boreholes. This was computed in Excel and was plotted on a timescale graph. The phreatic level in standpipe S10 was also included on the graph.

4) A critical point was chosen on the timescale graph, when the phreatic level dropped and never returned to stable conditions. Corresponding '*indicative flow*' values were read from the time-scaled graph.

5) Local and regional critical water levels, established during hydrograph analysis, and presented in Table V-6, were applied to the Equation V-3 to compute critical *'indicative flow*' rates. Water levels were reduced by 65.0 m prior to this computation to reflect impermeable base conditions. Results of these computations were then compared with the critical '*indicative flow*' values read from the timescaled graph.

## V-3.2. Results

1) & 2) Table V-7 – Table V-10 show that all datasets were very well correlated, regardless of the time scale chosen. The Pearson's correlation coefficients exceeded 0.9 value in all cases, which indicates a strong, positive linear relationship between the variables tested. The significance of the correlation coefficient was tested at a level of 0.01 and was proved high for all pairs of piezometers. A strong linear

relationship between the variables justified, therefore, use of the linear regression to extrapolate the MB29 data. The assumption was made that the relationship remains linear outside the tested range. Regression constants and regression coefficients were calculated in SPSS for the four scenarios tested. Graphical interpretations were produced in Excel and are presented below in Figure V-12 - Figure V-15. It is apparent from these figures that a regression constant has changed for the MB29 – MB30 pair between the two time series investigated and this suggests changing characteristics of the relationship within tested ranges. However, regression constants and coefficients remained similar for the two different time series for the pair of MB6 - MB29, and therefore the monitoring borehole MB6 was eventually used to extrapolate MB29 data. The ultimate regression line equation was established at $y = 2.286x - 112.16$. Monthly water level data for MB6, MB29 and MB30 as well as results of this extrapolation is presented in full in Appendix 32.

**Table V-7 Descriptive statistics for monthly water level data from monitoring boreholes MB6, MB29 and MB30, 1998-2005**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| **MB6** | 89.06 | 0.3 | 84 |
| **MB30** | 91.56 | 0.7 | 84 |
| **MB29** | 91.66 | 0.6 | 69 |

**Table V-8 Summary of coefficients and significance of correlation between monitoring boreholes MB29, MB30 and MB6, 1998-2005**

| | | MB6 | MB30 | MB29 |
|---|---|---|---|---|
| **MB6** | Pearson Correlation | 1 | 0.983(**) | 0.981(**) |
| | Sig. (2-tailed) | | 0.000 | 0.000 |
| | N | 84 | 84 | 69 |
| **MB30** | Pearson Correlation | 0.983(**) | 1 | 0.986(**) |
| | Sig. (2-tailed) | 0.000 | | 0.000 |
| | N | 84 | 84 | 69 |
| **MB29** | Pearson Correlation | 0.981(**) | 0.986(**) | 1 |
| | Sig. (2-tailed) | 0.000 | 0.000 | |
| | N | 69 | 69 | 69 |

*** Correlation is significant at the 0.01 level (2-tailed).*

**Table V-9 Descriptive statistics for monthly water level data from monitoring borehole MB6, MB29 and MB30, 2001-2005**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| **MB6** | 88.95 | 0.23 | 56 |
| **MB30** | 91.25 | 0.62 | 56 |
| **MB29** | 91.41 | 0.59 | 41 |

**Table V-10 Summary of coefficients and significance of correlation between monitoring boreholes MB29, MB30 and MB6, 2001-2005**

| | | MB6 | MB30 | MB29 |
|---|---|---|---|---|
| **MB6** | | 1 | 0.985(**) | 0.979(**) |
| | Sig. (2-tailed) | | 0.000 | 0.000 |
| | N | 56 | 56 | 41 |
| **MB30** | Pearson Correlation | 0.985(**) | 1 | 0.986(**) |
| | Sig. (2-tailed) | 0.000 | | 0.000 |
| | N | 56 | 56 | 41 |
| **MB29** | Pearson Correlation | 0.979(**) | 0.986(**) | 1 |
| | Sig. (2-tailed) | 0.000 | 0.000 | |
| | N | 41 | 41 | 41 |

** *Correlation is significant at the 0.01 level (2-tailed).*

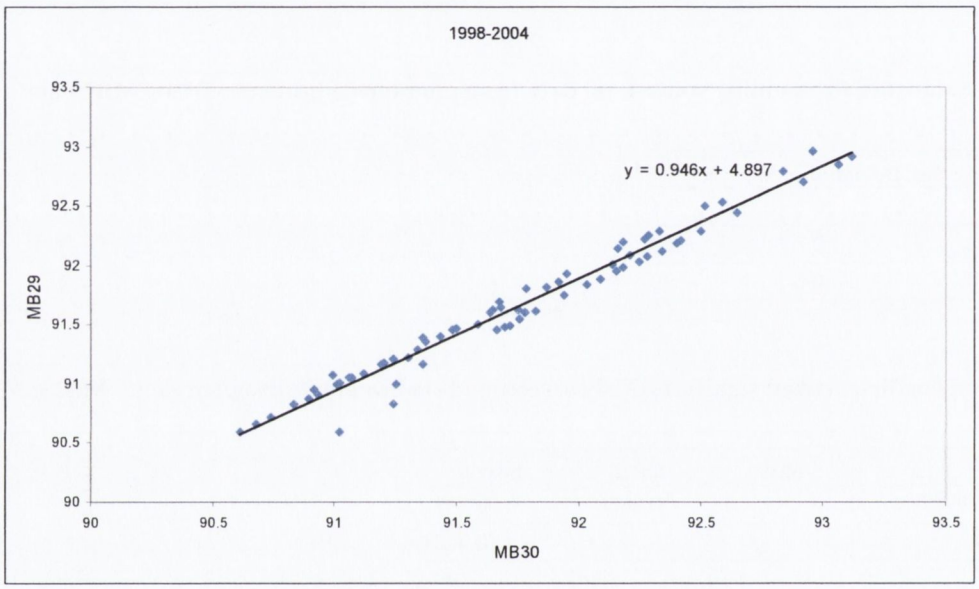



*Figure V-12 The linear relationship between data from monitoring boreholes MB30 and MB29 for the period 1998-2004*

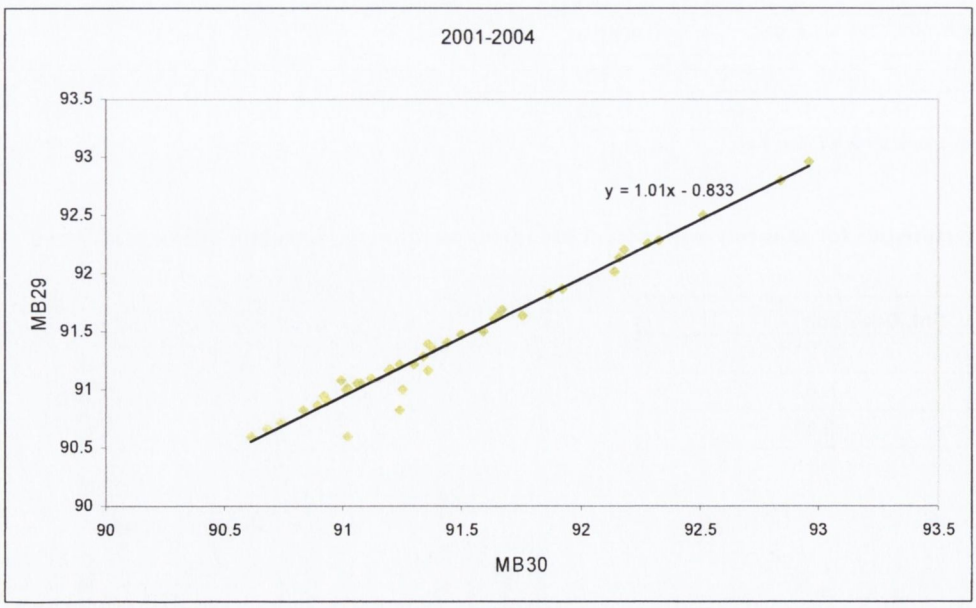



*Figure V-13 The linear relationship between data from monitoring boreholes MB30 and MB29 for the period 2001-2004*

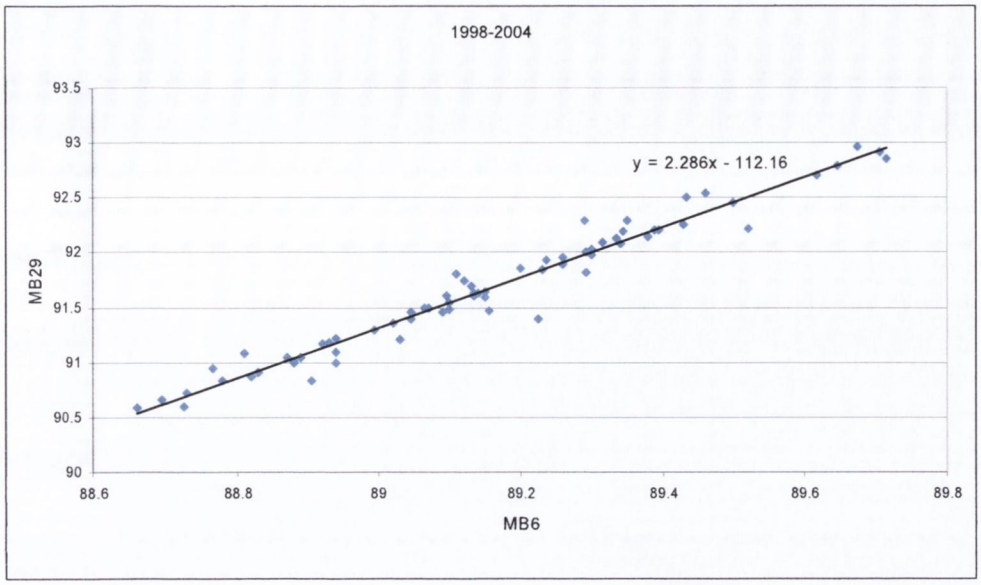



*Figure V-14 The linear relationship between data from monitoring boreholes MB6 and MB29 for the period 1998-2004*

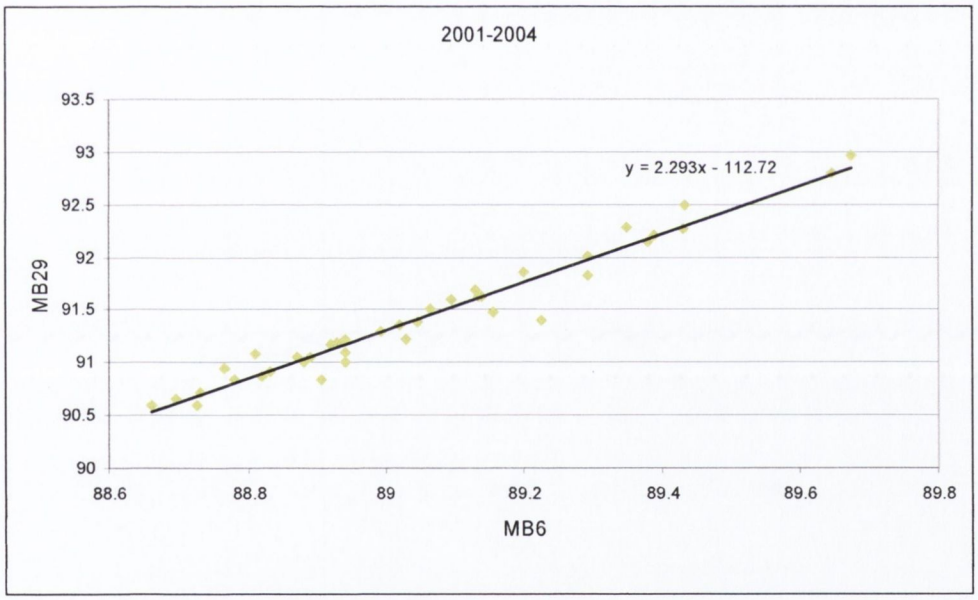



*Figure V-15 The linear relationship between data from monitoring boreholes MB6 and MB29 for the period 2001-2004*

3) The '*indicative flow*' was computed between the following pairs of piezometers:

- MB29 and SP31;
- MB6 and SP31; and
- MB29 and MB6.

Numerical results of this computation can be viewed in Appendix 32. Temporal distribution of the '*indicative flow*' between the above pairs throughout 1998-2005 can be seen in Figure V-17 and Figure V-18. It can be noted that although water elevations in the relevant pairs of piezometers were very well correlated, patterns of the '*indicative flow*' are not parallel, which endorses changes in the hydraulic

gradient across the transect reflecting non linearity of groundwater table in an unconfined aquifer. Figure V-16 demonstrates the correlation among the determined '*indicative flow*' values between different pairs of observation boreholes, and a summary Table V-11 presents the numerical results of this analysis. As expected, all three sets of data show a strong relationship at a level of confidence at 0.01; however, the best correlation was found between the MB29-MB6 vs. MB29-SP31 dataset. This suggests that groundwater flow rates along these two pathways have the same characteristics, and this provides further evidence that the groundwater head in MB6 responds in a very similar fashion to SP31, and as such can be chosen as indicative of groundwater conditions at the fen margin.

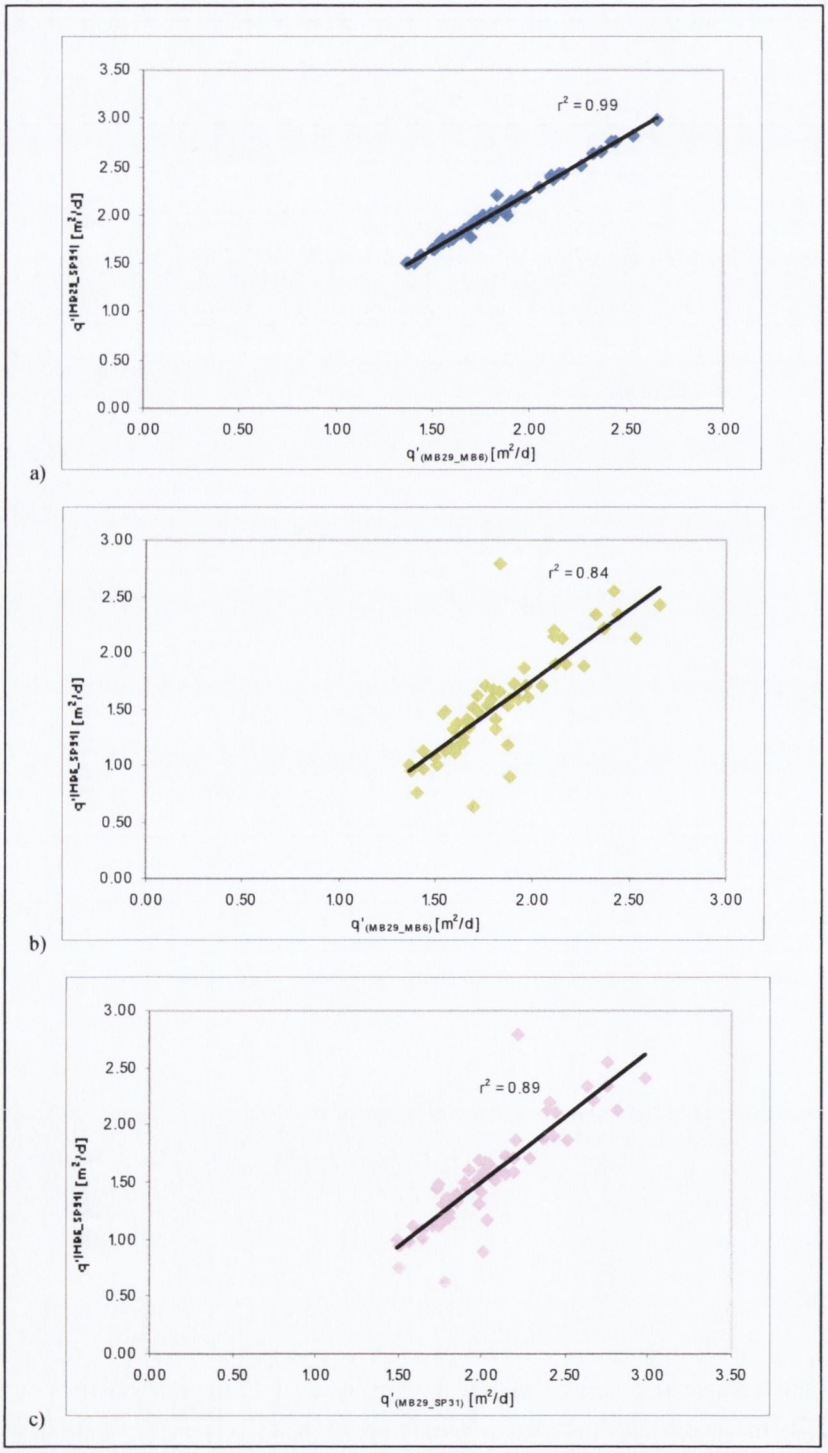



*Figure V-16 Scatter diagrams of the 'indicative flow' computed between the selected pairs of piezometres a) MB29-MB6 vs. MB29-SP31; b)MB29-MB6 vs. MB6-SP31; c) MB29-SP31 vs. MB6-SP31.*

