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# The Hydrogeology and Restoration of a Raised Bog

Volume I of II
Text, Figures, Tables

By

Shane Regan

Department of Civil, Structural & Environmental Engineering,
University of Dublin,
Trinity College

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An tOllamh Veronica Campbell
BSc (Edin) PhD (Lond), FTCD
Déan an Léinn Iarchéime,

Oifig na nIarchéimithe,
Foirgneamh na nEalaíon,
Coláiste na Trionóide,
Baile Átha Cliath 2, Éire

Prof Veronica Campbell
BSc (Edin) PhD (Lond), FTCD
Dean of Graduate Studies,

Graduate Studies Office,
Arts Building,
Trinity College,
Dublin 2, Ireland

T +353 (0)1 896 1166
F +353 (0)1 671 2821

gradinfo@tcd.ie
www.tcd.ie/Graduate_Studies

## Abstract

The occurrence of ecological communities of conservational value on the surface of raised bog wetlands requires that specific hydrological conditions are maintained. The management of raised bogs, as active peat-forming ecosystems, therefore requires an understanding of the relationships between regional hydrology and the hydroecological processes operating within the wetland system. Raised bogs are often considered to be isolated hydrological systems, separated from regional groundwater flows in underlying groundwater bodies. However, a wetland system does not need to be an outlet zone for groundwater discharge to be groundwater dependent. Research on Clara Bog, Ireland, indicates a more complicated relationship between the bog and regional groundwater system. This interconnection has significant implications for ecological engineering/ restoration design.

Peripheral drainage of Clara Bog has resulted in dramatic morphological changes, with areas of the bog getting wetter, while the bog on a whole has become drier since the early 1990s. Differential peat consolidation has fragmented what was one high bog topographic catchment area into four distinct catchment areas, with runoff reducing by c.40% from the original main catchment area. Catchment alteration has resulted in hydroecological changes, with a c. 26% decrease of active raised bog areas supporting growth of *Sphagnum* moss species. Water is no longer retained in the system as it once was and water balance computations coupled with ground level subsidence surveys over a 20 year period show that water is being released from storage in the peat bog body.

In undisturbed bog systems the recharge rate of water seeping through the bog body to the regional groundwater table is in the order of 40 mm/ year. Water balance calculations show the leakage rate is now between 70 and 140 mm/ year. The Clara bog system is in an unsteady state of flux, with large tracts of the bog following linear rates of ground level subsidence; in the order of 0.05 mm/ year. A reduction in pore water pressure, due to drainage of the regional groundwater table, has induced excess water loss from the peat substrate, resulting in catchment fragmentation and hydroecological modification of Clara Bog. The areas of water loss from peat substrate are associated with areas where lacustrine clay, a natural hydraulic barrier, is absent and till subsoil, which is a groundwater body supporting the regional groundwater table, lies directly beneath peat substrate, thereby creating a hydraulic connection. The linkage becomes apparent when the piezometric level in the groundwater body drops, due to drainage, resulting in a decreased piezometric water level in the bog body.

Numerical finite element modelling of the Clara bog regional groundwater system demonstrates that raising the regional groundwater table in the underlying aquifer, by means of blocking groundwater-fed drains and dam construction, reduces the leakage rate by between 40 to 60 %. The inference is that the vertical hydraulic gradient between the phreatic water table in the bog and the potentiometric surfaces in peat and subsoil bodies must be kept low to maintain saturated conditions on the bog surface. This constitutes an *indirect* groundwater dependency.

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# 1. Introduction

## 1.1. Peatlands

Peatlands, which are understood to comprise mountain and coastal/lowland blanket bogs, raised bogs and fen peats, are Ireland's most important terrestrial ecosystems supporting a rich variety of specialist flora and fauna species. They are specialised terrestrial freshwater wetland ecosystems that are distinguished by an annual accumulation of organic matter that results from the decay of plant material under water-logged conditions and which forms a peat substrate. Peatlands that actively accumulate peat material are considered to be 'active' ecosystems.

Approximately 20 % of the Irish landscape may be considered to be peatland, and 3%, or c. 200 $km^2$ hectares, of this is designated as protected habitat. Of particular significance is the occurrence of 'raised bogs', which are recognised as being of national and international conservation importance. Raised bogs have disappeared almost entirely in Western Europe due to land reclamation for agriculture, fuel production and population growth. There are no intact raised bogs remaining in Ireland, with all bogs having undergone varying degrees of 'damage' due to human interference. However, there are raised bogs that still retain ecological features deemed worthy of conservation under the EU Habitats Directive (92/43/EEC), which aims to conserve habitats of unique conservational value.

## 1.2. Conservation

In total, 53 Special Areas of Conservation (SACs) are designated for raised bogs under the Habitats Directive in Ireland. The directive defines habitats of Community Interest as those that (i) are in danger of disappearance in their natural range; or (ii) have a small natural range following their regression or by reason of their intrinsically restricted area; or (iii) present outstanding examples of typical characteristics of one or more of the seven following biogeographical regions: Alpine, Atlantic, Boreal, Continental, Macaronesian, Mediterranean and Pannonian (Evans, 2006). Raised bogs are priority habitat under Annex 1 of the Directive.

The Habitats Directive requires the monitoring and management of raised bog habitats to ensure they remain, or can be restored to, a favourable condition. Management measures must be implemented so to control and maintain the environmental conditions which are necessary to maintain the bog's dependent ecology, which is characterised, primarily, by bog mosses (sphagnum species). Sphagnum communities require the free-surface water table in the bog to be almost permanently high, close to ground level, and with minor fluctuations in the water level. The existence and widespread growth/ expanse of bog mosses (*Sphagnum* species) indicates whether a raised bog, as an ecosystem, is in a poor or favourable condition.

Conservation management measures of raised bog ecosystems are intrinsically linked to an understanding of the hydrology of the system as a whole – processes operating (1) within the peat substrate that forms the bog body and (2) in the regional groundwater/ hydrologeological setting that encompasses the bog system. In this regard, a raised bog may be viewed as a hydrological entity with its ecological functioning being primarily dependent upon the dynamics of the hydrological flows, inside and outside of the bog. The functioning of raised bog peatlands, including their role in maintaining biodiversity, in controlling their greenhouse/carbon emissions, and in flood attenuation, as well as other generic ecosystem services, depends upon maintaining near-natural hydrological conditions. Hydrology is therefore a key context within which to consider the sustainability of a bog wetland.

There are no intact raised bogs remaining in Ireland, with all bogs having undergone varying degrees of 'damage' due to human interference. However, the 53 raised bogs designated as SACs still retain ecological features deemed worthy of conservation under the Habitats Directive. The management of raised bogs, which largely focuses on restoring wet conditions on the bog surface so as to allow the regeneration of flora such as *Sphagnum*, has traditionally concentrated on solving the immediate problems such as blocking man-made drains, in order to raise the water table. However such solutions are rarely adequate due to the complicated nature of the peat substrate and the drainage pathways in the bog system itself.

### 1.3. Clara Bog

Though one of the best preserved raised bogs in Ireland, Clara Bog has been extensively damaged in the past and it is estimated that the bog, as it exists now, covers less than half of the extent it once did in its pristine state. The bog can be considered as two bogs, Clara Bog West and Clara Bog East, as a road, the Clara to Rahan 'bog road', bisects the wetland into two separate bog entities (figure 1.1).

An extensive network of drains was installed on each side of the 'bog road' between 1838 and 1884 (Crushell, 2008). Consequently, the marginal drainage associated with the bog road, and the associated drains, has permanently altered the hydrology of the bog resulting in severe subsidence, which is essentially a consequence of shrinkage of the peat substrate. It is believed that the location of the 'bog road', as it exists today, would originally have been where the bog dome, the highest elevation point of the bog, protruded above the surrounding landscape (Bell, 1991). Instead, the bog surface on Clara Bog East and Clara Bog West now slopes towards the road with the road itself being c.6 m lower than the highest elevation on the high bog either side of it (Bell, 1991).

Clara Bog is of particularly high conservation importance because it supports two ecological features that are almost completely absent from other Irish Bogs, and have disappeared entirely from raised bogs in Western Europe – soak systems. Soaks are areas of fen-type vegetation occurring on the surface of a nutrient deficient, or ombrotrophic bog surface. Their maintenance requires large

catchment areas and long flow path lengths for surface water flowing on the bog surface (Van der Schaff & Streefkerk, 2002). The water molecule becomes more nutrient rich over time due to its long path of travel and results in nutrient rich vegetation on the bog surface, where flows converge, relative to its surroundings. On Clara Bog West, two soak systems of international conservational importance are present – that of the Western Soak in the Western area of the bog, and Shanely's Lough in the central/ eastern area of the bog. Their locations, and other morphological features that are important in the study, are displayed in figure 1.2.

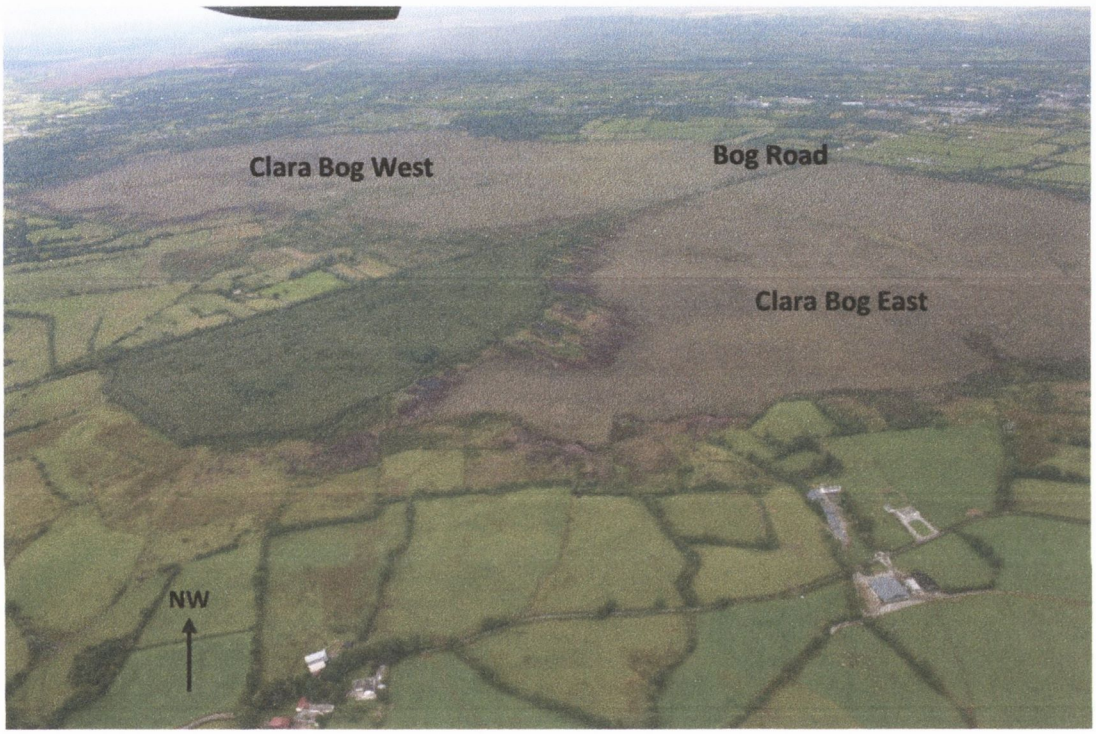


**Figure 1.1**. Clara Bog (Photograph courtesy of Colm Malone, NPWS).

### 1.3.1.Irish-Dutch Raised Bog Study (1989-2001)

Much of the knowledge of raised bog hydrology was garnered through an Irish-Dutch collaborative research project in the early 1990's. Indeed, Irish, Dutch and international scientists have been working together since the early 1980's, initially by raising the importance of bogs to the Irish public and later by highlighting their importance internationally.

The interdisciplinary project was supported by the National Parks and Wildlife Service (NPWS), the Geological Survey of Ireland (GSI) and the Dutch state body for nature conservation, Staatsbosbeheer. Its aim was to better understand the processes controlling the geological, hydrological and ecological characteristics on two of Ireland's best persevered raised bogs, namely Clara Bog and Raheenmore Bog, both of which are designated nature reserves and scientific areas of conservation (SACs).

Clara Bog and Raheenmore Bog were both originally the property of Bord na Mona, the semi-state body for the use of peat in fuel utilisation. However, recognising their importance in Irish nature conservation, Raheenmore Bog was given back to the Irish State in the early 1980s and Clara Bog in 1986. While Raheenmore Bog was preserved in its entirety, Clara Bog was not, with c.465 ha of a total of c.665 ha preserved as nature reserve. Unfortunately, the areas of bog cover that are not state owned is privately owned and until recently (turf cessation ban 2010) was cut locally for turf production.

The Dutch-Irish project greatly enhanced the ecohydrological understanding of how raised bog systems worked and functioned, internally, and externally with its surroundings. Numerous M.Sc. theses, reports, scientific papers and three Ph. D theses were produced by Irish, British and Dutch researchers, for the most part in the early 1990's. A book, entitled 'Conservation and Restoration of Irish Raised Bogs' (Schouten et al, 2002), which essentially collates and summarises this work, was subsequently published in 2002 and is a legacy of the work done during this productive period.

### 1.3.2.Clara Restoration Project 2008-2011

In the recent past, the southern margins of Clara Bog West have been cut for turf. The removal of peat on the bog margin removes the natural boundary between bog and elevated mineral subsoil, a so-called *lagg* zone where bog water and mineral groundwater mix to form fen-type nutrient-rich vegetation, and results in vertical peat banks on the margins of the main bog body. Coincident with peat-cutting/ removal activities, is the development of a drainage system, which deepens as cutting extends into the bog, and serves to dry peat at the bog margin so future removal is easier.

As part of the hydro-ecological work in the 1990s, Van der Schaff (1999) produced a PhD thesis on the hydrology of Clara Bog and Raheenmore Bog. Following this work, which was based on field studies carried out between 1990 and 1993, Van der Schaff, J. Streekerk and the NPWS (per comm.) noticed in the late 1990's that the surface level of the Clara West high bog had begun to subside and that water levels in peat substrate had declined. The NPWS then commissioned a small-scale field project to investigate this phenomenon (Ten Heggler et al, 2003).

Ten Heggler et al (2004) found that the southern sections of Clara Bog West had subsided locally by over 1 metre since 1991 and coincident with the subsidence was the development of bog pools and lakes (figure 1.3), presumably due to differential rates of peat consolidation. While drainage on the high bog (i.e. internal drainage) affects the upper layers of the peat profile, drainage in cut-away sections by the high bog will reduce the piezometric head at the base of the peat profile, by reducing pore water pressure, and in the subsoil deposits underlying the peat (Ten Heggler et al, 2004). As a consequence, peat consolidation concentrates in the deeper layers of the peat profile.

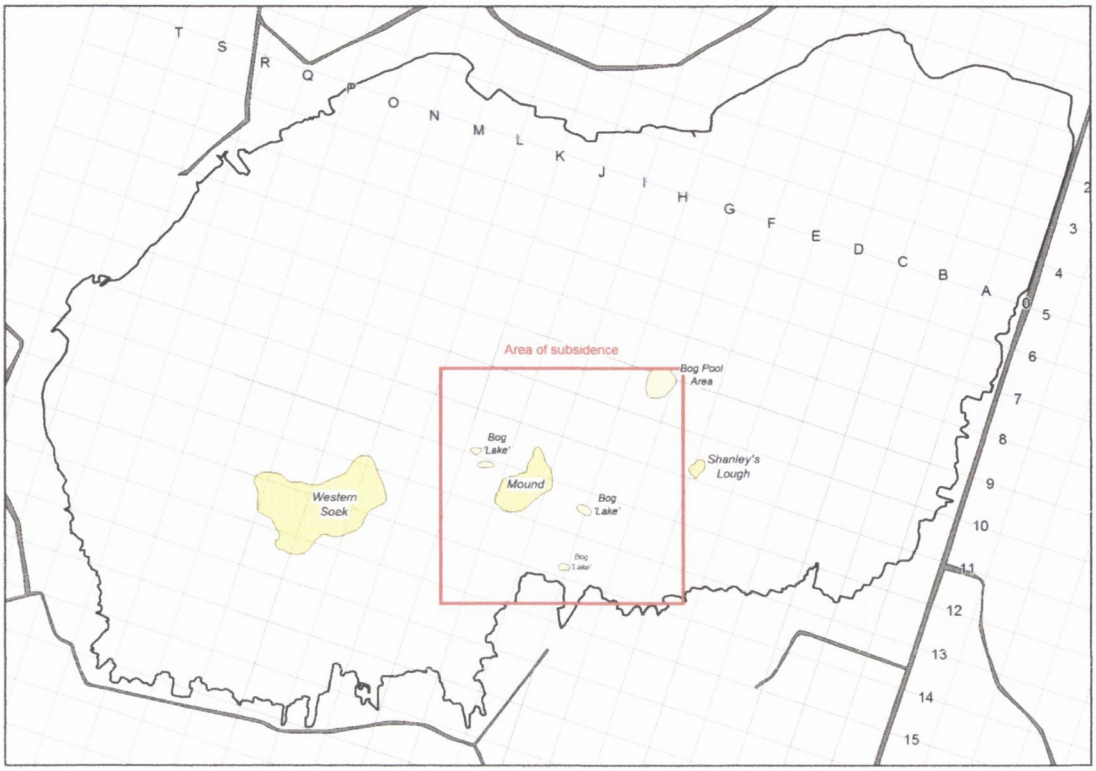


**Figure 1.2** General locations of soak features, new bog pools and area of subsidence (Note: 100m bog grid – referred to as OPW grid).

As such, it is now known that Clara Bog West has subsided significantly since the early 1990's due to the drainage associated with the peat-cutting activity (Ten Heggler et al, 2004), thereby altering the surface level gradients on the bog which in turn alters the flow paths on the bog surface that maintain sensitive rheotrophic ecotopes, such as the soak systems. The acrotelm, which is the living 'layer' on the bog surface and where the majority of the hydrological processes operate, will therefore also be affected as its occurrence depends on the maintenance shallow slope gradients (gradient must not exceed 0.3 m/100 m; Van der Schaff & Streefkerk, 2002).

Following this, a new research project was initiated by the NPWS and Staatsbosbeheer in 2008 in order to establish how, and why, the bog is subsiding, to understand the effects of subsidence and to ultimately engineer a restoration measure to slow down, or stop, subsidence of the Clara West high bog. The 'Clara Bog Restoration Group' was spearheaded by Jan Streefkerk (Staatsbosbeheer) and involved Jim Ryan (NPWS), Paul Johnston (TCD), Ray Flynn (Queens University Belfast) and the author.

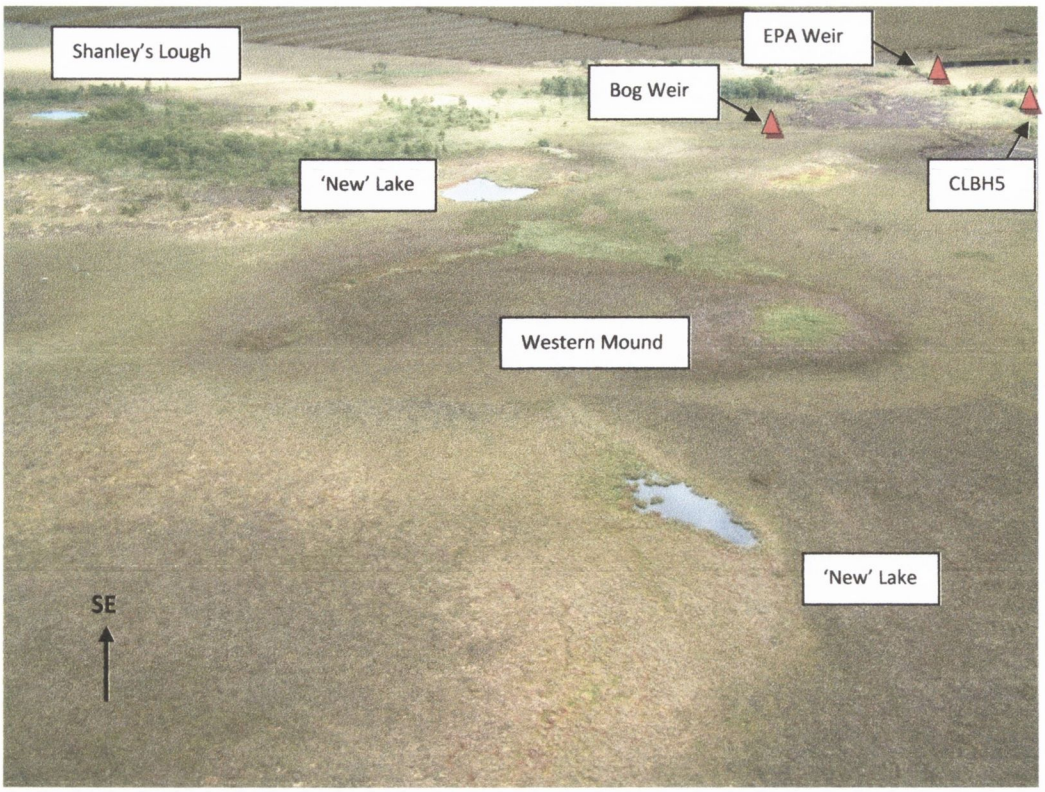


**Figure 1.3.** Location of the Western Mound, Shanley's Lough, recent lake formation, CLBH5 and proposed weir. Photograph courtesy of Colm Malone (NPWS).

**Figure 1.4.** View looking south at Western Mound, Shanley's Lough and recent lake formation. Photograph courtesy of Colm Malone (NPWS).

### 1.4. Project aims and objectives

Peat cutting, which ceased in the summer of 2010 following a turf-cutting ban/ cessation originally proposed in 1999 for Special Areas of Conservation (SACs), has resulted in rapid subsidence of Clara Bog West, leading to changes to the hydrological processes that support the internationally important soak systems. It is also leading to significant losses of the EU Habitat Directive priority habitat Active Raised Bog which has declined by approximately one third since 1992 (per comm. NPWS).

There is strong evidence that the fundamental problem is associated with decreased groundwater heads in permeable geological layers under the bog due to increased marginal drainage associated with peat cutting. If the hydraulic head in peat and underlying mineral subsoil, and by extension the hydraulic gradient, is an environmental supporting condition, this has further implications under the Water Framework Directive.

The European Water Framework Directive (WFD) (2000/60/EC) is a legislative framework to protect and improve the quality of all water resources within the European Union such as rivers, lakes, groundwater, estuarine and coastal waters. The classification of groundwater bodies (GWBs) into either 'good' or 'poor' status, as required by the WFD, depends on an assessment of a number of elements, of which 'significant damage' to groundwater dependent terrestrial ecosystems (GWDTEs) from anthropogenic pressures on the associated GWB is one. GWDTEs, under the WGD, are considered to be wetlands that depend on a significant proportion of their water supply (quality and quantity) from groundwater. Based on this broad classification, raised bogs are not GWDTEs and are therefore not monitored as GWDTEs under the WFD in Ireland.

The main objective of the research is to therefore:

(1) Evaluate the hydraulic connection between the bog body and regional groundwater system

(2) Calculate the rate of subsidence and assess whether the bog has reached, or is reaching, a state of equilibrium or steady state

(3) Determine how groundwater hydraulic head under the high bog may be raised to stop, or limit, bog subsidence

(4) Assess the relative dependency of Clara Bog West on the regional groundwater system

To answer such research questions essentially requires the computation of the bog systems water balance – the results of which are used to assess the bogs dependency on regional groundwater and to model the predicted behaviour of the bog system in the future as a response to continued subsidence or implemented conservation management measures to limit or arrest peat consolidation. The fundamental aim of the research is to demonstrate that Clara West is indirectly supported by groundwater pressure in underlying geological units – i.e. that Clara, and other raised bogs, are groundwater dependent ecosystems.

## 2. The Hydrology of Bogs

### 2.1. Introduction and Objectives

The objective of this chapter (literature review) is to assess the hydrological behaviour and functioning of peat wetlands (peatlands). The synthesis will use an approach first described in the paper 'the water balance of bogs and fens', by Dooge (1975), where the position of the wetland in the hydrological cycle is used to define the various components of the wetland water balance. The form of the water balance equation dictates the water regime of the wetland and is expanded to classify the wetland based on the hydrological flows encompassing the system. Quantifying the water balance, which is an evaluation of the components of the hydrological cycle, allows the identification of the principle sources of water inputs and outputs to a wetland and their role in the functioning of the wetland. The hydrological sustainability of peatlands will therefore ultimately depend on the hydrological drivers maintaining the peatland as a functioning ecosystem.

To characterise the various tiers of hydrological behaviour operating within and external to a wetland system the review is divided into nine sections:

- *Section 1* considers the general dynamics of the hydrological cycle, its components and the formulation of the water balance equation
- *Section 2* applies the principles of the water balance to peat wetlands and examines its basis in wetland classification
- *Section 3* describes the properties, or nature, of peat as a geological medium and how particular peat types influence hydrological behaviour in wetlands
- *Section 4* examines the physical properties and hydrological characteristics of peat and their influence on water movement into, through and out of the peat deposit
- *Section 5* addresses the characteristics of individual components in the wetland water balance equation
- *Section 6* discusses the overall peatland water balance
- *Section 7* examines the current understanding of bogs as groundwater dependent terrestrial ecosystems
- *Section 8* examines the sensitivity of peatlands to drainage and its impact on hydro-ecological functioning
- *Section 9* discusses the conclusions and the current state of the art of peatland hydrology

## 2.2. Hydrological cycle and components of the water balance equation

### 2.2.1. The hydrological cycle

Hydrology is concerned with the occurrence and movement of water in the hydrosphere – i.e. above, on and below the surface of the earth. The total amount of water in this hydrosphere remains constant but an appreciable amount of it is in the course of transformation from one form of water to another or of movement from one location of water storage to another. The hydrological cycle for the earth as a whole is driven by the energy available from solar radiation. Water balances can be drawn up not only for the earth as a whole but also for a continental region, for an individual catchment area regardless of size, or for a small area within a particular catchment (Dooge, 1979). Quantifying the amount of water in the different phases of the cycle and evaluating the rate of transfer of water from one form to another within the cycle are two of the greatest challenges in any hydrological study (Shaw, 2004). Figure 2.1 (A) depicts a generalised hydrologic cycle applied to a catchment area on a regional scale and illustrates the relationship between the various forms of water storage and water movement.

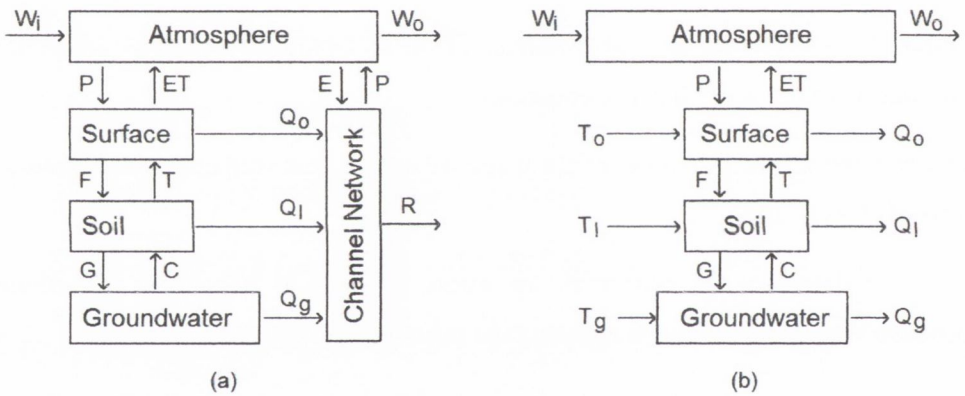


**Figure 2.1. (a)** Water balance for a complete catchment **(b)** Modified water balance for part of a catchment. $W_i$: inflow of precipitable water into the atmosphere above the catchment area. $W_o$: outflow of precipitable water from the atmosphere above the catchment area. *P*: precipitation of water from the atmosphere to the surface of the ground. E: evaporation of water into the atmosphere from surface storage on the ground. *F*: infiltration through the surface of the ground into the soil. *T*: transpiration of water from the soil, through the vegetation and its subsequent evaporation to the atmosphere. *G*: recharge of groundwater. C: capillary rise from groundwater to the soil. $Q_o$: overland flow across the surface of the ground to the drainage network. $Q_l$: lateral flow of water through the unsaturated soil to the drainage network. $Q_g$: groundwater flow (or base flow). *R*: total runoff of the catchment. To: inflow of water to the area of study over the surface of the ground. $T_l$: inflow of water to the area of study as interflow through the unsaturated soil. $T_g$: inflow of water to the area of study as groundwater flow.

It is widely accepted that wetlands have a significant influence of the hydrological cycle (Bullock & Acreman, 2003). The position of a wetland in the landscape is a function of the dominant hydrological processes in the region. It is therefore important to consider the hydrological cycle on a local cycle and to evaluate the various hydrological processes in operation and the time periods and spatial extents to which they apply and vary. Linking hydrological processes and the ecological behaviour of wetland systems is crucial for their management, and ultimately, their sustainability.

### 2.2.2. Hydrological cycle and the water balance

A water balance, or budget, accounts for all the water entering, leaving and stored within a particular area/ system. It may be calculated on various different scales, e.g. global, continental, regional, major or minor catchment, or on the scale of micro-relief of the landscape (Dooge, 1975). Peatland ecosystems are generally not considered on large scales, but rather on a localised regional scale, and it is therefore important to understand the characteristics of the local catchment(s) water balance that controls water movement and storage within the area.

A general water balance for a particular catchment/ system may be expressed simply by the following equation:

$$inflows = ouflows \pm changes\ in\ storage \qquad \text{Equation 2.1}$$

The water balance/ hydrologic equation essentially provide a quantitative means of evaluating the hydrologic cycle and can be applied to systems of any size (Fetter, 2001). This is a fundamental equation in hydrology and follows the law of mass conservation, which states that the mass of a closed system remains constant over time, regardless of the processes acting inside the system. The equation is thus time-dependent and the inflows must be measured over the same time periods as the outflows.

In an idealised catchment, which in surface-water hydrology consists of all the land sloping towards a particular discharge point, the precipitation ($P$) and the runoff ($R$) [i.e. water that is not 'lost' as evaporation or downward infiltration] is measured and the evapotranspiration ($ET$) is either measured or estimated (Dooge, 1975). It is generally assumed that the catchment is watertight and that no subsurface movement of water across the defined watershed is occurring (Shaw, 2004). However, though the surface-water catchment is outlined by topographic divides, the same is not necessarily the case for groundwater catchments/ basins, i.e. the subsurface volume through which ground water flows toward a specific discharge zone (Fetter, 2001). Groundwater divides may not be coincident with topographic catchment areas, particularly when the underlying bedrock is dominated by fractures and faults such as in karst terrains. The water balance/ budget must therefore account for both surface and groundwater contributions. Accordingly, the following water balance equation for a stated time period may be expressed as:

$$P = ET + R + \Delta S \qquad \text{Equation 2.2}$$

where $\Delta S$ represents the total storage in the system/ catchment area. Total storage includes surface-water storage ($SS$), field moisture storage ($FMS$), groundwater storage ($GWS$) and channel storage ($CS$) [see figure 2.1]. For a detailed water balance calculation, each of these water storage elements must be accurately quantified or shown to be negligible (Dooge, 1975). However, in the long-term average, it can be assumed that $\Delta S$ is constant, and becomes insignificant in the water balance, which can therefore be simplified to (Baumgartner & Reichel, 1975):

$$P = ET + R \qquad \text{Equation 2.3}$$

Changes in storage over short time periods, such as one year, can become significant in instances when human activities, such as drainage, modify the natural hydrological balance of a wetland. The storage component is important on the scale of the local catchment area, particularly in peatland systems with active vegetative growth, and cannot be assumed to be negligible. Figure 2.1, adapted from Dooge (1975), illustrates the water balance for an individual catchment area and for an isolated part of a catchment area. A water balance equation for part of a catchment area, which encompasses the wetland system of interest, may be expressed as follows:

$$\frac{\Delta V}{\Delta t} = P + S_{in} + G_{in} - ET - S_{out} + G_{out} \qquad \text{Equation 2.4}$$

where $P$ = precipitation, $ET$ = evapotranspiration, $S_i$ = surface inflow, $S_o$ = surface outflow, $G_i$ = groundwater inflow, $G_o$ = groundwater outflow, $\Delta V/\Delta t$ = change in storage per unit time.

A strict water balance will measure each of the components separately and if the elements are measured accurately the equation will balance. However, in reality, due to expense, difficulty of direct measurement, data limitations and time constraints, it is often difficult to measure each of the water balance components independently. As a result, the storage component is often assumed to be negligible in long-term catchment studies, which may be reasonable if the nature of the catchment does not change significantly during that time period (Dooge 1975).

However, the same logic cannot be applied to wetlands, particularly peatlands, which are often drained for agricultural and peat-extraction/ mining purposes, thereby affecting the storage properties of the peat material that persists long after the wetland was first drained (i.e. drainage releases water held in storage in the peat body). It is also common procedure that the water balance equation, when it is assumed to hold, is used to determine the value of a component, which has not been measured.

## 2.3. Wetland water balance

### 2.3.1. Wetland hydrology

Wetlands are heterogeneous but distinctive ecosystems, which develop naturally, or are the product of human activities. They are hydrologic features that occur in physiographic and climatic settings that favour the accumulation, or retention, of surface water and (or) soil water (Winter & Llamas, 1993). As such, it is the hydrology of a wetland that creates the unique physiochemical conditions that make such an ecosystem different from both well-drained terrestrial systems and deepwater aquatic systems (Mitsch & Gosselink, 2007).

The availability of water is of fundamental importance to the character of all wetlands and the effects of excess water dominate their formation and considerably control their processes and characteristics

(Wheeler, 1999). The occurrence of any wetland ecosystem requires that the substratum be kept in a suitably wet condition for all, or part, of the year. Such saturation results from an interaction between landscape topography and sources of water. These wet conditions occur primarily because of water detention (impeded drainage) and because of high rates of water supply, or both. Supply may consist of telluric water (water derived from the earth, e.g. river water, ground water discharge) or meteoric water (precipitation) [Wheeler, 1999]. There is much variation in the behaviour of the water table in wetlands with some wetlands having an almost constant water table and others showing variable water table juxtaposition induced by varying rates of water loss and groundwater recharge. As such, the magnitude and period of water table fluctuation has a profound impact upon the character of wetlands (Wheeler, 1999).

There are many ecological systems that may be considered to be wetlands; however, this synthesis describes the hydrology of wetlands where the main substratum in the system is peat. Peats producing ecosystems, or mires, are dynamic ecological entities that are constantly changing, growing, spreading and eroding (Moore & Bellamy, 1974). The use of the term mire is often used, and misused, in wetland/ peat literature and classification but is considered here as areas of peatland where peat is currently being formed (Joosten & Clarke, 2002). As such, peatlands may be considered to be wetlands that accumulate peat when the water table remains close to the surface for much of the year and where the normal amplitude of water table fluctuation is relatively small. Changes in the hydrological regime that sustains the peatland, which is essentially a hydrological entity, will invariably disturb the normal hydroecological functioning of the peatland. Thus, hydrologic conditions are extremely important for the maintenance of a wetland's structure and function.

The water balance of an area dictates the form, or type, of peatland that develops. As peat is decaying organic matter that has accumulated under saturated conditions, its formation occurs in areas of positive water balance (Holden et al, 2004) where the volume of water entering the wetland system is greater than that leaving the system. As such, the hydrological sustainability and management of peatlands requires knowledge of the systems water regime, which is dependent upon characterising and quantifying the hydrological mechanisms at work.

Table 2.1, collated by Moore and Bellamy (1974) and based on work by the Polish scientist Kaczynski (1949) describes seven hydrological types of peatland. There are three general categories, namely rheophilous (meaning 'loving the flow'), transition and ombrophilous (meaning 'loving the rain') and they essentially describe the extent to which the peatland is influenced by outside drainage/ water flow. Modern terms for these categories are minerotrophic, transition and ombrotrophic (Mitsch & Gosselink, 2007). This classification scheme still serves as the basis on which modern classifications are based as it combines the chemical and physical conditions of the wetland with its vegetation description, thereby presenting a balanced wetland classification (Mitsch & Gosselink, 2007).

Table 2.1. Early hydrologic classification of European peatlands (Moore & Bellamy, 1974)

| |
|---|
| **Rheophilous mire** – Peatland influenced by groundwater derived from outside the immediate watershed |
| Type 1 – Continuously flowing water that inundates the peatland surface |
| Type 2 – Continuously flowing water beneath a floating mat of vegetation |
| Type 3 – Intermittent flow inundating the mire surface |
| Type 4 – Intermittent flow of water beneath a floating mat of vegetation |
| **Transition mire** – Peatland influenced by groundwater derived solely from the immediate watershed |
| Type 5 – Continuous flow of water |
| Type 6 – Intermittent flow of water |
| **Ombrophilous mire** |
| Type 7 – Peatland never subject to flowing groundwater |

Peatlands can also be classified based on ecological function, soil characteristics and plant assemblages, as well as hydrology, thereby resulting in many different peatland sub-types. However, a broad division between fens and bogs, which are permanent peat producing wetlands, is commonly made. Fens are connected to regional groundwater flows and, thus, have water and nutrients moving into and out of the ecosystem, whereas bogs are hydrologically isolated and rely on precipitation as the only water and nutrient input source (Lafleur, 2005). Bogs may therefore be considered to be ombrotrophic, or ombrophilous, because their vegetation thrives under heavy precipitation, thereby making them acidic (pH <4) and are said to be oligotrophic because the nutrient supply is low and contain low amounts of calcium and magnesium. Fens are considered to be minerotrophic, or rheophilous, because of the supply of minerals by inflowing water and are said to be rheophilous or soligenous because of the flow of water through the body of the fen, thereby making fens less acidic than bogs and also a tendency to be base rich. This invariably controls the vegetation present on the surface of the wetland, with characteristic vegetation types such as *Sphagnum*, which are more tolerant of conditions of acidity and scarcity of nutrients, dominant on bogs and vegetation indicative of nutrient rich groundwater, such as various sedge and reed species, dominant on fens. The chemical quality of the water is therefore also important in differentiating between bogs and fens (Dooge, 1975).

### 2.3.2. Peatland water balance

The basic classification of mires into bogs or fens is related to the water balance equation 2.4. The mire, in simple terms, is classified as a bog when the inflow to the system from surrounding areas is negligible and classified as a fen when the inflow to the system is significant. Figure 2.2 illustrates the broad differences between the water balance of fens, which are often hollow and concave in relief due

to their position in the landscape, and raised bogs, which are typically domed in profile and raised above the regional groundwater table (i.e. groundwater table, or potentiometric surface, hosted in subsoil/ bedrock that underlies and surrounds the system). It is clear from the diagram that peatlands with a concave relief are fed by groundwater and precipitation, whereas bogs that are elevated in the landscape receive water wholly from precipitation (after Streefkerk & Casparie, 1989).

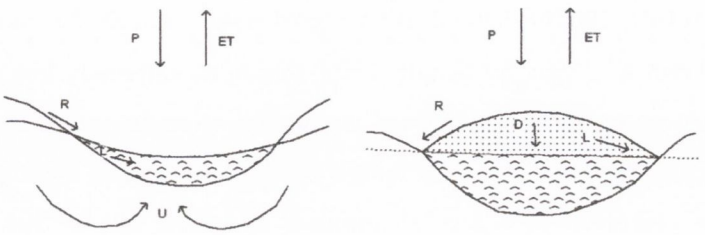


**Figure 2.2.** Simple conceptual representation of the supply and discharge of water in peatlands with (1) concave relief and with (2) domed relief (Streefkerk & Casparie, 1989).

The water balance quantifies the relationship between the supply and discharge of water in both systems. Over a typical hydrological year (in Ireland a typical hydrological year is between the 30th September and the 1st October), water storage in both systems should be equal to zero. However, drainage activities will alter this balance by releasing water held in peat-storage. As such, the water balance equation 2.4 may then be altered slightly to adjust for fens and raised bogs respectively:

$$P - ET + R + L + U \; or - D = \Delta S \qquad 2.5$$

$$P - E - R - L - D = \Delta S \qquad 2.6$$

where $R$ = surface runoff or supply, $L$ = lateral seepage, $D$ = downwards vertical seepage, $U$ = upwards vertical seepage.

Groundwater input to raised bogs, and blanket bogs, is minimal to the extent that it is generally exempt from a water balance equation – as the bog body is generally isolated from regional groundwater flows. In raised bogs micro-topography on the bog surface is important in regulating runoff and the distribution of ecological communities. Raised bogs, particularly in functioning raised bogs with peat growth, may simply be differentiated into two layers, an 'active' layer, or acrotelm, and an underlying 'inactive' layer, or catotelm, which forms the main bog body (as first described by Ivanov, 1957, and later refined by Ingram, 1978). Essentially the catotelm is composed of peat layers in different stages of decay and with different botanical components (Ivanov, 1981), whereas the acrotelm is a relatively thin (varies in thickness from < 10 to 70 cm) layer which is composed of actively growing vegetation and peat material which has not yet fully decomposed. As such, the acrotelm is the 'peat-making' part of the bog (Ivanov, 1981) that is periodically aerated (Ingram, 1983) and where the majority of the bogs biological activity occurs (Ingram, 1982). Significantly it is also the zone where water and heat exchange occurs due to the physical properties of the acrotelm and

the plant cover that it supports (Ivanov, 1981). In contrast, the catotelm is an anaerobic layer due to the permanently waterlogged nature of the peat deposits and the imperceptibly slow rate of diagenesis (Ingram, 1982). The concept of the acrotelm and catotelm is referred to as the theory of diplotelmy, the processes in which are crucial in raised bog hydrology and their conservation.

Despite its limited thickness, the acrotelm rather than the catotelm is the crucial zone in raised bog hydrology (Van der Schaff, 2002b). Lateral discharge of water through the catotelm body is minimal (between 0.5 and 1.0 mm $a^{-1}$ ; Van der Schaff, 1999) due to its extremely low permeability, whereas the phreatic, or 'free', water table is contained within the acrotelm and is therefore the regulating system for runoff from a raised bog (Van der Schaff, 2004). Thus, from a hydrogeological perspective, the catotelm may be perceived as a sort of aquitard/ hydraulic barrier that transmits very small volumes of water (which is an important 'function' in itself), whereas the acrotelm may be considered to be an unconfined aquifer where the majority of the bogs flow processes occur, including those that create the distinct ecological communities that develop on the surface of natural raised bogs.

### 2.3.3.Classification based on water supply mechanisms

The hydrological factors that compose a wetland water balance are influenced by physical factors in the local and regional landscape. The topography of the wetland area, the geomorphology of the wetland area and the subsurface soil and geology will dictate how a wetland receives and discharges surface water and groundwater, as well as its ability to store water (Heathwaite, 1995). A more robust wetland/ peatland hydrological classification is necessary in order to account for the range of biotic and abiotic factors that influence a wetland water balance. Wheeler & Shaw (2000) have proposed that wetlands should be classified based on linkages between wetland topography, hydrology/ hydrogeology, hydrochemistry, ecology and conservation interest. The water supply mechanisms (i.e. the ways in which water can move into or out of a wetland) operating within a particular wetland system will control how the system operates. Indeed, a prerequisite to assessing the implications for a wetland of any external hydrological impacts is to understand the ways in which water enters and leaves the wetland and to quantify the associated rates of water movement (Acreman & Miller, 2006).

It is thereby essential to identify which water transfer/ supply mechanisms are operating at a wetland and which of these are the most important in maintaining the ecology present. Precipitation on raised bogs and blanket bogs is the dominant water transfer mechanism supplying the ecosystem with nutrients. However, fens, flush systems on blanket bogs, and lagg zones and soak systems on raised bogs represent peatland areas where water movement is linked to an extraneous source. Whether movement of groundwater to or from a wetland is an important mechanism depends not only on the presence of an aquifer/ groundwater body, but also on the nature of the soils and rocks between the aquifer and the wetland (Acreman & Miller, 2006) as the characteristics of the wetland soil and underlying substratum determine the rate of subsurface water movement, the infiltration rate (either

from precipitation or inundation) and the retention of water within the wetland (Gilvear & Bradley, 2000).

Table 2.2. Revised WETMEC wetland classification [SNIFFER WFD62].

| |
|---|
| **Type A: Seepage Slope Wetlands** |
| A1: artesian + strong spring flows |
| A2: diffuse / permanent seepage slope |
| A3: intermittent, shallow subsurface seepage slopes |
| **Type B: Seepage Basin Wetlands** |
| B1: fluctuating seepage basins |
| B2: seepage / summer dry percolation basins |
| **Type C: Valley Bottom Wetlands** |
| C1: small floodplain 'Valley Fens' |
| C2: wet valley bottom (8c) (exclusive of valley head valley bottoms |
| **Type D: Special Sites of Local or Regional Interest** |
| turloughs |
| raised Bogs |

A proposed classification scheme based on the identification and characterisation of wetland water supply mechanisms (WETMECs) has been devised by Wheeler & Shaw (2000) for selected wetland sites in Britain. The WETMECs reflect 'how wetlands' work - hydrologically. They are based not only on water source but also water levels and piezometric heads, and upon near-surface conditions within the wetland substratum which influence the source and distribution of the water relevant to the main rooting zone of the wetland vegetation (Wheeler & Shaw, 2001). However, work is required to adapt this mode of classification to the peatlands of Ireland. The Scotland and Northern Ireland Forum for Environmental Research (SNIFFER WFD62) have devised a preliminary classification scheme for wetlands in Ireland and Scotland, based on the WETMEC model and consists of four major wetland types: Seepage Slope Wetlands, Seepage Basin Wetlands, Valley Bottom Wetlands and Special Sites of Regional Interest (table 2.2). The first three classes are further divided into subclasses and the forth type, 'Type D', is included as a means of covering special and local/ regionally important sites such as turloughs and raised bogs. This revised classification allows wetland locations to be assigned to distinct wetland types, taking into account the currently available data.

## 2.4. Peat as a geological medium

### 2.4.1.Peat

Peatlands are specialised terrestrial freshwater wetland ecosystems, distinguished by an annual accumulation of peat. In these systems, annual production of organic matter exceeds its annual decomposition, resulting in the build-up of partially decomposed organic matter or peat. Over time these annual increments produce peat deposits of considerable depth (Doyle & Criodain, 2003), reaching depths of between 10 m and 15 m in the centre of raised bogs. The majority of the world's peatlands by area occur in boreal and temperate zones where they have formed in low-relief (poorly

draining) environments under high precipitation-low temperature climatic regimes. The dominance of a living plant layer and thick accumulations of preserved plant detritus from previous year growth sets peatlands apart from mineral wetlands, which lack any substantial thickness and accumulation of organic remains (Charman, 2002).

Peat, as a geological medium, is not a homogeneous substance. The physical composition of peat deposits varies as a result of their botanical composition, mineral content and degree of decomposition (Eggelsmann et al, 1993). As such, it is a variable, unconsolidated, deposit whose properties change with time. The geological nature of the peat deposit, which will be shaped by the ecological and hydrological regime at the time of formation, invariably controls the hydrological processes that occur within the substrate. Peat is essentially an organic waterlogged deposit, which has not been completely oxidised because the prevailing conditions are oxygen deficient due to permanent saturation.

### 2.4.2.Peat types

In raised bog systems, the bog body is that of the catotelm. The catotelm contains peat of different botanical compositions, age, compaction and state of decay and insight into the formation and accumulation of peat and into the mechanism of bog growth is mainly founded on the results of palaeobotanical and stratigraphical research on bogs (Streefkerk & Casparie, 1989). Mire types may be differentiated based on the dominant source of water entering the system. Flow-fed (rheotrophic) mires are often relatively rich in nutrients and contain clastic material while rain- fed (ombrotrophic) mires are poor. The transition from one hydrological state to the other can occur during mire development and involves a physical elevation of the mire surface by the growth of peat (Moore, 1995). The physical characteristics of the peat deposit will therefore also change due to the decomposition of botanical assemblages that developed in differing water-type conditions, i.e. groundwater and rainwater. Therefore, the peat stratigraphy preserved in the mire system allows a reconstruction of the vegetation changes that have occurred over time, all of which are ultimately associated with hydrological transitions.

In Ireland, following the last glaciation c.10 ka, glaciers bean to retreat and this led to the creation of new landforms, such as eskers and moraines, and erosion of large segments of the landscape, resulting in valleys and topographic depressions. Lakes naturally formed in such depressions and over time became inundated with sediment from their surrounding topographic highs, which eventually compacted to form glacio-lacustrine clay and/or marl deposits (i.e. mineral subsoil). Due to the impeded drainage associated with the low-permeability clay deposits, vegetation then began to encroach these areas, which were fed by mineral-rich groundwater (the degree of mineralisation depending on the local geology), and following the decomposition and accumulation of this vegetation, fen peat first began to consolidate some c.8 ka. Over time the lakes were completely overgrown, and as the vegetation continued to accumulate, the mire became raised above the regional

groundwater table, thereby becoming isolated from the mineral-rich groundwater, and ombrotrophic peat formation began c.7 ka. However, this is not to say that the underlying mineral subsoil, which almost always underlies the peat material of a raised bog, does not influence the hydrology of a raised bog. The isolation of peat from the subsoil is never truly complete and this is not only at the edges of the bog, but also in the centre of raised bog complexes (Streefkerk & Casparie, 1989).

It is possible to define a variety of stratigraphical peat types and two main peat types are identified, namely *fen peat* and *sphagnum peat*, both of which essentially mark the physical transition from fen mire to bog mire. Rheotrophic mires are almost always better supplied with the nutrients required for plant growth than are the ombrotrophic mires (Moore, 1995). As such, fen peats invariably contain partial remains of vegetation indicative of minerotrophic conditions such as grass and sedge species, whereas ombrotrophic peat is dominated by sphagnum species. There is often a transition phase between the two, marked by the appearance of combined nutrient-poor and nutrient rich vegetation. The transition from fen to bog environments requires that adequate environmental conditions be in place. As such there must be (1) sufficient precipitation to provide an adequate water resource for the maintenance of water logging above the ground water table, (2) a mechanism to prevent the rapid loss of water from the elevated peat (i.e. a hydraulic barrier), leading to the development of aerobic conditions in which decomposition will be enhanced and (3) there must be present species of plant that are capable of active growth in these new conditions of low nutrient availability and often relatively low pH (Moore, 1995). As such, raised bogs develop above groundwater level and under the influence of rainfall. Such systems derive their nutrition almost entirely from the atmosphere and their water table is maintained by the systems itself. It is the latter characteristic that distinguishes bogs, particularly raised bogs, from other systems that accumulate peat (Streefkerk & Casparie, 1989). However, *Sphagnum* peat does not necessarily have to be preceded by a fen stage, as under favourable climatic and topographic conditions, peat will also develop directly onto the land surface to form blanket bogs (Hobbs, 1986).

A variety of models have been developed to describe how peatlands develop and form, the most famous of which are Ingram's (1978 & 1982) groundwater mound hypothesis model and Clymo's (1984) bog growth model, both of which are based on the diplotelmy theory of bog structure. A key prediction of the Clymo model is that the rate of peat accumulation decreases over time, using a proportional decay function to represent decay processes in the acrotelm and catotelm, resulting in a concave profile of peat depth versus peat age. However, Belyea & Baird (2006) show that both the Ingram and Clymo models fail to take into account peatland heterogeneity and the changing hydrological conditions over time. Belyea & Baird (2006) demonstrate that bog height growth and lateral expansion change the boundary conditions constraining peatland dynamics, and so determine the direction of ecosystem development.

### 2.4.3. Decomposition and accumulation

Mires are characterised by an incomplete cycling of organic matter and a portion of the energy fixed in photosynthesis remains in the ecosystem and accumulates after the various respiratory activities of the vegetation on the surface of the bog (Moore, 1995). As plant production exceeds decay, a carbon surplus is accumulated as peat, resulting in a positive carbon balance (Joosten & Clarke, 2002). The imbalance in the energy budget of mire ecosystems that permits the accumulation of the peat energy reserve is a consequence of the low microbial respiration rather than the high primary productivity of the system (Moore, 1995). Indeed, peatlands are ecosystems that sequester carbon through peat accumulation. The suppression of microbial decomposition by water logging is a common feature to all active mires and is the prime cause of organic accumulation (Moore and Bellamy, 1974). As such, peat accumulation generally takes place as a result of limited decay (decomposition) of plant material (Clymo, 1983). Water is the most important external factor limiting decay (Joosten & Clarke, 2002) and the relative position of the water table within the peat ultimately controls the balance between accumulation and decomposition (Holden et al, 2004).

The most important producers of organic matter in a raised bog are *Sphagnum* species. These *Sphagnum* species only grow in situations with small seasonal fluctuations of the phreatic level, or 'free water table', and a mean phreatic level near or at the surface. The Sphagnum species help to create the characteristically low pH environment of bogs and they can store a large volume of water (Wheeler and Shaw, 1995). The presence of *Sphagnum* communities on raised bogs, and blanket bogs, is therefore indicative of healthy conditions, as peat will only actively accumulate when such species are present. Drainage and peat extraction activities will inevitably alter the phreatic level, damage acrotelm development and therefore impede active peat accumulation.

## 2.5. The hydrological properties of peat

The botanical assemblages that form a peat deposit and the degree to which they have decomposed and compacted will invariably dictate the hydrological parameters of the peat substrate itself. Knowledge, and when necessary calculation, of the moisture characteristics that control the movement of water into, through and out of the peat deposits composing a bog system is an essential perquisite to the water balance computation.

Much research has been carried out on the physical properties of peat, including, amongst others, summary studies by Hobbs (1986) and Eggelsmann et al (1993). Much of the knowledge of Irish raised bog hydrology was garnered through the Irish-English-Dutch collaborative research project in the early 1990's. This research developed new insights into the hydrological properties of the catotelm as applied to Clara and Raheenmore raised bogs, particularly with regards to its vertical and lateral outflow characteristics. As such, the hydraulic conductivity ($k$) and water yield of the catotelm peat was a key hydraulic property to measure and characterise. The relationships between hydraulic

conductivity and the degree of humification ($H$), peat type, compaction, organic matter content ($\phi_o$) and peat depth ($D_p$) was analysed by Van der Schaff (1999), the results of which led to new insights into the hydrological functioning of the catotelm. An overview of the most important moisture characteristics is discussed below.

### 2.5.1. Humification

Though humification is not a hydrological property in itself, the properties of peat of interest in hydrology vary greatly with the degree of decomposition (Dooge, 1975). The process of humification ($H$) describes the change, or decay, of fresh plant tissue to peat (Hobbs, 1986). The vast majority of plant decay occurs within the acrotelm, implying the highest degrees of humification are close to the surface and in the upper sections of the peat profile. The typical peat profile of a raised bog consists of an upward (i.e. older to younger) succession of 'fen peat' to 'highly humified *Sphagnum* peat' to 'fresh *Sphagnum* peat'. This implies a downward decrease in humification 'value' (based on the Von Post scale of decomposition assessment), which is true in a broad sense, though it is by no means a monotonous increase due to deviations in peat stratigraphy and local variations in hydrological conditions at the time of formation (van der Schaff, 1999). Bloetjes & Van der Meer (1992), in their stratigraphical study of Clara Bog, described the humification values for the fresh Sphagnum peat (FSP) as varying between H1 to H4, the highly humified Sphagnum peat (HSP) as varying between H6 to H9 and the fen peat (FP) as varying between H5 to H9. Similar values of humification and stratification types were found on Raheenmore Bog (Sijtsma & Veldhuizen, 1992). However, little correlation is found to exist between humification value and peat stratigraphic type.

### 2.5.2. Water content

Peat is able to hold a relatively large quantity of water, particularly when it is in the original saturated condition and has not been subject to decomposition (Dooge, 1975). Indeed, it is often said that a litre of milk contains more solid matter than an equivalent lire of peat. This is due to the striking ability of peat to retain water. The high void ratios associated with peat, especially those associated with high contents of *Sphagnum*, give rise to large water contents (Gill, 2005). Three states of water retention within a peat deposit are generally recognised (Hayward & Clymo, 1982; Hobbs, 1986): (i) intracellular water held within the internal cells of *Sphagnum* under a suction of less than 10 kPa; (ii) interparticle water held by capillary forces in any part of the *Sphagnum* or peat under a suction exceeding 10 kPa. This would include absorbed water; and (iii) absorbed water retained under a suction not exceeding about 20 MPa.

According to Hobbs (1986), the bulk of water in any given area of peat is held in states (i) and (ii) and that only water in states (i) and (ii) can be expelled by consolidation, while water in state (iii) is likely to participate in flow due to drainage under gravity. Hobbs (1986) suggests that moisture contents can range between 800 and 1300%, with moisture content typically increasing with increasing

humification. Hebib found moisture contents between 800 and 1600% from Clara Bog and Raheenmore Bog, while Gill (2005) found moisture contents varied between 500 and 800% from strongly humified peat in Raheenmore Bog. As such, it is believed that the water holding capacity of peat depends greatly on its degree of decomposition (Dooge, 1975). Lowering of the water table in the peat profile will therefore decrease the moisture content of the peat substrate that is no longer saturated with respect to water. From a geotechnical perspective, the moisture content of peat is important as it controls the strength of the peat and is an indicator of its permeability.

### 2.5.3. Hydraulic conductivity

A property of fundamental significance to the study of any soil is its hydraulic conductivity (Rycroft et al, 1975) and an essential parameter to define in water balance studies. The hydraulic conductivity controls the infiltration rate of precipitation through the peat column and also the proportion of water carried away by surface flow. The concept of hydraulic conductivity, or permeability, describes the movement of water through a porous media and is assumed to take place in accordance with Darcy's Law:

$$Q = kA\frac{dh}{dl} \qquad \text{Equation 2.7}$$

where $Q$ is the volume rate of flow, $k$ is the hydraulic conductivity, $A$ is the cross-sectional area of flow and $dh/dl$ is the slope of the hydraulic gradient.

Though there is debate in the literature doubting that water movement in peat can be adequately explained by Darcy's Law, as peat is not a permeable substrate like a sand or gravel type subsoil, an alternative model has not yet been developed and Hemond and Goldman (1985) demonstrate that it is still the most appropriate tool with which to model wetland flow. The hydraulic conductivity ($k$) value of peat, will dictate the flux of water that may move through the peat profile, both vertically and horizontally, meaning it will also indicate how much water loss may occur due to drainage.

Peat decomposition increases with depth below the ground surface, resulting in a decrease in the diameter of soil pores (Quinton et al., 2000). The latter strongly controls the resistance to flow, as the hydraulic conductivity increases with the square of pore diameters (Freeze and Cherry, 1979). Van der Schaff (1999), Sijtsma & Veldhuizen (1992) and Leene & Tiebosch (1993) found that $k$ generally decreases with fractional depth ($d_f$) in Irish raised bogs. Hydraulic conductivity generally varied by half an order of magnitude or less over horizontal distances of a few metres and by 5 orders of magnitude (i.e. from c. 1 to $10^{-5}$ m $d^{-1}$) within the peat substrate of the entire bog. The smallest values were found at depth in the peat profile and the largest towards the upper margins of the peat profile, particularly in central areas of a bog. Eggelsmann et al (1993) quotes $k$ values ranging in the order of $10^{-1}$ – $10^{-3}$ m $s^{-1}$ for undecomposed peats and $k$ values reducing to as low as $10^{-6}$ m $s^{-1}$ for highly decomposed peats.

There are a number of factors that control and determine the value of hydraulic conductivity, in particular the pore size distribution or porosity of the soil, as defined by Poiseuille's law. The porosity of peat is not uniform or smooth but rather irregular, tortuous and intricate (Eggelsmann et al, 1993). As such, the hydraulic conductivity depends mainly on the geometry and distribution of the water-filled pores. Eggelsmann et al (1993) also suggest that hydraulic conductivity decreases in highly humified peat because the proportion of physically bound water increases as the pore size decreases. Significantly, the main processes in peat that affect pore size distribution are compaction and humification (Van der Schaff, 1999), both of which would be expected to decrease pore size.

However, the key processes by which peat conducts, retains and redistributes moisture are poorly understood. This is in large part due to the lack of understanding of how water flows among the organic fragments through the highly inter-connected pore space, and how the nature of this flow changes with variations in soil moisture content (Quinton et al, 2009). This inter-particle pore space is referred to by Hoag and Price (1997) as the 'active porosity', since it is the fraction of the total porosity that conducts water when the peat is saturated. The void space within the peat fragments, including the remains of plant cells and other dead-end spaces, does not normally conduct water and is therefore referred to as the inactive porosity (Hayward and Clymo, 1982 and Hoag and Price, 1997).

### 2.5.4.Organic matter content

Drainage and cultivation of peat soil brings about irreversible changes in their physical and chemical charcteristics (Dooge, 1975). Peat, by its nature, is a deformable/ flexible material with an extremely high water content compared to saturated mineral soils. As such, peat shrinks when it loses water thereby resulting in subsidence of the bog surface. The ability of peat to retain water is of obvious importance to the well-being of bog system as the surface of the catotelm controls the slope of the acrotelm, which needs to be shallow (< c. 0.5 %) to support *Sphagnum* species (after Van der Schaff & Streefkerk, 2002).

The volume fraction of organic matter ($\phi$) in profiles of undisturbed bogs lies approximately between 0.02 and 0.08. Peat is buried gradually deeper as a result of continuing production of new peat material at the surface. The pressure exerted by the overlying material increases with time and the gradual loss of elasticity resulting from the humification process continues. Hence, a positive correlation between the peat depth and the fraction of organic matter may be expected. One should realise that seemingly small changes of the volume fraction of pores, may mean a large compaction of the peat. For example, decrease of the volume fraction of pores from 0.98 to 0.96 means a volume reduction by 50%.

The organic matter ($\phi$) content of peat is therefore an important hydrological and geotechnical property, as it provides indirect information on water losses/ drainage from a bog. Van der Schaff (1999) observed a good correlation between $\phi$ and $d_f$ in the peat depth profiles of both Raheenmore

and Clara bogs and demonstrated that the values of $\phi$ increased from the marginal areas towards the bog centre. This is difference in $\phi$ is a result of peripheral drainage to the bog body.

## 2.6. Components of the water balance

In sections 2.2 and 2.3, the principles and formulation of the water balance, which provides a means of testing the hydrological understanding of a particular system and quantifying water transfer rates, was applied to wetland systems, and in particular, peatlands. To reduce error in water balance computation, individual components should ideally be measured directly.

### 2.6.1. Precipitation

Precipitation is the sole water input in raised bog ecosystems. Blanket bogs occur where mean annual precipitation exceeds 1250 mm and is evenly distributed over the year to an extent that on average 225 or more rain days (>0.2mm day$^{-1}$) per annum occur (Van der Schaff 2002a). Raised bogs require a minimum precipitation of 700 mm/ year under sub-oceanic climate conditions to exist. Evapotranspiration must be less than 550 mm/ year, meaning an effective rainfall amount of at least 150 mm/ year is necessary, implying a minimum of 100 mm/ year of surface water runoff is required to keep the bog surface wet enough to support sphagnum growth. Raised bogs require less effective rainfall (even as low as 300m/m year) than blanket bogs as topography limits their drainage.

As such, in bog systems, precipitation must exceed potential evapotranspiration in almost every year. These conditions are required to permit peat to accumulate above the level of the mineral ground or the influence of telluric water (Leene and Tiebosch, 1993; Van der Schaaf, 2002a). Figure 2.3 illustrates the various flow paths within the main body of the bog, the catotelm.

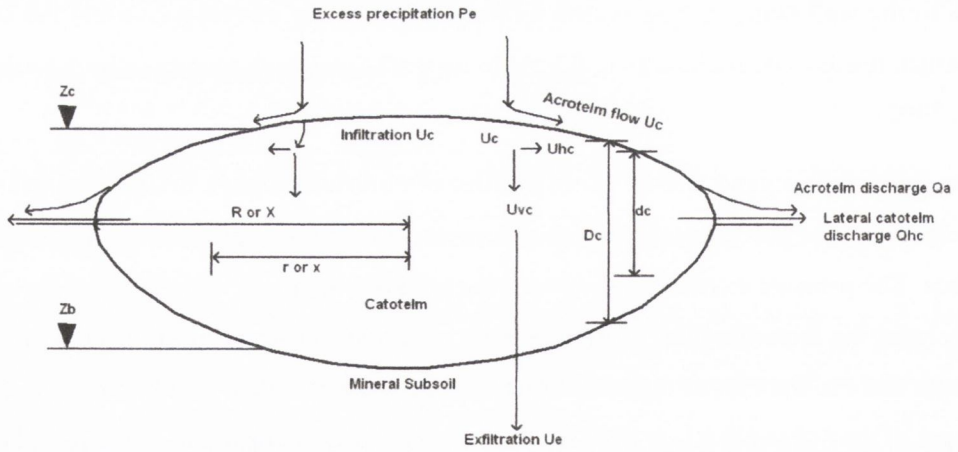


**Fig. 2.3.** Flow pathways in the catotelm peat body (after Van der Schaff, 1999)

Water that infiltrates into the acrotelm 'layer' is referred to as $P_e$, and is essentially surplus water from precipitation that has not been lost to evapotranspiration (i.e. effective rainfall) and is expressed in equation 2.8 [L T$^{-1}$]:

$$P_e = P - ET \qquad \text{Equation 2.8}$$

In the acrotelm, which may be considered to be the main 'aquifer' of an undisturbed raised bog, $P_e$ splits into two flow components, the acrotelm flow rate ($U_a$) and the infiltration rate ($U_c$) to the catotelm peat body.

### 2.6.2. Evapotranspiration

Evapotranspiration is a major component of the wetland water budget as it is the mechanism by which most water lost is lost from the wetland catchment area. Regardless of the fundamental difference in water supply of fens and bogs, evapotranspiration ($ET$) is always a large component of the water balance of each system (Fraser et al., 2001; Lafleur et al, 2005) and, thus, can be a key determinant of ecological functioning.

Evapotranspiration from a terrestrial ecosystem such as a wetland is considered to be the sum of three processes: (1) direct evaporation, which is the water that vaporizes from water or soil in a wetland, (2) transpiration, which is the moisture that passes through vascular plants to the atmosphere (Mitsch & Grosselink, 2007) and (3) interception loss, which is a measure of the evaporation of water from plant surfaces which have been wetted by rain, dew or fog (Ingram, 1983). As such, the physical process of water transport drives the evaporative processes (Shimoyama et al, 2004). Measuring each of the water loss components separately is difficult, and often not necessary, and therefore it is practical to measure evapotranspiration as a single process. It is also necessary to distinguish between *potential evapotranspiration*, which is the maximum water loss rate, and *actual evapotranspiration*, which is the amount of water that is actually removed from the surface.

In bog habitats, evapotranspiration from the system is the most important long-term water loss and accurate measurement of this component is critical in water balance studies. As the volume of water lost by evaporative processes on wetlands is controlled by the water availability on the surface of the wetland, a large volume of literature exists on the processes controlling evapotranspiration from the wetland surface and the variety of methods used to calculate relative evaporative fluxes to the atmosphere (see Drexler et al, 2004, for a comprehensive review of these methods).

The actual evapotranspiration of bogs and fens can be measured (1) directly by using lysimeters which are large containers holding soil and plants and used to measure changes in soil moisture content (2) using micrometeorological methods such as the Bowen ratio energy balance and (3) empirically using methods such as the Penman-Monteith mode of calculation, which accounts for both radiation and aerodynamic contributions of energy for the vaporisation process. Indirect methods are ultimately based on the energy balance equation, which accounts for all the sources and losses of energy that are available for vaporising water. The formal, steady-state, energy balance equation is given by:

$$R_n = G + H + \lambda E + M \qquad \text{Equation 2.9}$$

where $R_n$ is the net radiation (or radiation surplus), $G$ is the heat flux transfer to and from the soil and water, $H$ is the sensible heat flux density, $\lambda E$ is the latent heat flux, $M$ is the energy flux used for photosynthesis and respiration, and $S$ is the energy transfer into and out of plant tissue (after Drexler et al, 2004).

The Penman-Monteith formula is expressed as:

$$\lambda E = \frac{\Delta(R_n - G) + \rho C_p(\frac{e_a - e_d}{r_a})}{\Delta + \gamma^*} \qquad \text{Equation 3.0}$$

where $\Delta$ (kPa °C-1) is the slope of the saturation vapour pressure curve at air temperature T (°C), $\rho$ is the density of air, $C_p$ is specific heat of air, ($e_a - e_d$) is the saturation deficit, $r_a$ is the net resistance to diffusion through the surfaces of the leaves and soil and $y^*$ is s a modified psychrometric constant that accounts for surface resistance to water vapour flux (after Drexler et al, 2004).

It is not possible to go into the details of the physics behind atmospheric energy fluxes for this review and their various modes of calculation. However, the energy available for evaporation is a controlling factor on the evaporative flux at any one time as it is the radiant energy that vaporizes the available water. As such, it is the surface energy exchanges and atmospheric fluxes that influence the temperature and wetness of the soil surface layers of a wetland (Kellner, 2001). It is therefore important to quantify the energy balance components in order to understand how different factors influence these terms and how they can be represented by physically-based models (Kellner, 2001) such as the Penman-Monteith equation. In the study of actual evapotranspiration from Clara Bog and Pollardstown Fen, Doležal (2008) and Kuczyńska (2008) respectively, considered the empirical Penman-Monteith equation mode of calculation to be the most feasible way of characterising the bog micrometeorology. Such methods are dependent on micrometeorological factors, as well as on the surface characteristics, and ultimately describe evaporation from a vegetated surface in any state of water stress (Campbell & Williamson, 1997).

The availability of water for evapotranspiration depends in a complex way upon the physical and physiological nature of the surface and its interaction with the water table (Lafleur, 1990). It has been long recognised, that the type of vegetation cover is an important control on transpiration fluxes. Indeed, different functional groups of vegetation may have different levels of water conductance to the atmosphere (Lafleur, 1990). Ingram (1983) found that vascular plants, in particular, have a large influence on wetland evapotranspiration. The presence of non-vascular *Sphagnum* on raised bogs is also important. Streefkerk & Casparie (1989) found that the evaporation of peat moss vegetation is higher than that of open water during the winter months, though less in the summer months during its period of growth. Shimoyama et al (2004) also recognised the importance of understanding both

vascular plant transpiration and Sphagnum moss evaporation when determining total wetland evapotranspiration. As such, a combination of vegetation, surface topography, water table fluctuation, saturation deficit and energy supply are important parameters controlling the evapotranspiration flux from peatlands.

### 2.6.3. Water levels

Water level measurements, which are closely connected with a number of the elements in the water balance equation, in various parts of a peatland serve the basis on which to construct a wetland water balance. Water table (where atmospheric pressure is equal to water pressure) and piezometric water level information, in conjunction with the hydrological properties of the substrate, allow for the calculation of various hydrogeological parameters including storage coefficients and specific yields, hydraulic gradients and seepage velocities.

Peatlands tend to have a high water table and this is significant in terms of sustaining its distinct ecology, as the ground surface remains almost wholly saturated. The occurrence of any plant association/ community (i.e. units of vegetation characterised by a distinctive species composition) and its constituent species is always a result of their adaptation to the whole external environment (Ivanov, 1981). The position of the water table in wetland soils undoubtedly exerts a major influence upon the distribution and performance of plant species and the composition of vegetation (Wheeler, 1999). The relationship between vegetation and water is therefore of undoubted importance to the character of any given wetland. This is particularly the case on raised bogs where the occurrence of all peat-mosses (Sphagna), the most characteristic plant on raised bogs, is tied to very wet conditions (Streefkerk & Casparie, 1989). Mosses may be considered to be constant and sensitive indicators of the long-term level of the water table (Ivanov, 1981) and are therefore important species to characterise in raised bog systems, changes in which signify a change in the local hydrological dynamics.

### 2.6.4. Storage

In conventional hydrogeology, the concept of the storage coefficient, or storativity ($S$), is an important one and refers to the volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head (Fetter, 2001). It is a dimensionless quantity with values between 0 and 1. Raised bogs are typically characterised by having a large storage coefficient value. In the catotelm, peat is permanently saturated and little water is released from storage, either laterally or to the subsoil beneath. However, in the acrotelm, the phreatic surface, or 'free' water table, fluctuates, meaning it is periodically aerated. Similar to hydraulic conductivity, compression and decay processes control the storage coefficient value, which is essentially the amount of water an aquifer can release or take into storage. As the acrotelm is not completely humified, like that of the catotelm, the upper parts of the acrotelm, where there is living vegetation and vegetation in a state of decay, will invariably

transmit greater quantities of water that the underlying catotelm. As such, in a living bog the storage coefficient ($\mu$) is a property of the acrotelm as it is in this zone in which the phreatic surface fluctuates (Van der Schaff, 1999).

As discussed previously, hydraulic conductivity is essentially the ability of water to move through an earth material. The porosity of the material will, to a large extent, govern the quantity of water that can be transmitted, thereby strongly controlling the materials hydraulic conductivity value. The volume of water that an aquifer can take into or release from storage for a given change in head, or water level, is therefore often determined by its porosity. By its nature, the acrotelm will have larger pore sizes that the catotelm, particularly close to the bog surface. As such, the storage coefficient value ($\mu$) of the acrotelm is generally large (between 0.4 and 0.8; Van der Schaaf and Streefker, 2002) and is a function of the proportion of large pores within the layer and also as a result of the bogs micro-topography where there are often surface water bodies on the bog surface, thereby increasing the $\mu$ value. The change of $\mu$ with depth of the phreatic level will also indicate the transition of hydrophysical properties from the acrotelm to the catotelm (Van der Schaff, 1999).

*Factors influencing the storage coefficient ($\mu$)*

Sijtsma & Veldhuizen (1992) considered the storage coefficient ($\mu$) to be the ratio of the water quantity (mm) added/ subtracted to the change in water table (mm). They considered the following factors to affect the value of $\mu$:

- The phreatic level – it is assumed $\mu$ increases with higher water tables.
- "Mooratmung" – in 'healthy' raised bogs, changes in surface level over the course of a year will also alter the density of the acrotelm.
- Time – pore-size distribution will determine the amount of time it takes for the acrotelm to become completely de-aerated as air bubbles can become trapped following heavy rainfall events.
- Acrotelm development – it is assumed that a better-developed acrotelm will have a higher $\mu$ due to a higher proportion of pores.

Van der Schaff (1999) found a distinct relationship between specific storage and phreatic level. Such a relationship results in the value of $\mu$ decreasing with increasing depth of the phreatic level. Van der Schaff (1999) found that $\mu$ decreases from approximately 0.4 at the surface to < 0.2 at a depth of 0.15 m, with an average $\mu$ value of 0.3 in the upper 0.15 m of the acrotelm and an average $\mu$ value of 0.4 in deeper sections of the acrotelm. In degraded acrotelms $\mu$ lies below 0.2 and where there are areas of open water, such as in hollows, $\mu$ is as high as 0.8. As such, the importance of the storage coefficient in bog hydrology lies in it relation to fluctuations of the water level, because it is inversely

proportional to the change of the phreatic level caused by a change in the amount of water stored in the bog (Van der Schaff, 2002b).

### 2.6.5.Runoff

As precipitation exceeds evapotranspiration in bog systems, runoff on the surface and subsurface is an important component of water balance computation. Water movement through the catotelm is considered to be very slow (Van der Schaaf, 1999; Bragg, 2002) and little water escapes from the main bog body via lateral discharge. In contrast, the acrotelm, in a functioning raised bog (i.e. actively accumulating peat), is a much more dynamic system and the zone where most of the bogs hydrological processes take place; such as the conversion of precipitation to discharge, changes in water storage and alternating aerobic and anaerobic conditions (Van der Schaff, 1999).

Thus, in terms of water discharge from the bog surface and the fluctuation of the 'free water table', or phreatic surface, there are two main mechanisms that determine a bogs response to precipitation and evapotranspiration processes (Van der Schaff, 2002): (1) The rapid decrease in hydraulic conductivity from the surface down into the catotelm and (2) the storage properties of the acrotelm which ultimately depend on the condition of the catotelm and the local micro-topography of the bog. Both mechanisms are effectively controlled by the degree of decomposition with depth (Van der Schaff, 2002). As such, because of the sharp downward decrease in the hydraulic conductivity, the transmissivity of the acrotelm strongly depends on the level of the water table and is a regulating system for the outflow of water from a raised bog (Van der Schaff, 2004).

In an intact raised bog the annual fluctuation of the phreatic water table is less than 0.30 m (Kelly & Schouten, 2002). The large storage coefficient of the acrotelm is crucial in limiting fluctuations of the water table. The hydraulic conductivity in the acrotelm decreases rapidly with depth (Van der Schaff and Streefkerk, 2002). The hydraulic gradient in the acrotelm is approximately equal to the surface slope and is therefore transmissivity-controlled (Van der Schaaf, 1999). When the water table in the acrotelm drops, transmissivity decreases thereby reducing discharge from the high bog. In this instance, there is less water on the bog to keep it in a suitably saturated condition. The transmissivity of the acrotelm strongly depends on the level of the water table and is a regulating system for the outflow of water from a raised bog (Van der Schaff, 2004). Discharge through the acrotelm is a therefore a key measure by which to assess the hydrological condition of a raised bog – i.e. a measure of the *acrotelm capacity* on the high bog and the potential for active peat accumulation. Figure 2.4 schematises a streamline, through a catchment area, on a hypothetical bog surface. Acrotelm discharge ($Q_a$) can be calculated, using a Darcy Law groundwater flow-type equation, as follows:

$$Q_a = -T_a \frac{dH}{dL} w \qquad \text{Equation 3.1}$$

where $T_a$ is the transmissivity of the acrotelm [$L^2T^{-1}$], d$H$/d$L$ is the hydraulic gradient and w is the width of the flow path [L].

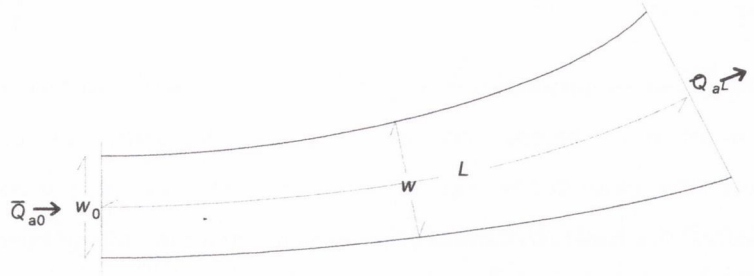


**Figure 2.4.** Flow path length (L) between two streamlines (Ten Heggler et al, 2004).

The research by Van der Schaff (1999) concludes that the hydraulic gradient in the acrotelm aquifer is determined by the shape of the catotelm, which is approximately constant in time, and that acrotelm flow is not directly controlled by a varying hydraulic gradient, but by transmissivity, which in turn is controlled by the phreatic level. As such, discharge virtually ceases at low phreatic levels, preventing further losses of water, and high discharge values occur at high phreatic levels, ensuring a quick release of water. In areas with shallow acrotelms, Van der Schaff (1999) found that phreatic levels often reached the surface resulting in high discharge, whereas in areas with a well-developed acrotelm, discharge is regulated, as the slope is less than 0.5% (Van der Schaff, 2002b). As such, man-induced drainage, which increases the slope of the bog surface, destroys the natural drainage system of the acrotelm, often within a period of 10 years (Van der Schaff, 2002b). Where there is no acrotelm development, discharge from the bog surface is not regulated and water will therefore move as overland flow from the bog surface.