**Table V-11 Descriptive statistics of the *'indicative flow'* [$m^2/d$] between MB29-MB6, MB29-SP31, and MB6-SP31**

| | Mean | Std. Deviation | N |
|---|---|---|---|
| $q'_{(MB29_MB6)}$ | 2.02 | 0.38 | 84 |
| $q'_{(MB29_SP31)}$ | 2.07 | 0.39 | 55 |
| $q'_{(MB6_SP31)}$ | 1.57 | 0.50 | 55 |

**Table V-12 Summary of the SPSS correlation analysis between the selected *'indicative flow'* values**

| | | $q'_{(MB29_MB6)}$ | $q'_{(MB29_SP31)}$ | $q'_{(MB6_SP31)}$ |
|---|---|---|---|---|
| $q'_{(MB29_MB6)}$ | Pearson Correlation | 1 | .0996(**) | 0.841(**) |
| | Sig. (2-tailed) | | 0.000 | 0.000 |
| | N | 84 | 55 | 55 |
| $q'_{(MB29_SP31)}$ | Pearson Correlation | 0.996(**) | 1 | 0.886(**) |
| | Sig. (2-tailed) | 0.000 | | 0.000 |
| | N | 55 | 55 | 55 |
| $q'_{(MB6_SP31)}$ | Pearson Correlation | 0.841(**) | 0.886(**) | 1 |
| | Sig. (2-tailed) | 0.000 | 0.000 | |
| | N | 55 | 55 | 55 |

** *Correlation is significant at the 0.01 level (2-tailed).*

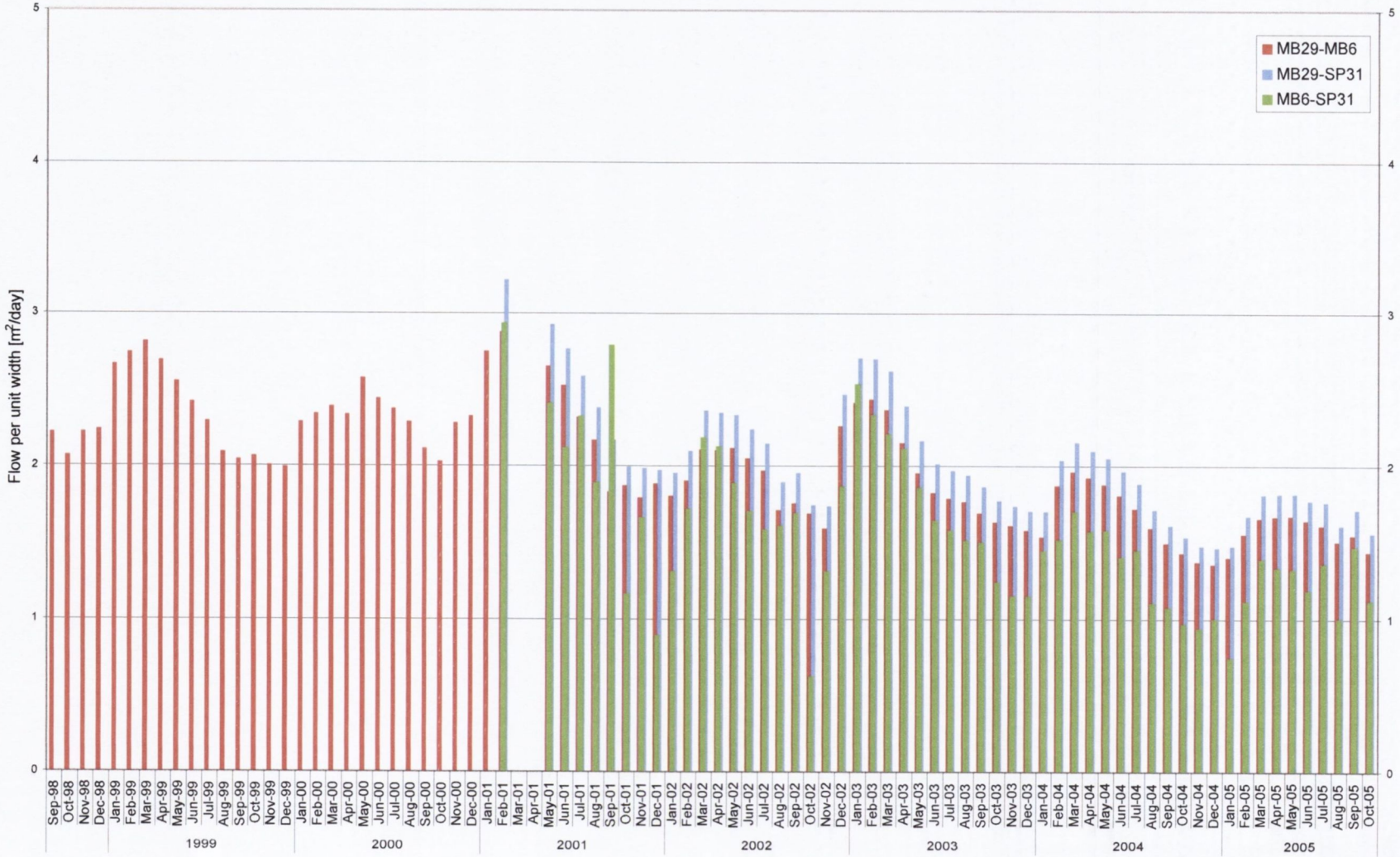



*Figure V-17 Distribution of the 'indicative flow' between: MB29 and SP31; MB6 and SP31; and MB29 and MB6 over 1998-2005*

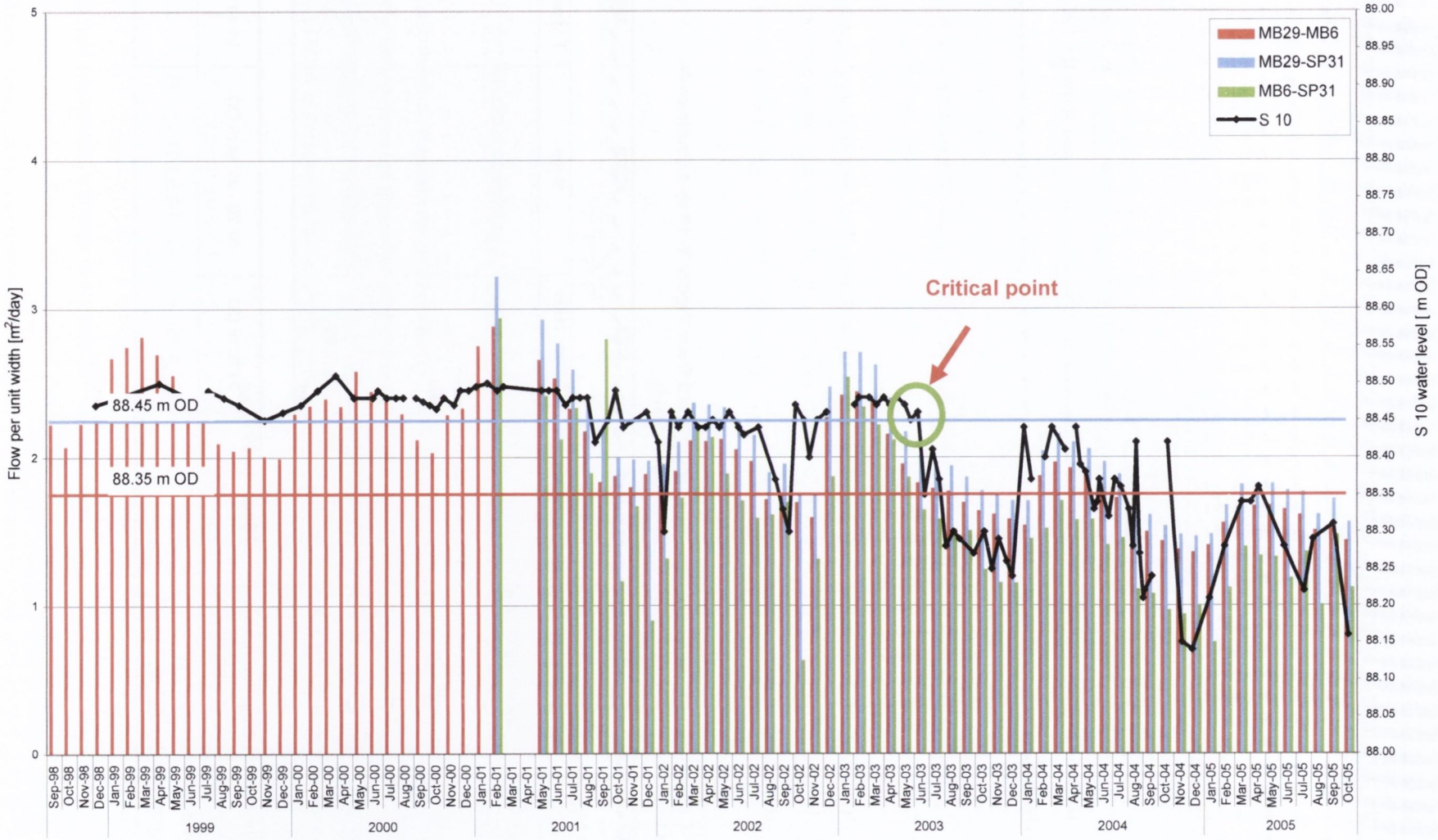



*Figure V-18 Distribution of the 'indicative flow' between: MB29 and SP31; MB6 and SP31; and MB29 and MB6 (left axis) vs. fluctuation of the phreatic surface in piezometer S10 at the fen margin (right axis).*

4) The distribution of the computed '*indicative flow*' between selected pairs of piezometers and the water table fluctuation within the fen peat at the fen margin, particularly in standpipe S10 is presented in Figure V-18. A critical point was chosen based on hydrograph for S10 location, when the phreatic level drops and never recovers to a stable position, which indicates groundwater flow conditions not sufficiently supporting the required seepage rate at the fen margin. The '*indicative flow*' values that correspond with the selected critical point were read from this graph and are:

- MB29-MB6: = ~1.95 [$m^2/d$]
- MB29-SP31: = ~2.15 [$m^2/d$]
- MB6-SP31: = ~1.65 [$m^2/d$]

5) The '*indicative flow*' rates computed from critical local and regional water levels as established from the hydrograph analysis in V-2.2 are presented in Table V-13 below, and show the following results:

- MB29-MB6: = ~1.90 [$m^2/d$]
- MB29-SP31: = ~2.07 [$m^2/d$]
- MB6-SP31: = ~1.49 [$m^2/d$]

Results of this computation show a very good fit with '*indicative flow*' threshold levels established directly from Figure V-18. It is therefore concluded that critical levels determined previously are reasonable.

**Table V-13 Comparison of '*indicative flow*' rates established from Figure V-18 and empirically determined based on established local threshold water levels.**

| S10 | SP31 | MB6 | MB6 | MB29 | MB29 |
|---|---|---|---|---|---|
| Local ($h_1$) | | Regional ($h_2$) | | | |
| | | Range | Trigger value | range | Trigger value |
| Critical water level at 88.35 m OD | Critical water level at 88.67 m OD | - | 88.92 m OD ↓ | 91.08-91.20 m OD | 91.20 m OD ↓ |
| Corresponding computed *indicative flow [$m^2/d$]* | | | 1.49 | 1.96-2.07 | 2.07 |
| | | | | | |
| *indicative flow [$m^2/d$] read from the 'indicative flow' graph* | | | 1.65 | | 2.15 |
| | | | | | |
| Mitigation threshold level of 88.45 m OD | Mitigation threshold level of 88.75 m OD | 88.92 – 89.06 m OD | 89.06 m OD | 91.20 - 91.44 m OD | 91.44 m OD |
| Corresponding computed *indicative flow [$m^2/d$]* | | | 1.85 | 2.0-2.21 | 2.21 |

*Note: base level at 65.00 m OD*

### V-3.3. Conclusions

The similarity of results achieved through three different analyses, i.e. hydrograph analysis, soil moisture model and analysis of the *'indicative flow'* allows the conclusion that the hypothetical model tested in this thesis that stability of the phreatic level at the fen margin depends on a balance between groundwater seepage rate and the actual evapotranspiration rate are reasonable, and that the critical local and regional water levels are realistic. The fact that local threshold levels determined by the hydrograph analysis correspond well with the triggers computed by application of the proposed soil moisture model supports this model as a general groundwater recharge model for the fen margin. Employment of summer evapotranspiration rates, determined from long term meteorological monitoring, combined with an arbitrarily chosen phreatic level which was selected after careful analysis of the *Vertigo geyeri* habitat, led to the discovery of critical levels that compared well with observed values. Further analysis of the *'indicative flow'* rates showed that the selected earlier threshold levels based on hydrograph analysis correspond well with threshold levels established from computing '*indicative flow*' values. The local critical levels were determined to be 88.35 m OD in standpipes S10 and 88.67 m OD in piezometer SP31. In a regional context, these correspond to 88.92 m OD in monitoring borehole MB6 and 91.20 m OD in monitoring borehole MB29.

Selection of mitigation threshold levels is subjective; however, employment of statistical characteristics of the mean summer water table led to establishment of trigger levels that precede the critical levels by approximately two months. Considering six month period when *Vertigo geyeri* snail's activity is highest (May-October), a two month notice that critical levels are being approached seems a practical period for mobilisation of adequate mitigation action. However, considering conditions at the fen margin in standpipe S10 as unacceptable from 2003 - 2005, which signifies the gentle balance that governs the fen's margin sustainability; it might be appropriate that general mitigation plans are available at the time when mitigation threshold levels are met.

It shall be remembered however, that the above thresholds were determined for the particular southern site, Site A and other threshold levels might be more relevant for other sites of ecological interest.

The final conclusion is that the groundwater response observed in the groundwater borehole MB6 (upgradient from the fen), mirrors the groundwater response at the fen margin (SP31), and as such this borehole can be used as a monitoring point representative of the fen conditions. This is a useful observation considering the easy access to MB6 in comparison to the lengthy and physically challenging access to SP31.

## V - 4. Assessment of Sensitivity of the Fen Margin to Changes in the Regional Hydrogeology

In this final assessment, a change in summer flow rates during 1999 - 2005 was evaluated. This assessment was based on the '*indicative flow*' which assumed that the base of the gravel layer is at 65.00 m OD and isotropic conditions prevail across the investigated transect with a hydraulic conductivity of k=100 m/d. The '*critical indicative flow'* rates established in V-3.2 were used in this evaluation as reference values to estimate water surplus or deficit that occurred during the 1999-2005 monitoring period. This was compared with other *in situ*

observations including the malacological interpretation. Strong relationships in groundwater behaviour found between monitoring borehole MB6 and piezometer SP31 suggests that long term trends in the '*indicative flow*' between monitoring borehole MB29 and MB6 are representative of the fen margin and therefore this transect was analysed in detail. The analysis was based on data from months between May to October as the snail's reproduction activity is highest in these months and therefore sustainability of preferred snail habitat is most important during this period. The 'May-October' observation period will be used interchangeably with 'summer' observation period.

### V-4.1. Methods

1) Firstly, '*indicative flow*' rates for the months of May – October were plotted on a timescaled graph for the consecutive years 1999-2005 and are presented in Figure V-19.

2) The consecutive summer '*indicative flows*' for the period of 1999 – 2005 were divided by the '*critical indicative flow*' values determined in part V-3.2. The results are presented as a percentage of the '*critical indicative flow*' and represent a change in the actual groundwater flow rate along given transects with respect to the critical flow rate.

### V-4.2. Results

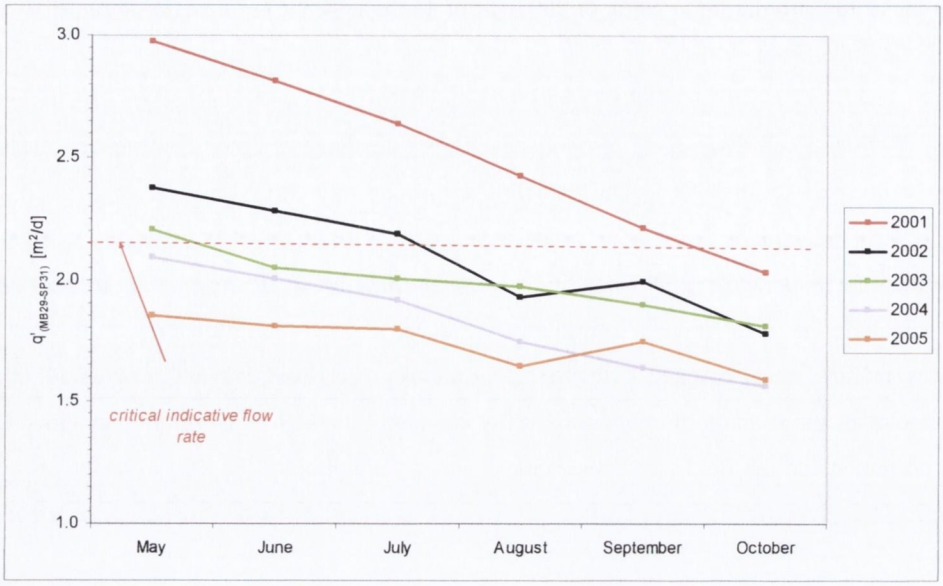
1) As can be seen in Figure V-19, there was a continuous decrease in summer flow rates throughout the observation period, which corresponds to decreasing groundwater levels across the Curragh aquifer. The most pronounced drop was noted between 2001 and 2002 and this was noted for all transects. This drop in the flow rate corresponds with the step shift in groundwater levels. Reduction of flow is proportional to the actual reduction in water depth and therefore the highest decline was noted for the MB29 - SP31 transect and lowest for the MB6 - SP31 transect. Figure V-19 suggests also that critical flows required to sustain the water table at a stable condition at the fen margin in location S10 were observed in summer 2002 which conforms to the earlier interpretation of the local critical levels established from hydrographs.

2) When compared with the '*critical indicative flows*', these were exceeded by approximately 5% in 1999 and 2000 and were just slightly below 100% in 2001 (Table V-14, Figure V-19 and Figure V-20). Between 2002 and 2003 the '*critical indicative flow*' rates were crossed between June - August (depending on the transect) and this indicates that mitigation measures should have been in operation already during those summers. Data for the summers of 2004 and 2005 shows that '*critical indicative flows*' were not met at all. For the MB29 - MB6 transect, a range of the *'indicative flow'* with reference to the critical level varied from approximately 132% - 104% throughout the summers

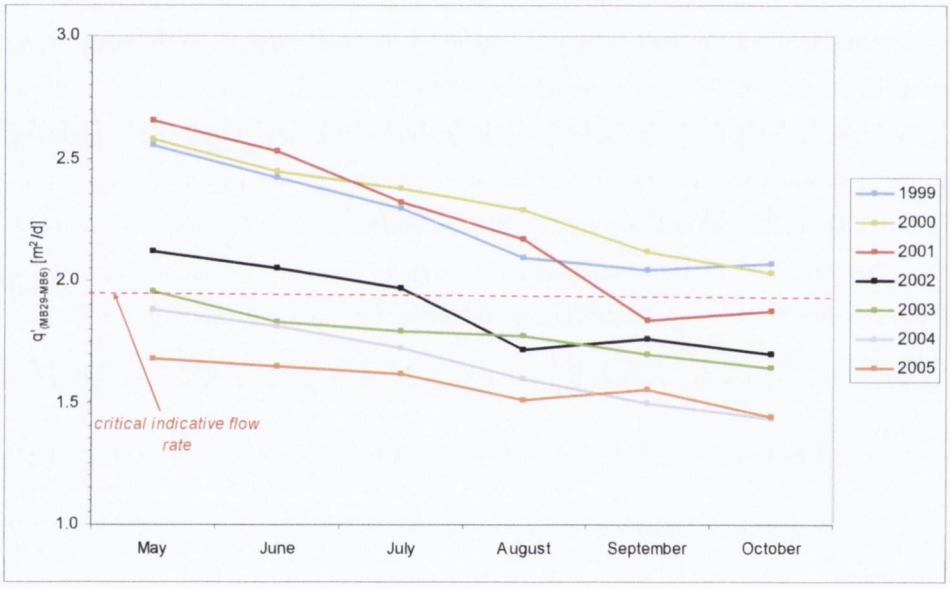
of 1999 and 2000; from 136% - 96% in 2001; from 108% - 84% over 2002-2003 and from 96% - 73% in 2004-2005 (Table V-14).

Adopting 1999 as a reference point, groundwater flow rates have declined continuously throughout the monitoring period 2001-2005. The reduction in groundwater flow rates increases each year as follows; a 10% reduction in 2001; a 20% reduction in 2002 - 2003; and 30% reduction in 2004-2005. While we cannot assume that 1999's conditions were normal (due to lack of existing monitoring data) we can conclude that data suggests continuously reduced groundwater flow rates to the fen. These reductions in flow rates, coupled with their continuously increased magnitude, coincide with the disappearance of the snails at the topographically elevated Site A. It is therefore concluded that the models presented and the field work observations support adoption of the critical levels presented in this work.

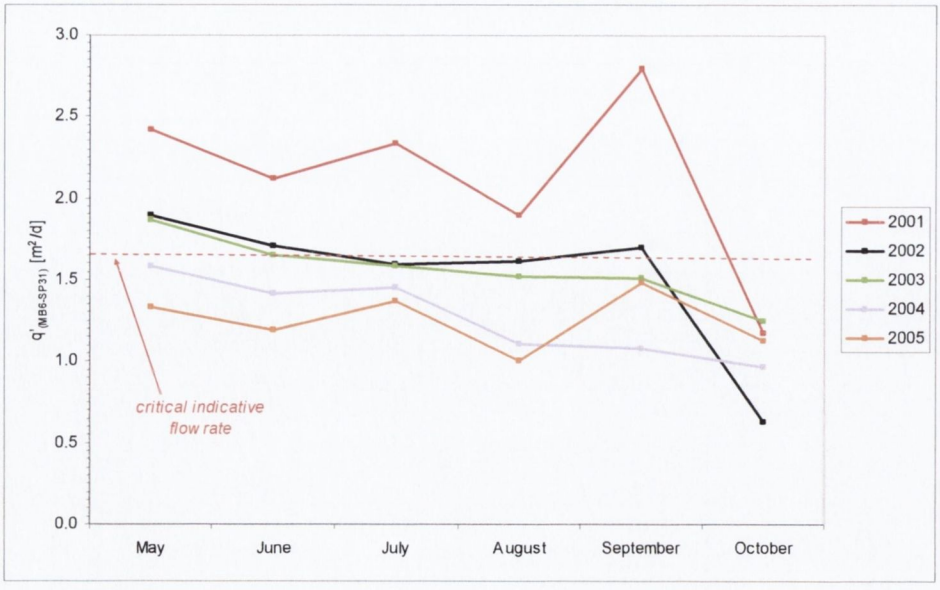
The lack of snails in the uppermost zone of the fen margin at site A in 2004 and 2005 proves that a drop in flow rates to a level of 96% – 73% of critical levels is not suitable for the snail. Considering the continuous decrease in flow rates throughout 1999 - 2005 and the relatively short life span of the *Vertigo* snail (and its opportunistic nature), it is also possible that the 2002 - 2003 conditions, when groundwater flow was provided only at rates that were just enough to support the required seepage at the fen margin, might have already stressed the species and have led to its extinction from upper parts of site A in 2004 and 2005. Lack of quantitative analysis of the snail population within the site from before 2001 restricts definite conclusions and verification of the above hypothesis.




a)




b)




c)

*Figure V-19 The summer distribution of the 'indicative flow' along transects: a) MB29-SP31, b) MB29-MB6 and c) MB6-SP31*

**Table V-14 Summary of the summer '*indicative flow*' rates between selected monitoring boreholes MB29 and MB6 and the fen piezometer SP31, 1999-2005**

| | MB29-MB6 | | MB29-SP31 | | MB6-SP31 | |
|---|---|---|---|---|---|---|
| *Critical indicative flow* [$m^2$] | 1.95 | | 2.15 | | 1.65 | |
| | q' | q'/1.95 | q' | q'/2.15 | q' | q'/1.65 |
| | [$m^2$/d] | [%] | [$m^2$/d] | [%] | [$m^2$/d] | [%] |
| May-99 | | | | | | |
| Jun-99 | | | | | | |
| Jul-99 | | | | | | |
| Aug-99 | | | | | | |
| Sep-99 | 2.2 | 113.9% | | | | |
| Oct-99 | 2.1 | 106.3% | | | | |
| | | | | | | |
| May-00 | 2.6 | 131.0% | | | | |
| Jun-00 | 2.4 | 124.2% | | | | |
| Jul-00 | 2.3 | 117.7% | | | | |
| Aug-00 | 2.1 | 107.3% | | | | |
| Sep-00 | 2.0 | 104.8% | | | | |
| Oct-00 | 2.1 | 106.1% | | | | |
| | | | | | | |
| May-01 | 2.6 | 132.3% | | | | |
| Jun-01 | 2.4 | 125.3% | | | | |
| Jul-01 | 2.4 | 121.9% | | | | |
| Aug-01 | 2.3 | 117.5% | | | | |
| Sep-01 | 2.1 | 108.5% | | | | |
| Oct-01 | 2.0 | 104.2% | | | | |
| | | | | | | |
| May-02 | 2.7 | 136.2% | 3.0 | 138.5% | 2.4 | 146% |
| Jun-02 | 2.5 | 129.8% | 2.8 | 130.8% | 2.1 | 129% |
| Jul-02 | 2.3 | 119.2% | 2.6 | 122.5% | 2.3 | 141% |
| Aug-02 | 2.2 | 111.3% | 2.4 | 112.7% | 1.9 | 115% |
| Sep-02 | 1.8 | 94.1% | 2.2 | 102.7% | 2.8 | 169% |
| Oct-02 | 1.9 | 96.1% | 2.0 | 94.4% | 1.2 | 71% |
| | | | | | | |
| May-03 | 2.1 | 108.8% | 2.4 | 110.4% | 1.9 | 115% |
| Jun-03 | 2.1 | 105.2% | 2.3 | 106.1% | 1.7 | 104% |
| Jul-03 | 2.0 | 101.1% | 2.2 | 101.5% | 1.6 | 96% |
| Aug-03 | 1.7 | 87.9% | 1.9 | 89.8% | 1.6 | 98% |
| Sep-03 | 1.8 | 90.4% | 2.0 | 92.5% | 1.7 | 103% |
| Oct-03 | 1.7 | 86.9% | 1.8 | 82.7% | 0.6 | 38% |
| | | | | | | |
| May-04 | 2.0 | 100.3% | 2.2 | 102.5% | 1.9 | 113% |
| Jun-04 | 1.8 | 93.8% | 2.0 | 95.3% | 1.6 | 100% |
| Jul-04 | 1.8 | 91.9% | 2.0 | 93.2% | 1.6 | 96% |
| Aug-04 | 1.8 | 90.8% | 2.0 | 91.8% | 1.5 | 92% |
| Sep-04 | 1.7 | 87.1% | 1.9 | 88.3% | 1.5 | 91% |
| Oct-04 | 1.6 | 84.1% | 1.8 | 84.0% | 1.2 | 76% |
| | | | | | | |
| May-05 | 1.9 | 96.4% | 2.1 | 97.2% | 1.6 | 96% |
| Jun-05 | 1.8 | 93.0% | 2.0 | 93.1% | 1.4 | 86% |
| Jul-05 | 1.7 | 88.4% | 1.9 | 89.2% | 1.5 | 88% |
| Aug-05 | 1.6 | 82.0% | 1.7 | 81.3% | 1.1 | 67% |
| Sep-05 | 1.5 | 76.9% | 1.6 | 76.4% | 1.1 | 65% |
| Oct-05 | 1.4 | 73.6% | 1.6 | 72.8% | 1.0 | 59% |




*Figure V-20 Distribution of summer groundwater flow rates between selected observation points within the fen catchment with reference to the critical groundwater flow rates, 1999-2005; based on the 'indicative flow' assessment.*

## V-4.3. Conclusion

In conclusion, the above analysis showed continuously changing conditions with regard to groundwater flow rates that were delivered to the fen margin throughout the 1999 - 2005 monitoring period. Comparison with the established earlier critical flow rates, that are necessary to sustain the groundwater seepage at the fen margin at rates that will counteract evapotranspiration forces to secure wet and stable conditions within the phreatic zone, showed clearly that these rates were sustained fully only until the end of summer 2001. In 2002 and in 2003 the sufficient conditions were delivered only throughout part of the observation period May-October and in 2004 – 2005 they were below the level that could support production of the required vertical seepage rate at the fen margin.

Provision of a sufficient vertical seepage rate throughout the summer is necessary to maintain a healthy population of the indicator species of *Vertigo geyeri* snail as these are active only in the summer and hibernate in winter. Although reproduction can occur few times during the summer, appearances of the snail at a site in a given year depend on successful mating in the previous year. As an opportunist, the snail can recruit at any time during the summer providing the micrometeorology and microhydrology are favourable. The optimal conditions were established in Chapter IV of this thesis to be stable water level and high humidity ($\geq$ 80%). The fact that the snail vanished from the uppermost part of the fen in 2004 suggests that stressful conditions had occurred at the fen margin in 2003 which possibly led to ineffective reproduction and this coincides with the range of conditions when critical levels were met only partially during the summer period, specifically in the first 2-3 months of the 6 months analysed. Discussion with *Vertigo* expert Dr. Evelyn Moorkens confirmed that the site conditions were not optimal at times in 2002 and 2003, although these recovered quickly after longer rainfalls. Appearance

of other mollusc species of *Vitrea crystellina* and *Nesovitrea hammonis*, which are indicators of a transition from fen into grassland, within IQABQ1 in July 2003, conforms to the above assessment of groundwater flow rates. This provides further support for the determined trigger values. As conditions in 2004 and 2005 became unacceptable for the snail it is hard at this stage to definitely say if conditions from 2002-2003 were stressing the *Vertigo geyeri* in the long term. Nevertheless, drying of a habitat is a gradual process and hence it is likely that stress conditions precede total loss. Dr. Moorkens suggested also that there would have been loses through death of areas that dried out in 2002 and 2003 and that the wet conditions that returned after drying worked because the snail must have come from wetter areas back into quadrats that became suitable again.