Surface water discharge from peatlands occurs when the phreatic level is at the surface, thereby highlighting the importance of a well-developed acrotelm in attenuating surplus precipitation. The acrotelm may also be considered to exist in blanket bogs (Holden & Burt, 2003b) and fens (Kvaerner & Klove, 2008), as well as raised bogs on which the research described above is based. Indeed, Kvaerner & Klove (2008) found that during high flows, surface water runoff from the landscape surrounding a boreal flat fen in Norway was attenuated and delayed within the fen acrotelm, whereas at low flows, runoff at the fen outlet was generated from shallow subsurface flow in the acrotelm.

Little study has been conducted on the runoff behaviour from Irish blanket bogs. Research in Britain and Canada by Price (1992), Evans et al (1999) and Holden & Burt (2003a) demonstrate that intact and degraded blanket bogs are extremely productive of runoff and have flashy regimes, as indicated by hydrograph analysis, with little base flow contribution. This indicates that blanket bogs do not attenuate rainfall excess to the same extent as relatively intact raised bogs or fens, which are situated in lower elevated areas on the landscape. Holden & Burt (2003b) therefore suggest that blanket bog catchments tend to be sources of flooding and water to rivers in upland headwaters rather than

attenuators of flow. Holden & Burt (2003b) also highlight that there are other flow pathways on blanket bogs not confined to the acrotelm, namely water flow from subsurface soil pipes and macropores within the blanket peat, each of which contribute to outflow discharge from blanket bogs.

### 2.6.6. Vertical and lateral seepage

The hydrological properties of peat as a geological medium invariably control the ability of water to move through the peat profile in of a bog body. Of particular interest it was highlighted that permeability (or hydraulic conductivity) and water yield of humified peat substrate (i.e. the catotelm) are important physical characteristics controlling hydrological processes in bog systems. As the catotelm contains peat of different botanical compositions, age, compaction and state of decay, its hydraulic conductivity ($k$) value will vary according to these characteristics, thereby influencing the flow of water, vertically and horizontally, through the catotelm body. The catotelm is permanently saturated (except in disturbed bogs where there is no acrotelm, thereby exposing the catotelm peat to the surface) and though the peat material composing the catotelm itself can contain more than 90% water, the amount of water that actually moves through the body of peat and discharges to its surrounding is minimal. This small outflow of water from the catotelm is essential for its sustainability (Van der Schaff, 1999).

In the catotelm, water will move both vertically ($U_{vc}$) and horizontally ($U_{hc}$). Water will also escape at the base of the catotelm to the underlying subsoil, and this is referred to as the exfiltration rate ($U_e$), which is equal to $U_{vc}$ (Van der Schaff, 1999). All of these flow rates ($U$) have dimensions [L $T^{-1}$] that, when integrated over the bog area, may be expressed as discharge fluxes ($Q$) with dimensions [L $T^{-3}$]. It is often more practical to work with specific discharge ($v$), or Darcian velocity/ flux, which may be defined as the average flux density of a flow component over an area (i.e. $v = Q/A$), thereby giving it a dimension of [L $T^{-1}$]. The water balance of the catotelm over a bog area may therefore be written in terms of $v$ as:

$$v_{vc} + v_e + v_{hc} = \frac{dS_w}{dt} \qquad \text{Equation 3.2}$$

where $S_w$ is specific storage [L] and $v_e$, $v_{vc}$ and $v_{hc}$ are $U_e$, $U_{vc}$ and $U_{hc}$ respectively, averaged over a bog area.

In order to deduce the flux densities of the catotelm, Van der Schaff (1999) developed the components $C_c$, which is the local vertical 'resistance' between two hydraulic head measurements in the peat profile, and $T_c$, which is the catotelm transmissivity between two piezometric water level points, for estimating vertical and horizontal fluxes respectively. As such, the following equations were developed assuming isotropy and perfect horizontal layering where $k$ changes in the vertical direction only

$$T_c = \int_{z_B}^{z_C} k(z)dz \qquad \text{Equation 3.3}$$

and

$$C_c = \int_{z_B}^{z_C} \frac{1}{k(z)} dz \qquad \text{Equation 3.4}$$

where $z$ [L] is the vertical position of the $k$ value, $z_C$ is the vertical position of the surface of the catotelm [L] and $z_B$ is the vertical position of the base of the catotelm [L].

*Lateral seepage*

As such, values of specific catotelm lateral discharge ($v_{hc}$) were estimated by van der Schaff (1999) using values of $T_c$ located on specific flow lines on the bog, piezometric levels and from horizontal hydraulic gradients of hydraulic head. Van der Schaff (1999), estimated $v_{hc}$, at a site $i$, with the following equation:

$$v_{hc} \approx \frac{T_c(i)}{x_i} \frac{dh(x)}{dx} \qquad \text{Equation 3.5}$$

where $x_i$ is the distance to the catchment boundary and $dh(x)/dx$ the hydraulic gradient.

Van der Schaff (1999) found that the specific catotelm discharge for different 'sites' on Clara Bog West varied by some orders of magnitude with lateral flow generally decreasing towards the marginal areas. However, van der Schaff (199) considers a $v_{hc}$ value between 0.5 and 1.0 mm $a^{-1}$ to be a representative value of lateral catotelm flux rate. Van der Schaff also concluded that due to the low lateral outflow values, the reduced $T_c$ values at the bogs margins, which effectively dictate the $v_{hc}$ value, have no function in preventing the bog from drying out. Thus, as lateral seepage from the catotelm body is minimal, the horizontal outflow from raised bogs may be confined to that in the overlying acrotelm body and bog surface when the acrotelm is absent.

*Downward seepage*

The catotelm peat body will invariably loose water to the underlying subsoil. Quantifying this water loss is an important part of the water balance equation. In intact bog systems, the downward infiltration rate should be in the order of 400 mm/ year (Streefkerk & Casparie, 1989). To calculate exfiltration, or downward seepage, from the catotelm, Van der Schaff (1999) used the component of vertical resistance in the catotelm, $C_c$, and the differences between piezometric levels at different depths. As such, Van der Schaff (1999) developed the flowing equation, a variant of the specific discharge equation, to estimate the vertical component of a flow rate over a depth interval:

$$U_{vc} \approx -k_v \frac{dh}{dz} \approx \frac{(h_1 - h_2)}{C_C(z_1, z_2)} \qquad \text{Equation 3.6}$$

where $U_{vc}$ is the vertical component of flow rate density in the catotelm [$LT^{-1}$], $z$ is the vertical position ($z_1 < z_2$ meaning $z_1$ is the deepest position) [L], $h_1$ and $h_2$ are the piezometric levels at vertical positions $z_1$ and $z_2$ respectively [L] and $C_c$ ($z_1$, $z_2$) is the vertical resistance of the catotelm between vertical positions $z_1$ and $z_2$ [T].

As mentioned previously, at the bottom of the catotelm, $U_{vc}$ is identical with exfiltration, $U_e$. However, this assumption neglects the exchange of water with horizontal fluxes, $U_{hc}$, as well as the uncertainties in calculating $C_c$. However, Van der Schaff (1999) considers these uncertainties to be negligible when averaged out over an area covering several hectares and that a realistic value of $U_e$ can be estimated on the scale of a bog.

Van der Schaff (1999) estimated values of $U_e$ based on depth intervals between piezometers at adjacent depths. As discussed in section 5, due to the anisotropic nature of peat, hydraulic conductivities will vary through the peat profile. However, anisotropy decreases with depth due to the increasing degree of humification and it can be assumed that large differences do not occur between the horizontal and vertical permeability, at comparable depths below the bog surface (Streefkerk & Casparie, 1989). As such, Van der Schaff (1999) found that $U_e$ was most reliably estimated by using the deepest pair of piezometers from a particular site/ piezometer nest, thereby reducing the effects of anisotropy.

Van der Schaff (1999) has estimated that the specific exfiltration discharge $v_e$ of Raheenmore Bog lies between 10 and 15 mm $a^{-1}$, while in Clara Bog West it lies between 5 and 10 mm $a^{-1}$. Values of $v_e$ were also found to decrease from the central areas to the marginal areas of both bogs, where the vertical resistance $C_c$ also tends to have its largest values (van der Scahff, 1999). Compared to the lateral discharge values, it is clear, that the discharge through the catotelm is greater in the vertical direction than in the horizontal direction.

### 2.7. Overall water balance

It is rare that the individual components of a water balance study are calculated directly. Rarer still, is the formation of a water balance for a single raised bog entity and examples in the scientific literature are scarce. However, the Irish-Dutch research project in the early 1990's greatly enhanced the hydroecological understanding of how raised bog systems worked and functioned and led to the quantification of the water balance for Clara Bog and Raheenmore Bog.

Figure 2.5 illustrates a schematic representation of the flow processes that occur in the Clara Bog area and summarises the water balance procedure and a full water balance between July 1992 and July

1993, quantified by Leene & Tiebosch (1993) and later adjusted by Van der Schaff, (1999), is presented in Table 2.3.

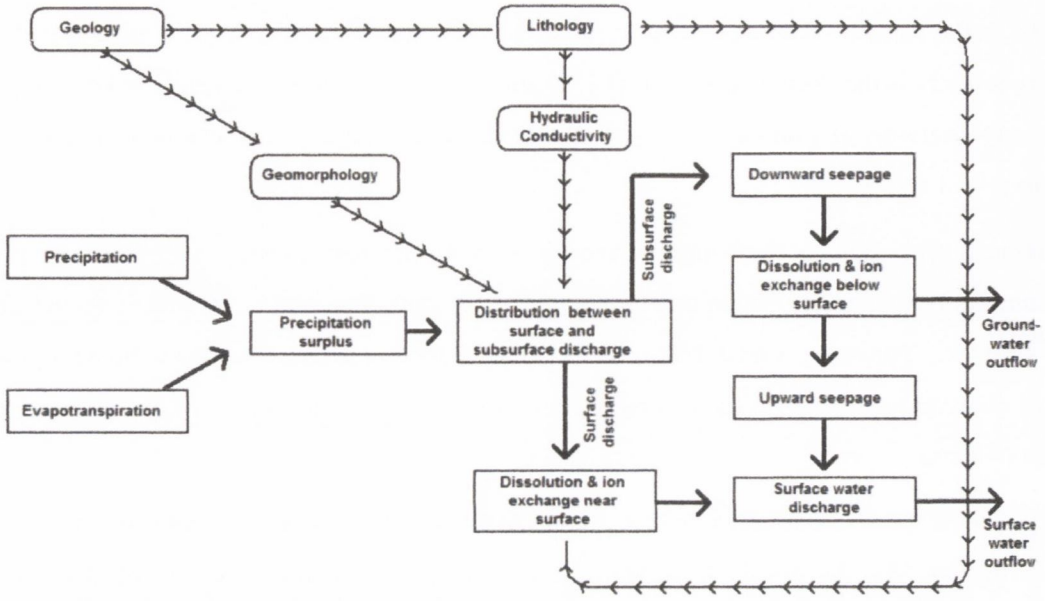


**Fig. 2.5.** Schematic representation of flow processes that occur in Clara Bog (Van der Schaff et al, 2002).

Table. 2.3. Water balance of Clara Bog West from July 1992 to July 1993 (Leene & Tiebosch, 1993; Van der Schaff, 1999; Van der Schaff 2002b).

| Component | Aug | Sept | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Precipitation** | 101 | 87 | 40 | 100 | 59 | 97 | 11 | 41 | 117 | 102 | 105 | 62 | 922 |
| **Evapotranspiration** | -66 | -32 | -23 | -14 | -15 | -21 | -25 | -44 | -62 | -98 | -86 | -87 | -573 |
| **Discharge** | -4 | -22 | -9 | -36 | -48 | -45 | -16 | -7 | -53 | -22 | -56 | -5 | -323 |
| **Vertical seepage** | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -8 |
| **$\Delta S_h$** | -24 | -9 | -3 | -17 | 14 | -7 | 17 | -4 | -6 | -9 | 18 | 6 | -24 |
| **$\Delta S_s$** | -7 | -6 | 0 | -13 | -9 | -1 | 11 | 0 | -9 | -1 | 9 | 11 | -15 |
| **Unexplained** | -1 | 17 | 4 | 19 | 0 | 22 | -3 | -15 | -14 | -29 | -11 | -14 | -21 |

Note: values are in mm. Inputs are positive; outputs are negative. Positive values in storage terms $\Delta S_h$ and $\Delta S_s$, which refer to storage by changing phreatic level and fluctuation of the surface level respectively, denotes release from storage. Evapotranspiration was calculated directly using lysimeters with a variety of vegetation types that occur on the bog. Discharge calculated using v-notch weirs installed on the main drain exiting the bog.

In most water balance studies, some components are worked out directly while others need to be calculated indirectly using empirical formula. The water balance is unique in that all of the components have been measured directly. The vertical seepage, or exfiltration rate, is extremely low in Clara Bog and Van der Schaff et al (2002) attributes this as a result of the extremely low permeability ($> 10^{-7}$) of the underlying lacustrine formation. Downward infiltration was also found to be < 40 mm/year at Raheenmore Bog over the same time extent. This implies that the bogs are isolated from the hydraulic head/ regional groundwater flows in the surrounding till and bedrock aquifer. The

unexplained sum is negligible and a natural consequence of moderate measurement inaccuracies applied to all of the components.

The water balance component rates are similar to rates measured in other raised bog systems. A review by Streefkerk & Casparie (1989) found that yearly evaporation from German and Dutch bogs was in the order of 550 mm. Similarly, downward seepage (or recharge to the regional groundwater table in subsoil units underlying a bog system) is generally 10 to 15 % of total yearly runoff (where minimum precipitation is 700 mm/ year).

### 2.8. Groundwater dependence

In recent years, wetlands that are sustained by groundwater flows, referred to as groundwater dependent terrestrial ecosystems (GWDTEs), has become important under the Water Framework Directive (WFD). GWDTEs may be defined as ecosystems for which current composition, structure and function are reliant on a supply of groundwater (Klove et al, 2011). Figure 2.6 illustrates a conceptual water balance model, based on Lloyd & Tellam (1995), for groundwater fed wetlands. The figure illustrates a generalised wetland overlying a subsoil or bedrock aquifer in which groundwater is a component of the water balance.

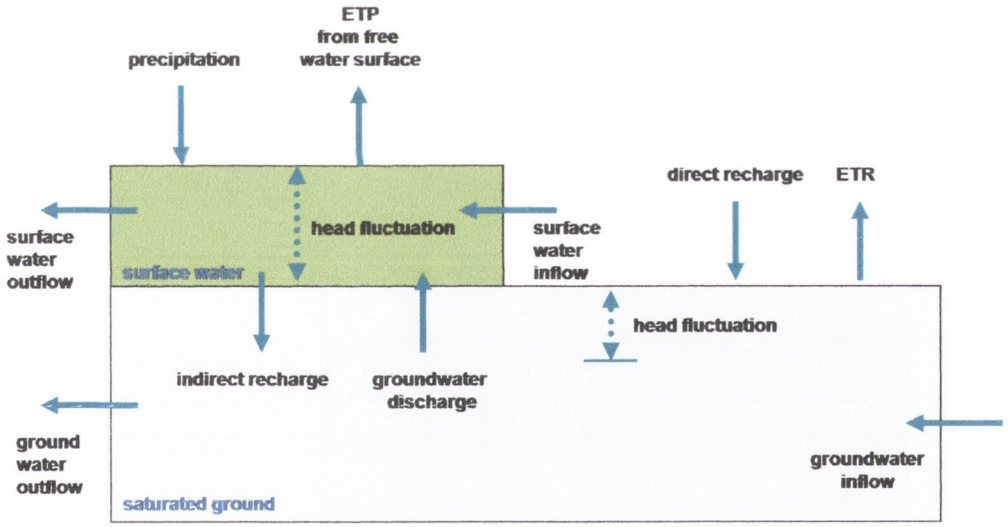


**Figure 2.6.** Generalised conceptual water balance for groundwater fed wetlands (after Lloyd & Tellam, 1995).

Due to their mode of formation and presence of an underlying relatively impermeable substratum such as a significant thickness of lacustrine clay, bogs are generally isolated from the regional groundwater table and therefore receive or discharge minimal water to the groundwater table (Ingram 1982; Bragg, 2002), though the research presented in this thesis will indicate this is not always the case. The water balance of fens however is intrinsically linked to piezometric water levels in adjacent groundwater bodies. While effective rainfall (i.e. infiltrating water that is not lost to evapotranspiration or surface water outflow) is generally the sole water source/ input in bogs, groundwater is often the predominant water source in fens.

In terms of groundwater dependent wetlands, such as fens and flush systems on blanket bogs, where there is a local hydraulic connection with regional groundwater (Regan, 2007), Lloyd & Tellam (1995) suggest that there are two fundamental settings: (1) groundwater fed wetlands associated with an independent surface water body and (2) groundwater through-flow wetlands, which are predominantly independent of extraneous surface water bodies. These broad settings are illustrated in Figure 2.7 and it is clear from the diagram that the first wetland setting is a zone of groundwater discharge adjacent to a surface water body whereas the second setting is a zone of recharge and discharge within a topographic depression. Thus, identifying, and differentiating between, a groundwater component in a peatland system is essential for its classification and water balance calculation. Attention should also be drawn to the margins of raised bogs where, in pristine conditions, there exists a *lagg* zone, which is an area where mixing of groundwater and precipitation takes place (Streefkerk & Casparie, 1989), therefore giving rise to vegetation characteristic of bog and fen environments. Similar to the margins of a fen, groundwater supply at the lagg zone is sensitive to water levels in the adjacent groundwater body, and thus sensitive to relative water level and land-use changes, particularly those associated with drainage.

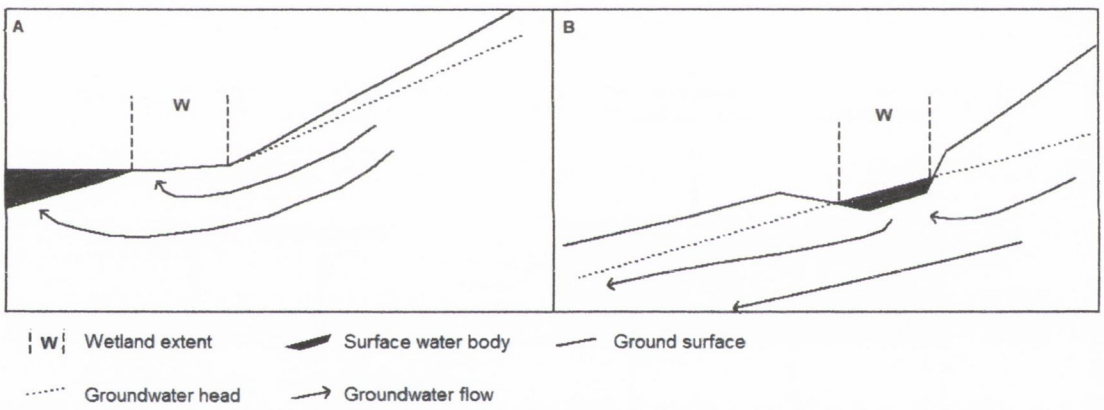


**Figure 2.7.** Settings of groundwater fed wetlands. (a) Wetlands adjacent to surface water bodies with extraneous head controls. (b) Wetlands adjacent to surface water bodies without extraneous head controls (i.e. surface water head is controlled by wetland discharge) [after Lloyd & Tellam, 1995].

However, the role of groundwater in raised bog system dynamics is poorly understood. It is clear that peatlands can have a direct dependence on groundwater; however, peatlands such as raised bogs can have a direct dependence on groundwater. Fens receive a continuous supply of groundwater and bogs receive only precipitation on the surface but groundwater pressure provides buoyancy and prevents drainage (Klove et al, 2011). Raised bog reliance on groundwater only becomes apparent when the supply of groundwater is removed for a sufficient length of time that changes in plant function (typically rates of water use decline first) can be observed (Klove et al, 2011). Damage to peatlands has been noted after tunnel construction in Norway (Kvoerner and Snilsberg, 2008), due to leaking of groundwater and lake and peat water to the tunnel through fracture zones in crystalline rocks (Figure 2.8); Klove et al, 2011.

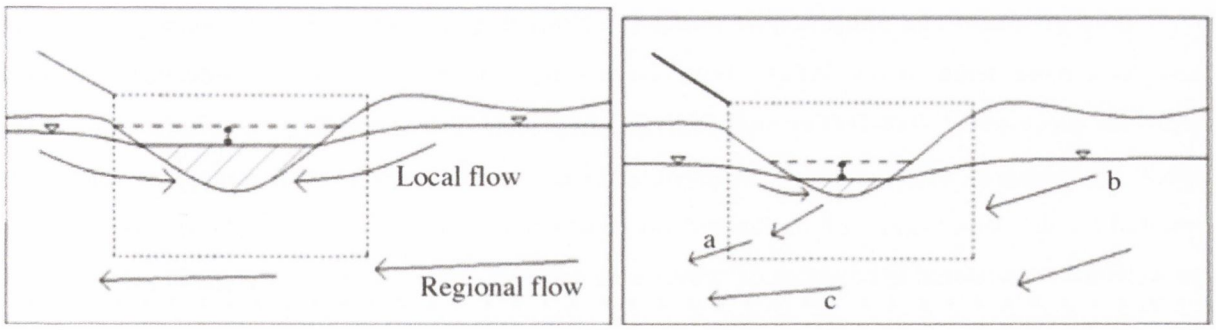


**Figure 2.8.** Conceptual presentation of flow paths in a GDE before and after lowering of the groundwater level (Klove et al, 2011)

In normal conditions, the water table and flow velocity in wetlands located in a depression depend on the local water balance or surplus of water. In a stable situation the regional flow has little or no impact on the variation in the water balance components of the wetland (Klove et al, 2011). However if hydrological modifications occur, then these may become apparent in the regional flow patterns. A reduction in regional flow will then increase the flow from the wetland to the deeper groundwater and result in a decrease in the water level and dryer conditions. This was seen in Norway, where peat surfaces were compacted and degraded after drainage for tunnel construction (Kvoerner and Snilsberg, 2008). Excavation, tunnel construction and mining have caused severe impacts by reversing flow patterns, causing wetland desiccation. The review by Klove et al (2011) demonstrates the potential support function of regional groundwater in raised bog maintenance.

## 2.9. Hydrological sustainability of peatlands

### 2.8.1. Environmental supporting conditions

Water is the crucial element sustaining peatland ecosystems and understanding how a particular wetland system works hydrologically is imperative for their management and long-term sustainability. The components of the wetland water balance, as dictated by its position in the hydrological cycle, are the basic framework on which to assess how a particular wetland system is maintained and functions. It was highlighted in section 2.3 that the mechanism by which water is supplied to the wetland is controlled by geological and geomorphological factors. As such, the hydrodynamics of bogs and fens are determined by the characteristics of their main water sources and sinks, and the interaction of these with the topography of the site and its wetland substratum, peat. Indeed, the nature of peat as a medium and its unique hydrological properties within the bog body controls how water moves into, through and out of a peatland. Quantifying this flux of water is critical in the water balance calculation.

Bogs and fens, by their composition and position in the hydrological cycle, are particularly sensitive to anthropogenic activities and pressures. Indeed, even slight changes in their hydrological regime can impact on hydro-ecological functioning. In recent years, the protection of water bodies has led to the development of the Water Framework Directive (WFD), a legally binding European Union legislation

to its member states. The protection of wetland habitats that are sustained by regional groundwater flows is a basic tenet of the WFD. Such systems are considered to be 'groundwater dependent terrestrial ecosystems' (GWDTEs) and understanding their 'environmental supporting conditions', which are primarily represented by their dependency on the prevailing hydrological regime, is essential for the conservation of wetlands. Consequent restoration measures can be developed when the wetland is considered to be at risk of 'significant damage' due to local anthropogenic pressures.

Kilroy et al, 2009 defined GWTDEs as those that depend on a significant proportion of their water supply (quality and quantity) from groundwater. Fig. 2.9 illustrates a conceptual framework model, devised by Kilroy et al (2009), which may be used for assessing the environmental supporting conditions of GWTDEs under the WFD. The x, y and z-axes demonstrate the variability in groundwater level, groundwater contribution and the degree of mineralisation respectively. Thus, the axes incorporate the main geohydrological and hydrochemical attributes of GWDTEs and represent the main intrinsic groundwater conditions required by different wetlands to maintain their habitats in good condition (Kilroy et al, 2009).

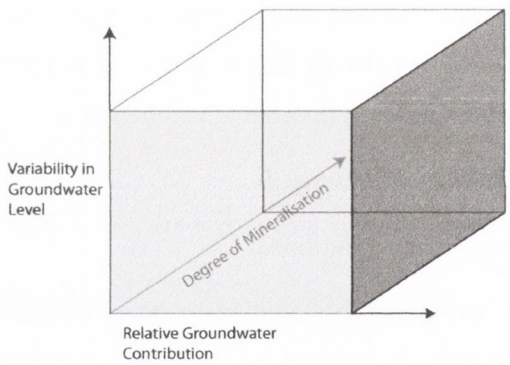


**Fig. 2.9.** A conceptual framework encompassing the main environmental supporting conditions of GWDTEs. The location of a particular habitat within the cube highlights its key geohydrological and hydrochemical supporting conditions (Kilroy et al, 2009).

By this reasoning, though fen systems are obvious GWTDEs, the protection of raised bogs is not clear or absolute as such systems are generally fed wholly by rainfall and isolated from the regional groundwater table. The development of an acrotelm layer, which supports *Sphagnum* growth thereby constituting 'active' peat accumulation, is dependent on a shallow surface slope on the bog (< 0.5 %), micro-relief and the length of surface water flow pathways; not on groundwater flow *per se*. However, research by Klove et al (2011) indicate a support function from groundwater pressure and this idea is central to the postulations made to describe the dramatic hydro-ecological changes of Clara Bog in the proceeding thesis.

### 2.8.2.Hydrological drivers

The sustainability of a peatland as an ecosystem depends on an understanding of the hydrological mechanisms at work. The environmental supporting conditions of a peatland, as illustrated in Figure

2.9, are ultimately controlled by the hydrological driver(s) sustaining the ecosystem. For instance, the hydrological driver to a fen system is an upward gradient and flow of mineral rich groundwater (Kuczyńska, 2008). The maintenance of the acrotelm in raised bog systems is crucial and subsidence of the bog surface, as a result of shrinkage in the peat body due to drainage, reduces the areal extent of acrotelm on the bog surface and ultimately ecologically important ecotopes. In this case, a groundwater connection is undesirable as, when the geological conditions allow a connection between the high bog and regional groundwater table via the absence of a stratigraphy with a hydraulic resistance, water losses are enhanced as there is a downward vertical pathway for seepage in the bog body. In this case, Clara Bog may be placed at the front of the cube in Figure 2.9. In conventional terms the bog has a low groundwater dependency overall, but a drop in regional groundwater table, even if only a localised phenomenon, implies that a high bog-regional groundwater connection has developed. The bog, as a whole, should therefore be considered groundwater dependent, albeit indirectly. As such, in Figure 2.9, variability in groundwater level, particularly a decrease over time, is undesirable.

## 2.10. Conclusions

### 2.9.1. Hydrology and sustainability

The sustainability of peatlands is intimately related to the understanding of their role as wetlands. As such, the hydrology is a key context within which to consider sustainability. Peat as a naturally developing medium requires prolonged saturated conditions and the maintenance of that condition requires a good understanding and management of the components of the hydrological cycle as well as the characteristics of the peat itself. Natural peat conditions require the right balance between inflows and outflows (rainfall, evapotranspiration and surface and groundwater discharges). Peat in its natural condition can only be sustained when the balance of inflows sufficiently exceed the outflows which, in turn, will partly depend upon the morphology of the particular peatland. In Ireland, peatlands are understood to comprise mountain and coastal/lowland blanket bogs, raised bogs and fen peats. Where natural drainage is less constrained by topography as in blanket peats, a net rainfall (rainfall-evapotranspiration) of 1000 mm/yr prevails although in the steeper gradients of mountain bogs, evidence shows that some 1300 mm/yr is needed. However, where topography constrains drainage such as in raised bogs, less excess rainfall is required, down to as little as 300mm/yr. Fen peats are essentially driven by groundwater/nutrient inputs and the recharge and upgradient hydrogeological storage feeding seepages and springs governs the sustainability of fens.

Understanding the water balance of a given peatland is thus the key to its maintenance, or to its restoration where it has been cutaway or partially impacted by cutting. The functioning of peatlands, including their role in maintaining biodiversity, in controlling their greenhouse gas/carbon emissions, and in attenuation of water quality all depend upon maintaining near natural hydrological conditions.

Isolated, but significant, research over many years has been undertaken in Ireland to identify more precisely what the appropriate hydrological indicators should be. This work has been undertaken particularly for raised bogs, encapsulated in the research undertaken on the raised bogs in County Offaly (Clara and Raheenmore) partly under the aegis of the Dutch-Irish project, which has continued for over 20 years. Moreover, hydrological sustainability of fen peatland has been explored extensively in Co. Kildare (Pollardstown Fen) and in smaller locations within blanket bogs in North Mayo. Nevertheless, the hydrological understanding of peatland functioning is still needed in the face of often complex hydrogeological conditions. The stimulus for improving this understanding is coming from the requirements of the EU Water Framework Directive which requires quantification of the linkages between wetland habitats and the relevant environmental/hydrological supporting conditions.

### 2.9.2. Hydrological conditions

While the broad water balance conditions for a peat wetland can be seen from mapping the relevant hydrological parameters, specific local conditions are often unique to the particular peatlands as described in this synthesis. An important characteristic in the functioning of active peatlands is the acrotelm which is a self-regulating layer on bogs and fens, storage in which regulates the amount of discharge from the bog. It is a crucial zone in both blanket and raised bog hydrology. Storm-flows will be attenuated and delayed within the acrotelm of both raised bogs and fens. The Irish-Dutch research conclusively found that a well developed acrotelm is effective in keeping water inside a raised bog and in attenuating the response of collecting streams and drains to high rainfall/ storm events. However, where there is an absence of a functioning acrotelm layer, surface runoff is increased and the bog no longer attenuates water flow. The preservation of a functioning acrotelm with a significant thickness (>0.2 m) is also important if a bog is to be considered 'active' and therefore retain the capacity to accumulate peat and continue to serve its function as a carbon store. Subsidence of raised bogs, which results from shrinkage of peat due to drainage, and can extend hundreds of metres from a face bank, is therefore a critical issue and the greatest challenge in raised bog/peatland conservation.

### 2.9.3. Hydroecological criteria

Hydrological requirements of peat wetlands are ultimately linked to the needs of dependent ecology. The hydroecological indicator species of raised bogs, *Sphagnum* species, occurs within specific zones on the surface of a high bog and has been shown to be very sensitive to even slight changes in surface level gradient, and will only develop in specific environments where water is allowed to accumulate and where acrotelm gradients allow. The correlation between the needs of a particular 'key' species and the relevant hydrological drivers is a further key criterion in determining the sustainability of a particular peatland habitat.

### 2.9.4.Cutaway peatlands

Similar criteria also apply to cutaway peatlands but their management requires an understanding of how the natural hydrological conditions have been altered by the removal of significant thicknesses of peat. Large scale harvesting of peat frequently occurs on raised bogs and cutover bog in Clara is characterized by a piezometric head from the underlying regional groundwater (in tills, gravels and limestone bedrock) naturally occurring within the peat of the original bogs. A consequence of harvesting is that the piezometric head now occurs above the base of the cutaway, causing artesian conditions and potential springs where the basal marl or clay is breached. Thus 'restoration' or rehabilitation needs to consider carefully the strategy/management objectives for any re-created wetland habitat, as water quality within and beneath the wetland could differ markedly and may now interconnect.

### 2.9.5.Summary

Identifying ecological indicators, such as the presence of *Sphagnum* species, in tandem with hydrological indicator information, such as piezometric water level, are crucial for assessing the long term sustainability of a peatland, whether relatively intact or cutaway. The environmental supporting conditions will differ in contrasting peatlands, but the identification of such conditions should inform how the peatland should be managed and maintained. A policy for peatland management must take account of the required hydrological supporting conditions, which necessitates an understanding and quantification of a water balance. While much is known about these conditions now in Ireland, there remains a need for developing a methodology or approach to systematically investigating and quantifying the hydroecological linkages which, nevertheless, may be peculiar to a given peatland. In turn, appropriate criteria will depend upon the overall policy objectives for peatland management.

# 3. The Geo-Hydrological Framework

## 3.1. Introduction and objectives

In chapter 1 the morphological changes of the Clara West high bog were briefly described and the assumption is that the changing Clara West high topography over time is a consequence of excess water loss from the high bog peat substrate – i.e. the peat substrate is being drained and is consolidating. However, consolidation of the peat substrate appears to proceed at different rates, as morphological changes on the high bog surface since 1991 are more severe in particular, and localised, areas compared to others (described in chapters 7 and 10). Subsidence of the high bog is therefore a non-uniform process.

The mechanisms initiating the drainage of water from peat substrate were not understood at the outset of the study. However, it was known that coincident with bog subsidence was the creation and deepening of existing drains south of the Clara high bog (chapter 4) in the mid-1990s (as per communication with the NPWS). Measurements of water level from piezometry installed in the early 1990s also indicated that water level in peat and subsoil underlying peat had decreased since drain formation (after Ten Heggler et al, 2003). As such, leakage of water from peat appeared to be associated with decreased hydraulic heads in permeable geological layers under the bog due to increased marginal drainage associated with peat cutting since 1991 (described in chapter 8).

The objective of the geo-hydrological investigation was to therefore evaluate the hydraulic connection between the bog and regional groundwater system (i.e. the groundwater flows and heads in subsoil and bedrock units underlying and surrounding the raised bog peat body) by:

(1) Characterising and mapping the geological units of the system
(2) Installing instrumentation to measure groundwater head and flow in the subsurface
(3) Determining the hydraulic properties of the instrumented geological units and the rates of groundwater flow
(4) Characterising and mapping the Clara West drainage system; and identifying areas where groundwater is discharging
(5) Quantifying the flow rates and hydrochemical compositions of waters in surface water bodies connected to the regional groundwater system

In short, the overall aim was to quantify downward seepage/ leakage rates from the bog body to the regional groundwater table by the formulation of a water balance(s) for the Clara hydrological system; chapters 4 to 10 are oriented around, and focused on, solving this problem. This chapter details the geological make-up of the Clara groundwater system and the instrumentation installed in order to understand the regional groundwater flows.

### 3.2. Geological investigation

Knowledge and characterization of a systems geo-hydrological framework is a key basis in which to begin a hydrological study. In essence, the geo-hydrological framework of a wetland system describes (1) the general geo-hydrological setting within which the wetland is situated and (2) the drainage pathways of surface and subsurface flow and (3) the governing water balance maintaining saturated conditions in the bog system.

Mapping the distribution of geological units is a perquisite in all detailed groundwater studies. The local geological framework and its material properties invariably control the movement of water in the subsurface. The hydraulic movements of groundwater will be governed by the composition, or make-up, of the local rock/ mineral soil. As such, the ability of bedrock and mineral subsoil units to transmit groundwater is dependent on hydrogeological properties such as porosity and permeability. Groundwater will invariably flow differentially in distinct geological mediums, particularly at the interface boundaries. Ordinarily an aquifer is a groundwater body that is able to transmit quantities of water that can be economically utilised for human water supply. However, in the Clara groundwater system an aquifer is considered to be a saturated geological unit that is able to transmit significant quantities of water that are significant in terms of the sustainability of the wetland as an ecosystem. The term aquifer is used loosely in this context. By the same logic, geological units that impede or transmit very low volumes of water are considered to be aquitards.

#### 3.2.1.Objectives

Though much work was done on the geology and hydrology of the Clara Bog area in the 1990's (Van der Schaff, 1999; Warren et al, 2002), it was considered at the onset of the research project in November 2008 that the information available at that time was not sufficient to explain why the Clara Bog West high bog had undergone such dramatic morphological changes. Following an initial period of compiling and organizing data from research projects in the 1990's a fieldwork study was initialized to investigate the subsoil geology, groundwater hydrology and surface water hydrology of the Clara West high bog and drainage area.

The aims of the geological investigation were to:

(1) Identify and differentiate between geological subsoil types/ units

(2) Describe the texture of the differing geological subsoil units

(3) Map the distribution of the differing geological subsoil types underlying the Clara West high bog, particularly in areas where the bog has subsided, and to also characterise the subsoil geology in cutover areas where restoration works could potentially occur

(4) Map the topographic surface of mineral subsoil underlying peat in the high bog and cutover bog and when possible, map the thickness and depth of mineral subsoil

### 3.2.2.Geological units

Typical of most raised bogs in Ireland, Clara Bog formed in a topographic basin that was carved into the landscape following the retreat of the last glaciation, c. 10ka. Material removed from the bedrock by the glacial ice movements resulted in the deposition of mineral subsoil of variable composition - material referred to as till. Such subsoil types are unconsolidated superficial deposits and in the Clara region, they are saturated and in hydraulic contact with the underlying limestone bedrock (chapter 5). The composition of the till material reflects that of its underlying parent bedrock, Carboniferous Limestone, and is a calcareous lithology. Regionally, the bog is bounded by an east-west trending esker on its northern side and is surrounded by an elevated undulating topography consisting of glacial till, known locally as 'The Island', on its eastern, western and southern sides. A low-lying interval of cutover bog extends from the SE side of the bog to the Silver River in the south. Figure 3.1 illustrates the position of Clara Bog, as mapped originally in 1809, and the relative position of the bounding esker and glacial till complexes.

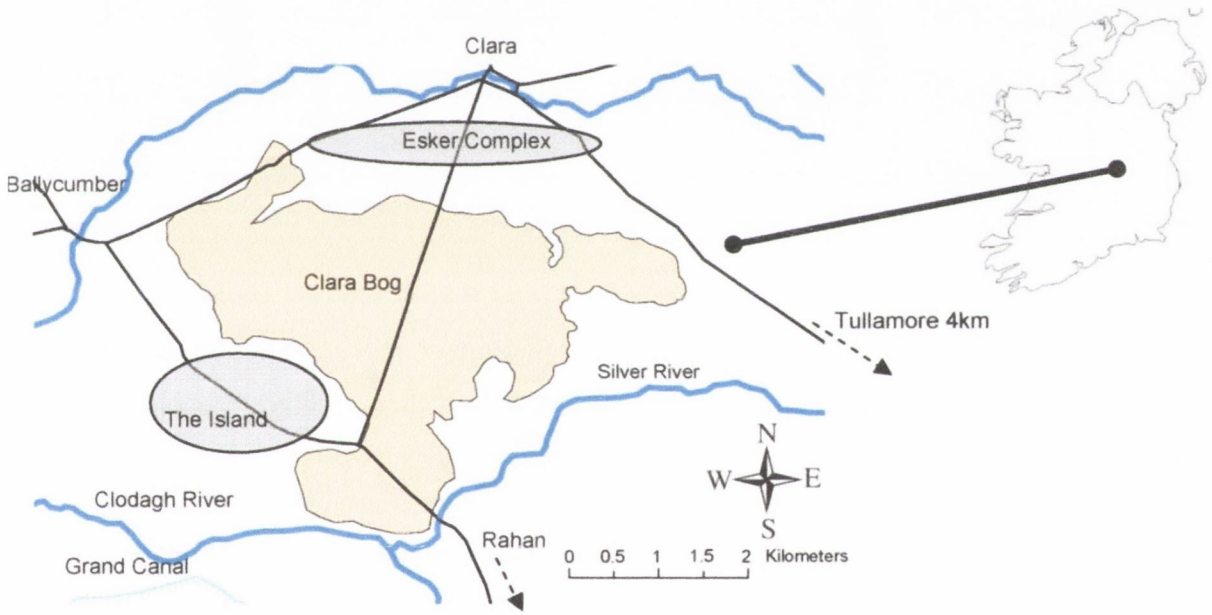


**Figure 3.1.** Map showing the location of Clara Bog (at its maximum 'original' extent) in relation to features in the surrounding landscape (Crushell et al, 2008).

Till is a massive-type quaternary deposit in that it displays no bedding or obvious stratification. Its composition make-up consists of a clay-silt based matrix that is supported by gravel, cobble and boulder clasts. The composition of such material can change drastically over short distances - in the order of tens of meters, both vertically and laterally. When the till matrix is dominated by sand sized particles with a high gravel content, the tills ability to transmit water increases greatly from those that consist largely of high clay content units. In the Clara West region till subsoil is widespread and is present throughout the landscape basin that is occupied by the bog. The till subsoil body is considered to be an aquifer in the study as it hosts the regional groundwater table (described in Chapter 5). Figure 3.2 displays a photograph of a till outcrop, overlain by peat, in a marginal drain. The till

outcrop in figure 3.2 can be divided into two distinct units – an upper 'clay' till unit and a lower 'sand and gravel' till unit. The upper unit is less permeable than the lower unit, the significance of which is discussed in Chapter 5.

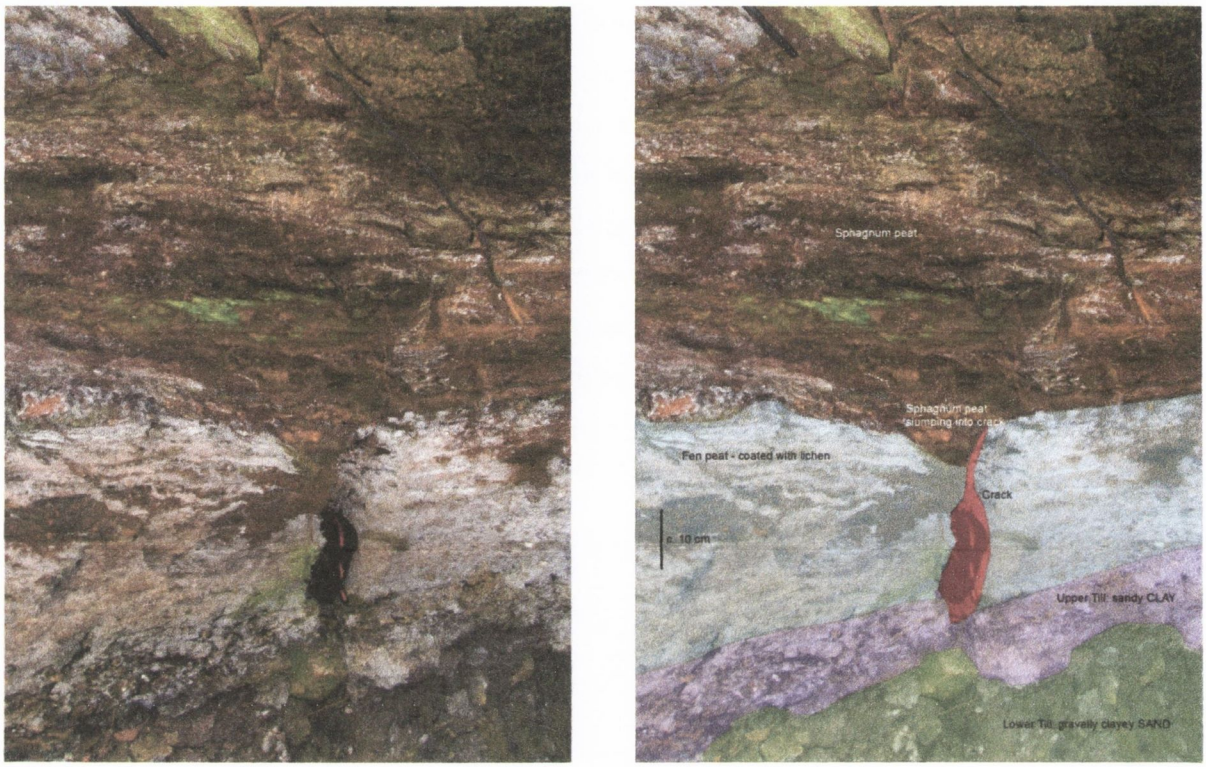


**Figure 3.2.** Peat-till outcrop at marginal drain – confluence of drain CT2 and TD2 (see appendix B for location map)

Lying above the till subsoil is a clay bed of glacio-lacustrine origin. This clay layer varies in thickness from 0.5 m to > 4.0 m and represents an old lake environment which in-filled the topographic depression following glaciation. In contrast to till, the lacustrine clay is often laminated indicating a low energy and slow accumulation period. There is little coarse material present within the clay profile; rather the small clay particles are compacted together to form a deposit that does not transmit water easily. The lacustrine clay effectively behaves as an aquitard, or 'hydraulic barrier', by isolating the bog from regional groundwater flows in the subsoil (glacial till) aquifer and thus minimising downward leakage of water from peat to the subsoil. However, the lacustrine clay unit is often absent from the geological stratigraphy, as identified in Figure 3.2. The absence of lacustrine clay becomes significant in areas where the bog is drained and its significance will become apparent through the rest of the thesis.

Figure 3.3 exhibits a core through lacustrine clay and till mineral subsoil. The differing textures and matrix compositions are notably different with the lacustrine clay composed wholly of very fine grained sediment and the till consisting of a silty sandy matrix with gravel and cobble clasts. An additional lacustrine sediment known as marl overlies the lacustrine clay in the central areas of the old

lake basin. It is a fossil rich deposit, rich in freshwater mollusc shells that are < 2 mm in diameter. Its properties and texture are similar to lacustrine clay and is no greater than 0.5 m in thickness.

**Figure 3.3.** (a) Lacustrine clay core from piezometer nest 57. (b) Till core from piezometer 913 (see Appendix C for location map)

### 3.2.3. Subsoil investigation

*Original investigations*

In the early 1990's much work (Bloetjes (1992), Rijsdijk (1991), Lenting (1992), van der Boogaard (1993), Bell (1991), Samuels (1992), Moll & Peters (1996) and van der Schaff (1999)), and more recently by Ten Heggler et al (2003), was carried out on characterising the type, extent/ distribution and depth of peat and the underlying subsoil of Clara Bog and the surrounding cutover areas. Lacustrine clay was found to underlie the majority of the Clara East high bog and most of the Clara West high bog. The occurrence of areas where peat directly overlies till was first encountered by

Bloetjes (1992), who first mapped peat depth and underlying subsoil type in Clara Bog, and the occurrence of peat-till interfaces was mapped further by Ten Heggler et al (2003) in the areas around the prominent topographical feature, the Western Mound.

*Investigations carried out during study*

To establish the relationship between subsoil geology and subsurface drainage it was necessary to better define the distribution of till and lacustrine clay underlying peat on the high bog, but also in the cutover margins where restoration activities could conceivably take place (Chapter 12). A number of piezometers (below; Section 3.3) have been installed into the till subsoil and concurrent with this, the subsoil geology was logged. Using a window sampler and hydraulic hammer (i.e. a drill rig capable of extracting soil samples using a series of steel tubes), powered by a generator, to core beneath the ground surface (to a maximum of 10 m), twelve subsoil geology logs surrounding the high bog have been constructed and are presented in Table A3, Appendix A.

It was not possible to core while drilling, and thereby extract subsoil samples, during piezometer installation on the high bog due to the weight of the equipment involved. The first phase of subsoil piezometer installation (Section 3.3) on the high bog simply 'drove' galvanised steel piezometers into the till subsoil using the hydraulic hammer. The thickness of till was therefore estimated based on the known peat thickness and depth of 'refusal' at these locations. Tables A1 and A2 lists the piezometers used in the project and the depth of peat and mineral subsoil, if known, at each location.

To map the wider extent of mineral subsoil a simpler method of characterising the subsoil geology was utilised by simplifying coring through the peat and into the topmost section of the underlying subsoil using a hand auger, referred to as a gouge core or Russian auger. In June and July 2010, TCD and Queens University Belfast (QUB) (McGinn, 2011), cored forty-two holes on the Clara West high bog. Table A4 lists the cores and their relevant information. In an important area of cutover bog, referred to as the Restoration Area (Chapter 4), thirty-one gouge core holes later cored (Table A5). The locations of all subsoil investigation holes, including those done by researchers in the 1990's, is presented in Figure A3.

### 3.2.4. Subsoil distribution map

Combining the information obtained in the 1990s and from Ten Heggeler et al (2003) with the work carried out as part of the current research, a subsoil geology map of the Clara West area was generated and is presented in Figure 3.4 (also Figure A3; Appendix A). It can be observed in Figure 3.4 that much of the western section of the high bog is underlain by glacial till, a larger area than first mapped in the early 1990s by Bloetjes (1992; see Figure A2, Appendix A). This subsoil groundwater body protrudes through the lacustrine clay beneath the high bog at localised connections and, significantly, directly underlies the peat substrate in an area between the two most important ecological features of Clara Bog West, namely the Western Soak and Shanely's Lough. The significance of the till subsoil

distribution in relation to the Clara West drainage system and rate of high bog subsidence will be discussed in Chapters 4 to 10. Lacustrine clay dominates the rest of the high bog area and is overlain by marl close to its eastern boundary, and it is this area that is the old lake basin.

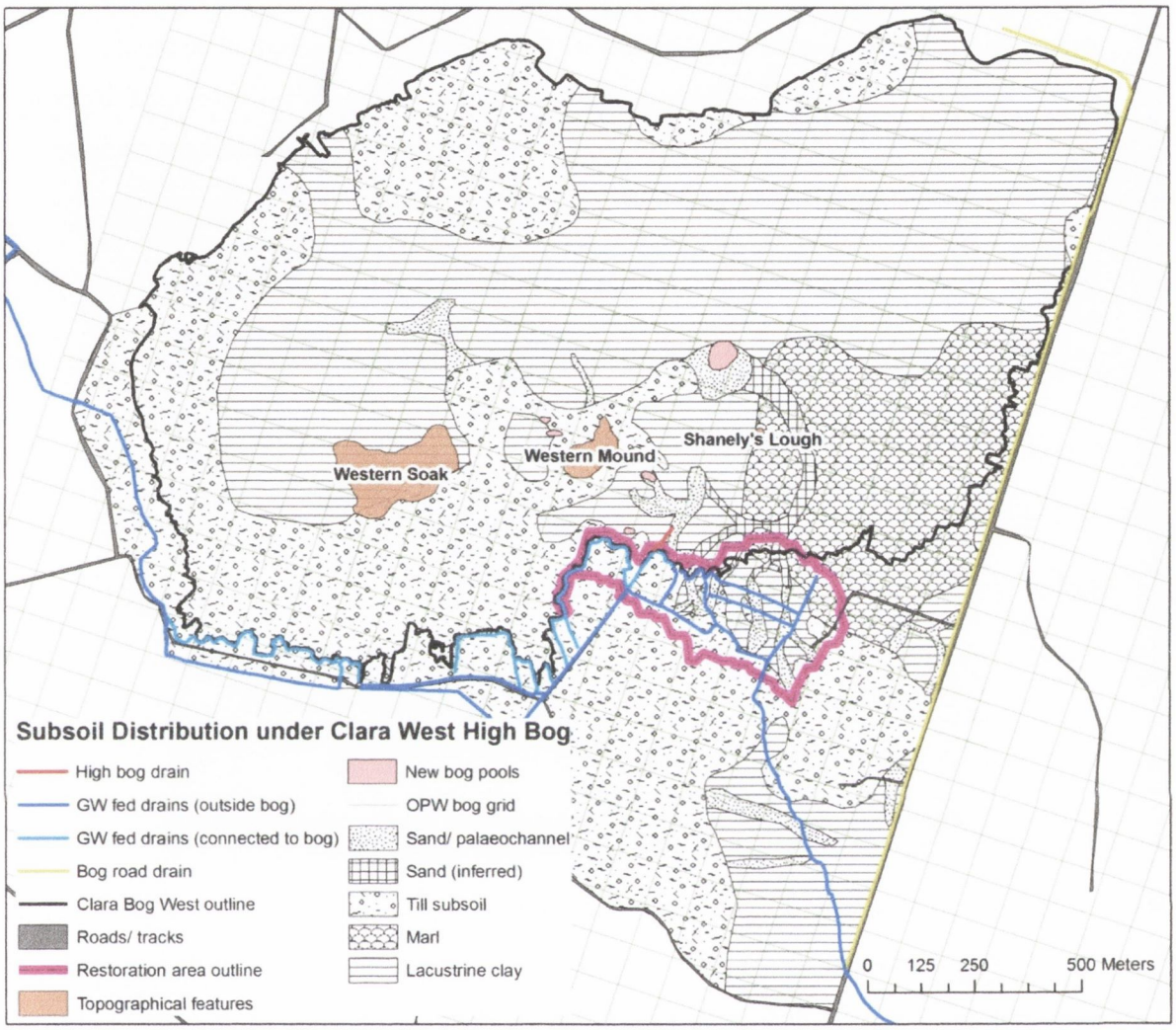


**Figure 3.4.** Subsoil geology underlying Clara West High bog and cutover bog areas

*Occurrence of palaeo-channels*

In addition to identifying till and lacustrine clay subsoils in cored holes, which were expected based on field research in the 1990's, an additional subsoil unit was discovered during the course of the field investigations – that of a sand 'lense'. The cores where sand was discovered on the high bog are listed in Table A4. The sand 'lense' is a silty-sand unit, between 5 cm and 30 cm thick, and appears to 'flow' into the marl unit, implying it is effectively a type of palaeo-channel that at one time drained water towards the centre of the old lake basin from bounding elevated till bounds – indicating a former high energy environment that transported sediment towards the centre of the old lake basin. The sand lense is everywhere underlain by lacustrine clay and not till mineral subsoil.

The sand lense distribution is illustrated on Figure 3.5 and it can be observed there are a number of sand 'lenses', or sand 'stringers'. Based on the subsoil elevation contours in Figure A4 (Appendix A), the sand lenses have been interpreted as joining together in a depression underlain by marl substrate. Additionally, cores taken close to the Western Mound are coarse in texture (GC36; Table A4) and grey/ white in colour, indicating the sand 'lenses' are the remnants of reworked till material. Interestingly, a bog lake, between the Western Mound and Shanel's Lough, has developed adjacent to the sand 'lense', implying localised peat consolidation and a vertical subsurface leakage pathway drawing water from overlying peat substrate.

**Figure 3.5.** Sand unit underlying peat (right) and overlying lacustrine clay (left)

The sand lenses cored close to the marl unit and in the 'bog pool' area, north of Shanley's Lough, are more clayey and silty in composition and mollusc shell fragments were found in GC2 and GC3, suggesting mixing of sediment in the old lake basin. South of the high bog margin, in the area of cutover bog, the sand is again coarser and 'sandier', most possibly because of its close proximity to elevated areas of till subsoil to the south. Table A3 lists the geological logs from the piezometer installations and it can be observed that sand was also discovered at piezometer nest 927. Though the sand is only 5cm thick here, it appears to form part of the same 'sand' body that borders the marl unit on the high bog – the sand lenses are connected but it is unclear where they terminate. In essence, the till and sand lense(s) are significant pathways for water flow of vertically drained peat (Chapters 7 and 8).

### 3.2.5.Peat depth

The Clara West peat depth map is illustrated in Figure 3.6 and the underlying topographic elevation of the subsoil-peat interface is presented in Figures A4 and A5 (Appendix A). As peat depths have changed over time due to peat consolidation the peat depths used in Figure 3.6 are based on the peat

depth as it is currently estimated to be now (i.e. referenced to Malin Head datum using the measured peat depths at the time of study). Peat depths were cored in the 1990s at the grid points of the OPW Bog Grid (Chapter 1). Surface ground level elevations were measured at this time and were levelled again as part of this study (chapter 7). As such, historic peat depths could be adjusted using current level information and Figure 3.6 is a combination of historic work and recent work, as described above.

The thickness of peat in the high bog ranges between c. 2.5 m and > 10.0 m in the centre of the bog. In Figure 3.6 two peat basins may be observed – west-northwest and east/northeast of the Western Mound. Shallow peat depths, < c. 4.0 m, are associated with areas where there are local till mounds, protruding through lacustrine clay, underlying the high bog and close to the high boundary. Significantly, subsidence has occurred where lacustrine clay is absent in the shallow peat areas; and propogrates into areas with deeper peat depths (expanded upon in Chapter 7). In areas of cutover bog, to the southeast of the high bog boundary, peat depth is generally < 3.0 m. The relative depth of peat will influence subsidence and settlement rates (Chapter 7) and inform future restoration hydrological scenarios (Chapters 11 & 12).

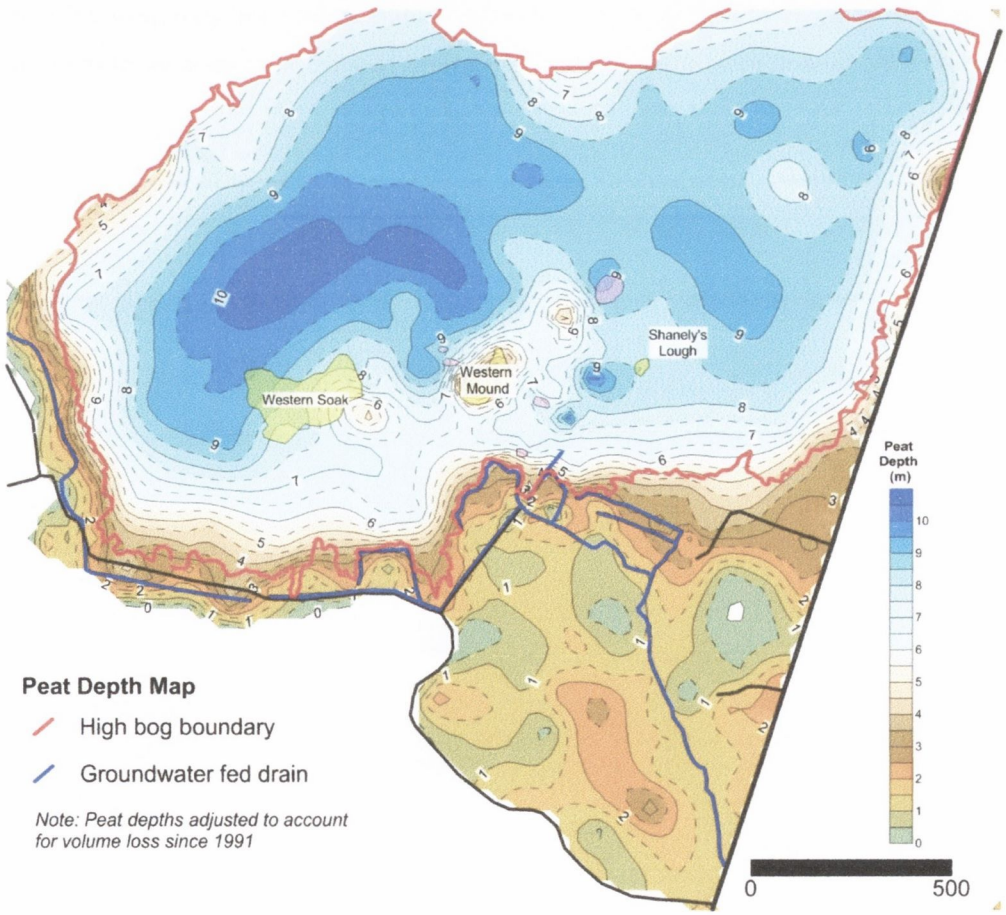


**Figure 3.6.** Peat depth underlying Clara West High bog and cutover bog areas

### 3.2.6.Summary

Clara Bog formed within a glacial basin and is bounded by an east-west trending esker on its northern side and is surrounded by an undulating topography consisting of glacial till on its eastern, western and southern sides. The predominant geological succession underlying the bog consists of (1) Carboniferous Limestone bedrock to (2) glacial till deposits of varying permeability, which can be grouped into a lower 'more permeable' sub-unit and upper 'less permeable' sub-unit, to (3) low permeability lacustrine clay sediment, which is overlain by shelly marl in the central areas of the glacial basin. The lacustrine clay effectively acts as an aquitard, or 'hydraulic barrier', by isolating the bog from regional groundwater flows in the subsoil (glacial till) aquifer and thus preventing downward leakage of water from peat to the till aquifer.

However, there are areas in Clara Bog West where the till subsoil 'aquifer', or groundwater body, protrudes through the lacustrine clay beneath the high bog at localised connections. In addition to till-peat connections, there are areas of sand lenses, which represent old drainage channels, underlying peat and overlying lacustrine clay adjacent to marl substrates associated with the old lake basin. The occurrence of till and sand are outlets, under particular hydrogeological conditions, for subsurface vertical groundwater flow from high bog peat substrate. Understanding and quantifying this flow forms the basis of the hydrological study. Figure 3.7 summarises the basic geology of the Clara West region.

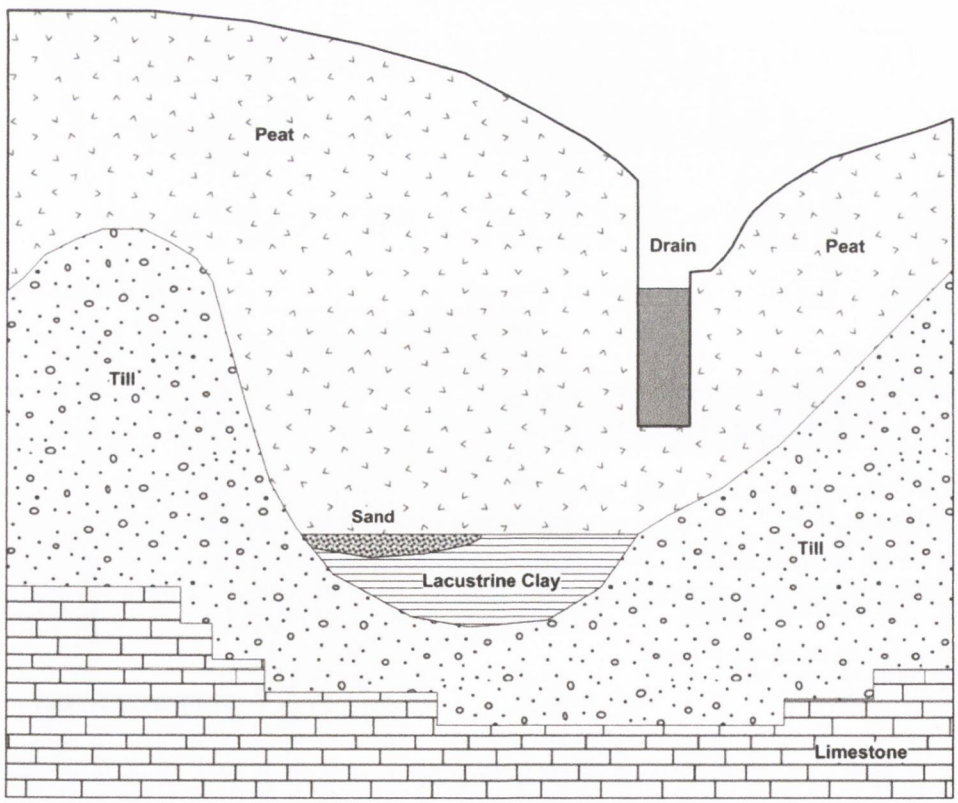


**Figure 3.7.** Simplified conceptual diagram of Clara West geological framework (not to scale)

## 3.3. Hydrogeological investigation

### 3.3.1. Objectives

To investigate how a wetland works, hydrologically, instrumentation must be put in place so that information on groundwater flows and surface water flows can be measured and used to interpret the systems hydraulic dynamics, both at a local scale and at a regional scale within the groundwater system area – i.e. to works out rates of flux between different water bodies enabling the calculation of a water budget or balance.

To achieve this objective, a series of piezometer nests, consisting of piezometers at different depths, must be installed in the systems geological substrates – in this case peat and till. Monitoring the water levels in the piezometers over a period of time, such as one year, will allow an understanding of how water in an area is moving, both vertically and horizontally. Using this information in a wetland where peat is the substrate, a phreatic surface (i.e. the 'free water table') and a piezometric, or potentiometric, surface (i.e. the piezometric water levels at depth, representing 'pressure') may be interpreted.

In a typical bog environment where meteoric water (i.e. precipitation) is the sole water source, the phreatic surface will be 'above' the 'piezometric' surfaces at depth, thereby constituting a 'downward gradient' and movement of water flow. However, if there is a discharge/seepage of groundwater from underlying mineral soil or rock into the peat, the piezometric level of the water at depth will be elevated, due to the increase in pressure, and this will often result in a piezometric surface being above the phreatic surface, thereby creating an 'upward gradient' and movement of water flow. This type of phenomenon is expected in areas of cutover bog and where there is marginal drainage as such areas are typically cut below the regional groundwater table.

As such, the aim of the hydrogeological investigation was to establish the connection between the mineral subsoil ridges underneath the high bog and the Clara West drainage system and following this, to estimate how much water is leaking from peat on the high bog to the regional groundwater table. To achieve this aim the following plan was set at the onset of the project:

(1) Install piezometers into till subsoil beneath the high bog and cutover bog.

(2) Define the groundwater catchment that encompasses the Clara West drainage system

(3) Measure hydraulic heads every two weeks and establish highest and lowest regional groundwater levels and their relative fluctuations.

(4) Determine where high bog peat is losing water to groundwater

(5) Measure subsoil permeability by applying small pumping tests

(6) Estimate groundwater discharge to drains.

### 3.3.2. Piezometer installation

The mineral subsoil ridges that underlie the Clara West high bog are located adjacent to areas where peat has consolidated; implying water is being 'lost' to the subsurface, and by inference the regional groundwater table. A large area of till underlies the high bog, and this same body of till is found outside the high bog in cutover areas, as discussed in Section 3.2 and mapped on Figure 3.4. Piezometers were therefore installed into the till body, both on the high bog and in cutover bog so to (1) understand the high bog and cutover bog groundwater connection and to (2) construct a groundwater catchment encompassing the Clara West drainage system which is described in Chapter 5. Figures A8 to A11, Appendix A, illustrates the location of piezometers installed to subsoil, historic boreholes and high bog piezometer nests installed in the 1990's.

*Historic Piezometers*

In the Clara eco-hydrological studies of the 1990s a network of piezometer and phreatic tubes were installed on Clara Bog West by Gloudemans (1990), Huisman (1991), Leene & Tiebosch (1993) and van der Boogaard (1993) – e.g. Figure 3.8. Additional piezometers surrounding the Western Mound were later installed by ten Heggler et al (2003). Figure A11 (Appendix A) illustrates the location of these 'historic' piezometer nests. Boreholes measuring groundwater level in till subsoil and bedrock were also installed in the early 1990s. A location map of all subsoil monitoring boreholes/ piezometers is illustrated in Figure A7, Appendix A, and those that are abbreviated 'CL' are boreholes installed in the early 1990's. Tables A1 and A2 provide details on the screen depth of the respective piezometers and the water level measuring geological unit.

**Figure 3.8.** Piezometer nest 905, installed in the 1990s by the Western Soak (location: Figure A8; Appendix A)

*Installation of new piezometers*

Following a survey of the 'old' piezometers at the beginning of the research project, it was clear additional piezometers were required to monitor water levels in the till (subsoil) aquifer underlying the high bog and in the peripheral cutover bog areas. Locations were chosen based on the perceived groundwater flow paths, inferred from existing borehole installations into subsoil, and where it was suspected that a hydraulic connection had been created between the high bog and the marginal face-bank drains. Elevated electrical conductivities (> 200 µS/cm) at localised areas in the face-bank drains suggest that the regional groundwater table has been intercepted at these areas, indicating it has been lowered due to peat cutting activities (Chapter 4).

At the start of the study, regional groundwater level information was available only from boreholes installed by the Geological Survey of Ireland in the 1990's in areas surrounding Clara Bog. One piezometer, CLCD3, was installed on the high bog. As there were obvious gaps in groundwater level information, piezometers were first installed into till on the high bog. Subsequent water level monitoring then dictated where further information was required and additional piezometers were installed accordingly. During the course of the study, twenty 'new' piezometers were installed into the till aquifer and their details are listed in Table A1 and their locations are illustrated on Figure A12. Eight of these piezometers are on the high bog and the remaining piezometers are in cutover bog and surrounding land. The piezometers were installed over three different time periods – June 2009, March/ April 2010 and October 2010 and their method of installation is described below.

Subsoil piezometer installation phase 1

The first suite of piezometer installation into the mineral subsoil took place between the 22nd and 26th of June 2009. Minerex Environmental Limited (MEL) was hired by Trinity College Dublin (TCD) to install the piezometers, in tandem with TCD, owing to their ownership of window sampler equipment. Using a local metal work supplier, MEL also supplied the piezometers, which were 1.75-inch outer diameter galvanised steel constructions. The piezometers were 1 m and 3 m in length with the 3 m lengths slotted over 1 m from their base (Figures 3.9a).

The method used for installing the piezometers to the till-bedrock interface was relatively simple and essentially involved using the window sampler's hydraulic breaker hammer, powered by a portable Honda generator, to drive the galvanised steel piezometer though the peat and subsoil until it reached the solid limestone bedrock (or possibly a large boulder) [Figure 3.9b]. Ordinarily the hammer drives a series of sampling tubes to depth where soil samples may then be extracted. However, due to the difficulty in carrying the window sampler equipment across the unstable and wet terrain of the bog surface it was decided to simply use the window sampler hammer to drive the piezometers into the till material without using a rig and sample tubes to enable the extraction of soil samples. Employing this method, the 3 m piezometer lengths were installed through the till subsoil and were supplemented

with 1 m piezometer lengths as necessary. Subsequent cores, using a Russian auger, through the peat profile confirmed the depth of peat and occurrence/ absence of lacustrine clay.

**Figure 3.9.** (A) Galvanised steel piezometer construction (B) View looking eastwards from piezometer 908 – during installation

In total, one 1-inch PVC piezometer and five galvanised steel piezometers were installed into till subsoil at six locations on the high bog and two locations on cutover bog, the details of which are listed in Table A1 and their location illustrated in Figure A12. Subsoil piezometer 906 was installed on cutover bog adjacent to the high bog face-bank drain and subsoil piezometer 913 was installed on elevated ground adjacent to a north-easterly flowing till drain and access track. The till material was sampled at location 913, due to its ease of access, and consisted of a silty matrix with a high proportion of gravel and cobble sediment (see Figure 3.3b). On the high bog, subsoil piezometer 907 was installed north of 906, close to the face-bank and subsoil piezometer 908 was installed southeast of the Western Soak where there is an existing piezometer, tL14, installed by ten Heggler et al 2003, and which measures water level at the base of peat. The peat depth in this area is shallow, c.4.6 m, relative to peat depths elsewhere on Clara Bog West, and implies a till 'mound' sub crops in this area.

Three subsoil piezometers, namely 909, 910 and 911, were installed on the south-western, south-eastern and north-western boundaries of the Western Mound respectively. Ten Heggler et al, 2003, previously installed and monitored a piezometer, tdJ13, to the base of peat at location 909. However, this piezometer no longer exists and was replaced in the present study. Subsoil piezometer 912 was installed close to the high bog face-bank south of the Western Mound and southwest of the 'new' bog pools that have developed due to peat consolidation (ten Heggler et al, 2003).

All the piezometers, with the exception of 912 where there is a shallow lacustrine clay thickness of c.0.2 m between the peat and till substrate, are located in areas where peat directly overlies the till subsoil and are therefore located in areas where bog water could conceivably 'escape' to regional groundwater in the till 'aquifer', particularly if the organic matter content of the peat material in these areas has been reduced due to water losses associated with the marginal drainage.

Additional piezometers, to measure water levels at the base of peat and in the mid-section of the peat profile were installed in August 2009. Phreatic tubes, to measure the surface water table, were also installed at each location. 1.0-inch outer diameter PVC piezometer tubes with attached 0.35 m lengths of 0.75-inch piezometer tip filters were used for the 'deep peat' installations. 0.75-inch outer diameter PVC piezometer tubes with attached 0.35 m lengths of 0.75-inch piezometer tip filters were used for the 'mid peat' installations. Slotted 0.75-inch piezometer tubes, wrapped within geo-sock filters, were used to construct the phreatic installations. As such, installations 906 to 912 are piezometer nests consisting of piezometers monitoring water level in till, deep peat, mid-section peat and the water table at the bog surface – e.g. Figure 3.10.

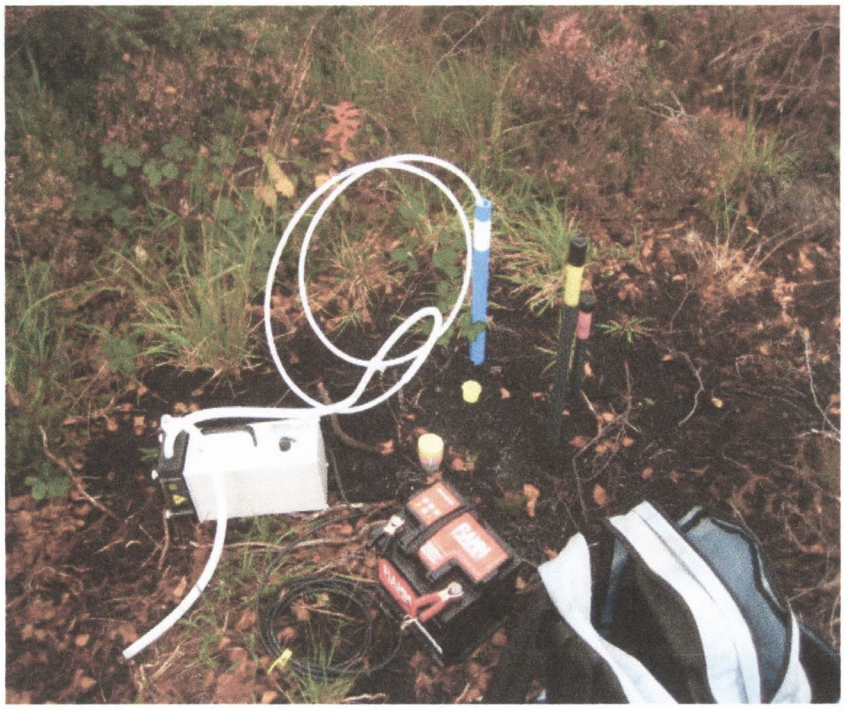

**Figure 3.10.** Piezometer nest 906 (location: Figure A12; Appendix A)

Subsoil piezometer installation phase 2

Two piezometer nests, 920 and 921, consisting of piezometers to the base of peat and mid-section of peat, as well as phreatic tubes to monitor the 'free' water table, were installed by TCD and Hydro-Environmental Services (HES) on the 10th October 2009 in an area of cutover bog, south of the high bog boundary in an area referred to as the Restoration Area, for reasons that will be apparent in Chapter 4. Piezometer designs are identical to the PVC piezometer designs to those in phase 1 except the 'deep peat' piezometer at 920 is a 0.75-inch PVC tube, not a 1.0-inch PVC tube.

Additional piezometer nests, similar to those of 920 and 921, were also installed in the face-bank drains adjacent to piezometer nest 912 and in the face-bank drain between piezometer nests 906 and 907. These piezometer nests are referred to as 914 and 918 respectively (Figure 3.11). To complement these piezometer nests and to better understand and develop flow path movements in the respective areas, an additional piezometer nest, 915, was installed between 913 and 914, and a single piezometer to the base of peat, 919, was installed to the base of peat south of piezometer nest 906. Two piezometer nests, 916 and 917, consisting of a piezometer to the base of peat and a phreatic tube, were also installed adjacent to their respective face-bank drains. The locations of all piezometers are illustrated in figures A7 to A12 and their level and depth information are listed in Tables A2 and A3.

**Figure 3.11.** Piezometer nest 914 (location: Figure A12; Appendix A) – note iron iridescence in drain

Subsoil piezometer installation phase 3

Following the installation of piezometers in June 2009 and October 2009, a period of water level monitoring, every two weeks, was undertaken so to get a handle on the relative groundwater flow movements in the till subsoil and high bog peat. Following this it was necessary to install additional

piezometers in the till subsoil so to better define the groundwater catchment area encompassing the Clara drainage system (Chapter 4).

In March and April 2010, TCD and HES installed piezometers into subsoil at seven additional locations (Figure A11) – piezometers 915, 920, 924, 925, 926, 927, 928 and 929. The installation method again involved the use of a window sampler. However, as the piezometers are located in marginal areas of the bog, it was possible to log the subsoil lithology concurrently with piezometer installation (Table A1; Appendix A).

The piezometers are 0.75 inch galvanised steel or PVC tubes and each piezometer was attached with a 0.35 m screen tip at its base so to measure the piezometer level (hydraulic head). In piezometer installation phases 1 and 2, piezometers were driven into the mineral subsoil, meaning the holes did not have to be sealed as the method employed means they were sealed naturally by the process involved. However, in this period a hole was first created in the ground with the window sampler. The piezometer was therefore installed so that its filter was located within water bearing sandy gravel unit, before being backfilled with pea-sized gravel so to maintain a hydraulic continuity between the filter and surrounding, natural gravel body. The hole, c. 4 inch in diameter (Figure 3.12), was then backfilled with clay material and a bentonite seal was applied to the top of the installation to prevent surface water seepage at ground level. In areas where there was peat, a 3 inch PVC outer casing was inserted in the window sample hole so to prevent it collapsing. The subsoil logs of these piezometers are listed in Table A1.

**Figure 3.12.** Subsoil piezometer 924 – before core-hole is backfilled and sealed.

In September 2010 three more additional piezometers were installed into till subsoil – 934, 935 and 936. Again, further groundwater catchment delineation was required and the piezometers were installed in the same way the April 2010 piezometers were installed. Two additional piezometers, 912

and tL12, were installed in December 2010. Piezometer 912 was discovered to be leaking and was replaced by a 1.0 inch galvanised piezometer that was 'hammered' into the till subsoil until the top of the filter was below the peat-subsoil interface. In the TCD-QUB subsoil investigation (Section 3.2), till was discovered at tL12 and it was possible to core > 5 cm into the subsoil. Similar to 912, a 1.0 inch outer diameter galvanised steel piezometer, with a 0.3 m filter tip, was manually hammered into the till subsoil at tL12.

Subsoil piezometer installation phase 4

In section 3.2.4, the discovery of a sand lense, or palaeo-channel, was described. This sand lense is an important drainage pathway and its influence on drawing down the potentiometric surface within the high bog peat substrate is discussed in Chapter 8. Galvanised steel piezometers, 1.0 inch in diameter, were installed into this sand lense in December 2010 at three different locations – 937, 51 (an old piezometer nest) and 927. The thickness of the sand, which is between 10 and 30 cm thick, in the aforementioned locations were known from coring (section 2.2) and screen lengths were designed in the TCD civil engineering laboratory using this sand thickness information. A further piezometer, 939, was installed by TCD in January 2011 in peat overlying the sand lense close to the margin of the high bog.

### 3.3.3. Water level monitoring

A series of monitoring transects were decided upon following the installation of subsoil piezometers in 2009. The monitoring transects encompassed the 'new' piezometer nests on the high bog and cutover bog and also some of the 'old' piezometer nests already existing on the high bog (Figure A8). Regular water level monitoring was necessary in areas of the bog known to have subsided in the recent past and in areas, such as surrounding the Western Soak, which appeared to be particularly sensitive to future water losses and peat consolidation. As such, six monitoring transects, encompassing 'historic' piezometer nests and the 'new' piezometer nests on the high bog described in section 3.2.2, were chosen so as to transverse the 'sensitive' areas where it is suspected a localised groundwater connection has developed, thereby allowing the hydrological and hydrogeological regime of Clara Bog West to be developed and conceptualised (Figure 3.13).