Causes of falling water levels and subsequent flow rates are not being investigated in this thesis. Only establishment of optimal hydrological conditions at the fen margin as defined by the chosen indicator species are examined. It can be concluded, then, that in order to provide fully satisfactory conditions at the southern fen margin, groundwater flow rates and subsequent water level conditions should be not less than those recorded on site A in summer 2001. Due to the fact that this work involved monitoring a natural system that demonstrated constant change and instability, typical groundwater flow rates cannot be specified. However, adoption of 1999 as a reference level facilitates some appraisal that the habitat remains suitable when flow rates decrease by ~10%. Observations further suggest that higher fluctuations cause imbalances in the system (between seepage and evapotranspiration rates), which in turn cause a lowering on the phreatic table to levels below those determined to be 'critical' for the local scale. Under these conditions, the snail may persist but there is potential for stress that may have a future impact in terms of decreased activity and subsequently survival of the species. Further decline in groundwater seepage leads also to lowering the phreatic level and an increase in fluctuation range and responsiveness to direct rainfall.

# VI Chapter Six: Synthesis, Conclusions and Recommendations

This dissertation has detailed the findings of a three and a half year study of the hydroecology of a calcareous spring-fed fen at Pollardstown in Co. Kildare. There are many species and habitats living on the fen that are listed in both Annex I and Annex II of the EU Habitats Directive, for which the fen requires the maximum protection. This in turn requires a very good understanding of the general workings of the system, the local hydrological regime and factors controlling this regime. Recognition of the links between hydrology and ecology is the key to facilitating the sustainability of the habitat, whose flora and fauna solely depend on the calcareous water supplied from the groundwater aquifer. Quantification of this relationship plays an important role in the context of the Water Framework Directive (2000/60/EC) which promotes provision of 'good status' of all waters by implementation of an integrated water management plans within selected River Basins Districts. The WFD places particular emphasis on the need to understand the linkages between groundwater bodies and hydrology of wetlands (Groundwater Dependent Terrestrial Ecosystems, GWDTE) of which Pollardstown Fen is a classic example. Assessment of the sensitivity of the fen ecosystem with reference to conditions in the groundwater body is a scientific study, one with a practical view of meeting the objectives of the Water Framework Directive. A particular emphasis was placed on evaluating the recharge mechanism of seepage occurring at the fen margin as this was believed to support the habitat of the rare species of snail *Vertigo geyeri,* which is listed in Annex II of the EU Habitats Directive, and chosen as an indicator for the protected habitat of the fen margin.

The results of this research show the high complexity of the fen ecosystem within the hydrological system. A strong hydrological connection between the wetland and groundwater supply from the Curragh aquifer was observed. Detailed analysis of the fen fauna on the example of the chosen indicator species emphasised high sensitivity of the wetland to changing hydrological conditions. Detailed experimental and analytical work has been undertaken to build this comprehensive picture, which required a good understanding of the interacting hydrogeology, hydrology, soil mechanics, water chemistry, meteorology and wetland ecology. This chapter will summarise the major findings of this study and synthesise the major concepts in the fen eco-hydrology.

## VI - 1. Pollardstown Fen – Origins and Attributes

Pollardstown Fen lies in a shallow depression north-east of Kildare town and is an example of a valley fen. The substrates of the fen consists of mostly fine and horizontally layered sands, gravels and alluvial clay deposited during the last glaciation process. The clay deposits are thick in central parts of the wetland but are fairly thin and discontinuous at the edges of the wetland, which allows for water to discharge into the fen from the local gravel aquifer. This variability of clay at the fen margin plays an important role in controlling the velocity of the oozing water and its spatial distribution, which leads to rather scattered dissemination of seepages. Water supplied to the fen originates in an extensive gravel aquifer of area approximately 200 $km^2$ with a thickness ranging from 20-60 metres. The fen is located on the north eastern edge of the Curragh plateau which embodies this aquifer.

Areas of the groundwater discharge found within the fen were either discrete or diffuse. The difference in the hydrological characteristics between the two gives rise to different habitats. Discrete springs are mostly fast flowing springs or dug-out springs with gravely beds at the discharge point. Their banks are often covered with well structured deposits of precipitated calcite $CaCO_3$, which happens when water that is rich in calcium bicarbonate $Ca(HCO_3)_2$ comes to the ground surface and carbon dioxide is released from the solution of the bicarbonate. These springs are easy to find and majority of them occur on the south side of the fen with the best examples present in the forest below the Spring Bank House and further south-east towards the public entrance. The diffuse discharge occurs in many places along the fen margin on both sides, and in some locations it can be associated with expanses of quaking soil, in others it may occur as a collection of small seeping springs. Calcite deposits are often seen in a loose particulate form on the surface of the peat soil or precipitated on plant stems creating a characteristic crunchy structure. *Cratoneuron commutatum,* a calcium-loving species of mosses is indicative of these petrifying tufa springs, habitats of which belong to priority category (7220) listed in Annex I of the EU Habitats Directive (92/43/EEC). These habitats are well represented along both sides of the fen margin; although the majority of them were found on the southern side. In total, over 40 springs were identified along the fen margin during the study. The continuous inflow of water to the fen creates waterlogged conditions, which has led to peat formation. There are layers of calcareous marl in the fen peats, which reflect the inundation by calcium-rich water. High levels of calcium in groundwater are linked to the geological setting of the Curragh aquifer, which consists of unsorted, cross bedded gravels, silts and sands and is underlain with limestone bedrock. The peat deposits within the fen are relatively thin and uneven, especially at the fen margin, but central deposits were found to extend up to 6m and are underlain with thick clay (Daly, 1981). The valley floor is very gently sloping towards the fen centre, where a complex drainage system collects water from all the springs around the fen margin and diverts it to a main channel. The outflow from the fen occurs through this drain, which is known as the Milltown Feeder, and which supplies water to the Grand Canal System. The amount of water delivered depends on the uninterrupted flow from the Curragh Aquifer via the fen. The quality of this water may be described as good due to filtration by passing through the gravel and fen peats. The topography of the central part of the fen is flat. This topographical setting of relatively flat basin maintains a relatively high water table across the wetland. The constant inflow of alkaline water prevents acidic vegetation from establishing over the fen peat. The total area of the wetland fen habitat is approximately 2.2 $km^2$. The majority of this habitat may be classified as *Cladium mariscus, Schoenus nigricans* fen and is the largest such stand in Ireland and reputedly also the largest in Europe (WYG Ltd., 2004). This is also a priority habitat listed in Annex I of the EU Habitats Directive (7210). *Cladium mariscus* is associated with shallow, calcium rich water and occurs predominantly in the central and northern side of the fen. The other species, *Schoenus nigricans* is known as a good indicator of diffuse groundwater discharge areas (7230) in Alkaline fens habitat in Annex I of the EU Habitats Directive) and its distribution on Pollardstown fen is rather scattered. It is predominantly present on the highest parts of the southern fen margin and also in the central parts, on the north-eastern margin and on the northern most parts of the fen.

## VI - 2. Hydrological Regime of Pollardstown Fen

The primary objective of this research was to define the hydrological regime of this important habitat. The results show that the predominant regional direction of flow in the deeper horizons is in a northerly direction;

however there are evidently different patterns of groundwater flow in the gravel on both the southern and northern fen margins which respond to the spring drainage system directing the flow towards the Milltown Feeder. While flow along the southern margin trends toward the north and north-east, flow on the northern side will drain generally towards the west, although on the local scale, the south-western direction will be predominant. The direction of flow at the phreatic level is highly variable and is driven by local topography, hydrogeological conditions and the alignment of the drainage system.

The catchment area for the groundwater inflow to the fen covers 32.2 $km^2$ and its extent follows the line from Red Hill, along the northern boundary of Kildare town, through the Curragh Army Camp on the south and at the north it runs along the R416 road linking Newbridge with Milltown village (Figure III-2). As the majority of the recharge area lies on the southern side of the fen, some 90% - 95% of the discharge in the Milltown Feeder comes from the southern part of the catchment which includes discharge through the Seven Springs. This is the point of the greatest discharge and its mean contribution to the total flow in the Milltown Feeder was established as 61%. Flow velocities measured in the Milltown Feeder were very low; often less than 0.01 m/sec and the channel was subject to extensive weed growth during the summer months. This weed growth, if not controlled, can significantly reduce the flow velocities and raise the water level in both the main and tributary drains. The tributaries, although they may have only a localised effect on the hydrology of the fen may affect the habitats along the drainage network. In this study, the annual discharge from the fen was determined to range from 8.6 x $10^6$ $m^3$ to 11 x $10^6$ $m^3$ for the hydrometric year of 2004. Historical studies suggest discharge flows of 9.1 x $10^6$ $m^3$ per annum (Daly, 1981) and 10.1 $10^6$ $m^3$ per annum (Collins, 2002). Therefore, the hydrological conditions observed in this study compare well with those observed 20 years ago.

Differences between the southern and northern parts of the catchment were also expressed by information returned by the piezometry and the hydrochemical data collected. A consequence of the northern side being recharged relatively locally is that it responds relatively quickly to the rainfall, often within a day or so and the chemistry of the discharge often reflects relatively shallow subsurface drainage and likely agricultural practice nearby. The southern side may take longer (a few days) to respond to heavy rainfall at the phreatic level but in all cases, the speed of the response depends on season (soil moisture deficit) as well as the scale of the site itself (phreatic levels at small scale sites can be seen to respond to direct rainfall input). The seasonal patterns are such that the deeper groundwater recharge period on the south side starts between November – January depending on the climatic characteristics of a given year and on the north side this usually starts between October-November and the difference can be attributed to the proximity to the catchment boundary. Amplitudes of fluctuation within deep boreholes on the north side are nearly double of those found on the southern side, which again reflects differences in the size of the catchment and rapidity of response between the two sides, possibly controlled by topography, changes in geology and different specific yields.

Differences in hydrochemical signatures observed on the southern and northern fen margins at two distinct depths (in middle and deep screens) suggest that on the north side both depths receive relatively local recharge, while on the south side it is the middle depth that is recharged locally. This is based on nutrient concentration levels found in deep screens, which were much higher on the north side than on the south side. Nevertheless, high nutrient levels found in middle screens on the south side indicate the influence of local land use (hence local recharge) on the chemical signature at this depth. Lower nutrient loadings in the deeper screens found on the

south side suggest that water at this depth is likely to come from further parts of the catchment area, which are observed to have less intensive agricultural use.

Data from the shallow screens provided evidence of groundwater mixing with surface water on either side of the fen. The fen surface is also affected by the biodegradation of organics in the overlying peat and this is reflected in lower pH and hardness values. Nevertheless, variations in nutrient levels, hardness and electrical conductivity between inner and outer shallow piezometers on the south side suggests an ingress of mineral rich groundwater (i.e. seepage) between the sampling locations. Groundwater movement in these locations could be facilitated by reduced thickness and/or discontinuity of clay located below the peat which provides a window for water to move upwards from the upper gravels.

With respect to observed fluctuations in phreatic level, two factors have a significant influence and these are site elevation and the underlying geology.

The climatic characteristics of the region are such that the annual gross rainfall over the fen ranges between 750-850 mm and potential evapotranspiration (for a grassy surface) is approximately 490-540 mm. To compute the actual evapotranspiration for the fen area, three different approaches derived from the literature were tested and the final estimates computed using a mean crop coefficient based on floral composition of the fen (Tiemeyer *et al.*, 2006). This resulted in actual evapotranspiration values in a range of 547-595 mm per annum and suggested AE/PE ratio of 1.2. In contrast, actual evapotranspiration in the fen catchment, but outside the fen area, was determined to range from 423 – 475 mm per annum and suggested AE/PE ratio of 0.82-0.9. The difference in the AE/PE ratio between the fen and the rest of the catchment results from differences between the fen and the Curragh's plant composition and unlimited water supply at the fen for vegetation to transpire. The higher evapotranspiration needs recorded at the fen resulted in the effective rainfall ranging between 179-262 mm/yr at the fen and between 335–374 mm/yr within the Curragh area. This showed that the effective rainfall at the fen is reduced with regard to the Curragh area by as much as 30-50%.

The upward seepage seems to occur in many places and is not only restricted to the fen margin, as areas of localised groundwater discharge were also identified in the central parts of the fen. The upward flow was determined for the following locations: Permanent Quadrats 1, 2, 4, 6, 7 and 10.

All intensively studied sites (Sites A-D), which were located at the immediate margin of the fen adjacent to surrounding fields, showed that the dominating mechanism of phreatic water flow at these sites was a lateral seepage discharging at the immediate fen boundary driven by the groundwater head in upgradient gravels, amplified by a strong upward flow from deeper groundwater in places where geology was favourable (shallow peat, lacking a clay layer) or where the old drainage systems facilitated the seepage. The mechanism of seepage delivery is dependent on the layering of peat, clay and gravel at a given site. Giving that there is a significant driving head in the regional gravels, the rate of delivery (discharge) is essentially controlled partly by the relative elevation of the site and partly by the hydraulic resistance offered by the overlying layers. The thickness of clay layer was identified as the important factor controlling the seepage velocity (measured here as a specific discharge). The complexity of these conditions is unique at each of the studied sites and that was reflected in the habitats it supported. Nevertheless, each of the four study sites revealed much localised upward seepage at a

range between 0.0001-0.002 m/day at site A, 0.002-0.004 m/day at site B, 0.002-0.003 m/day at site C and 0.0002-0.002 m/day at site D. A detailed conceptual model for water delivery was built for the most elevated of these sites (Site A), as it was considered the most sensitive of the fen habitats. The basis of this model lies in the moisture balance in the upper layer of peat, which is controlled by the scale of upwelling flow balanced by the evapotranspiration from the peat surface. The model shows high sensitivity to the properties of the resisting layer and it is desirable to determine the relevant soil permeability values *in-situ*. The numerical analysis based on Darcy's equation allowed the establishment of minimum seepage rates, which are required to counterbalance the depleting mechanism of evapotranspiration. Assuming the mean permeability of the vertical profile at $4.72 \times 10^{-7}$ m/sec, it was determined that this seepage rate must be at least equal to actual evapotranspiration rate during the summer time in order to maintain the fen surface wet. On the basis of average summer daily actual evapotranspiration at approximately 2-3 mm/day, this is the minimum specific discharge rate that is required. An analysis of temperature gradients in the peat suggested similar rates of upwards flow. Therefore, validation of the method was accepted.

## VI - 3. Characteristics of the Microhabitat at the Fen Margin

The second major objective of the research was to identify the hydrological characteristics of the key habitat areas, required for the sustainability of the species concerned. Very detailed studies of the quadrats in which *Vertigo sp.* occurred, as reported in Chapter IV, involved study of molluscan species and associated measurements of hydrometeorological parameters at surface level. These included incident and reflected radiation, relative humidity, air and soil temperature. Micrometeorology of the fen margin at the sub-vegetation level was found to be relatively uniform across the whole fen in both *Vertigo* positive and negative zones. It can therefore be inferred that meteorology is not the most significant factor in the occurrence of the *Vertigo* snails.

The most significant findings were that no major differences were found in the micrometeorological conditions between various locations on the fen margin (on both sides of the fen) and observations from the weather station. The only exception was that incoming radiation was circa 50% less under the vegetation canopy than it was at the exposed weather station.

On an annual scale, two main periods can be distinguished, during which meteorological parameters significantly differ. Winter months can be taken as November to February, when meteorological variability is the lowest. These stable conditions are characterised by relatively small diurnal amplitudes for all parameters, with humidity ranging between 65-95% and the daily average being above 90%. Average daily air temperature is below 10°C in this period but values as low as (–9)°C were recorded. Soil temperature is at its lowest in these months with a minimum at the end of February but the temperature never dropped below 0°C during the observation period. Radiation is significantly reduced during winter. Summer months are considered from March-October and all parameters increase in both absolute values and diurnal amplitudes with maximum values occurring in July. June to August are the hottest months on the fen with average daily temperatures reaching nearly 20°C. Increased air temperature affects the temperature of the soil, which correspondingly increases. However the highest soil temperatures were recorded in August (2 months after highest air temperature). The

summer soil temperature ranges between 10-15°C. Humidity is the only parameter that decreases during the summer but despite higher daily fluctuations, the average level still remains above 80%.

## VI - 4. Physical Controls on the Occurrence of the Vertigo geyeri Species

This study ultimately revealed two physical factors controlling the occurrence of the protected mollusc species *Vertigo geyeri* on the fen margin, and these are the surface wetness and proximity of the water table to the surface. Various measurements of soil moisture, surface wetness and soil water content proved the very high saturation of subsurface soil which in turn controlled surface wetness conditions. On average, relative soil water content was between 70-80%, however in places soil moisture remained as high as 88.6%. The surface wetness conditions, which were investigated using small size clay-balls, indicated that the surface conditions were also wet, with 69 % samples measuring more than 80% saturation. Wetness of the ground surface depends on local physical characteristics such as elevation and vegetation (whether open or covered with moss, shaded by plants, etc.). The dampness of the substrate is driven by two interconnected mechanisms – capillary rise and upwards seepage, both of which vary depending on the piezometric pressure gradient in the underlying substrate and the proximity of the phreatic level to the ground surface. Long term observations of the phreatic surface in immediate snail locations revealed that the snail can accept a fluctuation range of 0 - 20 cm below ground level; however the average water table requires to be maintained within approximately 10 cm below the ground surface. Higher fluctuations (up to 30 cm) were observed during the study, although, extended dry periods and decreasing trends in local hydrological regimes resulted in absence of the species at these studied sites. This observation suggests the need for establishing a minimum summer water level, which establishes a criterion for managing the sustainability of the system. Maintaining a minimum summer water table restricts the fluctuation range, sustaining the surface wetness conditions at a sufficiently moist level and also protects the snail from a possible risk of flooding after heavy rainfall events. The minimum summer phreatic level was determined therefore, at a level of - 20 cm below the ground surface in the seepage areas. It is also useful to note that the water levels concerned are not necessarily those of the fen as a whole (or even correlated to them) but locally maintained, as a result of local topography at the fen margin. The results of our study suggest that management of soil water levels within 20 cm of ground level is critical to the local snail habitat and hence the conservation of the fen margin. This is supported by literature as presented in section I – 4 (e.g. Weltzin *et al.*, 2003).

## VI - 5. Hydrological Controls on Sustainability of the Habitat on the Southern Fen Margin

The dependence of Pollardstown fen's diverse ecology on the regional hydrogeological regime is clear; therefore to protect this habitat a quantitative analysis of the flow rates supplying water into the fen was deemed necessary. This study focused on the southern and most elevated of all sites site A, which was deemed potentially threatened by ongoing changes in hydrogeological regime on a regional scale. To maintain the rare and protected habitats at this site, local and regional critical water levels and mitigation threshold levels were determined. The water levels presented are those that will indicate the time for immediate implementation of some mitigation measures (critical water levels) and conditions that indicate approaching critical levels

(mitigation thresholds). The elevation of site A was determined to be 88.55 m OD Poolbeg (at piezometer S10); therefore following earlier findings, the local critical water level is set at 20 cm below the ground surface and therefore the minimum summer phreatic level measured in standpipe S10 should not drop below 88.35 m OD between May and October. To sustain this level, coupled with the seepage rate at the required ~2.5 mm/day, which will counterbalance the water losses due to evapotranspiration process, the hydraulic head in the underlying gravel layer was determined to be at a minimum level of 88.67 m OD, which was measured in piezometer SP31. This is the groundwater control level, which relates to sufficient gradient to drive the upward seepage flow in order to keep the soil surface wet and the phreatic surface at the required level. The local mitigation threshold levels were specified to allow for approximately 2 months preparation for arrival of the critical levels. The local mitigation level in SP31 was chosen at a level of 88.75 m OD, which corresponds with the phreatic level in S10 of 88.45 m OD.

The comparison with regional hydrogeology was carried out with the aim of translating the above local controlling triggers into the regional scale. This study was based on a comparison between borehole data from the Curragh aquifer at the groundwater divide and the fen margin, and revealed very strong hydraulic connectivity between the selected boreholes, which were separated by over 3000 metres. A correlation coefficient was determined as 0.98 and the hydrograph analysis revealed similar patterns in groundwater response. No time lag was distinguished in groundwater response patterns between the two locations which emphasises high transmissivity across the aquifer and also indicates the criticality of the water management practices on the regional scale. Such a synchronous behaviour prevents establishment of a time-related trigger levels away from the fen that could be used as an advance warning system of undesirable pressures propagating towards to the fen margin, causing risk to the fen ecosystem. However, the study was aimed at establishing the minimum summer hydraulic head measured at the top of Curragh (in MB29) that would still provide sufficient gradient to sustain the necessary corresponding hydraulic head in the gravels at the fen margin. On account of the linear correlation between the water levels in the selected boreholes (SP31 vs. MB29), these critical levels were determined from the spatial distribution of the groundwater levels across the aquifer and the critical water level near the groundwater divide in MB29 was established at 91.20 m OD. If the hydraulic head in monitoring borehole MB29 drops below this level during the summer months (May to October), it is highly probable that the hydraulic head at the fen margin would also be below the required 88.67 m OD. Below these levels, the vertical seepage rate at site A will be insufficient, resulting in increased fluctuations of the phreatic level. If the decrease continues, the phreatic level will drop below the acceptable range for the habitat to survive unaltered. The regional mitigation level in monitoring borehole MB29 was established to be 91.44 m OD.

The above regional trigger values were then validated using Dupuit (1863) approximation, which describes the flow in unconfined aquifer. The results corresponded very well with the previous findings established from hydrographs and this suggests that the selected trigger levels are realistic and can be used in future management of the Pollardstown Fen. The analysis led to establishment of the concept of '*critical indicative flow*', expressed in units of flow per unit width [$L^2/T$] and this critical flow was established to be 2.15 $m^2$ per day for MB29-SP31 pair.

The hydrological controls were further investigated by analysis of the behaviour of the groundwater flow between the groundwater divide and the fen margin for three different pairs of piezometers. The analysis showed

that the groundwater flow between MB29 and MB6 correlates well with the flow between MB29 and SP31 (correlation coefficient of 0.99 with significance at 0.01 level). This suggests that MB6 can be deemed representative of the fen conditions, therefore critical water levels and mitigation thresholds were also established for this borehole and are: 88.92 m OD (critical water level) and 89.06 m OD (mitigation threshold level).

## VI - 6. Assessment of Sensitivity of the Fen Margin to Changes in the Regional Hydrogeology

The Wetland Risk Assessment Framework presented by the Convention on Wetlands (1999) placed the changes to the water regime as the first among five primary pressures to the wetland ecosystems. The others are water pollution, physical modification, exploitation of biological products and the introduction of exotic species, but these pressures were not relevant in this study.

The evidence reported in this work suggests that small changes in the regional hydrogeology can pose a very serious threat to the integrity of Pollardstown fen's diverse ecology. This is particularly important at the most elevated, southern fen margin where the topographic settings impose very strict requirements on the hydraulic gradients required for sustainability.

The investigated habitat was shown to have a very narrow range of water level fluctuations, assumed acceptable in view of the most sensitive species of snail. However, changes outside this range have been recorded during the observation period. Lack of historical information puts constraints on the analysis, although the fact that the fen ecosystem survived thousands of years suggests that having such a narrow range of acceptable changes, the conditions for the supply mechanism, flow rates, and hydraulic heads must have been relatively stable historically. Annual variations in hydrological regime are likely to have had a narrow range, allowing the habitat to recover successfully from occasional droughts. Alternatively, the mobility and survival ability of the *Vertigo* species has to be greater than currently understood.

The sensitivity of the fen margin was assessed by comparison of the groundwater flow rates discharging at the fen margin over the period from 1999 until 2005 and the results were interpreted against the developed concept of '*critical indicative flow*', stability of the phreatic water level and the occurrence of the *Vertigo* species of molluscs. Results of this study revealed a progressive decrease in groundwater flow during 1999-2005, which was expected from the observed corresponding decreasing trends in the groundwater levels. With regard to first available records from 1999, this reduction in flow was established at ~10% in 2001, ~20% in 2002-2003 and ~ 30% in 2004 and 2005. The analysis also showed that the established critical flow rates were exceeded by at least 4% throughout May-October 1999-2000 and were just at the required rates in 2001. In 2002 and 2003, the '*critical indicative flows*' were met only partially throughout the summer period, i.e. in first 1-3 months and were below the required rates at the end of the summer. In 2004-2005, the groundwater flow was so low that was not enough to support stable conditions even in the earliest months of the summer. Discussion with *Vertigo* expert Dr. Evelyn Moorkens confirmed that the site conditions were not optimal at times in 2002 and 2003, although these recovered quickly after longer rainfalls. Appearance of other mollusc species of *Vitrea crystellina* and

*Nesovitrea hammonis*, which are indicators of a transition from fen into grassland, within IQABQ1 in July 2003, conforms to the above assessment of flow rates. This provides further support for the presented trigger values. As conditions in 2004 and 2005 became totally unacceptable for the snail it is hard at this stage to definitely say if conditions from 2002-2003 were stressing the *Vertigo geyeri* in the longer term. Nevertheless, drying of a habitat is a gradual process and hence it is likely that stress conditions precede total loss. Dr. Moorkens suggested also that there would have been loses through death of areas that dried out in 2002 and 2003 and that the wet conditions that returned after drying worked because the snail must have come from wetter areas back into quadrats that became suitable again.

**To conclude, the optimum conditions for sustainability of the southern fen margin (Site A) are those that exceed the critical water levels that we have presented. Ensuring that the determined critical values are met throughout months of May-October will secure sufficient groundwater seepage rates at the fen margin, which will balance depletion of water, governed by actual evapotranspiration. These conditions are as follows:**

- **Water level in SP31 : 88.67 m OD**
- **Water level in MB6: 88.92 m OD**
- **Water level in MB29: 91.20 m OD**

As presented in Chapter 1, Section 4, international evidence suggests that unless a wetland's hydrological regimes are managed, then habitat loss occurs. The specification and validation of critical water levels as trigger values to Early Warning Systems (Section 1.6.3) represents a novel contribution to Irish eco-hydrological research.

## VI - 7. Framework for Evaluation of Groundwater Dependent Terrestrial Ecosystems (wetlands) as a Part of Integrated Water Resource Management Plans

To summarise the results of this project and to put them into the broader framework, it must be emphasised that wetland habitats including the groundwater dependent terrestrial ecosystems are very complex systems. This study proved the extreme sensitivity of some components in GWDTE to alterations in the hydrogeological regime which, if not assessed in time, may lead to irreversible damage before a proper understanding of the ecosystem is achieved. The example of this study shows strong variation between a few sites in the same wetland that on the basis of different geology and topography gave rise to different habitats within the overall ecosystem of the fen. This diversity suggests that each GWDTE must be treated independently with respect to its localised geological and topographical features. Nevertheless, the key most sensitive species (such as *Vertigo geyeri* in this case) is likely to drive the assessment of overall risk to the wetland.

Quantitative assessment of the sensitivity of a GWDTE of wetland habitats requires a clear understanding of the links between the hydrology of a given wetland and the regional hydrogeology. Only then can possible pressures and prediction of impacts be clearly defined. On the other hand, the receptor of possible impacts must be also well understood in terms of its dynamics and its long term dynamic scenarios. Results of this study suggest

carrying out both investigations in parallel. The presence of different habitats within a wetland ecosystems need to be recognised as these different habitats may lead to different definition of acceptable pressures.

As the fundamental basis of a fen wetland ecosystem lies in its hydrogeology, the workings of this system with a focus on the delineation of the surface water, meteorological and groundwater inputs, including the supply mechanism, is regarded as a critical investigation. Good understanding of these mechanisms allows the assessment of the importance of a given pressure in causing an environmental risk to the system. The groundwater discharge areas need to be distinguished with reference to the topography of the site, as topography and geology were found to play important roles in the workings of the discharge mechanism.

With regards to the habitats at risk, the following questions should be asked:

- What is the most hydrologically sensitive habitat that is to be protected?
- What are the best, i.e. most sensitive indicators for this habitat?
- Which are the controlling factors for sustainability of this habitat?

The list of priority habitats and species requiring the most protection is provided by EU Habitat Directive. Unfortunately, hydroecological requirements for these habitats are often not well understood.

This project gives an example of a more advanced approach, based on the principle that wetlands are complex, dynamic systems whose existence depends on interrelation of various processes. This approach requires a multidisciplinary study, which has linked various elements of the system including those of zoology, botany, micrometeorology and microhydrology and allowed the linkage of the habitat's needs to local and regional hydrogeology. Such an approach is necessary if sustainability is to be defined and understood. Only then can this understanding feed into regional water resource management plans which will meet requirements imposed by the Water Framework Directive.

## VI - 8. Recommendations

An improved understanding and specification of the hydrological mechanisms underpinning the more sensitive ecosystems in Pollardstown Fen wetlands are the most important outcomes of this research. The variation of hydrological conditions under which a key sensitive species occurred were investigated and are quantitatively defined for the first time. There was no other preceding eco-hydrological study focusing on the microhabitat of the selected indicator *Vertigo geyeri* that could have informed the design of the monitoring methodology and therefore, looking retrospectively, the study design was not perfect. Relatively short periods of observation do not easily facilitate definitions of the normal, long-term range of variation in the so-called favourable state of conservation. However, this is a facet of all wetland studies as previously outlined by works of Lloyd *et al,* (1995), Wheeler *et al.* (1995 a&b), Ertsen *et al.*(1995), Toner & Keddy (1997), Wierda *et al.* (1997), Keddy (2000), Pezeshi, (2001), Porporato *et al.* (2002), Reeves *et al.* (2004), McCartney *et al.* (2004), Rodriguez-Iturbe & Porporato (2004), Niemi & McDonald (2004). It is clear that the studied habitat was investigated during a period of continuously falling water levels, which seem unlikely to represent its normal condition, and biological observations suggest that the studied ecosystem at site A was undergoing transition into a drier habitat. As such,

these conditions were not perfect for defining so called normal conditions. Therefore, this investigation should be treated as a lead to further investigation of the *Vertigo geyeri* habitat and specifically its proximity to phreatic levels in a vertical sense. As the upper zone of site A became unacceptable for the snail in 2004, it is necessary to choose a down gradient location for the groundwater level monitoring with other positive *Vertigo* Quadrat located nearby. The study revealed an upward seepage in piezometers nest SP35 which is located relatively close to *Vertigo* Quadrat VQ6. Long term, regular and frequent monitoring of seepage rates in this location will provide further understanding of the optimal snail habitat. Limited observations of the *Vertigo* negative habitat is a weakness of this research; however hydrological controls of the snail habitat were not known at all at the beginning of this study, and the transport mechanism of the species was not well understood either; therefore defining appropriate *Vertigo* negative locations was very difficult. However, we now have information about locations that represent negatively affected environment, which could be used for such monitoring. Specifically IQABQ1 and corresponding SP31 and S10 should be further monitored to see whether a reverse trend, back into favourable habitat occurs and how long (if at all) does it take to restore a healthy population of the snail. It is important to carry out water level observations on a regular basis and preferably using data loggers that provide continuous records. At the minimum, manual water level monitoring should be carried out on the same days as the malocological observations.