*Monitoring transects*

The positioning of the monitoring transects is illustrated in Figure 3.13 (and Figure A8; Appendix A). Transect T1 trends in a west-east to northeast-southwest orientation on the high bog and includes piezometer nests that monitor water levels in the Western Soak, either side of the Western Mound and west of Shanley's Lough. Transect T2 trends in a broadly north-south orientation from the centre of the high bog to cutover bog and includes piezometer nests that monitor water levels in the centre of the bog, either side of the Western Soak and either side of a face-bank drain where it is suspected that the regional groundwater table has been intercepted. Transect T3 trends in a southeast-northwest

orientation from the high bog to cutover bog and includes piezometer nests that monitor water levels in the area of recently formed (<20 years BP) bogs pools northwest of the Western Mound, west of the Western Mound itself and either side of a face-bank drain where it is suspected that the regional groundwater table has been intercepted. T3 also includes piezometer nests in three additional face-bank drains and terminates at the bedrock and mineral subsoil monitoring installation CLBH5.

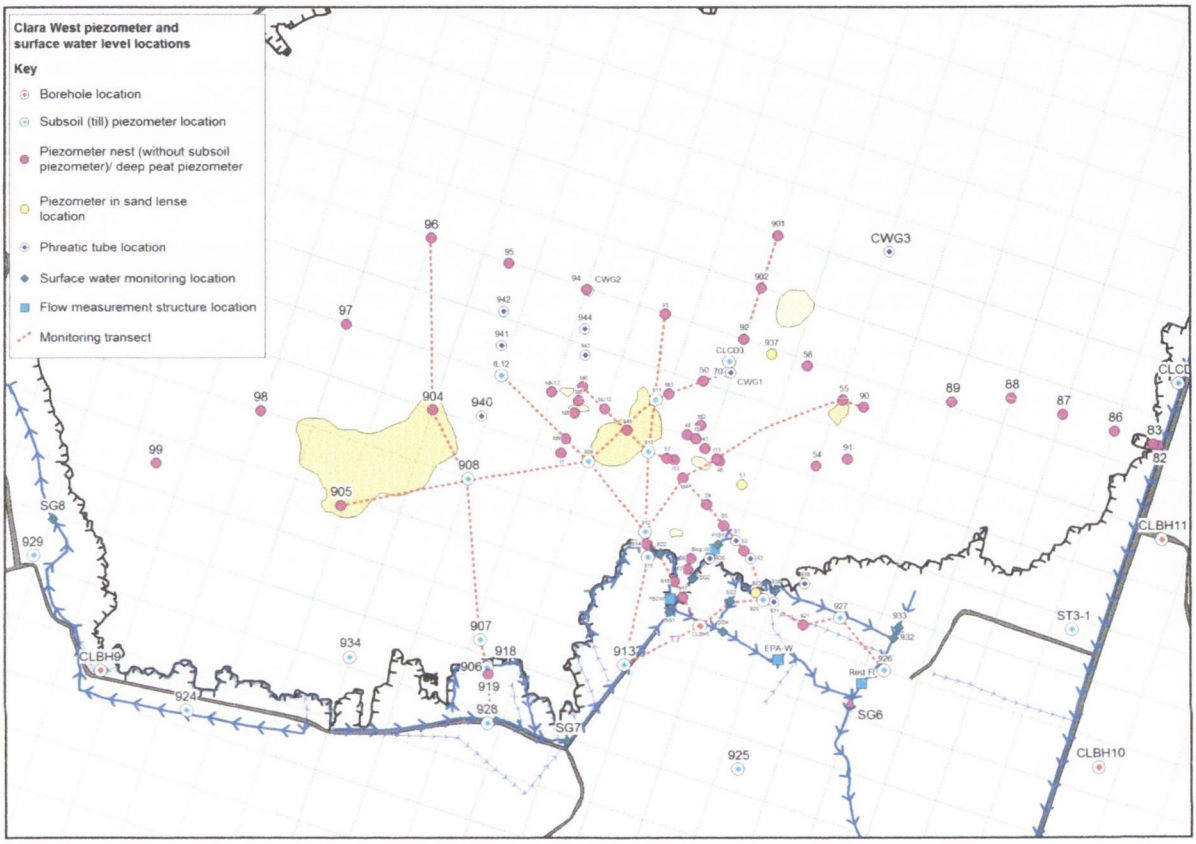


**Figure 3.13.** Location of piezometers and monitoring transects.

Transect T4 also trends in a southeast-northwest orientation from the high bog to cutover bog and includes piezometer nests that monitor water levels in the area of recently formed (<20 years BP) bogs pools west of the Western Mound, southeast of the Western Mound itself, in the area of recently formed (<20 years BP) bogs pools east of the Western Mound and south of Shanely's Lough and either side of a face-bank drain where it is suspected that the regional groundwater table has been intercepted. T4 also includes piezometer nests in the probable area for restoration works. Transect T5 trends in a broadly north-south orientation from near the centre of the high bog to elevated ground on cutover bog and includes piezometer nests that monitor water levels northeast and southeast of the Western Mound and either side of a face-bank drain where it is suspected that the regional groundwater table has been intercepted. Transect T6 trends in a northeast-southwest orientation from the high bog to cutover bog and includes piezometer nests that monitor water levels surrounding Shanley's Lough, in the area of recently formed (<15 years BP) bogs pools east of the Western

Mound and south of Shanely's Lough and either side of a face-bank drain where it is suspected that the regional groundwater table has been intercepted.

All piezometers installed to subsoil were monitored twice a month between August 2009 and August 2011. All piezometers on the high bog monitoring transects were monitored once a month between September 2009 and December 2010. Intermediate and occasional monitoring of all piezometers took place until February 2012. In addition to this, Diver water level data loggers (i.e. pressure transducers), measuring water pressure every hour and correct to within c. 2 cm, were installed in subsoil piezometers CLBH5, CLBH9, 908, 910, 915, 920 and 934.

### 3.3.4.Installation summary

Twenty 'new' piezometers were installed into the till aquifer to compliment the installations that already existed in the Clara West area from work carried out in the 1990s. Eight of these piezometers are on the high bog and the remaining piezometers are in cutover bog and surrounding land. The piezometers were installed over three different time periods – June 2009, March/ April 2010 and October 2010. The subsoil piezometers were complimented with shallow piezometers in peat and when present, sand, as well as free surface tubes to measure the phreatic water level on the high bog.

The subsoil piezometer nests were measured bi-weekly between August 2009 and August 2011 and permanent water level records are available from seven subsoil piezometers which were assigned continuous pressure transducers. A series of monitoring transects, encompassing piezometer installed to peat in the 1990's, were monitored once a month from January 2010 to January 2011 so to get a broader picture on groundwater movement in the high bog peat.

# 4. Hydrological Characterisation

## 4.1. Introduction and objectives

The Clara West high bog borders an area of cutaway bog on its southern margin. Most of the bog boundary has been cut for turf, resulting in vertical cliff faces, or 'face-banks', and they mark the boundary between high bog and cutover bog. Face-banks rarely just cut into the upper margins of the peat profile, leaving a dry face of exposed peat. Generally a face-bank is associated with a drain – the drains are important hydrologic features. These drains are important surface water bodies in the Clara region as their base, at a number of locations, is located below the regional groundwater table – i.e. they do not serve to simply collect surface waters from the surrounding topography, but are also zones for groundwater discharge from underlying subsoil and bedrock units. The face-banks are also not isolated features. A network of drains have been artificially created in the Clara West area since the early 1990s to facilitate drainage of the bog – the waters from the face-bank drains enter these drains which proceed to exist Clara West area. This network of drains are termed marginal drains as they lie adjacent to, or close to, the Clara West high bog and together they are referred to as the Clara West drainage system/ hydrological system in the text.

Hydrological processes operating on the surface of the bog are of most importance as it is these processes that sustain the ecological communities, or ecotopes, of conservational and scientific value (Chapter 1) and those that must be protected under the remit of the Habitats Directive. Hydrological processes on the surface of a raised bog, as described in Chapter 2, are highly dependent on low ground level gradients in order to keep the bog wet and to maintain an active and functioning acrotelm. Consolidation of peat thereby alters topographic gradients and the relationship between high bog hydrology and cutover bog groundwater hydrology must be verified if peat settlement is a consequence of marginal drainage. However, before linking both sets of processes, the hydrological characteristics of the high bog must first be described.

Thus, the aim of the hydrological investigation of Clara West was to characterise:

1. The Clara West drainage system by identifying zones where groundwater discharges into the various surface water bodies by (a) levelling and mapping the various drainage features using Trimble GPS, (b) identifying zones where groundwater is discharging into the drains using simple field hydrochemical measurements, (c) installing piezometer nests and surface water monitoring structures in drain sections where groundwater seepage is suspected and (d) installing hydraulic flow measurement structures with continuous logger devices so to measure runoff in drains deemed the most significant.
2. The Clara West high bog system using level information generated by a LiDAR survey. This will allow (a) the delineation of topographic catchment areas, (b) calculation of topographic

gradients/ slopes and (c) estimation of flow path lengths to 'wet' ecotopes. Water level information from the hydrogeological investigation, Chapter 5, is combined with ecotope mapping of the high bog (i.e. analysing the occurrence of biological communities with water table depth and fluctuation).

### 4.2. Marginal areas and cutover bog

At the beginning of the study little was known on the Clara West drainage system and how it connected with the high bog and regional groundwater table. As such, simple field observations on where water was flowing, on the high bog and cutover bog were made and simple field measurements of electrical conductivity, temperature and pH were made so to provide clues on where groundwater was possibly discharging. The drains were subsequently levelled using a Trimble GPS system (correct to c. 2 mm) and using the drain depth elevation data, directions of water flow were inferred and the drainage system mapped. Figure 4.1, and Figures B1 and B2 (Appendix B), illustrates the Clare West drainage system, monitoring points and location of hydraulic measuring structures.

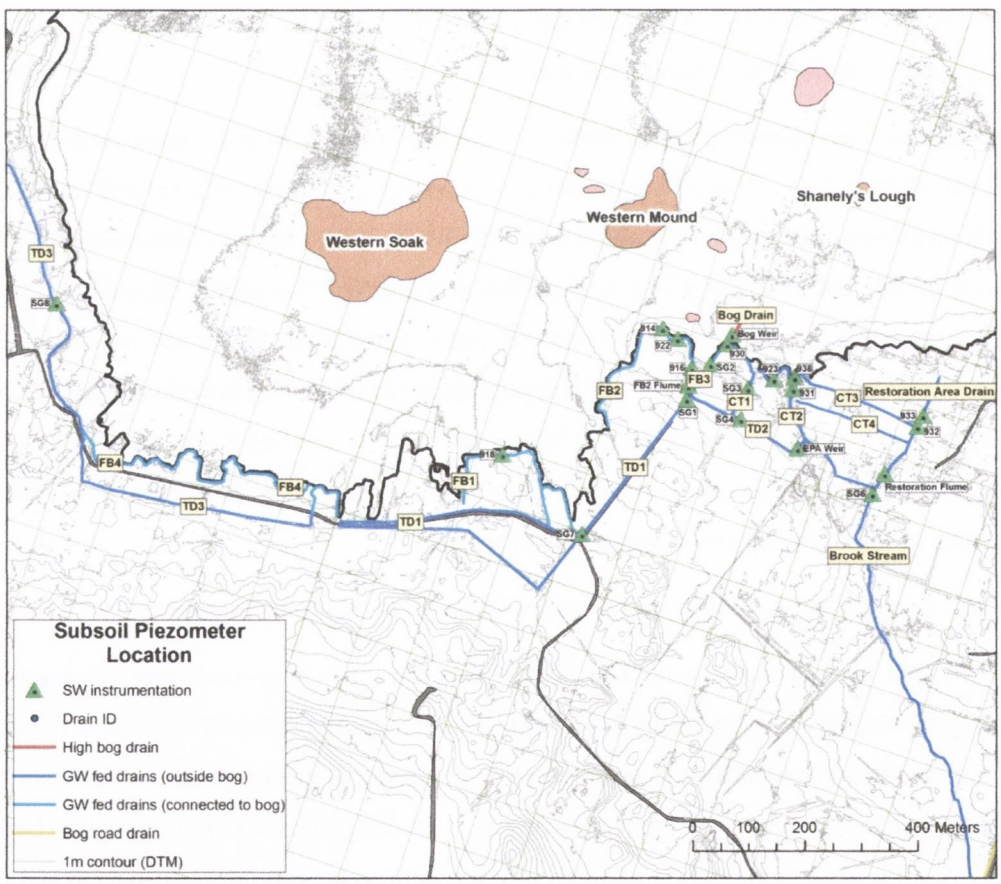


**Figure 4.1.** Clara West drainage system and surface water level and flow instrumentation location (100m grid)

#### 4.2.1. Surface water level monitoring

Combining the levelled drainage system and electrical conductivity measurements, assessments on the important surface water bodies that required water level information throughout the year were made.

Following this, the surface water bodies in the Clara West region were instrumented with staff gauges and phreatic tubes, most of which were monitored every two weeks between July 2010 and July 2011. Table 4.1 lists the monitoring installations and their locations and their locations are illustrated in Figure 4.1 and Figure B1 (Appendix B). Knowledge of surface water level fluctuation is important for understanding the dynamics of the Clara West hydrologic system, but also for assigning boundary conditions in a numerical groundwater model of the system and calibration (Chapter 11).

Table 4.1. Surface water level monitoring installations.

| Staff Gauge ID | Location | Phreatic ID | Location |
|---|---|---|---|
| SG1 | TD1 | 914 | FB2 |
| SG2 | FB3 | 916 | FB2 |
| SG3 | CT1 | 918 | FB1 |
| SG4 | TD2 | 922 | FB2 |
| SG5 (FW-SG) | Restoration Area Drain | 923 | CT2 |
| SG6 | Brook Stream | 930 | FB3/CT1 |
| SG7 | TD1 | 931 | CT2 |
| SG8 | TD3 | 932 | Restoration Area Drain |
| EPA-SG | TD2 | 933 | Restoration Area Drain |

Stilling-wells with continuous water level monitoring devices were installed in four drains, namely the main Bog Drain, the Restoration Area drain, the FB2 Drain and the till drain TD2, that are considered to be important in the study. Section 4.2.2., below, will describe the drains themselves and section 4.2.4 will describe the characteristics of the stilling wells and their associated hydraulic measuring structures.

Table 4.2. Stilling-well installations

| Stilling-well ID | Structure Type | Location |
|---|---|---|
| BW | V-notch weir | Bog Drain |
| Rest Fl | Flume | Restoration Area Drain |
| FB2W | Flume | FB2 Drain |
| EPAW | V-notch weir | Till Drain TD2 |

Piezometer nests have also been installed at three locations in drains that border the high bog, the so-called 'face-bank' drains. The piezometers, which consist of a phreatic tube measuring water table and piezometers measuring water pressure in the mid-section of the peat profile and at the peat-subsoil interface, were installed in areas inferred to be groundwater discharge zones (Chapter 3). Water level monitoring of these installations, namely piezometer nests 914, 918 and 923, provides information on the direction of water movement and their gradients adjacent the bog margin. The results of this monitoring are discussed in the text below.

### 4.2.2. Drain surveying and characterisation

In addition to knowledge of subsoil geology the level at the base of drains in the Clara West region aids in developing a relationship between the surface water bodies and the regional groundwater table. The various face-bank and peripheral drains in the Clara West region have been mapped and levelled. Figures B1 and B2 illustrate the main drainage patterns, and they are labelled accordingly.

There are four main divisions of drainage types identified: (1) Till drains (TD), which refer to drains peripheral to cutover bog areas and have till subsoil defining the drain base for much of its length, (2) Cutover bog drains (CT), which refer to drains in cutover bog adjacent to the high bog, (3) Face-bank drains (FB), which refer to drains that mark the boundary between the high bog and surrounding area and (4) drains on the high bog itself.

*Till drains*

Agricultural drains in the southern regions of Clara Bog West were deepened into till subsoil in the mid 1990's. Three main 'till' drains have been identified and are referred to as TD1, TD2 and TD3 on Figure 4.1 and B1 and B2 (Appendix B).

Drain characteristics

Drain TD1, which is c. 760 m in length, begins south of the Western Soak in a former area of bogland. The drain is bordered by an east-west trending road and flows eastwards and then northeast, broadly following the pattern of the high bog boundary. In chapter 5 the regional groundwater table, as hosted in till subsoil, is described and it can be observed that the start of TD1 also marks the groundwater catchment divide. The elevation at the base of TD1 varies between c. 57.56 mOD, at its highest point at the beginning of the drain, and c. 50.58 mOD, at its lowest point at the end of the drain. As such there is a significant drop in base level in TD1, which mirrors the topography. The steep gradient of the northernmost section of the drain may be observed in Figure 4.2.

Drain TD2, which is c. 400 m in length, is a south-easterly flowing drain in the eastern region of Clara West. The drain is a continuation of TD1 and it eventually becomes the Brook Stream. The reason for separating TD2 from TD1 is that TD2 also receives runoff from the high bog, cutover drains and face-bank drains and will be discussed below. Improved agricultural fields to the south, and cutover bog to the north, border the drain. The elevation at the base of TD2 varies between c. 50.58 mOD, at its highest point at the beginning of the drain, and c. 48.19 mOD, at its lowest point at the end of the drain, which marks the confluence with the Brook Stream.

Drain TD3 begins southwest of the Western Soak in a former area of bogland. The drain is bordered by an east-west trending road and flows westwards and then northwards, broadly following the pattern of the high bog boundary, before draining into the Silver River, c. 1.4 km west of the high bog

boundary. The drain is separated from TD1 by a groundwater divide, the significance of which is discussed below.

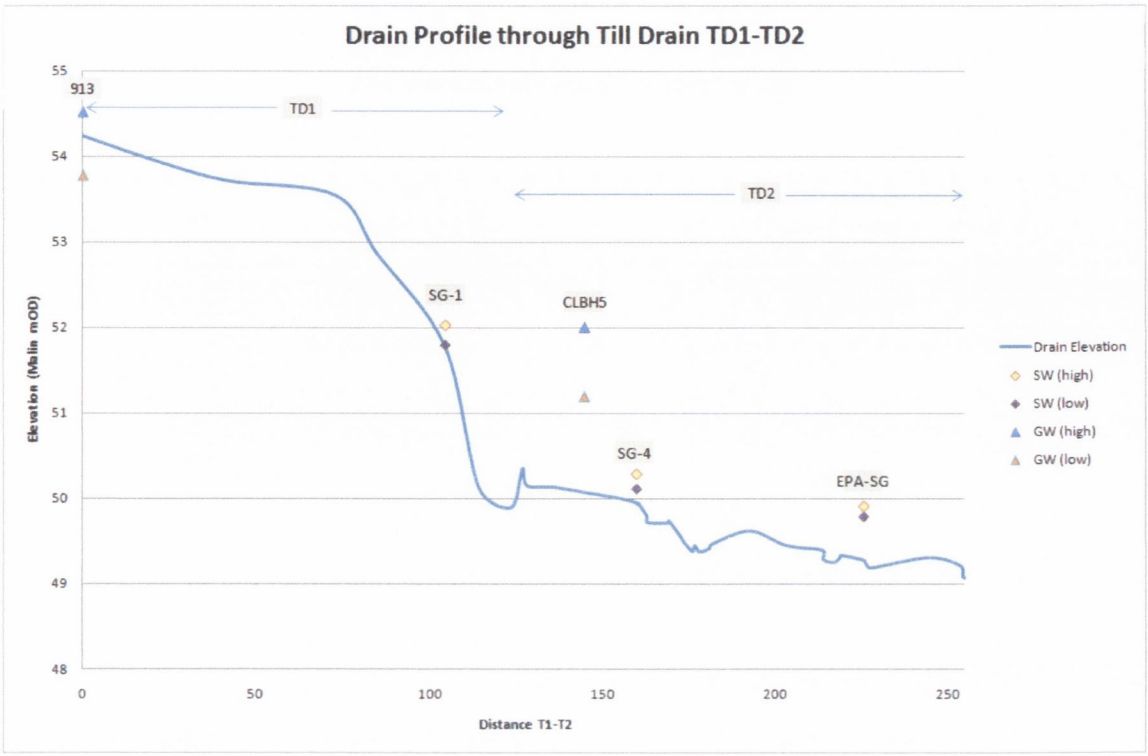


**Figure 4.2.** Drain profile through TD1 and TD2 (see figure B1 for location).

Water levels

The till-drains receive water as overland flow from the surrounding landscape, runoff from peripheral drains and groundwater seepage. Figure 4.2 illustrates a section through TD1 and TD2 where there is groundwater level and surface water level information available. From Figure 4.1, two important observations can be made:

1. Groundwater level in drain TD1 fluctuates from being below and above the base of the drain, as indicated by information from subsoil piezometer 913. TD1 was observed to be dry in July and August 2010 (and again over the same time period in 2011), following a sustained period of low rainfall. The drain then fills in wetter periods and spot electrical conductivity measurements at SG1 reveal values > c. 300 µS/cm, indicating a large groundwater component (Figure B3; Appendix B). In essence, as the groundwater table rises, the drain receives groundwater via a piston flow type-mechanism. The majority of water in this drain is groundwater, and chemical analysis also shows this to be the case (Chapter 6). A hydrograph of SG-1 is presented in Figure B3 and a summary of the water level fluctuation is presented in Table 4.3. Figure 4.2 compares the groundwater level in subsoil piezometer 913 to the surface water level at SG-1. Simple visual observation of both hydrographs indicates that as the groundwater level increases, so too does the surface water level in the drain, and the opposite

occurs when water level decreases, therefore in accordance with the piston-flow inference method of water movement. Chapter 6 will discuss groundwater-surface-water interactions in more detail.

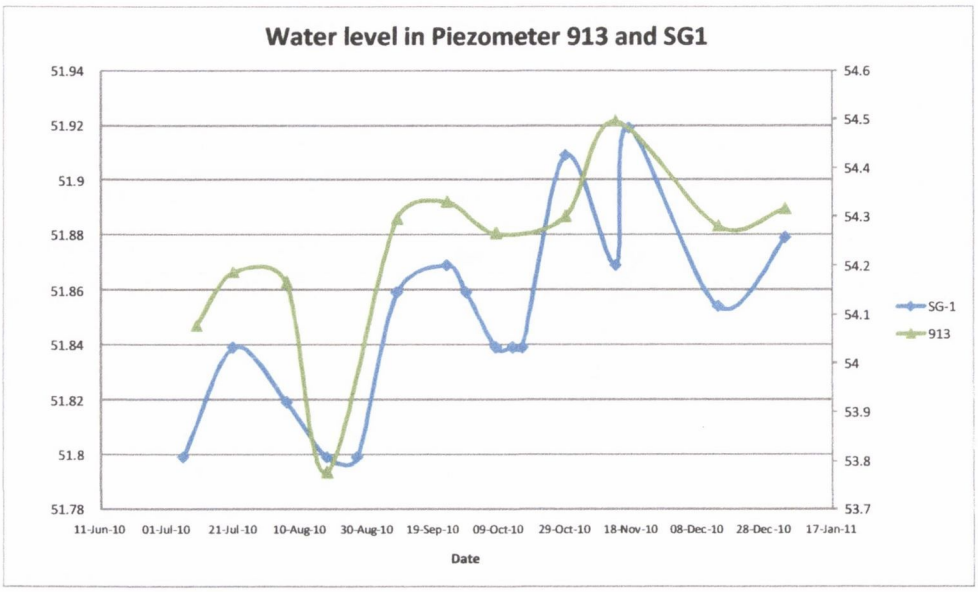


**Figure 4.3.** SG-1 and subsoil piezometer 913 hydrograph comparison

2. Groundwater level in drain TD2 is consistently above the base level in the drain, as indicated by information from borehole CLBH5. The drain receives waters from a number of outlets and complicates the water 'content' of TD2. As well as TD1, the drain receives water from a face-bank drain (FB2), cutover bog drains (CT1 and CT2) and the majority of high bog runoff (via the Bog Drain). In July and August 2010, both TD1 and the Bog Drain were observed to be dry, whereas there was a consistent flow of water in TD2. This indicates a consistent baseflow in the drain. As the drain is located close to the high bog (closest – c. 80 m) and the potentiometric surface of groundwater head in the till aquifer (Chapter 5) shows the groundwater under the high bog flows towards this area, drain TD2 is a very significant drain and a zone of groundwater discharge. A hydrograph of SG-4, located in TD2, is presented in Figure B6 and a summary of the water level fluctuation is presented in Table 4.3. The 'flashy' nature of the SG4 is immediately apparent and may be attributed to the nature of the recordings (i.e. manual and not continuous). Chapter 6 will discuss results in more detail.

*Cutover bog drains*

The southern margins of the Clara West high bog are bordered by areas of cutover bog. Hydrogeological interpretation (Chapter 5) indicates that an area of cutover bog south of Shanely's Lough is highly significant and is essentially a regional zone for groundwater discharge owing to its low topographic elevation, shallow peat depths, absence of lacustrine clay subsoil and drainage system. This area is referred to as the Restoration Area as it is here restoration and engineering activities will conceivably occur to arrest bog subsidence (Chapter 12). Four main cutover drains,

CT1, CT2, CT3 and CT4 are identified in this zone, each of which receives groundwater discharge. Figure 4.4 illustrates this area with the main drainage features

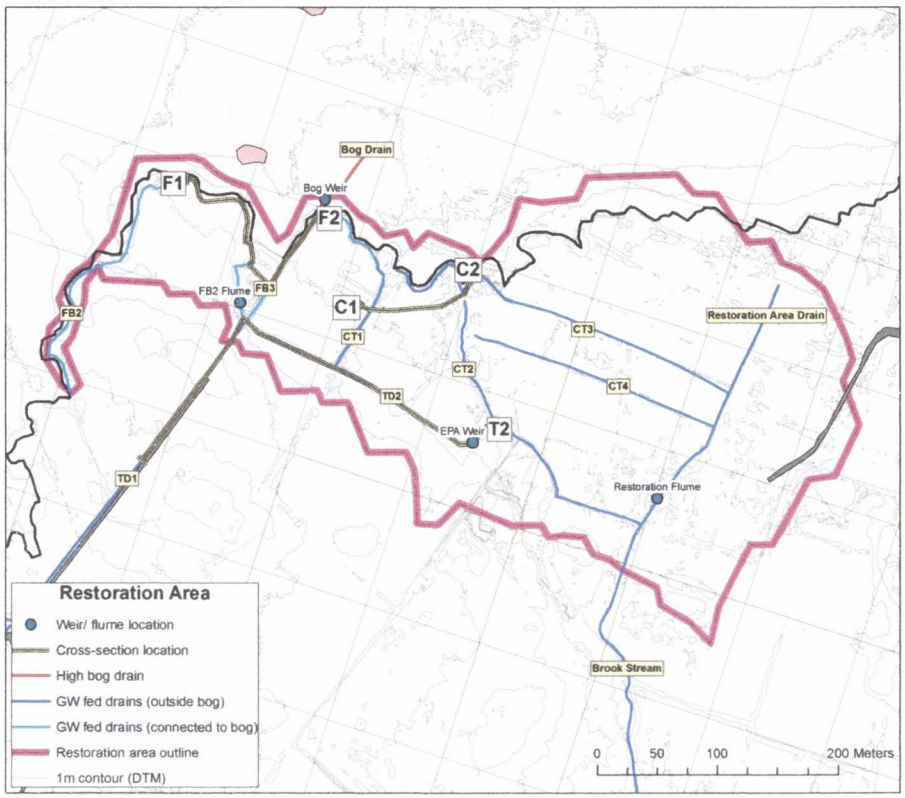


**Figure 4.4.** Restoration area with drainage system and cross-section locations

Drain characteristics

Drain CT1, which is c.105 m in length, begins south of the high bog and drains from a face-bank drain, FB3. The drain flows southwards and drains into TD2. The entire stretch of the drain is underlain by till subsoil and peat thickness is less than 2.8 m thick. The elevation at the base of CT1 varies between c. 50.26 mOD, at its highest point at the border between FB3 and CT1, and 50.01 mOD, at its lowest point, where it drains into TD2. As such there is a modest base level gradient in CT1. Drain CT1 is significant in that it receives runoff from the high bog, via the Bog Drain, and discharges into drain TD2.

Drain CT2, which is c.110 m in length, begins south of the high bog and at one time received runoff from the high bog and is commonly illustrated as marking the beginning of the Brook Stream on historical 6-inch maps. However this is no longer the case and there is minimal water movement in the drain which connects with TD2. The drain 'flows' southwards and drains into TD2. The entire stretch of the drain is underlain by till subsoil and peat thickness is less than 2.4 m thick. The elevation at the base of CT2 varies between c. 49.83 mOD, at its highest point, and c. 49.32 mOD, at its lowest point, where it 'drains' into TD2. As such there is a modest base level gradient in CT2 (c. 0.5 %). CT2 is constantly recharged with groundwater and displays a fluctuation of only 0.05 m over

the hydrological year (phreatic tube 931) and electrical conductivity of the water in the drain is consistently > 400 µS/cm.

Drain CT3, which is c.340 m in length, begins south of the high bog, east of CT2, and begins as a face-bank drain. The drain flows eastwards and drains into the Restoration Area Drain, which marks the eastern boundary of the Restoration Area. The drain is underlain by a variety of subsoil types (see Figure 4.5) and peat thickness is less than 3.4 m thick. Where the drain is underlain by till, groundwater discharge occurs. The elevation at the base of CT1 varies between c. 49.55 mOD, at its highest point and c. 48.51 mOD at its lowest point, where it drains into the Restoration Area Drain. In times of heavy rainfall, an old drain on the high bog, which was blocked in the 1990s, is a conduit for water flow on the bog surface and discharges into CT3. Drain CT4, which is c.210 m in total length, is located south of CT3 and flows eastwards into the Restoration Area Drain, almost parallel with CT3. It is similar to CT3 but does not receive any high bog runoff, but appears to be a groundwater seepage zone.

The Restoration Area Drain, which is c.230 m in length, begins south of the high bog, southeast of Shanely's Lough and marks the eastern boundary of the Restoration Area. The drain flows southwards and drains into the Brook Stream and marks a confluence with TD2. The entire stretch of the drain is almost wholly underlain by marl and lacustrine clay (see Figure 4.5) and peat thickness is less than 3.5 m thick. The elevation at the base of CT2 varies between c. 49.52 mOD, at its highest point, and c. 48.19 mOD, at its lowest point, where it 'drains' into TD2/ Brook Stream confluence. As such there is a moderate base level gradient in CT2. Groundwater appears to feed this drain via CT3 and CT4, rather than direct seepage. However, observed flows in the drain and the field hydrochemistry measurements taken in TC3 and CT4 suggested the Restoration Drain was significant and a flume, the Restoration Flume, was designed and installed downstream in the drain in January 2011.

Water levels

The cutover bog drains described above all receive a significant amount of groundwater and are zones for groundwater discharge (as best indicated by pH and electrical conductivity measurements in Figure 4.5), though the Restoration Area Drain appears to receive this groundwater from CT3 and CT4. Figure 4.5 illustrates spot electrical conductivity measurements taken in June 2010, during a dry/ low flow period, and it can be observed that minor drains in the Restoration Area do not receive any groundwater whereas the afro-mentioned cutover drains do. The drains that do no record high pH or electrical conductivity values are located in the north-eastern area of the Restoration Area and are separated from regional groundwater flows by a significant thickness of lacustrine clay. Cutover drains CT1 to CT4 are the drains receiving groundwater discharge .

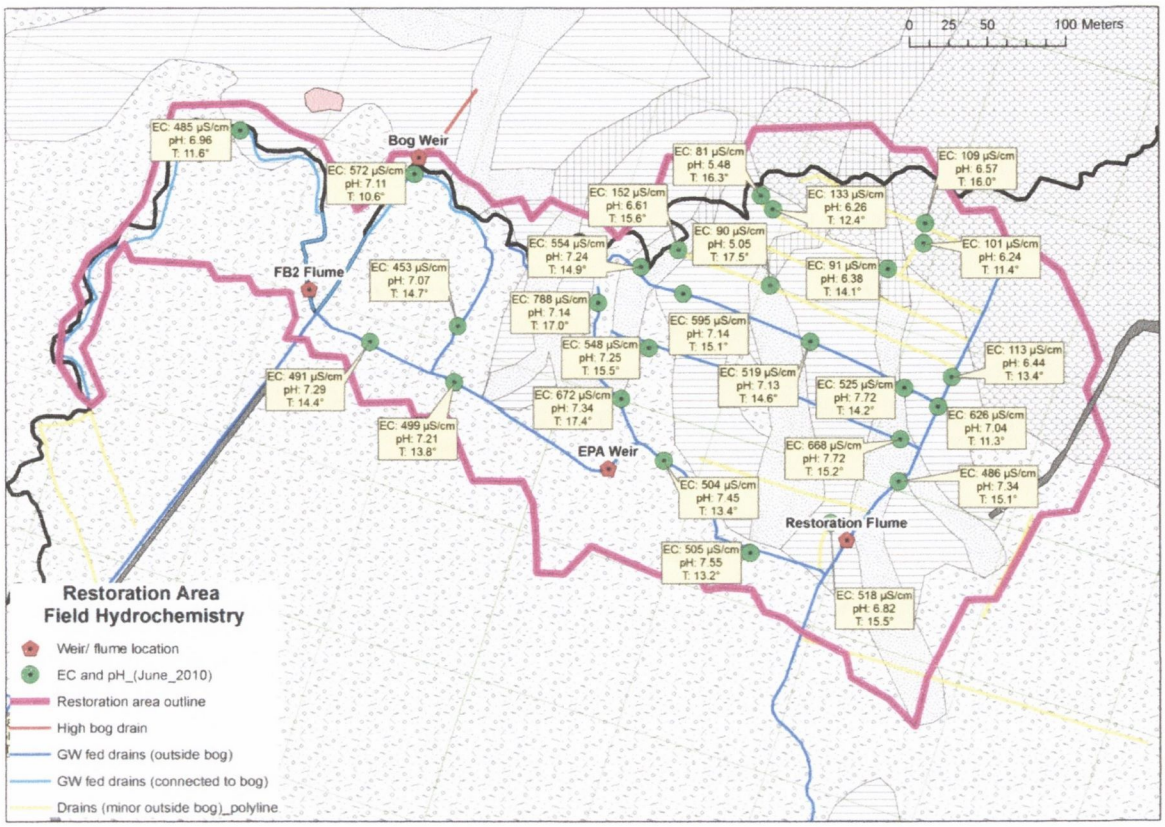


**Figure 4.5.** Electrical conductivity measurements in drains in Restoration Area, June 2010.

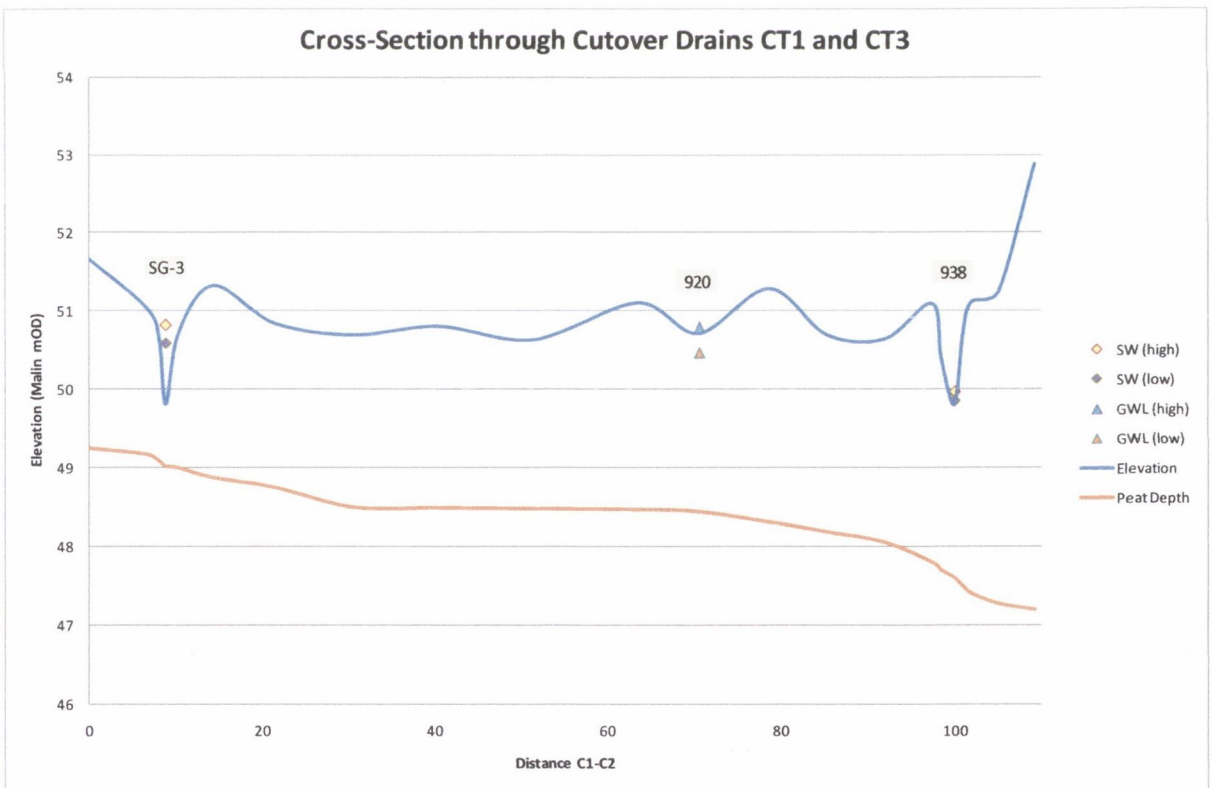


**Figure 4.6.** Cross-Section through CT1 and CT3.

A simple cross-section, Figure 4.6, through drains CT1 and CT3 illustrates the depth of the drain in relation to peat depth, high and low surface water level and high and low groundwater levels as measured at piezometer nest 920. The peat substrate is underlain by till subsoil in this section and it can be observed that groundwater level is always higher than the elevation at the base of the drain at CT1 and CT3. The inference is that groundwater is discharging into these drains in the same way as described for the till drains TD1 and TD2, where lacustrine clay is absent and till is close to the base of the drain. An artesian groundwater pressure is also observed at piezometer 927, located adjacent to CT3 and groundwater level at subsoil piezometer 926 is consistently greater than that in the Restoration Area Drain. An analysis of groundwater levels is described in Chapter 5.

*Face-bank drains*

The face-bank drains refer to drains that border the high bog. In the mid 1990's, turf cutting on the southern margins of Clara Bog West accelerated to the extent that face-bank drains cut close to the underlying mineral subsoil (till). Four main 'face-bank' drains have been identified and are referred to as FB1, FB2, FB3 and FB4 in Figures 4.1 and B1 and B2 in Appendix B.

Drain characteristics

Drain FB1, which is c.340 m in length, borders the southwest-centre of the high bog and is located southeast from the Western Soak. The drain follows the high bog boundary and flows eastwards to southwards into till drain TD1. The entire stretch of the drain is underlain by till subsoil (see Figure A2) and peat thickness varies between 0.8 m and 2.4 m. The elevation at the base of FB1 varies between C. 56.42 mOD at its highest point at the beginning of the drain and C. 54.35 mOD, at its lowest point, where it drains into TD1. As such there is a modest base level gradient in FB1. A cross-section along the length of FB1 is illustrated in Figure 4.7.

Drain FB2, which is c.425 m in length, borders the southeast-centre of the high bog and is located south from the Western Mound. The drain follows the high bog boundary and flows from north to east to south before draining into till drain TD2. The majority of the drain is underlain by till subsoil, except a small tract near piezometer 915 where lacustrine clay < 0.5 m thick is found, and peat thickness varies between 2.0 m and 2.8 m. The elevation at the base of FB2 varies between c. 54.86 mOD, at its highest point at the beginning of the drain, and c. 50.58 mOD, at its lowest point, where it drains into TD2. As such there is a significant base level gradient in FB2, which mirrors the underlying subsoil topography. A cross-section along the length of FB2 is illustrated in Figure 4.7.

Drain FB3, which is c.175 m in length, borders the southeast-centre of the high bog and is located south from the Western Mound. The drain follows the high bog boundary and flows northwards to eastwards into cutover drain CT1. The beginning of the drain is at a confluence between till drains TD1 and TD2 and face-bank drain FB2. The majority of the drain is underlain by till subsoil (see Figure A2), except at a small tract near phreatic tube 930 where lacustrine clay < 0.5 m thick is found,

and peat thickness varies between 0.5 m and 2.8 m. The elevation at the base of FB3 varies between c. 50.58 mOD at its highest point at the beginning of the drain and c. 49.88 mOD, at its lowest point, close to where it drains into CT1. As such there is a very moderate base level gradient in FB1. A cross-section along part of the length of FB3 is illustrated in Figure 4.7. FB3 also receives runoff from the high bog via the Bog Drain. In addition to this high bog runoff, FB3 also receives additional runoff, via a peat pipe (Chapter 9), which appears to be the focal point for water discharge for a small high bog catchment southeast of the Western Mound.

Drain FB4, which is c.645 m in length, borders the south-western margin of the high bog. The drain follows the high bog boundary and flows westwards until it drains into till drain TD3. The entire stretch of the drain is underlain by till subsoil and peat thickness varies between 0.6 m and 5.2 m. The elevation at the base of FB1 varies between c. 57.21 mOD at its highest point close to the beginning of the drain and c. 54.87 mOD, at its lowest point, where it drains into TD3. As such there is a modest base level gradient in FB4. A cross-section along part of the length of FB4 is illustrated in Figure 4.8.

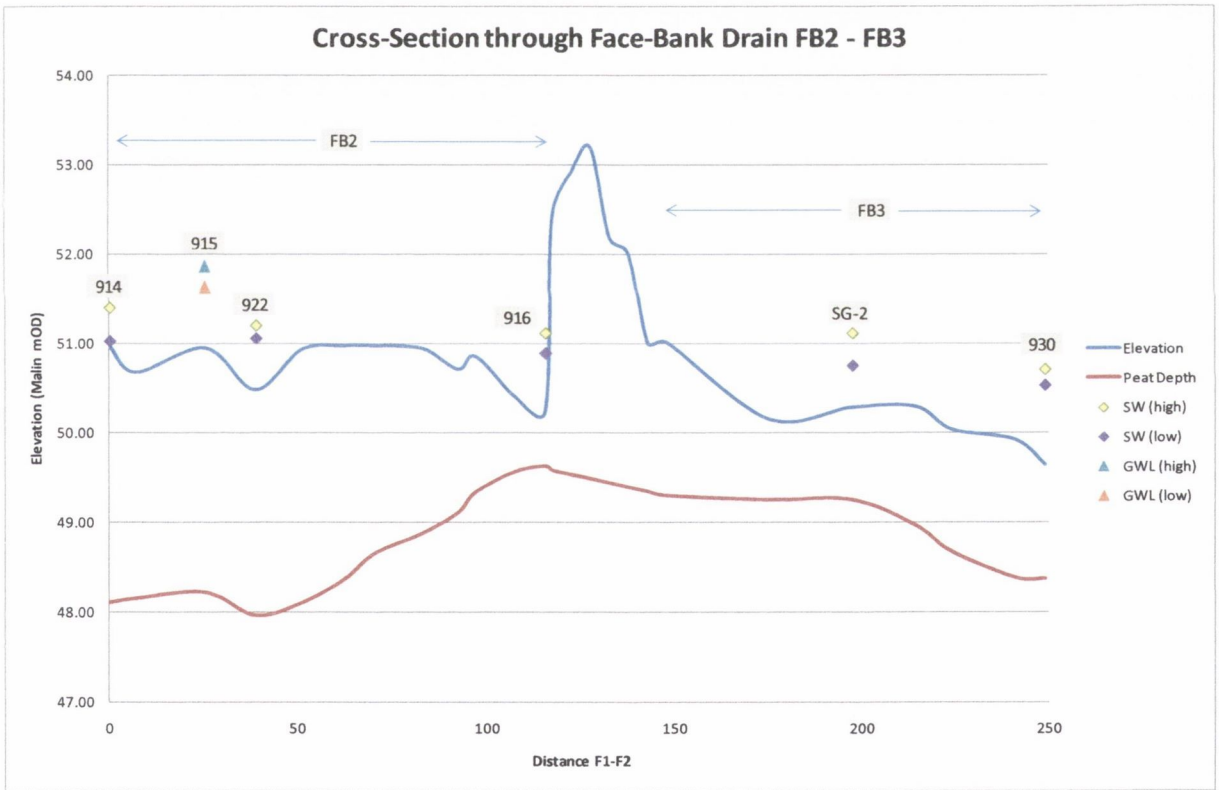


**Figure 4.7.** Cross-Section through part of FB2 and FB3.

Water levels and groundwater discharge

Figure 4.8 illustrates a longitudinal cross-section through the face-bank drains bordering the southern margin of Clara Bog West. Also illustrated on the figure are results from an electrical conductivity survey of the drain water in April 2010, which was a dry month, and groundwater level monitoring from piezometers close to the bog margin at the same time. In addition to this, the topographic profile

of the peat-subsoil interface is illustrated on the figure. The subsoil geology of Clara Bog West is illustrated in Figure A3 (Appendix A) and it can be observed, as alluded to above, that most of the southern high bog boundary is underlain by till subsoil with a small pocket of lacustrine clay close to piezometer 915 and phreatic tube 930.

If elevated electrical conductivity (i.e. > 250 µS/cm) is taken to represent groundwater discharge into the drain, it is clear from Figure 4.8 that drains FB1, FB2 and FB3 are zones for groundwater discharge. A localised pocket of groundwater discharge also occurs in FB4. It is interesting to note that groundwater discharge does not occur in the face-bank drains in the vicinity of piezometer 934, where groundwater level is above the base of the drains in the area. Drains in this area, which are often dry, are fragmented and do not form a distinct drainage feature, as the drains described in the previous section do. It appears that peat between FB4 and FB1 is significantly thick to balance the groundwater hydraulic head in the till subsoil. The same phenomenon can be observed between FB1 and FB2, where though groundwater level is above the level of the drain (inferred from groundwater table; Appendix C), the thickness of peat prevents groundwater discharge.

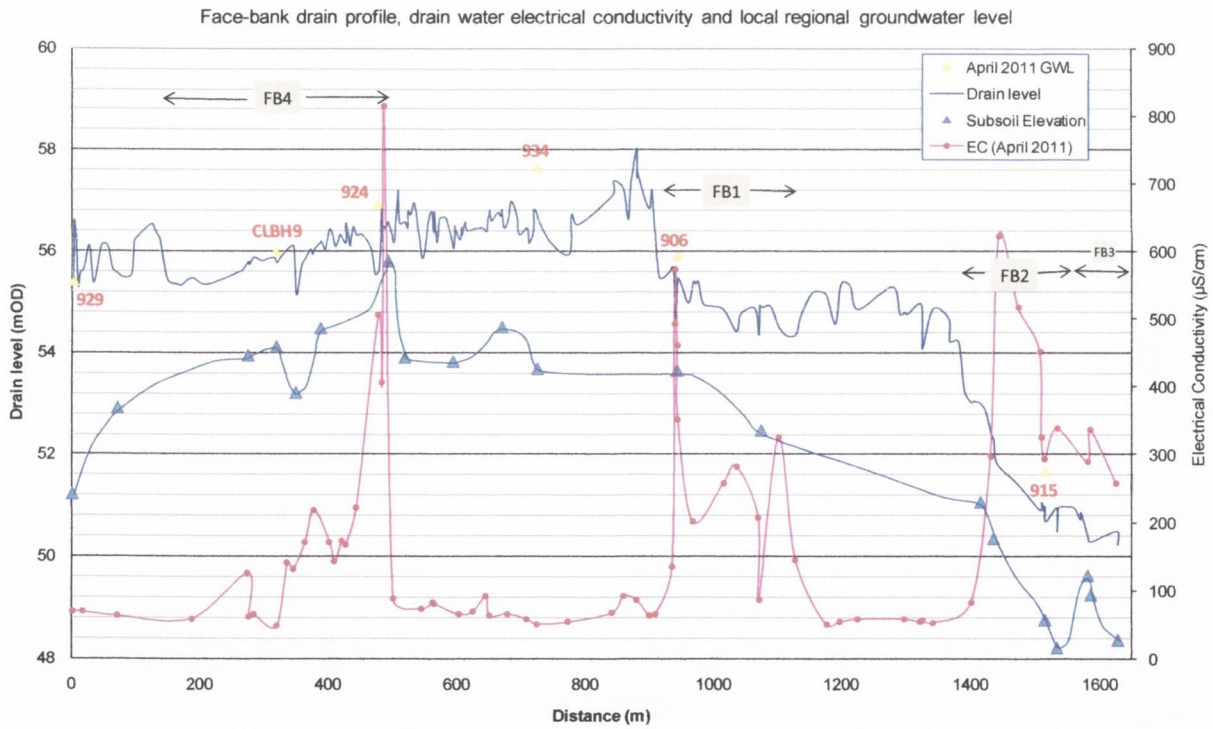


**Figure 4.8.** Relationship between face-bank drain base elevation, peat-subsoil elevation, electrical conductivity and local regional groundwater level (see figure B1 for location).

As such, though till underlies the majority of the face-bank drains, groundwater discharge is relatively localised (i.e. groundwater discharge does not occur due to the absence of lacustrine clay alone) and this appears to be due to the combination of two factors: (1) where regional groundwater level is higher than the base of the drain and (2) where the thickness of peat is relatively shallow (< 2.0 m) so that groundwater moves upwards, whereas in areas where peat is greater than c. 2.0 m, the downward

movement of water in the peat substrate appears to be balanced against the hydraulic head in the till subsoil, meaning groundwater discharge in the drain does not occur.

A longitudinal cross-section through part of face-banks drains FB2 and FB3 is presented in Figure 4.7. Water level information from installations in the drains and groundwater level information from subsoil piezometer 915 located adjacent to FB2 is also included on the figure. The relative fluctuations in water level are summarised in Table 4.3. The peat substrate is underlain by till subsoil in this section, except for a thin (<0.5 m) pocket of lacustrine clay in the vicinity of 914, and it can be observed that regional groundwater level is always higher than the drain base depth, even at low levels. The water levels in the drain installations (phreatic tubes 914, 916, 922 and 930 and staff gauge SG-2) at low-flow is base flow, meaning the drains have water throughout the year, which is not the case at drains which are not groundwater discharge zones, like most of the length of FB4.

As such, the profile section with water level information in Figure 4.8 is in accordance with the observed hydrochemical and water level gradient information described above, and supplants the conceptual model of FB2 being a zone of groundwater discharge. The same inference may also be applied to FB1 and FB2. FB4 is not a groundwater discharge zone though there are isolated pockets were groundwater discharge occurs, as may be observed from Figure 4.7, near subsoil piezometer 924.

Face-bank drain hydrographs

Hydrographs from the 2009-2010 hydrological year for piezometer nests 914 and 918, located in drains FB2 and FB1 respectively, are illustrated in Figures B7 and B8. It is clear that water flow follows an upward gradient at both piezometer nests. It is also interesting to note that the phreatic water table (i.e. the water level in the drain itself) in both nests mirrors the fluctuations in water level of piezometers installed to the base of the peat in the drain (see Appendix A for depths of piezometers). This implies there is a connection between the two water levels, indicating there is little resistance in the peat substrate and that there is an upward seepage of water.

It can be observed that the phreatic water level in 918 fluctuates less (c. 0.095 m) than it does in 914 (c. 0.37 m) over the hydrological year 2009-2010. This suggests that FB1 receives little water as overland flow and is constantly recharged by groundwater flow, which is also indicated by the electrical conductivity of water in the drain where values are consistently > 300 µS/cm. The larger fluctuation at 914 indicates that FB2 receives more surface water runoff as electrical conductivity as fluctuates between 50 and 500 µS/cm. The piezometer nest is located at the base of a steep topographic gradient and in periods of heavy rainfall receives water as overland flow from the area of cutover bog to the south. Surface water runoff from the high bog does not contribute water to FB2 - instead high bog runoff is concentrated in the Bog Drain and the peat pipe (Chapter 9).

A spot discharge measurement of 0.9 L/s and electrical conductivity measurement of 450 µS/cm was measured on 26-08-2010 at 914 following a sustained dry period, indicating this low flow was essentially groundwater and a good indication that FB2 is recharged constantly by groundwater. FB2 is considered to be the main face-bank zone of groundwater discharge and viewing the groundwater table in Figures C14 and C15 (Appendix C), this is unsurprising as the potentiometric contours converge in the FB2 region, suggesting the drain is drawing down the groundwater table. On this basis, a flow measurement structure, the FB2 Flume was installed in May 2011 in order to measure runoff in the FB2 drain (Section 4.2.4).

*High bog drains*

There is only one 'true' drain on the high bog – the Bog Drain. The catchment area encompassing the Bog Drain is complicated and has changed since the work of Van der Shaff (1999), Chapter 2, and this change is discussed in Chapter 10. The high bog catchment areas will be discussed separately, in Section 4.3 and in detail in Chapters 9 and 10. The Bog Drain is c.70 m in length, and is located southeast from the Western Mound. The drain flows southwest and drains into the face-bank drain FB3. The elevation at the base of the drain varies between c. 53.20 mOD at its highest point close to the beginning of the drain and c. 51.58 mOD, at its lowest point, where it drains into FB3. The drain receives the majority of the high bog runoff and is a very important hydrological feature as a topographic catchment area can be delineated to the drain outlet – and knowledge of runoff from the high bog will allow an assessment of hydrological changes since the work by Van der Schaaf (1999) in the 1990's (Chapter 11).

While the Bog Drain is the only true drain on the high bog there are two additional outlets for high bog runoff, which become active during periods of heavy rainfall:

(1) A peat pipe, located southwest from the Bog Drain discharges water following periods of heavy rainfall. The pipe is the outlet for a small catchment, southeast of the Western Mound on the high bog and its location is illustrated on Figure E1. The face-bank in this region is characterised by cracks that appear to be connected. The cracks collect water during heavy rainfall and water discharges into face-bank drain FB3 via the peat pipe – i.e. it is essentially a karstified effect. Discharge was measured from the pipe following such an event on 2nd February 2011. A flow rate of c. 4 L/s was measured from the pipe and on the same day a flow rate of c. 10 L/s was measured from the bog drain. The pipe is therefore a significant drainage feature in this part of the high bog.

(2) A blocked drain, which was active in the early 1990's before it was blocked with plastic sheeting in the mid 1990's, is also an outlet for high bog runoff following heavy rainfall events. The drain is located east of the Bog Drain and it discharges from the high bog into cutover drain CT3. Similar to the peat pipe, the drain is generally dry but following a period

of heavy rainfall a significant volume of water can be observed discharging into CT3. Unfortunately the water does not discharge from one discreet point, but rather there are 3 separate outlets from the high bog meaning discharge cannot easily be measured. The 'drain' is the outlet for a small high bog catchment south of Shanely's Lough.

4.2.3.Surface water level summary

Table 4.3 summarises the maximum and minimum water levels recorded at each of the water level structures installed into the various drains of the Clara West drainage system. The fluctuation between the highest and lowest water level recordings is also collated in the table. The most relevant levels have been discussed in section 4.2.2. The water level data has been used to compute mean stage levels in model design (Chapter11) and runoff and water balance is calculated using continuous records from stilling wells, which will be discussed below in Section 4.2.4 and in Chapter 9.

Table 4.3. Summary water levels from monitoring installations in the Clara West drainage system.

| ID | Period | Max WL (mOD) | Min WL (mOD) | Fluctuation (m) |
|---|---|---|---|---|
| SG-1 | 06-07-10 to 24-10-11 | 52.03 | 51.78 | 0.25 |
| SG-2 | 06-07-10 to 09-08-11 | 51.11 | 50.75 | 0.36 |
| SG-3 | 06-07-10 to 09-08-11 | 50.815 | 50.595 | 0.22 |
| SG-4 | 06-07-10 to 04-10-11 | 50.287 | 50.107 | 0.27 |
| 914 | 14-10-10 to 24-09-11 | 51.394 | 51.024 | 0.37 |
| 916 | 14-10-10 to 03-01-11 | 51.112 | 50.888 | 0.224 |
| 918 | 14-10-10 to 24-09-11 | 55.716 | 55.621 | 0.095 |
| 922 | 04-02-10 to 03-01-11 | 51.198 | 51.053 | 0.145 |
| 923 | 04-02-10 to 04-11-11 | 50.087 | 50.047 | 0.04 |
| 930 | 18-08-10 to 03-01-11 | 50.706 | 50.53 | 0.176 |
| 931 | 18-08-10 to 24-07-11 | 50.096 | 50.041 | 0.055 |
| 932 | 08-09-10 to 24-07-11 | 49.424 | 49.164 | 0.26 |
| 933 | 08-09-10 to 24-07-11 | 49.551 | 49.456 | 0.095 |
| 938 | 14-12-12 to 27-09-11 | 49.96 | 49.85 | 0.11 |

Note: Restoration Flume, FB2 Flume and EPA Weir discussed separately (Chapter 6)

4.2.4.Flow measurement structures

To develop an accurate water balance model, knowledge of runoff (surface water and groundwater) is crucial. Sections 4.2.1 to 4.2.3 served as an investigation into where to best place flow measurement structures to (1) measure runoff from the high bog flow and (2) measure base flow from recharge originating from beneath the high bog by means of hydro-chemically separating the flow components (Chapter 6).

On this basis, four hydraulic structures have been installed in the Clara West drainage system – a weir in the Bog Drain, a weir in Drain TD2, a flume in Drain FB2 and a flume in the Restoration Area

Drain. Their locations are illustrated in Figure 4.1 and 4.4 and their design and calibration is discussed below.

*Bog-weir*

The Bog Drain is the only drain on the high bog where runoff can be measured. The drain was therefore instrumented with a weir in order to calculate runoff and infiltration through the drains catchment area (Section 4.3 and Chapter 9). To achieve this aim, a simple weir and stilling-well was installed and is described below.

Installation and design

A simple thin-plate weir with a V-notch, constructed in the TCD Civil Engineering structural laboratory, was installed in November 2010 and instrumented with a stilling well and logging device in January 2011. The weir structure is a simple thin-plate V-notch composed of a 6 mm thick steel plate with a 60° V-notch, the bisector of which is equidistant from the walls of the channel. The notch is also tapered at 60° in the direction of flow and is 2 mm thick. To prevent the weir from sinking in the peat substrate that forms the drain, two flanges, or wings, were fastened on the top section, either side of the weir plate. A photograph of the structure is presented in Figure 4.9.

**Figure 4.9.** High bog v-notch weir and stilling well installed in the Bog Drain

The weir is vertical and perpendicular to the walls of the approach channel. The weir plate is 1.4 m in width and the channel itself is 0.6 m in width, meaning 0.4 m on each side of the plate is in peat. The weir plate is 1.0 m in height and the channel is 0.4 m deep, meaning 0.6 m of the plate is below the base of the channel. As the weir effectively dams water in the approach channel there will inevitably

be erosive effects at the base of the weir and along its sides. Indeed, in January 2011, water had eroded beneath and around the weir plate. To fix this problem, the channel was first filled in with local peat material. Paving stones/ concrete slabs were then placed on the base of the channel and along its sides, either side of the weir plate. Care was taken so not to create any subtle hydraulic jumps or obstructions and to allow water to flow as freely as possible through the V-notch.

Having installed these measures to prevent erosion it is assumed there is no leakage of water 'around', or beneath, the weir plate – the water level in the stilling well, in the logger download, never noticeably dropped implying the assumption is correct. As peat is a relatively soft material, erosive effects would quickly manifest themselves and there would be a considerable drop in stage behind the weir plate. The weir was watertight and firm during the study period and flow measurements during a high flow high event confirmed it withstood large discharges.

Calibration

In order to calculate discharge from the weir and develop a rating curve, it is necessary to record the head, or stage, of water behind the weir. A stilling well, 2 inches in diameter, was therefore installed 0.6 m behind the weir plate in the approach channel and contains an OTT Orpheus Mini water level logger, which has been set-up to record water level and temperature every hour. The measuring cell within the logger is sensitive to small fluctuations in water level and is ideally suited for continuous measurement of stage behind the weir plate. The position of the stilling well was placed a sufficient distance upstream so head measurements are not in the area of back-flow induced by the V-notch. The stilling well is however close enough to the weir so that energy loss between the head–measurement section and the weir is negligible. In essence, the positioning of the stilling well follows British Standard guidelines (BS 3680).

The basic principle of a thin-plate V-notch weir is that the head ($H$) above the crotch of the V-notch is directly related to discharge ($Q$). To calibrate the weir, a number of discharge measurements, using a simple bucket and stop-watch method, were performed in the field, over a range of low and high flows. Table B6 in appendix B lists the field $Q$ measurements. Figure B20 plots the measured discharge against $H$ – i.e. the rating curve for the bog-weir. It is clear from the figure that there is an excellent linear relationship between $Q$ and $H$. The trend follows a power law distribution – i.e. flow rate versus head is non-linear.

As the weir is an accurately designed hydraulic measuring structure, a discharge equation can be applied to stage measurements. The discharge is a function of the head on the weir, the size and shape of the discharge area, and an experimentally determined coefficient which takes into account the head on the weir, the geometrical properties of the weir and approach channel and the dynamic properties of the water (BS 3680-4A:1981). For V-notch weirs, the discharge equation is as follows:

$$Q = C_e \frac{8}{15}\sqrt{2g}tan\frac{\phi}{2}H^{5/2} \qquad \text{Equation 4.1}$$

where $Q$ is discharge over the weir, $C_e$ is a coefficient of discharge, $g$ is acceleration due to gravity, $\phi$ is the angle of the V-notch and $H$ is head above the bottom of the notch.

Results

Table B6, appendix B, compares $Q$ measurements in the field to those calculated using measured $H$ values applied to equation 4.1. Figure B21 plots measured Q values from the field against calculated Q clues using equation 4.1. It is clear from figure B21 there is an excellent correspondence between the two methods of $Q$ calculation. All of the $Q$ comparisons are in excellent agreement with slight deviations in the linear regression trend most probably due to slight inaccuracies in field measurement.

As the weir is functioning correctly and equation 4.1 can be applied to known $H$ values, a continuous record of discharge from the high bog can be computed. Figures B22 and B23, Appendix B, plot hydrographs for stage and flow rate respectively from the Bog Weir between the period from 13-01-11 to 05-12-12. The period of analysis was used to compute a water balance for the weir catchment area and is discussed separately in Chapter 9. The stage fluctuates within 0.37 m and discharge from the bog fluctuates within 13 L/ s. In the water balance period, maximum discharge from the high bog occurred on the 30$^{th}$ November 2011 and the minimum discharge, 0.05 L/ s, occurred between the 19$^{th}$ and 21$^{st}$ May, 11$^{th}$ to 16$^{th}$ June and on the 20$^{th}$ and 23$^{rd}$ June 2011.

The Bog Drain was also instrumented with a v-notch weir in the eco-hydrological studies of the early 1990's (Van der Schaff, 1999). Considering the bog has subsided since that time, it is expected the high bog catchment areas have also changed since that time, resulting in a change in runoff from the Bog Drain. As such, the runoff data for 1991 (Van der Schaff's water balance analysis period) and 2011 can be compared and analysis to see if subsidence has affected high bog hydrology. Chapters 9 and 10 will discuss this in detail.

*EPA weir*

The increasing awareness of Clara Bog as a probable groundwater dependent ecosystem (GWTDE) stimulated the Environmental Protection Agency (EPA) to monitor the bog system under the remit of the Water Framework Directive (WFD) [Regan, 2010b]. As such, in November 2010, the EPA in conjunction with TCD installed a broad crested V-notch weir in the main drain exiting Clara Bog West (Figure 4.1) – till drain TD2. The position of the weir, which is envisaged as being a permanent structure, was chosen so to measure groundwater discharge from beneath the high bog and runoff from the high bog as accurately as possible - a hydrochemical mixing model (Chapter 6) has been developed to separate groundwater flows from high bog runoff from the Bog Weir. The weir was

placed close to the high bog so to reduce water flows from drains not connected to the high bog system, thereby distorting the *actual* total runoff from the Clara Bog West hydrologic system. The gradient of the channel was suitable for weir construction and, importantly, consent was given by the local landowner to install the structure.

Installation and design

Hydrogeological monitoring of subsoil piezometers in the vicinity of the EPA weir (namely CLBH5, 920 and 927; see Figure A6) reveal that drain TD2 is between 0.8 m and 1.8 m below the regional groundwater table. As discussed in section 4.2.2, most of the channel base is that of till subsoil material. A localised drop in regional groundwater level, discussed in Chapter 8, is almost certainly associated with this drain, which has deepened considerably in the early 1990'a (per comm. NPWS). As such, groundwater discharge from waters originating beneath the high bog is not confined to the face-bank drains, but peripheral till drains such as TD2. It is for this reason the EPA installed the weir, which also has an OTT Orpheus Mini water level logger measuring water level continuously.

**Figure 4.10.** EPA Weir installed in drain TD2

The weir itself is 1.0 m in width and consists of a large rectangular 'box' which is 2.0 m in length and serves to contain the water flow, which is directed into the structure by means of flanking wings either side of it. A thin 6 mm V-notch plate, with the V-notch at an angle of 30°, defines the weir-plate. Such a flat V-notch weir is ideal for measuring low flows. The drains contributing water to TD2 were described in section 4.4. TD2 was dry in July and August 2010 and discharge from the bog drain was observed to be minimal during the same time period - a spot discharge of 2.17 L/s was measured on 26-08-2010 at SG-4, which is c. 100 m upstream from the weir. The inference is that this flow of

water was largely groundwater base flow. The weir can therefore be used to accurately measure base flow, from beneath the high bog, during low flow periods (Chapter 6).

Calibration

The EPA Weir was calibrated by measuring flow rate in the field at a range of high and low flows. At low flows a simple bucket and stop watch discharge measurement was possible, however, the geometry of the v-notch weir meant most flow measurements were calculated using velocity-area techniques, downstream of the weir in an area where the bank geometry is relatively uniform and flow is steady. Flow measurements were also taken by the EPA and the weir has been rated using EPA flow measurements and TCD flow measurements – Table B4 in Appendix B summarises this data.

To calibrate the weir using the measured discharge measurements, a stage-discharge relationship was employed using the methods described by Herschy (1995). A rating method was employed so to account for a 'background' water level – i.e. stage never reached zero meters in the drain and the rating must account for this. By plotting stage ($h$) versus discharge, on a log scale, a relationship can be deduced and the following equations are used to determine the rating equation that solves for discharge ($Q$):

$$LogQ = LogC + nLog(h + a) \qquad \text{Equation 4.2}$$

To solve for a:

$$a = \frac{h_1 h_3 - h_2^2}{h_1 + h_3 - 2h_2} \qquad \text{Equation 4.3}$$

To solve for Q:

$$Q = C(h + a)^n \qquad \text{Equation 4.4}$$

where $C$ is the intersection of the slope of $h$ versus $Q$ on the y-axis, $n$ is the gradient of the slope and $a$ is a coefficient that determines the background, or lowest water level. The $h$ values used in equation are taken at any point along the $h$ versus measured $Q$ line.

Figures B13 and B16 plot stage versus discharge and also stage adjusted for background water level ($H$-$a$) versus discharge. It can be observed that when stage is adjusted for background water level the rating curve follows a power-law distribution, like it did for the Bog Weir. There are also two sets of rating curves and equations for the EPA Weir. The reason for this is that in June 2011 the weir was vandalised and the v-notch plate was absent for c. 6 weeks. Two rating equations, either side of this period, are necessary as stage is very sensitive to backwater effects, which alter slightly based on the geometry of the weir plate. In the original rating equation it can be seen that there are three slopes to the stage-discharge plot, whereas there are only two slopes in the adjusted rating. The reason for this is that the plate was lowered by c. 15 cm, meaning the approach geometry was altered, thereby

altering the rating equation. However, results have been combined to produce a continuous record for flow rate at the weir. The period of 'missing' data has been estimated using flow rate data from the FB2 and Restoration Area Flumes, described below.

Results

Figures B14 and B15 plot measured discharge versus rated discharge for the original rating equation and adjusted rating equation respectively. The figure indicates an excellent correlation between the measured calculated and calculated values - the weir has been calibrated successfully.

As the weir is functioning correctly and equation 4.4 can be applied to known stage values, a continuous record of discharge from the EPA Weir can be computed. Figures B24 and B25, in Appendix B, plot the hydrographs for stage and flow rate respectively from the EPA Weir between January and December 2012. The period of analysis was used to compute a water balance for the weir catchment area and is discussed separately in Chapter 9. The stage fluctuates within 0.23 m and discharge from the bog fluctuates between c. 3 and 154 L/ s. In the water balance period, maximum discharge from the high bog occurred between the 6th and 7th February (142 L/s) and on the 25th October (154 L/s) and the minimum discharge, c. 3 L/ s, occurred between the 1st and 9th August 2011. The discharge from the EPA Weir will be discussed in Chapters 6 and 9.

*Restoration Area Flume*

Flume hydraulic structures are also effective water measuring devices in open channel flow. A flume has been installed in the main drain exiting the Restoration Area (section 4.2.2) [Figure 4.11].

**Figure 4.11.** Restoration Area Flume installed in Restoration Drain (note: stilling well and staff gauge later moved away from incoming channel stretch to ensure laminar flow).

The channel is a result of former turf cutting activities where the drain served to drain the local cutover bog area so to allow movement of machinery. The gradient in the channel is low and there is no *real* definition in channel geometry. A weir structure is not suitable in such an area as the risk of local flooding would be high due to low bank heights and the 'backing-up' effect on the water profile induced by a weir structure.

A simple flume measuring structure, based on the design by Samani & Magallanez (2000), Samani et al (2006) and Baiamonte & Vito (2007), was installed in the drain in January 2010. The measurement principle of this flume is based on establishing a channel contraction, thereby creating a critical flow, using two semi-cylinders applied to the walls of a fixed channel.

Installation and design

The flume is made out of galvanised steel and consists of a rectangular section of channel constricted in the middle by two half sections of metal pipe - a conceptual plan-section and cross-section is presented in Figure 4.12 and the flume design is illustrated in Figures B30 and B31, Appendix B. The central, narrow section of the flume ($B_c$) is the throat, the width of the rectangular channel is $B$ and the vertical pipe half-section diameter is $d/2$. The contraction creates a critical flow, making it possible to calculate the water flow by simply measuring the water depth upstream of the constriction.

According to Samani et al (2006) the contraction ratio (i.e. $B_c$ divided by $B$) must be between 0.4 and 0.6. Spot $Q$ measurements in the field gave an initial estimation of $Q$ values, or ranges of flow, to be expected in the channel. Using this information, the flume was designed with $B_c$ equal to 0.132 m and $d/2$ equal to 0.084m. The approaching channel length is 0.6 m and the exiting channel length is 0.4 m. A stilling well, 2 inches in diameter, was installed adjacent to the approach channel and contains an OTT Orpheus Mini CTD water level logger, which was been set-up to record water level and temperature every hour.

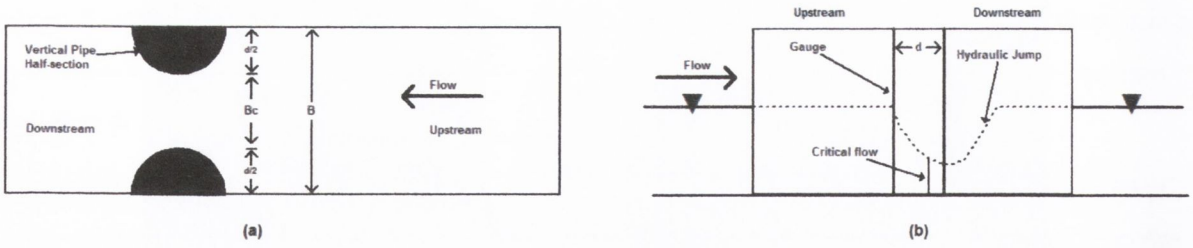


**Figure 4.12.** (a) Plan view of flume (b) Cross-section view of flume.

Calibration

Similar to a weir, a discharge equation, expressing the relationship between the depth of water ($h$) and the flow rate of water, can be developed and solved for known values of head or stage. According to Baiamonte & Vito (2007) the relationship between critical flow ($K_c$) in the flume and upstream normal water level ($h$) may be expressed by:

$$\frac{K_c}{B_C} = a(\frac{h}{B_c})^n \qquad \text{Equation 4.5}$$

where $a$ and $n$ are numerical constants.

Following this, the $K_c$ /$B_c$ ratio has the following expression:

$$\frac{K_c}{B_C} = \frac{Q^{2/3}}{g^{1/3}B_c^{5/3}} \qquad \text{Equation 4.6}$$

Replacing equation 4.6 into equation 4.7, the following relationship between $h$ and $Q$ (i.e. the stage-discharge relationship of the flume) is deduced (Baiamonte & Vito, 2007):

$$Q = a^{3/2}\sqrt{g}\, B_c^{5-3n/2}h^{3n/2} \qquad \text{Equation 4.7}$$

Flume discharge equation 4.7 may then be applied to the Restoration Flume. However, it was first necessary to calibrate the flume in the field by measuring critical and normal water levels (facilities were not available to do this in the TCD Civil Engineering hydraulics laboratory). Figure 4.13 plots $K_c/B_c$ versus $h/B_c$ for measurements taken at high and low flows. There is a clear linear relationship between $K_c$ and $h$, meaning the flume is effective at inducing small head loses, thereby creating a critical flow through the channel constriction.

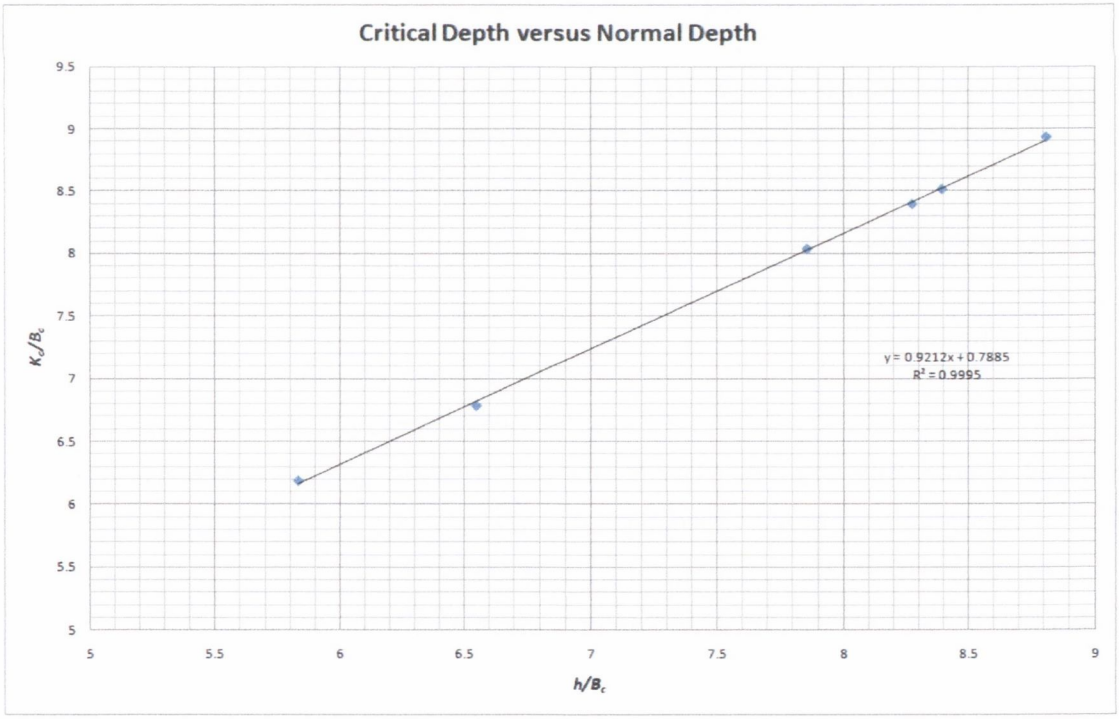


**Figure 4.13.** Field measured Kc/Bc versus h/Bc at Restoration Area Drain flume

However, to solve equation 4.7, the coefficients $a$ and $n$ must first be determined. The flume design by Samani et al (2006) was based on the channel having a flat gradient. The Restoration Flume is

situated in a stretch of the Restoration Drain where the gradient is c. 0.6 %. Baiamonte & Vito (2007) extended the work of Samani (2006) by determining the coefficients *a* and *n*, which are controlled by the geometry of the flume and the slope of the channel, over a range of contraction ratios (between 0.17 and 0.81) and channel gradients (< 3.5 %). Baiamonte & Vito (2007) calculated that flow rates using equation 4.7 were within 10 % of measured values.

The flumes were calibrated in the field by taking a number of flow rate measurements and using these values, from a range of low and high flows, to construct a rating curve. Dilution gauging was the flow measurement technique employed as at low flows the velocity area method, using a current meter, was not accurate due to the low head levels above the meter sensor. Trial and error measurements in the field found dilution gauging methods to be most accurate.

The flume discharge equation was applied to stage measurements assuming the water level in the stilling well upstream from the constriction is equal to the water level at the suggested measuring point in Figure 4.12. Coefficients *a* and *n* were solved to be 0.75 and 1.14 respectively. The flume discharge equation for the Clara flumes, both of which have a constriction ratio of 0.41, has been calculated as follows:

$$Q = 0.65 \sqrt{g}\, B_c^{0.79}\, h^{1.71} \qquad \text{Equation 4.8}$$

The flow rates calculated using equation 4.8 compared favourably to those calculated using rating equation 4.4– flow rates are within 10 to 20% of each other up until a flow rate of 60 L/ s, after which the flume-discharge equation becomes less accurate. The rating curve itself is most probably +/- 10 to 20% of the actual flow rate as it is constructed on field measurements which are never perfect. Calibrating a flume in a laboratory, as Baiamonte & Vito (2007) did, is invariably more accurate than using field measurements.

Results

Figures B11 and B12 plots measured discharge versus rated discharge and the flume equation derived discharge respectively. Again it can be observed that when stage is adjusted for background water level the rating curve follows a power-law distribution, like it did for the Bog Weir and EPA Weir. The figure indicates an excellent correlation between the measured and calculated values - the weir has been calibrated successfully. However, it is found that the flume discharge equation becomes less accurate > 60 L/ s and the rating equation is used to generate the flow rate hydrograph for the Restoration Flume.

Figures B26 and B27, Appendix B, plot the hydrographs for stage and flow rate respectively from the Restoration Flume between January and December 2012. The period of analysis was used to compute a water balance for the weir catchment area and is discussed separately in chapter 8. The stage fluctuates within 0.53 m and discharge from the bog fluctuates between c. 0.8 and 96 L/ s. In the

water balance period, maximum discharge from the high bog occurred between the 6th and 7th February (80 L/s) and on the 25th October (96 L/s) and the minimum discharge, < 1 L/ s, occurred between the 1st and 6th June 2011 and between the 11th and 16th June 2011. The discharge from the Restoration Flume will be discussed in Chapters 6 and 9.

*FB2 Flume*

A flume (Figure 4.14), with identical dimensions was installed in drain FB2 on the 31st May 2011 and it location can be found in Figure B2. The flume is located before the confluence of drains TD1 and TD2 and there are no marginal drains draining into it – the FB2 Flume receives water from the high bog and groundwater catchment area. Its calibration process was identical to that of the Restoration Flume and equation 4.7 can also be applied to the FB2 Flume – the channel gradient is almost identical to that of the Restoration Flume. Figures B18 and B19 plot the measured discharge against the rated discharge and discharge estimated using equation 4.8.

As before, there are excellent correlations but the rated equation is used for hydrograph flow rate as it seems to be more accurate at high flows. Over the water balance period, the stage fluctuates within 0.46 m and discharge from the bog fluctuates between c. 1.5 and 7 0 L/ s. In the water balance period, maximum discharge from the high bog occurred on the 29th No1vember (60 L/s) and on the 25th October (70 L/s) and the minimum discharge, < 1.6 L/ s, occurred between the 2nd and 6th August 201.The stage and discharge hydrographs from the FB2 Flume are included in appendix B and the significance of the results obtained from the FB2 Flume will be discussed in Chapters 6 and 9.

**Figure 4.14.** FB2 Flume installed in the FB2 Drain (note: stilling well and staff gauge later installed upgradient of flume).

#### 4.2.5.Cutover bog and marginal drainage summary

Before beginning to understand the connection between the Clara West high bog and the regional groundwater table hosted in till subsoil, the Clara West drainage system had to be mapped, levelled and described. Three broad types of drain are described in the drainage system: (1) face-bank drains bordering the high bog, (2) cutover bog drains in areas that were formerly bogland areas and (3) marginal or agricultural drains which border the cutover drains. Zones of groundwater discharge were found through simple field hydro-chemistry analysis of waters in the respective drains. Elevated electrical conductivities (> 250 μS/ cm) were found to be good indicators of groundwater discharge.

A system of drains in cutover bog southeast of the Western Mound and southwest of Shanely's Lough is particularly important and the area is termed the Restoration Area as groundwater discharge appears to concentrate in this zone. A comparison of surface water levels with piezometer levels from surrounding subsoil piezometers installed to till indicates that most drains are below the regional groundwater table – particularly in the Restoration Area. The most important face-bank drain is that of Drain FB2, which border the south portion of the high bog and flows into till drain TD2, which marks the southern boundary of the Restoration Area. Initial flow and chemistry analysis shows this drain to be a significant zone of groundwater discharge.

Following drain characterisation and an initial period of surface water level monitoring and electrical conductivity measurements, flow measurement structures were installed in four drains considered most important in which to measure runoff for water balance calculation and base flow runoff, and by inference recharge and infiltration calculation. The drains instrumented with continuous loggers and weir/ flume hydraulic structures are the Bog Drain (Bog Weir), Drain TD2 (EPA Weir), FB2 Drain (FB2 Flume) and the Restoration Drain (Restoration Flume). Each hydraulic structure has been calibrated and stage and runoff hydrographs have been generated form each, the information of which will be analysed throughout the rest of the thesis.

### 4.3. High bog

A functioning raised bog contains a well developed acrotelm layer that is near-permanently wet with a low level of water table fluctuation (< c. 0.2 m), as described in Chapter 2. For the high bog to remain wet the gradient of the high bog ground level must be sufficiently low so that most of the rain water that falls onto the bog is retained by the system – i.e. there is little overland runoff and downward infiltration. Bog subsidence, which alters the high bog topography, affects the hydrological processes on the surface of the bog which maintain ecological communities dependent on saturated and ombrotrophic conditions. Additionally, the leakage rate of water through natural raised bogs is small, in the order of 40 mm/ year (Streefkerk & Casparie, 1989). Subsidence, which is peat consolidation (i.e. water loss), will increase the rate of infiltration through the peat substrate forming the bog, meaning water is lost to the subsurface that is ordinarily stored in the peat substrate. In essence, water

must be held within a raised bog system and when it is released either as downward infiltration or overland flow, the integrity of the high bog ecology is compromised. Chapter 10 will describe the effects of subsidence on hydro-ecology and the sections below describe the hydrological characteristics of the Clara West high bog as it is now.

### 4.3.1.LiDAR Survey

Accurate elevation, or topographic, data on a high bog is a critical measurement, particularly on a bog such as Clara where topographic elevation is changing over time. The topography of a high bog is highly variable, due to local hydro-ecological features, and high resolution data is required to properly distinguish between areas where water accumulates and where there are steep and gentle slope gradients, as well as other drainage features such as small gullies and drainage channels. In response to the changing morphology of the Clara West high bog (Chapter 1), the NPWS commissioned a LiDAR survey of the bog, which was carried out by Terra-Imaging in November 2008.

LiDAR (Light Detecting and Ranging) is a remote sensing technology that uses laser scanning to collect height or elevation data. The theory behind LiDAR elevation application is beyond the scope of this study; however, its strength is its ability to generate high resolution digital surface models (DSMs) that can be further processed to produce digital terrain models (DTMs). The difference between a DSM and a DTM is that while a DTM measures all elevations, such as tree heights/ canopies etc, a DTM measures the ground surface and effectively filters out elevation data that is not required – in this case it is high bog topography and drainage features.

*LiDAR calibration*

The LiDAR elevation points were levelled by Terra-Imaging by means of calibrating the data to ground truthing elevation data measured using a Trimble G6 GPS system by TCD, coincident with the LiDAR survey (Terra-Imaging, 2009). The reference areas were sections of road, at three locations surrounding the bog. The differences between the LiDAR and reference GPS elevations are summarised in Table 4.4. The average differences between the ground and LiDAR survey elevation data are between c. -2 cm and 5cm, with larger differences, of e.g. 13cm and 14cm, localised and reflective of local elevation differences where the ground survey point and LiDAR point was not measured in close vicinity. As such, the LiDAR survey accurately measured the elevations of the hard surfaces surrounding, and within, Clara Bog.

Table 4.4. Difference between ground truthing GPS data and LiDAR elevation data

| Reference Area ID | Average Difference | Maximum Difference | Minimum Difference | Standard Deviation | Number of Measurements |
|---|---|---|---|---|---|
| RA1 | 0.045 | 0.13 | 0.01 | 0.033 | 40 |
| RA3 | -0.008 | 0.04 | -0.05 | 0.021 | 36 |
| RA4 | -0.019 | 0.14 | -0.08 | 0.041 | 36 |

LiDAR measurement on hard/ solid structures is very accurate and reliable – however, ecosystems are not hard surfaces. To assess whether the LiDAR survey measured the high bog topography accurately, ten reflective 1.2m$^2$ marker boards were placed in separate areas on Clara Bog in order to act as reference points to the LiDAR survey. The marker boards were placed on the bog to essentially 'act' like a hard surface on the bog and to reflect the pulses of laser light emitted during the LiDAR survey (Figure 4.15). The ground elevation measurements taken on and around the marker boards were not used to calibrate the LiDAR elevation data (Terra Imaging, 2009). However, the marker boards were detected in the LiDAR survey allowing a comparison with measured GPS elevations (Table 4.5).

Table 4.5. Difference between marker board GPS data and LiDAR elevation data

| Marker Board ID | Average Difference | Maximum Difference | Minimum Difference | Standard Deviation | No. of Measurements |
|---|---|---|---|---|---|
| MB1 | -0.004 | 0.03 | -0.06 | 0.041 | 4 |
| MB2 | -0.044 | 0 | -0.09 | 0.035 | 4 |
| MB3 | -0.055 | -0.04 | -0.07 | 0.016 | 4 |
| MB4 | -0.057 | -0.05 | -0.07 | 0.012 | 3 |
| MB5 | 0.029 | 0.04 | 0.02 | 0.011 | 4 |
| MB6 | -0.093 | -0.07 | -0.11 | 0.02 | 3 |
| MB7 | -0.048 | -0.01 | -0.1 | 0.044 | 4 |
| MB8 | -0.085 | -0.06 | -0.1 | 0.019 | 3 |
| MB9 | -0.062 | -0.05 | -0.07 | 0.014 | 2 |
| MB10 | 0.001 | - | - | - | 1 |

The results indicate a relatively good correlation between the ground and LiDAR elevations with average differences within c. 6 cm, not unlike the results of the LiDAR and hard ground comparison. Marker board 6 (c. 9 cm difference) and 9 (c. 8.5 cm difference) are not quite as accurate but are <10cm in difference. Marker boards 6 and 8 were placed in areas with heavy heather growth, implying an unstable surface, which may have moved after the boards were surveyed on the ground. Analysis of the GPS measurements taken around the marker boards on the high bog itself found differences to range from (-) 0.42 m to 0.44 m with a mean value of 0.08 m and standard deviation of 0.1 m. The mean difference, < 0.1 m, is an acceptable resolution considering the inherent error associated with both methods of elevation measurement. However, the large differences in maximum and minimum values are a result of vegetation differences. While the LiDAR is very accurate on flat vegetation surfaces such as sphagnum lawns, it does not penetrate through thick expanses of heather. Such heather expanses are common on the boundaries of the bog and on the Western Mound – caution is therefore taken when interpreting elevation values in these areas. However, overall, the LiDAR data and DTM model is accurate and can be used with confidence to characterise the high bog hydrology.

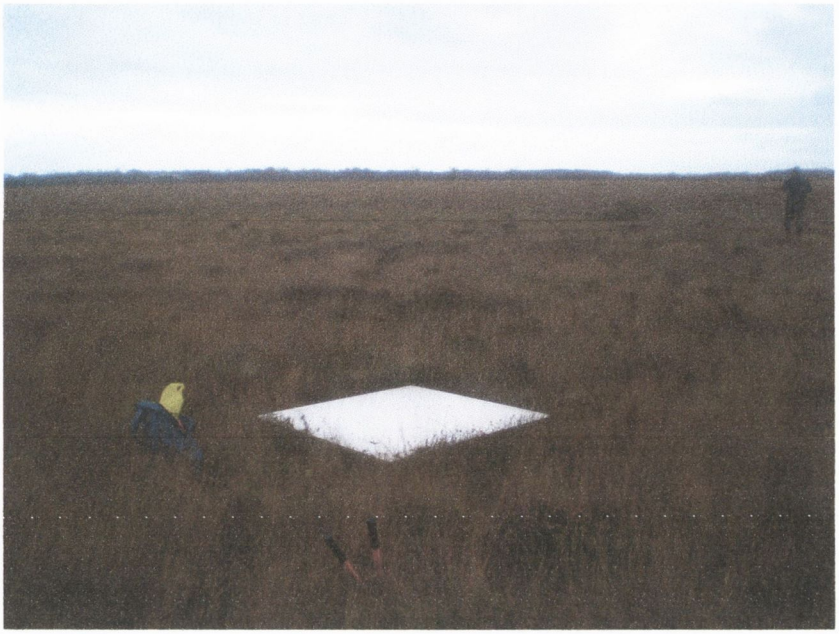

**Figure 4.15.** Marker board area

### 4.3.2.High bog catchment areas

A catchment, also referred to as a drainage basin and watershed, is a topographic area that collects and discharges surface streamflow through one outlet or mouth (Mays, 2012). The catchment divide is the line dividing land whose drainage flows toward the given stream from land whose drainage flows away from that stream (Mays, 2012). Accurate delineation of catchment areas is critical in a hydrological study as the catchment area is used to calculate flow rates in the water balance (Chapter 9).

The LiDAR survey has been used to create a DTM for the Clara West high bog, using a grid at a resolution of 1.0 m. High bog catchment areas have been drawn using the generated topographic data and are illustrated in Figure 4.16 (also in Appendix B). Four distinct catchment areas have been identified on the high bog:

(1) The FB2 Flume catchment area, which covers an area of c. 0.57 $km^2$ and encompasses the Western Soak, is located in the western/ south-western area of the high bog and drains into the FB2 Flume

(2) The Bog Weir catchment area, which is c. 0.31 $km^2$, is located northwest, north and northeast of the Western Mound and converges/ 'pinches' east of the Western Mound and drains into the Bog Weir, which is the only direct runoff measuring structure on/ from the high bog

(3) The Restoration Area Weir catchment area, which covers an area of c. 0.72 $km^2$ and encompasses Shanely's Lough, is located north, northeast and east of the Western Mound and drains into the Restoration Area where runoff is then measured at the Restoration Area Flume

(4) The Peat Pipe catchment area, which is c. 0.045 $km^2$, is located east and southeast of the Western Mound and drains into a peat pipe, as described in Section 4.2.2.

The high bog catchment areas have changed significantly since the work by Van der Schaff (1999), and the changes will be discussed in Chapter 10, following the calculation of the water balance for each of the respective catchment areas in Chapter 9.

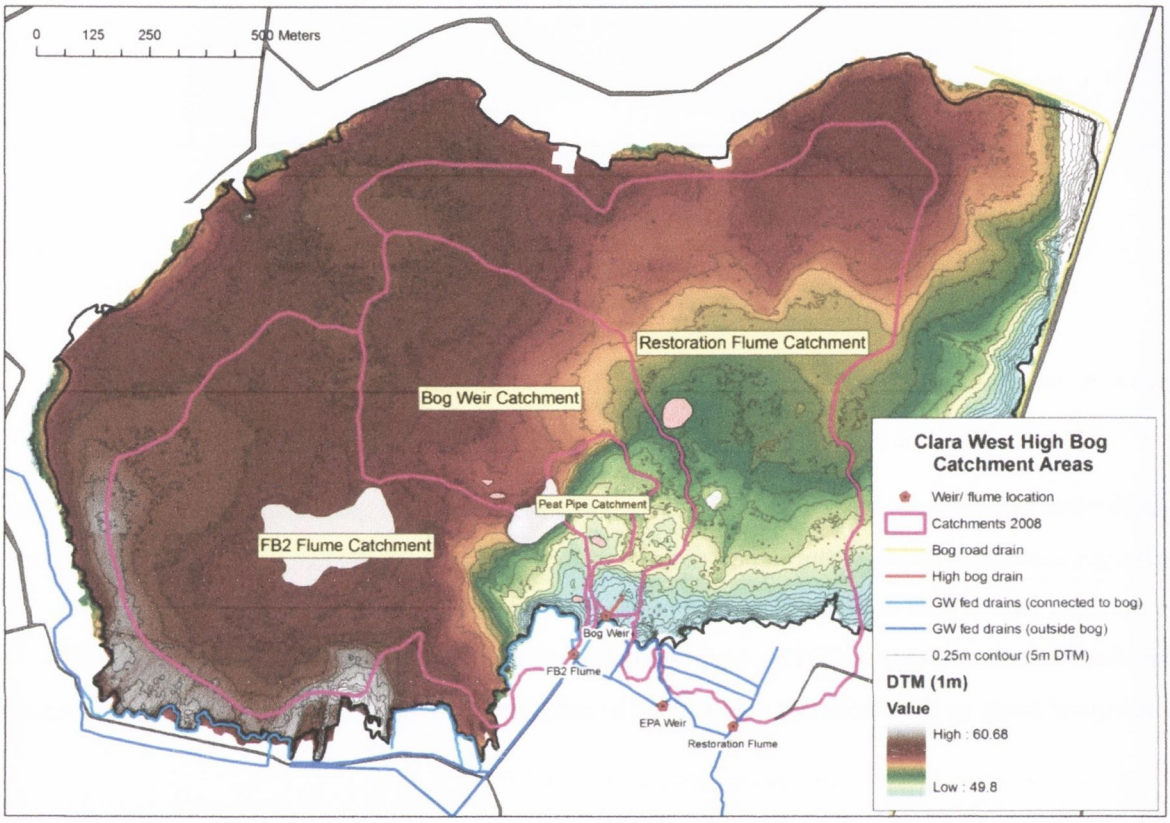


**Figure 4.16.** DTM of Clara West high bog and location of high bog catchment areas

### 4.3.3. Ecotopes

The Clara West high bog is characterised by botanical communities that, when grouped together based on similar and particular characteristics, form a collection of 'ecotopes' on the high bog surface. Essentially, an ecotope encompasses several more or less related botanical community complexes (Van der Schaff & Streeferk, 2002). The type of ecotope that develops is dictated by the surface water flow regime on the surface of the high bog. Kelly (1993) first mapped and defined the various ecotopes characterising the Clara West high bog. Table 4.6 summarises the characteristics associated with the six ecotope types that were first described by Kelly (1992) and Kelly & Schouten (2002).

Ecotopes can be used to assess wet and dry conditions on the high bog surface. Therefore, mapping ecotopes over time allows an assessment on whether the bog is getting wetter or drier, or whether it is in a steady state, implying no change. Ecotope mapping has been carried out on Clara Bog on three occasions – Kelly (1993), Fernandez (2005) and Fernandez (2009). Coincident with ecotope mapping

has been topographic surveying. As such, the effects of subsidence on bog ecology can be assessed and this is discussed in Chapter 10. As means of an introduction, Figure 4.17 illustrates the most recent ecotope map for Clara Bog West, as mapped by Fernandez (2009). Of particular importance is the occurrence of central, subcentral and active flush ecotopes – these ecotopes are indicative of wet conditions whereas the remaining ecotopes signify dry/ drying out conditions.

Table 4.6. Summary of important hydro-ecological characteristics of Clara Bog ecotopes (after Kelly, 1993, Kelly & Schouten, 2002 and Fernandez 2009).

| **Ecotope** | **Characteristics** |
|---|---|
| Facebank | No acrotelm; low water table; disturbed conditions |
| Marginal | Dry conditions; acrotelm mostly absent, very thin (< 0.5 cm) when present |
| Submarginal | Dry conditions; some indictation of wettness; water table relatively low; acrotelm generally absent and < 0.5 cm thick |
| Subcentral | Acrotem sometimes present and < 0.2 m thick; transistion of wet to dry conditions; sometimes associated with pools |
| Central | Wettest area of bog; abundant *Spahgnum*; acrotelm well developed, often deep < 0.4 m |
| Soak/ Active Flush | Open water present; nutrient enrichment; acrotelm well-developed > 0.4 m thick |
| Inactive Flush | Limited acrotelm development; deep water table |

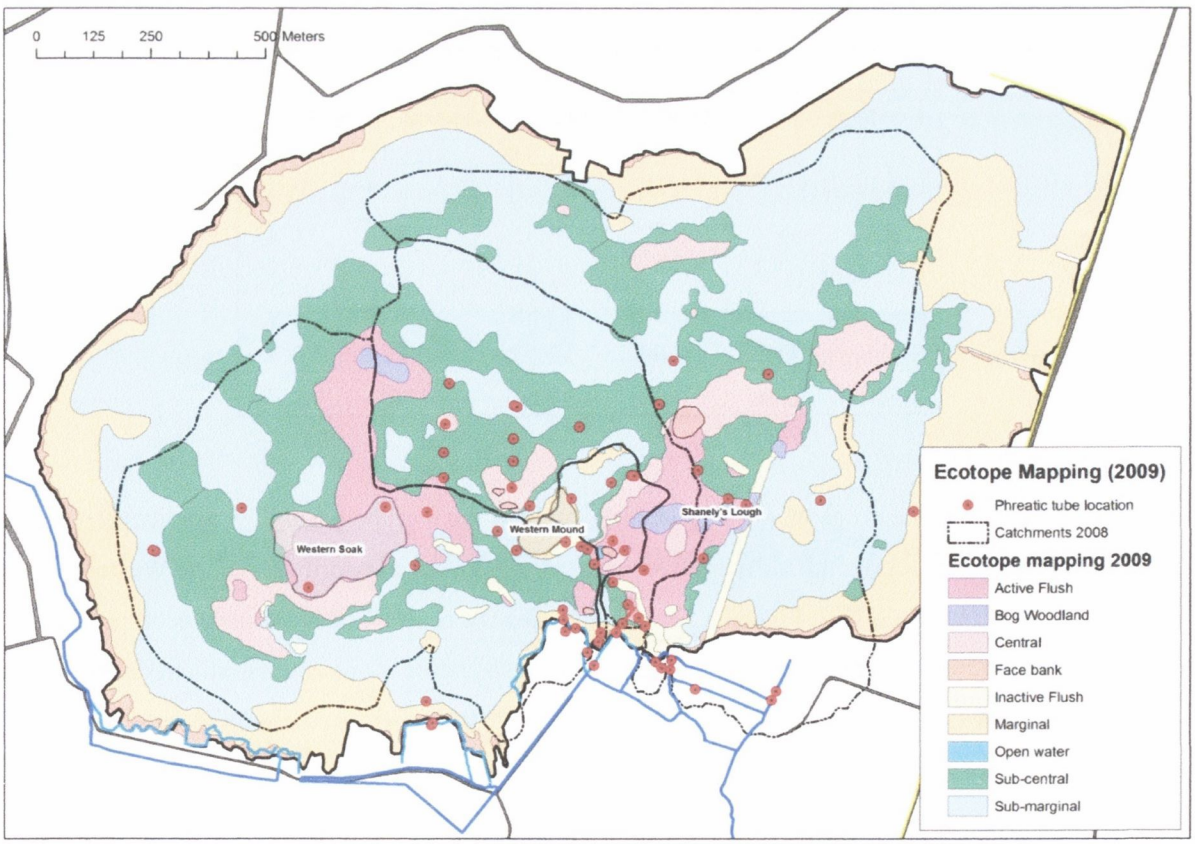


**Figure 4.17.** Ecotope distribution on Clara West high bog in 2009 (after Fernandez, 2009)

### 4.3.4.Slopes

The morphology of the catotelm surface determines the surface slope and thus the horizontal component of the hydraulic gradient in both acrotelm and catotelm (Van der Schaff & Streefkerk, 2002). Shrinkage of the catotelm therefore affects the surface slope of the bog and eventually alters the hydrological conditions maintaining the ecological communities. Van der Schaff (1999) found that the maintenance of ecotopes is dependent on the maintenance of shallow surface slope gradients, generally in the order of < 0.3 % - < 0.5 % for flush areas.

Table 4.7 summarises the slope gradients, calculated using ArcMAP Geographic Information System (GIS) spatial analyst and the 2008 LiDAR DTM, underlying the ecotopes as mapped by Fernandez in 2009. It can be observed that the wettest ecotope, central, has a mean slope of 0.23 %, which is near identical to that calculated by Van der Schaff (1999). Subcentral ecotopes, which are less wet and have a less well-developed acrotelm, have a mean slope of 0.37 %, again similar to that calculated by Van der Schaff. The drier ecotopes of face-bank, marginal and submarginal have mean slopes of 3.55, 1.97 and 0.61 % respectively. Acrotelm will not develop on such slopes, just within occasional pockets of submarginal slope areas. Active flush ecotopes, which include the Western Soak and Shanely's Lough soak systems, have a mean slope of 0.51 %. However, these ecotopes are labelled flushes for good reason – water flows through the areas (as opposed to collecting and slowly moving in shallow gradient central ecotope areas) meaning long flow path lengths are required to keep such areas saturated.

Table 4.7. Summary of slope gradients (%) underlying Clara Bog West ecotopes

| **Ecotope** | **Min** | **Max** | **Mean** | **S.D.** |
|---|---|---|---|---|
| Central | 0.00 | 1.35 | 0.23 | 0.19 |
| Subcentral | 0.00 | 3.90 | 0.37 | 0.33 |
| Active Flush | 0.02 | 3.55 | 0.51 | 0.43 |
| Facebank | 0.02 | 12.65 | 3.55 | 2.52 |
| Marginal | 0.00 | 12.58 | 1.97 | 1.93 |
| Submarginal | 0.00 | 12.22 | 0.61 | 0.71 |
| Inactive Flush | 0.04 | 9.61 | 1.90 | 1.70 |

Figure 4.18 illustrates the range of slope gradients found on the high bog. Shallow gradients (< 0.2 %) are concentrated in the topographically high areas west, northwest and northeast of the Western Mound. Visual comparison with Figure 4.17 indicates that the central and subcentral ecotope are underlain by shallow gradient areas and that the active flush ecotopes are down gradient of the shallow gradient areas. However, the overall surface level gradient has increased under the high bog and this is addressed in Chapter 10.

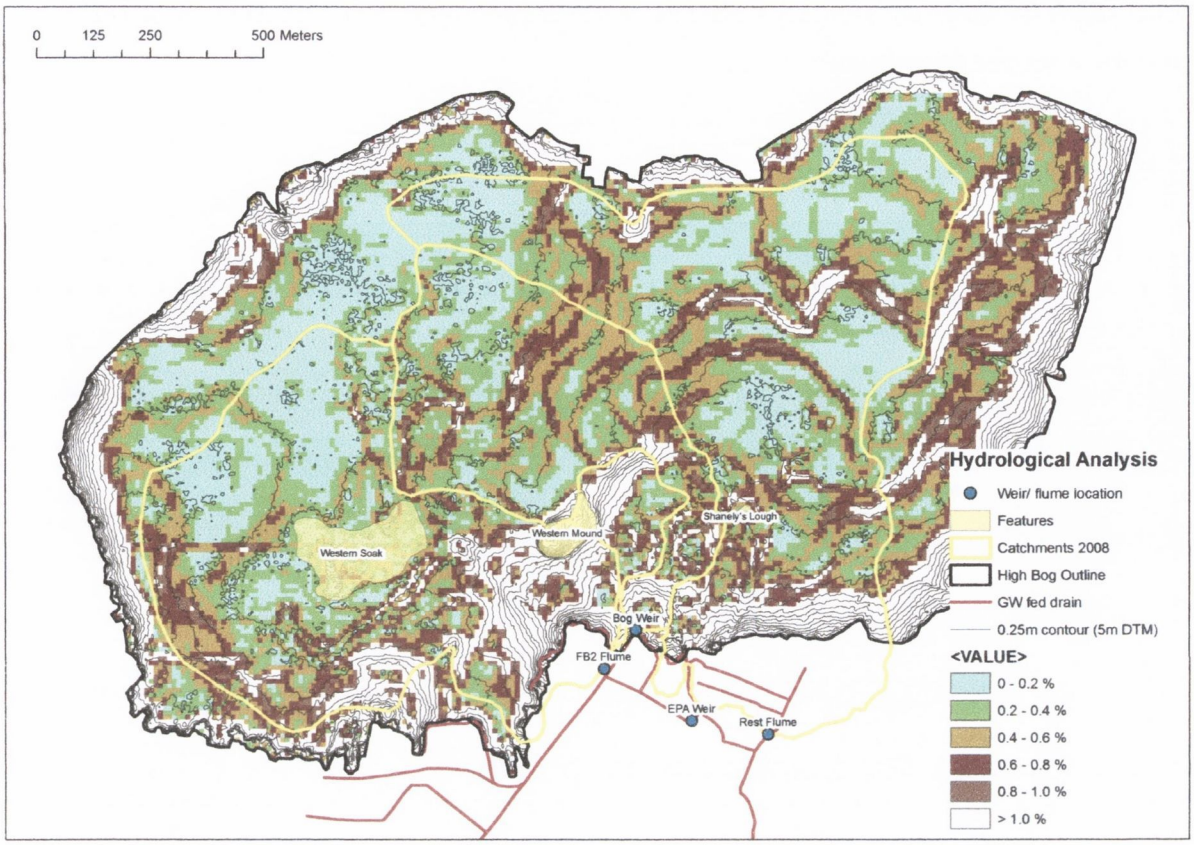


**Figure 4.18.** Slope gradients (%) on Clara West high bog

### 4.3.5.Flow Paths and Lengths

Figure 4.19 illustrates flow paths, or streamlines, of a water particle, that does not evaporate or infiltrate downwards, in the high bog catchment areas. The flowlines were generated using a 100m grid (using 2008 DTM) so to enable comparison with flowlines on the high bog catchment as calculated in 1992 by Van der Schaff (1999). The differences will be described in Chapter 10. However, from Figure 4.19 it can be observed that flowlines converge in the area of the Western Soak and long flow path lengths supply water to the Shanely's Lough soak system and area of active flush in the bog weir catchment. Both flush systems require a large volume of water to function as soak systems, which are nutrient rich relative to their ombrotrophic surroundings, and it is believed this is a consequence of the long flow path lengths supplying the soak areas (Kelly, 1993).

Tables 4.8, 4.9 and 4.10 summarise the flow path lengths that carry water to the boundaries of the wet ecotopes, namely central, subcentral and active flush. The flow path lengths are notably different in the Western Soak catchment, with mean flow path lengths of 326 m and 174 m supplying water to active flush and central ecotopes respectively. In contrast, mean flow path lengths of 713-735 m and 430-685 m supply water to active flush and central ecotopes respectively in the bog weir and restoration area catchments. It seems therefore that the Shanely's Lough soak system is dependent on long flow paths lengths, whereas the Western Soak system has shorter flow path lengths, but a lot of

water enters the soak area. Both soak systems, which are priority habitats, are therefore sensitive to changes in surface flow regime.

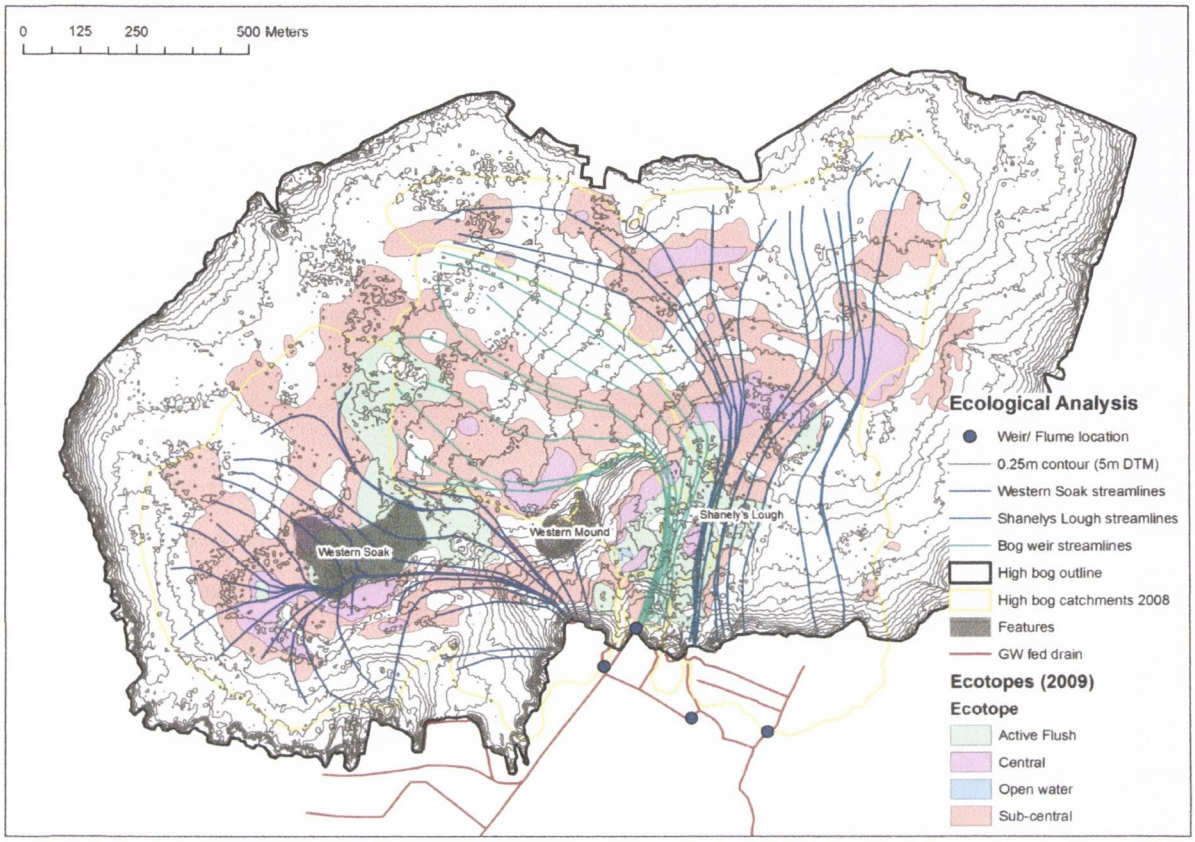


**Figure 4.19.** Flow path lengths in high bog catchment areas and distribution of 'wet' ecotopes

Table 4.8. Flow path lengths (m) in the Western Soak catchment

| | Active Flush | Central | Subcentral |
|---|---|---|---|
| **Max** | 413 | 281 | 712 |
| **Min** | 81 | 51 | 50 |
| **Mean** | 326 | 174 | 133 |
| **S.D.** | 79 | 65 | 228 |
| **n** | 13 | 11 | 20 |

Table 4.9. Flow path lengths (m) in the Bog Weir catchment

| | Active Flush | Central | Subcentral |
|---|---|---|---|
| **Max** | 766 | 711 | 630 |
| **Min** | 592 | 337 | 35 |
| **Mean** | 713 | 684 | 90 |
| **S.D.** | 56 | 143 | 258 |
| **n** | 9 | 6 | 7 |

Table 4.10. Flow path lengths (m) in the Restoration Area Flume catchment

| | Active Flush | Central | Subcentral |
|---|---|---|---|
| **Max** | 1065 | 850 | 400 |
| **Min** | 630 | 310 | 75 |
| **Mean** | 735 | 430 | 254 |
| **S.D.** | 140 | 150 | 108 |
| **n** | 10 | 10 | 16 |

### 4.3.6. Water levels

In Chapter 5, the hydrogeological monitoring of piezometers and phreatics tubes, which were described in Chapter 3, is discussed. However, Table 4.11 below summarises the mean water level, or phreatic water level, of phreatic tubes installed to measure the high bog water table, as hosted in the acrotelm when present, across a variety of ecotopes on the high bog. Figure 4.20 plots the water levels relative to ground level (i.e. 0 m).

Table 4.11. Mean phreatic water level and fluctuation for Clara West ecotopes

| Ecotope | No. tubes | Mean WL (m) | Fluctuation (m) |
|---|---|---|---|
| Active flush | 6 | -0.04 | 0.21 |
| Central | 3 | 0.00 | 0.23 |
| Subcentral | 8 | 0.04 | 0.22 |
| Inactive flush | 3 | -0.02 | 0.45 |
| Marginal | 1 | 0.06 | 0.28 |
| Submarginal | 8 | 0.03 | 0.32 |
| Cutover bog | 3 | 0.11 | 0.52 |

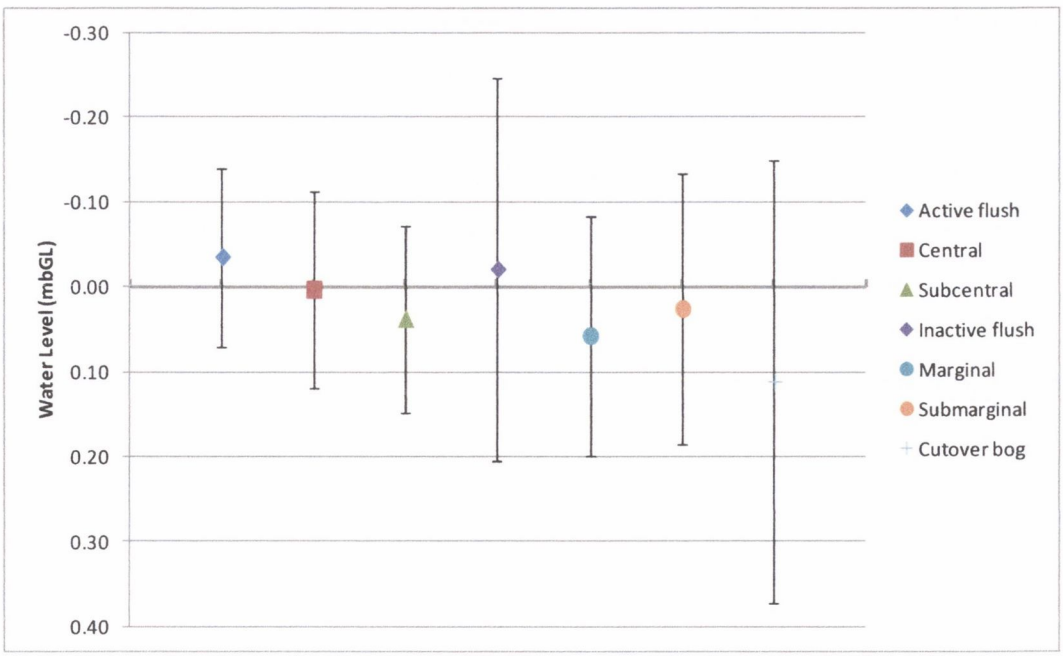


**Figure 4.20.** Phreatic water table mean and fluctuation relative to ground level for Clara West ecotopes

It can be observed from Table 4.9 and Figure 4.20 that the wet ecotopes have relatively low levels of fluctuation (c. 0.2 m) and mean phreatic water level is within 5 cm of ground level. This is consisntent with the slope and flow length calculations and agrees with the calculations made by Van der Schaff (1999). As the ecotopes become 'drier', fluctuations in water level increase and the mean phreatic water level gets deeper, implying a thin/ absent acrotelm. In ideal conditions, water levels across the bog surface would behave like those of the wet ecotopes. The dry ecotopes are indicative of disturbed conditions and Chapter 10 will discuss this significance.

### 4.3.7.High bog summary

A high resolution (1m) LiDAR survey of the Clara area has permitted the hydrological characterisation of the Clara West high bog. Four catchment, or drainage, areas have been delineated on the high bog – namely the FB2 Flume catchment, the Bog Weir catchment, the Restoration Area catchment and the Peat Pipe catchment. The ecological communities of the high bog have been mapped and grouped into distinct groups called ecotopes. Ecotopes can be broadly divided into wet and dry ecotopes, thereby serving as an indicator of the hydrological condition on the surface of the bog. Wet ecotopes are associated particular morphological and hydrological characteristics.

Central ecotopes, which have well developed acrotelms and are indicative of 'healthy' conditions, have (a) mean slope gradients of c. 0.2 %, (b) mean flow path lengths of either c. 200 m when the area is a focal point for water movement or mean flow path lengths c. 400 m when the area is a flow-through point for water movement and (c) mean phreatic water tables of 0.0 mbGL and a fluctuation of c. 0.2 m. Subcentral ecotopes, which have less well developed acrotelms and are indicative of wet conditions, but under threat from drying out, have (a) mean slope gradients of c. 0.35 %, (b) flow path lengths between 0 and < 250 m (c) mean phreatic water tables of 0.04 mbGL and a fluctuation of c. 0.2 m. Active flush ecotopes, which have well developed acrotelms, nutrient-rich vegetation relative to its surroundings and are indicative of 'healthy' conditions, have (a) mean slope gradients of c. 0.5 %, (b) mean flow path lengths of either c. 325 m when the area is a focal point for water movement or mean flow path lengths c. 700 m when the area is a flow-through point for water movement and (c) mean phreatic water tables of - 0.04 mbGL (i.e. free surface water) and a fluctuation of c. 0.2 m.

# 5. Hydrogeological Analysis

## 5.1. Introduction and objectives

In chapter 3, the installation of piezometers to measure piezometer level (hydraulic head) in peat and till subsoil deposits was described. The water levels measured in these units allows the mapping of groundwater flow directions, groundwater catchments at high and low levels to be delineated, and the vertical direction of groundwater movement, between the geological bodies to be identified. Hydraulic gradients in the vertical direction provide information on the connectivity of water levels in different units, and hydraulic gradients in the horizontal direction, in combination with the hydraulic conductivity of the deposit, allows calculation of flow/ flux rates through the groundwater body.

Hydrogeological information, measured in the field, is therefore used to:

(1) Understand the hydraulic connection between the subsoil ridges and sand units underlying the high bog with drainage in the cutover bog

(2) Calculate the hydraulic conductivity and transmissivity of the peat and subsoil units for use in a groundwater flow model

(3) Delineate groundwater catchments to the Clara West hydraulic measuring structures in order to calculate recharge and infiltration rates, as well as information on groundwater model boundary conditions and;

(4) Calculate preliminary estimates of leakage rates from peat on the high bog to the regional groundwater table

## 5.2. Water level monitoring

Regular water level monitoring of piezometers in Clara West began in August 2009 and ceased in August 2011; occasional water levels were measured between August 2011 and April 2012. Tables C1 to C7, in Appendix C, summarise the maximum, minimum and mean water levels from the monitoring study and sections 5.2.1 and 5.2.2 evaluates this data. Hydrographs from piezometers nests on the high bog and cutover bog for the hydrological year 2009-2010 are presented in figures C4 to C13.

### 5.2.1. Regional groundwater level

Regional groundwater level refers to the level of hydraulic head in the till subsoil aquifer, or groundwater body, that underlies and surrounds the Clara West high bog. The regional groundwater level is a potentiometric surface underneath the high bog as it is confined by lacustrine clay and catotelm peat. In cutover bog areas and in the elevated topographical highs (The Island) outside of the high bog area, the potentiometric surface is no longer confined (in terms of its areal extent; it is confined in local areas) and can be considered as the regional groundwater table. With these

assumptions in mind, and for simplicity, regional groundwater level and regional groundwater table are used loosely; but everywhere refers to the level of hydraulic head measured in the till subsoil groundwater body and underlying limestone bedrock. Figures C2 and C3 (Appendix C) illustrate hydrographs for boreholes BH9 and BH5 respectively over the hydrological year 2009-2010. It can be observed that the head in subsoil and bedrock (limestone) is near equivalent, implying hydraulic continuity between the two lithologies. As such, regional groundwater level and table in the text refers to that in the till (which is assumed to be equal to limestone; except in local areas, such as BH2 (Figure C1) which is located adjacent to an esker northeast of Clara West and in the Restoration Area, which will be described in Chapter 6).

The fluctuation in groundwater level is a response to climatic conditions (i.e. the intensity of rainfall) and is a relative measure of how quickly the groundwater table is recharged in a particular area. The piezometers with the largest fluctuations, > 0.7 m, are 909, 912, 913, 924 and BH5, indicating these areas respond very quickly to rainfall events. With the exception of piezometer 909, these piezometers are also located adjacent to deep drains (Figure 5.1), which may permit to increase water level fluctuations as the drains, which have a low resistance when lacustrine clay is absent and peat thickness is less than 2.0 m, effectively 'pull down' the potentiometric surface in the till groundwater body.

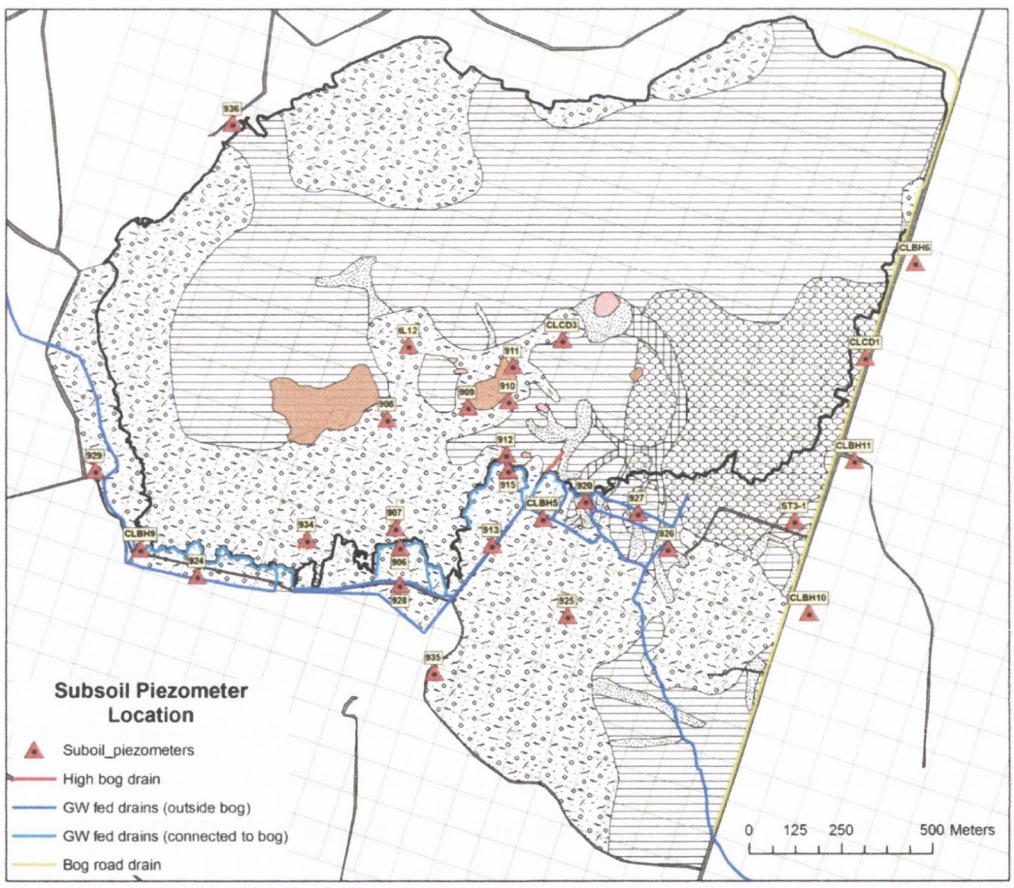


**Figure 5.1.** Location of till piezometers and distribution of subsoil geology (see Chapter 3)

The large fluctuation at 909 is most likely a result of it being positioned adjacent to the Western Mound, which is a natural till mound overlain by 2 to 3 m of highly humified/ dried fractured peat. Piezometer 910 also exhibits a high water level fluctuation, 0.63 m, implying the Western Mound area is a localised zone of recharge on the high bog. This is significant as it implies water quickly penetrates through the peat substrate and into till subsoil in this area – leakage through peat should be small in natural conditions (c. 8mm/ year; Van der Schaff, 1999). Water level fluctuation, 0.42 m, is also relatively high at piezometer 908, which is also underlain by a subsoil mineral ridge.

The lowest levels of fluctuation are, unsurprisingly, exhibited at piezometers in the Restoration Area, which, as illustrated on the groundwater contour map in Figure C15 (Appendix C) is a zone where groundwater flow beneath the high bog in the north and elevated till defined topography in the south converge. The hydraulic gradient of the groundwater table is shallow in the Restoration Area, which is, effectively, a zone of groundwater discharge, as opposed to an area of groundwater recharge. Low water level fluctuations are also found at piezometers outside the Restoration Area, such as CLCD1 and CLBH6. Neither of these piezometers is located close to a groundwater fed drain, implying drainage below the regional groundwater table increases fluctuation of hydraulic head in till subsoil. Table 5.1 summarises water level measurements made in subsoil piezometers between August 2009 and August 2011.

Table 5.1. Mean water level and fluctuation from till subsoil piezometers in the Clara Bog West area

| ID | WL (mbGL) | Range (m) | ID | WL (mbGL) | Range (m) |
|---|---|---|---|---|---|
| 912 | 1.30 | 0.87 | CLBH9 | 0.56 | 0.42 |
| 913 | 0.94 | 0.81 | CLBH2 | 0.22 | 0.41 |
| CLBH5 | 1.09 | 0.81 | CLBH10 | 0.20 | 0.40 |
| 909 | 1.81 | 0.78 | 926 | 0.26 | 0.38 |
| 924 | 1.49 | 0.73 | 911 | 1.66 | 0.36 |
| 925 | 0.78 | 0.69 | 915 | 0.07 | 0.34 |
| 934 | 1.43 | 0.67 | 935 | 0.85 | 0.32 |
| 928 | 0.82 | 0.63 | 920 | 0.17 | 0.32 |
| 910 | 1.00 | 0.63 | Tl12 | 0.78 | 0.30 |
| 929 | 0.75 | 0.62 | 927 | -0.14 | 0.29 |
| 906 | 0.49 | 0.56 | CLBH6 | -0.47 | 0.24 |
| 907 | 1.45 | 0.53 | CLCD1 | -1.44 | 0.23 |
| CLCD3 | 1.92 | 0.45 | ST3-1 | -0.66 | 0.20 |
| 908 | 1.05 | 0.42 | CLBH11 | -0.27 | 0.13 |

Note: mbGL is meters below ground level

### 5.2.2. Piezometer water levels in peat

*High bog*

The fluctuations in water level from piezometers installed at the peat-subsoil interface is a measure of how resistant the peat is to the downward infiltration of water and its connection with the hydraulic

head in the underlying till aquifer, when lacustrine clay is absent. Similar to the observations of piezometer level in till, large fluctuations, > 0.6 m, are observed at piezometers surrounding the Western Mound, 909 and 910, and a very large fluctuation of 1.25 m is found at piezometer 912. This large fluctuation is most probably a result of the peat being heavily cracked in this area, meaning the water level is a response to conduit water flow, much like a karst system as speculated in chapter 4 (peat pipe ). In essence, large water level fluctuations, > c. 0.3m, imply a high infiltration rate through the peat substrate and is associated with the marginal areas of the high bog (e.g. 67 and 59) and where there are subsurface till mounds (e.g. tdJ12, 909 and 910).

Low water level fluctuations (c. < 0.15 m) are associated with areas that have not subsided significantly since 1992 (Chapter 7), such as piezometers 82 and 88, located on the eastern margin of the high bog and piezometers 95 and 97, located in the north-western area of the high bog. Low water level fluctuations are also found in the Western Soak area (904 and 905) and the Shanley's Lough area (55 and 91). Very low fluctuations of c. < 0.1 m is possibly a result of peat in these areas, generally close to drains, being so compact at its base that it is highly resistant to water infiltration – there is little pore space for water flow; in contrast to areas where the peat is fractured (water flow is essentially a function of macro-pore porosity in these areas). Table 5.2 summarises water level measurements made in high bog deep peat piezometers between August 2009 and August 2011.

Table 5.2. Mean water level and fluctuation from deep peat piezometers on the Clara West high bog

| ID | WL (mbGL) | Range (m) | ID | WL (mbGL) | Range (m) | ID | WL (mbGL) | Range (m) |
|---|---|---|---|---|---|---|---|---|
| 912 | 1.10 | 1.25 | t6 | 0.84 | 0.25 | 99 | 1.77 | 0.15 |
| 910 | 0.46 | 0.86 | tdL12 | 0.63 | 0.24 | 54 | 0.50 | 0.13 |
| 909 | 0.81 | 0.61 | t4 | 0.57 | 0.24 | 904 | 0.36 | 0.13 |
| 67 | 1.11 | 0.52 | 92 | 1.20 | 0.22 | 50 | 0.95 | 0.13 |
| 59 | 0.48 | 0.47 | t3 | 0.98 | 0.21 | 902 | 0.68 | 0.13 |
| 906 | 0.56 | 0.45 | 937 | 1.03 | 0.21 | 90 | 0.40 | 0.12 |
| 911 | 1.56 | 0.35 | 907 | 1.52 | 0.20 | 97 | 1.58 | 0.11 |
| 96 | 1.18 | 0.33 | tdk12 | 0.55 | 0.20 | 87 | 0.31 | 0.10 |
| t5 | 0.84 | 0.31 | 905 | 0.36 | 0.20 | 98 | 0.60 | 0.09 |
| tdj12 | 0.75 | 0.31 | 48 | 0.39 | 0.19 | 901 | 0.49 | 0.09 |
| 61 | 1.29 | 0.30 | 93 | 1.20 | 0.19 | 82 | 0.36 | 0.08 |
| 63 | 1.54 | 0.29 | t8 | 0.28 | 0.19 | 88 | 0.29 | 0.08 |
| t13 | 0.74 | 0.27 | 47 | 0.76 | 0.19 | 95 | 0.70 | 0.08 |
| 908 | 0.48 | 0.26 | 89 | 0.44 | 0.19 | 83 | 0.64 | 0.07 |
| 86 | 0.40 | 0.26 | t2 | 0.72 | 0.18 | 91 | 0.40 | 0.07 |
| t10 | 0.53 | 0.26 | t1 | 0.62 | 0.18 | 94 | 0.70 | 0.06 |
| 57 | 0.44 | 0.26 | t9 | 0.39 | 0.18 | 56 | 0.34 | 0.05 |
| 70 | 1.04 | 0.25 | 55 | 0.62 | 0.17 | | | |

*Cutover bog*

Water level fluctuations in the cutover bog areas range between 0.04 m and 0.47 m. The relatively high fluctuations, > 0.25 m, at 914, 915, 918 and 921 is presumably a consequence of the piezometer being located in/ adjacent to a groundwater discharge drain (as well as the reduced resistance to downward infiltration due to peat removal). Fluctuations are higher, > 0.35 m, at piezometers 917 and 920, possibly indicating subsurface cracking in the peat substrate allowing a quick route/ pathway for infiltrating water to recharge the peat substrate, similar to the observations made on the high bog. Table 5.3 summarises water level measurements made in cutover bog deep peat piezometers between August 2009 and August 2011.

Table 5.3. Mean water level and fluctuation from deep peat piezometers in the Clara West cutover bog areas

| ID | WL (mbGL) | Range (m) | ID | WL (mbGL) | Range (m) |
|---|---|---|---|---|---|
| 917 | 1.33 | 0.47 | 939 | -0.03 | 0.29 |
| 921 | 0.18 | 0.31 | 923 | -0.06 | 0.04 |
| 915 | 0.11 | 0.30 | 918 | -0.06 | 0.26 |
| 920 | 0.11 | 0.39 | 916 | -0.12 | 0.22 |
| 927 | -0.02 | 0.21 | 914 | -0.13 | 0.31 |

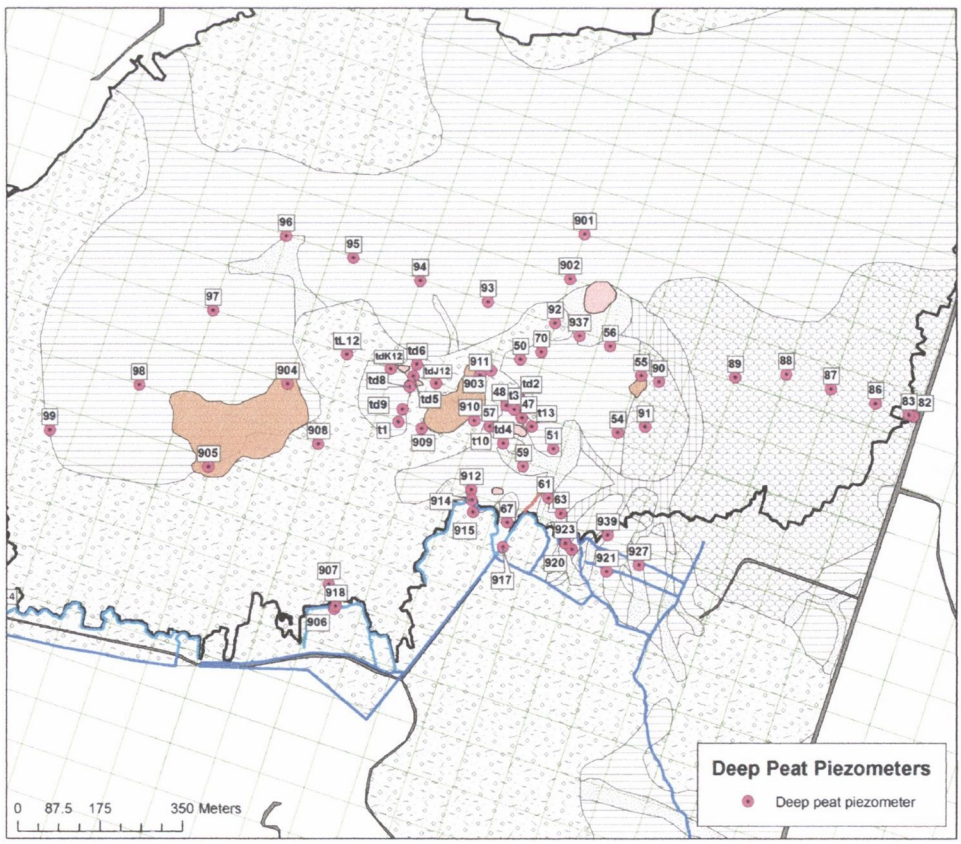


**Figure 5.2.** Location of deep peat piezometers and distribution of subsoil geology

### 5.3. Vertical hydraulic gradients

The measurements of hydraulic heads at piezometer nest installations with a piezometer installed in subsoil and at the subsoil-peat interface permits a calculation of the vertical hydraulic gradient. The hydraulic gradients can then be used to calculate Darcian/ seepage velocity, or leakage rate, from peat to subsoil and this is discussed in Section 5.7. However, the gradients themselves can provide useful information on areas of probable 'water losses' and mean vertical hydraulic gradients are presented in Table 4.4.

Table 5.4. Mean vertical hydraulic gradient from deep peat to mineral subsoil.

| ID | Gradient | ID | Gradient |
|---|---|---|---|
| 906 | -0.007 | 912 | 0.564 |
| 907 | -0.003 | tL12 | 0.449 |
| 908 | 0.084 | CLCD3* | 0.127 |
| 909 | 0.403 | 915 | 0.001 |
| 910 | 0.313 | 920 | 0.021 |
| 911 | 0.064 | 927 | -0.030 |

Note: negative value implies hydraulic gradient is upward. * Hydraulic gradient calculated using deep peat piezometer 70.

Upward vertical hydraulic gradients are found at piezometers 906, 907 and 927, which is unsurprising as the piezometers are located adjacent to drains cut below the regional groundwater table. Underneath the high bog, hydraulic gradient is shallow at piezometer 911 and relatively shallow at piezometer CLCD3, which is perhaps unsurprising as a significant thickness of lacustrine clay separates peat from till at CLCD3 and hydraulic conductivity measurements of the till at piezometer 911 (Section 5.7) indicates the till unit in this area is resistant to downward infiltration. Hydraulic gradient is shallow at piezometer 908, which is surprising as peat thickness is shallow (c. 4.0 m) and lacustrine clay is absent.

However, hydraulic gradient is steep at piezometers 909, 910, 912 and tL12. This implies these areas are hydraulically connected with underlying till subsoil, consistent with the observations made from their respective water level fluctuations and the piezometers are also located in areas where the bog has subsided significantly (Chapter 7 and 8).

### 5.4. Hydrograph analysis of piezometer nests

Hydrograph analysis of a piezometer nest provides information on the vertical direction of groundwater flow between the monitored units, the range of water level fluctuation and the degree of water level connectivity. A number of piezometer nests with a piezometer installed to till, deep peat, mid-section peat and a phreatic water table tube were installed in areas where suspected water loses were occurring (Chapter 3). An analysis of these piezometer nests, as well as piezometer nests

installed by the high bog boundary adjacent to drains with known groundwater discharge and in cutover bog is described below.

### 5.4.1. High bog nest hydrographs

The piezometer nests on the high bog, 907 – 912, behave as expected, with a downward movement of water from the phreatic water table, through the peat profile and to the regional groundwater table in the till/ mineral subsoil underlying the peat substrate. However, the piezometer nests were positioned purposely in order to detect differences in the behaviour of the piezometric water levels in the peat and till. Indeed, the water level monitoring indicates differing hydrogeological behaviour between the piezometer nests, which is ultimately dependent on their position on the bog.

Figures C4 to C9 (Appendix C) display the hydrographs for high bog piezometer nests with a subsoil installation over the hydrological year 2009-2010. Using this information and comparing the relative water levels within the nest, inferences can be made on (1) whether or not there is an upward seepage of groundwater and (2) whether water from peat is 'draining' downwards to the regional groundwater table.

*Piezometer nest 907*

Piezometer nest 907 is located c.40 m north of the high bog face-bank. Figure C4 displays the hydrograph for piezometer nest 907 over the hydrological year 2009-2010. The phreatic water table fluctuates between 57.63 mOD and 57.30 mOD, the piezometer in the upper-mid profile section of the peat fluctuates between 57.37 mOD and 57.27 mOD, the lower-mid profile section of the peat fluctuates between 56.95 mOD and 56.82 mOD, the piezometer at the peat-subsoil interface fluctuates between 55.98 mOD and 56.03 mOD and the piezometer at the base of till fluctuates between 56.34 mOD and 55.81 mOD.

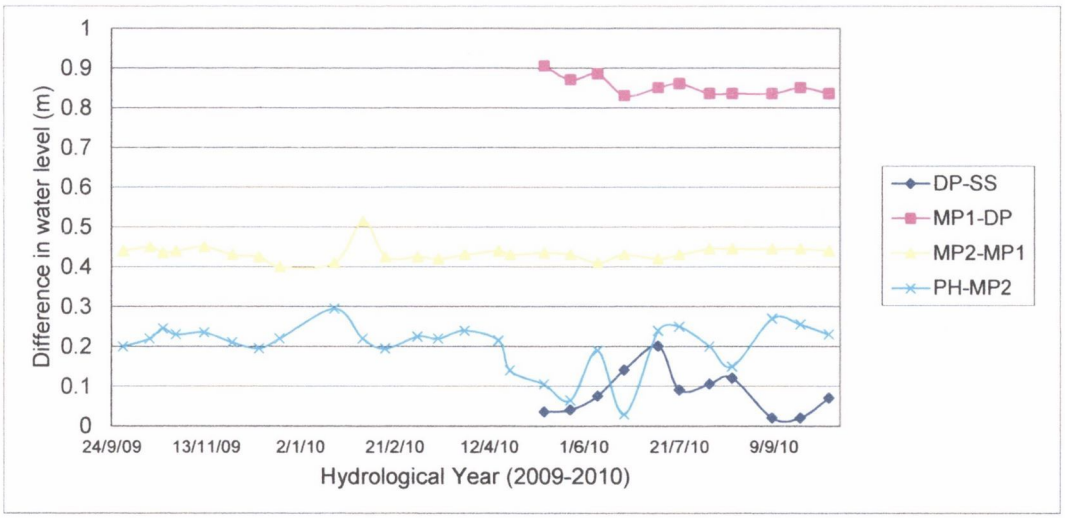


**Figure 5.3.** Hydrograph analysis from piezometer nest 907 (hydrological year 2009-2010)

The water level fluctuation in the till is quite high, extremely small at the base of the peat and very small in the mid-section peat piezometers. The hydrographs from the peat piezometers do not follow the trend of the subsoil hydrograph implying the piezometer level in till is independent from the high bog in this area. Figure 5.3 illustrates an interpretation of the hydrograph in figure C4, which basically compares the difference in water level from two piezometers closest to each other in cross-sectional profile. It may be observed that there is little difference in relative water levels from piezometers in mid-section peat and at that at the base of peat (i.e. MP1-MP2 & MP1-DP), implying downward seepage and a connection between MP and DP. The fluctuation observed between subsoil (SS) and deep (DP) is a result of the large water fluctuation in the subsoil and the very small water level fluctuation in deep peat, which indicates the bog is not draining to the regional groundwater table in this area. A large fluctuation is also apparent in phreatic water level, implying acrotelm development here is damaged which is unsurprising considering the piezometer is located adjacent to face-bank drain FB1.

*Piezometer nest 908*

Piezometer nest 908 is located south east of the Western Soak and c.300 m north of piezometer nest 907. Subsoil is elevated in this area, c.1.5 m higher than the subsoil elevation at 907 and c. 3m higher than the subsoil elevation at 905. This subsurface 'mound' appears to be an extension of the Western Mound (see Figure C17). Figure C5 displays the hydrograph for piezometer nest 908 over the hydrological year 2009-2010. The phreatic water table fluctuates between 57.64 mOD and 57.32 mOD, the piezometer at the peat-subsoil interface fluctuates between 57.01 mOD and 56.74 mOD and the piezometer at the base of till fluctuates between 56.69 mOD and 56.27 mOD.

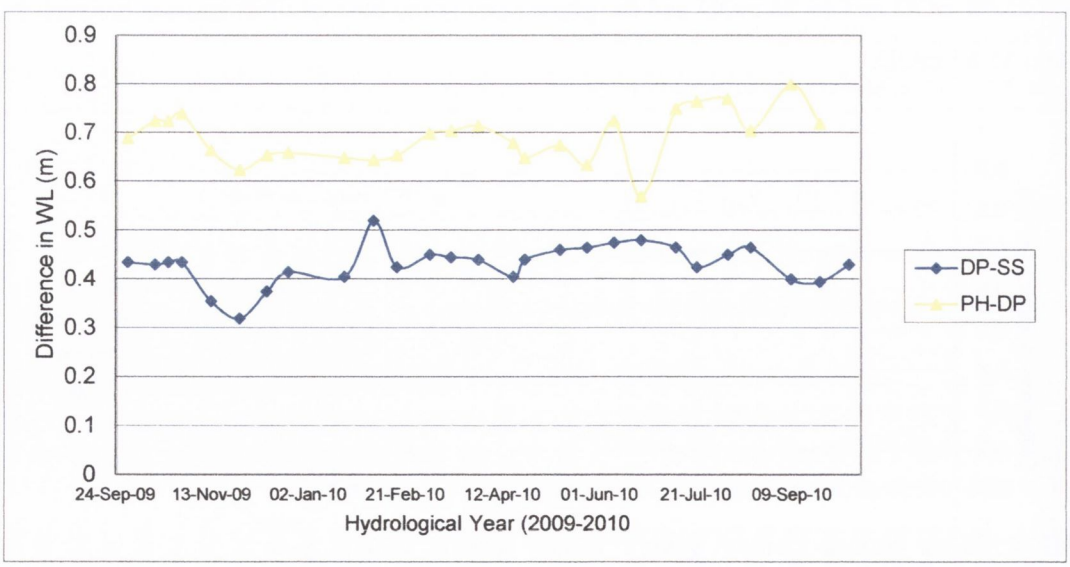


**Figure 5.4.** Hydrograph analysis from piezometer nest 908 (hydrological year 2009-2010)

The deep peat and subsoil hydrographs in figure C5 are broadly coincident, implying there is a connection between the peat substrate and mineral subsoil. This is perhaps to be expected considering

peat is relatively shallow here (c. 4 m) and is underlain by a mineral ridge. Figure 5.4 illustrates a water level analysis of the hydrograph in figure C5. The fluctuation in water level difference between deep peat and subsoil is relatively small (< 0.1 m) implying the water levels are connected. There are two peaks on the DP-SS curve in figure 5.4 and these peaks occur on the 27th November 2009 and 4th February 2010 - both dates following periods of heavy rainfall, suggesting peat and subsoil are hydrologically connected with some resistance in the peat, though, on a whole, the hydrograph suggests piezometer levels in peat and till are hydraulically connected at piezometer location 908.

The phreatic water table fluctuation at 908 is also significant. On figure C5 a large dip in water level occurs on 22nd June 2010, following a sustained dry period, though the fluctuation is relatively small throughout the rest of the year (within 14 cm), implying the levels are connected, but the drop in phreatic water level implies poor acrotelm development.

*Piezometer nest 909*

Piezometer nest 909 is located at the base of the Western Mound, on its south-western side. Subsoil elevation within the Western Mound itself is c.4.5 m higher than at 909 and subsoil elevation at piezometer nest 908, located c. 200m west of 909, is c.2.0m higher (see Figure C17). Figure C6 displays the hydrograph for piezometer nest 909 over the hydrological year 2009-2010. The phreatic water table fluctuates between 56.49 mOD and 56.09 mOD, the piezometer at the in the mid-section of the peat profile fluctuates between 56.25 mOD and 55.76 mOD, the piezometer at the peat-subsoil interface fluctuates between 55.74 mOD and 55.36 mOD and the piezometer at the base of till fluctuates between 55.17 mOD and 54.38 mOD.

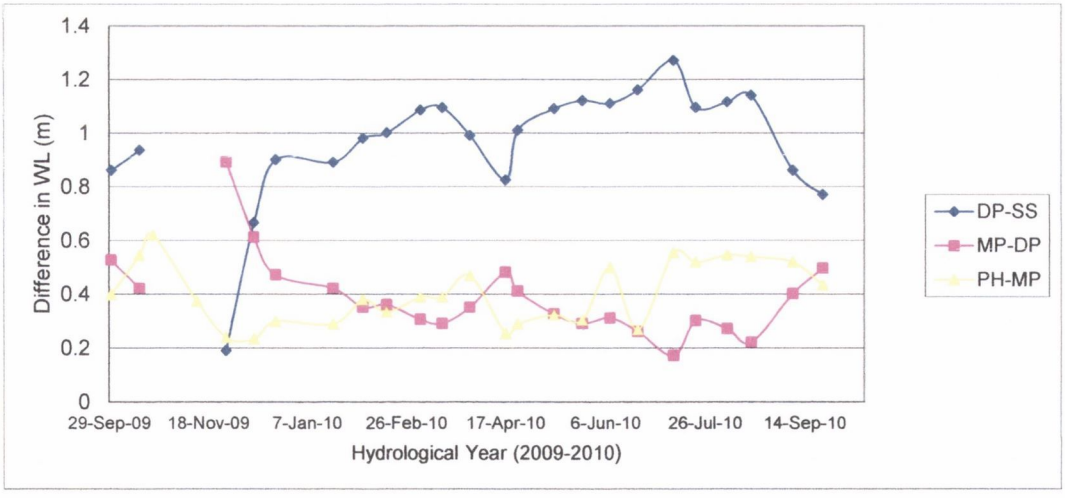


**Figure 5.5.** Hydrograph analysis from piezometer nest 909 (hydrological year 2009-2010)

The water level fluctuation in the till is very high (0.8 m), relatively high at the base of the peat (0.37 m), high in the mid-section peat piezometers (0.49 cm) and high in the phreatic water table (0.4 m). Viewing the hydrograph in figure C6 the hydrograph trend in the mid-peat is relatively similar to that in the subsoil, whereas the hydrograph trend in deep peat is different to that in the subsoil. The

inference is that there is a big resistance in the deep peat - implying the peat at the 909 has consolidated at its base.

Hydrograph analysis in Figure 5.5 would appear to substantiate the inference that there is little connection between deep peat water level and subsoil water level due to peat compaction (> 1.0m subsidence at this location; Chapter 7). The large fluctuation in the DP-SS profile in figure 5.5 implies the subsoil water level is not connected to the deep peat water level. While the till body is recharged via the Western Mound, the mid-peat water level is recharged by direct infiltration, which also recharges the deep peat, but at a much slower pace due to its reduced permeability.

*Piezometer nest 910*

Piezometer nest 910 is located at the base of the Western Mound, on its south-eastern side. Subsoil elevation is c.2.0 m lower than at piezometer nest 911, c.100m north of 910, and subsoil elevation is c.1.5 m higher than at piezometer nest 912, located c. 150m south of 910 (see cross-section T5; appendix C). Figure C7 displays the hydrograph for piezometer nest 910 over the hydrological year 2009-2010. The phreatic water table fluctuates between 55.33 mOD and 54.80 mOD, the piezometer at the in the mid-section of the peat profile fluctuates between 55.12 mOD and 54.65 mOD, the piezometer at the peat-subsoil interface fluctuates between 54.99 mOD and 54.54 mOD and the piezometer at the base of till fluctuates between 54.60 mOD and 53.98 mOD.

The water level fluctuation in the till is very high (0.62 m), high at the base of the peat (0.46 m), high in the mid-section peat piezometers (0.47 m) and high in the phreatic water table (0.37 m). Viewing the hydrograph in figure C7 the hydrograph trend in mid-peat and deep peat piezometers is near coincident with that in the mineral subsoil. The inference is that while there may be some resistance in the peat profile, there is a connection between water level in the peat and water level in the underlying till subsoil, implying this is an area where water loss to the regional groundwater table is occurring.

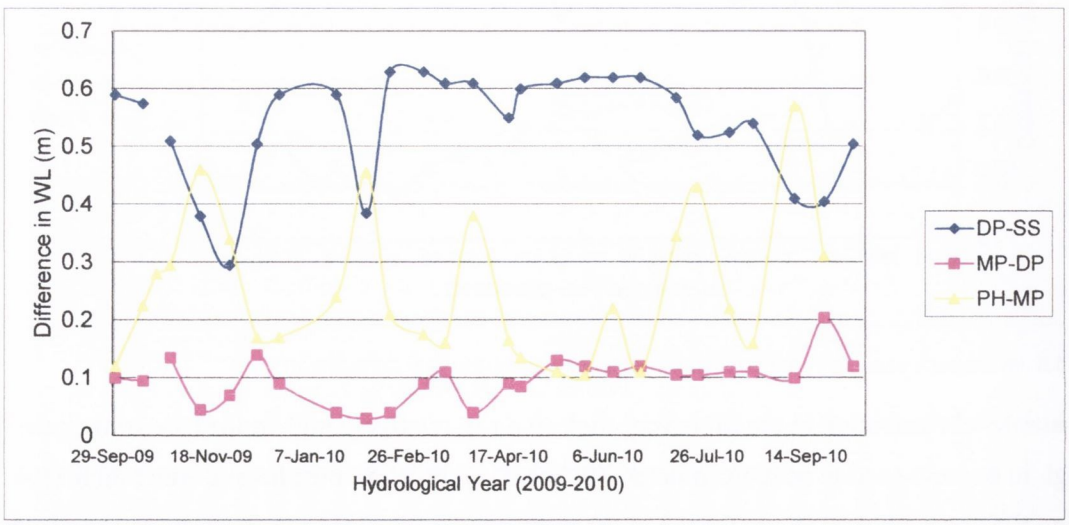


**Figure 5.6.** Hydrograph analysis from piezometer nest 910 (hydrological year 2009-2010)

Hydrograph analysis in Figure 5.6 would appear to substantiate the inference that the water levels are connected. The MP-DP profile is relatively steady with minor fluctuation suggesting recharge infiltration through the peat profile is similar at mid and deep peat. The DP-SS profile is also relatively steady with peak fluctuations occurring after heavy rainfall events on the 27th November 2009 and 4th February 2010 – similar to the observation made at piezometer nest 908. The relationship becomes less steady between the 10th July 2010 and 23rd September 2010, which was a period of sustained dry weather. This is a result of the water level in deep peat decreasing faster than that in the subsoil, suggesting water is not being contained in the bog, as it should be, and is seeping downwards into the mineral subsoil.

The PH-MP profile in Figure 5.4 is also curious. The profile is characterised by large fluctuations, which is unsurprising when viewing the phreatic hydrograph in figure C7. The fluctuations in the phreatic water table are quite large at location 910 indicating there is little or no true acrotelm in this location due to the surface level gradient conditions in this area of the bog (Chapter 3).

*Piezometer nest 911*

Piezometer nest 911 is located at the base of the Western Mound, on its north-eastern side. Subsoil elevation is c.5.0 m higher than at piezometer nest 50, c.90m northeast of 911 (Figure C17), and subsoil elevation is c.5.0 m higher than at piezometer nest 93, located c. 160m north of 911 (Figure C21). As such, piezometer nest 911 is located on a ridge that trends between two 'deep' peat basins. Unfortunately, at the time of installation there were not enough materials to install the piezometer as far as the till-bedrock interface. The piezometer tip was installed 2.0 m below the top of the till-peat interface.

Figure C8 displays the hydrograph for piezometer nest 911 over the hydrological year 2009-2010. The phreatic water table fluctuates between 56.68 mOD and 56.20 mOD, the piezometer at the in the mid-section of the peat profile fluctuates between 55.38 mOD and 55.05 mOD, the piezometer at the peat-subsoil interface fluctuates between 55.15 mOD and 54.80 mOD and the piezometer at the base of till fluctuates between 55.06 mOD and 54.79 mOD.

The water level fluctuation in the till is low (0.27 m), relatively high at the base of the peat (0.35 m), relatively high in the mid-section peat piezometers (0.33 m) and high in the phreatic water table (0.48 m). Viewing the hydrograph in Figure 5.7 the hydrograph trend in mid-peat and deep peat piezometers is near coincident with that in the mineral subsoil. The inference is that there is little resistance in the peat profile and that there is a probable connection between water level in the peat and water level in the underlying till subsoil. The water level in deep peat is very close to that in mineral subsoil, implying that while the bog is hydraulically connected to the till unit, the small hydraulic gradient means there is little downward infiltration form peat to till.

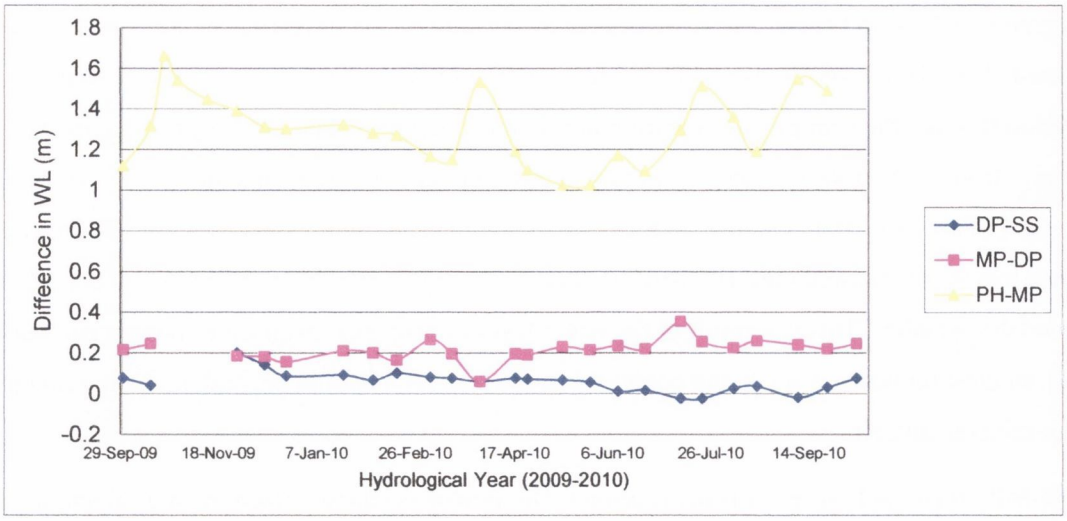


**Figure 5.7.** Hydrograph analysis from piezometer nest 911 (hydrological year 2009-2010)

The PH-MP profile in Figure 5.7 is also curious, similar to that at piezometer nest 910. The profile is characterised by some large fluctuations, which is unsurprising when viewing the phreatic hydrograph in figure C8. The fluctuations in the phreatic water table are quite large at location 911 indicating, like at 910, there is little or no true acrotelm in this location due to the surface level gradient conditions in this area of the bog.

*Piezometer nest 912*

Piezometer nest 912 is located c.20 m north of the high bog face-bank in an area where the subsoil elevation has decreased southwards from the Western Mound (see Figure C21). Figure C9 displays the hydrograph for piezometer nest 912 over the hydrological year 2009-2010. The phreatic water table fluctuates between 54.19 mOD and 53.71 mOD, the piezometer at the in the mid-section of the peat profile fluctuates between 53.48 mOD and 52.78 mOD, the piezometer at the peat-subsoil interface fluctuates between 53.47 mOD and 52.31 mOD and the piezometer at the base of till fluctuates between 52.98 mOD and 52.26 mOD.

The water level fluctuation in the till is very high (0.72 m), very high at the base of the peat (1.16 m), very high in the mid-section peat piezometers (0.7 m) and high in the phreatic water table (0.48 m). Viewing the hydrograph in figure C9 the hydrograph trend in mid-peat and deep peat piezometers is near coincident with that in the mineral subsoil. The inference is that there is little resistance in the peat profile and that there is a probable connection between water level in the peat and water level in the underlying till subsoil, implying water is seeping downwards into the mineral subsoil. The high fluctuations in the peat profile, which are higher than anywhere else recorded on the bog, are a result of the fractured nature of the peat substrate in this area.

Hydrograph analysis of piezometer nest 912 in Figure 5.8 indicates that the water level in peat and subsoil is connected, though the fluctuations imply high infiltration through the peat due to cracking

effects. The MP-DP profile is relatively flat with some spiked fluctuations, which are due to the water level in the deep peat responding very quickly to rainfall events.

The PH-MP profile in figure 5.6 is also curious, similar to that observed at piezometer nests 910 and 911. The profile is characterised by large fluctuations, which is unsurprising when viewing the phreatic hydrograph in figure C9. The fluctuations in the phreatic water table are quite large as there is no true acrotelm in this location due to drainage by the adjacent face-bank drain, FB2, and the high surface level gradient conditions in this area of the bog.

**Figure 5.8.** Hydrograph analysis from piezometer nest 912 (hydrological year 2009-2010)

### 5.4.2.Cutover bog nest hydrographs

To understand the hydrogeological linkages between the high bog and cutover bog, piezometer nests were installed in the cutover bog so as to complement the piezometer nests on the high bog monitoring transects (Chapter 3 and 4). On transect T5, piezometer nest 915 is located c.25 m south of piezometer nest 914 and subsoil piezometer 913 is located c. 230 m south of 914 on an elevated area of till. Piezometer nest 917 is located close to a face-bank drain on transect T3 and piezometer 919 is located c.12 m south of piezometer nest 906 on an elevated area of till on transect T2. Piezometer nests 920 and 921 are positioned on transect T4, within the Restoration Area, c. 350 m south of Shanely's Lough.