The other issue that is recommended for further investigation is the baseflow from Milltown Feeder and its relationship with groundwater levels noted on both the southern and northern fen margins. Although it was originally believed that the base flow in the Milltown Feeder is largely fed from the south, the analysis presented in Chapter III suggests that when discharge from the southern fen margin decreases, the contribution from the northern margin increases.

Ultimate management of hydrological risk to the GWDTE requires good hydrological prediction in terms of the link between a groundwater body and the fen wetland. Thus, the final recommendation is to extend this work to develop an appropriate probabilistic rainfall-groundwater response method with which to evaluate levels of risk to the wetland under prescribed pressures.

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# ADDENDUM

# BASIC WETLAND CLASSIFICATION CONCEPTS

There are many terms in wetland terminology including mires, moors, peatlands, swamps, bogs, marshes, fens and fen carrs which reflect differences between different types of wetlands in relation to various environmental conditions, including hydrology, soil composition, vegetation structure, fertility as well as topography (Dooge, 1975; Wheeler, 1984; Succow and Lange, 1984). This terminology has a long history dating back to the early 19$^{th}$ century when the first concepts of different wetland types, namely ombrogenous bog and fens were developed by Schimper (1889 in Wheeler & Proctor, 2000). Since then, an increasing realisation of the complexity of wetland ecosystems, together with a variety of scientific disciplines interested in studying wetland resources resulted in complex and often dubious wetland classifications. Nevertheless, there seems to be a distinct division between ecologists and hydrologists in their attempts to classify wetland habitats. While ecologists try to group wetlands, looking at plant communities and their associations, and on that basis conceptualise their hydrological and chemical controls (Wheeler and Proctor, 2000; Økland *et al.*, 2001; Nakamura *et al.*, 2002; Bragazza *et al,.* 2005; Hàjek *et al.*, 2006), hydrologists are more interested in geological, topographical and hydrological settings which give rise to the creation of habitats (Dooge, 1975; Gilman, 1994b; Heathwaite, 1995; Hughes & Heathwaite, 1995; Lloyd & Tellam, 1995; Crushell, 2000). The interaction between groundwater and a surface body of water, a recharge mechanism, and catchment characteristics with their effects on water quality are key factors which provide a basis for distinguishing different wetland types. Increasing pressures on wetland habitats, which may arise from both hydrological and ecological conditions, also give scope for differentiating between hydrological and ecological gradients, and this leads to different definitions of impact and risk, an issue that becomes ever more important. When it comes to impact assessment, hydrology is considered to be a more sensitive gradient than ecology because impacts (*i.e.* hydrological changes) can be measured quickly, while ecological responses usually take longer periods due to long (annual) reproduction cycles. Therefore, changes in ecological patterns reflect states in which ecological damage has already occurred, while hydrological changes are drivers for ecological damage to occur. So far, no consensus has been arrived at between hydrologists and ecologists in a multidisciplinary characterisation of all wetland types; nevertheless, such work is ongoing as the need for them has been clearly defined by E.U. legislation including the Water Framework Directive. *Ecohydrological Guidelines for Lowland Wetland Plant Communities* by Wheeler *et al.* (2004) present early classification documents, which unfortunately covers mainly ombrotrophic bog habitats. Nonetheless, as the document constitutes excellent guidance material for water resource managers and policy makers, further work to extend cover over other wetland habitats is ongoing.

## Hydrological Concepts in Wetland Classification

Hydrologists usually group wetlands using soil substrate, source hydrochemistry and hydromorphological gradients. The first distinguishes *peatlands*, which possess an organic substrate, and *marshes, swamps* and *meadows*, which have a predominantly mineral substrate and do not accumulate peat (Kirkby *et al.*, 1995). The second divides wetlands into those recharged by precipitation (*ombrotrophic)* and by groundwater (*minerotrophic*), and the last uses topography and local hydrology as controlling factors of different wetland habitats. In this classification, fluctuation and flow direction of water constitutes a basis for providing two major types, namely *topogenous* and *soligenous* mires in which water moves in vertical and horizontal directions respectively.

1. Soil substrate gradient

**CRITERION: CHARACTERISTICS OF WETLAND SUBSTRATE (ORGANIC *VS.* MINERAL) DISTINGUISHED WETLAND TYPES:**

- **PEATLANDS (MIRES) – ORGANIC SUBSTRATE**
- **WET HEATH, MARSHES AND MEADOWS – MINERAL SUBSTRATE**

*Peatlands* are composed of deep layers of waterlogged peat and a surface layer of living vegetation. It consists of the dead remains of plants (and to a lesser extent of animals) that have accumulated over thousands of years. Peat accumulates in areas where the rate of plant production exceeds the rate of plant decomposition. Complete plant decomposition is prevented in areas where waterlogging occurs. In Ireland, high rainfall and low temperatures result in low evaporation (Rohan, 1986) which means that waterlogged soils are a common feature, for example in shallow basins. These waterlogged soils are anaerobic or poor in oxygen and it is oxygen that is essential for the growth of the soil micro organisms (bacteria and fungi) that bring about the complete breakdown of plant material (Wild, 1993). As a result of poor microbial activity, dead plants accumulate in waterlogged areas as peat.

Another factor which contributes to the accumulation of peat by preventing the growth of soil micro organisms is the acidity of groundwater. In bogs, the acid nature of groundwater is produced by plants known as bog mosses, or *Sphagnum* species. These plants absorb the cations (positive ions) from rainwater (for example calcium and magnesium) and release hydrogen ions into the water. The more acidic the soil water, the less suitable it becomes for micro organisms to grow, and the plant remains therefore accumulate at a faster rate.

Among mineral based mires, *wet heath* is distinguished by acidophilus vegetation (Hughes & Heathwaite, 1995). *Marshes* and *meadows* commonly occupy hydrologically active floodplains, which provide significant supply of sediment and result in a higher base status (mineral content) than in wet heaths and peatlands.

2. Hydrochemical gradient

**CRITERION: RECHARGE MECHANISM / WATER SOURCE (RAINFALL *VS.* GROUNDWATER) DISTINGUISHED WETLAND TYPES:**

- **BOGS – RAINFALL**
- **FENS – GROUNDWATER**

Gilman (1994b) divides peatlands into two types, namely bogs and fens. This classification is based on wetland ionic supply and is commonly adopted by European (Gilman, 1994b; Hughes & Heathwaite, 1995) and American scientists (Mitsch & Gosselink, 2000; Johnson, 2000). *Bogs* are peat-accumulating wetlands whose biota has become isolated from groundwater flow due to peat accumulation. Due to peat accumulation, plants only receive nutrients and moisture from precipitation and dust, and mostly support acidophilic mosses, particularly *Sphagnum*. Bogs are therefore referred to as *ombrotrophic* (*ombro* – precipitation, *trophic* – nourished). *Fens* refer to peatlands fed by mineral rich groundwater, which are usually supported by marsh like vegetation. Since they are influenced by groundwater, fens are termed *minerotrophic* (*minero* – mineral, *trophic* – nourished). Fens are generally more nutrient rich and alkaline than bogs, and fen species require comparatively high nutrient levels and are dominated by sedges and shrubs.

The similarities and differences between bogs and fens are summarised as below:

1) Fens are alkaline with a pH of 7 to 8
2) Bogs are acid with a pH of 3.2 to 4.2

3) Fens and bogs are waterlogged habitats, i.e. with high static water level
4) Fen peat has a relatively high ash content, circa 10% or more
5) Bog peat has a low ash content, circa 3% or more
6) The average peat depth in a fen is up to 2m
7) Peat depth in a bog varies from 2 to 12m

Some middle classes have also been differentiated in the literature (Hughes & Heathwaite, 1995) indicating systems where water recharge comes from more than one source as in transitional wetlands (*ombro-minerogenic*). For example, Gilvear and McInnes (1994) divided wetlands into 12 classes with regard to their water sources and delivery mechanism (such as flushing), seasonality and output types (*i.e.* into the groundwater or surface water). This resulted in differentiating the following classes, ranging from pure precipitation driven to complex systems recharging from a mixture of groundwater, surface water and rainfall with both surface water and groundwater output:

A. Ombrotrophic (originating from precipitation)
B. Flushed ombrotrophic
C. Rheotrophic (originating from surface water)
D. Flushed rheotrophic
E. Minerotrophic (originating from groundwater)
F. Flushed minerotrophic
G. Seasonally minerotrophic
H. Flushed seasonally minerotrophic
I. Omnitrophic (originating from all different sources of water)
J. Flushed omnitrophic
K. Seasonally omnitrophic
L. Flushed seasonally omnitrophic

Graphical representation of all classes is given in Figure A.

Such a classification concept emphasises the complexity of existing wetlands with respect to their input and output. It is also likely that few of the above classes can be found within one wetland system. The advantage of this system is that it allows the wetland in question to be classified into a relatively narrow group which allows for quick selection of potential pressures which are often related to water input characteristics.

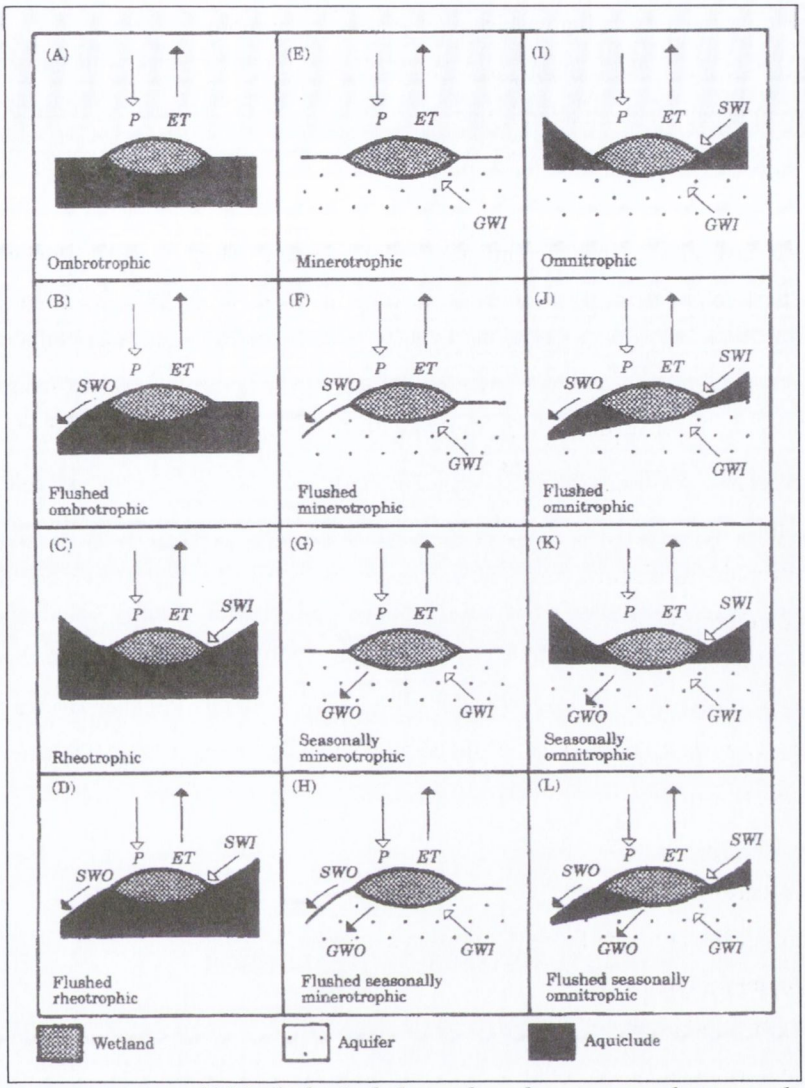


*Figure A Schematic representation of 12 hydrological classes based on water recharge mechanism proposed by Gilvear and McInnes (1994).*

## 3. Hydromorphological classification

**CRITERION: LOCAL TOPOGRAPHY AND HYDROLOGY (VERTICAL *VS.* HORIZONTAL WATER FLOW SYSTEM)**
**DISTINGUISHED WETLAND TYPES:**

- **TOPOGENOUS – VERTICAL FLOW**
- **SOLIGENOUS – HORIZONTAL FLOW**

Hydromorphology describes the interrelation between topography and local hydrology, and is used as another hydrological criterion to group peatlands (mires). Hughes and Heathwaite (1995) distinguish six classes of mire within this classification, including: soligenous mires, basin mires, valley mires, floodplain mires, raised mires and blanket mires with the last two representing strict ombrotrophic habitats. This classification was recently advanced and adapted to Irish conditions by Crushell (2000), who under the auspices of the Irish Peat Conservation Council undertook a national Irish fen inventory and proposed the following classification: *topogenous fens* and *soligenous fens.* This will be discussed in a further paragraph regarding Irish wetland habitats.

## Ecological Concepts in Wetland Classification

Up until 2000, when Wheeler and Proctor reviewed worldwide wetland studies with the aim of establishing a firm classification and definition of different wetland habitats, wetland terminology describing various habitat types was often misused and misinterpreted as having different meanings in various parts of the world (Wheeler & Proctor, 2000; Økland *et al.*, 2001; Hájek *et al.*, 2006) and was often very confusing. As an outcome of their work, Wheeler and Proctor proposed a classification using various ecological gradients and assessed their global significance. The most noteworthy ecological gradients are believed to be the mineral-soil water limit (ombrotrophic *vs.* minerotrophic; equivalent to the hydrochemical classification described above), soil water pH gradient (base richness) and fertility gradient (availability of growth limiting nutrients, mainly N and P). Other local gradients such as the water level gradient, the mire expanse - mire margin gradient, the deep peat mineral soil gradients, *etc.* have also been discussed in the literature (Wheeler and Proctor, 2000; Økland *et al.*, 2001; Nakamura *et al.*, 2002; Bragazza *et al.*, 2005; Hajek *et al.*, 2006) but, having little significance on a global scale, these are often omitted. Although it is still an ongoing debate which of the above gradients discriminates the most between wetland habitats, studies from UK (Wheeler and Proctor, 2000), Scandinavia (Økland *et al.*, 2001), Japan (Nakamura *et al.*, 2002) and Italy (Bragazza *et al.*, 2005) suggest somehow that the soil water pH gradient (base richness gradient) is the best indicator of the habitat boundary. Other studies also emphasise the importance of fertility gradients (Hájek *et al.*, 2006) and the depth to the water table (Økland *et al.*, 2001). These are described below.

### 1. Base richness gradient

**CRITERION: CHEMICAL CHARACTERISTSICS OF THE SUBSOIL**
**DISTINGUISHED WETLAND TYPES:**

- **BOGS - pH < 5.0, low $Ca^{2+}$, and high $Cl^-$ and $SO_4^{2-}$**
- **FENS - pH > 6.0, high $Ca^{2+}$ and high $HCO_3^-$**

According to Wheeler and Proctor (2000) the base richness gradient (based on the ionic composition of the water in wetland subsoil) is the most prominent of all ecological gradients. Bogs and fen habitats are distinguished based on it with bogs having a pH < 5.0, low $Ca^{2+}$, and $Cl^-$ and $SO_4^{2-}$ as the main inorganic anions and fens having a high pH > 6.0, high $Ca^{2+}$ and high $HCO_3^-$. The acidity of wetlands depends on the balance between metallic cations and strong acid anions, which depends on the composition of water sources and the capacity to buffer acidity produced by plants or imported in acid rain. Recharging water influences the soil composition, hence the humification process and peat production. Water chemistry is modified during groundwater flow depending on the mineral composition of parent material. The chemical status of groundwater reflects the properties of the catchment, through which it flows absorbing the vulnerable solutes. According to Haslam (2003) the highest number of nutrients is gathered in silt catchments. Gravel and sand washed free of silt contain the lowest levels of nutrients. Silty gravel from high nutrient catchments may nevertheless have a higher nutrient status than silt from a low nutrient one. Of all available minerals, calcium has a special importance in wetlands and in the case of fens - this has the power to determine its type.