Figures C10 to C13 display hydrographs for cutover bog piezometer nests with a subsoil installation over the hydrological year 2009-2010 and an analysis from each of the piezometer nests is discussed accordingly below.

*Piezometer nest 906*

Figure C10 displays the hydrograph for piezometer nest 906 over the hydrological year 2009-2010. The phreatic water table fluctuates between 56.29 mOD and < 55.97 mOD, the piezometer in the med-section of the peat fluctuates between 56.24 mOD and 55.68 mOD, the piezometer at the peat-

subsoil interface fluctuates between 55.71 mOD and 56.16 mOD and the piezometer at the base of till fluctuates between 56.25 mOD and 55.73 mOD.

The water level fluctuation in the till is high (0.52 m), high at the base of the peat (0.45 m), high in the mid-section peat piezometers (0.56 m) and high in the phreatic water table (> 0.32 m; water level drops below screen during dry periods). Viewing the hydrograph in figure C10 the hydrograph trend in mid-peat and deep peat piezometers is near coincident with that in the mineral subsoil. The water levels are connected and it may also be observed that the gradient of water movement is almost wholly upwards from the hydraulic head in till subsoil to the water table in the phreatic tube. The gradient from till subsoil to deep peat is upward throughout the year and in dry periods water moves downwards through the peat profile, but the upward head in till is almost always maintained, except in sustained dry periods.

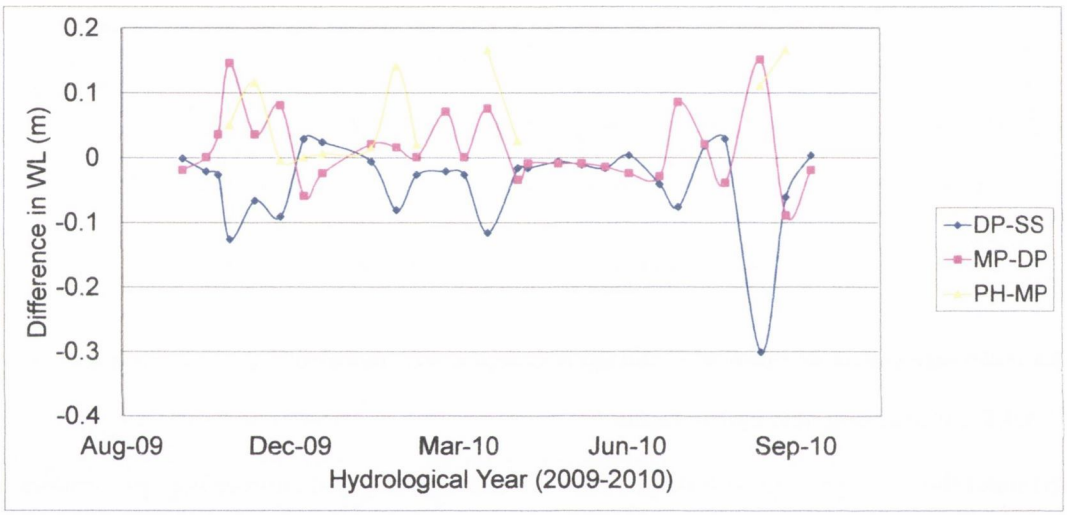


**Figure 5.9.** Hydrograph analysis from piezometer nest 906 (hydrological year 2009-2010)

Hydrograph analysis in Figure 5.9 substantiates the inference that the water levels are connected and that there is an upward seepage of groundwater. The negative difference in relative water level means the water level in the deeper piezometer is higher than in the overlying piezometer – i.e. upward seepage. The DP-SS profile shows there is an upward seepage from till to deep peat with large negative spikes in the profile occurring during wet periods, such as in November 2009 and February 2010. There are occasional reversals to downward seepage, such as in December 2009 and August 2010, and this occurs following a sustained dry period, though the difference in head is very small (<3 cm).

*Piezometer nest 915*

Figure C11 displays the hydrograph for piezometer nest 915 over the hydrological year 2009-2010. The phreatic water table fluctuates between 51.82 mOD and 51.24 mOD, the piezometer in the mid-section of the peat fluctuates between 51.79 mOD and 51.54 mOD, the piezometer at the peat-subsoil

interface fluctuates between 51.81 mOD and 51.56 mOD and the piezometer at the base of till fluctuates between 51.86 mOD and 51.63 mOD.

The water level fluctuation in the till is low (0.23 m), low at the base of the peat (0.25 m), low in the mid-section peat piezometers (0.25 m) and high in the phreatic water table (0.42 m). Viewing the hydrograph in figure C11 the hydrograph trend in mid-peat and deep peat water level is broadly coincident with that in mineral subsoil. The water levels in peat and subsoil are connected and it may also be observed that the gradient of water movement is almost wholly upwards from the hydraulic head in till subsoil to the water table in the phreatic tube. The phreatic water table behaves differentially to the piezometric heads, with periodic upward and downward seepages between water table and piezometric head in peat. The 'flashy' pattern of the phreatic level indicates the water table recharges quickly during wet periods and decreases quickly in dry periods as there is no acrotelm in this area, but rather the surface is bare peat.

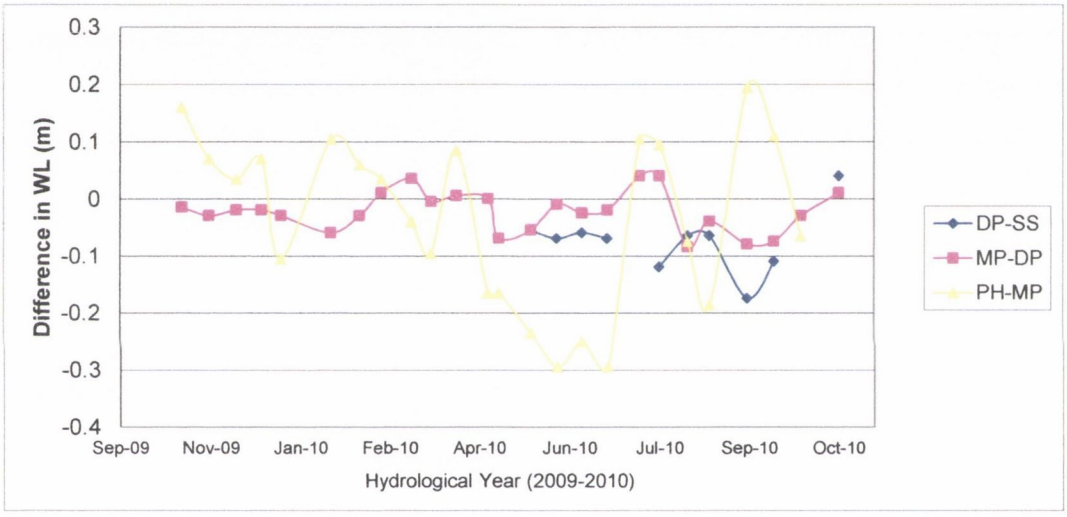


**Figure 5.10.** Hydrograph analysis from piezometer nest 915 (hydrological year 2009-2010)

Hydrograph analysis in figure 5.10 substantiates the inference that the water levels in peat and subsoil are connected and that there is an upward seepage of groundwater. The negative DP-SS profile shows there is an upward seepage from till to deep peat. There is a reversal to downward seepage on the 29th October 2010, which was a dry period, but subsequent water level monitoring shows this to be an isolated case and the pattern is generally upward seepage. The MP-DP profile also shows there is an upward movement of water from deep peat to mid-peat through most of the year. Movement is downward through the peat profile in dry periods March and July 2010, though the hydraulic head in subsoil is still greater than it is in peat, showing the upward pressure from subsoil to peat is maintained.

The PH-MP profile in Figure 5.10 shows there are periodic upward and downward seepages between the phreatic water table and piezometric heads in the peat profile and subsoil. Upward movements occur in wet periods and downward movements in dry periods. The phreatic table is not as well

connected to water levels in the subsurface, which themselves are well connected. This suggests subsurface water level is controlled mainly by upward movements of water from the till subsoil, meaning subsoil controls water level at piezometer location 915, more so than direct water infiltration.

*Piezometer nest 920*

Figure C12 displays the hydrograph for piezometer nest 920 over the hydrological year 2009-2010. The phreatic water table fluctuates between 50.93 mOD and 50.43 mOD, the piezometer in the mid-section of the peat fluctuates between 50.84 mOD and 50.31 mOD, the piezometer at the peat-subsoil interface fluctuates between 50.86 mOD and 50.47 mOD and the piezometer in till fluctuates between 50.79 mOD and 50.47 mOD (record begins 23rd April 2010).

The water level fluctuation in the till is low (0.32 m), relatively high at the base of the peat (0.39 m), high in the mid-section peat piezometers (0.53 m) and high in the phreatic water table (0.50 m). Viewing the hydrograph in figure C12 the hydrograph trend in mid-peat and deep peat water level is broadly coincident with that in mineral subsoil, though there are differences, which is perhaps unsurprising as 1.8m of lacustrine clay separates peat from till at this location.

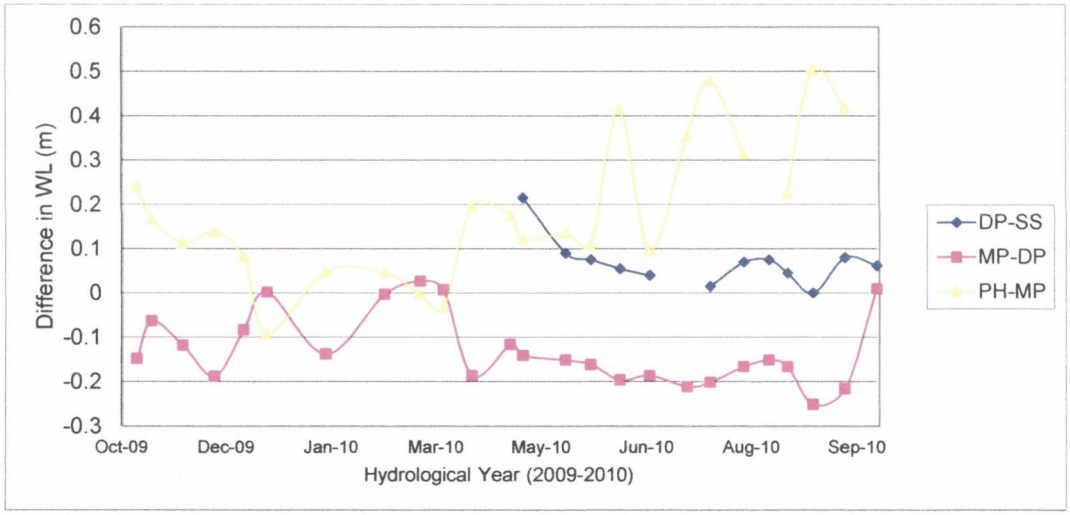


**Figure 5.11.** Hydrograph analysis from piezometer nest 920 (hydrological year 2009-2010)

The water levels in peat are connected and it may also be observed that the gradient of water movement is almost wholly upwards from deep peat to mid-peat. The phreatic water table is 'flashy' like that at 915 and behaves differentially to the subsurface piezometric levels. Curiously, while the subsoil water level is generally higher than that in mid-peat, it is also generally lower than in deep peat, implying a resistance effect from lacustrine clay. The upward movement of water in the peat profile may therefore be driven by groundwater pressure that seeps upwards where lacustrine clay is absent, west of location 920 (see figure C15). The groundwater level in 920 may also be lower than it otherwise should be due to the piezometers position close to drains CT2 and CT3.

Hydrograph analysis in Figure 5.11 substantiates the inference that the water levels in peat are connected and that the subsoil water level is separated due to drainage effects and the presence of lacustrine clay. The MP-DP profile shows there is an upward movement of water from deep peat to mid-peat through most of the year. As speculated above, the upward seepage of groundwater in the peat substrate is perhaps driven by groundwater pressure adjacent to the piezometer nest, where peat directly overlays till. The positive DP-SS profile shows that water actually moves downwards from deep peat to subsoil. However, subsequent water level monitoring since October 2010 shows the trend is reversed in wet periods, though the difference in head is minor.

The PH-MP profile in Figure 5.11 shows that water movement is generally upward through the peat profile, with downward seepage in drier periods. The phreatic table is broadly connected to water levels in peat, but not connected to the level in the subsoil. This suggests subsurface water level is controlled by a combination of downward infiltration and upward groundwater movements giving the hydrograph in figure 5.11 a slightly disjointed appearance.

*Piezometer nest 921*

Figure C13 displays the hydrograph for piezometer nest 921 over the hydrological year 2009-2010. The phreatic water table fluctuates between 50.03 mOD and 49.55 mOD, the piezometer in the mid-section of the peat fluctuates between 49.89 mOD and 49.61 mOD and the piezometer at the peat-subsoil interface fluctuates between 49.91 mOD and 49.60 mOD.

The water level fluctuation is relatively low at the base of the peat (0.31 m), relatively low in the mid-section peat piezometers (0.28 m) and high in the phreatic water table (0.48 m). Viewing the hydrograph in figure C13 the hydrograph trend in mid-peat and deep peat water level is broadly coincident with each other, though there are some differences with the phreatic water table. It can be observed that there is almost always downward seepage from mid-peat to deep peat, except in wet periods such as November 2009 and March 2010 when the deep peat piezometric level becomes periodically raised above that of mid-peat. Interestingly, the phreatic level drops below the piezometric level in dry periods, such as March and May 2010.

Hydrograph analysis in Figure 5.12 substantiates the inference that there is periodic upward seepage of groundwater at 921. The MP-DP profile shows there is some upward movement of water from deep peat to mid-peat where there are negative values. Similar to 920, the upward seepage of groundwater in the peat substrate is perhaps driven by groundwater pressure adjacent to the piezometer nest, where peat directly overlays till, as piezometer nest 921 is underlain by lacustrine clay.

The PH-MP profile in Figure 5.12 is curious in that there are periods when water moves downwards from the phreatic water table to mid-peat and at the same time water moves upwards from mid-peat to deep peat (November 2009) and the opposite also occurs (May 2010). Similar to 920, this may imply drainage effects as the piezometer nest is located adjacent to groundwater discharge cutover drain

CT4 and water moving downwards through the peat profile through infiltration and upwards from upward groundwater pressure from areas west of the piezometer where till directly overlies peat.

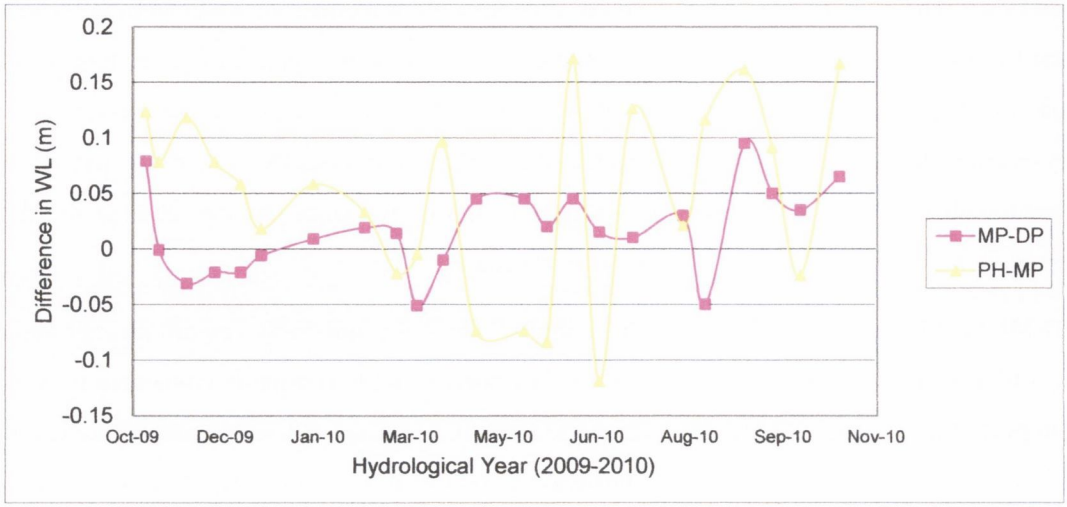


**Figure 5.12.** Hydrograph analysis from piezometer nest 920 (hydrological year 2009-2010)

### 5.4.3.Drain nest hydrographs

Piezometer nests 914, 916 and 918 were installed in face-bank drains where it is believed the regional groundwater table had been intercepted (Chapter 3 and 4; e.g. Figure 5.13 – iron iridescence in drain FB3). The behaviour of the phreatic and piezometric water levels in the peat substrate, illustrated in the hydrographs of appendix C, indicates that this is the case. Figures B7 to B9 display hydrographs for bog piezometer nests installed in drains with groundwater discharge over the hydrological year 2009-2010. An analysis from each of the piezometer nests is discussed below.

**Figure 5.13.** Evidence of groundwater discharge at drain FB3, adjacent to piezometer nest 918

*Piezometer nest 914*

Figure B7 displays the hydrograph for piezometer nest 914 over the hydrological year 2009-2010. The phreatic water table fluctuates between 51.39 mOD and 51.11 mOD, the piezometer in the mid-section of the peat fluctuates between 51.35 mOD and 51.11 mOD and the piezometer at the peat-subsoil interface fluctuates between 51.36 mOD and 51.12 mOD. The significance of the drain FB2, in which piezometer nest 914 is located, has been discussed in Chapter 4 in the context of its position within the Clara West drainage system.

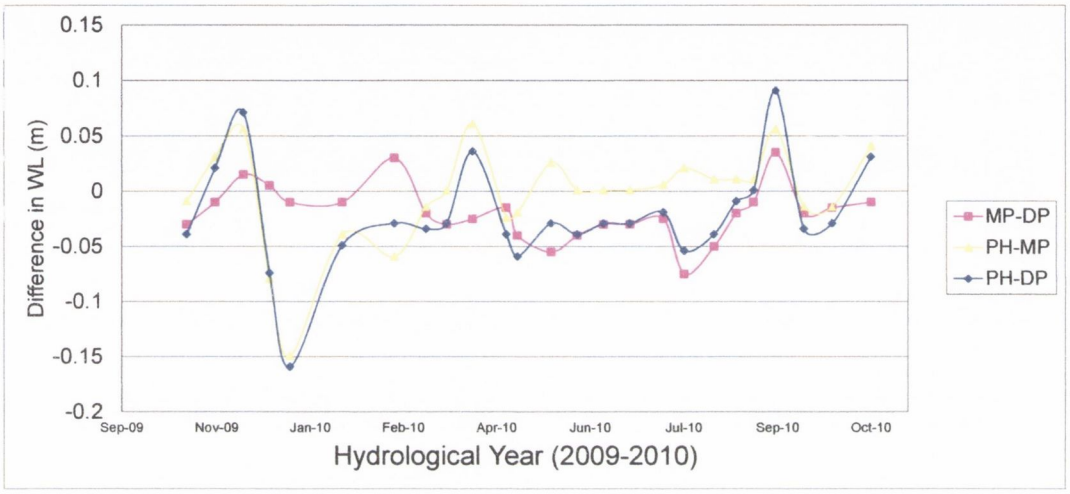


**Figure 5.14.** Hydrograph analysis from piezometer nest 914 (hydrological year 2009-2010)

The water level fluctuation is relatively low at the base of the peat (0.24 m), relatively low in the mid-section peat piezometers (0.24 m) and relatively low in the phreatic water table (0.28 m). Viewing the hydrograph in figure B7 the hydrograph trend in phreatic water level and mid-peat and deep peat water level is broadly coincident with each other. It can be observed that there is almost always upward seepage from deep peat to mid-peat and to phreatic water level. This is in keeping with the inference that this drain is a zone of groundwater discharge. Hydrograph analysis in Figure 5.14 substantiates the inference that there is almost constant upward seepage of groundwater at 914 and that the water levels are connected with minimal resistance. The PH-DP and PH-MP profiles shows there is upward movement of water from deep peat and mid-peat to the phreatic level through most of the year except in very wet periods, such as in November 2009, when the gradient temporarily reverts to a downward seepage regime. Flume FB2 was installed down-gradient of piezometer nest 914.

*Piezometer nest 918*

Figure B8 displays the hydrograph for piezometer nest 918 over the hydrological year 2009-2010. The phreatic water table fluctuates between 55.72 mOD and 55.62 mOD and the piezometer at the peat-subsoil interface fluctuates between 55.95 mOD and 55.70 mOD. The significance of the drain FB1, in which piezometer nest 918 is located, has been discussed in chapter 4 in the context of its position within the Clara West drainage system.

The water level fluctuation is relatively low at the base of the peat (0.25 m) and very low in the phreatic water table (0.10 m). Viewing the hydrograph in figure B8 the hydrograph trend in phreatic water level and deep peat water level is broadly coincident with each other, but the fluctuation is much larger in deep peat. It can be observed that there is a constant upward seepage from deep peat to phreatic water level. This is in keeping with the inference that this drain is a zone of groundwater discharge

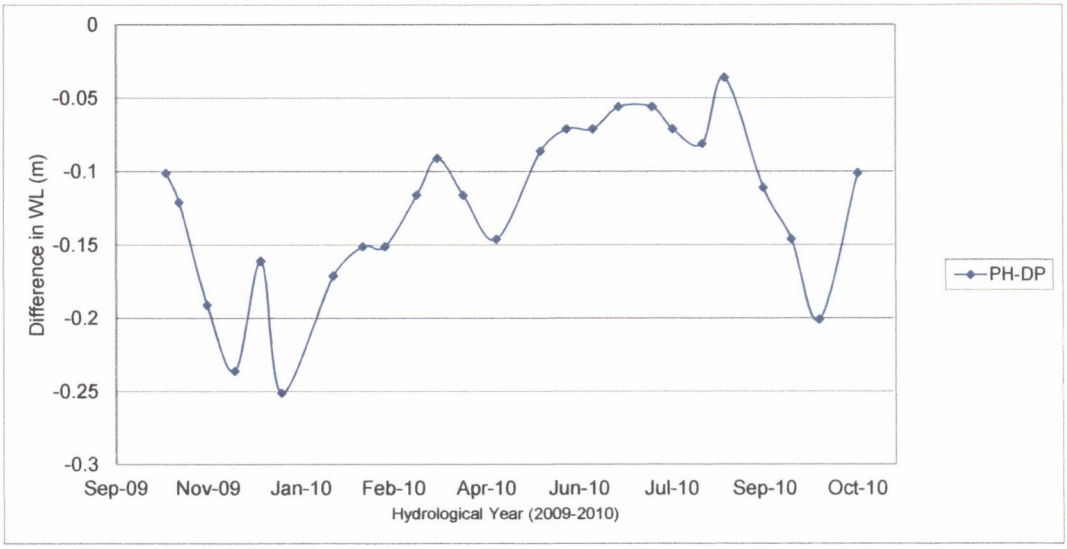


**Figure 5.15.** Hydrograph analysis from piezometer nest 918 (hydrological year 2009-2010)

Hydrograph analysis in Figure 5.15 substantiates the inference that there is a constant upward seepage of groundwater at 918. The PH-DP profile shows the biggest differences in water level occur in wet periods as deep peat is recharged quickly from groundwater seepage, implying a strong connection in this area between peat and mineral subsoil, similar to the observations made at piezometer nest 906, which is located close to 918.

*Piezometer nest 923*

Figure B9 displays the hydrograph for piezometer nest 923 between February 2010 and January 2011. The phreatic water table fluctuates between 50.09 mOD and 50.06 mOD and the piezometer at the peat-subsoil interface fluctuates between 50.17 mOD and 50.13 mOD. The significance of the drain CT3, in which piezometer nest 923 is located, has been discussed in Chapter 4 in the context of its position within the Clara West drainage system.

The water level fluctuation is very low at the base of the peat (0.04 m), very low in the mid-section peat (0.03 m) and very low in the phreatic water table (0.03 m). Viewing the hydrograph in figure B9 the hydrograph trend in phreatic water level and deep peat water level is coincident with each other, though the very low level of water level fluctuation suggests the peat is drained in this area and is resistant to infiltration and seepage water movements. It can be observed that there is a constant

upward seepage from deep peat to phreatic water level. This is in keeping with the inference that this drain is a zone of groundwater discharge.

Hydrograph analysis in Figure 5.16 substantiates the inference that there is a constant upward seepage of groundwater at 923. Each of the water level difference profiles exhibits constant negative values with little in the way of fluctuation. Interestingly the piezometer nest is located in a drain where the sand lense, described in Chapter 3, is found beneath the peat substrate. It is probable that the peat is resistant to water level fluctuations due to subsurface drainage associated with the sand lense, which has lowered the potentiometric surface in the peat substrate. The effects of the sand lense will be discussed in chapters 7 and 8.

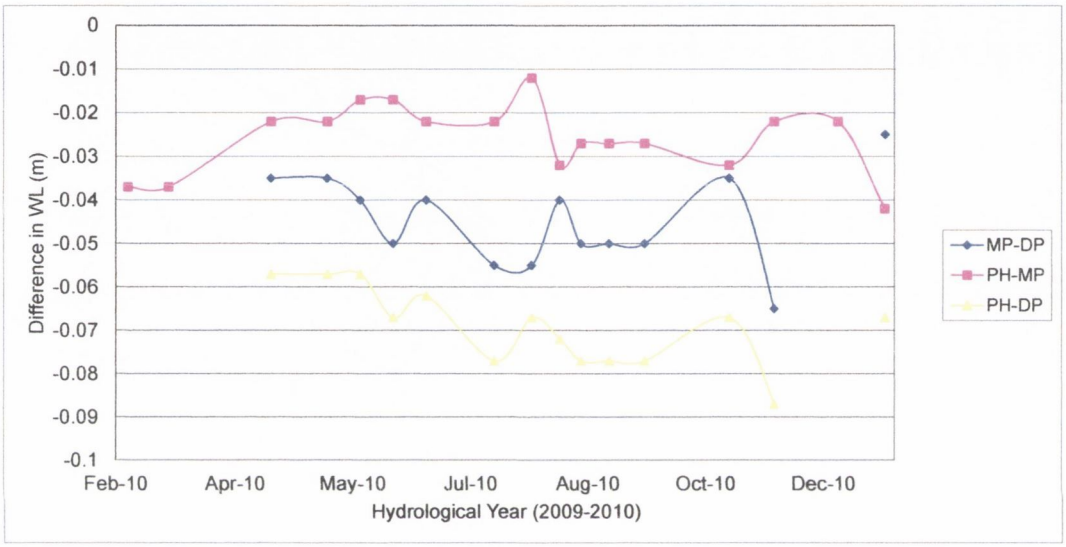


**Figure 5.16.** Hydrograph analysis from piezometer nest 923 between February 2010 and January 2011

### 5.5. Hydrogeological Cross Sections

Hydrogeological cross-sections, displaying hydraulic head distribution in peat and the underlying till aquifer, through monitoring transects T1 to T5 (section 3.3.3) are illustrated in figures C17 to C21 in appendix C and their locations are illustrated below in Figure 5.17. The cross-sections have been constructed to approximately follow hydrogeologic flow lines toward the marginal face-bank drains where groundwater seepage is inferred. The transects were positioned based on where piezometers were installed into the till and face-bank drains - so to understand the connection between the high bog and Clara West drainage system.

The water level data used in the hydrogeological cross-sections is from monitoring data recorded in August 2010. Regional groundwater level is low at this time and is discussed in section 5.6 – the sections are drawn in a steady state period. The influence of mineral subsoil on downward seepage from peat to groundwater beneath the high bog and the subsequent upward seepage from mineral subsoil to the marginal drains is most apparent during low groundwater level periods and so it is

deemed appropriate to construct the hydrogeological cross-sections using water level data from this time.

Examining the equipotential lines in each of the cross-sections, the movement of water flow can be deduced and then be compared to the patters of water flow that are illustrated on two-dimensional potentiometric contours lines in figures C14 to C16 and described in section 5.6. An analysis of each hydrogeological cross-section is discussed below.

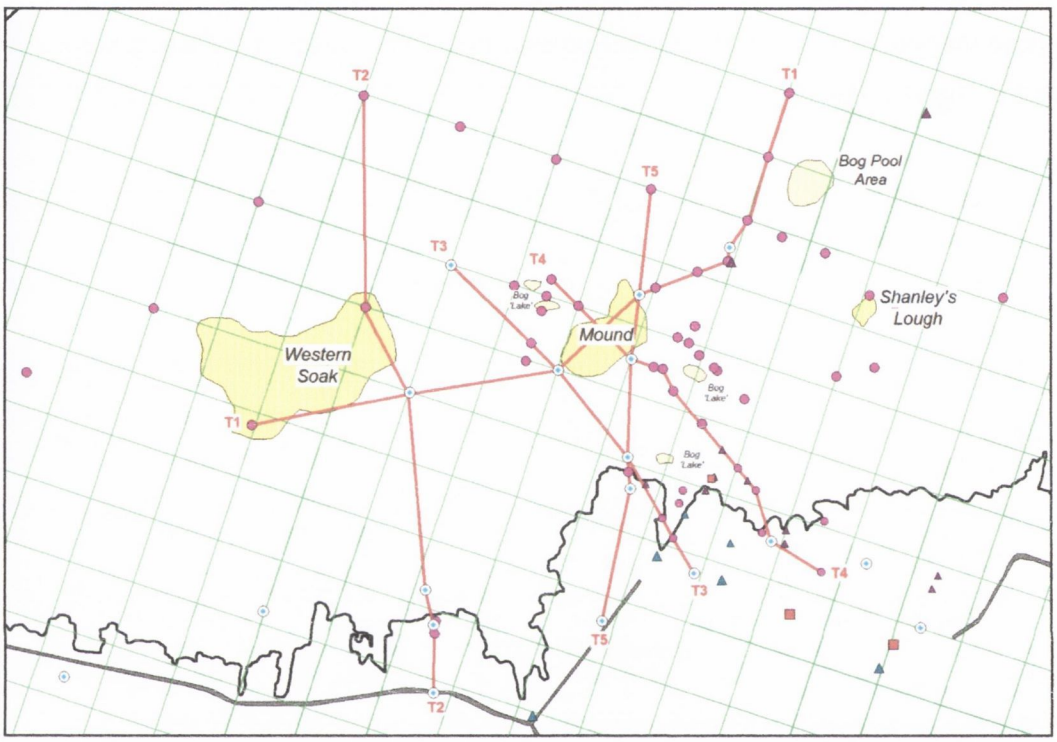


**Figure 5.17.** Hydrogeological cross-section transects

### 5.5.1. Transect 1

Figure C17 displays the hydrogeological cross-section through transect 1. The transect, which is on the high bog, runs from piezometer nest 905 in the west, located in the Western Soak, through to subsoil piezometer nests 908, 909 and 911 by the Western Mound and through to high bog piezometer nests 50, 70, 92, 901 and 902 in the east.

The equipotential lines on figure C17 all indicate downward seepage of water, as would be expected on the high bog. The transect is purposely positioned to so cross sections of the bog where till mineral ridges directly underlie the peat substrate – at the Western Mound and the shallower till mound underlying piezometer nest 908. The equipotential lines indicate that these mineral ridges are influencing the pattern of subsurface water movement. In section 5.4, hydrograph analysis indicated that water was being lost from peat to subsoil at piezometer nest 908. The cross-section substantiates this inference as the gradient between the 55.5 and 56.5 equipotential line is relatively shallow and seems to deflect at the till mound, implying some water loss in the area.

Hydrograph analysis from subsoil piezometer nests 909 and 911 indicated that while there was some resistance in the peat substrate, most probably as a result of drainage to subsoil, water was still being lost to the mineral subsoil. Equipotential lines are quite steep in the Western Mound area, between 909 and 911, indicating resistance, but are shallower either side of the mound indicating water level is being pulled down in these areas and water is being lost to the mineral subsoil. This is unsurprising, as the bog has subsided either side of the Western Mound (i.e. west and east; Chapter 7). As a result the surface level gradient is visibly quite steep on the cross-section, with a 'bowl' type topography resulting from subsidence either side of the Western Mound.

An 'equipotential mound' in the vicinity of piezometer nest 70, which is underlain by lacustrine clay, indicates that the mineral ridges either side of it are both drawing down water level in the peat. The lacustrine clay is preventing downward seepage of water, but the equipotential line pattern indicates a clear mineral subsoil influence. The steep equipotential lines in the vicinity of piezometer nest 92 indicate the peat is resistant and again, the underlying mineral subsoil has most probably drained water from the base of peat. The effect of the mineral subsoil is less pronounced in the vicinity of piezometer nests 901 and 902, where the lacustrine clay appears to be preventing downward seepage of water, and at piezometer 901, in particular, there appears to be little downward water movement.

### 5.5.2. Transect 2

Figure C18 displays the hydrogeological cross-section through transect 2. The transect begins in the centre of the high bog at piezometer nest 96, runs south through the eastern margin of the Western Soak, through subsoil piezometer nests 908 and 907 and crosses face-bank drain FB1 before passing through subsoil piezometer nest 906 and finishes at subsoil piezometer 928.

The equipotential lines on figure C18 all indicate downward seepage of water on the high bog and an upward seepage of water at the drains and in cutover bog. Similar to the observation made in transect 1, the till ridge underlying piezometer nest 908 appears to be having an effect and the difference between the 57.5 and 57 equipotential lines, and the inflection of the latter at the ridge, indicates water is being lost from the high bog to mineral subsoil in this area.

The equipotential lines between piezometer nests 96 and 908 also indicate some downward seepage, though lacustrine clay is found between piezometer nests 96 and 904, presumably preventing water loss. However, viewing the subsoil geology map in figure A2, till subsoil directly underlies peat close to the transect – at its closest point till is found 20 m east of transect 2, 120 m north of piezometer nest 904. It is highly probable that there is a connection in this area, explaining why there appears to be some water loss indicated by the equipotential lines north of piezometer nest 904.

The cross-section passes through face-bank FB1, which was described in Chapter 4 as being a zone of groundwater discharge. Subsoil piezometer nests 907 and 906 lie either side of the drain. Hydrograph analysis of piezometer nest 907 indicates that there is little connection between the base of peat and

the mineral subsoil. The equipotential lines substantiate this inference with the steep gradient north of the drain indicating the peat is highly resistant in the area and that little water is being lost to mineral subsoil. Water loss occurs north of piezometer nest 907 and a tension crack, illustrated on the section, is a result of peat consolidation due to water loss to mineral subsoil. It appears the groundwater in FB2, as monitored at drain nest 918, originates largely from beneath the high bog, west and northwest from the drain itself (as inferred from the groundwater table; section C15). Some groundwater flows from the south (head in piezometer 928 is 56.17 while phreatic level in drain is 56.00) but the gradient is very small, as indicated on the cross-section.

#### 5.5.3.Transect 3

Figure C19 displays the hydrogeological cross-section through transect 3. The transect begins in the centre of the high bog, west-northwest of the area of new bog pools, passes through subsoil piezometer nest 909 by the Western Mound, through subsoil piezometer nest 912 and crosses face-bank drains FB2 and FB3, till drain TD2 and terminates at borehole CLBH5.

The equipotential lines on figure C19 all indicate downward seepage of water on the high bog and an upward seepage of water at the drains and in cutover bog. The equipotential lines between piezometers td9 and tL12 indicate little water loss, which is unsurprising as lacustrine clay underlies the peat in this area. However, the gradient increases beneath td9 where lacustrine clay is absent, suggesting there is water loss to mineral subsoil in this area of the bog. This was also indicated from the hydrogeological cross-section through transect 2, which is located c. 120 m west of tL12. In August 2010, only piezometers to the peat-subsoil interface existed at td9 and tL12. Since that time, piezometers have been installed to the middle of the peat profile at both locations and a piezometer has been installed into the top of the till at tL12, and information from more recent monitoring is used to make inferences on the equipotential lines.

The equipotential gradient increases at 909, which borders the Western Mound. Similar to the observations made from transect 1, though there is some resistance at the base of peat, the mineral subsoil is having an effect here and water loss from the high bog to mineral subsoil is occurring. The equipotential lines also indicate water loss between piezometer nests 909 and 912, which is unsurprising as lacustrine clay is bordered by ridges of till in this area, and the area itself is known to have subsided.

The equipotential gradient increases steeply at the boundary of the high bog and drain FB2. Peat is highly resistant here, and as described in section 3.4.4, the peat is fractured and bog runoff moves through a series of conduits in the area of piezometer nest 912. Little water loss occurs beneath piezometer nest 912 and little water will move laterally through the peat profile itself. Instead, downward seepage of water to mineral subsoil is concentrated north of 912, and the equipotential line profile appears to substantiate this inference.

There is an upward movement of water at the drains in figure C19. The cross-section passes through face-bank drain FB2, which is a significant drain of groundwater discharge, at two points on the transect - phreatic tubes 922 and 916. Water in the drain at 922 appears to be largely from beneath the high bog to the north and at 916, and FB3 and TD2, appears to be a mixture of water from beneath the high bog and cutover bob to the west and south (as inferred from the groundwater table; section 5.5). The hydrogeological cross-section therefore substantiates the inference that the high bog and the Clara West drainage system is connected due to the drains lowering the groundwater table and inducing water loss from peat to mineral subsoil beneath the high bog.

#### 5.5.4. Transect 4

Figure C20 displays the hydrogeological cross-section through transect 4. The transect begins north of the Western Mound in an area of 'new bog pools', passes through the Western Mound and subsoil piezometer 910, passes though an area of new bog pools southeast of the Western Mound and crosses cutover bog drain CT3 before passing through subsoil piezometer nest 920 and terminates at cutover bog piezometer nest 921.

The equipotential lines on figure C20 all indicate downward seepage of water on the high bog and an upward seepage of water at the drains and in cutover bog. The equipotential lines between td6 and tdJ12 indicate a connection between peat and mineral subsoil and that water is being lost to till. This area has subsided and downward seepage from the high bog to the regional groundwater table is unsurprising. The equipotential gradient increases through the Western Mound, where peat is highly compact, and the gradient decreases between subsoil piezometer nest 910 and piezometer nest 57. Hydrograph analysis of 910 indicated a strong connection between water level in the peat and water level in the mineral subsoil and water losses to the underlying mineral subsoil is almost certainly occurring in this area. The equipotential gradient substantiates this inference.

The equipotential profile between piezometer nest 57 and 63 is curious. The till ridge west of 57 is inducing water level drawdown in the vicinity of 57, as indicated by the equipotential lines 54.5 and 54. Water loss appears to be minimal, or has reached equilibrium, between piezometer t10 and piezometer nest 59. However, between 59 and 63 the equipotential lines suggest water is seeping downwards and water loss is occurring. In this part of the section till does not underlie the peat substrate. However, the sand lense, as described in section 2, is found in this area and it appears to be drawing down the water level in peat. Subsidence has occurred in this area and the hydrogeological cross-section suggests the sand lense is the drainage pathway for bog-water loss. The equipotential gradient at the top of the peat profile is steep, implying resistance and little lateral movement of water- again suggesting water is lost at its base, through the sand lense.

The transect crosses the cutover bog drain CT3 at piezometer nest 923. The movement of water is upwards at 923 and as discussed in the hydrograph analysis, the water levels at 923 fluctuate little.

Piezometer nest 923 is also underlain by a sand lense, water loss through which has consolidated the peat, and sand appears to induce an inflection in the 50.5 equipotential line. The groundwater is this drain appears to originate from till mounds in cutover bog to the south, as till is overlain by lacustrine clay to the north. The equipotential profile on the section also indicates this is the case. Groundwater in the cutover till mounds does, however, originate from beneath the high bog. Cutover bog drains, CT1, CT3 and CT4, as illustrated on the section are groundwater discharge zones (Chapter 4) and the equipotential profiles in the section seems to confirm this.

It may be observed on the cross-section that a 'rotating' groundwater flow line is drawn beneath piezometer nest 920. The water level in the till is higher than it is in mid-peat, but lower that it is in deep peat. It is inferred that this groundwater level is lower than it would ordinarily be, in natural conditions, and is lowered due to drainage. The rotating flow line indicates that water is being drawn down outside of the section, possibly due to till drain TD2. The hydrogeological section through T4 therefore illustrates, in profile, the effects of the sand lense and mineral subsoil on inducing water loss from peat due to marginal drainage.

### 5.5.5. Transect 5

Figure C21 displays the hydrogeological cross-section through transect 5. The transect begins north of the Western Mound near the centre of the bog at piezometer nest 93, passes through subsoil piezometer nests 911 and 910, either side of the Western Mound and passes through subsoil piezometer nest 912 at the high bog boundary and then crosses face-bank drain FB2, passes through cutover subsoil piezometer nest 915 and terminates at subsoil piezometer 913.

The equipotential lines on figure C21 all indicate downward seepage of water on the high bog and an upward seepage of water at the drains and in cutover bog. The equipotential profile between piezometer nest 93 and subsoil piezometer nest 911 indicates that the mineral subsoil ridge is also having an effect in this area and that some water losses are occurring in the lower margins of the peat profile, close to the ridge where lacustrine clay is absent. Similar to the description through T5, the equipotential gradient increases through the Western Mound and decreases between subsoil piezometer nests 911 and 910, suggesting water loss to the subsoil, which again substantiates the inferences made in hydrograph analysis. The equipotential gradient between 910 and 912 is relatively shallow and the till ridge seems to be having an effect and is a zone for water loss from the peat substrate.

The section crosses face-bank drain FB2 at drain piezometer nest 914. As described in T4, the equipotential gradient is steep at the high bog boundary meaning little water is seeping downwards to mineral subsoil beneath piezometer nest 912. The movement of water is upward at 914 and the equipotential and groundwater flow lines indicate that water in the drain is a mixture of waters originating beneath the high bog to the north and The Island, a topographic high composed of till

subsoil, to the south. The cross-section provides more evidence that drain FB2 is inducing groundwater discharge from the underlying till body, which is in turn inducing water loss from peat to till underneath the high bog, particularly in areas close to the Western Mound and piezometer nest 910.

## 5.6. Contour Maps

### 5.6.1. Regional groundwater table

Figure C14 illustrates the mineral subsoil (till) potentiometric surface in August 2010 when the regional groundwater level is at, or close to, its lowest and figure C15 illustrates the mineral subsoil (till) potentiometric surface in February 2011 when the regional groundwater level close to its highest. The contours encompass water level measurements taken from piezometers installed into the till subsoil on the high bog, cutover bog and from borehole installations surrounding Clara Bog West. The summer (August) and winter (January) groundwater tables are discussed below.

*Regional groundwater levels*

In the 2009/ 2010 hydrological year, the highest groundwater levels occur in the month of November and the lowest groundwater levels occur between June and August 2010. In June 2010, groundwater level is lowest at 908, 912, and 915, CLBH5, CLCD3 and ST3-1. In July 2010, groundwater level is lowest at 907, 909, 910, 926 and 927. In August 2010, groundwater level is lowest at 906, 911, 913, 920, 924, 925, 928, 929 and CLBH9.

The lowest groundwater level therefore does not appear to manifest itself at the same time at all piezometers and the period between late June and late August may be taken as representing a low groundwater table 'period' in Clara West. A groundwater table map from August 2010 is presented in figure C14 as this is the period when groundwater level is low in all piezometers (see hydrograph figures). A full suite of water levels was taken at this time across the bog and so the detailed hydrogeological cross-sections in section 5.5 can be compared to the analysis below.

*Winter regional groundwater table*

Figure 5.18 (and Figure C15; Appendix C) illustrates the regional groundwater table in January 2011. The Feruary2011 water level data has been used to construct the winter groundwater table map because a full suite of groundwater level data is available at this time. The direction of groundwater flow can be deduced from the subsoil potentiometric surface. Groundwater flows eastwards in the western half of Clara West, begins to flow to the southeast, west of Shanely's Lough, before flowing southwards in the eastern half of Clara West. The gradient of the groundwater table is relatively shallow in the eastern and western sections of Clara West but increases greatly in the area between the Western Soak and Shanely's Lough. It is in this area that till directly underlies high bog peat and it is adjacent to these steep potentiometric gradients that face-bank drains, FB1-FB3, which are zones of

groundwater discharge, are situated. It can also be observed from the map that the gradient of the potentiometric surface also increases greatly at till drains TD1 and TD2. As discussed in Chapter 4, the elevation at the base of the face-bank and till drains is below the regional groundwater table.

Thus, it is clear that the face-bank drains and till drains south of the Western Soak and Shanely's Lough are having a big effect on the regional groundwater table beneath the high bog and the drains are effectively outlets for groundwater discharge, as shown by the various hydrogeological cross sections. As the drains are receiving groundwater from beneath the high bog, they are having the effect of lowering the regional groundwater table, which is discussed further in chapter 9.

The gradient of the groundwater table becomes less steep in the Restoration Area. It can be observed from Figure 5.18 that the groundwater table converges in this area with groundwater flowing from the west and north beneath the high bog and from the elevated area, known locally as The Island, to the south. The effect of the cutover drains in the Restoration Area seems to be less pronounced than the till and face-bank drains, but rather the Restoration Area as a whole is a zone for groundwater discharge, with groundwater seeping upwards where lacustrine clay is absent. Artesian pressures recorded at subsoil piezometers 926 and 927 and groundwater discharge into cutover drains CT1-CT4 substantiates this inference and the upward pressure in the region has important implications for restoration measures (Chapter 12).

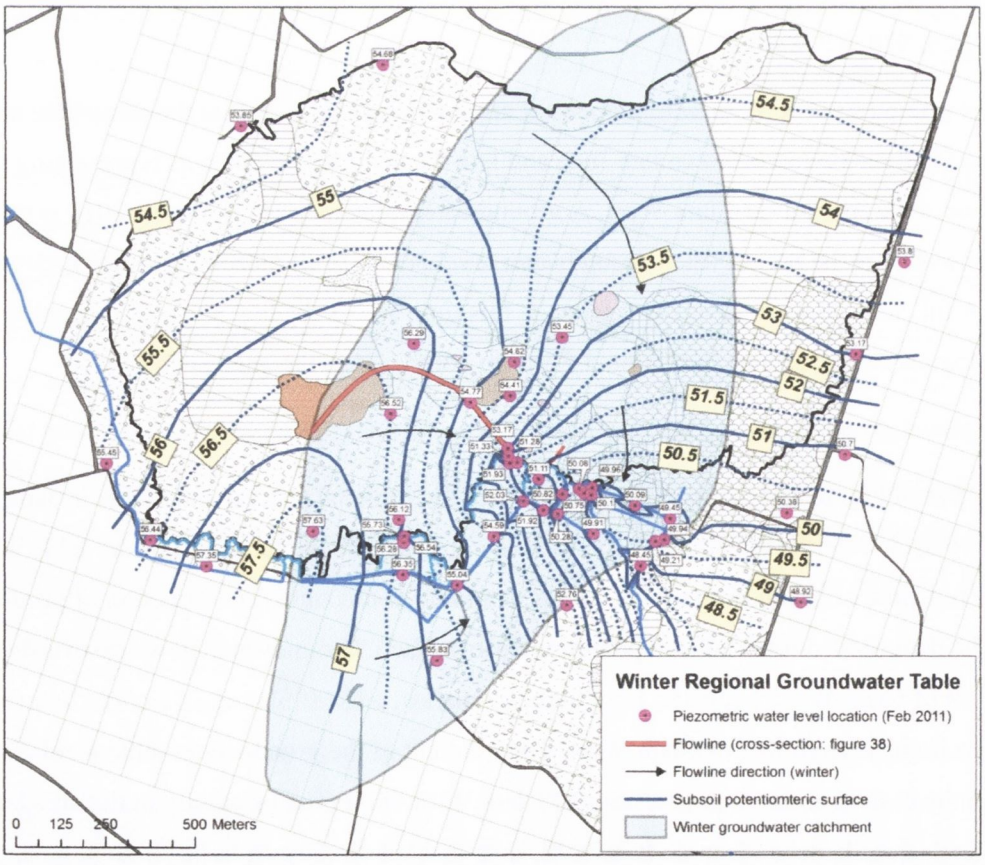


**Figure 5.18.** Winter regional potentiometric surface in till groundwater body

*Summer regional groundwater table*

Figure C14, Appendix C, illustrates the regional groundwater table in August 2010. The 'summer' regional groundwater table pattern is almost identical to that of the 'winter' groundwater table and the descriptions and inferences made on the February 2011 map can equally be applied here. A summary table of regional groundwater LEVELS is presented in table 4.1 and it can be observed that the minimum fluctuation in groundwater level has been recorded at ST3-1 (0.2 m) and a maximum groundwater level fluctuation has been recorded at 912 (0.87 m). The average difference between maximum (winter) and minimum (summer) water level is c. 0.5 m, meaning the hydraulic gradient is moderately higher in summer than it is in winter, though this makes little difference to the regional groundwater movements.

*Groundwater catchment*

The surface water (topographic) catchment of the regional potentiometric surface, to the Restoration Flume in is also illustrated in Figure 5.18. The catchment area was delineated by the potentiometric surface in combination with water balance computation and baseflow separation analysis (Chapters 6 and 8). However, based on water balance and baseflow separation analysis (Chapters 6 and 8) the groundwater catchment area to the Restoration Flume is smaller in the summer 'dry' period than it is in the winter 'wet' period, particularly south and north of the Restoration Area.

The general summer groundwater catchment area is c. 1.06 $km^2$, 0.72 $km^2$ of which is overlain by high bog. The Clara West high bog covers an area of 2.42 $km^2$ implying c. 30% of the high bog is, theoretically, in hydraulic contact with marginal drainage where groundwater discharge is known to occur (at baseflow conditions). Importantly, the Western Soak and Shanely's Lough are positioned within the groundwater catchment, as are the areas of bog that have subsided since the early 1990's. The groundwater catchment area increases to 1.77 $km^2$ when the water level is highest in winter – the increase in catchment area occurs outside of the high bog and encompasses more of the surrounding elevated till mound areas.

### 5.6.2. Deep peat potentiometric surface

Figure C16 (Appendix C) and Figure 5.19 illustrates the mean potentiometric surface for water level measured at the base of the peat profile in high bog and cutover bog (i.e. water level in peat that is overlying subsoil underneath). Mean water levels were used to generate the map so to use the entire suite of deep peat piezometers (which were rarely measured at the same time) and to analyse the effects of till and sand on subsurface drainage routes.

The potentiometric surface is broadly similar to that of the groundwater table. Water flow at the base of peat flows in an easterly direction from the Western Mound, before flowing in a southeast direction around the Western Mound and in a southerly/ south-westerly direction in the Shanely's Lough area.

The deep peat potentiometric flow pattern in the western region of Clara West is similar to that of the regional groundwater table. The hydraulic gradient is also very steep in this region, similar to the regional groundwater table. The steep hydraulic gradient occurs where till directly underlies peat and that same till body is peripheral to face-bank drains FB1-FB3, which are zones of groundwater discharge. It can also be observed that groundwater flow, from the west, at the base of peat diverges around the Western Mound. This implies the mound itself is a barrier to deep peat groundwater flow – but water appears to drain in areas surrounding the mound and this is discussed in Chapter 8.

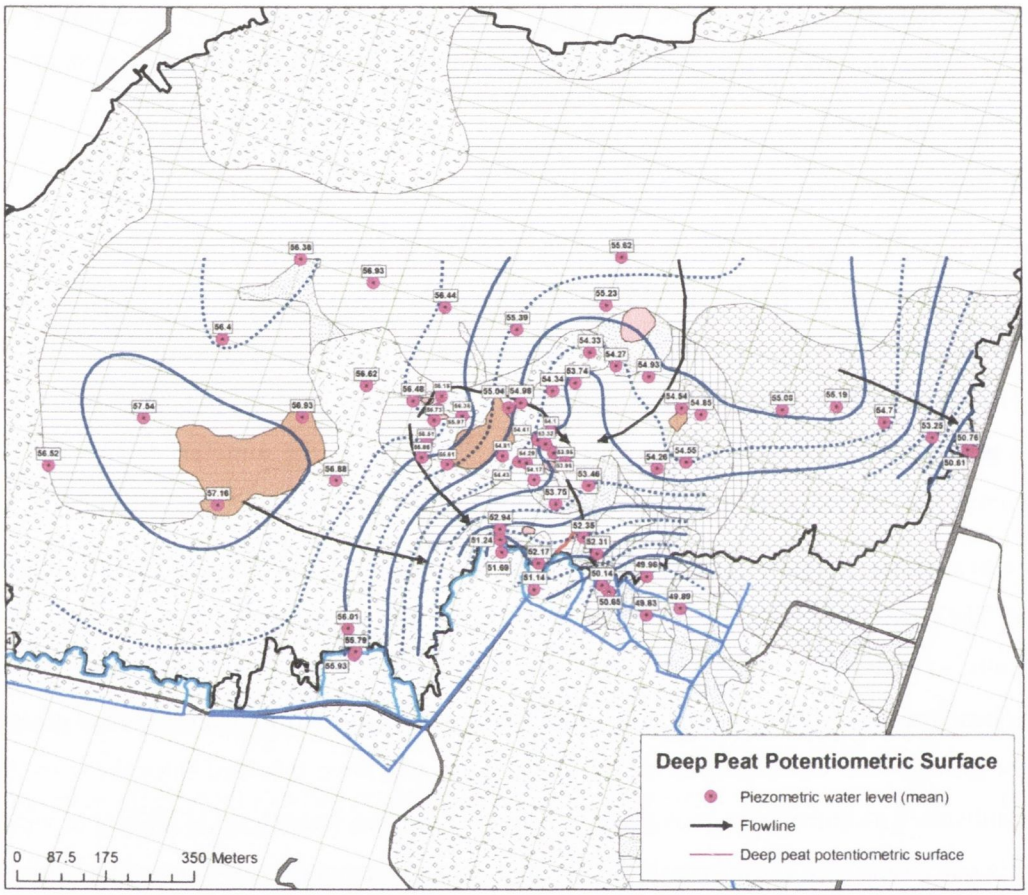


**Figure 5.19.** Mean deep peat potentiometric surface (Malin mOD) and underlying subsoil geology (see Figure C16; Appendix C)

Steep deep peat potentiometric surface hydraulic gradients are also found southwest of Shanely's Lough. Till does not underlie the high bog in this region and instead the gradient appears to be induced by the occurrence of sand lenses, both under high bog and cut bog. The steep hydraulic gradients to the west and the steep gradients to the east converge between the Western Mound and Shanely's Lough to produce a clear drainage pattern that trends from north to south under the high bog and from northwest to southeast outside the high bog.

As such, the steep hydraulic gradient of the deep peat potentiometric surface and the drainage pattern in the area between the Western Mound and Shanely's Lough is a combined effect of reduced water level due to (1) water loss to mineral subsoil where marginal drainage has created a local connection

with the regional groundwater table and (2) where sand underlies peat and the water pressure in the sand unit is reduced by marginal peat-cutting and drainage in the cutover areas bordering the high bog in the Restoration Area.

### 5.6.3.Phreatic water table

Figure 5.21 illustrates the phreatic water table in August 2010 when surface water level is at, or close to, its lowest and figure 5.20 illustrates the phreatic water table in January 2011 when the surface water level is close to its highest. The contours encompass water level measurements taken from shallow phreatic tubes on the high bog. The summer (August) and winter (January) phreatic water tables are discussed below.

*Winter phreatic surface*

Figure 5.20 illustrates the phreatic water table in January 2011. Similar to regional groundwater levels, the phreatic water table is at its highest in November, both in 2009 and 2010, but viewing the hydrographs figures, the phreatic water table is also high in January. A full suite of measurements in all phreatic tubes was made in January 2011 and so this period is used to illustrate the high bog phreatic water table during the 'winter' period.

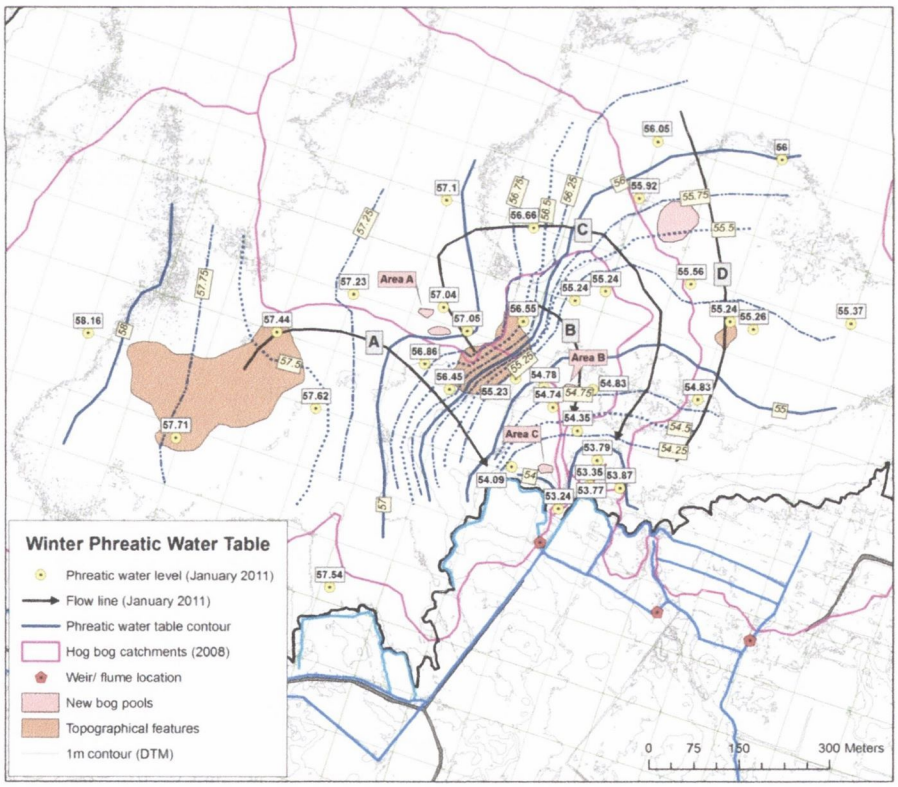


**Figure 5.20.** Phreatic water table in January 2011

Flowlines are also illustrated on Figures 5.20 and the patterns of surface water movement on the high bog can be summarised as follows:

- Flow line A: Shallow surface water gradients encompass the Western Soak. Surface water flows eastwards through the Western Soak and then in a south-easterly direction, west of the Western Mound
- Flow line B: Water flows southeast from the Western Mound into bog pool area B and then flows south before running off the high bog surface. Water is also lost through cracks in the underlying peat substrate. The phreatic hydraulic gradient is steep surrounding the Western Mound, implying fast surface water movement
- Flow line C: Water flow north of the Western Mound flows north into bog pool area A and then flows in an east to south-easterly direction around the Western Mound, before flowing southwards, east of bog pool area B, before then running off the high bog surface
- Flow line D: Shallow surface water gradients encompass the Shanely's Lough soak system. Surface water flows southwards, north and south, of Shanely's Lough. Importantly the soak area receives no water from the Western Mound area to the west. This coincides with the observations made regarding the high bog catchment area changes from the 1990s until now (Chapter 10)

*Summer phreatic surface*

Figure 5.21 illustrates the phreatic water table in August 2010, when the phreatic water table is at/ close to its lowest. The 'summer' regional groundwater table pattern is very similar to that of the 'winter' phreatic water table and the descriptions and inferences made on the January 2010 map can equally be applied here.

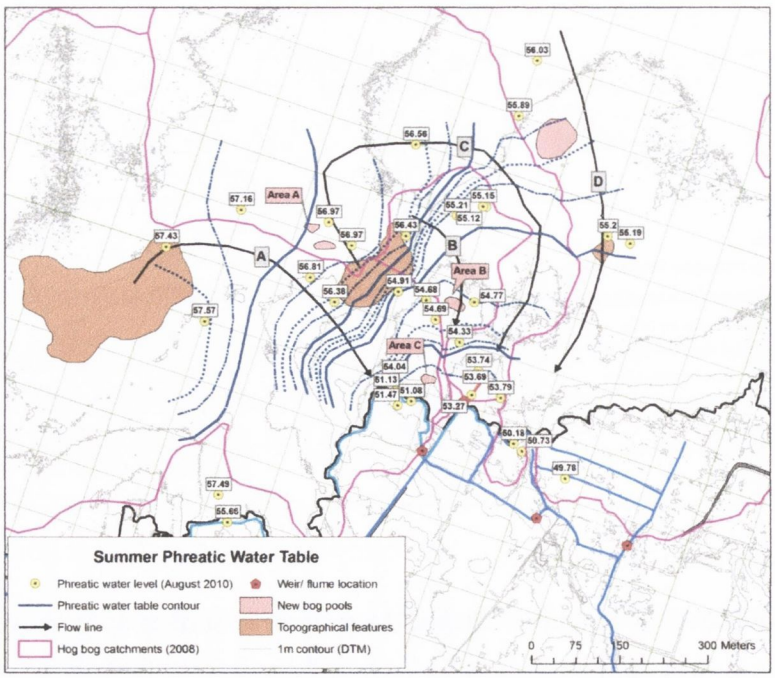


**Figure 5.21.** Phreatic water table in August 2010

*High bog catchment*

The phreatic water table maps in Figures 5.20 and 5.21 indicate that the high bog catchment has changed since the early work in 1991. Of most significance is the reduction in catchment size west of the Western Mound. Long flow paths from an area north and east of the Western Soak maintain the Shanely's Lough soak system. The original catchment divide between the Western Soak and the Western Mound has moved northwards, by over 100 m, implying flow paths in this area have been diverted and instead of flowing to the Shanely's Lough soak system they now flow towards and around the south western half of the Western Mound. Chapters 8 and 10 will discuss the change in high bog catchment area.

## 5.7. Geological relationship with water level

The patterns in water level gradient and flow direction described for the phreatic water table, deep peat potentiometric surface and regional groundwater table are related and a function of the subsoil geology underlying the peat substrate.

Hydrograph analysis and interpretation of subsoil and deep peat potentiometric contour maps indicate thatt water loss from the peat substrate is a result of two drainage mechanisms:

1. Where lacustrine clay is absent and peat is underlain directly by till (mineral subsoil) a hydraulic connection exists between the high bog and regional groundwater table. Water loss from the base of the peat profile in the high bog occurs when peripheral drainage cuts close to the peat-till interface (Chapter 4) thereby creating an outlet for groundwater discharge. This has resulted in the regional groundwater level being lowered in local areas (section 5). The subsoil potentiometric surface in the till aquifer (Chapter 8) indicates that this is the case as the hydraulic gradient increases significantly where till underlies peat and where groundwater-fed face-bank drains FB1-FB3 border the high bog boundary. The potentiometric surface from water level at the base of peat mirrors that of the regional groundwater table, implying water is being lost to till. The phreatic water table gradient is also steep in such areas implying peat consolidation has increased the surface level gradient. As such, the water level patterns in till, peat and in the free water table are linked and all indicate water loss where gradients are steep in areas where till underlies the peat profile.
2. The deep peat potentiometric surface shows that the occurrence of sand lenses, overlying lacustrine clay and underlying peat, is an important drainage pathway. The sand lenses appear to have developed next to the old lake basin and next to the Western Mound and extend southwards into the Restoration Area. Drainage in the cutaway area has presumably decreased the hydraulic head in the sand lense, which has induced a decrease in water level in peat surrounding the sand lense in the high bog. Figure C16 illustrates a clear drainage pattern in

deep peat and the steep water table gradient in the phreatic surface, southwest of Shanely's Lough is most likely a result of this drainage mechanism.

### 5.8. Seepage and flow rate

Hydrological and hydrogeological analysis indicates that drains close to the southern margin of the Clara West high bog are outlets for groundwater discharge. A large proportion of the groundwater catchment is underneath the high bog in areas where lacustrine clay is absent and where peat consolidation has occurred. Hydrograph analysis coupled with hydrogeological cross-sections and potentiometric contour maps all indicate peat is losing water to till and that groundwater seepage is discharging from the till into drains where an outlet exists.

To estimate the seepage rate of groundwater flow into the drains and how much water seeps downwards through the peat profile and into the till aquifer, a series of simple calculations can be made using Darcy and Dupuit equations for groundwater flow. Such calculations in this study are estimates and more accurate estimations of water seepage can only be made using a numerical model (Chapter 11). However, initial estimates are made here and are a good perquisite to the model development. In Figure 5.20 a series of streamlines, or flow lines, which run perpendicular to the regional groundwater table and have a subsoil piezometer either end of the line are illustrated. The streamlines are basically groundwater flow lines. Knowledge of hydraulic head in the till aquifer underneath the high bog and close to a drain where groundwater discharge occurs, allows an estimation of groundwater flux through the till body to be made and is discussed below.

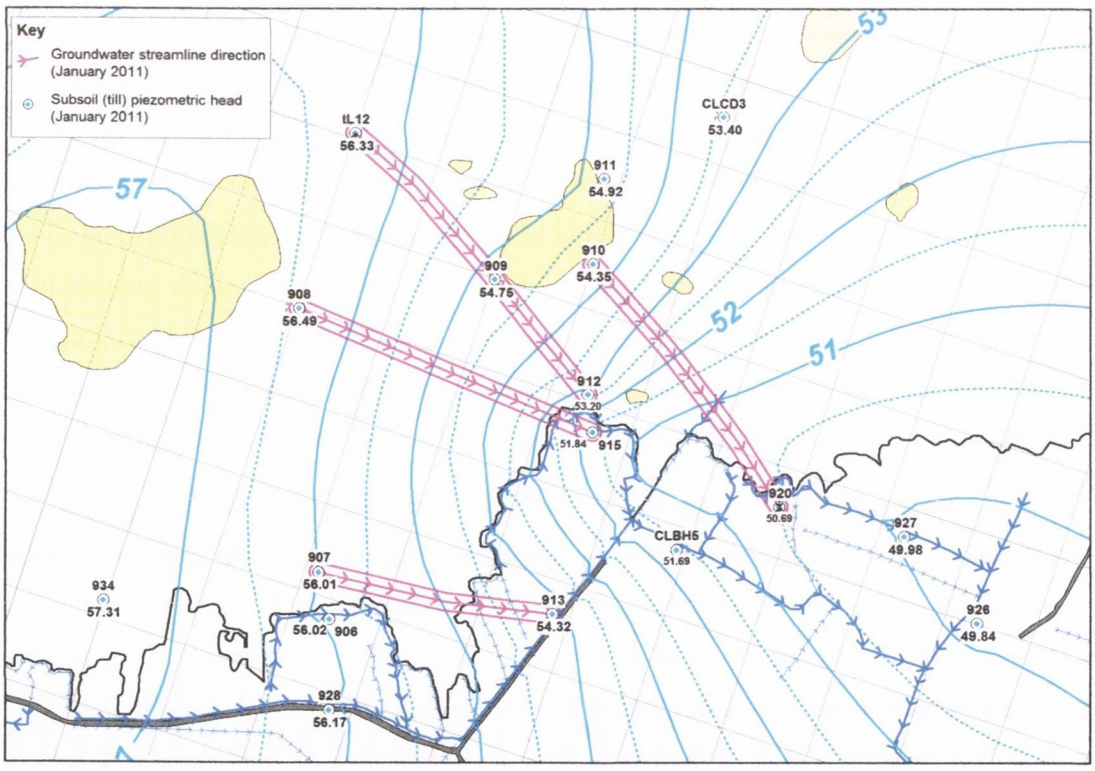


**Figure 5.22.** Groundwater streamlines towards marginal drains (January 2011).

The permeability or hydraulic conductivity ($K$) of a geological material will dictate how quickly water will move through it, and is therefore an important quantity to determine. The permeability of peat and lacustrine clay is very low ($10^{-3}$ to $10^{-7}$; Van der Schaff et al, 2002), implying water moves slowly through the peat profile, while the hydraulic conductivity of till is far greater and varies between 0.1 m/day to 1000 m/day (Flynn, 1993).

### 5.8.1. Hydraulic conductivity

A geological medium has a unit hydraulic conductivity if it will transit in unit time a unit volume of groundwater at the prevailing kinematic viscosity (i.e. the dynamic viscosity divided by the fluid density) through a cross-section of unit area, measured at right angles to the direction of flow, under a unit hydraulic gradient (Bay, 2009).

The piezometers installed in the Clara West system are narrow installations. Slug rising head tests, which involve extracting a volume of water from the piezometer and timing its response, were performed on installations of most interest using a method developed by Hvorselv (1951) and recommended by Fetter (1999):

$$K = \frac{r^2}{2L_e t_{37}} ln \frac{L_e}{R} \qquad \text{Equation 5.1}$$

where $K$ is hydraulic conductivity, $r$ is the radius of the well casing, $L_e$ is the length of the well screen, $t_{37}$ is the time it takes for the water level to rise or fall 37% of the initial change.

Permeability measurements (rising head/ slug tests) have been carried out in piezometers measuring water level at the base and mid-section of peat in areas where peat directly overlies till subsoil. The results are presented in Tables 5.5 and 5.6.

Table 5.5. Measured deep peat hydraulic conductivity (m/day)

| ID | K | ID | K | ID | K |
|---|---|---|---|---|---|
| 48 | 8.41E-03 | 96 | 1.26E-05 | 918 | 2.12E-03 |
| 50 | 9.96E-04 | 97 | 1.92E-03 | 920 | 5.77E-03 |
| 55 | 6.51E-02 | 98 | 7.34E-04 | 923 | 4.25E-02 |
| 56 | 2.69E-03 | 901 | 3.60E-03 | 927 | 7.34E-05 |
| 57 | 8.77E-02 | 903 | 1.01E-03 | t1 | 2.37E-02 |
| 70 | 2.57E-03 | 904 | 2.52E-03 | t10 | 5.77E-05 |
| 86 | 4.20E-02 | 906 | 3.88E-02 | t13 | 5.38E-03 |
| 87 | 1.35E-03 | 907 | 6.31E-06 | td2 | 2.52E-03 |
| 88 | 1.15E-03 | 908 | 2.12E-01 | td4 | 1.39E-02 |
| 89 | 1.15E-03 | 909 | 6.00E-05 | td5 | 9.61E-05 |
| 92 | 5.38E-03 | 910 | 1.39E-03 | td9 | 1.12E-01 |
| 93 | 1.61E-03 | 911 | 3.10E-05 | tdJ12 | 1.15E-02 |
| 94 | 5.04E-04 | 912 | 1.65E-03 | tdK12 | 5.77E-03 |
| 95 | 3.23E-04 | 914 | 2.52E-03 | tL12 | 1.12E-02 |

Table 5.6. Measured till and mid-section peat hydraulic conductivity (m/day)

| *Subsoil* | | *Mid-section Peat* | | | |
|---|---|---|---|---|---|
| **id** | **k** | **id** | **k** | **id** | **k** |
| 906 | 1.00E+01 | 56 | 6.96E-02 | 902 | 6.21E-03 |
| 907 | 1.75E+00 | 57 | 5.61E-02 | 903 | 1.89E-03 |
| 908 | 1.15E+01 | 70 | 1.94E-03 | 904 | 2.12E-02 |
| 909 | 1.65E+01 | 86 | 5.04E-03 | 906 | 1.19E-03 |
| 910 | 2.25E+00 | 87 | 6.21E-02 | 909 | 1.35E-03 |
| 911 | 2.24E-05 | 88 | 9.61E-02 | 910 | 1.15E-02 |
| 912 | 3.00E-03 | 89 | 3.36E-01 | 912 | 1.01E-04 |
| 913 | 4.00E+00 | 92 | 2.02E-01 | 914 | 3.00E-04 |
| 915 | 1.68E-04 | 93 | 6.73E-01 | 920 | 1.00E-05 |
| 920 | 1.49E-02 | 94 | 1.00E-05 | 923 | 5.77E-02 |
| 926 | 4.48E+00 | 95 | 8.07E-03 | 907-1 | 2.88E-03 |
| 927 | 8.07E-03 | 96 | 1.75E-01 | 907-2 | 3.67E-03 |
| 928 | 1.39E-02 | 97 | 1.61E-01 | td9 | 9.00E-05 |
| 934 | 3.67E-03 | 98 | 2.88E-03 | tL12 | 3.10E-03 |
| CLCD3 | 2.92E-01 | 901 | 7.21E-02 | | |
| BH5 | 3.53E+00 | | | | |

A number of observations can be made from the *K* results from measurements in deep peat:

- Hydraulic conductivity is very high at location 908 at c. $10^{-1}$ m/day. Peat is shallow in this area (c. 4m thick) and is underlain by a till mound. It is probable there is sub-surface peat cracking in this area, which is also indicated by a peat crack, which is visible on the ground, less than 50 m, to the south. A very high hydraulic conductivity (c. $10^{-1}$ m/day) is also measured at piezometer td9, which is located c. 100 m east from 908, and close to the Western Mound, indicating peat cracks are widespread in this part of the bog
- High hydraulic conductivity of c. $10^{-2}$ m/ day in deep peat is also found at tdJ12 and tL12 and relatively high hydraulic conductivities of $10^{-3}$ m/ day are found at tdK12 and 910. These piezometers are located close to the Western Mound and the high values are most likely associated with subsurface cracking. Similarly, a high hydraulic conductivity (> $10^{-2}$ m/day) is found at 912, which is located close to a heavily fissured face-bank adjacent drain FB2
- Hydraulic conductivity is low at 909 – c. $10^{-5}$ m/ day
- The high hydraulic conductivities ($10^{-1}$ to $10^{-3}$ m/day) suggest a connection between water level in the till and in the base of peat and subsurface cracking. The areas where high hydraulic conductivities are measured are not isolated and are associated with areas where deep peat is underlain by till subsoil and where the regional potentiometric surface has decreased (see figure 21)

- High hydraulic conductivities (> $10^{-3}$ m/day) are also encountered in piezometers located adjacent to the bog road, namely 86-89. This implies the road is still having an effect on subsurface flow movements
- The low hydraulic conductivities (< $10^{-4}$ m/day) are typical of what is normally measured at the bottom of peat. However, low hydraulic conductivities can also be a consequence of compaction, such as at piezometer 909, where ground level has decreased by c. 1.0 m since 1991 (see section 7)

Hydraulic conductivity values on Clara West are also available from the research period in 1991 (Van der Schaaf, 1999). Figure 5.23 compares the results carried out in this study with those of Van der Schaaf (1999):

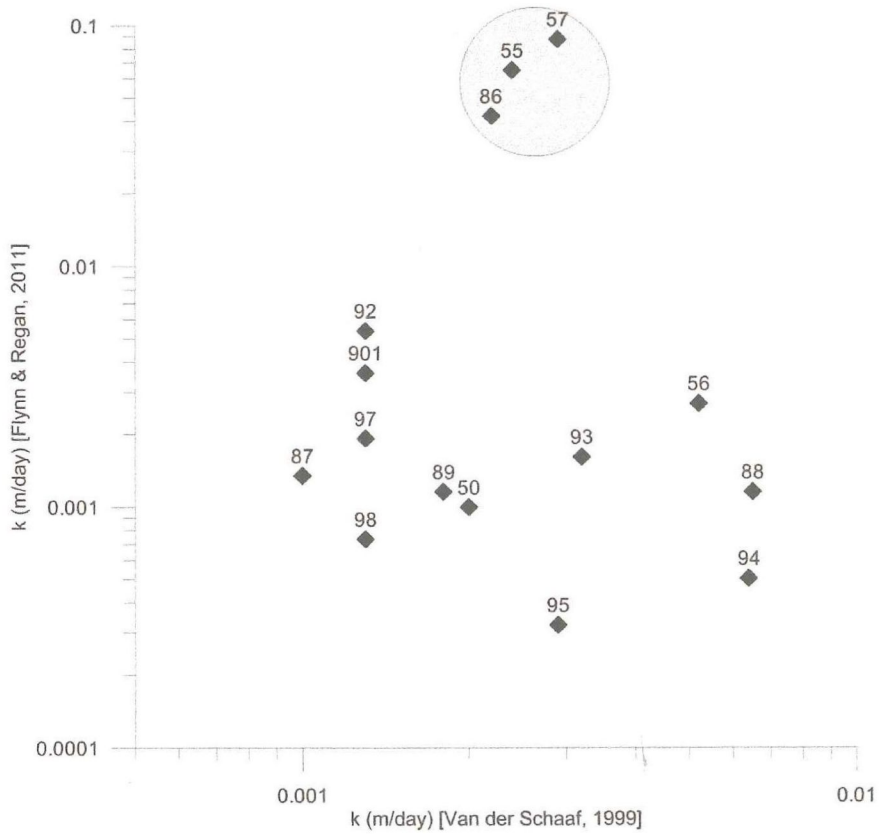


**Figure 5.23:** Plot of Hydraulic conductivity values measured by Van der Schaaf (1993) and by Flynn & Regan (2011)

The results indicate that in areas where hydraulic conductivity has decreased, the peat has compacted and the organic matter content in the peat interval has increased. Hydraulic conductivity declines by up to an order of magnitude at piezometers 95, 96 and 98, which are located in the central regions of the bog. Elsewhere changes in hydraulic conductivity are moderate.

In areas where hydraulic conductivity has increased, it is probable sub-surface cracking is increasing the local permeability of the peat substrate. Hydraulic conductivity is c. two orders of magnitude higher at piezometers 55, 57 and 86 since 1991. Piezometer 57 is located close to piezometer nest 910

and the Western Mound and subsurface cracking is probable in this area. Piezometers 55 and 86 are located adjacent to Shanely's Lough and the main bog road respectively. It is probable piezometer 55 is located to a sand lense, based on subsoil investigations, and it is probable the bog road is still having an effect on the high bog located adjacent to it.

As such, comparison of hydraulic conductivity measurements made in the early 1990s and as part of the recent research indicates that hydraulic conductivity values have either increased or decreased.

- Where hydraulic conductivity values have decreased it implies peat settlement/ compaction that can be attributed to subsidence.
- Where hydraulic conductivity values have increased it implies preferential flow pathways in the peat substrate that may be attributed to sub-surface peat cracking, which can also be attributed to an increase in effective stress which in itself is associated with a drop in regional potentiometric surface.

Figure 5.24 summarises where peat has compacted and cracked due to an increase in effective stress (discussed in Chapter 7). Hydraulic conductivity measurements recorded in 2011 indicate there is a high (> 10-2 m/day) hydraulic conductivity zone located between the Western Soak and the Western Mound. The high hydraulic conductivities are most likely associated with subsurface peat cracking, and are coincident with areas of bog where there has been a drop in regional groundwater level. It is highly unlikely that restoration works will have a positive impact in this area of the bog.