Early works by Du Rietz (1949, 1954) cited by Wheeler and Proctor in their discussion of the mire classification (2000), distinguishes three distinct mire classes, namely *bogs*, *poor fen* and *rich fens*. *Poor fens* are very similar to bogs. They are recharged by low nutrient water with possibly rainwater recharge being an important element in their overall water budget. Poor fens occur in areas where the underlying rock is acidic (granite, shale or

sandstone) or are seen in association with blanket bogs. The pH of poor fens is slightly higher than in bogs, but both habitats have some species in common (*Sphagnum* moss). *Rich fens* are characterised by having a high nutrient status with a high calcium concentration. Haslam reports (Haslam, 2003) that excessive concentrations of calcium may, however, reduce the availability of many other nutrients accessible to the plants from soil, which creates a separate habitat equivalent to poor fen or bog with a similar level of nutrients apart from calcium. In soil made nutrient poor by high calcium, nutrients can be made available to plants by mineralisation (in dried precipitated form). Rich fens appear in areas where groundwater is influenced by underlying alkaline rock, such as limestone or calcareous drift or sand.

Johnson (2000), who extensively worked on fens in Colorado, USA introduced a more complex subdivision within fens splitting them into *poor, moderate, extreme* and *extremely rich* classes with typically poor fens having a pH of 4.0-5.5 and calcium concentration of 2-7 mg/l. The pH of moderate fens is 5.5-7.1 with calcium concentration ranging between 10-50 mg/l, rich fens are pH 6.0-7.5 and calcium between 25-80 mg/l, while an extremely rich fen pH is 6.5-8.5 and calcium greater than 30 mg/l (Table A). Czech and Slovak scientists (Hájek *et al.*, 2006) suggest an additional class of *Calcareous (tufa forming) fens*. The suggested boundary between extremely rich and calcareous fens is the point at which calcium carbonate starts to precipitate and forms a persisting consolidated tufa or unconsolidated marl. The range of different wetland types in this classification is not exhaustive, which can be proven by the Pollardstown Fen example, which suggests that the fen does not fall within one group but can be classified as both extremely rich and calcareous (tufa forming) fen.

**Table A Water chemistry values for four fen classes. Source: Johnson, 2000**

| Reference | Study Area | pH | EC µS | Ca mg/l | Mg mg/l | Na mg/l | K mg/l |
|---|---|---|---|---|---|---|---|
| **POOR FENS** | | | | | | | |
| Zoltai & Johnson(1987) | West-Central Canada | 4.8 | 53 | 2.9 | 3.9 | 3.9 | 1.3 |
| Zoltai & Johnson (1985) | Alberta | 4.7 | 45 | 2 | 0.8 | 4 | 0.9 |
| Comeau & Ballamy (1986) | Eastern Canada | 4.3 | - | 7 | 2 | 4 | 0.4 |
| Karlin & Bliss (1984) | Alberta | 3.5-6.1 | - | 2 | 1-3 | 0 | - |
| Glaser et al. (1981) | Minnesota | 4.0-4.6 | 25-50 | 2.0-2.1 | - | 0 | - |
| Vitt et al. (1975) | Alberta | 5.2 | - | 2.3 | 0.4 | 3.0 | - |
| Bellamy (1968) | Western Europe | 4.5 | - | 20 | 5 | 7 | 2 |
| Sjörs (1963) | Ontario | 4.1-5.4 | 16-22 | 2 | 0.5 | 0.3 | 0.1 |
| Sjörs (1948) | Sweden | 4.2 | - | 6 | 2 | 2 | 0.4 |
| **MODERATE AND MODERATE - RICH FENS** | | | | | | | |
| Chee & Vitt (1989) | Alberta | 5.3-7.1 | 18-240 | 19-22 | 4-5 | 4-7 | 16-1.7 |
| Zoltai & Johnson(1987) | West-Central Canada | 5.8 | 212 | 25.0 | 10.2 | 4.7 | 1.4 |
| Zoltai & Johnson (1985) | Alberta | 6.0 | 249 | 28 | 11 | 5.1 | 1.8 |
| Comeau & Ballamy (1986) | Eastern Canada | 5.5 | - | 15 | 6 | 7 | 1 |
| Karlin & Bliss (1984) | Alberta | 4.6-7.1 | - | 4-51 | 2-12 | - | - |
| Yefimov & Yefimov (1973) | Russia | 6.1 | - | 18 | 8 | 1 | 0.3 |
| Persson (1961) | Sweden | 5.4-7.0 | - | 40-50 | 30 | 85-93 | 10 |
| Sjörs (1948) | Sweden | 6.0 | - | 68 | 12 | 2 | 0.4 |
| **RICH FENS** | | | | | | | |
| Glaser et al/(1981) | Minnesota | 5.1-7.0 | 23-82 | 3-56 | - | - | - |
| Bellamy (1968) | Western Europe | 6.6 | - | 183 | 19 | 11 | 2 |
| Sjörs (1948) | Ontario | 5.8-7.4 | 48 | 9 | 2 | 1 | 0.3 |
| **EXTREMELY RICH FENS** | | | | | | | |
| Glaser et al/(1981) | Minnesota | 6.6-7.5 | 16-30 | - | - | - | - |
| Zoltai & Johnson(1987) | West-Central Canada | 6.5 | 374 | 54 | 14 | 6.54 | 0.1 |
| Karlin & Bliss (1984) | Alberta | 7.2-8.2 | - | 31-120 | 10-53 | - | - |
| Slack et al. (1980) | Alberta | 6.8-7.9 | 140-456 | 18-37 | 4-18 | - | 1.4-8.0 |
| Sjörs (1961) | Ontario | 7.9 | 207 | 32 | 7 | 5 | 0.6 |
| | | | | | | | |
| **POLLARDSTOWN FEN** | | **6.31-7.65** | **220-829** | **65-114** | **39-69** | **-** | **0-0.93** |

2. Fertility gradient

**CRITERION: AVAILIBILITY OF NUTRIENTS: NITROGEN, PHOSPHORUS AND POTASSIUM DISTINGUISHED WETLAND TYPES:**

- **OLIGOTROPHIC – LOW AVAILIBILITY (HIGHLY ACIDIC BOGS)**
- **MESOTROPHIC – MEDIUM AVAILIBILITY (FENS)**
- **EUTROPHIC – HIGH AVAILIBILITY (FENS)**

Fertility is understood as a means to support plant growth and is controlled by the availability of nutrients such as N, P and K. The relationship between soil fertility and base richness status is controversial. Studies by Wheeler (*et al.,* 1992) and Wheeler and Shaw (1995a) demonstrated that the fertility gradient is independent from the base richness gradient but this contradicts Dutch studies (Grootjans *et al.*, 1996) where distribution of natural soil fertility, soil types and macro ecological patterns were proven to be directly related to the soil base status. The acidic peat characteristics of bogs are the least fertile substrata. Nevertheless, high pH values do not always coincide with greater nutrient availability due to immobilisation of phosphorus by precipitation with calcite, of which high concentrations are typical for extremely rich fens (Boyer & Wheeler, 1989; Haslam, 2003). Based on the fertility gradient, wetlands are classified into the three following categories: *oligotrophic, mesotrophic* and *eutrophic*. Only highly acidic wetlands are defined as the oligotrophic wetlands while all fens are treated as either mesotrophic or eutrophic. More information on the trophic status of wetlands can be found in Moore (1984).

## Wetland Classification - Irish Perspective

Wetlands in Ireland occur in a wide range of environmental conditions and they do not exactly fit into any of the earlier classifications. However, typology has been adopted as the main element differentiating three broad classes of Irish wetlands, namely *bogs*, *fens* and *turloughs*. In this classification, bogs refer to ombrothrophic wetlands for which precipitation is the major or the only source of water, and fens are groundwater fed wetland and turloughs are (uniquely to Ireland) seasonally flooded depressions found predominantly in the karst areas of the west of Ireland. There are also lagg zones, which naturally surround raised bogs and are currently very rare due to increased drainage and turf cutting practices.

### 1. Irish Bogs

Two types of bogs can be found in Ireland; *blanket bogs* and *raised bogs*. In blanket bogs, peat develops due to a continuous supply of water from rainfall, maintaining waterlogged conditions on the ground although the presence of blanket bogs is usually dependent on basins and topographic features. Water logging in these areas is secured by the so called iron pan, which is an impermeable layer formed beneath the surface due to deposition of minerals such iron. This deposition occurred some 4000 years ago and is associated with climate change during which Ireland became wetter and heavy rainfalls persisted, causing the washing out and leaching of minerals from the surface layer into the deeper soil profile (Foss *et. al,* 2001). As a result of being recharged by precipitation only, blanket bogs are acidic and their pH lies between 3.5 and 4.2. In Ireland, the distribution of blanket bogs is confined to an area west of the 1,200 mm isohyet, and all upland areas where precipitation is high and evaporation is low. There are two types of blanket bog in Ireland; *Atlantic blanket bogs* and *mountain blanket bogs*. The first are found in low lying coastal plains and valleys in mountainous areas of western counties, below 200 m OD. They are particularly well developed in counties Donegal, Mayo, Galway, Kerry, Clare and Sligo. Mountain blanket bogs occur on relatively flat terrain in the higher Irish mountains above 200 m OD, and are more widely distributed than the Atlantic blanket bog.

Raised bogs are dome shaped bogs that have developed in former lake basins or topographic depressions. As their nutrient supply is obtained mainly from rainfall which creates acidic conditions, raised bogs support mainly acidophilic habitats. They are most abundant in the lowlands of central and mid western counties (Fossit, 2000).

### 2. Turloughs

Turloughs are karst wetland ecosystems that are unique to Ireland (Sheehy Skeffington *et al.,* 2006). They mainly occur in the West of Ireland and can be defined as depressions in karst areas, seasonally inundated mostly by groundwater and supporting vegetation and soil characteristic of wetlands. They usually flood through underground passages and springs in autumn (when rainfall exceeds evapotranspiration) form a lake for several months in winter, and empty underground through swallow holes in springtime. There may also be sporadic rises at other times in response to high rainfall. Some turlough basins retain standing water in channels, pools or small lakes when flooding subsides. Although they harbour aquatic fauna, they are not true lakes, since most drain in the summer, revealing fen or grassland vegetation which is frequently grazed by livestock. They are priority habitats in the E.U. Habitats Directive and support a variety of wet grassland and fen type vegetation.

## 3. Irish Fens

As already outlined, fens differ from bogs, with their water supply mechanism controlled mainly by groundwater input. Crushell (2000), in his Irish fen inventory, distinguishes six sub types of fen wetlands, which he grouped into two broad categories, namely *topogenous* and *soligenous*.

***Topogenous fens*** form within basins in the landscape, where water fluctuations are vertical. Water accumulates on account of the topography of the landscape. Three sub types of topogenous fens are:

a) Open water transition fens
b) Floodplain fens
c) Basin fens

**a) Open Water Transition Fens** (e.g. Lough Corrib, Co. Galway) are the most common class of fens in Ireland. They form around a body of open water such as the edges of lakes. They usually cover a relatively small area when compared to an open body of water. The fen is usually present on the land-ward side of the emergent reed vegetation which occurs in deeper water. The lake shore has to be very gently sloping for the fen to develop, and the underlying sediment must be permanently waterlogged. This type of fen usually occurs in limestone regions which controls the nutrient status and acidity of both water and substrate. Nutrient poor lakes rarely develop this type of fen.

**b) Floodplain Fens** (e.g. along the river Shannon) develop on a waterlogged flood plain adjacent to a river or stream. They may be often flooded by the river. Water collecting in low laying areas and depressions within a floodplain is necessary for the establishment of fen vegetation.

**c) Basin Fens** (found in terrains with steep slopes, in basins of deep lakes) develop in a waterlogged basin with little through flow of water and have a constantly high water table. They usually develop in lakes and kettle holes. The proportion of open water in this type of fen is rather small. Often, floating rafts of vegetation are present. During the development of a fen, floating vegetation sinks, forming layers of peat. Between successive sheets of vegetation, semi liquid lenses are formed. If conditions are appropriate, basin fens often transform further into raised bogs over time if conditions are favourable. The slow development of a fen is controlled by the low nutrient status of a lake of origin.

***Soligenous fens*** form in sloping areas, with a continuous supply of flowing water. Water predominantly moves in horizontal direction in this type of fen. There are three types of soligenous fens:

d) Valley fens
e) Flush fens
f) Calcareous spring fens

**d) Valley Fens** (e.g. Pollardstown Fen) occur in shallow valleys with the main movement of water along the x-axis. No pronounced slope is obvious (Crushell, 2000). The source of water is from springs and seepages

occurring in the sides of the valley. The valley floor is usually flat or gently sloping, which prevents the retention of a high water table. Constant inflow of alkaline water stops acidic vegetation from establishing itself over the fen peat. In Ireland, these types of fen are usually seen in the eastern part of the country. Lower rainfall and inflow of alkaline groundwater are major factors allowing for the development of valley fens in this part of the country.

**e) Flush**[15] **Fens** occur where the sloping terrain provides a continuous supply of flowing water. They may arise in all different topologies, such as upland and lowland, usually as small features within other peatland types, particularity blanket bogs. They can also occur within raised bogs if water movement close to the surface is present. Localised flow of water brings more minerals, which allow fen vegetation to develop within an ombrotrophic wetland system. The vegetation is easy to discern by its vivid green colours and patterns that are distinct from those of typical acidic bogs. The diversity of vegetation and plant species in flush fens depends on the water chemistry passing through them.

**f) Calcareous Spring Fens** occur beneath permanent springs and seepages, usually at the margin of a larger fen system that is fed by groundwater from a calcium rich aquifer. Springs are present at the interface between permeable and impermeable strata. Where water is highly saturated with calcium, calcite (calcium carbonate) may deposit on spring banks, around plant stems where the water oozes out of the ground. This is known as *tufa spring* or *petrifying spring.*

From a hydrological viewpoint, topogenous fens are mainly rainwater fed and soligenous fen are based on groundwater input. A graphical presentation of topographical settings of the above fen types is offered in Figure B.