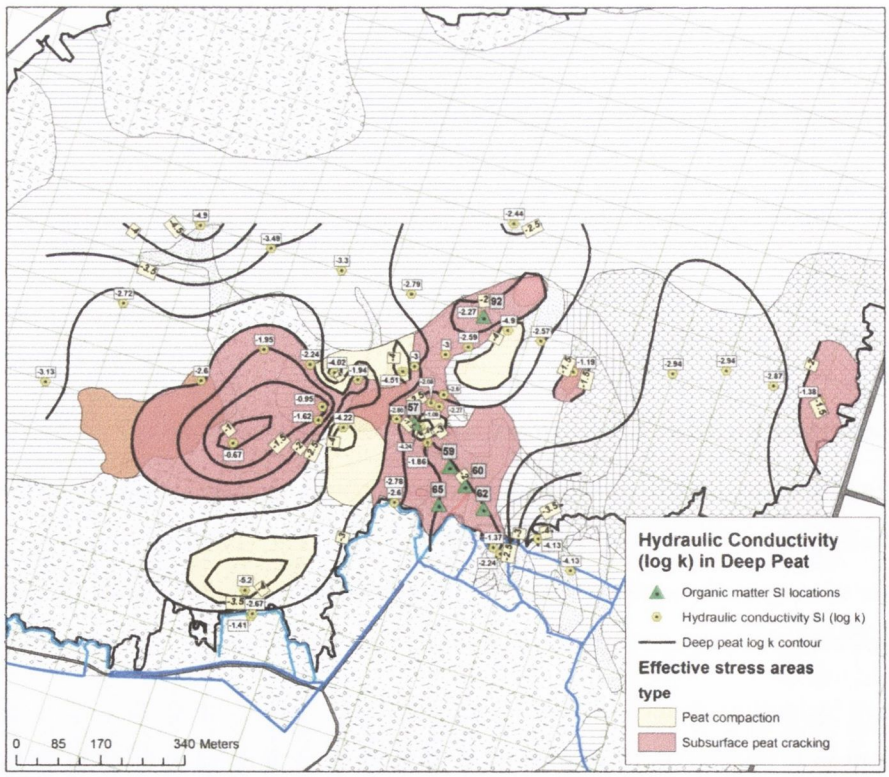


**Figure 5.24.** Hydraulic conductivity contour map and areas of peat under effective stress

5.8.2.Downward seepage

To calculate downward seepage through the peat profile at locations where water loss to till is speculated, a simple Darcian flux calculation can be performed:

$$q_{dw} = \frac{\Delta h}{R} \qquad \text{Equation 5.2}$$

and

$$R = \frac{T}{k_v} \qquad \text{Equation 5.3}$$

where $q_{dw}$ is downward seepage, $k_v$ is the vertical hydraulic conductivity, $\Delta h$ is the difference in hydraulic head between piezometric head in deep piezometer ($h_1$) and piezometric head in mineral subsoil ($h_2$), $R$ is the hydraulic resistance of the peat and T is the thickness of the peat between the bottom of the deep peat piezometer filter and the underlying peat – subsoil interface/ boundary.

Table 5.7 lists the estimated downward seepage fluxes from peat to till at subsoil piezometer nests tL12 and 907 to 912. Each of these piezometer nests are located on the streamlines illustrated on Figure 5.22. The hydraulic conductivity values listed in Table 5.5 were used to work out each of the seepage rates.

Table 5.7. Estimated downward seepage rates through peat profile at selected piezometer nests

| | **907** | **908** | **909** | **910** | **912** | **tL12** |
|---|---|---|---|---|---|---|
| mm/ d | 0.000 | 16.8 | 0.024 | 0.425 | 0.759 | 2.22 |
| mm/ yr | 0.001 | 6132 | 9 | 155 | 277 | 810 |

The results reveal high seepage rates on the bog where peat overlies till. The seepage rate at 908 is exceptionally high and is a result of the high permeability measured in the deep peat piezometer. The high value of downward seepage is most probably associated with a subsurface crack as peat in its natural state would not transmit water, vertically, so quickly .A very high seepage rate (2 mm/day) is also recorded at tL12. High seepage rates of 0.42 and 0.75 mm/ day are recorded at 910 and 912 respectively and a relatively low seepage rate of 0.02 mm/ day is recorded at 909.

However, the piezometer nests analysed are located in areas where the ground level has subsided (Chapter 7) and suspected water losses to the regional groundwater table area occurring; as indicated by hydrograph analysis and hydrogeological cross-section examination (Chapter 8). The high downward seepage rates are most probably localised. The seepage rate at 908 and tL12 are not realistic – the approach using a simple Darcian velocity equation does not appear adequate in this case and water balance computation in Chapter 8 will provide more realistic values of areal downward seepage.

5.8.3.Horizontal flow in till aquifer using Darcy equation

The downward seepage rates (or infiltration/ recharge rate) can further used to estimate horizontal flow in the till aquifer beneath the high bog using equation 5.4, which is essentially Darcy's Law applied to a streamline as illustrated in figure 5.20:

$$q_h = T_a \frac{\Delta h}{L} \qquad \text{Equation 5.4}$$

where $q_h$ is the horizontal flow rate ($m^2$/ day), $T_a$ is transmissivity ($m^2$/ day), $\Delta h$ is the difference in hydraulic head between piezometric head in mineral subsoil near the catchment boundary ($h_1$) and piezometric head in mineral subsoil in cutaway ($h_2$) and $L$ is the distance between measured piezometric heads on the flow line (m).

Recharge ($m^2$/ day) to the till aquifer can be calculated by using the downward seepage rate and applying it to a flow line of known length $L$ and a given width, e.g. 1 m.

$$Recharge = q_{dw} * L * 1 \qquad \text{Equation 5.5}$$

Equation 5.5 can be rearranged to find transmissivity and the horizontal flow rate $q_h$ can be found by dividing transmissivity by the estimated aquifer thickness. Table 4.8 lists calculations and estimated horizontal flow rates (or horizontal hydraulic conductivity, $k_h$ [m/ day]) for flow lines 908 – 915, tL12 – 912 and 910 – 920.

Table 5.8. Estimated horizontal flow rates through till aquifer along selected flow lines (Figure 5.22)

| | **908 - 915** | **t12 - 909 - 912** | **910 - 920** | *unit* |
|---|---|---|---|---|
| **Recharge** | 0.27 | 0.40 | 0.15 | $m^2/d$ |
| **L** | 357 | 400 | 344 | m |
| **dh** | 4.65 | 3.13 | 3.64 | m |
| **$T_a$** | 20.81 | 51.16 | 13.81 | $m^2/d$ |
| **T** | 3.50 | 4.00 | 3.50 | m |
| **$k_h$** | 5.95 | 12.79 | 3.94 | m/day |

Note. Downward seepage measured at 912 used in 908 – 915 flowline, average of 909 and 912 downward seepage rate used in tL12 to 912 flowline and 910 downward seepage rate used in 910 – 920 flowline.

Measured till permeability indicates that the hydraulic conductivity range of the till subsoil beneath the high bog is between 2 and 22 m/ day (Table 5.7). The results in Table 5.8 are similar to that measured in the field, with horizontal permeability ranging between 4 and 13 m/ day. The horizontal flow rates are controlled by the downward seepage rates from the peat through to the till aquifer, meaning the vertical hydraulic conductivity of peat is important to measure accurately - controls the horizontal flow rate value.

5.8.4.Horizontal flow in till aquifer using Dupuit equation

An alternative method to calculate the groundwater flow rate in the till aquifer is to use the Dupuit equation:

$$q_h = \frac{1}{2}k\left(\frac{h_1^2 - h_2^2}{L}\right) + w(x - \frac{L}{2}) \qquad 5.6$$

where $q_h$ is groundwater horizontal flow per unit width ($m^2$/day), $k$ is till hydraulic conductivity (m/day), $h_1$ is hydraulic head at the beginning of the streamline, $h_s$ is hydraulic head at the end of the streamline, $L$ is the length of the streamline (m), $x$ is the distance from the origin or catchment divide (m) and $w$ is the recharge rate (m/day).

The Dupuit equation is normally applied to unconfined aquifers. The till unit is not a true unconfined aquifer, but rather it may be considered to be a semi-confined/ leaky aquifer where till is overlain directly by peat, which, slowly, recharges the till groundwater body. However, the equation may still be applied to the streamlines on Figure 5.22. Using measured $k$ values from subsoil piezometers 908, 909 and 910, flow rates are calculated and presented in Table 5.9.

The Dupuit flow rates are controlled by the till hydraulic conductivity values used in the calculation. The groundwater flow rates in Table 4.9 are lower, overall, that the transmissivity values in table 4.7. This is due to the value of hydraulic conductivity applied to the downward seepage calculation.

The presented calculations serve as a prelude to recharge calculation from the Clara West hydraulic flow measurements structures and numerical model design and calibration. However, the Dupuit flow rates appear to be reasonable, varying between c. 2 and 13 $m^2$/day along flow lines where till underlies peat and where groundwater discharges to the peripheral drains that mark the boundary of the high bog.

Table 5.9. Groundwater flow rates using Dupuit equation

| | **908 - 915** | **t12 - 909 - 912** | **910 - 920** | *unit* |
|---|---|---|---|---|
| ***k*** | 14 | 22 | 2 | m/ day |
| ***h1*** | 56.49 | 56.33 | 54.35 | m |
| ***h2*** | 51.84 | 53.2 | 50.72 | m |
| ***L*** | 357 | 400 | 344 | m |
| ***w*** | 0.017 | 0.002 | 0.0004 | m/ day |
| **Dupuit:** | 12.87 | 9.87 | 1.18 | $m^2$/d |

Note. $k$ value used from field measurement made at 908*, 909' and 910^.

### 5.9. Conclusions

Hydrograph analysis indicate that groundwater fluctuations are greatest where till is most permeable and is recharged quickly. Piezometer nests 908 and 910 on the high bog indicate that water level in

peat is connected to the water level in till – implying water is being lost to the regional groundwater table. Hydrograph analysis from piezometer nests in the marginal drains installed adjacent to the high bog indicates the drains are consistently recharged by groundwater as hydraulic gradients are almost wholly upwards. Water loss from peat on high bog is due to two main drainage mechanisms: (1) where the sand lense is inducing a drawdown of the potentiometric surface in deep peat in the high bog and (2) where peat overlies till and peripheral drainage has created a hydraulic connection, a drawdown of the regional groundwater table is induced.

The hydraulic conductivity of peat that overlies till subsoil varies between $10^{-1}$ to $10^{-5}$ m/ day. Comparison of hydraulic conductivity measurements from deep peat in 1991 and 2010 indicate that there are areas where hydraulic conductivity has decreased, meaning the peat has compacted and the organic matter content in the peat interval has increased, and that there are areas where hydraulic conductivity has increased, meaning subsurface cracking in the peat profile has formed preferential pathways for water flow, thereby creating a form of macro-porosity in the subsurface, leading to unusually high peat hydraulic conductivity values.

Downward seepage calculations indicate infiltration rate from peat to till beneath the high bog varies between 0.02 and 17 mm/day - where there is a hydraulic connection between peat and till. Darcian flux calculations estimate the horizontal flow rate through the till aquifer to vary between 4 and 13 m/day, similar to field measured hydraulic conductivity values in the till subsoil, while Dupuit calculations estimate groundwater flow rate through the till aquifer, beneath the bog surface, per unit width, to vary between 2 and 11 $m^2$/ day. The flux calculations provide the basis on which to develop the conceptual model for the bogs subsurface drainage system and as estimate for hydraulic input parameters into a numerical model for the Clara West groundwater system.

# 6. Groundwater-Surface-Water Interaction

## 6.1. Introduction and objectives

In Chapter 4 the Clara West drainage system was described and site investigations found that marginal drains, south and southeast of the high bog, have been cut below the regional groundwater table hosted in the till groundwater body. The potentiometric surface maps for hydraulic head in the till subsoil were discussed in Chapter 5 and the potentiometric surface contours show that the drains are 'gaining' drains – i.e. the drains are receiving groundwater. Such an inference is based on the inflexion in contour lines as they approach a groundwater-fed drain – i.e. the water table is at a lower elevation upstream either side of the contour line; the contour line points upstream as it crosses the drain (s). Cross-sections through the drainage system in Section 4.2 demonstrate that the base of the drains is located between c. 0.5 and 1.0 m below the regional groundwater table. The drains have effectively created a depression in the regional groundwater table and this is most prevalent in the area of cutover bog referred to as the Restoration Area.

The interaction between the bog and regional groundwater system is a complex one. Geo-hydrological analysis (Chapter 5) has demonstrated that the drains in the Clara West drainage system are groundwater-fed and are therefore considered to be zones for groundwater discharge. This amounts to a groundwater-surface water interaction. To investigate the nature of this interaction hydro-chemical and stable isotope techniques were employed so to:

1) Separate out groundwater types in the drains based on their source and hydrological history
2) Identify ones of groundwater recharge and discharge from till and limestone and;
3) Quantify the quantity of groundwater discharging into the drains by the application of a hydrochemical mixing model

## 6.2. Stage and groundwater level connectivity

In Section 4.2 the characteristics of the Clara drainage system was described and it was found that face-bank drains east of the groundwater catchment divide were cut below the regional groundwater table. Figure 4.7, Section 4.2, demonstrated this by means of a simple electrical conductivity survey – elevated electrical conductivity values, in the order of 400 µS/ cm, were found along much of the face-bank stretch bordering the high bog, indicating upward movement of groundwater and subsequent discharge. Hydraulic gradients from piezometer nests bordering the high bog were described in Section 5.4, and upward gradients of water were found at piezometer nests 906 and 914/ 915 – confirming that groundwater, from underlying till subsoil and possibly limestone discharges into the drain when an outlet exists due to the absence of a confining layer, or pressure/ weight, to counteract the upward pressure gradient.

As such, hydrograph analysis of water levels in the flumes and weirs (Section 4.2) should demonstrate a hydraulic connection with piezometric levels measured in the till groundwater body. Appendix D,

figures D1 to D6, contains hydrographs, over the water balance period discussed in Chapter 9, that compare water level (stage) in the surface water structures to groundwater level in piezometers installed to the base of till subsoil. The comparisons avail of continuous water level recordings – OTT Orpheus Mini data loggers that record water level in the instrumented flow structures (Section 4.2) and Diver groundwater level data loggers in instrumented subsoil piezometers (Section 3.3).

The hydrographs in Figures D1 to D6 are remarkably similar. In figure D1, and Figure 6.1 below, stage (malin MOD) in the Restoration Area Flume is plotted against groundwater level (malin MOD), or hydraulic head, in piezometer 920, which is located c. 200 m northwest of the flume in the Restoration Area. Water levels rise and descend in tandem with each other. As the water level rises in the piezometer, due to recharge, so too does the water level in the drain. However, the drain will receive overland flows, so this may be expected. However, as the water level recedes in piezometer 920, so too does water level in the drain. The water level recession in the drain hydrograph is quick, whereas there is a lag in the groundwater level in the piezometer and this is a result of the slow release of water from storage in the subsoil body. Overland flow in during storm events quickly leaves the drain system and the decreasing water level in the drain is effectively that of groundwater – base flow recession curve.

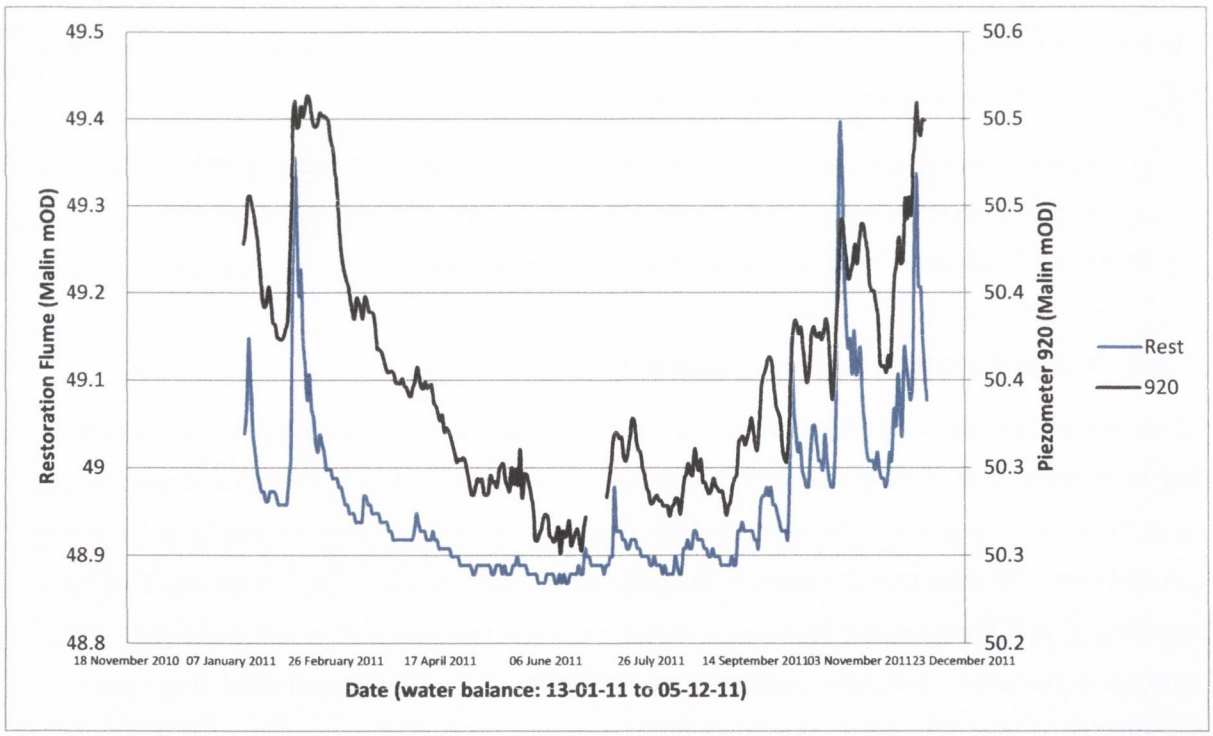


**Figure 6.1.** Restoration Area Flume: Stage level in drain and groundwater level in till subsoil piezometer 920 in cutover bog (water balance period)

Figure D2 plots the Restoration Flume hydrograph with a hydrograph from groundwater level measured in till at piezometer 910 on the high bog. The same observations can be repeated – the water levels move in tandem and water is released slowly from storage in the till body beneath the high bog.

However, it is noteworthy that the level of fluctuation in piezometer 910 (0.55 m) is twice that of 920 (0.25 m) and similar to that in the Restoration Flume (0.53 m). The inference is that 910 is recharged more quickly than 920, which is overlain by lacustrine clay and is in a 'groundwater basin' (section 5.3), and that groundwater discharge to the Restoration Flume is equally as rapid.

Table 6.1. Fluctuation in water level in surface water and groundwater (water balance period; see Chapter 9)

| SW | Range | Period | GW | Range | Period |
|---|---|---|---|---|---|
| **FB2** | 0.47 | 1-6-11 to 5-12-11 | **910** | 0.52 | 1-6-11 to 5-12-11 |
| **Rest** | 0.53 | 13-1-11 to 5-12-11 | **910** | 0.55 | 13-1-11 to 5-12-11 |
| **EPA** | 0.25 | 11-11-11 to 18-1-12 | **915** | 0.38 | 1-6-11 to 5-12-11 |
| | | | **920** | 0.26 | 13-1-11 to 5-12-11 |

Similar to the Restoration Flume, Figures D3 and D4 plot the hydrograph measured at the EPA Weir against groundwater level from subsoil piezometers 920 and 910. The same observations made for the Restoration Flume analysis can be applied to the EPA Weir. In section 4.2 it was noted that drain TD1 is dry in the summer months but in wet periods, when the regional groundwater table rises, the drain discharges to drain TD2, which hosts the EPA Weir. The groundwater level is observed to rise rapidly, contributing flow in a piston-flow type fashion, indicating how quickly groundwater flow can recharge the drains when there is an adequate connection. The inference is that groundwater level rise in the till groundwater body is a measure of how quickly groundwater flow to the drains will be – and this is shown in the hydrographs.

Figures D5 and D6 plot the hydrograph measured at the FB2 Flume against groundwater level from subsoil piezometers 915 and 910, over a shorter time period, between June and December 2011. The same inference made for the Restoration Flume and the EPA Weir can be applied to the FB2 Flume. The hydrographs from 910 and 915, which is located close to the FB2 Drain < 50 m north of the flume, ascend and descend in tandem with water level in the flume. The range in fluctuations is similar, though water level fluctuation in a drain is a function of its geometry.

### 6.3. Groundwater level connectivity in till and peat

In Chapter 5, hydrograph analysis of piezometer nests on high bog, cutover bog and in face-bank drains was described. It was noted, from manual water level monitoring, that there appeared to be a strong connection between water level in till subsoil and basal peat at piezometer nest 910. Simple seepage flux calculations indicate this area is a zone of regional groundwater table recharge (Section 5.8).

Figure 6.2 illustrates a hydrograph of groundwater level in till and deep peat at piezometer nest 910. It can be observed that groundwater level rises and falls in deep peat and till are near-coincident with

each other and both water levels respond quickly to heavy rainfall events and dry-periods. The deep peat hydrograph is flashy in appearance and water level fluctuations, within c. 0.59 m, are greater than in the till subsoil body, which are within c. 0.46 m. The reasons for the fluctuation difference is that water is infiltrating quickly through the peat profile at piezometer nest 910, which is unsurprising considering it location beside the Western Mound, due to the occurrence of subsurface cracks in the peat body – i.e. drainage pathway for infiltration. Recharge to the till body is not as quick as infiltration through the peat body, due to the presence of an upper till unit which is more clay rich than the lower clay unit, which is far more permeable (Section 3.2) – i.e. there is a steady rate of recharge to till whereas the presence of cracks gives the peat substrate hydrograph an appearance that suggests it is a permeable lithology; in reality the cracks are a form of macro-pore porosity.

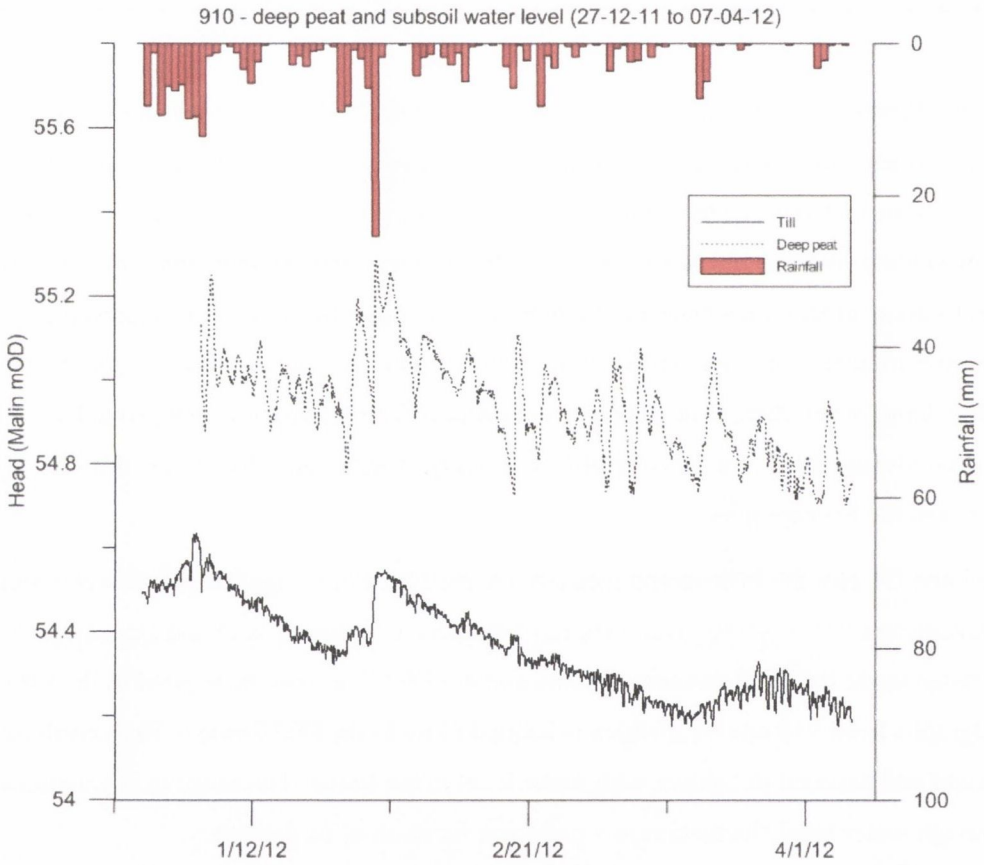


**Figure 6.2.** Groundwater level in till and deep peat at piezometer nest 910 (27-12-11 to 07-04-12)

Figure 6.3 illustrates the relationship between groundwater level in till at piezometer 910 and deep peat groundwater level at face-bank drain piezometer 914 (see streamlines in Figure 5.20). Similar to Figure 6.2, the deep peat groundwater hydrograph is flashy in appearance. However, 914 is located by a groundwater discharge drain, FB2, and the hydrograph illustrates a clear relationship between groundwater level in till beneath the high bog and groundwater level in peat at drain FB2, again substantiating the inferences made in Chapter 5, that water level in the marginal drains is hydraulically connected to piezometric level in till beneath the high bog.

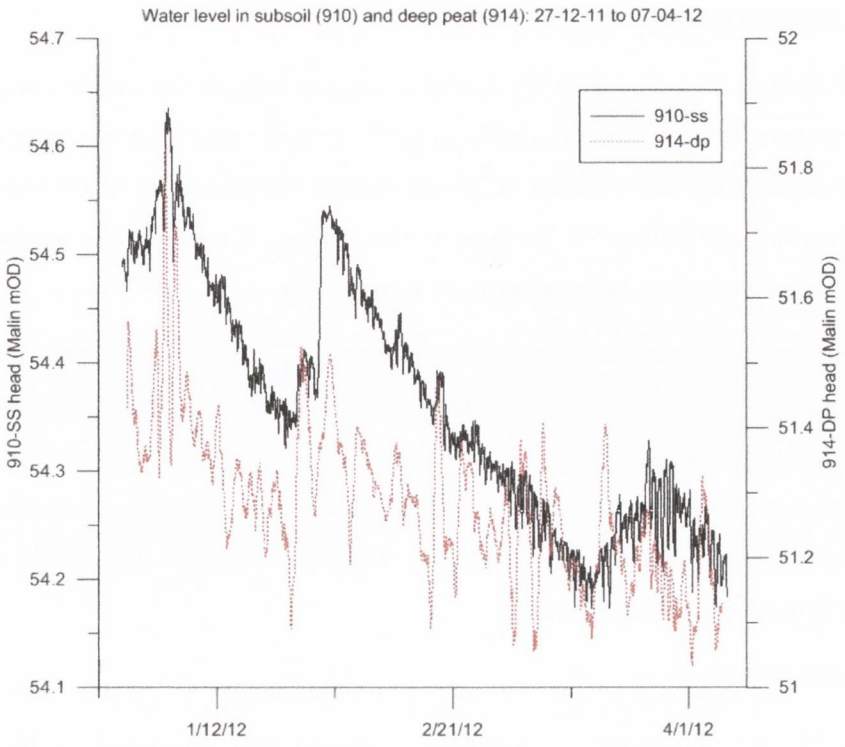


**Figure 6.3.** Groundwater level in till (910) and deep peat (914) (27-12-11 to 07-04-12)

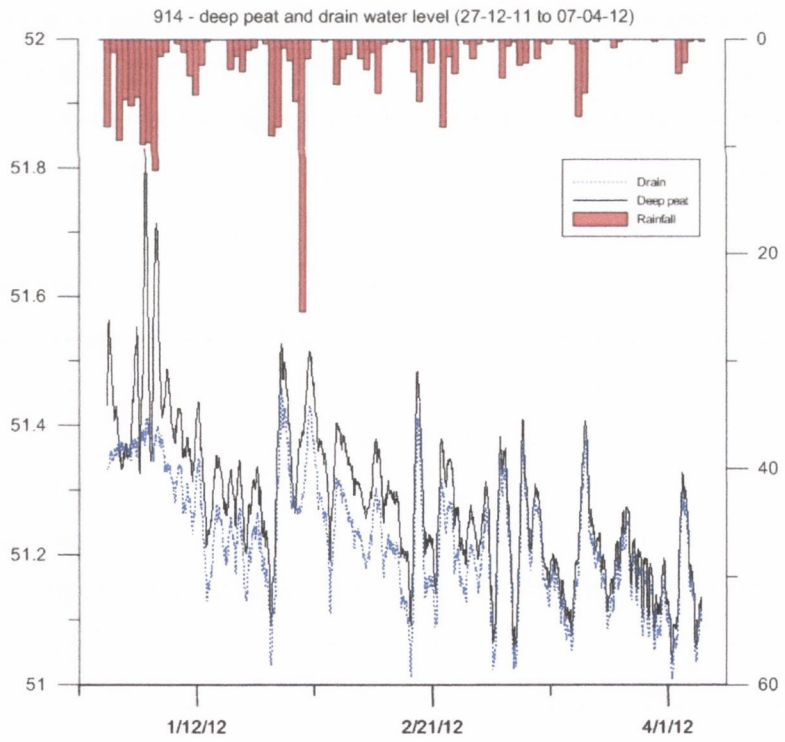


**Figure 6.4.** Groundwater level in deep peat and phreatic water level at piezometer nest 914 (27-12-11 to 07-04-12)

Figure 6.3 displays the hydrographs of deep peat piezometric level and surface water level in drain FB2 at piezometer nest location 914. It can be observed that during the hydrograph period, the movement of groundwater is almost wholly upward – i.e. there is an upward hydraulic gradient. This is consistent with the analysis described in Sections 4.2 and 5.4.

## 6.4. Hydrochemical relationships

The hydrograph analysis from the Clara West marginal drains indicate, by simple visual observation, a hydraulic connection between groundwater level in till subsoil, under high bog and cutover bog, and surface water level in the drains – as inferred, on the ground, from the drain surveys in Section 4.2 and hydrograph analysis in Section 5.3. To quantify this linkage, in terms of a groundwater flow rate to the drains, or recharge, hydro-chemical analysis is necessary.

Water that travels through geological materials such as peat and glacial till will have different chemical characteristics to surface water that enters the drains via overland flow from the high bog, surrounding cutover bog and agricultural land. Mineral groundwater is chemically distinct to water that does not percolate into an aquifer and, instead, travels almost directly to a connecting stream or drain. Hydrochemical analysis of the major ions may therefore be used to characterise the differing water types in a hydrogeological system.

## 6.5. Hydrochemical tracers

Cations (such as calcium, magnesium, sodium and potassium) and anions (such as chloride, bicarbonate and sulfate) may be used as chemical tracers to determine groundwater input to a drain/ stream during high flow and low flow periods. On this basis, water samples from differing water types were analysed from the Clara Bog West hydrologic system. Major ion chemical analysis may be used to identify solutes (i.e. a chemical element dissolved in water) present in water samples that may conveniently be used to indicate water source types in the marginal drains.

Solutes that are present in groundwater are derived from two main sources: (i) input from rainfall and (ii) acquisition during weathering and water-rock/subsoil interactions. A number of processes will affect the hydrochemical characteristics of a water molecule (e.g. acid-base reactions, precipitation and dissolution of minerals, sorption and ion exchange) and hydrochemistry may then be interpreted to understand the key processes that have occurred during the movement of water through aquifers and surface water bodies. The concentration of a solute will invariably increase the longer it is in the groundwater system due to contact with the surrounding geological materials and its longer residence time (i.e. the period between recharge and discharge of groundwater from an aquifer). Solutes will have a chemical concentration that is reflective of their relative residence times and are therefore effective environmental chemical tracers.

### 6.5.1. Measurement and results

Table 6.2 lists the major/ trace elements and nutrients tested in the hydrochemical investigation and their method of analysis. Chemical analysis were performed in the Trinity College civil engineering laboratory using a combination of (i) chemical reagents test kits developed for Hach Lange and Nova photometers and (ii) using an inductively coupled plasma atomic emission spectrometer (ICP-AES).

Table 6.2. Element and nutrient analysis methods

| Element | Symbol | Test Method |
|---|---|---|
| Calcium | $Ca^{2+}$ | ICP-AES & Nova |
| Magnesium | $Mg^{2+}$ | ICP-AES |
| Sodium | $Na^{+}$ | ICP-AES |
| Potassium | $K^{+}$ | Hach |
| Strontium | $Sr^{2+}$ | ICP-AES |
| Chloride | $Cl^{-}$ | Nova |
| Fluoride | $Fl^{-}$ | Nova |
| Sulphate | $SO_4^{2-}$ | Hach |
| Total Alkalinity | $CaCO_3$ | Lovibond test kit |
| Silicon | $SiO_2$ | Nova |
| Nitrate | $NO_3^{-}$ | Nova |
| Total Phosphorus | P | Nova |

The purpose of the analysis was to identify chemical solutes with distinctive concentrations for differing 'water types' – i.e. identifying solutes with distinctive end-member value concentrations allowing water sources to be identified so they could be applied to a hydro-chemical mixing model to separate particular flow components (Section 6.9). As such, following an initial period of water sampling and chemical testing, solutes of most practical use were identified and subsequent investigation focused on the chemical parameters that provided the most useful information on the Clara West hydrological systems relative groundwater – surface water interactions at low and high flows.

The analysis indicated that Calcium ($Ca^{2+}$), Silica ($SiO_2$) and Strontium ($Sr^{2+}$) were the most useful chemical tracers of groundwater discharge into the marginal drains. Concentrations of the aforementioned elements are far higher, by up to two orders of magnitude, in mineral groundwater (till and bedrock) than in surface water bodies where it is known there is no groundwater influence (e.g. bog lakes). The marginal drains with a groundwater component should by inference display tracer concentrations that are elevated above water bodies where their concentrations are minimal. The analysis shows this to be the case and the results of the analysis are presented in tables D1 to D16; appendix D.

### 6.5.2. Water types and hydrochemical concentrations

Chemical analysis of water samples from till, peat and surface water bodies indicates that each water body has a distinct chemical signature. Table 6.3 summarises the average concentrations of $Ca^{2+}$, $SiO_2$ and $Sr^{2+}$, and additionally stable oxygen isotope 18 (Section 6.7) measured from different water types, which have been differentiated into: (1) groundwater in till subsoil and bedrock under high bog and cutover bog, (2) peat water in high bog and cutover bog and (3) surface water bodies in low flow, high

flow and in areas where there is no groundwater discharge to drains and areas where the regional groundwater table is 'perched' within the drain (Section 5.4).

Table 6.3. Average calcium, silica, strontium and stable oxygen 18 values for differing water types in the Clara West hydrogeological system

| | | Groundwater | | Peat water | | Runoff | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *unit* | **HB** | **CB** | **HB** | **CB** | **Dr-GW** | **Dr-SW** | **Dr-LF** | **Dr-HF** | **Sand** |
| **Ca** | **mg/ l** | 97 | 111 | 9 | 53 | 98 | 3 | 90 | 18 | 50 |
| **$SiO_2$** | **mg/ l** | 3.62 | 4.45 | 0.71 | 3.95 | 3.11 | 0.56 | 3.42 | 0.71 | 1.77 |
| **Sr** | **µg/ l** | 152 | 162 | 15 | 92 | 148 | 10 | 132 | 30 | 99 |
| **$\delta^{18}O$** | **‰** | -5.49 | -5.83 | -6.02 | -6.86 | -5.31 | -4.98 | -6.00 | -4.97 | -5.26 |

Note: HB is high bog, CB is cutover bog, Dr-GW is a drain groundwater fed almost exclusively by groundwater, Dr-SW is a drain fed wholly by meteoric water, Dr-LF is groundwater-fed drain at low flow and Dr-HF is groundwater-fed at high flow.

*Chemical concentrations*

The sampling points and areal distribution of $Ca^{2+}$, $SiO_2$ and $Sr^{2+}$ concentrations are illustrated in figures D8, D9 and D10 in appendix D respectively and it is clear from table 6.3 and the plots in appendix D that there is a distinct chemical separation between groundwater bodies and surface water bodies without a groundwater input. $Ca^{2+}$ concentrations for groundwater in till range between 70 and 115 mg/ L underneath the high bog and between 70 and 150 mg/ l under cutover bog. $SiO_2$ concentrations for groundwater in till range between 1.30 and 6.45 mg/ l underneath the high bog and between 1.7 and 7.1 mg/ l under cutover bog. $Sr^{2+}$ concentrations for groundwater in till range between 0.105 and 0.184 mg/ l underneath the high bog and between 0.101 and 0.305 mg/ l under cutover bog. Highest concentrations are found in cutover bog and this is most probably a consequence of longer residence times of groundwater flow.

Concentrations of peat water are markedly lower than those in mineral groundwater. $Ca^{2+}$ concentrations for high bog peat range between 1.3 and 33 mg/ L and between 20 and 77 mg/ L in cutover peat. $SiO_2$ concentrations for high bog peat range between < 0.21 and 2.6 mg/ L and between 2.0 and 5.6 mg/ l in cutover peat. $SiO_2$ concentrations for high bog peat range between 0.003 and 0.048 mg/ l and between 0.076 and 0.19 mg/ l in cutover peat. Concentrations are low in the high bog and markedly higher in cutover bog and this is the result of groundwater upwelling – the Restoration Area is a zone of groundwater discharge (Section 4.2).

The concentrations measured from the till and peat water bodies allow an assessment of their respective flows to the marginal drains. In areas where drains have no groundwater influence, such as face-bank drains not cut below he regional groundwater table and the main bog drain, concentrations for all elements are very low that there is no contribution from groundwater detectable. Drains, such

as FB1 (piezometer nest 918) and CT3 (piezometer nest 923) (section 5.3), which are wholly groundwater fed and receive little meteoric water, have concentrations similar to that measured in till. These two sets of drains are essentially representative end-members for identifying periods when drains, that are fed by surface water and groundwater, are mostly surface water fed or groundwater-fed – i.e. hydrograph separation (section 6.9).

Chemical concentrations at low flow in drains FB2 (FB2 Flume), TD2 (EPA Weir) and the Restoration Area drain (Restoration Area Flume) are similar to those found in the wholly groundwater-fed drains and chemical concentrations at high flow are similar to that of surface water drains without a groundwater flow component. However, at high flow, chemical concentrations are never quite as low as surface water drains with a groundwater flow component, implying the drains are constantly receiving contributions from subsurface flow.

*Chemical plots*

Figures D13, D14 and D15, appendix D, plots $Sr^{2+}$ versus $Ca^{2+}$, $Sr^{2+}$ versus $SiO_2$, and $SiO_2$ versus $Ca^{2+}$ respectively for the various water 'types' listed in table 6.3. In each plot there is a clear distinction between waters from high bog peat, high flow in the marginal drains and from surface water drains without a groundwater input. Waters from cutover bog and predominantly groundwater fed drains plot in between mineral groundwater in till and the predominantly meteoric surface water types; though concentrations are elevated, particularly with regards $Sr^{2+}$ and $SiO_2$. The chemical concentrations of groundwater under the cutover bog are more variable than those under the high bog, and are possibly reflective of variable flow lengths from different areas of the groundwater catchment – groundwater collects in this area. Chemical concentrations at low flow in the marginal drains plot within the lower bounds of the groundwater chemical ranges – the concentrations at low flow are high; similar to that encountered in the till groundwater body.

In figures D13, D14 and D15 it can be observed that the strongest relationship is between $Sr^{2+}$ and $SiO_2$. The less consistent plots with $Ca^{2+}$ may be the result of a moderately elevated $Ca^{2+}$ background concentration in the peat substrate itself – which is not unexpected considering fen peat generally sits beneath *Sphagnum* peat in the peat profile. As the cutover area is close to the old bog basin, indicated by the presence of marl substrate in the area (Chapter 3) fen peat will be prevalent. Fen peat is typically more mineral rich than *Sphagnum* peat and will have, in particular, elevated $Ca^{2+}$ concentrations as a consequence of peat developing in mineral-water saturated conditions. Though the permeability of peat is very low, when it is drained it dries and often cracks, resulting in what is effectively a karstified effect on the peat structure, producing peat pipes and channels (Section 4.2). Such structures allow an additional pathway for subsurface water movement and may increase the concentration of solutes such as $Ca^{2+}$, as water passes through fen peat. The fact $Sr^{2+}$ and $SiO_2$ produces the strongest chemical relationship is possibly a result of $Sr^{2+}$ and $SiO_2$being less soluble

than $Ca^{2+}$ - i.e. $Ca^{2+}$ dissolves quicker in water than either $Sr^{2+}$ and $SiO_2$, reflecting its groundwater residence time.

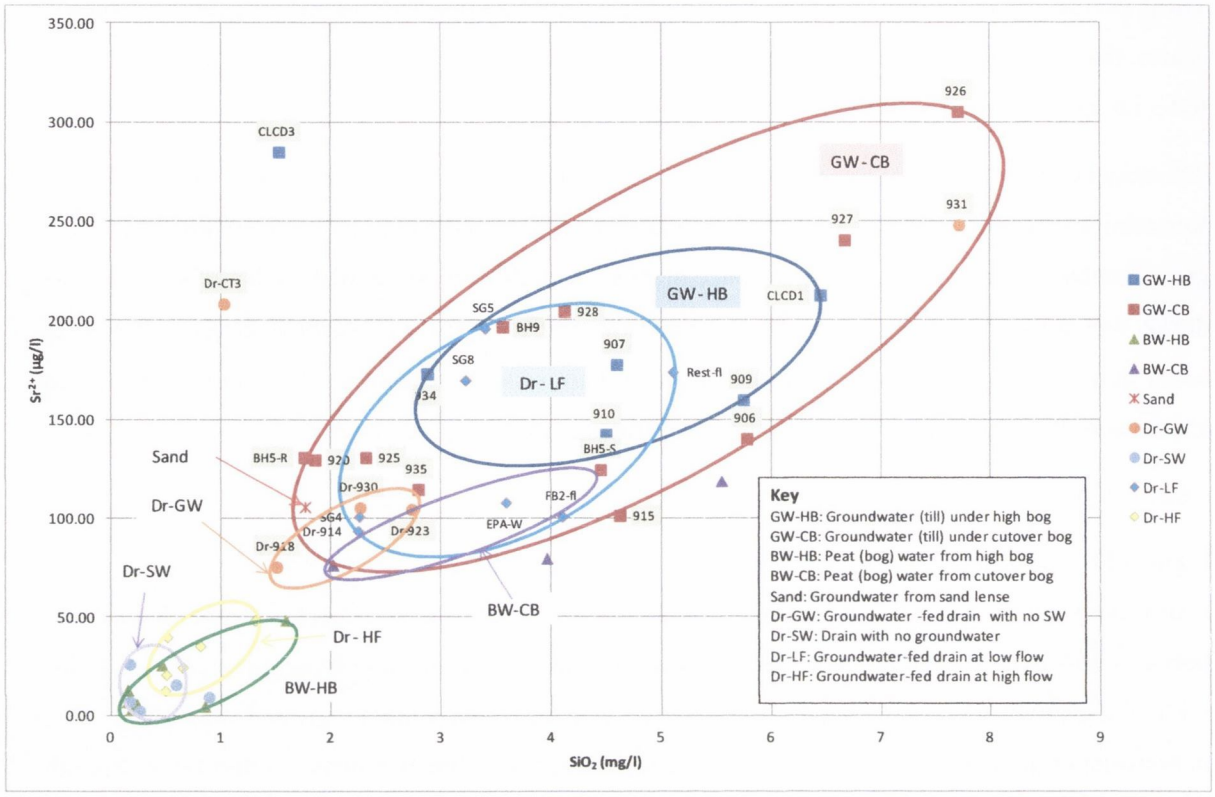


**Figure 6.5**. Strontium (Sr2+) and Silica (SiO2) water source analysis

## 6.6. Discharge and hydrochemistry

The low flow chemical concentrations measured at the FB2 Flume, Restoration Area Flume and EPA Weir indicates that the drains are receiving a significant volume of groundwater. Water samples were therefore analysed for $Ca^{2+}$, $SiO_2$ and $Sr^{2+}$ at a range of low and high flows to ascertain whether a relationship between flow rate (Section 4.2.4) and hydrochemistry could be used so separate out flow components based on the water chemistry.

Chemographs in figures D17 to D21, appendix D, plot electrical conductivity, $Ca^{2+}$, $SiO_2$ and $Sr^{2+}$ versus flow rate over time respectively. A clear relationship exists between flow rate and the solute concentration - it is found that there is a power law relationship between the solute concentration and flow rate (i.e. $y = a * x^b$), with solute concentration increasing significantly at low flows. This relationship enables the hydrographs from the weir and flume structures, illustrated in appendix B (figures B24 to B29), to be separated into a base flow and meteoric components and is discussed in Section 6.9.

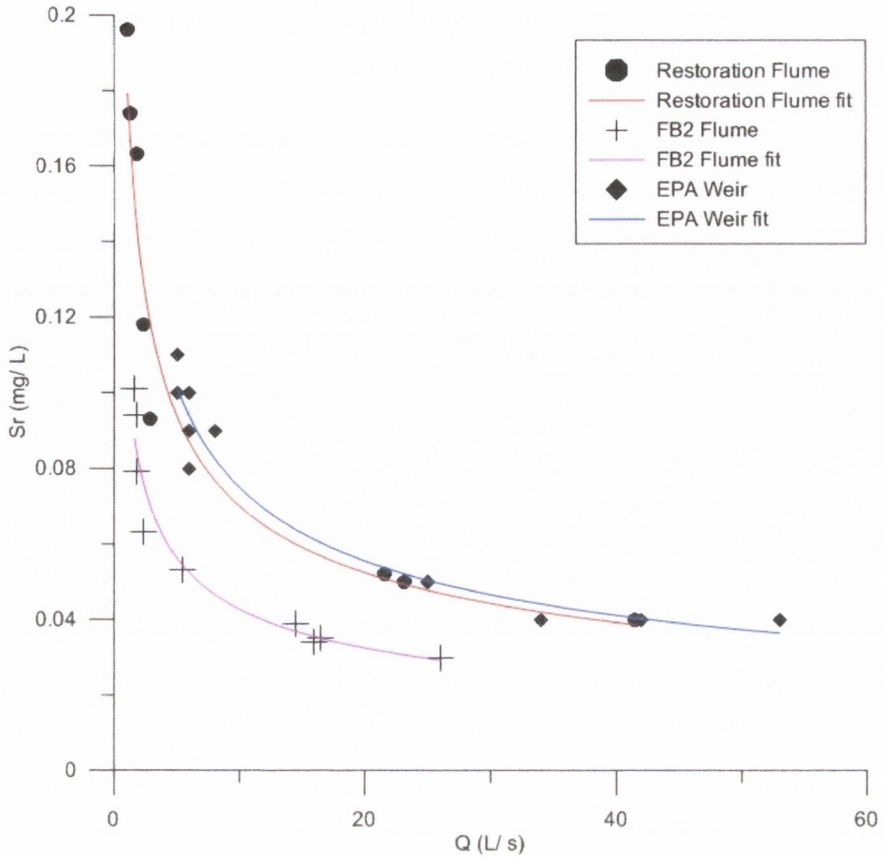


**Figure 6.6.** Strontium (mg/ L) versus flow rate (L/ s) in instrumented groundwater-fed drains

## 6.7. Stable Oxygen Isotopes

In addition to hydrochemical analysis, water samples for differing water types were analysed for stable oxygen isotopes. Isotopes, while related to the chemistry of the water, are utilised differently as their part in the hydrological cycle is not necessarily the same as that of the chemical solute.

### 6.7.1. Background

Isotope hydrology has long been used as a technique to better understand the water cycle (Aggarwal et al, 2005) and its hydrological fluxes. Following World War II radioisotopes were easily available, due to the expansion of the nuclear energy industry, and were used as artificial tracers in groundwaters and surface waters so to better understand their mixing patterns, transit times and transmissivities. However, the injection of radioisotopes into natural water bodies soon became obsolete and research into the use of "environmental isotopes" began.

Initially, tritium, a radioactive isotope, was used as nuclear testing in the 1940's inadvertently introduced tritium into the hydrological/ water cycle (which is present in natural amounts). The tritium excess in the water cycle brought about a new understanding on its dynamics on a global scale, the knowledge from which researchers later used to apply to local hydrologic systems. Thereafter, isotope hydrology, in conjunction with the development of mass spectrometers equipped to measure isotope ratios (McKinney, 1950), as a discipline of hydrological science quickly expanded to include

the use of stable isotopes - most notably hydrogen (H) and oxygen (O) as H and O are principal elements in hydrological, geological and biological systems.

The emphasis on the early stable isotope studies was, amongst others, on understanding the global patterns of precipitation, the linkages between the stratosphere and troposphere, the residence times of waters in different stages of the water cycle, the differences between different climatic areas of the globe and the linkages between climate and stable isotope signatures. Such work was, and has continued to be, carried out by the Isotope Hydrology Section of the International Atomic Energy Agency (IAEA) in Vienna, who has had a station measuring the isotopic content of precipitation in Ireland on Valentia Island since 1957.

### 6.7.2. Measurement and results

Stable environmental isotopes fractionate into separate light and heavy fractions and they are therefore measured as the ratio of the two most abundant isotopes of a given element. In the case of oxygen, it is the ratio of 18O, with a terrestrial abundance of c. 0.204%, to common 16O, which represents c. 99.796% of terrestrial oxygen (Clark & Fritz, 1997). Measurements are referenced to mean ocean water composition due to the pre-dominance of ocean water in the hydrosphere and that, compared to the rest of the hydrological cycle, the isotopic composition of ocean waters remains relatively homogenous. A standard hosted at the IAEA, referred to as the Vienna Standard Mean Ocean Water (VSMOW), is the reference used for all international water sample measurements. Isotopic abundances are reported as $\delta\ ^{18}O$ values, with units expressed in permil (‰) – $\delta\ ^{18}O$ values are extremely low.

There has been remarkably little work carried out in Ireland using stable isotope techniques in hydrological/ hydrogeological studies. A large reason for this is that a suitable, and affordable, laboratory with a mass spectrometer equipped to measure the isotopic ratios of oxygen and hydrogen has not been available. However, The Department of Geology in TCD acquired instrumentation in 2009 to upgrade its mass spectrometer so to enable the measurement of the 18O/16O ratio in water samples, and this instrumentation was used to analyse water samples from Clara.

*Results*

The results of the $\delta\ ^{18}O$ analysis for differing water types are presented in tables D13 to D16, appendix D, and summarised in table 6.3. Distinguishing between different water types based on their $\delta\ ^{18}O$ O signature is not as straight forward as using solute concentration – however relationships do exist.

In the Clara region, the $\delta\ ^{18}O$ value of rainfall is between -4.5 and -4.8 ‰, with the overall average being c. -4.7 ‰ – based on surface runoff from the bog weir during heavy rainfall events. Figure D11

illustrates δ $^{18}O$ values measured from piezometers measuring water level in till subsoil. The δ $^{18}O$ value of groundwater in till ranges between -5.1 and -6.9 ‰ and has an average value of c. -6.2 ‰.

The δ $^{18}O$ value of peat, overlying lacustrine clay/ till ranges between -5.5 and -7.4 ‰ and has an average value of c. -6.4 ‰ - there is a wide variability in the δ $^{18}O$ values of peat. Figure 6.7 illustrates a profile of peat depth versus δ $^{18}O$ and there is a good relationship – the δ $^{18}O$ signature becomes more depleted with depth. Peat water at the surface is enriched due to low evaporative effects (this is most probably highly variable across the bog surface) but it is not clear why peat water becomes depleted at depth – it may be that the rainfall signature has changed over time (δ $^{18}O$ is very sensitive to climatic effects) or that when water fell on the ground, it became depleted through evaporative effects and as it infiltrated downward other process, which are generally temperature dependent, affected the water molecules δ $^{18}O$ signature. The deep peat values may also be associated with the occurrence of fen peat.

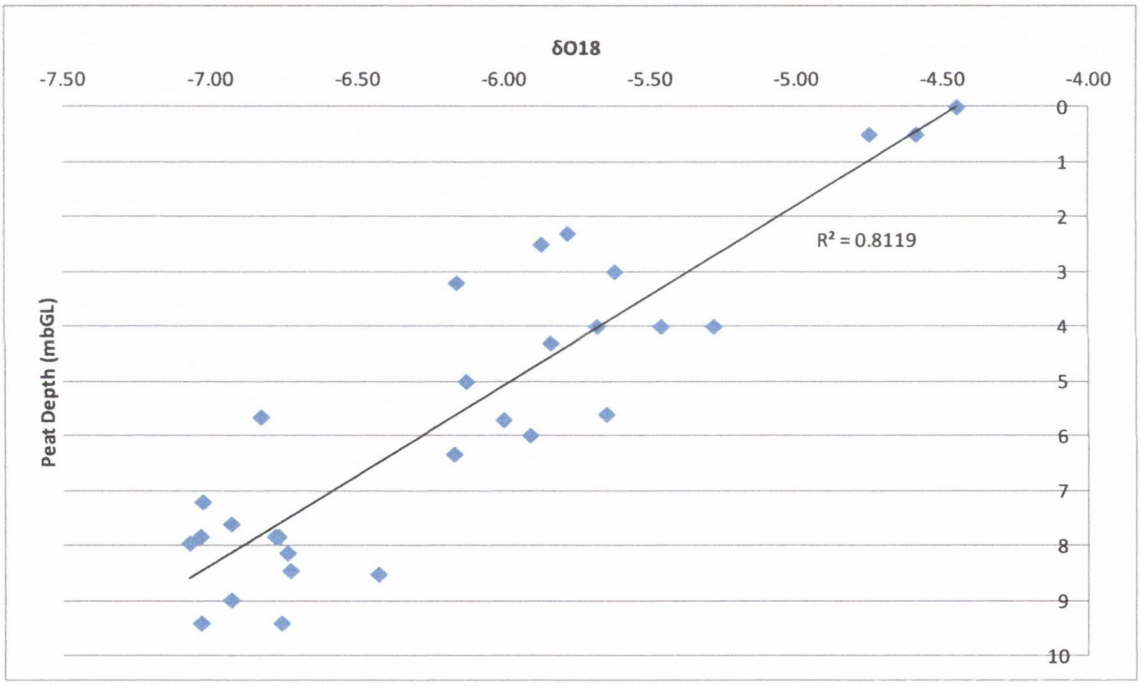


**Figure 6.7.** Peat water δ 18O (‰) versus peat depth

However, in terms of separating flow based on the δ $^{18}O$ signature of water types, there is a distinct difference between meteoric water and shallow groundwater in the till unit - though there are exceptions and this is discussed in Section 6.9. Similar to the observations made from solute analysis, the oxygen isotope signature differs at low and high flows, enabling a chemograph, plotting δ $^{18}O$ against flow rate, to be generated (figure D1).

### 6.8. Identifying zones of discharge from shallow and deep groundwater

Water in an aquifer or groundwater body will have a distinct δ $^{18}O$ isotopic signature. As rain falls on the surface, the water that infiltrates and ultimately recharges the groundwater table will have a

relatively depleted δ $^{18}O$ signature as the water molecule, while exposed on the surface over a sufficiently long time period, will have undergone evaporative processes before it infiltrated downwards. However, if the aquifer is recharged quickly, the water molecule will preserve a signature resembling meteoric water as the water molecule will not have undergone as much evaporation. The water molecule does however undergo fractionation processes, which are temperature dependent, in the groundwater body. Using stable isotopes in a hydrogeological study is therefore only useful if distinct 'water types' can be identified - if the water molecule in a groundwater body is simply a mean average of the precipitation δ $^{18}O$ isotopic signature it is of no real, practical, use.

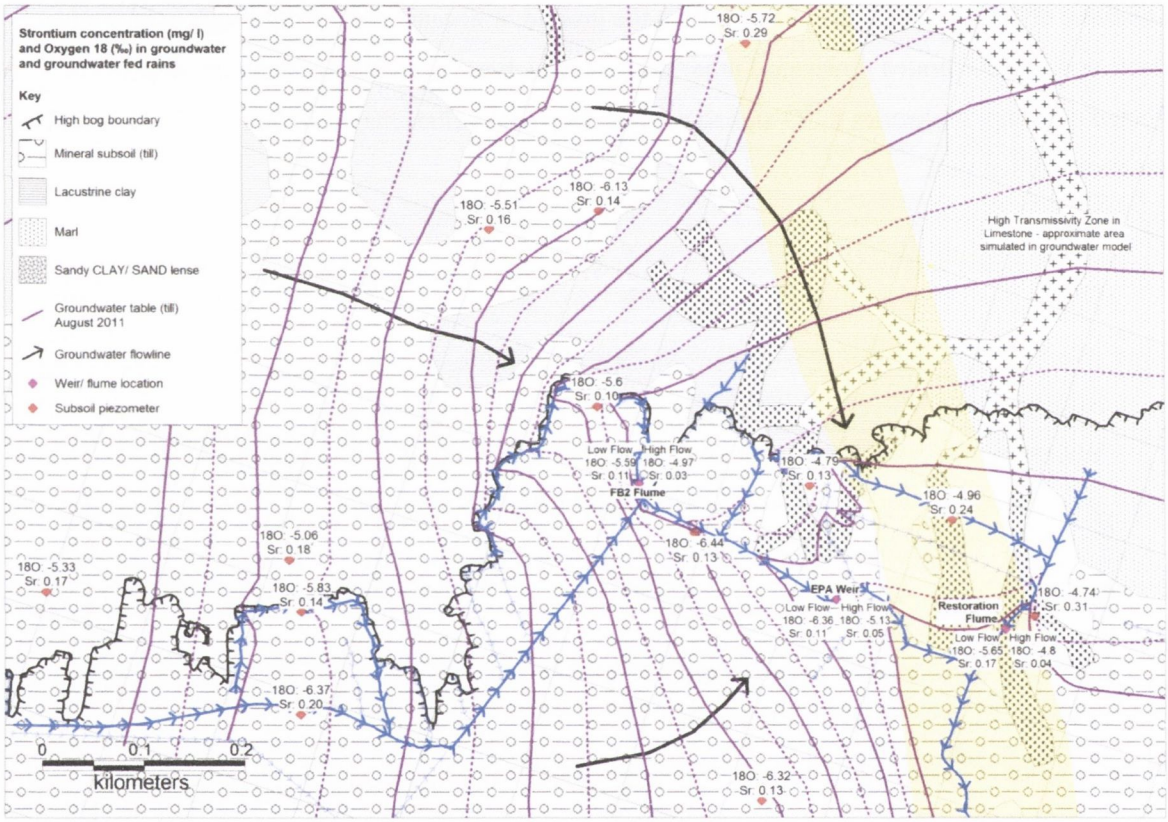


**Figure 6.8.** Strontium concentrations (mg/ l) and δ 18O values (‰) from piezometers and drains in Clara West drainage system

In section 6.7 the range of δ $^{18}O$ values found in groundwater, from till, were presented. The water that recharges the till has undergone evaporative process before, and during, infiltration, giving it a separate δ $^{18}O$ to surface water runoff. However, there are areas where the δ $^{18}O$ signature of shallow groundwater is similar to rainfall, suggesting quick recharge – which is highly unlikely as these particular areas are overlain by a significant thickness of lacustrine clay which has permeability in the order of $10^{-7}$ m/ day.

In figure 6.8 $Sr^{2+}$ concentrations are plotted with δ $^{18}O$ concentrations –both concentration values are from the same water sample. The average $Sr^{2+}$ concentrations in rainfall and overland flow following a storm event have been calculated to be c. 1-3 µg/ l. The average $Sr^{2+}$ concentrations in peat substrate are marginally higher (average: 0.01 mg/ l) and significantly higher in till, with an average

concentration of 0.15 mg/l. However, there are areas where the $Sr^{2+}$ concentration is significantly higher again (between 0.2 and 0.3 mg/l), and these areas coincide with enriched $\delta\ ^{18}O$ signatures. Elevated $Sr^{2+}$ concentrations such as these suggest a limestone provenance – there are artesian pressures in this region, as measured at piezometer 927, and it seems groundwater is moving upwards, periodically, from limestone to till, and this seems to explain the observed $Sr^{2+}$ concentrations.

### 6.9. Baseflow separation

The composition of water in a drain will depend on its origin and hydrological history. Groundwater-surface water mixing models, or hydrograph separation models, are built on the premise that the two main components in the runoff stream – overland flow/ surface water runoff and base flow/ groundwater discharge can be identified using an appropriate tracer.

To construct such models the tracer, which may be artificial or natural, must be chosen so that (1) it is significantly different to water from overland flow in a storm event and (2) it may be assigned to a specific and distinct source. The hydrochemical and stable isotope analysis therefore permits the construction of a hydrochemical separation model – solute concentrations, particularly those of $SiO_2$ and $Sr^{2+}$ distinguish between groundwater, peat/ bog water and surface water and $\delta$ 18O concentrations provide information on the source of the water molecule itself.

#### 6.9.1. Two component hydrochemical mixing model

A hydrochemical mass balance approach has been used to separate baseflow and peat flow from overland flow in the Clara marginal drains. A simple two component mixing model to separate flows can be solved by using the following equation (Clark & Fritz, 1997):

$$Q_t C_t = Q_{gw} C_{gw} + Q_n C_n \qquad \text{Equation 6.1}$$

which can be rearranged to solve for baseflow runoff:

$$Q_{gw} = Q_t\left(\frac{C_t - C_n}{C_{gw} - C_n}\right) \qquad \text{Equation 6.2}$$

where $Q_{gw}$ is groundwater discharge, $Q_t$ is total drain discharge, $C_n$, $C_{gw}$ and $C_t$ are solute concentration for overland flow/ new water, groundwater from till and drain water respectively.

In section 6.5, electrical conductivity, $Ca^{2+}$, $SiO_2$ and $Sr^{2+}$ were identified as conservative tracers (i.e. no chemical reactions) and the chemographs in appendix D plot their relationship with flow rate. Any of the measured chemical solutes or electrical conductivity can be used in equation 6.2, together with calculated flow rates (Q). End-member concentrations were identified in section 6.5 and these serve as the bounding conditions in the model. $SiO_2$ and $Sr^{2+}$ are found to be the most effective hydrochemical tracer, with $Ca^{2+}$ and electrical conductivity seeming to underestimate groundwater flow. Baseflow separations, using $SiO_2$ and $Sr^{2+}$, for runoff measured at the FB2 Flume, EPA Weir

and Restoration Flume have been performed using equation 6.4, the hydrographs of which are presented in appendix D, figures D22 to D24.

The base flow separations were performed over the water balance periods for the flow measurement structures and are discussed further in chapter 9. The percentage runoff that may be attributed to base flow, or groundwater flow from till/ limestone, is c. 17%, 28% and 32% of total runoff in the FB2 Flume, EPA Weir and Restoration Flume respectively. The percentage of groundwater in the drain ranges between c. 5 and 50 %, 10 and 70 %, and 10 and 90 % at the FB2 Flume, EPA Weir and Restoration Flume respectively.

*Base flow and groundwater level*

In section 6.2, stage level in the FB2 Flume, EPA Weir and Restoration Flume were compared with piezometric level in till subsoil and it was observed that that there is a hydraulic continuity between the two water levels. In appendix D, figures D25 to D28, base flow runoff are compared to groundwater level measurements from piezometers installed in till subsoil. Similar to the analysis in section 6.2, as groundwater level rises, so too does the base flow rate, and as groundwater level recedes, the baseflow flow rate descends in tandem.

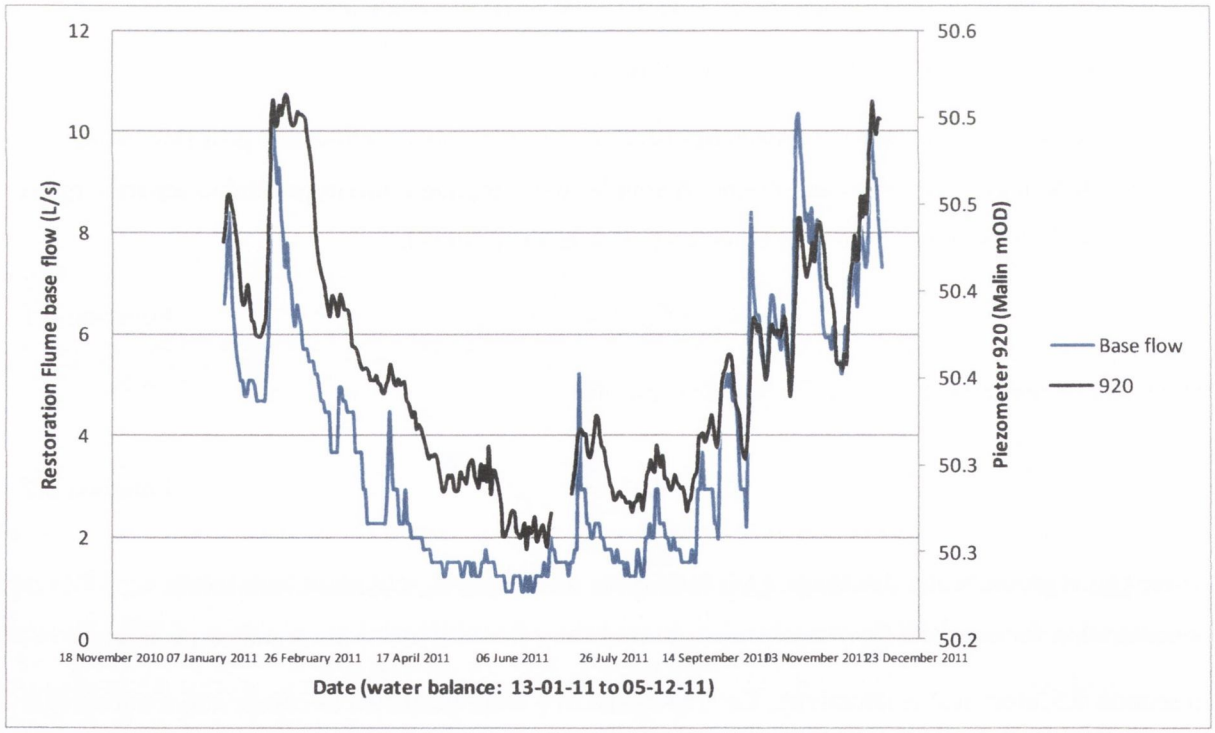


**Figure 6.9.** Restoration Area Flume base flow hydrograph and groundwater level in subsoil piezometer 920 (water balance period: 10-01-11 to 05-12-11)

In section 6.2, it was noted that as the stage level decreased, it do so at a quicker rate than the decrease in groundwater level due to the slower release of water from storage in the groundwater body and the quick release of surface water in high energy flows in the drain. The same effect can be observed in the base-flow rate of decrease in the Restoration Flume – the descending gradients are very similar

indicating that groundwater level and base flow discharge are strongly linked (Figure 6.9). A similar relationship can be inferred at the FB2 Flume – base flow and groundwater level increase and decrease in tandem. The relationship between base flow and groundwater level is slightly different at the EPA Weir – the groundwater level descent is still slower than the rate of base flow and this is mostly probably a result of groundwater quickly recharging the drain from the periodically filled TD1 drain.

*Runoff from peat*

Separating peat runoff from till runoff is difficult because it necessitates a three component hydrograph separation model which requires two conservative tracers (see section 6.9.2). However, if runoff from peat and till is grouped together (chemical concentration of solute in high bog peat is marginally higher than meteoric water; table 6.3), and runoff from till has been calculated, a simple subtraction (i.e. $Q_{peat} = Q_{gw+peat} - Q_{gw}$) provides an estimate on runoff from the peat substrate. However, this may not be reflective of the actual infiltration rate through the peat – water that infiltrates through the peat and into mineral subsoil will, after a sufficiently long period of time, have a chemical signature indicating a mineral groundwater source.

Table 6.4. Runoff from peat and till/ limestone calculated using two component hydrochemical mixing model

| | mm/ day | | |
|---|---|---|---|
| **Runoff** | **Rest** | **FB2** | **EPA** |
| **Peat** | 0.03 | 0.051 | 0.029 |
| **Till/Lst** | 0.335 | 0.241 | 0.316 |

The calculated runoff from peat in table 6.4 may therefore represent 'new' peat water that has 'quickly' recharged the mineral subsoil - the water has discharged into the drain before the solute concentration of the water molecule has had the necessary residence time to increase its solute concentration. The rates compare favourably with subsidence rates that are calculated in chapter 7 – 0.025 to 0.051 mm/ day.

### 6.9.2. Three component hydrochemical-isotope mixing model

Groundwater discharge in marginal drains until this point has been assumed to originate from till subsoil. However, a proportion of groundwater discharge in the Restoration Flume appears to be flow derived from underlying limestone.

*Identification of deep groundwater flow in drainage system*

The electrical conductivity and solute concentrations of solutes such as $Ca^{2+}$ and $Mg^{2+}$ in groundwater, as measured from piezometers screened in till, is relatively constant in the Clara region. However, $Sr^{2+}$ and $SiO_2$ concentrations are markedly higher in the Restoration Area - e.g. the average

$Sr^{2+}$ concentration in till groundwater is 0.15 mg/ l; in till piezometers 926 and 927 $Sr^{2+}$ levels are c. 0.24 and 0.3 mg/ l respectively. Additionally, stable oxygen isotope analysis ($\delta\ ^{18}O$) of groundwater indicates $\delta\ ^{18}O$ values are, on average, between -5.5 and -6.2 ‰, whereas meteoric water is c. -4.5 ‰. The average $\delta\ ^{18}O$ values at till piezometers 926 and 927 are -4.8 and -4.9 ‰ respectively – considerably lower than groundwater from till elsewhere. Figure 6.8 illustrates $Sr^{2+}$ concentrations (mg/ l) and δ 18O values (‰) in this region. Viewing chemographs for the Restoration Flume in appendix D, the plots of flow rate versus $Sr^{2+}$, $SiO_2$ and $\delta\ ^{18}O$ are noticeably different to those from the EPA Weir and the FB2 Flume – the Restoration Area seems to have an additional groundwater flow component from deeper groundwater in limestone bedrock.

It may appear contradictory to have an elevated Sr concentration and an enriched $\delta\ ^{18}O$ signature. However, if groundwater is moving upwards from limestone this is perfectly reasonable. Limestone in the Clara region is massive in structure and groundwater flows in a system of fractures and conduits – it is most probably karstified. The $\delta\ ^{18}O$ signature suggests limestone is recharged very quickly, and this is why $\delta\ ^{18}O$ is enriched – the groundwater itself will have a residence time long enough to account for the observed $Sr^{2+}$ levels. Analysis of waters from piezometers installed to limestone outside the region displayed in figure 6.8 also finds the limestone $\delta\ ^{18}O$ signature to be enriched – particularly adjacent to an esker, located < 1.0 km north of figure 6.8 (CLBH2). Additionally, the areas with enriched $\delta\ ^{18}O$ values and elevated Sr concentrations also coincide with a high limestone transmissivity area (30-120 $m^2$/ day) simulated in the Clara West groundwater model in order to account for low hydraulic heads measured in till screened piezometers in the area.

*Hydrochemical-stable isotope mixing model*

To separate overland flow from shallow groundwater flow in till and deeper groundwater flow in limestone, it is necessary to construct a three component mixing model. In such a model both tracers need to be conservative – the tracer should provide information on the flow path (i.e. a reactive geochemical; Sr or $SiO_2$) and information on the water source (i.e. $\delta\ ^{18}O$).

To demonstrate this, figure 6.2 plots the end-member concentrations, for meteoric water, groundwater from till and groundwater from limestone, for two sets of conservative tracers - $Sr^{2+}$ versus $SiO_2$ and $Sr^{2+}$ versus $\delta\ ^{18}O$ with drain concentrations from three different runoff periods. In figure 6.10 (a) the plot between the $Sr^{2+}$ and $SiO_2$ end-member concentrations form a straight line. To form a three-component missing model there must 'space' within the model where the drain sample can be plotted – i.e. the end members must plot similar to the vertices of a triangle so that there are sufficient boundary conditions within the model to contain drain solute concentrations from high and low flows. Figure 6.10 (b) plots the end member concentrations using $Sr^{2+}$ and $\delta\ ^{18}O$ as the model tracers. The end members are sufficiently different enough to form boundaries where drain solute concentrations can plot – i.e. it is a conservative mixing model.

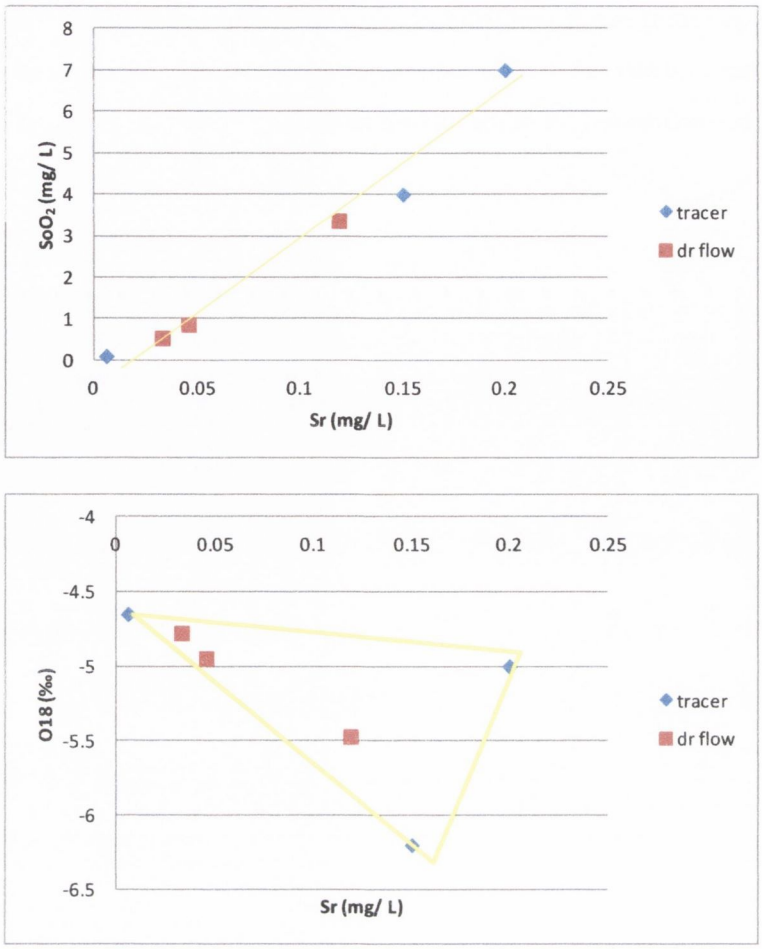


**Figure 6.10.** Test of tracer conservation for (a) Sr2+ versus SiO2 and (b) Sr2+ versus δ 18O

Therefore a combined geochemical and stable isotopic mixing model has been used to estimate baseflow from till and limestone at the Restortaion Flume. The model, like equation 6.1, is essentially a mass balance equation that is formulated as follows (after Hinton et al, 1994):

$$C_b Q_b + C_t Q_t + C_n Q_n = C_T Q_T \qquad \text{Equation 6.3}$$

where $C$ is either Sr concentration or $\delta\ ^{18}O$, $Q$ is discharge and the subscripts $T$, $b$, $t$ and $n$ refer to total, bedrock, till and new water respectively. There are three unknowns in the equation – discharge from till, limestone and 'new' water from overland flow. The unknown components are solved first by calculating proportions of flow using the two tracers and then using a set of linear equations to calculate proportions of flow using one of the two tracers (Hinton et al, 1994).

*Restoration Flume base flow hydrograph separation*

Figure 6.11 displays a hydrograph with base flow separation for the Restoration Flume between January 2011 and January 2012. Equation 6.3 has been solved using the tracer data described in section 6.8. As alluded to in section 6.8, the $\delta\ ^{18}O$ signature of surface water is highly sensitive to evaporation. Surface runoff following heavy rain periods has a $\delta\ ^{18}O$ signature similar to rainfall. The surface runoff signature will change and become more enriched due to partial evaporation in

intermittent periods as runoff is released from storage rather than coming from directly from rainfall. However, the volumes of water released in such periods are relatively minor, in an overall flow balance, and have been accounted for in the mixing model.

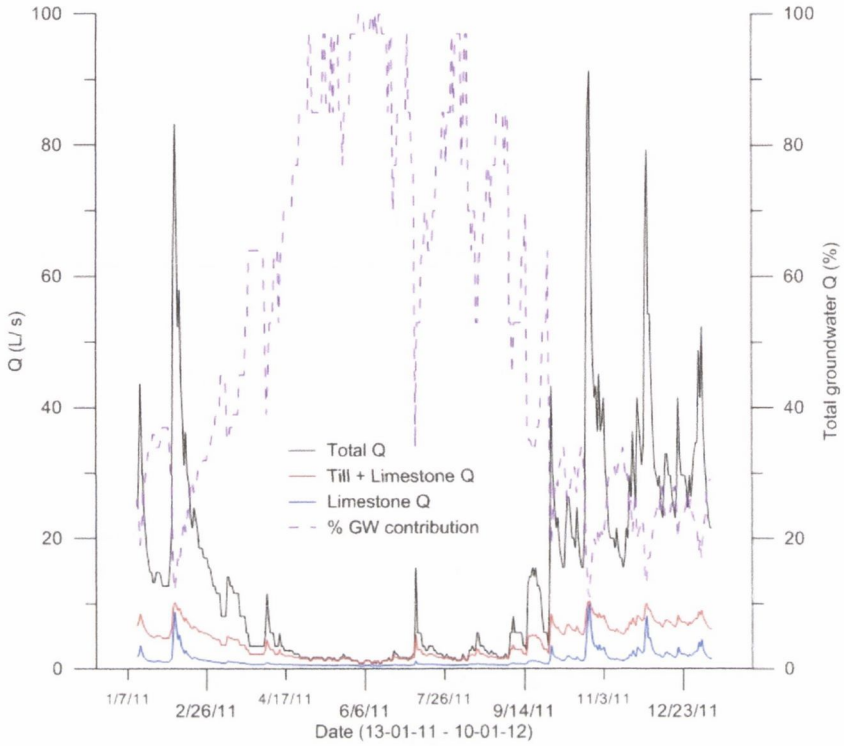


**Figure 6.11.** Restoration Flume hydrograph with base flow separation (Jan 2011 – Jan 2012)

Over the hydrograph period c. 28% of runoff is groundwater from till and limestone; 9% of which is from limestone. Between late April and early September the overall groundwater contribution in the drain is very high, > 70%, except for isolated wet periods. The hydrograph also shows that the groundwater contribution from limestone is greater than the till contribution in storm events – indicating limestone is recharged very quickly, possibly through a fracture or conduit zone which becomes most active during storm events. The inferences from the hydrograph match those made from the Sr and δ 18O observations and chemographs in appendix D.

*Peat flow separation using a three-component mixing model*

In section 6.8, runoff from peat in the marginal drains was estimated and attributed to 'new' peat water – i.e. recently 'released' peat water. The three component mixing model may also be applied to estimate infiltration through the high bog as the $\delta\ ^{18}O$ of peat water is more depleted (average of -6.5 ‰) than groundwater in till groundwater (average -6.0 ‰) – i.e. there are two end-members for peat water and groundwater; as there are for solute concentrations. Peat water that infiltrates quickly and preserves a solute concentration indicative of peat water in the marginal drain may also preserve a depleted $\delta\ ^{18}O$ signature as it has not mixed with the regional groundwater flows. 'Older' peat water will also maintain a depleted $\delta\ ^{18}O$ signature – but longer residence times in the till body will increase

the water molecules solute concentration so that it is elevated by the time it enters the drain. Using this logic, an infiltration rate of 0.14 mm/ day and 0.07 mm/ day has been calculated for the FB2 Flume and Restoration Flume surface water catchments.

### 6.10. Recharge rate

Recharge is the downward flow of water reaching the water table, ultimately adding to groundwater storage. In this case the water table is the regional groundwater table in till subsoil. The bog has lost a significant amount of water (chapter 7) since the early 1990's. It is therefore important that a recharge rate/ flux to till subsoil can be accurately calculated so to enable an estimation of the infiltration rate from the high bog to mineral subsoil - and how the infiltration rate is affected by marginal drainage. Calculation of a recharge rate is critical for numerical model design (chapter 11) and in predicting future hydrological scenarios and this is discussed in chapter 12.

Table 6.5. Estimated groundwater recharge through till (10-01-11 to 05-12-11)

| | | |
|---|---|---|
| **Total GW Q*:** | 222363 | $m^3$/ 327 day |
| **Catchment area^:** | 1766000 | $m^2$ |
| **Recharge to GWT:** | 125.91 | mm/ 327 day |
| **Recharge rate:** | 0.385 | mm/ day |

*Note: *Groundwater contribution from Restoration Flume does not include groundwater flow from limestone. ^Winter regional groundwater catchment area.*

Base flow separation for the Clara West hydraulic structures allowed a recharge rate to be calculated for each of the groundwater catchments contributing groundwater flow to the flow measurement structures. Table 6.4 lists groundwater runoff to the FB2 Flume, EPA Weir and Restoration Flume and these rates have been calculated as 0.24, 0.32 and 0.36 mm/ day respectively.

However, to determine a regional recharge rate for the Clara West hydrogeological system it is perhaps more appropriate to combine the base flow measurements in the EPA Weir and Restoration Flume as the two structures receive groundwater from the same groundwater catchment – the drains mark different outlets for groundwater discharge from the catchment. Following this, table 6.5 presents the calculated groundwater recharge from till subsoil. The calculation is based on the total groundwater catchment area encompassing the EPA Weir and the Restoration Flume (Figure D29; Appendix D) – both structures are within the same groundwater 'basin' and are positioned in separate streams (as opposed to the FB2 Flume which supplies runoff to the EPA Weir). Recharge is therefore simply calculated by the following equation:

$$R_t = \frac{Q_t}{A_g} \qquad \text{Equation 6.4}$$

where $R_t$ is recharge to till, $Q_t$ is the total till baseflow and $A_g$ is the regional groundwater catchment area.

Using this method, a groundwater recharge rate to till subsoil has been calculated as 0.385 mm /day (table 6.5). This figure is remarkably similar to the infiltration rate of 0.379 mm/ day calculated at the Bog Weir (Chapter 9). The recharge rate calculated at the FB2 Flume is 0.24 mm/ day and is 0.32 mm/ day at the EPA Weir. The lower recharge rate calculated at the FB2 Flume is possibly due to the water balance period analysed – overall baseflow contribution may be bigger over a longer time period. A larger catchment area may also have zones where there is a high recharge rate, such as areas where till is close to the surface and not overlain by peat and/ or lacustrine clay, thereby increasing the overall recharge rate for the catchment area. However, 0.39 mm/ day is taken to be the representative recharge rate for the Clara West hydrogeological system.

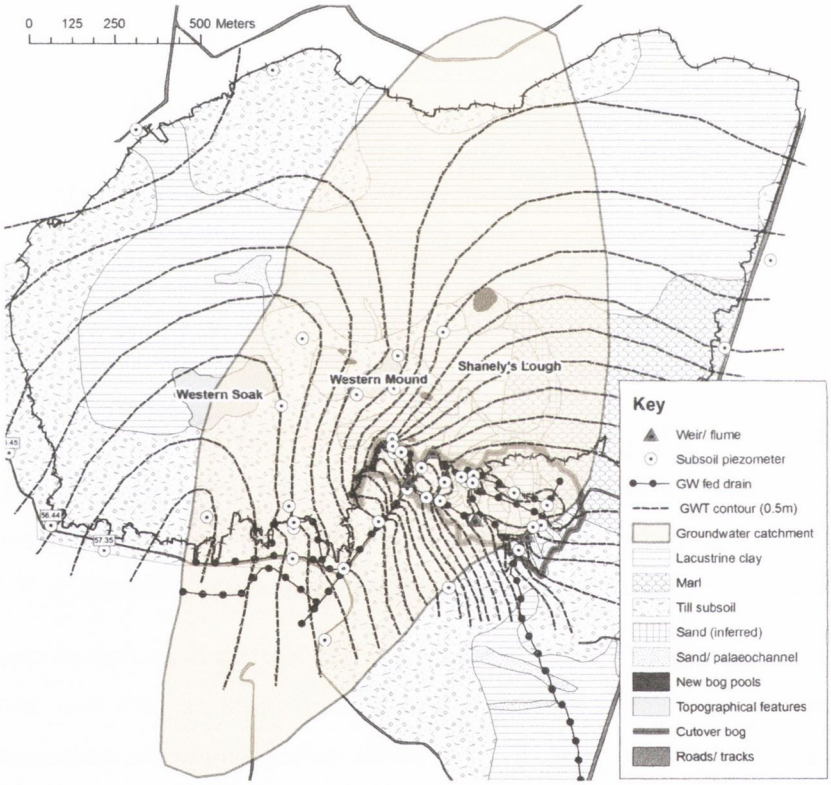


**Figure 6.12.** Groundwater catchment area to EPA Weir and Restoration Flume

## 6.11. Conclusions

There is a strong connection between regional groundwater flows and the Clara West drainage system. Hydrograph analysis of stage levels in drains instruments for flow measurement and piezometric levels in the till groundwater body, both in cutover bog and beneath the high bog, show that there is hydraulic continuity between surface water flows and subsurface groundwater flows. This relationship is best analysed by comparing base flow discharge rates to groundwater level recession rates – the hydrograph recessions work in tandem and base flow in the drains is groundwater released from storage in till and/ or limestone aquifers.

Water types, from different water bodies, in the Clara West hydrogeological system can be separated based on hydrochemistry. The most effective solutes are silica and strontium. Both solutes are found in only trace amounts in precipitation and increase marginally in peat substrate. Concentrations are elevated in till subsoil and limestone as there is sufficient time for which the solute to dissolve and increase its relative concentration in the groundwater system..

Stable oxygen 18 isotopes are less adapt at separating water types but are useful in identifying zones where groundwater from deeper limestone is contributing to base flow. A combined three-component hydrochemical-stable isotope mixing model enabled the separation of shallow and deep groundwater flows from overland flow in the Restoration Flume. This method estimates that c. 9% of baseflow in the Restoration Flume is deep groundwater from limestone.

Peat runoff is difficult to separate from groundwater flow in till as a second conservative tracer is required. The δ 18O signature of peat is variable but taking an average value an applying a three-component mixing model, with groundwater from till being the additional end-member to meteoric water, runoff from peat ranges between 0.07 and 0.14 mm/ day. Whereas separating peat runoff, on the basis of solute concentration in the two component mixing model, indicated peat runoff, from beneath the high bog, to the marginal drains is between 0.025 to 0.051 mm/ day.

However, there is uncertainty as to the validity of using stable oxygen isotopes in hydrograph separation analysis – i.e. the mixing models. While there is a division of water types based on the $\delta^{18}O$ signature, there is a wide variability in the values found in mineral and peat groundwaters. As such, the calculations for peat runoff and deep limestone runoff are treated with caution and in the absence of an additional and conservative environmental tracer, in addition to chemical solutes, the values quoted in the text serve as estimates only.

Both silica and strontium are conservative tracers and are applied to a mass balance two-component surface water-groundwater mixing model. There is also a degree of uncertainty as to their accuracy in separating water flows. By its nature, mixing models are controlled by the end-member chemical concentrations inserted in the model – there will inevitably be variability and error in this approach. However, both silica and strontium are stronger environmental tracers than calcium, magnesium, electrical conductivity and stable oxygen isotope. On this basis, groundwater runoff is calculated for the FB2 Flume, EPA Weir and Restoration Flume and amounts to 0.24, 0.32 and 0.36 mm/ day respectively. A more appropriate estimate of recharge for the Clara hydrogeological system is calculated by combining base flow volumes in the EPA Weir and Restoration Flume as the same groundwater catchment encompasses both structures - a regional recharge rate of 0.39 mm/ day is calculated. Due to variability in end-member calculation, the recharge rate may be subjected to change – a range of 0.31 mm/day to 0.45 mm/ day is deemed acceptable (i.e. +/- 20 %).

# 7. Subsidence

## 7.1. Introduction and objectives

The Clara West high bog has undergone significant morphological changes since the early 1990's (Chapter 1). Subsidence has altered the ground level gradient of the high bog in local areas meaning parts of the high bog are getting wetter, while other parts of the bog are becoming drier, thereby changing ecotope distributions and the flow paths and gradients supplying water to the sensitive soak systems (Section 4.3). However, it must be determined if the overall proportion of high bog that may be constituted as 'active' or 'peat-forming' raised bog is increasing or decreasing, as this, along with the conservation of the soak systems (Chapter 1), is the true measure on the integrity of Clara Bog as a functioning ecosystem and whether drainage has 'damaged' the bog under the remit of the Habitats and Water Framework Directives (Chapter 1).

To assess how changes in ground level, and by implication hydrology, on the surface of the bog, affects the ecological systems of conservational importance, the mechanism by which water is lost form peat must be understood. An analysis of subsidence must therefore:

(1) Identify the relative trends of ground level decrease and zones on the high bog where the trends differ and where subsidence has reached an equilibrium

(2) Quantify the rate of subsidence by calculating how much water is released from storage in the peat substrate over time, both from the entire peat column and per unit thickness of peat in the peat column and;

(3) Determine the controlling factors that limit or enhance the rate of water 'loss' from the peat substrate

## 7.2. Mechanisms of subsidence

Subsidence in a bog is caused by shrinkage of the peat. There are three main properties of peat that make it liable to shrinkage:

- The volume fraction of water in undisturbed peat is at least 0.95 (which means that only one twentieth of the volume is organic matter)
- Contrary to most mineral soils, which have an almost rigid matrix that consist of a grain skeleton, the matrix of organic soil is flexible.
- Peat can be oxidised to mainly carbon dioxide and water - it is noteworthy that this process can only occur where the water table is sufficiently deep to allow oxygen to enter the peat matrix (where the ground subsides and the drop in water table is such that the peat matrix remains saturated, oxidation will not occur)

The first two properties together may cause a relatively fast shrinkage after the bog has been drained (Van der Molen, 1975). The third property causes a relatively slow shrinkage (Schothorst, 1982).

Undisturbed raised bogs usually have a domed surface with a rather flat centre. Human interference can change the overall shape/ morphology of the bog. This process is referred to as subsidence of the high bog. In general two human interventions are responsible for this process, drainage on the high bog and peat cutting along the margins of the high bog.

- *Surface drainage*: Both intervention types can cause a lowering of the groundwater table on the bog and thus an increased drainage of the peat, in the upper margins of the peat profile, in the high bog or along the newly formed margin or face bank. As a result of the water loss by surface drainage, the peat shrinks. Shrinkage of peat means surface subsidence. For example surface subsidence took places at both sides of Rahan road through Clara Bog.
- *Subsurface drainage*: In this study a lowering of the regional potentiometric surface is found to be responsible for the surface subsidence of the high bog. Peat cutting has resulted in the subsurface drainage of the regional potentiometric surface. This process was initiated by intensive peat cutting at the south side of Clara Bog West. The effect of this intervention was large water losses in the high bog. Local increase of hydraulic conductivity and cracks are responsible for this process and shrinkage of the peat was a significant surface subsidence on the high bog.

On the high bog, an increased surface slope means an increased hydraulic gradient of the phreatic water table which results in a quicker discharge of water from the bog and, consequently, intensified drainage of more inwards areas of the bog. On too steep surface gradients (> 0.5 %) drying out occurs. In situations where the high bog has become dry, the phreatic water table on the bog has dropped. This has consequences for the physical conditions of the peat. When the moisture content in the peat substrate that is above a low phreatic water table begins to decrease, the aeration of the peat substrate above the water table increases. Due to this process the organic material mineralises relatively fast under the more oxygen rich conditions and as a result the organic particles become smaller. In the longer term this results in a denser peat substrate and the pore volume becomes smaller. The storage coefficient decreases (up to $\mu$ 0.1) and remains small. In marginal zones on the high bog the mean water table is between 0.40 and 0.60 mbGL and in face bank area > 0.60 mbGL (Van der Schaaf & Streefkerk, 2002). In these areas the peat has dried out over a longer period of time and at the surface the storage coefficient will be too small for Sphagnum growth.

### 7.3. Subsidence analysis area

The high bog topography has changed over time due to differential peat consolidation. The geohydrology of the Clara West system was discussed in Chapters 3 and 5 and it is clear that marginal drainage, when it has cut below the regional groundwater table and where peat thickness is < 2.0 m from the peat-till interface to the drain base, has created a hydraulic connection between the peat substrate on the high bog and underlying till subsoil in the absence of lacustrine clay. Such a

connection on the high bog, as inferred by analysis of the connection between water levels in the till groundwater body and overlying peat from piezometer such as 910 (Section 6.3), has induced drainage at the base of peat, resulting in surface level subsidence.

The hydrogeological cross-sections through the monitoring transects (Section 5.4) indicates areas where water is 'lost' from peat due to large vertical hydraulic gradients between the base of peat and till subsoil. Hydrochemical and baseflow separation analysis (Chapter 6) indicates a significant proportion, relative to natural infiltration rates, of runoff in the Clara West drainage system may be attributed to water derived from peat rather than overland flow or mineral water from till or limestone bedrock. Hydrogeological and hydrochemical data both strongly indicate that water is lost from the high bog vertically, and not laterally through the face-bank, again suggesting that water has been released from the peat substrate – water that would ordinarily be held in storage.

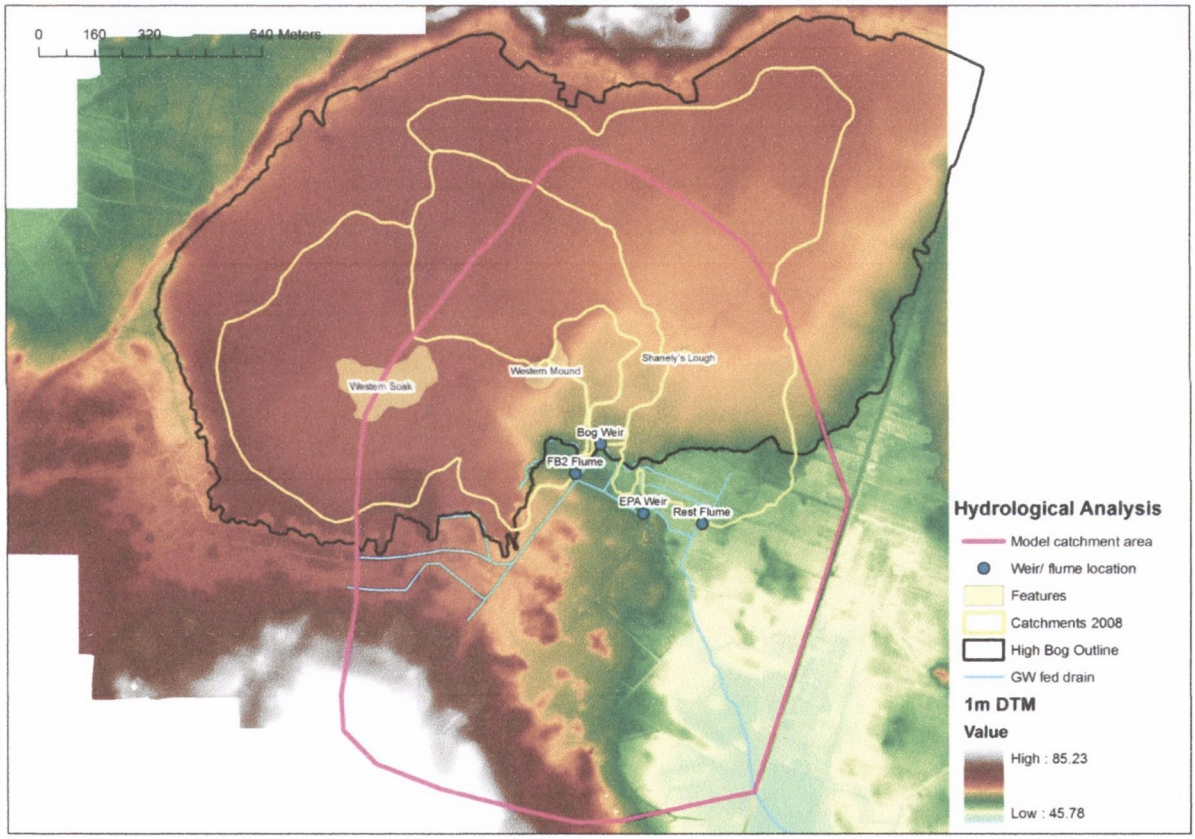


**Figure 7.1.** Location of model catchment area

Therefore, following hydrogeological and hydrochemical analysis, ground level changes on the high bog where studied more closely in the area encompassed by the regional groundwater catchment described in Section 56, as the hypothesis is that the lowering of the regional groundwater table by marginal drainage has induced peat consolidation by increasing the vertical hydraulic gradient between the high bog system and regional groundwater table in localised areas (Chapter 5). A groundwater flow model (Chapter 11), based on this hypothesis and generated to better understand the

importance of the regional groundwater table in supporting the high bog body has been generated using this groundwater catchment as its boundary conditions (Chapter 11) – the inference is that subsidence is mostly confined to within this groundwater catchment area.

As such, an area referred to as the 'subsidence analysis' area (Figure 7.1 and Figure E1; appendix E), which is the area of high bog encompassed by the regional groundwater catchment and used to generate the groundwater flow model (Chapter 11) has been analysed more closely, by means of elevation analysis, to identify subsidence trends over time and to calculate respective subsidence 'seepage' rates.

## 7.4. Subsidence over time

Ground level measurements of the Clara West high bog are available from four separate time periods. The 100 m OPW bog grid was levelled manually in 1991 and 2002 (Chapter 1) and a LiDAR survey of the entire bog, at a finer resolution of $1m^2$, of Clara Bog was carried out in November 2008 (Chapter 4). Additional manual ground level surveying was carried out in September 2011 and January and April 2012 so to (1) ascertain if the bog surface fluctuates in response to seasonal changes and (2) to assess if the high bog ground level is still decreasing over time and whether any decease in ground level fits in with observed subsidence patterns from earlier time periods.

### 7.4.1. Ground level decrease over time

Table E1 (appendix E) collates the ground level survey results at grid points in the subsidence analysis area between 1992 and 2011. A median value for 2011, based on measurements between September 2011 and April 2012, is used as the '2011 ground level' for analysis purposes and table E2 lists the September 2011, January 2012 and April 2012 ground level elevation results.

Figures E2, E3, E4 and E5 in appendix E, plot contours for ground level subsidence (i.e. the decreasing surface level of the high bog within the study period) in the Clara West high bog encompassed within the subsidence analysis area between (1) 1991 and 2012, (2) 1991 and 2002, (3) 2002 and 2012 and (4) 2008 and 2011 respectively.

*1991-2011 ground level decrease*

Figure 7.2 (and Figure E7; Appendix E) maps the level of overall subsidence between 1991 and 2011 and it may be observed that subsidence > 1.0 m and > 0.5 m occurs within c. 200 m and 500 m of the high bog-cutover boundary respectively. Subsidence > 0.1 m and > 0.2 m occurs within 900 m and 700 m respectively of the bog boundary. It is significant that subsidence is not limited to the margins of the high bog – it propagates beyond the centre of the bog. The area with an extreme (> 1.0 m) decrease in high bog ground level is concentrated adjacent to the groundwater fed drain FB2 and propagates c. 100 m northeast of the western margin of the Western Mound into the area of 'new bog pools'– in the vicinity of bog grid points K12 and J12. Such a ground level decrease will invariably

alter the hydrological processes on the surface of the bog as the gradient has increased considerably – which has significant implications for the hydrological maintenance of the Western Soak system.

In addition to subsidence concentrated at drain FB2, there has been considerable subsidence, > 1.0 m at bog grid points G13 and F13, located c. 100 m and 300 m north of groundwater-fed drain FB3. It is curious that these grid points appear to be isolated and seem to mark localised zones of extreme subsidence. It is possible there has been a surveying error – however, the locations of these grid points in the context of the underlying geohydrology are not surprising and is discussed in Chapter 10.

Clear changes on the high bog have occurred since the original ecohydrological work carried out in the 1990's (chapter 1) and the 'extreme' subsidence areas are have been highly influential in inducing these ecological changes. However, another revealing feature on Figure 7.2 is the level of ground level decrease, between 0.25 m and 0.45 m, across the majority of the subsidence analysis area – subsidence, on a whole, is not localised. The significance is that while extreme subsidence may be relatively localised, significant decrease in ground level (c. > 0.25 m) has affected the majority of the high bog. The only area of the high bog in Figure 7.2 is have remained relatively static is in north-eastern region of the subsidence analysis area.

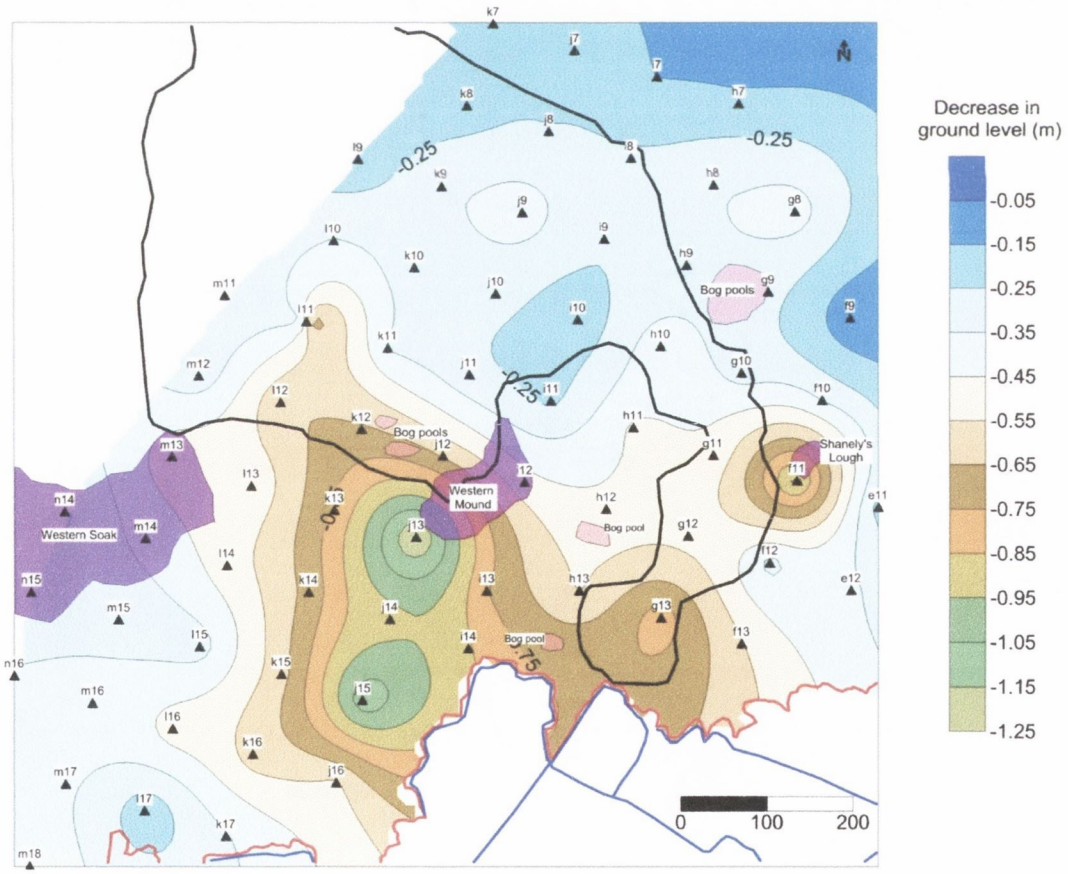


**Figure 7.2.** Decrease in surface ground level (m) between 1991 and 2011

However, while Figure F7 displays the level of ground level decrease over a c. 20 year period, it does not provide an adequate description of current or recent ground level subsidence, which is essential in

understanding current changes afflicting the bog – has subsidence reached steady state/ equilibrium? Therefore to assess the overall trend of subsidence, ground level changes must be analysed over more recent time periods – i.e. between 2002 and 2011 and 2008 and 2011.

*1991-2002 ground level decrease*

Figure 7.3 (and Figure F8; appendix F) maps the level of subsidence between 1991 and 2002 in the subsidence analysis area. The map is similar to that of the 1991-2011 map in Figure 7.2 in that the areas of greatest subsidence are concentrated within 200 m of the high bog boundary, adjacent to groundwater-fed drains FB2 and FB3. Bog grid points J13 and J15, each located c. 200 m north and west of drain FB2 respectively, mark the areas of most extreme subsidence - > 1.0 m. Subsidence > 0.7 m is recorded at bog grid points G13 and F13 and the southern area between the Western Soak and the Western Mound and the western region of Shanely's Lough is an area where substantial ground level decrease occurred in the 1991-2002 period. This pattern persists in the 1991-2011 analysis, implying the majority of subsidence within 200 m to 300 m of the bog boundary occurred before 2002.

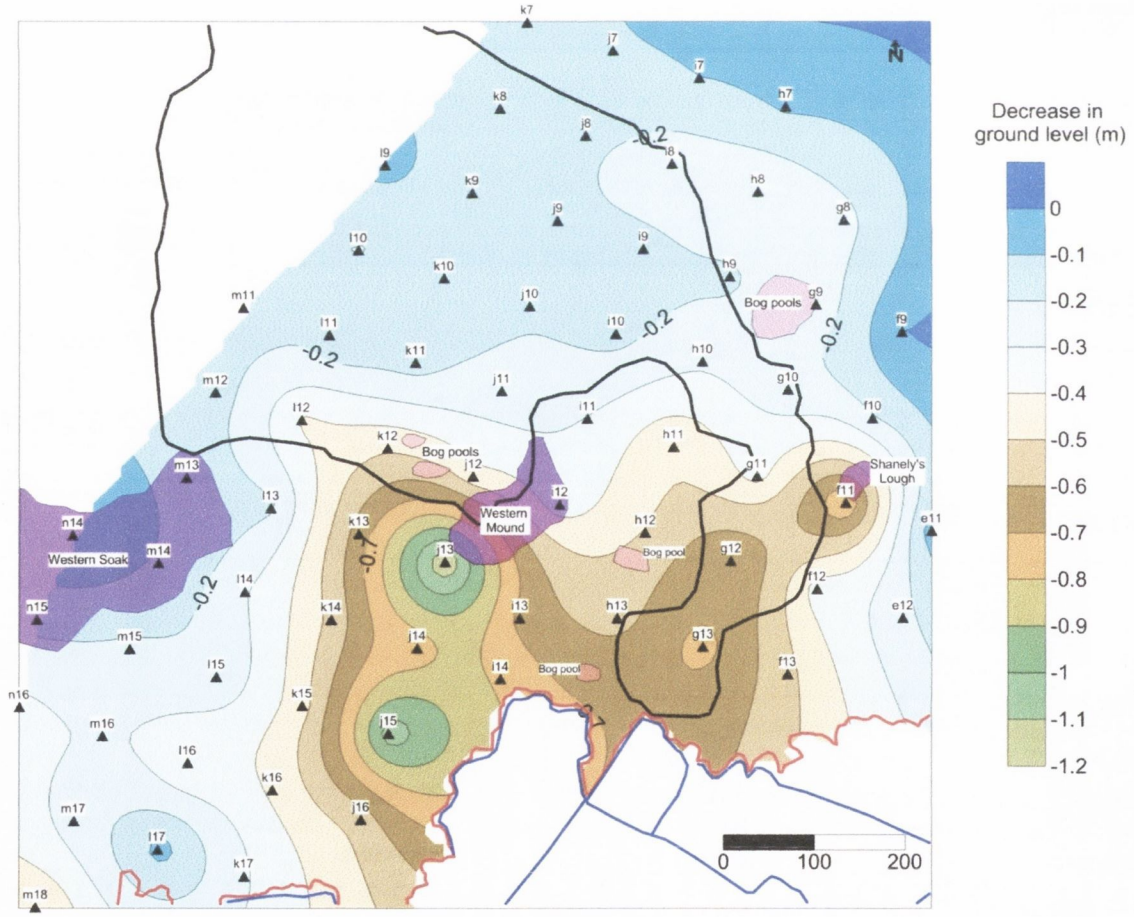


**Figure 7.3.** Decrease in surface ground level (m) between 1991 and 2002

Thus, while it is clear from comparing Figures 7.2 and 7.3 that the high bog peat substrate released water relatively quickly from storage following the creation/ deepening of a marginal drainage system

(drains where deepened in c. 1996), it is important to assess the level of subsidence since 2002. In Figure 7.3, it may be observed that the level of subsidence west, northwest and north of the Western Mound is relatively minor, < 0.2 m, and decreases towards the model boundaries. However, the 1991-2011 subsidence contours in Figure 7.2 indicates subsidence greater than 0.2 m – implying significant subsidence, in the more central areas of the bog, since 2002.

*2002-2011 ground level decrease*

Figure 7.4 (and Figure F9; appendix F) maps the level of subsidence between 2002 and 2011 in the subsidence analysis area. It can be observed that there has been significant subsidence, > 0.3 m, to the west and northwest of the Western Mound since 2002. Indeed, significant subsidence of > 0.2 m marks the western region of the subsidence analysis area, trending in a northeast-southwest pattern between the Western Soak and Western Mound, with subsidence increasing in the vicinity of the Western Mound. Curiously, significant subsidence of > 0.2 m also marks the eastern boundary of the subsidence analysis area in the vicinity of Shanely's Lough. In between these two 'subsidence' zones, ground level decrease is < 0.2 m and appears to be approaching some form of equilibrium or steady state, with the exception of one localised area, marked by bog grid points H9 and H10, adjacent to an area of new bog pools.

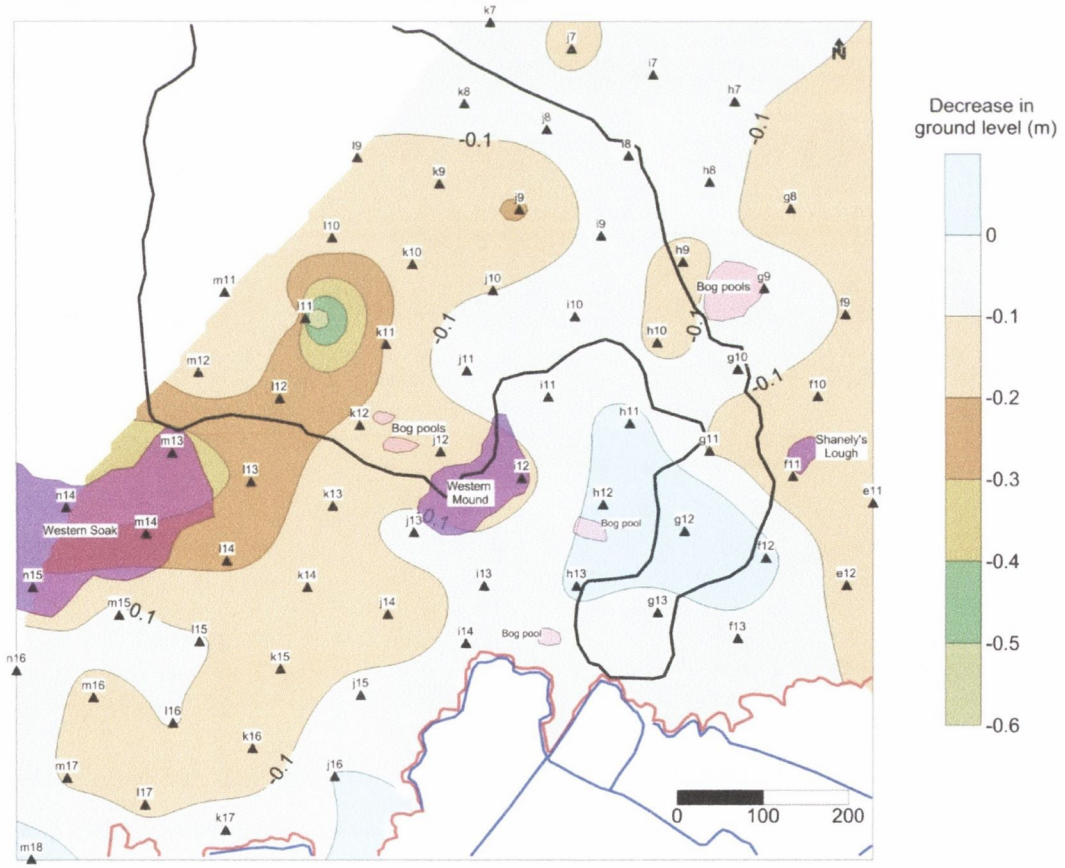


**Figure 7.4.** Decrease in surface ground level (m) between 2002 and 2011

Thus, figure 7.4 suggests that subsidence is proceeding at different rates as subsidence appears to be slowing down in the area between the Western Mound and Shanely's Lough – but not in the western or eastern part of the analysis area. To investigate if this is a real phenomenon, and a trend that is continuing, analysis between 2008 and 2011-2012 will provide additional confidence in the subsidence pattern and the trend it is following.

*2008-2012 ground level decrease*

Figure 7.5 (and Figure F10; appendix F) maps the level of subsidence between 2008 and 2011 in the subsidence analysis area. The 2008 LiDAR survey, described in Chapter 4 has been compared to the recent ground level surveys of 2011 and 2012, where the ground level used in analysis, for the most part, is that measured in January 2012 as it is at this time the bog surface level is at its highest (Section 7.4). Taking a summer ground level (i.e. September 2011) would overestimate the degree of subsidence since 2008 as it is found ground level was low at this time.

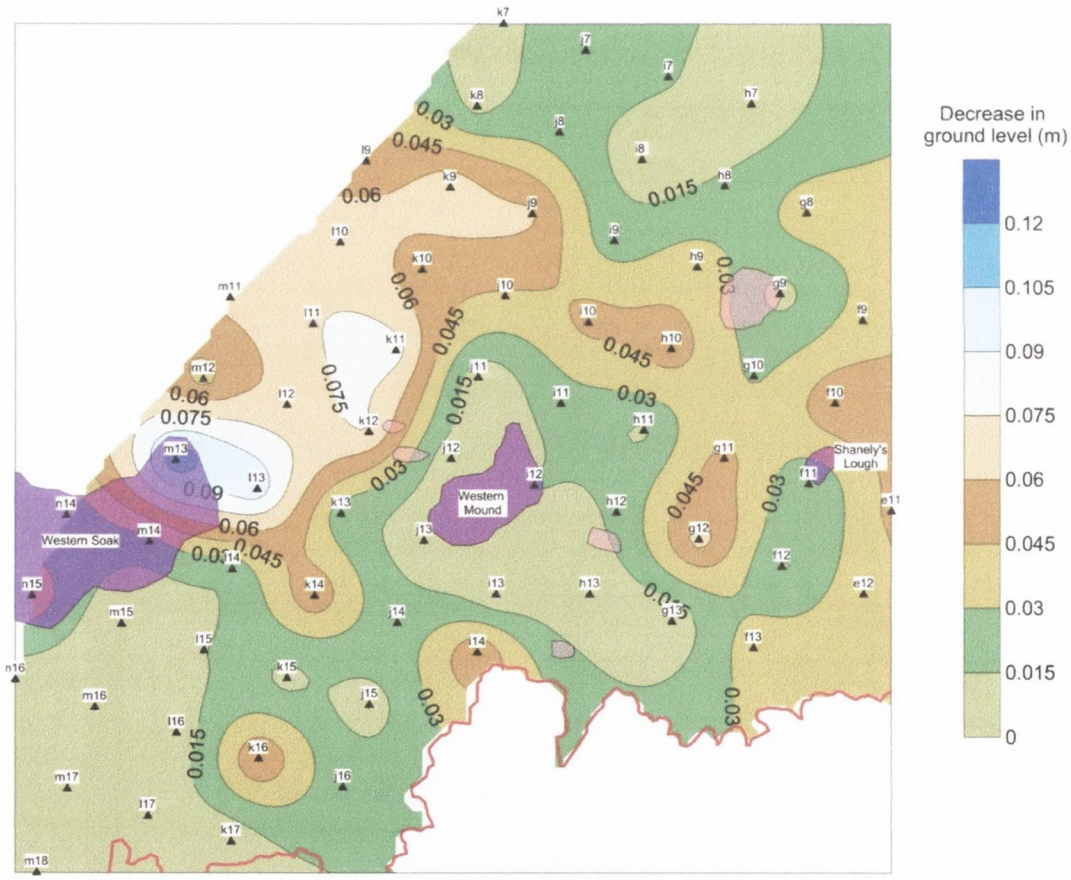


**Figure 7.5.** Decrease in surface ground level (m) between 2008 and 2011

The subsidence pattern described between the period 2008 and 2011 is similar in Figure 7.5. Since November 2008, ground level has decreased by c. 0.045 m in zones east and west of Shanely's Lough. Similar to the 2002-2012 subsidence pattern the greatest subsidence occurs west of the Western Mound in the vicinity of the Western Soak. There is a distinct region of large subsidence, where ground level decrease is > 0.045 m, west of the Western Mound that trends in a northeast-southwest

direction from the eastern margin of the Western Soak. It also appears that this large subsidence zone extends beyond the western limit of the subsidence analysis area. Thus, it is clear the high bog ground level is still decreasing within the subsidence catchment area.

Ground level decrease in the area surrounding and southeast of the Western Mound appears to be levelling out. Subsidence in the northern and western areas of the subsidence analysis area also appears to be slowing down, with ground level decrease estimated to be < 0.03 since 2008. However, there are still isolated pockets where ground level decrease is still occurring at bog grid points I14 and K16. Overall, in the area south and southeast of the Western Mound, the areas with extreme levels of subsidence described in Figures 7.2 and 7.3 now appear to be levelling out.

## 7.5. Ground level oscillation

The Clara West high bog has effectively been measured on four, distinct, times since 1991. To identify trends in ground level decrease a minimum of four data points are required if subsidence trends can be described with any degree of accuracy or confidence. The degree of ground level decrease described in Section 7.3 can therefore be combined to identify if subsidence trends exist. However, the descriptions of ground level decrease in section 7.3 assumed that ground level is static and only changes when it subsides - this is not the case.

### 7.5.1. Bog swelling

The surface level of natural intact bogs moves up and down throughout the course of a year; a phenomenon commonly referred to as Mooratmung, or 'bog breathing'. Such topographic oscillations on peatlands are related to changes in water storage and gas volume (Price, 2003). Peat substrates differ from mineral subsoil in that their matrix is non-rigid, which thereby allows the bog to store water by changing its peat volume rather than its water content (Kellner & Halldin, 2002). However, this process is complicated by irreversible subsidence processes associated with artificial drainage. Studies on undisturbed bog ground level fluctuation have found maximum differences between low and high levels of 0.07 m to 0.11 m (Uhden, 1965; described by Van der Schaff 1999), 0.015 m to 0.3 m (Baden & Eggelsmann, 1964; described by Van der Schaff 1999), 0.1 to 0.3 m (Ingram, 1983), 0.11 m (Almendinger et al, 1986), 0.03 to 0.11 m (Van der Schaff, 1999) and 0.08 m to 0.25 m (Glaser et al, 2004).

Surface level fluctuations will be greatest when *Sphagnum* is present on the bog surface as it has the capacity to store and release water in response to precipitation. The *Sphagnum* body will increase in volume with higher water tables – meaning surface levels will be at their lowest in dry conditions and at their highest in winter periods. When *Sphagnum* is absent from the bog surface, which indicates the absence of a functioning acrotelm, the phreatic water table fluctuation will be greater than in areas where acrotelm is present (Section 4.3.6) – however the surface level of the bog will fluctuate less in areas without an acrotelm/ expanse of Sphagnum species.

To establish a range of surface level oscillations on the Clara West high bog, the bog grid in the subsidence analysis area was surveyed on three occasions – (1) 2nd September 2011, (2) 7th and 11th January 2012 and (3) on the 7th and 8th of April 2012. These three survey time periods amount to levels taken from (1) summer, (2) winter and (3) spring, thereby allowing an assessment of relative ground level changes on the high bog surface relative to seasonal changes. To minimise instrument error the surface levels have been corrected, using fixed boreholes/ wells installed in till subsoil, so that the three survey periods are referenced to the same elevation datum.

### 7.5.2. Level of oscillation

Table E5 lists the surface level elevations from each bog grid point and the range of fluctuation within the surveying period. Four 'oscillation trends' may be identified – (1) minor oscillations in ground level, (2) seasonal ground level fluctuations, (3) ground levels that decrease in elevation through each of the survey periods and (4) ground levels that increase in elevation through each of the survey periods. Figure E11 (Appendix E) illustrates the afro-mentioned bog ground level oscillation zones in the Clara West subsidence analysis area.

The bog ground level at most grid points fluctuates seasonally – i.e. the bog surface is at its highest elevation in January (winter) and at its lowest elevation in early September (summer). The level of fluctuation ranges between 0.02 m and 0.17 m; though the larger fluctuations (> 10 cm) may be due to the placement of the GPS in areas of hummock-type topography making ground level measurement unreliable as the measurement is not taken from a fixed position – bog topography is highly variable and a margin of error in the order of > 5cm is inevitable. However, the large fluctuations of c. 10 cm are in accordance with the findings by Van der Schaff (1999) on the Clara West high bog in 1992.

To find the mean ground level of the bog surface over a period, such as one year, it is possible to fit a cosine wave curve through the measured elevation data points (Table E4). The process assumes the oscillation is repetitive and in the absence of a larger number of data points in which to analysis the bog surface oscillation, the cosine wave method is a reasonable approximation of the mean bog ground level in the survey period. Figures E14 to E16 illustrates cosine curves though three example grid points, H11, I11 and L14 where the bog surface fluctuates depending on the time of year.

Eleven grid points remain relatively static in each of the survey periods (I8, J7, J8, J9, J14, K7, K12, K16, L10, L17 and M16) with maximum fluctuations of 0.04 m. Eight grid points (E11, F11, F12, H7, K9, K14, L11 and H7) decrease in elevation through the survey period – between 0.06 m and 0.17 m. Conversely, seven grid points (E12, F10, G13, H8, K15, L12 and L16) increase in elevation in the survey period – between 0.04 m and 0.13 m. The grid points in the static, decreasing and increasing ground level oscillation trends appear to be independent of seasonal/ water table effects – this is possibly an error resulting from the surveying technique employed; or other processes are occurring that are contributing to relative ground level increases and decreases.

### 7.5.3. Ground level oscillation type and ecotope distribution

Figure 4.17, Chapter 4, illustrates the Clara West 2009 ecotope map generated by Fernandez (2009). Figure E13 illustrates an image map of the oscillation ground level trends. Areas where the ground level remains relatively static (a longer time period is required to monitor real ground level changes attribute to subsidence) are located close to the Western Mound and the FB2 drain – areas where the ground level gradient is step - preventing acrotelm development. There are also pockets in the northern reaches of the figure and at bog grid point F11 south of Shanely's Lough.

Areas where the ground level appears to increase are located mainly close to the bog margin, but in isolated pockets. Areas where ground level seemingly decreases are located adjacent, and surrounding, the areas where ground level seemingly increases, implying some form of relationship - possibly one area of the bog swells while the adjacent area releases water in its upper layer.

Table 7.1. Surface level fluctuation and ecotope relationship

| | Fluctuation (m) | | | |
|---|---|---|---|---|
| **Ecotope** | **Average** | **Min** | **Max** | **n** |
| Marginal | 0.1 | 0.09 | 0.11 | 4 |
| Sub-marginal | 0.07 | 0.02 | 0.11 | 9 |
| Central | 0.12 | 0.10 | 0.16 | 4 |
| Sub-central | 0.09 | 0.03 | 0.15 | 15 |
| Active Flush | 0.08 | 0.04 | 0.17 | 7 |

However, the majority of the subsidence analysis area is characterised by fluctuating ground level topography (Figure E11). Table 7.1 summarises the ground level fluctuations measured at grid points within different ecotope types. The largest average ground level fluctuation, 0.12 m, is found in central ecotopes, which is unsurprising as central ecotopes are distinguished by active *Sphagnum* growth and acrotelm development. Sub-central ecotopes measure a smaller average range of ground level fluctuation at 0.09 m and the ground level fluctuation range is greater than in central ecotopes. Active flush ecotopes have an average ground level fluctuation of 0.08 m and a relatively large range of ground level fluctuation, which may, in part, be due to the more hummocky type micro-topography encountered in such areas.

Sub-marginal ecotopes display a greater level of fluctuation than central and sub-central ecotopes and have an average ground level fluctuation of 0.06 m, which again is unsurprising as such ecotopes do not have good actrolem development and where Sphagnum exists, it is localised. However, it is surprising that marginal ecotopes have a large ground level fluctuation of 0.1 m; albeit the value is based on a limited number of data points, such areas are characterised by the absence of an acrotelm, and it would be expected that such areas remain relatively static. If the ground level fluctuation is a

real one, it is likely that the peat column itself is swelling, as a decomposed upper layer is absent in such areas.

However, analysing the relative ground level fluctuations in each of the ecotopes a generic ground level fluctuation of 10 cm can be applied to the bog surface. As such, ground level measurements taken on the bog in the past may then be considered to be, at minimum, +/- 10 cm; such a figure is representative of relative surface level fluctuation and does not necessitate the need for a more complicated statistical analysis.

### 7.5.4. Peat column oscillation

The OPW bog grid is marked, in most locations, by a wooden survey post which is c. 1.0 m below the ground surface in the peat profile. The top of the OPW grid posts/ stakes were levelled in the January and April survey periods so to provide additional control on the accuracy of the GPS measurements and to monitor whether the post elevation decreases over time due to subsidence. The results from the two survey periods are collated in table E3 in appendix E.

The elevation difference between the January and April survey periods is illustrated in figure E17 in appendix E. The results are surprising. It may be observed from figure E17 that the OPW stakes increase and decrease by up to c. 0.02 m. The area(s) where the stakes increase in elevation are focused surrounding the Western Mound, with the large elevation increases > 0.01 m concentrated south of the Western Mound towards the high bog boundary.

The elevation of the OPW post decreases north of the Western Mound, west of the Western Mound in the vicinity of the Western Soak and east of the Western Mound in the vicinity of Shanely's Lough. The areas where the OPW posts decrease in elevation are near coincident with the areas of greatest subsidence described in section 8.2 and the areas where the post elevation seemingly increases in elevation is near-coincident with areas that appear to be reaching a form of subsidence equilibrium.

It appears that there are two processes controlling ground level oscillation – (1) 'natural' ground level oscillation due to increasing/ decreasing phreatic water table associated acrotelm occurrence/ expanse and (2) possible 'peat' swelling due to pore water pressures changes associated with the groundwater level in the peat itself, which is complicated by drainage and subsidence processes.

Therefore, measuring the top of the OPW grid posts is arguably a more accurate method of measuring relative changes to bog topography over time, due to the complications arising from acrotelm growth on the surface of the bog, which increases and decreases the ground level on the surface of the bog in accordance with changes in the phreatic water table, which fluctuates relative to the immediate precipitation input, and ground level oscillations are found to be in the order of 0.05 to 0.16 m from a dry period (summer) to a wet period (winter).

### 7.5.5. Ground level oscillation and water level fluctuation

Coincident with the 2011-2012 ground levelling surveys, water level measurements were taken at piezometer nests 908, 909, 910 and tdJ12 (see Chapter 5 for groundwater hydrograph analysis). Figures F19 to F22 in appendix F plot ground level versus (a) phreatic water level and (b) deep peat hydraulic head. Though there are only three data points (with the exception of piezometer 908; 4 periods of measurements, Figure 7.6) in which to analysis probable correlations, there appears to be a connection between phreatic water level and ground level fluctuation at each of the piezometers, though the relationship seems poor at 909 and tdJ12.

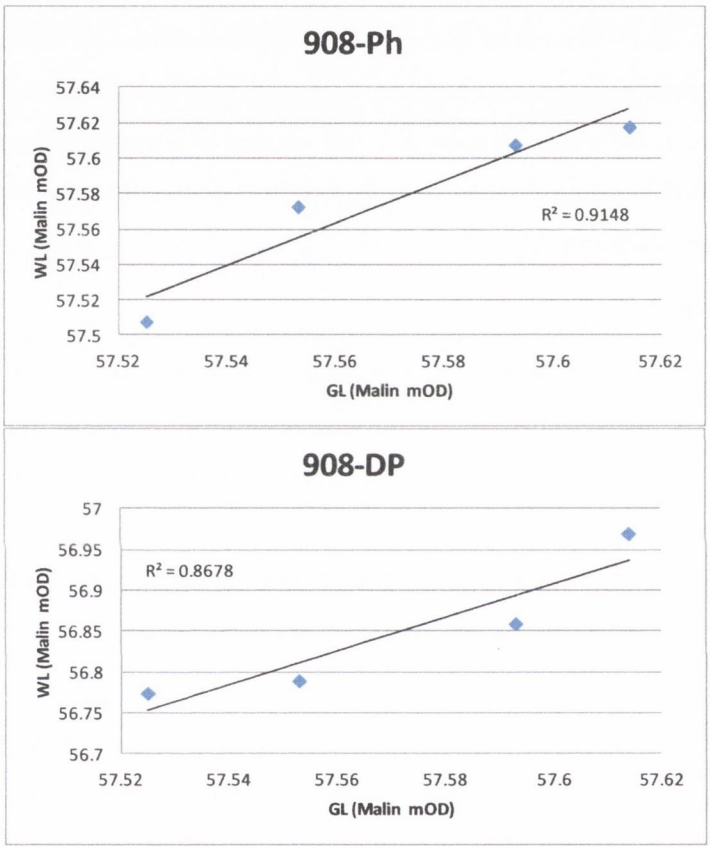


**Figure 7.6.** (a) Phreatic water level versus ground level and (b) deep peat piezometric level versus ground level at piezometer nest 908

Analysis of water levels from the Clara West piezometry was described in Chapter 5. A relationship between hydraulic head in till and basal peat was found at piezometer nests 908 and 910. Figures E18 to E21 indicate that there is a connection between ground level fluctuation and water level oscillation in deep peat at measured piezometer locations. Changes in storage capacity of a bog should be limited to the acrotelm, where voids filed with air in the vegetative structure are replaced by water in wet periods, increasing the relative ground surface elevation. Glaser et al (2004) found that surface elevations correspond with precipitation and local water table elevations. The ground surface then subsides as a response to runoff and in dry periods as a response to increased evapotranspiration. Such a process can also be inferred to apply to the Clara West surface level oscillation.

However, the oscillation of the OPW posts and the relationship between water level and ground level in figures E18 and E21 suggests that ground level also appears to be linked with the water level in basal peat in particular areas – implying pore pressure in the peat substrate influences bog topography. Ordinarily, it would be expected that the link between the deep peat and phreatic water levels would be separated by some form of a confining layer, meaning the phreatic level would mimic the ground level oscillation, but not necessarily the hydraulic head at depth. Glaser et al (2004) found that the hydraulic head at depth (3m in their study area) was disconnected from surface level oscillations. In chapter 5, the hydraulic head in deep peat at piezometer 909 was found to fluctuate independently of the hydraulic head in underlying till subsoil. Figure E19 suggests the ground level is independent to the water level in deep peat – in contrast to the other analysed piezometers. Piezometer 909 is also an area where extreme subsidence occurred between 1991 and 2002, but has slowed down considerably since 2002. This suggests the area, grid point J13, has reached or is approaching ground level equilibrium. However, the area north of piezometer J13, between the Western Mound and the Western Soak has not reached equilibrium.

### 7.6. Subsidence trend

Figures F7 to F10 suggests that subsidence is proceeding at different rates as subsidence appears to be slowing down in the area between the Western Mound and Shanely's Lough – but not in the western or eastern part of the subsidence analysis area. Therefore, to put the subsidence analyses described in sections 7.2 and 7.3 into context, overall, or generic, subsidence trends can be described. Table E1 in appendix E plots ground level elevation versus time for each of the bog grid locations levelled in the subsidence analysis area.

Analysis of the individual level locations indicates that the rate of subsidence follows two trends – (1) a linear rate of ground level decrease where subsidence is not slowing down and (2) an exponential rate of ground level decrease where subsidence is slowing down and approaching a steady state.

Figure E22 in appendix E, is an image map illustrating areas of the subsidence analysis area where ground level decrease is linear or exponential, or whether it is relatively level, implying steady state equilibrium. The distribution of the 'subsidence trend type' is similar to the patterns of subsidence described in section 7.2 and the areas of linear ground level decrease are near confident with the areas of bog where the OPW posts have decreased in elevation between January and April 2012 (Figure E17). Figure E23, Appendix E, illustrates graphs from each surveyed OPW point and an example of a linear and exponential rate of decrease id illustrated in Figure 7.7 below.

Additional grid point locations (e.g. along bog grid line D) were surveyed in April 2012 so to identify boundaries to the areas of linear ground level decrease identified in the earlier survey studies. However, it was found that zones of ground level decrease extend beyond the limits of the western and eastern boundaries of the analysis area. Whereas ground level decrease is slowing down

(exponential decrease) or more or less ceased south of the Western Mound, ground level decrease is still following a linear trend in the areas of the Western Soak, c. 200 m north of the Western Mound and north and southeast of Shanely's Lough.

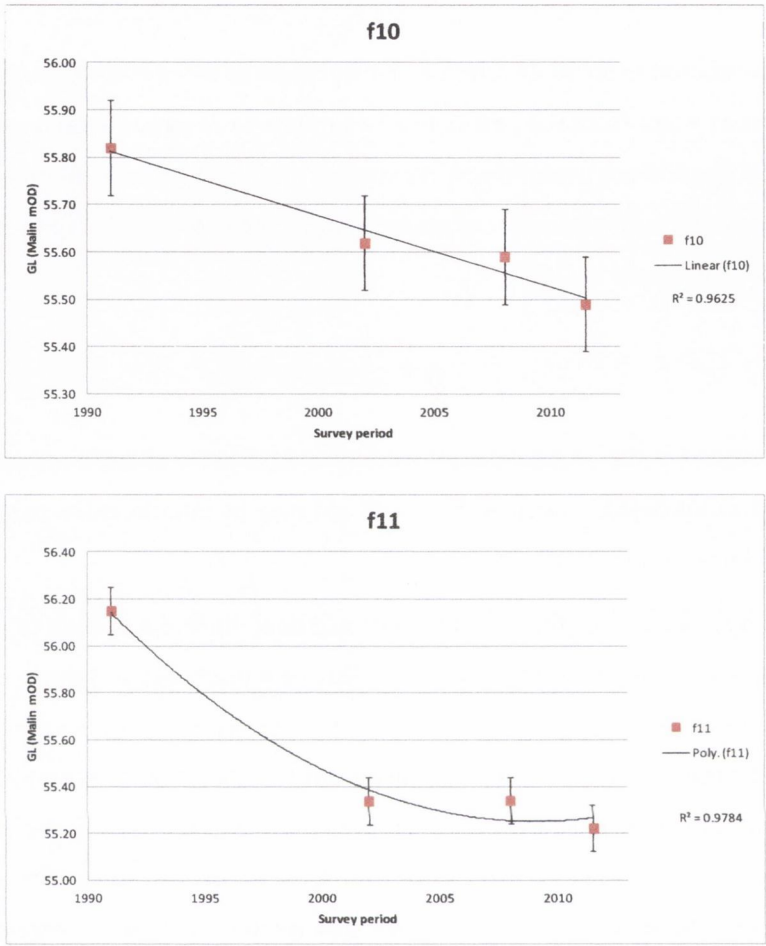


**Figure 7.7.** (A) Linear rate of subsidence at bog grid point F10 (B) Exponential rate of subsidence at bog grid point F11. Note: Mean 2011-2012 elevation used.

### 7.7. Strain analysis

Subsidence trends based on ground level alone may not necessarily correlate with changes in peat volume arising from the release of water from storage in the peat column. However, the level of ground level decrease since 1991 implies peat thickness has reduced considerably and the recently measured oscillations from the OPW posts indicate that volume changes are still occurring within the peat column - the change in the surface level of the bog, over time, is related to changes below the phreatic water table, while surface level oscillations are related to changes above the phreatic water table.

A more intuitive method of analysing subsidence, and the subsidence trend, is to analysis how the peat thickness changes over time – i.e. a measure of peat consolidation over time. As the peat has consolidated it has effectively deformed. The cause of the deformation is considered to be drainage from the base of peat, which has reduced the water content of the peat substrate and increased the

effective stress on the peat. Whether the deformation is elastic (i.e. it can recover by 'reswelling') or plastic (i.e. irreversible) is a geotechnical problem. However, it can be assumed that consolidation is plastic deformation as there is little evidence that peat expands after it has been artificially drained (Price, 1999).

Strain describes deformation in terms of relative displacement of the soil body in question. In this case it is the displacement of water from the peat body. Strain measurements are dimensionless and can be expressed as decimal fractions or percentages. As such, a strain is a normalised measure of deformation representing the displacement of water from the peat body, relative to its 'original' thickness and may be calculated as follows:

$$\epsilon = \frac{\Delta T}{T} \qquad \text{Equation 8.1}$$

where $\epsilon$ is normal strain, $T$ is the original peat thickness and $\Delta T$ is the change in peat thickness over time. Strain values are expressed in decimal fractions and may be interpreted as expressing the decrease in peat thickness in the strain period.

Table E1 and E5 in Appendix E list the ground levels and peat thickness at each of the bog grid points in the subsidence analysis area since 1991. Table 7.2 lists peat thickness and strain over time for measurement locations where the peat was cored in 1991 (chapter 3); peat thickness and strain have been estimated for the remaining bog grid points using subsoil elevation contour maps described in Chapter 3. Taking the values in table 8.2 as being representative of the subsidence analysis area, the largest strain values occur in the period 1991-2002 and decrease in each successive period, 2002-2008 and 2008-2011 – similar to the ground level decrease described in section 8.2. Strain values in the 1991-2012 period range between c. 2 and 20 % (i.e. the original peat column has reduced by x %) and range between c. 0.02 and 4 % in the 2002- 2011 period. Between 2008 and 2012 peat thickness reduced by less than 2 % of its original thickness, which is still a significant figure.

Plots in Appendix E23 plot peat thickness and strain over time for the grid points listed in Table 7.2 and trends can be identified in a similar way to the way they were identified for surface level decreases (e.g. Figure 7.7). Table 7.2 summarises the trend type observed for peat thickness change over time and strain measures from periods between the ground level surveys. Similar subsidence trends of linear and exponential decrease may be observed for ground level decrease, peat thickness decrease and % strain decrease. There are some exceptions, such as at grid point G9, where ground level decrease is approximately linear, whereas peat thickness and strain decrease is approximately exponential – however, the relationships are approximate and more data points are required to substantiate such inference about subsidence trends. Overall, subsidence trend from ground level, peat thickness and strain measure are similar and from this, it seems that peat thickness does not limit

subsidence, but rather the permeability of the underlying subsoil seems to be the controlling factor, and this will be discussed further in section 7.8.

Table 7.2. Peat thicknesses and normal strain from selected bog grid points within the subsidence analysis area over time

| ID | GL Trend | Thickness Trend | Peat depth (m) | | | | Strain Trend | Strain (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1991 | 2002 | 2008 | 2012 | | 91-12 | 91 - 02 | 02 - 12 | 02 -08 | 08 - 12 |
| F11 | Exp | Exp | 8.50 | 7.69 | 7.68 | 7.68 | Exp | 9.7 | 9.6 | 0.2 | 0.09 | 0.06 |
| G9 | Linear | Exp | 9.20 | 8.94 | 8.93 | 8.92 | Exp | 3.0 | 2.8 | 0.2 | 0.14 | 0.09 |
| G11 | Exp | Linear | 8.40 | 8.18 | 8.14 | 8.09 | Exp | 3.7 | 2.6 | 1.1 | 0.48 | 0.58 |
| G12 | Linear | Linear | 8.30 | 7.99 | 7.94 | 7.87 | Exp | 5.2 | 3.7 | 1.4 | 0.60 | 0.82 |
| G13 | Level | Exp | 7.75 | 7.02 | 6.97 | 6.96 | Exp | 10.1 | 9.4 | 0.7 | 0.67 | 0.08 |
| H8 | Exp | Exp | 9.00 | 8.72 | 8.70 | 8.68 | Exp | 3.5 | 3.1 | 0.4 | 0.19 | 0.20 |
| H9 | Linear | Linear | 9.15 | 8.97 | 8.88 | 8.84 | Linear | 3.4 | 2.0 | 1.4 | 0.94 | 0.45 |
| H10 | Linear | Linear | 5.20 | 4.91 | 4.86 | 4.81 | Exp | 7.6 | 5.5 | 2.1 | 1.04 | 1.02 |
| I12 | Linear | Linear | 5.20 | 4.85 | 4.75 | 4.73 | Linear | 9.0 | 6.7 | 2.3 | 1.98 | 0.31 |
| J7 | Linear | Linear | 9.80 | 9.69 | 9.61 | 9.58 | Linear | 2.2 | 1.2 | 1.1 | 0.77 | 0.31 |
| J9 | Linear | Linear | 8.60 | 8.41 | 8.27 | 8.21 | Linear | 4.6 | 2.2 | 2.4 | 1.64 | 0.73 |
| J11 | Linear | Linear | 9.40 | 9.15 | 9.07 | 9.02 | Linear | 4.0 | 2.7 | 1.3 | 0.80 | 0.51 |
| J12 | Linear | Linear | 6.40 | 5.96 | 5.79 | 5.72 | Linear | 10.7 | 6.8 | 3.8 | 2.70 | 1.13 |
| J13 | Exp | Exp | 6.15 | 4.95 | 4.85 | 4.85 | Exp | 21.2 | 19.5 | 1.7 | 1.63 | 0.05 |
| J14 | Linear | Linear | 7.30 | 6.56 | 6.43 | 6.41 | Linear | 12.2 | 10.1 | 2.1 | 1.78 | 0.30 |
| J16 | Exp | Exp | 7.10 | 6.60 | 6.59 | 6.57 | Exp | 7.5 | 7.0 | 0.4 | 0.14 | 0.30 |
| K10 | Linear | Linear | 10.50 | 10.35 | 10.26 | 10.21 | Linear | 2.8 | 1.4 | 1.3 | 0.84 | 0.47 |
| K12 | Linear | Linear | 8.75 | 8.26 | 8.18 | 8.10 | Exp | 7.4 | 5.6 | 1.8 | 0.94 | 0.87 |
| L9 | Linear | Linear | 10.00 | 9.93 | 9.87 | 9.82 | Linear | 1.8 | 0.7 | 1.1 | 0.58 | 0.52 |
| L10 | Exp | Linear | 10.50 | 10.29 | 10.27 | 10.25 | Exp | 2.4 | 2.0 | 0.4 | 0.19 | 0.19 |
| L11 | Linear | Linear | 8.60 | 8.44 | 8.34 | 8.27 | Linear | 3.9 | 1.9 | 2.0 | 1.15 | 0.86 |
| L12 | Linear | Linear | 9.30 | 8.88 | 8.74 | 8.68 | Linear | 6.7 | 4.5 | 2.2 | 1.55 | 0.67 |
| L13 | Linear | Linear | 7.50 | 7.32 | 7.15 | 7.05 | Linear | 6.0 | 2.5 | 3.5 | 2.21 | 1.33 |
| L14 | Linear | Linear | 4.80 | 4.50 | 4.34 | 4.32 | Linear | 9.9 | 6.2 | 3.8 | 3.42 | 0.35 |
| L15 | Linear | Linear | 7.80 | 7.58 | 7.49 | 7.47 | Linear | 4.2 | 2.8 | 1.4 | 1.19 | 0.19 |
| L16 | Exp | Exp | 6.90 | 6.50 | 6.42 | 6.42 | Linear | 7.0 | 5.8 | 1.2 | 1.12 | 0.06 |
| L17 | Linear | Exp | 5.30 | 5.24 | 5.20 | 5.20 | Linear | 1.9 | 1.2 | 0.8 | 0.74 | 0.02 |

### 7.8. Rate of subsidence

Peat soils are highly compressible, and consequently water storage changes result in volume changes in the peat (Price, & Schlotzhauer 1991). Surface level subsidence is considered to be a result of lowering the water table, in underlying mineral subsoil and peat, which then induces drainage at the base of peat resulting in peat consolidation due to an increase in effective stress. The ground level decrease in the subsidence analysis area may therefore be attributed to water released from storage in the peat substrate, the volumes of which can then be used to calculate subsidence rates over time.

Table 7.2 lists the decrease in peat volume, attributed to water loss from peat due to peat consolidation, and subsidence/ seepage rate since 1991 in the subsidence analysis area – which, as described in sections 7.2 and 7.3, is where the majority of subsidence has occurred. As surface elevations were measured at the same location in each of the survey years, it is possible to calculate overall volume decease – essentially a mass balance type calculation. Assuming that the water drained from the peat substrate infiltrates downwards, an overall seepage rate of 0.06 mm/ day, between 1991 and 2011, has been estimated. Analysis of the periods between the 1991, 2002 and 2011 surveys calculates a seepage rate of 0.09 mm/ day between 1991 and 2002 and a seepage rate of 0.04 mm/ day between 2002 and 2011 – most of the subsidence occurred within the first 10 years following the creation of marginal drains, in accordance with the descriptions made in sections 7.2 and 7.3.

Table 7.3. Estimated decrease in high bog peat volume between 1991 and 2011 and estimated seepage rates to underlying mineral subsoil between topographic survey periods (see figures E7 to E9)

| | **1991 - 2011** | **1991 - 2002** | **2002 - 2011** | |
|---|---|---|---|---|
| **Volume loss:** | 324349 | 248903 | 75445 | $m^3$ |
| **Area:** | 712693 | 703375 | 647564 | $m^2$ |
| **Subsidence rate:** | 0.455 | 0.354 | 0.117 | m/ t years |
| **Seepage rate:** | 0.062 | 0.088 | 0.035 | mm/ day |

Note: Seepage rates are based on areas where there have been decreases in peat volume.

Table 7.4. Estimated decrease in high bog peat volume since 1991 and estimated seepage rates to underlying mineral subsoil between topographic survey periods in areas where ground level decrease is linear (see figure E22)

| | **1991 - 2011** | **1991 - 2002** | **2002 - 2011** | |
|---|---|---|---|---|
| **Volume loss:** | 139583 | 88505 | 51078 | $m^3$ |
| **Area:** | 303990 | 303990 | 303990 | $m^2$ |
| **Subsidence rate:** | 0.459 | 0.291 | 0.168 | m/ t years |
| **Seepage rate:** | 0.063 | 0.073 | 0.051 | mm/ day |

Table 7.5. Estimated decrease in high bog peat volume since 1991 and estimated seepage rates to underlying mineral subsoil between topographic survey periods in areas where ground level decrease is exponential (see figure E22)

| | **1991 - 2011** | **1991 - 2002** | **2002 - 2011** | |
|---|---|---|---|---|
| **Volume loss:** | 184765 | 160398 | 24366 | $m^3$ |
| **Area:** | 360720 | 351438 | 295638 | $m^2$ |
| **Subsidence rate:** | 0.512 | 0.456 | 0.082 | m/ t years |
| **Seepage rate:** | 0.070 | 0.114 | 0.025 | mm/ day |

Table 7.6. Estimated decrease in high bog peat volume between 2008 and 2011 (1142 days) and estimated seepage rates (see figure E10)

| | Total area | Linear | Exponential | |
|---|---|---|---|---|
| **Volume loss:** | 20337 | 14236 | 5846 | $m^3$ |
| **Area:** | 638162 | 331360 | 260209 | $m^2$ |
| **Subsidence rate:** | 0.032 | 0.043 | 0.022 | m/ t years |
| **Seepage rate:** | 0.028 | 0.038 | 0.020 | mm/ day |

The overall seepage rate, between 1991 and 2011, is similar in both subsidence zones – between 0.06 and 0.07 mm/ day. In the linear subsidence zone the seepage rate has decreased slightly from 0.07 mm/ day between 1991 and 2002 to 0.05 mm/ day between 2002 and 2011 (table 8.4). In the exponential subsidence zone the seepage rate has decreased from 0.11 mm/ day between 1991 and 2002 to 0.025 mm/ day between 2002 and 2011 (table 7.5). The results mirror the observation that subsidence is either linear, meaning the seepage rate remains relatively the same or it is exponential meaning the seepage rate is large at the start and become small/ levels out over time.

Table 7.6 lists the estimated seepage rate in the subsidence analysis area between 2008 and 2011. The overall seepage rate of 0.028 mm/ day is similar to that (0.035 mm/ day) calculated for the 2002 to 2011 period. Seepage where the rate of ground level decrease is linear and exponential has been calculated as being c. 0.04 and 0.02 mm/ day respectively – similar to the c. 0.05 and 0.03 mm/ day rates calculated for linear and exponential ground level decrease zones respectively in the 2002-2011 period.

## 7.9. Controls on subsidence

In section 7.5 the trend of subsidence was described and it was shown that there are two patterns to ground level and peat thickness decrease – linear and exponential. However it must be ascertained why one particularly area subsides differentially to another, particularly if predictions on the future morphology of the bog topography are to be made (Chapter 10). There are three main factors that will control the magnitude of ground level subsidence – (1) the hydraulic characteristics of the underlying subsoil, (2) the thickness of the peat substrate and (3) the hydraulic gradient of the groundwater table in peat and mineral subsoil.

### 7.9.1. Underlying geology

*Subsidence trend and subsoil type*

Figure F22 illustrates the areas with linear and exponential rates of ground level subsidence and the image map can be compared the subsoil geology map in Figure A2. The areas where there is a linear rate of ground level decrease are north and west of the Western Mound, in the Western Soak region – most of this area is underlain by till. There is also a linear trend east of the Bog Weir catchment – this

area is associated with sand/ subsurface peat cracking. The area to the north and northwest of Shanely's Lough is also one of linear ground level decrease and appears to be associated with the 'pool' of sand encountered in the vicinity of bog grid point G9.

The areas where the ground level subsidence rate is exponential are at the boundary of the high bog and in an area between the Western Mound and Shanely's Lough. The channel area supplying the Bog Weir is also an area of exponential decrease. The linear areas in the north of the subsidence area become exponential zones before becoming areas where relatively little subsidence is taking place. An area south of the Western Soak is also one of exponential ground level decrease but is separated by a north-south trending linear ground level decrease subsidence zone which trends into the 'large' area of linear ground level decrease between the Western Soak and the Western Mound. Overall, exponential ground level decrease areas are underlain by lacustrine clay and where such areas are underlain by till or sand, it is adjacent to the high bog margin.

The subsoil geology underlying the strain measurement locations are listed in Table E5 (Appendix E). Strain and ground level subsidence trends are linear in most locations where peat sits on till – with some exceptions such as J13, where a resistance exists between the peat column and the till subsoil. In Table 7.2, ten investigation points are underlain by lacustrine clay (sand is underlain by lacustrine clay) and six of these points have an exponential subsidence rate. However, a linear rate of subsidence is found at five investigation points underlain by lacustrine clay – H9, J7, J11, J14 and K10. However, with the exception of investigation point J7 and J9, the afro-mentioned investigation points are located close, < 100 m, to the lacustrine clay-till boundary.

Peat thickness has reduced by c. 40 cm at j9 and by c. 20 cm at l9 since 1991 – significant subsidence in areas without a 'permeable' underlying subsoil unit. Viewing figure E22 it may be observed that a significant proportion of high bog is underlain by lacustrine clay, north of the Western Mound, and ground level subsidence is increasing at a linear rate. The base of peat is being drained but it is unclear how – the area may have sand lenses overlying the lacustrine clay or there is a drainage pathway in the peat to areas of the more permeable till subsoil. However, it is clear, and significant, that peat consolidation is not limited to areas where peat sits on till – the peat can also drain in areas where it sits on lacustrine clay, implying water may move laterally in the lower margins of the peat body, perhaps through a series of cracks before infiltrating downwards where there is more permeable till subsoil – assuming that no/ little water flows laterally through the peat body itself.

*Subsidence rate and subsoil type*

Seepage rates have been calculated at each surveyed bog grid location within the subsidence analysis area for (1) the whole peat column and (2) per unit thickness of peat in the peat column (i.e. settlement rate). Tables 7.7 to 7.9 summarise this data for the periods 1991-2002, 2002-2011 and 2008-2011. The seepage, or subsidence, rates are separated based on what the underlying subsoil

beneath the peat is – i.e. lacustrine clay, sand or till. Additionally, the subsidence rates are divided into areas where ground level decrease is linear and exponential.

Water released from the peat column

Tables 7.7 to 7.9 all clearly indicate that the subsoil type underlying the peat substrate in the high bog strongly controls the subsidence rate, in both linear and exponential ground level decrease areas. In the period 1991-2012, the subsidence rate from the peat column in areas of exponential decrease and underlain by lacustrine clay was on average c. 25 mm/ year. This rate increased by c. 35 % to 37 mm/ year in areas underlain by sand and by c. 55 % to 45 mm/ year in areas underlain by till. Similarly, in the linear subsidence areas, the subsidence rate from the peat column has been calculated as 15, 28 and 35 mm/ year in areas underlain by lacustrine clay, sand and till respectively. Subsidence rates are c. 40 %, 25 % and 20 % higher in the 'exponential' zone between 1991 and 2002, implying these areas of the high bog subside rapidly before gradually levelling off (i.e. a subsidence lag) over time.

Table 7.7. Estimated subsidence rate for peat column in linear and exponential subsidence areas underlain by differing subsoil lithologies

| | 1991 - 2002 | | | 2002 - 2011 | | | 2008 - 2011 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Rate** | mm/ year | | | mm/ year | | | mm/ year | | |
| **Subsoil** | Lac | Sand | Till | Lac | Sand | Till | Lac | Sand | Till |
| **Exp** | 24.6 | 37.1 | 44.9 | 3.4 | 6.4 | 8.9 | 3.4 | 5.7 | 4.6 |
| **Linear** | 15.1 | 17.7 | 27.8 | 12.7 | 10.4 | 18.5 | 10.4 | 12.9 | 14.0 |

The subsidence rates differ in the 2002-2011 analysis period. In the exponential ground level decrease area, subsidence rates from the peat column have been calculated as c. 3, 6 and 9 mm/ year in areas underlain by lacustrine clay, sand and till respectively. These rates are substantially different to those calculated from the 1991-2002 period – less than 20 %. However, it is significant that subsidence rate doubles and triples in the sand and till areas respectively compared to the lacustrine clay areas. In the linear zone of subsidence area, subsidence rates from the peat column have been calculated as c. 13, 10 and 19 mm/ year in areas underlain by lacustrine clay, sand and till respectively –less than c. 15 %, 40 % and 35 % of the values calculated in the 1991-2002 period. However, the subsidence rates are significantly higher, > 40 %, in the linear subsidence areas compared to the exponential subsidence areas. As such, subsidence rate is high initially in the exponential zone and decreases substantially over time, whereas subsidence is also high in the linear zone initially and decreases over time, but is still significantly higher than in exponential zones – regardless of subsoil type.

In the most recent subsidence analysis period, 2008-2011, the subsidence trend is similar to the overall subsidence trend in 2002-2011. In the exponential ground level decrease area, subsidence rates from the peat column have been calculated as c. 3, 6 and 5 mm/ year in areas underlain by lacustrine

clay, sand and till respectively. In the linear zone of subsidence area, subsidence rates from the peat column have been calculated as c. 10, 13 and 14 mm/ year in areas underlain by lacustrine clay, sand and till respectively. The subsidence rates are similar to that in the 2002-2011 period, though the subsidence rate in the areas underlain by till appears to be decreasing slightly.

Water released per unit thickness of peat

The section above describes the subsidence rates calculated for volume loss from the entire peat column over successive time periods. However, a more appropriate analysis is to calculate subsidence per unit thickness of peat as differing thicknesses of peat will invariably release different quantities of water from peat storage - table 7.8 summarises this data.

Table 7.8. Estimated subsidence rate for peat column in linear and exponential subsidence areas underlain by differing subsoil lithologies

| | 1991 - 2002 | | | 2002 - 2011 | | | 2008 - 2011 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Rate** | mm/ year/ m peat | | | mm/ year/ m peat | | | mm/ year/ m peat | | |
| **Subsoil** | Lac | Sand | Till | Lac | Sand | Till | Lac | Sand | Till |
| **Exp** | 2.7 | 4.8 | 6.4 | 0.4 | 0.9 | 1.4 | 0.4 | 0.8 | 0.7 |
| **Linear** | 1.7 | 2.1 | 5.0 | 1.4 | 1.3 | 2.6 | 1.2 | 1.6 | 1.9 |

The subsidence rate per one meter of peat mirrors the observations made for calculations based on the whole peat column thickness. In the exponential subsidence zone, subsidence rate is higher than in the linear zone in the period 1991-2002. Subsidence rate per meter of peat is c. 3, 5 and 6 mm/ year/ m of peat in areas underlain by lacustrine clay, sand and till respectively, compared to subsidence rates of c. 2, 2 and 4 mm/ year/ m of peat respectively. The subsidence rates differ in the 2002-2011 analysis period. In the exponential ground level decrease area, subsidence rates from the peat column have been calculated as c. 0.4, 0.9 and 1.4 mm/ year/ m of peat in areas underlain by lacustrine clay, sand and till respectively. These rates are substantially different to those calculated from the 1991-2002 period – less than c. 20 %. The subsidence rates are also significantly higher in the sand and till areas compared to the lacustrine clay areas. In the linear zone of subsidence area, subsidence rates from the peat column have been calculated as c. 1.4, 1.3 and 2.6 mm/ year/ m of peat in areas underlain by lacustrine clay, sand and till respectively –less than c. 18 %, 40 % and 48 % of the values calculated in the 1991-2002 period. However, the subsidence rates are significantly higher, > 30 %, in the linear subsidence areas compared to the exponential subsidence areas - in the 2002-2011 analysis period.

In the most recent subsidence analysis period, 2008-2011, the subsidence trend is similar to the overall subsidence trend in 2002-2011. In the exponential ground level decrease area, subsidence rates from the peat column have been calculated as c. 0.4, 0.8 and 0.7 mm/ year/ m of peat in areas underlain by lacustrine clay, sand and till respectively. In the linear zone of subsidence area,

subsidence rates from the peat column have been calculated as c. 1.2, 1.6 and 1.9 mm/ year/ m of peat in areas underlain by lacustrine clay, sand and till respectively. The subsidence rates are similar to that in the 2002-2011 period, though the subsidence rate in the areas underlain by till appears to be decreasing slightly.

However, it is clear that subsidence rate, whether per unit thickness of peat substrate, or through the entire peat column, is significantly influenced by the underlying subsoil lithology. In areas where lacustrine clay is absent and is underlain by sand or till subsoil, the subsidence rate increases significantly. The magnitude of subsidence rate becomes more apparent over time – initially, within the first 10 years, subsidence is greatest in areas which later become exponential zones of ground level decrease. The subsidence rate in these areas slows down considerably, but a more steady rate of subsidence in encountered in linear zones of ground level decrease, rates of which do not appear to be reaching a steady state consolidation equilibrium.

### 7.9.2. Peat thickness

The degree of subsidence varies across the bog and section 7.2 indicates that this variability is a function of the underlying subsoil type in connection with peat substrate in areas of the bog affected by marginal drainage. However, the thickness of the peat substrate may also dictate how much subsidence occurs – or is allowed to occur, with thicker columns of peat presumably having greater, overall, rates of subsidence.

Subsidence rates per unit thickness of peat, or settlement, have been calculated through the whole peat column for high bog areas underlain by lacustrine clay, sand and till. Table 7.9 summarises this data and compares the data for different peat depth zones in areas of linear and exponential ground level decrease underlain by lacustrine clay, sand or till.

Table 7.9. Mean settlement rates (mm/ year/ m) and peat depths for areas underlain by till, sand and lacustrine clay in zones of exponential and linear ground level decrease

| **Subsoil type** | **1991 - 2002** Peat depth (m) | | | | **2002 - 2011** Peat depth (m) | | | |
|---|---|---|---|---|---|---|---|---|
| **Till** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** |
| **Exp** | 11.2 | 6.7 | 5.1 | 3.7 | 2.4 | 1.4 | 1.2 | 0.7 |
| **Linear** | 5.6 | 4.8 | 2.8 | 2.5 | 3.2 | 3.1 | 2.9 | 1.4 |
| **Sand** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** |
| **Exp** | n/a | n/a | 7 | 2.6 | n/a | n/a | 1.1 | 0.6 |
| **Linear** | n/a | n/a | 2.7 | 2 | n/a | n/a | 1.3 | 1 |
| **Lac** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** | **< 6.0** | **6.0 - 7.0** | **7.0 - 8.0** | **> 8.0** |
| **Exp** | n/a | n/a | n/a | 1.9 | n/a | n/a | n/a | 0.4 |
| **Linear** | n/a | n/a | n/a | 1.5 | n/a | n/a | n/a | 1.5 |

Note: 1991-2002 subsidence calculation based on peat depth measured in 1991 and 2002-2011 subsidence calculation based on peat depth estimated in 2011.