[15] Gathered run-off

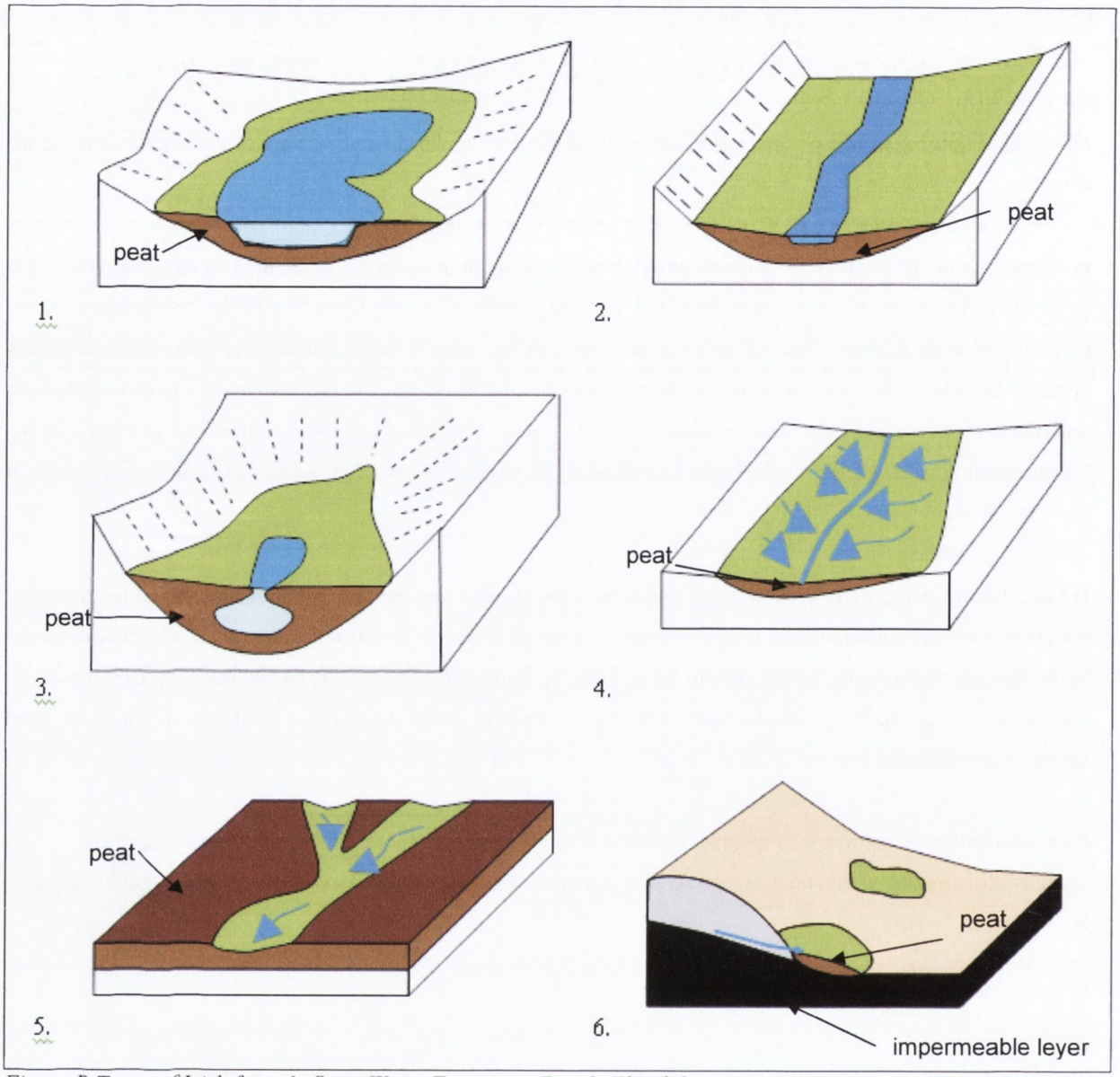


*Figure B Types of Irish fens: 1. Open Water Transition Fen, 2. Floodplain Fen, 3. Basin Fen, 4. Valley Fen, 5. Flush Fen, 6. Calcareous Fen. Modified after Crushell, 2000*

# IRISH FEN HABITATS: GENESIS AND CHARACTERISATION

Fens begun forming in Ireland about 10,000 years ago (Foss *et al.*, 2001) and are very often an early stage in the formation of raised bogs which develop on top of approx. 2.2 metres depth of fen peat.

The formation of fens occurred in lake basins or in waterlogged depressions, which are fed mainly by groundwater (*i.e.* springs) and occasionally by surface water rich in minerals, including calcium. The plants that grew under these mineral rich basic conditions included floating pondweed on and in the deeper water, water lilies rooted in shallower bays and reeds along the lake margins. As the annual cycle of growth and decay continued, vegetation gradually colonised the open water and eventually filled the lakes. The dead plants only partially decay in the waterlogged, anaerobic environment, and these fill and accumulate in layers in the lakebeds where they rest on silt, clay or shell marl (a white calcareous mud, found in abundance in shells of former freshwater snails). This partially decayed material formed the beginning of a fen peat layer, which is also called reed swamp peat.

As the lakes began to fill with this newly formed peat, mixed vegetation composed mainly of mosses (*non-Sphagnum* species), sedges, grasses and rushes, grew over the reed swamp layer. It sometimes included reeds and occasionally some birch trees. As this vegetation partially decayed it formed woody fen peat on top of the reed swamp peat. By that time, the lakes were completely filled in and the fen peatland (composed of reed swamp and woody fen peat) formed.

**Table B Characteristics of fens, after Otte (2003)**

| *CHARACTERISTICS OF FENS* | |
|---|---|
| pH (e.g a growing Fen such as Pollardstown Fen) | Approx. 7.1 |
| pH (when part of mature raised bog, i.e. flush fen) | 6.0 - 6.5 |
| Water content (undrained) | Approx. 95% |
| Solids content (undrained) | Approx. 5% |
| Organic content (Anhydrous) | Approx. 96% |
| Inorganic content (Anhydrous) | Approx. 4% |
| Depth (average) | 2.2 m |
| Water source | Groundwaters or surface waters.<br>(Alkaline, rich in minerals including calcium) |

Fens, due to their high mineral and nutrient content, are able to support much more diverse plant and animal communities than bogs. These systems are often covered by grasses, sedges, rushes, and wildflowers and host significant number of animal species, many of which are endangered or uniquely characteristic of fen habitats.

## Fen Flora and Fauna

Habitat conditions in Ireland are not different from typical temperate region wetlands. A very good description of a fen's vegetation with a distinction between nutrient poor and nutrient rich habitats, as well as an extensive listing of fen animal species can be found in O'Connell (1987), Crushell (2000), Fossit (2000) and Otte (2003).

### ***Flora***

Fen vegetation is much more diverse than in any other wetland system, where up to two hundred different plants can be found on any one site. Usually fens consist of a mosaic of different habitats, which include open water, with many aquatic plants fringed by dense stands of tall reeds and rushes, and drier scrub woodland known as 'carr' (Crushell, 2000). Fen vegetation consists of many layers of plants, but in general it is dominated by sedges (*Carex* species) and rushes (*Juncus* species). Among the *Carex* species, the most common are: *C. nigra* (Common Sedge), *C. aquatilis* (Water Sedge), *C. curta* (White Sedge), *C. diandra* (Lesser Tussock Sedge). Of the rushes, the most important species are: *Juncus articulatus* (Joined Rush), *J. effusus* (Soft Rush), *J.subnodulosus* (Blunt Flowered Rush), *Schoenus nigricans* (Black Bog Rush). The surface of fens is covered with a well-developed, thick carpet of bryophytes, which are often seen with a white lime coat from the mineral rich water. Typical bog species of *Sphagnum* moss are seen in fens; however, other mosses like *Campillium stellatum*, *Drepanocladus revolvens* and *Scorpidium scorpioides* are more indicative for alkaline conditions. Besides the mosses, sedges and rushes, plants dominating the surface of the fen include grasses *Molinia careulea, Phragmites australis* and other cyperaceous species *Cladium mariscus*. The latter is especially indicative of base rich conditions and is often found in rich fens. The wooded areas of fen support mainly willow, alder and birch trees, between which mosses and ferns are usually found.

Floristic characteristics of fens are highly dependent on their nutrient status. Similarity to the above classification is based on the chemical composition of water passing through the system, rich and poor fens having different vegetation composition.

#### ❖ ***Rich Fens***

The vegetation of rich fens is usually light brown, which is due to the presence of dead parts of small sedges characteristic of the *Caricion davallianae*. *Schoenus nigricans* known as Black Bog Rush and small sedges such as *Carex viridula, C. nigra, C. dioica* and *C. panacea* are dominant species in rich fens. Black Bog Rush occurs as tussocks, which are relatively dry and can support acidic species such as heather (*Calluna vulgaris, Erica tetralix*), Tormentil (*Potentilla erecta*), Bog Myrtle (*Myrica gale*) and Bog Asphodel (*Narthecium ossifragum*).

Other species that are specifically characteristic of rich fens include Blunt Flowered Rush *Juncus subnodulosus*, Purple Moor Grass (*Molinia caerulea*), Marsh Pennywort (*Hydrocotyle vulgaris*), Lesser Spearwort (*Ranunculus flammula*), Water Mint (*Mentha aquatica*), Common Marsh Bedstraw (*Galium palustre*), Grass of Parnassus (*Parnassia palustris*) and Devil's Bit Scabious (*Succisa pratensis*). Some plants belonging to the *Phragmito-Magnocaricetea* class also occur in rich fens and these are: the Common Reed (*Phragmites australis*), Saw Sedge (*Cladium mariscus*), Bulrush (*Typha latifolia*) and the Greater Tussock- Sedge (*Carex paniculata*).

Insectivorous plants such as Butterwort (*Pinguicula vulgaris*) and Bladderwort (*Utricularia sp.*) are also found on rich fens. Orchids, which are rare in Ireland, are also found in this habitat. These include the Marsh Orchid (*Dactylorhiza incarnate*), Marsh Helleborine (*Epipactis palustris*), the Fly Orchid (*Ophris insectifera*) and the Fragrant Orchid (*Gymnadenia conopsea*).

Mosses that occur in rich fens belong to so called brown mosses species and these are the lime loving species *Campillium stellatum*, *Drepanocladus revolvens* and *Scorpidium scorpioides*. As these are characteristic of flushes and seepages, they are often coated with precipitated calcite.

Among the aquatic species that flourish in the slow moving or still waters of the fens are Duckweed (*Lemna minor*), Pondweed (*Potamogeton coloratus*), Stonewort (*Chara sp.*) and Bogbean (*Menyanthes trifoliata*).

In the wooded areas of rich fens, the following trees can be found: Willow (*Salix cincrea*), Alder (*Alnus glutinosa*) and Birch (*Betula pubescens*). Inside forests, many mosses and ferns can be found on damp and shaded ground.

Some areas of fens can be quaking and these are dominated by transitional vegetation between rich and poor fens. This vegetation belongs to the order *Scheuchzerietalia palustris* and includes Lesser Tussock Sedge (*Carex diandra*) and Slender Sedge (*C. lasiocarpa*). Other important sedge species include *Carex viridula, C. limosa, C. rostrata, C.pulicaris* and *C. demissa.* Also found here are many marsh and wet meadow species such as Marsh Cinquefoil (*Potentilla palustris*), Marsh Lousewort (*Pedicularis palustris*), Meadowsweet (*Filipendula ulmaria*), Fen Thistle (*Cirsium dissectum*), Marsh Bedstraw (*Galium verum*), Wild Valerian (*Valeriana officinalis*), Lesser Spearwort (*Ranunculus flammula*), Lady's Smock (*Cardamine pratensis*) and Red Rattle (*Pedicularis sylvatica*).

Calcareous spring vegetation belongs to the *Cratoneurion* alliance and consists mainly of mosses. Other species found here are: Yellow Saxifrage (*Saxifraga aizoides*), Flea Sedge (*Carex pulicaris*), Black Sedge (*Carex nigra*), Dioecious Sedge (*Carex dioica*) and Glaucous Sedge (*Carex flacca*).

❖ ***Poor Fens***

Poor fens and flushes are fed by base poor, acidic water and have a predominantly acidic substrate. This supports small sedges such as the *Caricetalia nigrae* family with the following species: Bottle Sedge (*Carex rostrata*), Black Sedge (*Carex nigra*), White Sedge (*Carex curta*), Slender Sedge (*Carex lasiocarpa*) and Star Sedge (*Carex echinata*). With rushes, we can distinguish the Soft Rush (*Juncus effuse*), the Jointed Rush (*Juncus articulatus*) and the Sharp Flowered Rush (*Juncus acutiflorus*). Other plants found in this habitat are Velvet Bent (*Agrostis canina*), Common Cottongrass (*Eriophorum angustifolium*), Marsh Violet (*Viola palustris*), Heath Bedstraw (*Galium saxatile*), Tormentil (*Potentilla erecta*), Marsh Cinquefoil (*Potentilla palustris*), Bogbean (*Menyanthes trifoliate*) and Purple Moorgrass (*Molinia caerulea*). Shrubs such as Bog Myrtle (*Myrica gale*) and Cross Leaved Heath (*Erica tetralix*) are occasional and are indicative of flowing water. Among bryophytes, mainly *Sphagnum* species occur including *Sphagnum auriculatum, Sphagnum recurvum, Sphagnum palustre* and also *Pollutrichum commune.*

***Fauna***

The great diversity of fen vegetation, its high nutrient content and specific microclimate due to its proximity to open water makes fens an ideal habitat for many invertebrate species (Crushell, 2000). The abundance of food enables many different dragonflies, horse flies, midges, spiders, wasps, very rare moth flies and water beetles to be commonly seen on fens. Old stems of vegetation and tree trunks are perfect sites for insects to shelter over the winter period, when many species undergo hibernation. Water in pools between tussocks and in depressions is often used by larvae of flies (including dragonflies) and beetles. Flies use also moss in which to lay their eggs.

Butterflies and moths are very abundant on fens during the summer. Crushell (2000) reported that nearly 50% of the national suite of common butterflies was found during a brief investigation of Fenor bog in 2000. Among many different species, two very rare species are worth mentioning. These are the Wood White (*Leptidea sinapis*) and the Brimstone (*Gonpteryx rhamni*). Neither of these species breed on fens. One species listed in Annex II of the E.U. Habitats Directive is known to breed on Irish fens and this is the Marsh Fritillary (*Euphydryas aurinia*).

In total, hundreds of different species of insects can be found within a single site Crushell (2000).

The high calcium content of fens ensures that they are suitable habitats for molluscs, which require calcium to secrete their shells. Numerous studies (Holyoak, 2003; Killeen, 2003; Moorkens in WYG, 2004) show the presence of several rare species such as *Vertigo geyeri, Vertigo moulinsiana* and *Vertigo angustior,* which occur only in rare habitats listed in Annex II of the E.U. Habitat Directive, on Irish fens.

The abundance of invertebrates provides a source of food for a great variety of birds. High levels of vegetation, close proximity to water and inaccessible habitats create exceptionally good conditions for nesting. The Little Grebe (*Tachybaptus ruficollis*), Great Crested Grebe (*Podiceps cristatus*), Mute Swan (*Cygnus olor*), Teal (*Anas crecca*), Mallard (*Annas pltyrhynchos*), Water Rail (*Rallus aquaticus*), Moorhen (*Gallinula chloropus*) and Coot (*Fulica atra*) all are known to breed in Saw Sedge and reed beds, where they build their nests safely above the water level. The Sedge Warbler (*Acrocephalus schoenobaenus*) and the Reed Bunting (*Emberiza schoeniclus*) also breed on fens; however, their nests are built high up in the reeds. Wet marshy ground is perfect for the breeding of Lapwing (*Vanellus vanellus*) and Snipe (*Gallinago gallinago*). Other species on the fen include the Wren (*Troglodytes troglodytes*), Dunnock (*Prunella modularis*), Robin (*Erithacus philomelos*), Willow Warbler (*Phylloscopus trochilus*), Chiffchaff (*Phylloscopus collybita*), Cuckoo (*Cuculus canorus*), Wheatear (*Oenanthe oenanthe*) and many others. The Grey Heron (*Ardea cinerea*) is also a frequent visitor to the fens.

The alkaline waters of fens are good habitats for fish, especially species of stickleback: the Three Spined Stickleback (*Gasteroseteus aculeatus*) and Ten spined Stickleback (*Gasteroseteus punguilius*), both feed on invertebrates present on the fen. Fish constitute an important part of a food chain as birds (Grey Heron) and some mammals (Otter) feed on them.

Among amphibians, two species shall be distinguished and these are the Common Frog (*Rana temporaria*) and Common Newt (*Triturus vulgaris).* Newts are fairly rare species in Ireland and occur in fens. They live on dry land; however, they need waterlogged conditions for breeding, as they lay eggs on vegetation submerged in

water. They feed on earthworms, slugs and insects that again occur commonly on fens. They also hibernate in winter.

Mammals are not very common on fens; however foxes *(Vulpes vulpes)*, rabbits (*Oryctolagus cuniculus*), mink (*Mustela vison*) and otter (*Lutra lutra*) are seen within fen sites.