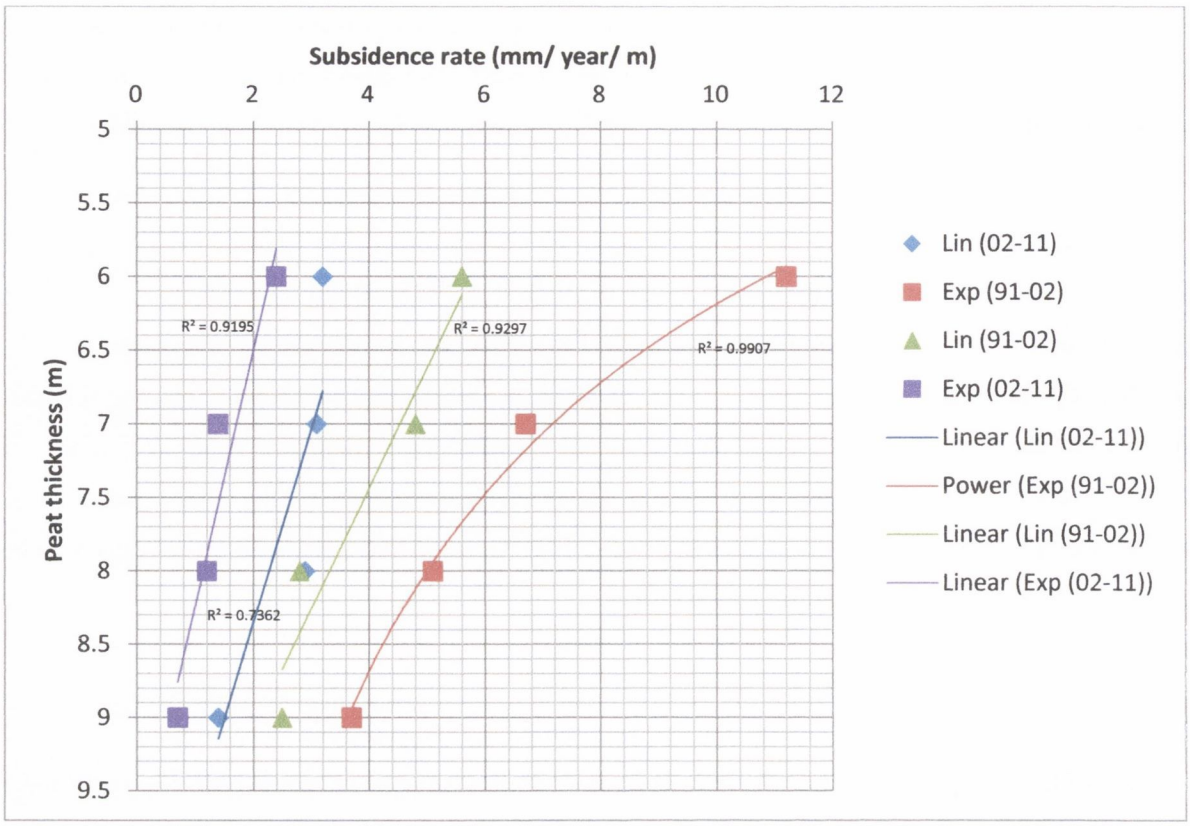


**Figure 7.8.** Subsidence rate and peat depth in linear and exponential ones of ground level decrease between 1991-2002 and 2002-2011.

The results in table 7.9 indicate that there is a relationship between subsidence rate and peat depth. In the 1991-2002 analysis period there is a marked decrease in subsidence rate with peat depth in both the exponential and linear zones. The greatest level of subsidence occurs when peat is < 6.0 m thick, c.11 mm/ year/ m and 6 mm/ year/ m in the exponential and linear zone respectively, and decreases when peat depth is greater than 8.0 m, with subsidence rates of c.4 mm/ year/ m and 3 mm/ year/ m in the exponential and linear zone respectively. Similar trends are observed in the 2002-2011 analysis period, though the level of subsidence in the exponential zone decreases substantially – as noted and described in section 8.6. Figure 8.1 plots subsidence rate versus peat depth (a representative peat depth is used here) and clear linear rates of subsidence rate decrease per meter of peat can be observed – interestingly, in the 1991-2002 period, the trend follows a power-law relationship, indicating rapid subsidence, which was also noted and described in section 7.7.

In the areas of peat underlain by sand and lacustrine clay peat depths are generally greater than 8.0 m. Subsidence rate in the lacustrine clay areas ranges between 0.4 and 2 mm/ year/ m and does not appear to vary significantly with depths greater than 9.0 or 10.0 meters. In the areas underlain by sand, subsidence rate does decrease with depth. In the 1991-2002 analysis period subsidence rate in the exponential zone was c. 7 mm/ year/ m where peat depth was < 7.0 m and decreased to c. 3 mm/ year/ m in areas where peat depth was > 8.0 m. This pattern persists in to the 2002-2011 analysis period with subsidence rates decreasing from c. 1.0 mm/ year/ m to 0.5 mm/ year/ m. In the linear

ground level decrease zones the decrease in subsidence rate is not as pronounced. In the 1991-2002 analysis period subsidence rate in the exponential zone was c. 3 mm/ year/ m where peat depth was < 7.0 m and decreased to c. 2 mm/ year/ m in areas where peat depth was > 8.0 m. This pattern persists in to the 2002-2011 analysis period with subsidence rates decreasing from c. 1.3 mm/ year/ m to 1.0 mm/ year/ m.

### 7.9.3. Relationship with geohydrology

In section 7.8.1 the relationship between subsidence rate and underlying subsoil type was described. However, this relationship must be placed into context – it is not the mere existence of a more permeable lithology underlying peat that allows drainage from the base of peat, but rather, it is the interaction between the flow dynamics in the high bog and regional groundwater system, induced by the marginal drainage system adjacent to the high bog, that has initiated subsidence. Chapter 8 will describe this relationship in more detail.

## 7.10. Conclusions

Subsidence analysis shows that the rate of ground level decrease follows two trends – linear and exponential. Areas of exponential decrease subside rapidly, in the first 10 years, before seemingly slowing down, and linear rates of decrease continue, at an almost constant rate, to subside over time. Subsidence is not limited to the margins of the high bog – it propagates beyond the centre of the bog. Ground level subsidence > 1.0 m and > 0.5 m occurs within c. 200 m and 500 m of the high bog-cutover boundary respectively and subsidence > 0.1 m and > 0.2 m occurs within 900 m and 700 m respectively of the bog boundary.

The cause of the deformation is considered to be drainage from the base of peat due to a drop in hydraulic head associated with marginal drainage, which has reduced the water content of the peat substrate and increased the effective stress on the peat. Similar to ground level change, largest strain values occur in the period 1991-2002 and decrease in each successive period, 2002-2008 and 2008-201. Strain values in the 1991-2012 period range between c. 2 and 20 % and range between c. 0.02 and 4 % in the 2002- 2011 period.

Over the subsidence analysis area, the seepage rate, or water loss rate, is 0.09 mm/ day between 1991 and 2002 and 0.04 mm/ day between 2002 and 2011 – most of the subsidence occurred within the first 10 years following the creation of marginal drains. The overall seepage rate, between 1991 and 2011, is similar in both subsidence zones – between 0.06 and 0.07 mm/ day. In the linear subsidence zone the seepage rate has decreased slightly from 0.07 mm/ day between 1991 and 2002 to 0.05 mm/ day between 2002 and 2011. In the exponential subsidence zone the seepage rate has decreased from 0.11 mm/ day between 1991 and 2002 to 0.025 mm/ day between 2002 and 2011.

Subsidence analysis shows that leakage rate is strongly controlled by the subsoil unit underlying the peat aquifer. Between 2002 and 2011, areas underlain by lacustrine clay in exponential decrease zones decreased by 3 mm / year and 12 mm/ year in linear zones. In areas underlain by till the decrease were 9 mm/ year in exponential zones and 19 mm/ year in linear zones. Subsidence is an order of magnitude bigger in areas underlain by till – but subsidence propagates into lacustrine clay areas as the potentiometric surface decrease, and vertical hydraulic gradient increase, extends beyond the areas of till-peat interface. In areas underlain by sand the decrease were 6.4 mm/ year/m in exponential zones and 10.4 mm/ year in linear zones.

Peat thickness controls the rate of settlement - between 2002 and 2001, areas underlain by lacustrine clay in exponential decrease zones decrease by 0.4 mm/ year/ m and 1.4 mm/ year/m in linear zones. In areas underlain by till the decrease were 1.4 mm/ year/m in exponential zones and 2.6 mm/ year in linear zones. In areas underlain by sand the decrease were 0.9 mm/ year/m in exponential zones and 1.3 mm/ year in linear zones.

# 8. Subsurface Drainage

## 8.1. Introduction

It is clear that ground level decrease on the high bog is inextricably associated with hydrology – the hydrogeological data (i.e. downward seepage rates; Section 5.8) and hydrochemical data (i.e. recharge rates; Section 6.9) implies that the leakage rate through the high bog has increased since the work by Van der Schaff (1999) and this will be demonstrated in Chapter 9. There are areas of high bog hydraulically linked with the potentiometric surface in the till groundwater body. Marginal drainage has lowered the regional groundwater table at the margins of Clara Bog West and drains in the Clara West drainage system are zones for groundwater discharge. Subsidence analysis in chapter 7 conclusively shows that peat substrate is releasing water from storage due to the drop in pore water pressure associated with the drop in the regional groundwater table, or potentiometric surface, in the till groundwater body. Peat consolidation is associated with areas where there is a subsurface drainage pathway and the geo-hydrological analysis show that these areas are those where peat sits on till subsoil or sand lenses, each of which whose regional body have been intercepted by drains, in cutover bog, thereby facilitating the discharge outlet for subsurface flow.

To put the various strands of hydrological and subsidence analysis into context, three hydrogeological cross-sections through groundwater flow lines have been drawn. The flow lines are drawn where (1) there is instrumented piezometry measuring water level in peat and till units and (2) the ground level of the high bog has decreased, in the order of > 0.5 m, since 1991. The flow line hydrogeological cross-sections will inform the development of the conceptual model that will be the basis of numerical model for the groundwater system in chapter 11. However, before the examination of subsurface drainage pathways, the drop in water level, or water pressure, in till and peat is described.

## 8.2. Water level decrease

The hydrological and subsidence analysis clearly indicates that a drop in vertical hydraulic gradient is inducing an increased vertical flow in the peat substrate – the ground level profiles indicate the degree to which peat has lost water; indicated by the respective volume changes. As such, there should be a corresponding drop in hydraulic head (not necessarily linear), both in the till groundwater body and in the peat body. A comparison between water levels measured in the 1990's, and since 2009 in the present study, will indicate to what extent water level has dropped in the till and peat deposits of Clara West.

### 8.2.1. Regional groundwater table

*Measurements in the 1990s*

In the early 1990's, the geological survey of Ireland (GSI) installed a series of boreholes surrounding Clara Bog with piezometer installations into bedrock, the base of subsoil and when appropriate, to the

base of peat. A number of these installations no longer exist and those that do exist, and are functioning, are illustrated in Appendix A, and have been monitored during the course of this study (Chapter 3).

Historic measurements of the piezometric level in bedrock and mineral subsoil (till) were taken from September 1990 to October 1992 by van den Boogaard (1993) and from May 1996 to August 1997 by Gill (1997). During the course of this study, intermittent measurements have been taken from March 2009 and regularly (bi-weekly) from September 2009 until August 2011.

*Comparison with recent water levels*

A comparison of historic and recent mineral subsoil piezometric water levels at installations CLBH2, CLBH5, CLBH6, CLBH9, CLBH11 and CLCD3 is illustrated on the hydrographs in Appendix F, Figures F1 to F6. To avoid misinterpretation, all piezometric levels from 1990-1992, 1996-1997 and 2009-2010 have been referenced to the same datum, Malin Head mOD, so that relative 'changes' in water level are real and not a result of levelling inaccuracies. Table 8.1 lists the average differences in mineral soil water level between the respective monitoring periods and Figure 8.1 compares piezometric water levels from the 1990's to 2009/2010 at CLBH5, CLBH6, CLBH9 and CLCD3.

Table 8.1. Average water level difference in mineral subsoil (till) piezometers CLBH5, CLBH6, CLBH9 and CLCD3 between monitoring periods of 1990/1992 and 2009/2010.

| ID | Mean WL Difference | Max WL Difference | Min WL Difference | n (1992) | n (2010) |
|---|---|---|---|---|---|
| **CLBH5** | 0.72 | 0.88 | 0.61 | 28 | 28 |
| **CLBH6** | -0.02 | 0.1 | 0.1 | 15 | 23 |
| **CLBH9** | -0.09 | -0.03 | -0.16 | 5 | 8 |
| **CLCD3** | 0.5 | 0.5 | 0.6 | 10 | 13 |

Note: *water level difference is an increase over particular period. N/A implies no water level measurements were made at installation over particular time period.

*Level of decrease*

Table 8.1 lists the average differences in mineral soil water level between the respective monitoring periods. The results in Table 8.1 show that the mean regional groundwater head/ piezometric level has decreased locally at CLBH5 and CLCD3, by c. 0.72 m and 0.5 m respectively, since the monitoring period 1991/1992 (monitoring carried out by Van den Boogaard, 1992). The changes are localized in the area where intensive peat cutting was carried out in the Restoration Area. The average regional groundwater head at the other locations, BH6 and B9, have increased marginally since 1991/1992. It is most probable the increases are a result of natural fluctuations and a sparse monitoring record – importantly there is no evidence of a decreased groundwater head as indicated at CLBH5 and CLCD3.

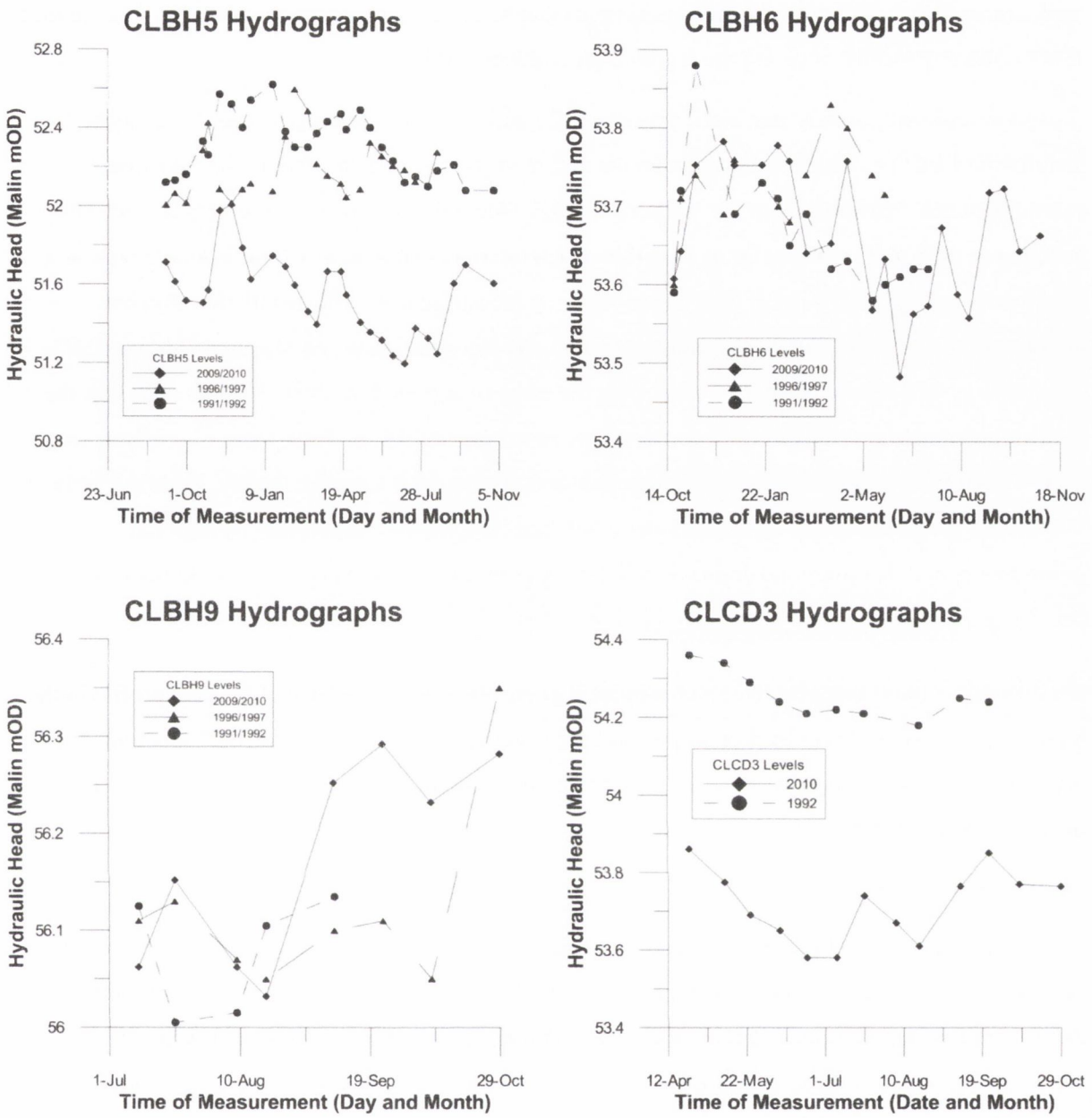


**Figure 8.1.** Hydrographs of mineral subsoil piezometric water levels from 1991/1992 to 2009/2010 at CLBH5, CLBH6, CLBH9 and CLCD3. Note: all levels are referenced to the same datum to avoid levelling inaccuracies.

The decrease in piezometric water level at CLBH5 and CLCD3 is significant. CLBH5 is located c.80 m southeast of the southern margin of Clara Bog West. It is located in an area where till drain TD2 is < 2.0 m below the ground surface. Viewing transect T3 (Figure C19; Appendix C) it is clear that the till in this area is part of the 'till body' that runs through to the Western Mound on the high bog. Groundwater flow patterns, described in Section 5.6, indicate that water movement is from the south western area of Clara Bog West. From Figure 8.1, the piezometric water level in the till at CLBH5 decreased by an average of 0.18 m between 1990/1992 and 1996/1997 and by an average of 0.48 m between 1996/1997 and 2009/2010. Thus, there has been a clear drop in water level at CLBH5 since the early 1990's. It is no coincidence that CLBH5 is located within 60 to 160 m of the drains and face-

bank drains (i.e. the Clara West drainage system) that began extending into the till subsoil in the mid 1990's, thereby locally lowering the regional groundwater table.

A drop in regional groundwater level, between c.0.3 and 0.5 m, has also been recorded at subsoil installation CLCD3 , which is located near the centre of the bog and adjacent to the till ridge, extending north-eastwards from the Western Mound, where the lacustrine clay unit is absent. The installation does not extend as far as the till-bedrock interface but rather its filter is located in the upper margins of the till subsoil which is overlain by lacustrine clay. The installation was not monitored in 1996/1997 but was monitored by van den Boogaard between May and October 1992. Comparison with recent monitoring data, over the same time period in 2009/ 2010, reveals that the relative piezometric water level has decreased by an average of 0.5 m. Thus, there is evidence from CLBH5 and CLCD3 that the regional groundwater table has been lowered, locally, since the early 1990's and feeds into the conceptual model that Clara Bog West is 'supported' by regional groundwater and that marginal drainage is inducing groundwater discharge that would not ordinarily

#### 8.2.2.Deep peat piezometric level

If a drop in regional groundwater level is inducing consolidation at the base of the peat profile in the high bog, there should also be drop in piezometric water level at the base of the peat substrate due to subsurface drainage – thereby increasing the hydraulic gradient from the phreatic water table to deep peat piezometer water level.

*Measurements in the 1990s*

An extensive network of piezometer nests was installed on Clara Bog West in the early 1990's, the details of which were described in Chapter 3. The majority of these piezometer nests have survived to the present day and their locations are illustrated on the piezometer location map in Appendix A10. A number of these piezometer nests are located on the monitoring transects and were monitored frequently between July 2009 and January 2011.

Water level monitoring of piezometers installed in the early 1990s were measured by a number of students, the data of which was not easily available. However, the water level measurements and levelling data from this period was provided by Sake Van der Schaff in November 2010. As many of the original piezometers have been cut due to damage and many other piezometers have 'subsided' due to peat compaction, it was important to use the 1990 water levels corrected to Malin Head reference datum. Monitoring of the same piezometers, which have been re-levelled, in 2009, 2010 and early 2011 thereby allowed a comparison between water levels spanning near twenty years. The comparison is based on levels referenced to the Malin Head datum and checks were performed to unsure the 1990 levelling was accurate and set to the same levelling base point as the more recent TCD surveys.

*Comparison with recent water levels*

Table 8.2 lists average water levels from 1990-1993 and 2009-2011 and the differences between them. A contour map of the drop in water level is illustrated in Figure 8.2. It is clear that there has been a significant drop in deep peat water level in the area between the Western Soak and Shanely's Lough – similar to that described for the level of ground level decrease in section 8.1.1. The biggest drop in water level, > 1.0 m, occurs at piezometers 47 and 57, which are located east of the Western Mound in an area where sand lenses underlie the high bog peat. These piezometers are also located close to the Western Mound. It also appears that sub-surface drainage, associated with underlying till, has propagated north of the Western Mound, as indicated by the drop in piezometer level at piezometer nest 94, which is underlain by lacustrine clay. The same inference was made in Chapter 7 regarding the level of surface level decrease.

Table 8.2. Average water levels (Malin mOD) and average decrease in water level from monitoring of deep peat piezometers between 1990-1993 and 2009-2010

| ID | 1990 | 2010 | Diff. | ID | 1990 | 2010 | Diff. |
|---|---|---|---|---|---|---|---|
| 47 | 55.1 | 53.96 | 1.14 | 87 | 54.72 | 54.71 | 0.01 |
| 48 | 55.23 | 54.39 | 0.84 | 88 | 55.28 | 55.2 | 0.08 |
| 50 | 55.03 | 54.31 | 0.72 | 89 | 55.33 | 55.13 | 0.2 |
| 54 | 54.75 | 54.26 | 0.49 | 90 | 55.19 | 54.85 | 0.34 |
| 55 | 54.94 | 54.55 | 0.39 | 91 | 54.9 | 54.55 | 0.35 |
| 56 | 55.36 | 54.93 | 0.43 | 92 | 55.01 | 54.33 | 0.68 |
| 57 | 55.43 | 54.43 | 1 | 93 | 55.94 | 55.21 | 0.73 |
| 59 | 54.35 | 53.75 | 0.6 | 94 | 56.45 | 55.64 | 0.81 |
| 61 | 54.04 | 52.35 | 1.69 | 96 | 57.11 | 56.71 | 0.4 |
| 63 | 53.24 | 52.39 | 0.85 | 96 | 56.76 | 56.29 | 0.47 |
| 67 | 52.88 | 52.18 | 0.7 | 97 | 56.75 | 56.41 | 0.34 |
| 70 | 54.59 | 53.75 | 0.84 | 98 | 57.83 | 57.55 | 0.28 |
| 82 | 50.59 | 50.6 | -0.01 | 99 | 57.87 | 56.57 | 1.3 |
| 83 | 50.82 | 50.74 | 0.08 | 901 | 55.99 | 55.53 | 0.46 |
| 86 | 53.36 | 53.25 | 0.11 | 902 | 55.61 | 55.15 | 0.42 |

The contours also suggest that deep peat water level has dropped by c. 0.4 m at both the Western Soak and Shanely's Lough. However, there is a lack of information between the Western Soak and the Western Mound – the level of decrease is most probably correlated with the level of ground level decrease, which in certain areas, such as at piezometer next 909, is > 1.0 m. While drainage through till appears to affect the Western Soak, drainage induced by the sand lense/ palaeochannel affects Shanely's Lough, possibly in tandem with till drainage. The complicated contour pattern between the Western Mound and Shanely's Lough suggests that both till and sand pathway drainage is operating in this area of the high bog.

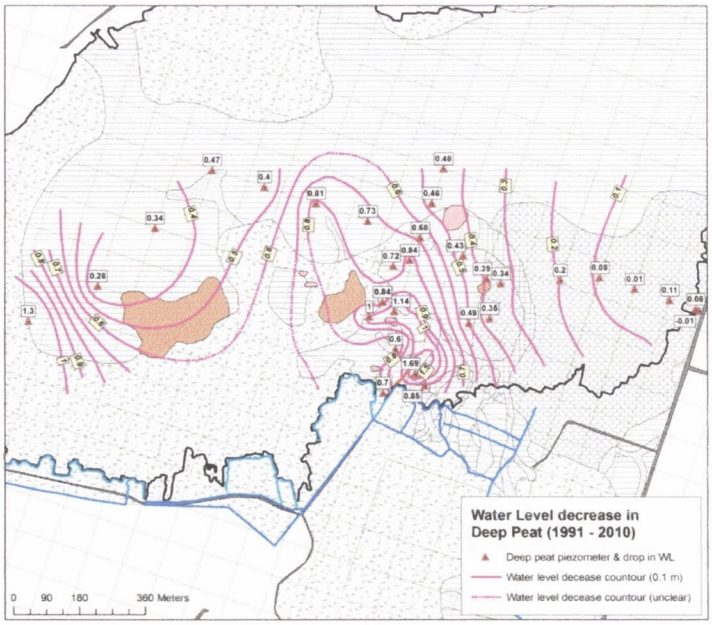


**Figure 8.2.** Average water level decrease in piezometers at base of peat between 1990-1993 and 2009-2011

Table 8.3 and Figure 8.3 compare the decrease in deep peat piezometric level with the decrease in ground level between 1991 and 2009/ 2011 at OPW bog grid points h8, h9, h10 and h11. The comparison suggests there is a clear link between a decrease in pore water pressure (i.e. piezometer level) in peat and the decrease in high bog ground level. However, only four data points are available in which to perform the analysis – so while the results make intuitive sense and compliment the hydrogeological and subsidence analysis described thus far, it is far from definitive due to the low number of data points used.

Table 8.3. Comparison between decrease in deep peat water level and ground level (1991-2011)

| ID | Tube | WL (m) | GL (m) |
|---|---|---|---|
| h8 | 901 | 0.46 | 0.40 |
| h9 | 902 | 0.42 | 0.38 |
| h10 | 92 | 0.68 | 0.43 |
| h12 | 47 | 1.14 | 0.47 |

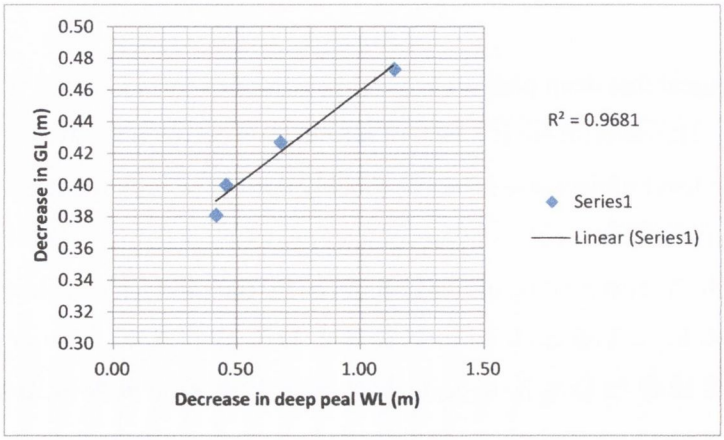


**Figure 8.3.** Deep peat water level versus surface ground level (1991-2011)

*Level of decrease*

It is interesting to note on Figure 8.2 that there has been little or no drop in deep peat water level on the western-most margins of the high bog, with a gradual decrease in water level eastwards towards Shanely's Lough. This suggests the eastern most section of Clara Bog West has reached equilibrium and will subside no more.

The other interesting observation to make from Figure 8.2 is the drop in water level at piezometer 99. Ground level has decreased in this area since 1991, implying the drop in deep peat water level has induced subsidence in this area. The face-bank to the west of piezometer 99 has not been cut below regional groundwater level, which is known from drain surveying. However, the marginal drain TD3 is below regional groundwater level. Subsoil piezometer 929 recorded a groundwater level of 55.46 mOD in January 2011 and a spot level of 54.23 mOD at the base of drain TD3, close to 929, has been measured. It therefore appears that TD3 is an important drain and has induced a local drop in groundwater level underneath the high bog. Subsidence has not occurred to the extent as it has in the Western Mound area, and this may be due face-bank drains (i.e. FB3) not being cut below regional groundwater level.

## 8.3. Subsurface drainage and ground level decrease

The inferences made in Chapter 7 and Section 8.1 that the level of ground level subsidence is dictated by (1) underlying subsoil type and (2) hydraulic gradient, can be substantiated by simply analysing a 2D section through a section of the bog where water loss from the peat substrate is known to have occurred. Figures F7 to F13 in Appendix F illustrates the flow line location maps and the hydrogeological cross-sections. Also illustrated on the sections is the surface level of the bog in 2008, which was used to draw the section topography and the surface ground level in 1991.

### 8.3.1.Flowline transects

The flow lines are drawn within the subsidence analysis area and the level of ground level subsidence between 1991 and 2011 and between 2008 and 2011 are illustrated together with the regional groundwater table in till, as it is now, and the subsoil geology. The cross-sections are similar to those described in chapter 5. However, in section 5.4, the hydrogeological cross-sections were drawn through the water level monitoring transects. The monitoring transects were positioned based on the perceived groundwater flow directions at the beginning of the hydrological study in 2009. The information gathered over the monitoring period, between August 2009 and August 2011, better described the groundwater system, as shown in the potentiometric surface contour maps in Appendix F, and the groundwater flow directions, in the peat and till bodies, are now well understood, particularly in the Western Mound area.

As such, the flow line transects are parallel to the groundwater flow direction in the till groundwater body from areas on the high bog to the marginal drainage system (Figure F1; Appendix F). Flow line 1 tracks the perceived groundwater flow line from piezometer next 905, located on the south western margin of the Western Soak, through to subsoil piezometer nest 908, which is located on a subsurface till mound, and the flow line direction then changes from a northeast flow direction to an easterly – southeast flow direction between the Western Soak and the Western Mound and then proceeds to pass through piezometer nest td9 and subsoil piezometer nest 909 by the Western Mound and the transect finishes by passing through subsoil piezometer nest 912, face-bank drain piezometer nest 914 before terminating at cutover bog subsoil piezometer nest 915.

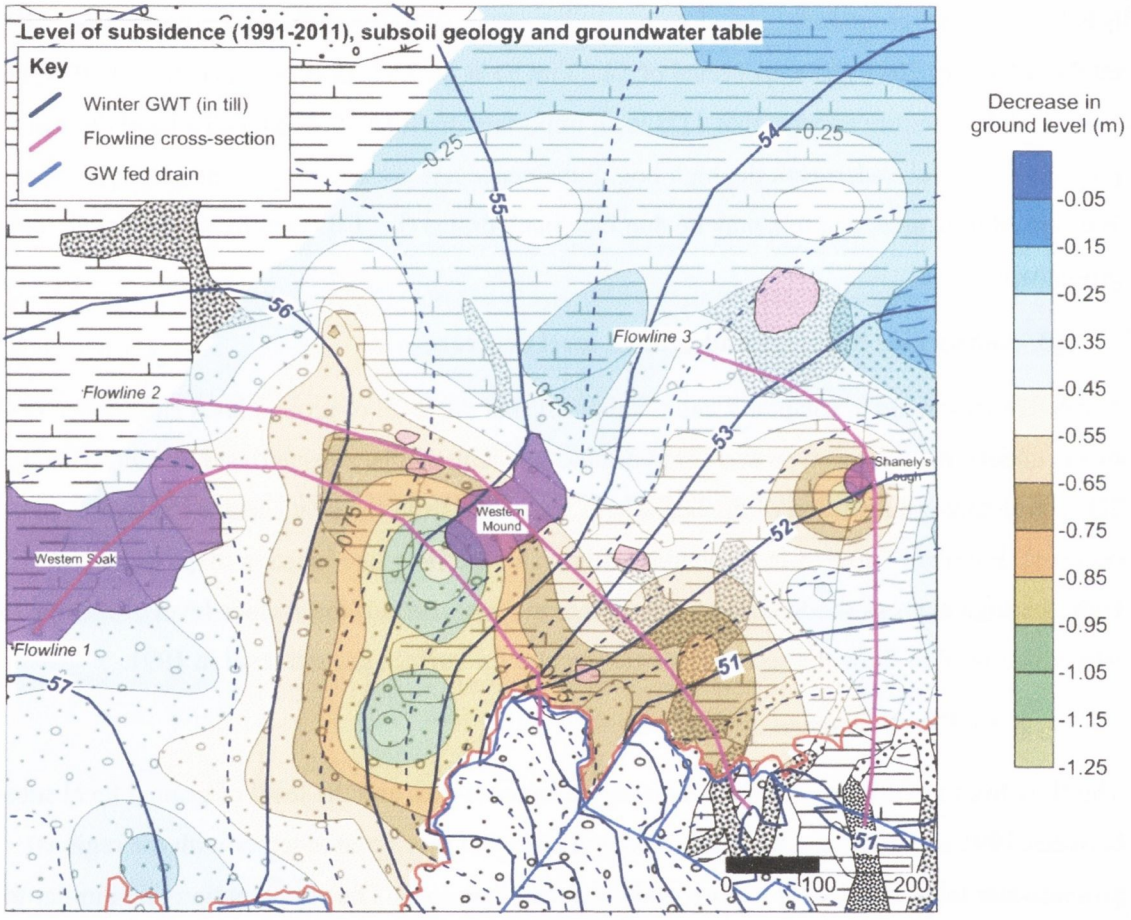


**Figure 8.4.** Flow line locations, subsoil geology, high level potentiometric surface in till and 1991-2011 ground level (see appendix F).

Flow line 2 tracks the perceived groundwater flow line starting c. 80m north of piezometer next 904, located on the north eastern margin of the Western Soak, and flows in a south-easterly direction passing through piezometer nests tdK12, t5 and tdJ12 on the western side of the Western Mound, and then flows through the Western Mound, passing through deep peat piezometer 945 before passing through subsoil piezometer nest 910 on the eastern side of the Western Mound. From piezometer nest

910, the transect flows southeast through high bog piezometers td4, 59 and 62 before crossing face-bank drain piezometer nest 923 before terminating at cutover bog subsoil piezometer nest 920.

Flow line 3 is located northeast of the Western Mound and begins at high bog piezometer nest 92, which is underlain by an extension of the Western Mound till ridge. From piezometer nest 92, the transect flows eastwards through piezometer nests 937 and 56, before flowing southwards through Shanely's Lough at piezometer nest 55 and then flows through piezometer nest 91 before crossing the high bog boundary and terminating at subsoil piezometer nest 927 in the Restoration Area. Flow line 2 is not as well instrumented as flow lines 1 and 2, in a large part because the area with a lack of piezometry is underlain by > 3.0 m of lacustrine clay. The installation of a subsoil piezometer (chapter 3) was attempted in this area in April 2010, but the highly resistance lacustrine clay subsoil made installation of a piezometer to underlying till impossible. However, there is still enough information available to make accurate inferences on groundwater flow movements in this area.

*Flow line 1*

The position of flow line 1 is illustrated in figure 8.4 together with the degree of ground level subsidence since 1991 and the underlying geology. Figure 8.5 illustrates the hydrogeological cross-section through the transect line (also in Appendix G).

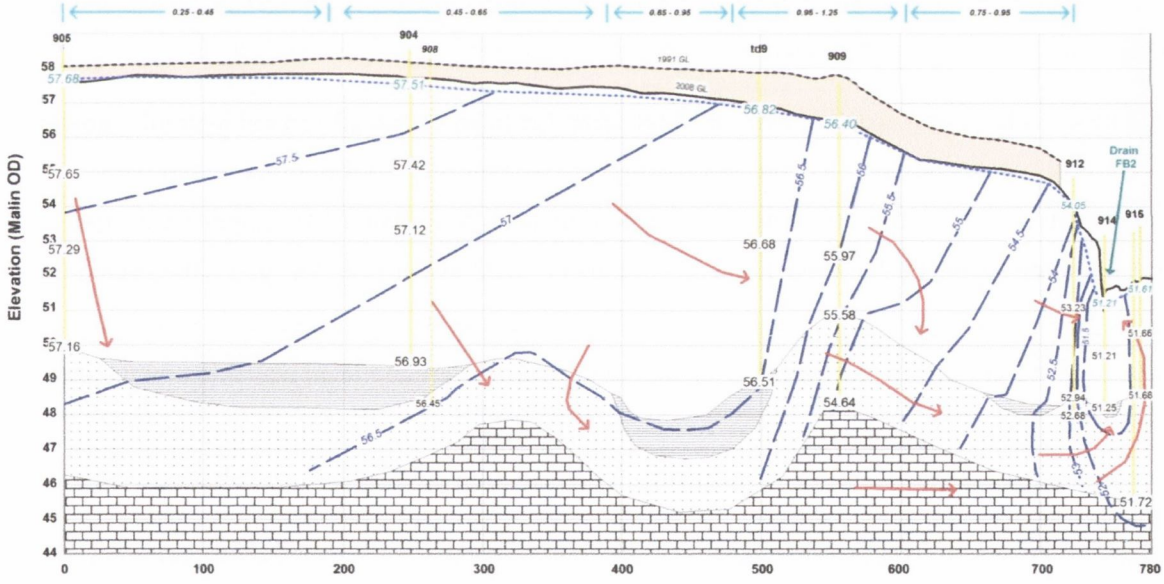


**Figure 8.5.** Hydrogeological cross-section and level of subsidence (1991-2011) through flow line 1 (see appendix G). Section is from west to east.

The hydrogeological cross-section is revealing and illustrates many of the processes discussed in the thesis. The equipotential lines in the section join contour lines of equal hydraulic head in the groundwater geological body. In the western part of the section there is a small vertical hydraulic gradient between the equipotential lines and flow is downwards through to subsoil. However the gradient increases eastwards in the vicinity of piezometer nest 904 and piezometer nests td9 and 909.

It can be observed that the till subsoil protrusion between piezometer nest 904 and td9 is drawing down the equipotential line – this is indicated by it kinked appearance. At piezometer nest td9, the large subsoil protrusion is that of a ridge which becomes the Western Mound east of the profile and the till ridge is also drawing down the potentiometric surface in peat. At piezometer nest 909 a higher resistance in the peat substrate can be inferred. This is indicated by the steep gradient in the equipotential lines. However, east of piezometer nest 909, the till ridge is again drawing down the potentiometric surface. Between this area and the high bog boundary by the drain, there does not appear to be much in the way of water table drawdown in the peat substrate – this process is concentrated at the subsurface till ridges – as assumed previously. At the bog margin itself, there is a big resistance in the peat substrate and groundwater flows horizontally in the till unit, before flowing upwards at the marginal drain before discharging into the surface water body.

Also plotted on the cross-section is the ground level surface in 1991 – the ground level surface used in the section is from the 2008 LiDAR survey. It can be observed that the surface level of the bog has decreased everywhere on the transect line. The greatest level of decrease, > 1.0 m, is at piezometer nest 909, by the Western Mound. This is highly significant as this area, in 1991, formed a subtle topographic divide for surface water flows on the bog surface (Chapter 10). It can be observed in figure 9.2 that the ground level gradient west of piezometer nest 909 was quite flat in 1991 – it now dips steeply from the area of piezometer nest 904. This is in accordance with the subsidence and water balance analysis in chapters 7 and 9.

The till mounds have drawn down the peat water table due to an increased vertical hydraulic gradient and the effect is not localised – it protrudes through the peat profile and the equipotential lines indicate that the bog is still losing water west of piezometer 909. In figure F10 (appendix F), the ground level has decreased between 0.03 and 0.09 m (+/ - 0.02 m error) in this area – the evidence clearly shows subsidence is still occurring. East of piezometer nest 909 subsidence is slowing down and as discussed in chapter 7, this area is an area of exponential ground level decrease and the drop in ground level from 1991 in figure F10 occurred mostly between 1991 and 2002. The equipotential lines suggest that while water is being lost at the Western Mound ridge, there is resistance south/ south east of this.

*Flow line 2*

The position of flow line 2 is illustrated in figure 8.4 together with the degree of ground level subsidence since 1991 and the underlying geology. Figure 8.6 illustrates the hydrogeological cross-section through the transect line (also in Appendix G).

The observations and inferences made from flow line 1 can also be applied to flow line 2. The equipotential lines are drawing down the potentiometric surface in peat either side of the Western Mound – though the mound itself is a barrier to groundwater flow in the peat, as indicated by the

steep gradient of the equipotential lines. Similar to flow line 1, resistance is met at the high bog boundary and groundwater discharge from till via an upward flow path at the drain where peat thickness is shallow and the lacustrine clay barrier is absent. The effect of the sand lense on the equipotential lines can be observed in flow line 2 between piezometers td4 and 59. The effect is similar to those of the till protrusions – the sand unit is inducing lateral flow by means of 'kinking' the equipotential' lines, inducing leakage from the peat due to the increased vertical hydraulic gradient.

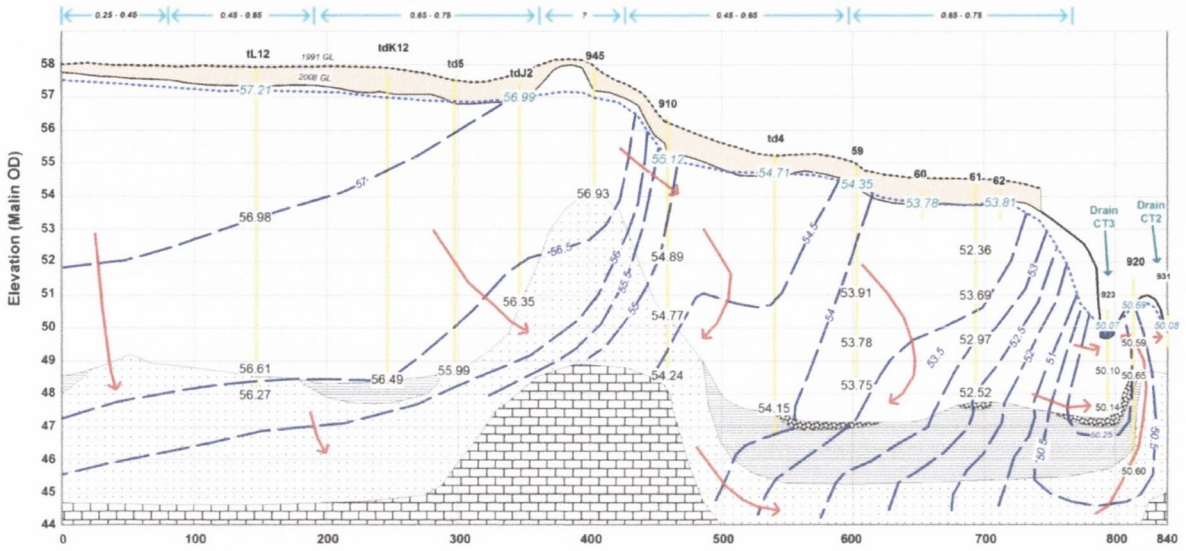


**Figure 8.6.** Hydrogeological cross-section and level of subsidence (1991-2011) through flow line 2 (see appendix G). Section is from west to east.

Similar to flow line 1, the greatest levels of ground level decrease, > 0.5m, are either side of the Western Mound. It can be observed that the surface level gradient has become steeper west of the Western Mound – similar to Flow line 1. Significant ground level decrease has also occurred close to the high bog boundary. This is associated with the initial exponential rate of ground level decrease described for the area (Chapter 7) and the influence of the subsurface drainage pathway associated with the sand lense. The equipotential lines, like those in flow line 1, indicate the peat is still losing water, and the water loss is concentrated either side of the Western Mound.

*Flow line 3*

The position of flow line 3 is illustrated in figure 8.1 together with the degree of ground level subsidence since 1991 and the underlying geology. Figure 8.7 illustrates the hydrogeological cross-section through the transect line (also in Appendix F).

The cross-section again shows that groundwater flow is influenced by till ridges. The equipotential line is drawn down in the vicinity of piezometer nest 92, which is situated on a till ridge which is an extension of the Western Mound. The lacustrine clay, which is thicker and more prevalent in this section as the flow line is located close to the old lake basin, provides a resistance to groundwater flow, and this is shown by the steep, horizontal, equipotential lines. The bog margin is also resistant to

lateral groundwater flow. The bog margin and lacustrine clay essentially work as a dam, containing groundwater flow within the high bog. However, the till ridge provides the pathway for leakage from the peat and it appears to be associated with the sand lense underneath piezometer nest 937. The other sand units also possibly draw down the water table in the peat, as subsidence analysis would suggest, but there is no piezometry in the southern part of the section to analyse this.

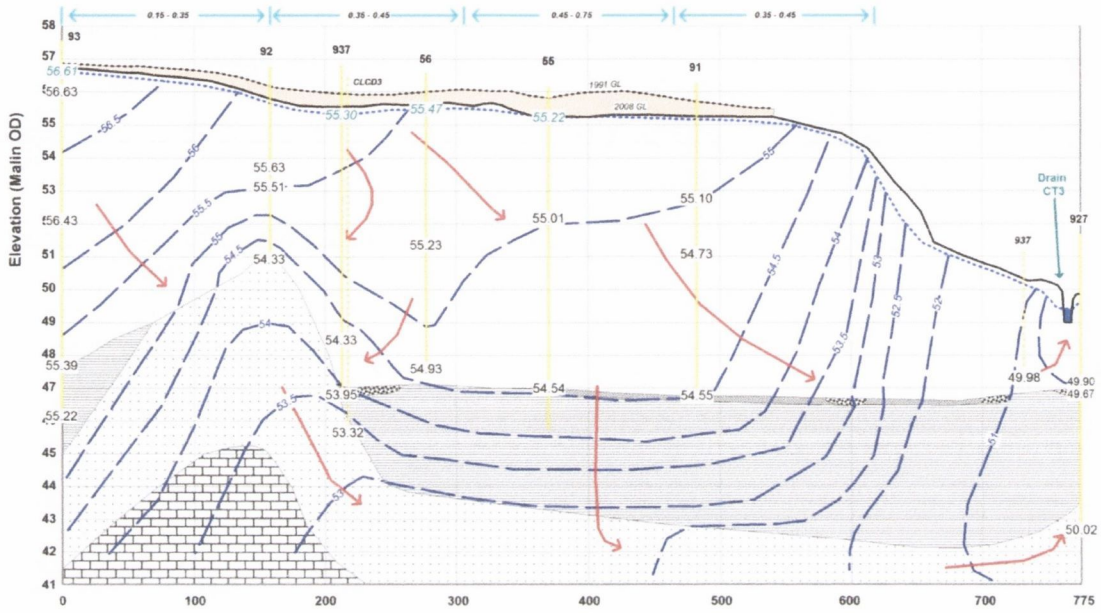


**Figure 8.7.** Hydrogeological cross-section and level of subsidence (1991-2011) through flow line 3 (see appendix G). Section is from north to south.

The greatest levels of subsidence, < 0.75 m, are in the area of Shanely's Lough – piezometer nest 55. Water loss in this area, which has been described in subsidence analysis, appears to be associated with the till protrusion underneath piezometer nest 92 and the sane lense, which is most likely an old drainage channel filled with sediment from the till ridge, underneath piezometer nest 937. In figure 9.4 it can be observed that the ground level gradient in 1991 sloped in towards piezometer nest 55, whereas in 2008 it is a relatively flat gradient. Further subsidence, south of piezometer nest 55 would therefore increase runoff from the bog surface; runoff that ordinarily supplies water to Shanely's Lough.

### 8.4. Conclusions

There has been a drop in water level at almost all of the deep peat piezometers on Clara Bog West since the early 1990's. The greatest level of decrease is in the area southeast of the Western Mound and southwest of Shanely's Lough. Deep peat piezometric water level has decreased by up to 1.0 m – similar to the level of ground level decrease. There is no information west of the Western Mound, in the area of linear subsidence in which to complete an analysis. However, piezometers west of the Western Mound, outside of the subsidence analysis area, show a decrease in deep peat water level of between 0.2 and 0.4 m. It can be inferred that the piezometric level between the Western Soak and the

Western Mound are greater than this, close to 1.0 m, as the ground level has decreased by this much in local areas (e.g. piezometer nest 909). The level of deep peat water level decrease levels out close to the main bog road suggesting the easternmost area of Clara West has reached an equilibrium – but not in its central areas.

The equipotential lines and patterns of water movement through each of the flowlines indicates that an increased vertical hydraulic gradient between till and peat in areas where till protrudes through the peat has initiated water loss from the peat column resulting in ground level subsidence of the high bog surface level. A similar phenomenon occurs where sand is deposited above lacustrine clay, the sand seemingly drawing down the peat water table and inducing surface level ground subsidence

Overall the drop in deep peat water level mimics that of ground level decrease described in Chapter 7. Peat consolidation seems to be intrinsically linked to the pore water, decreases in which increase the effective stress on the peat substrate, inducing water loss. The drop in regional groundwater level has induced the drop in deep peat piezometer level – and the drop in deep peat water level appears to be greater than that of the subsoil. There is only one measurement in which to make this comparison (CLCD3), but considering the compressibility of the peat matrix, this is not unreasonable. Piezometric level in CLBH5, located south of the high bog adjacent to drain TD2, has dropped by c. 0.7 m – similar, but slightly less, that the greatest water level decreases found in deep peat. The drop in piezometer level in both till and peat substrate appears to be intrinsically linked - again highlighting the dependency of the high bog on the maintenance of the regional groundwater table.

# 9. The Water Balance

## 9.1. Introduction and objectives

The water balance is a key measure on which to assess the sustainability of a wetland ecosystem – particularly in a bog system where downward infiltration to the regional groundwater table should be minimal. Van der Schaff (1999) calculated downward infiltration for the Clara West high bog to be 8 mm/ year, or 0.02 mm/ day. However, this calculation was based on piezometer measurements in areas underlain by lacustrine clay. It is clear from chapters 5 to8 that most infiltration occurs when lacustrine clay is absent - the calculation by Van der Schaff is underestimated. However an annual infiltration rate in the order of 40 mm is necessary if saturated conditions are to be retained in the bog substrate and the release of water from peat storage is at a minimum (after Streefkerk & Casparie, 1989).

The principle of the water balance was reviewed in chapter 2and the methodology described is applied to water balance calculation for the four flow measurement structures in the Clara West drainage system – namely the Bog Weir, the FB2 Flume, the Restoration Area Flume and the EPA Weir. The aim is to calculate:

(1) Catchment areas encompassing each of the flow measuring structures
(2) The rate at which water is infiltrating through the high bog peat substrate
(3) Recharge rates to the marginal drain hydraulic flow structures and;
(4) Rates of surface water runoff contributing to each of the drains

## 9.2. Water balance equation

A water balance is a measurement of continuity of the flow of water which holds true to any time interval and applies to any drainage system area – i.e. it follows the law of mass conservation and is time dependent. If the catchment area of study is considered as an open system, the quantification of the water balance is essentially a mass balance equation in which the change in storage of water with respect to time ($dS/dt$) in the system is equal to the inflows of the system minus the outflows of the system:

$$\text{inflows} = \text{ouflows} \pm \text{changes in storage} \qquad \text{Equation 9.1}$$

Over a sufficiently long time period, the storage component in a water balance may be considered to be equal to zero, as the water balance equation is at 'equilibrium' or 'steady state'. The Clara West water balances, described below, are assumed to be at steady state and the storage component is assumed to be negligible.

The surface water catchments and groundwater catchments are hydraulically connected, but their areal size/ extents are found to differ, meaning the surface water and groundwater water balance will also differ. Runoff in instrumented drains in the marginal areas adjacent to the Clara high bog have been

separated into runoff components derived from surface water runoff/ overland flow that has not infiltrated downwards into peat and subsoil, runoff from peat and runoff from till subsoil. Analysis of base flow (chapter 6) in the drain allows a recharge rate to be calculated from the groundwater catchment area and an infiltration rate may then be calculated for the surface water catchment area. The water balance for the surface water catchment area may then simply be expressed as follows:

$$P = ET + RO + I \qquad \text{Equation 9.2}$$

where $P$ is precipitation/ total rainfall, $ET$ is evapotranspiration, $RO$ is overland flow/ surface water runoff and $I$ is infiltration. The water balance equation is expressed in units of volume per unit time.

However, for analysis, it is convenient to express the water balance components in mm, which for runoff and infiltration, is achieved by dividing the total amount of water in the water balance period by the surface water catchment area. It is therefore important that the catchment area has been estimated correctly.

## 9.3. Water balance components

If a water balance is to be equated accurately the individual water balance components must be measured or estimated separately – namely rainfall, evapotranspiration, runoff and infiltration. The various components and methods involved in measuring them were reviewed in chapter 2.

### 9.3.1. Meteorology

The largest inflow component in a bog water balance is that of precipitation and the largest outflow component is that of evapotranspiration and their correct measurement critical in a water balance study.

*Precipitation*

Precipitation, which amounts to rainfall in Ireland, is measured at two rain gauges on the Clara West high bog located adjacent to piezometer nest 908 and piezometer nest 50( locations: Figure A8, Appendix A). Rain gauges require regular maintenance and it was a common occurrence that one of the two rain gauges at any particular time did not record rainfall accurately due to (1) a blockage in the rain gauge funnel, (2) vandalism and (3) the level recorder not working properly or the memory logger becoming full. Occasionally neither of the rain gauges worked. In these situations rainfall from a Met Eireann meteoric station, located in Mullingar c. 30 km north of the bog, was used.

However, when the two rain gauges were working in tandem their measured rainfall amounts were approximately the same – and approximately the same that measured from the Mullingar rain station. Therefore the rain gauges were combined and mean values were used to calculate l rainfall over the water balance period.

*Evapotranspiration*

Evaporative losses from raised bogs are a major part of the water balance. Evapotranspiration was calculated using potential evapotranspiration data from the Met Eireann weather station located in Mullingar. The Met Eireann data is calculated using the Penman-Monteith equation, described in section 2.6, and a crop factor of 1.3, which references potential evaporation to the vegetative type (by default potential evapotranspiration is equal to grassland actual evapotranspiration) was applied o equation 9.3, to account for the high evaporative losses encountered in wetland environments:

$$AE = PE * K_c \qquad \text{Equation 9.3}$$

where $AE$ is actual evapotranspiration, $PE$ is potential evapotranspiration and $K_c$ is a crop factor.

The rate of evapotranspiration is therefore controlled strongly by the value of the crop factor used in the evapotranspiration model used. Vascular plants generally decrease the rate of evapotranspiration, whereas plants such as *Sphagnum* increase it (Heijmans et al, 2008). The value of 1.3 was selected based on a review carried out by Heijmans et al (2008), who based their crop factors on work done by Clymo (1973) and the FAO, and their research shows the crop factor for *Sphagnum* species ranges between 1.2 and 1.4. A value of 1.3 is found for *Sphagnum* lawns – these areas dominate central ecotopes. As such, equation 9.3 was applied to the surface catchment area in question – values alternated between 1.3 (wet ecotope areas) and 1.0 (i.e. unadjusted; assuming grassland type conductions for marginal ecotope areas, cutover bog and surrounding land). As precipitation and runoff was measured directly, the evapotranspiration values are the most uncertain in the proceeding water balance calculations. However, the values computed agree with results found by Van der Schaaf (1999) in the original water balance study in 1991/1992.

### 9.3.2.Discharge

The measurement of runoff from each of the Clara West hydraulic structures was discussed in chapter 4, the results from which were used in base flow analysis to separate overland flows from subsurface groundwater flows. The results from this analysis are applied to the water balance calculation(s).

### 9.3.3.Recharge and infiltration

The recharge rate to the groundwater table hosted in till was calculated using base flow analysis in chapter 6; section 6.9. Recharge, using groundwater catchment areas to the hydraulic measuring structures, was calculated to range between 0.24 and 0.39 mm/ day.

*Recharge or infiltration?*

However, the water balance must contain an infiltration component that describes the rate of downward seepage n the high bog peat – which is not necessarily the same as the recharge rate as the surface water catchment areas do not mimic the groundwater catchment areas and recharge to till is

slower where lacustrine clay separates high bog peat from the till unit. Infiltration may then be considered as the entry of water into the subsurface that is potential recharge. As base flow in the instrumented drains is a measure of recharge to the regional groundwater table within the groundwater catchment area, an infiltration rate in the high bog may be estimated if the infiltration rate from peat to till and from peat to lacustrine clay can be calculated.

*Areal estimate of infiltration rate*

Infiltration through the high bog may not necessarily be equal to the recharge rate calculated from groundwater discharge from till subsoil. Water will be held in storage in the unsaturated zone (the acrotelm/ upper margin of peat where it is 'dry') and will infiltrate from peat to subsoil at different rates - depending on the permeability of the subsoil and the vertical hydraulic gradient between basal peat and subsoil. Using the till recharge rate calculated in section 6.9, the flux from peat to lacustrine clay and to the 'sand lenses' can be estimated. The total infiltration of water through the high bog surface water catchment area may be estimated using the following equation:

$$R_T = R_t * A_t + R_l * A_l + R_s * A_s \qquad \text{Equation 9.4}$$

where $R_T$ is total infiltration from peat to subsoil in the high bog surface water catchment area, $R_t$, $R_l$ and $R_s$ is infiltration to till, lacustrine clay and sand lense/ peat crack area respectively and $A_t$, $A_l$ and $A_s$ is the proportional area of the high bog surface water catchment underlain by till, lacustrine clay and sand lense/ peat crack area respectively.

*Infiltration rates*

Using equation 9.4, an infiltration rate of 0.02 mm/ day from peat to lacustrine clay has been calculated – which is near exactly the figure calculated by van der Schaff (1999). The infiltration to till is taken as that calculated from base flow analysis – 0.38 mm/ day. However, the infiltration rate to the sand lense areas is not clear – though the units are thin (< 15 cm) and are not wide in extent, they are associated with high infiltration zones. This is indicated by (1) the infiltration rate calculated at the Bog Weir (section 9.5) and (2) the low hydraulic heads measured at the base of peat in areas close to the sand lenses (Chapter 8) - which necessitated the inclusion of a high transmissivity zone in the sand zone underlying peat substrate in model calibration (chapter 11). It is possible that the high infiltration zone is associated with peat cracks, rather than the sand itself being highly transmissive. Using this logic, an infiltration rate of 0.6 mm/ day is assigned to the sand lense areas (infiltration will be higher at the crack itself, but spread across the area of the peat crack 'zone', a figure of 0.6 is reasonable). The areas of bog which have subsided most (chapter 8), east of the Western Mound, are associated with these areas – implying the localised high infiltration rate is not unrealistic. The infiltration rates presented for the high bog surface water catchments in tables 9.3, 9.4 and 9.5 has been estimated using the methods and values described above. The infiltration rates are very similar to

those calculated in chapter 6 using the three-component mixing model – rates of 0.14 mm/ day and 0.07 mm/ day were calculated for the FB2 Flume and Restoration Flume surface water catchments

## 9.4. Catchment areas

To interpret a water balance calculation by means of analysing rates of flux, it is necessary to first calculate the catchment area proving runoff to the measured flow measurement structure. There are four hydraulic structures measuring runoff in Clara West (figure B2; appendix B) – the Bog Weir measuring runoff on the high bog and the EPA Weir, FB2 Flume and Restoration Flume measuring runoff in marginal drains that receive overland flow from the high bog and groundwater flow from beneath the high bog and surrounding areas. Each of the hydraulic structures has its own surface water and groundwater catchment area, though the groundwater catchment areas do overlap. The catchment areas providing overland flow and groundwater flow differ in the Clara West drainage system due to the high bog topography not being coincident with the underlying subsoil geomorphology. The surface water and groundwater catchment areas must therefore be estimated separately – resulting in separate water budgets for groundwater flow and surface water flow.

### 9.4.1. Surface water catchments

The surface water catchment sizes have been estimated using ground level topography generated from a digital terrain model (DTM) produced from the 2008 LiDAR survey (Chapter 4). Though more recent surveying at 100 m grid intervals has measured ground level elevation on the high bog, the resolution is not good enough – changes in high bog catchment topography require a high resolution, $< 10\ m^2$, which can only be acquired using techniques such as a LiDAR.

The surface water catchment map (Figure G1; also Chapter) illustrates that there are five catchments in the Clara West drainage area:

- The Bog Weir Catchment - receives water from the western and northern regions of the Western Mound.
- The Restoration Flume Catchment – receives water from the northern and eastern regions of the bog, including the area encompassing Shanley's Lough.
- The FB2 Flume Catchment – receives water from the western region of the bog, including the area encompassing the Western Soak.
- The Peat Pipe Catchment – a small catchment between the FB2 Flume Catchment and the Bog Weir Catchment. Runoff, from an area east of the Western Mound, exits via a peat pipe in the facebank in wet periods. This is a distinct catchment and does not supply water to the bog weir or the FB2 flume.
- Additionally, the EPA Weir Catchment encompasses the FB2 Flume Catchment, the Bog Weir Catchment and the Peat Pipe Catchment. Surface runoff from high ground south and southeast of the EPA weir, namely the Island region, also forms part of the catchment area.

### 9.4.2.Groundwater catchments

The groundwater catchment sizes have been estimated using the potentiometric surface of the regional groundwater table in till subsoil (Figures G2-G4; appendix G) – the groundwater catchment size increases when the regional groundwater table is at its highest (Section 5.4). As shown in figures G2, G3 and G4, the surface water catchment area does not coincide with the groundwater catchment area, particularly at the Restoration Area flume – which complicates water balance computation. The size of each of the surface water and groundwater catchments areas are presented in table 9.1.

### 9.4.3.Catchment size

It is important that catchment area is estimated correctly in water balance computation. The surface catchment area used is that estimated using the LiDAR DTM model – it is a topographic catchment. It is possible to check that the estimated catchment area is accurate by analysing runoff and rainfall in a storm event - the catchment area that will contribute runoff to a drain will depend on the size of the storm event. By simply dividing overland flow runoff by total effective rainfall within the storm period and multiplying this by the estimated catchment area, a minimum catchment area can be calculated as:

$$C_{min} = \frac{Q_o}{RF_e} \, x \, C_{est} \qquad \text{Equation 9.5}$$

where $C_{min}$ is the minimum catchment area, $Q_o$ is overland flow, $RF_e$ is effective rainfall and $C_{est}$ is the estimated catchment area. In a storm period, total rainfall is assumed to be equal to effective rainfall (i.e. a negligible amount of water evaporates during a storm event).

Table 9.1. Surface water and groundwater catchment size – estimated and calculated minimum catchment area required to account for measured runoff

| | Bog Weir | Restoration Flume | FB2 Flume | EPA Weir | |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| Estimated: | 0.309 | 0.723 | 0.572 | 1.306 | $km^2$ |
| Minimum required: | 0.184 | 0.704 | 0.587 | 1.107 | $km^2$ |
| **Groundwater** | | | | | |
| Estimated: | | 1.052 | 0.718 | 1.410 | $km^2$ |
| Minimum required: | | 1.036 | 0.766 | 1.496 | $km^2$ |
| *Base flow: | | 32^ | 17 | 28 | % |

Note: *Base flow refers to the percentage of total runoff that is groundwater recharge from till over the water balance period. ^Restoration Flume base flow receives additional groundwater from limestone – 9% of total runoff.

Calculation of the minimum surface water catchment areas in table 9.1 was therefore based on an analysis of storm peaks – the largest storm event recorded at the Restoration Flume, FB2 Flume and EPA Weir (see hydrographs; appendix B) occurred between the 22nd October and 6th November 2011 and it is assumed the entire catchment area was utilised in this period. The results in table 9.1 show that there is a good correlation between estimated and calculated, surface water catchment areas.

The minimum groundwater catchment area is based on the area required to account for flow derived from till subsoil (considered to be the base flow) measured in the instrumented drains (chapter 4). The calculation is the same as equation 9.5, except runoff is the total runoff in the drain over the water balance period and the catchment area is the groundwater catchment area. The calculated minimum groundwater catchment areas also correlate closely with the estimated groundwater catchment areas - the recharge/ infiltration rates calculated in the water balances can be interpreted with confidence.

The calculated surface water and groundwater catchment sizes are within 10% of the estimated size – the water balances, presented below, may therefore be used to assess whether there have been any significant changes in catchment size encompassing the Shanley's Lough and Western Soak systems since the early 1990s.

## 9.5. Clara West water balances

A water balance should ideally be calculated over the hydrological year, between the 30th September and 1st October, as it is during this time that there is the best correspondence between precipitation and runoff and net storage is at a consistent minimum. However, data is not available for such a period although water balances maybe calculated for the high bog weir, the EPA weir and the restoration area flume between January 2011 and January 2012.

Nevertheless, following an analysis, a water balance between January 2011 and early December 2011 is considered more appropriate as December 2011 was extremely wet (total rainfall of 107.6mm), thereby giving an anomalous number of 'storm' events over the water balance period if the full year is used – i.e. gives an erroneous estimate of the infiltration rate and surface runoff (low ET in December and January). A water balance for the FB2 flume was calculated between June and early December 2011. Following a number of modelled scenarios the presented water balances below are deemed most representative of the hydrological regime.

### 9.5.1.Bog Weir Catchment

The high bog catchment area supplying water to the Bog Weir (figure G1), which measures runoff through the main bog drain on the high bog, is far smaller than estimated by Van der Schaff (1999) - it does not receive water from catchments containing either the Western Soak or Shanley's Lough (discussed in chapter 10). Table 9.2 presents the water balance for the Bog Weir Catchment between January 13th and December 5th 2011 (327 days).

Table 9.2. Bog Weir water balance (13-01-11 to 05-12-11)

| **Water Balance (327 days)** | **mm** | **mm** | **mm/day** | **% of TRF** |
|---|---|---|---|---|
| Total Rainfall (TRF): | 904 | | | |
| Actual ET: | | 597 | | 66 |
| Runoff: | | 184 | | 20 |
| Infiltration: | | 124 | 0.379 | 14 |

The Clara West high bog water balance calculated by Van der Schaff (1999) estimated that c. 35 % and c. 1 % of total rainfall became runoff and infiltration through the peat substrate respectively. The water balance presented in table 9.2 is considerably different with c. 20 % and c. 14 % of effective rainfall becoming runoff and infiltration respectively.

Water loss from estimated actual evapotranspiration was c. 62 % and c. 66 % of total rainfall in 1992 and 2011 respectively. The actual evapotranspiration presented in table 9.2, calculated using the empirical Penman-Monteith FAO method with a Sphagnum crop factor of 1.3 is possibly an overestimation. Van der Schaff (1999) estimated that c. 4 % of total rainfall is stored on the bog – if this is still the case the evapotranspiration rate is probably still c. 62 %, with the additional 4 % attributed to storage in the acrotelm and open water bodies. The reduced runoff is accurate (the weir has been calibrated and rated with field runoff measurements) and is a consequence of an increased infiltration rate from the bog surface to the underlying peat and subsoil.

However, c. 56 % of the Bog Weir catchment area is underlain by lacustrine clay. Infiltration, even accounting for the occurrence of till, should not be so high. The explanation for the calculated infiltration rate is that water is being lost via peat cracks, which are more than likely related to the occurrence of the 'sand lenses' (the groundwater model for the Clara hydrogeological system required a high transmissivity in peat in this exact area to account for the low hydraulic heads measured at the base of peat; chapter 11). The Bog Weir Catchment becomes narrow (50 to 150 m in width) and almost 'channel' like as it approaches the weir – which is the area where most of the 'sand' underlies peat and where subsurface cracking presumably occurs. There are topographic lows in this 'channel' area of the catchment, resulting in a series of subtle topographic basins – indicating differential peat consolidation that have most likely been induced by peak cracking.

Recharge and infiltration rates are discussed in section 9.3. From this, if an infiltration rate of 0.38 mm/ day and 0.02 mm/ day is applied to areas where peat overlies till and lacustrine clay respectively, and if an infiltration rate of 0.6 mm/ day is applied to areas where there is probable sand and peat cracks - the calculated infiltration rate for the Bog Weir Catchment can be explained. The Peat Pipe Catchment will presumably have an infiltration rate similar to that of the Bog Weir Catchment as it is also underlain by a mixture of till and lacustrine clay overlain by sand lenses.

9.5.2.Restoration Flume Catchment

The Restoration Flume is so-called because it is located in an area where perceived restoration works, to raise the regional groundwater table, will be recommended to take place – an area referred to as the Restoration Area (chapter 11). The surface water catchment area contains Shanley's Lough and receives overland flow from areas northwest, north and east of the soak. Importantly, much of the surface water catchment area is underlain by lacustrine clay subsoil. Table 9.3 presents the water balance computed between January 13th and December 5th 2011 (327 days).

Table 9.3. Restoration Flume water balance (327 days; 13-01-11 to 05-12-11)

| **Water Balance (SW)** | **mm** | **mm** | **mm/day** | **% of TRF** |
|---|---|---|---|---|
| Total RF (TRF): | 904 | | | |
| Actual ET: | | 558 | | 62 |
| SW Runoff: | | 323* | | 36 |
| Infiltration: | | 23^ | 0.070 | 3 |
| **Water Balance (GW)** | **mm** | **mm** | **mm/ day** | **% of TRO** |
| Total Runoff (TRO): | 344 | | 1.053 | |
| Recharge peat: | | 10 | 0.030 | 3 |
| Recharge till & Lst: | | 110 | 0.335 | 32 |

Note: *Surface catchment area is c. 30% smaller that the groundwater catchment area – overland runoff calculated separately gives a value of 228 mm. ^Infiltration rate is increased by presence of till and 'sand lense' areas in the surface water catchment area.

The surface water catchment encompasses a large area of high bog – the surface water catchment water balance may therefore be representative of the high bog. The water balance, computed over the same time period as the Bog Weir water balance, is markedly different to that of the Bog Weir - the results compare to those calculated by van der Schaff (1999) with actual evapotranspiration and surface water runoff being c. 62 % and 36 % of total rainfall.

Figure G2 illustrates the surface water catchment and groundwater catchment areas measured by the Restoration Flume. The catchment areas do not coincide and the groundwater catchment area is c. 30 % bigger than that of the surface water catchment – this complicates the water balance calculation as there is additional runoff from peat and till in the drain from outside the surface water catchment area. However, it is possible to reconcile the water balance - and as can be seen in table 9.3 there is a good correspondence between the surface water and groundwater water balance calculations.

A hydro-chemical mass balance approach was used to separate base flow and peat flow from overland flow in the Restoration Flume runoff (see chemographs; figures 10 to 14) and the method is discussed in section 6.9. Base flow separation (chapter 6) indicates that c. 32 % of runoff in the Restoration Flume over the water balance period is groundwater recharge and this accounts to a recharge rate of 0.335 mm/day in the groundwater catchment area. However, a proportion of this flow, c. 9 %, is

derived from limestone - recharge from till is c. 0.243 mm/ day. It is also possible to separate runoff derived from peat and this amounts to c. 3 % of total runoff at 0.03 mm/ day.

From figure G2 it can be observed that the high bog surface water catchment is underlain almost entirely by lacustrine clay (marl is < 50 cm thick and is underlain by clay; as is the 'sand' lense). An infiltration rate for the high bog may be adjusted to account for the absence of a peat-till connection and a seepage rate of 0.02 mm/ day is estimated – which is almost exactly the same as the figure calculated by van der Schaff (1999). An increased infiltration rate of 0.07 mm/ day is applied across the entire surface water catchment when outcrops of till and sand lense/ peat crack areas are accounted for, thereby increasing the overall infiltration rate.

### 9.5.3.FB2 Flume Catchment

The FB2 flume was installed on the 31st May 2011 in order to measure runoff in the drain FB2, which was observed to receive a significant amount of groundwater and is located adjacent to the high bog. Initially it was anticipated that the surface water runoff from the high bog to the flume would be relatively small as most of the surface water on the high bog discharged via the bog weir. However, the measured runoff between the 1st June and 5th December 2011 (table 9.4) shows that this is not the case – the runoff attributed to surface water runoff is significant and from an area of high bog that requires a large catchment area; an area that includes the Western Soak.

Table 9.4. FB2 Flume surface water catchment water balance (188 days; 01-06-11 to 05-12-11)

| **Water Balance (SW)** | **mm** | **mm** | **mm/day** | **% of TRF** |
|---|---|---|---|---|
| Total RF (TRF): | 592 | | | |
| Actual ET: | | 365 | | 62 |
| SW Runoff: | | 201 | * | 34 |
| Infiltration: | | 26 | 0.165 | 4 |
| **Water Balance (GW)** | **mm** | **mm** | **mm/ day** | **% of TRO** |
| Total RO (TRO): | 260 | | 1.646 | |
| Recharge peat: | | 10 | 0.051 | 4 |
| Recharge till: | | 45 | 0.241 | 17 |

Note: *Surface catchment area is c. 20% smaller than the groundwater catchment area – overland runoff calculated separately gives a value of 206 mm.

Figure G4 illustrates the surface water catchment area of the FB2 Flume, and it may be observed that the majority of this area is high bog. Figure G4 illustrates the position of the groundwater catchment, which while similar in area, is distinct from the surface water catchment area. Base flow separation indicates that c. 17 % of runoff in the Restoration Flume over the water balance period is groundwater recharge and this accounts to a recharge rate of 0.285 mm/day in the groundwater catchment area. Runoff from peat is c. 4 % of total runoff at c. 0.05 mm/ day – c. double that measured in the Restoration Flume.

An infiltration rate of 0.165 mm/ day has been calculated for the surface water catchment area, which is c. 4 % of total rainfall over the water balance period. The infiltration rate was adjusted to account for the proportion of surface water catchment area that is underlain by till and lacustrine clay subsoil. However, the infiltration rate had to be further reduced as it gave too large a value. The western groundwater divide passes through the western part of the surface water catchment – if the till within the region bounded by the western limb of the surface water catchment boundary and groundwater catchment boundary is considered to be lacustrine clay (which is not unreasonable as this area has not subsided and is not in hydraulic connection with a drain cut into till) the quoted infiltration rate is calculated.

A water balance over a longer time period will invariably be more accurate than that presented in table 9.4. However, the figures are consistent with estimates made from the other measuring structures which have measured runoff over a longer time period. Actual evapotranspiration is c. 62 % of total rainfall, identical to van der Schaffs estimation (1999) and surface water runoff is c. 34 %. Similar to the Bog Weir water balance, there is more water infiltrating downwards now than there was in the early 1990's.

### 9.5.4.EPA Weir Catchment

The EPA Weir receives overland flow from the Bog Weir, Peat Pipe and FB2 surface water catchments. The weir was installed in November 2010 and a water balance may be constructed for any period from that time (the weir was removed in June 2011 for c. 6 weeks – separate rating curves have been calculated either side of this period and flows have been estimated during the 'missing' period using data from the FB2 and Restoration flume, both of which have continuous records from the time of their installation; chapter 4). However, to keep the water balance results consistent the EPA Weir water balance has been calculated for the period January 13th to December 5th 2011, the results of which are presented in table 9.5.

The water balance results are similar to those calculated for the Bog Weir and FB2 Flume. Actual evapotranspiration is c. 62 %, identical to that calculated for the Restoration Flume and FB2 Flume. Approximately one third of the surface water catchment area is cutover bog/ agricultural land and surface water runoff and infiltration is c. 29 % and c. 9 % respectively. The increased infiltration rate, compared to the Restoration Flume and FB2 Flume, is a combination of quicker recharge to cutover bog areas where till is at, or close to, the surface and the high infiltration rate measured at the Bog Weir, which is most likely due to subsurface cracking in the peat.

Groundwater recharge to the EPA Weir is higher than that measured at the FB2 Flume and this is simply due to a larger groundwater catchment area and a larger area of till subsoil that is not overlain by peat and/ or lacustrine clay. The base flow component of total runoff is high at c. 28 % and this is explained by the high winter groundwater table discharging groundwater to till drain TD1 (dry

between April and August), which drains into the EPA Weir – this also indicates a quick release of water from storage in the till 'aquifer'.

Table 9.5. EPA Weir surface water catchment water balance (327 days; 13-01-11 to 05-12-11)

| **Water Balance (SW)** | **mm** | **mm** | **mm/day** | **% of TRF** |
|---|---|---|---|---|
| Total RF: | 904 | | | |
| Actual ET: | | 560 | | 62 |
| SW Runoff: | | 258* | | 29 |
| Infiltration: | | 85 | 0.261 | 9 |
| **Water Balance (GW)** | **mm** | **mm** | **mm/ day** | **% of TRO** |
| Total RO: | 371 | | 1.135 | |
| Recharge peat: | | 9 | 0.029 | 3 |
| Recharge till: | | 103 | 0.316 | 28 |

Note: *Surface catchment area is c. 10% smaller that the groundwater catchment area – overland runoff calculated separately gives a value of 257 mm.

### 9.6. The water balance as an approach to assessing groundwater dependency

The water balance calculations for the Clara West flow measurement structures are very revealing – the high bog is infiltrating far more water than is sustainable – between c. 60 and 140 mm/ year where part of the surface water catchment is underlain by permeable subsoil (however, due to water balance uncertainty, particularly with regards evapotranspiration, these values are +/- 10-20%). The total amount of downward seepage through peat in the high bog increases substantially when lacustrine clay is absent and where there is probable subsurface peat cracks associated with underlying sand lenses. In both situations, a drop in the groundwater table, due to marginal drainage, in both the till subsoil and basal peat increases the vertical hydraulic gradient between the upper margins of the peat and the base of peat and till subsoil, thereby increasing the seepage velocity of water moving downwards through the peat substrate (assuming the hydraulic conductivity of the peat does not change substantially) – an indirect groundwater dependency. This explains why the infiltration rate is far higher in the Bog Weir and FB2 Flume surface water catchments than in the Restoration Flume surface water catchment, where the high bog is underlain almost entirely by lacustrine clay. If the bog is to be maintained in saturated conditions the high downward leakage rates must be reduced to within the order of 40 mm/ year. To simulate such a change a predictive groundwater flow model is required, and this is developed in Chapters 11 and 12.

# 10. Effects of Subsidence

## 10.1. Introduction

In chapter 7 the process of subsidence in the Clara West high bog system was described and subsidence rates of ground level decrease and settlement rates of peat consolidation were calculated. It was show that since 1991 significant volume changes (strain) in the peat substrate have occurred due to small changes in effective stress. In the past, high groundwater pressures in the till deposits underlying the peat ensured that effective stress acting on the peat remained low (chapter 8). However, this regime has been strongly altered by the drains cut into mineral subsoil in the Clara West drainage system. The drains are now outlets for groundwater discharge from the till deposits (chapter 4). This has lowered both the water table in the peat and the pore water pressure in the deposits surrounding and underlying it (chapter 9). This loss of pore water pressure in the deposits below the bog has generated the increase in effective stress acting on the peat and the peat has compressed in response. Peat compression has resulted in differential subsidence and the development of significant relief on the bog surface.

The change in bog topography has dramatically altered hydrological processes with some areas paradoxically becoming wetter in response to drainage, resulting in the development of permanent lakes (chapter 1). Elsewhere mounds of drier peat have formed in areas corresponding closely to zones of elevated glacial till substrate – most notably the Western Mound. The changes in bog topography also indicate changes in catchment hydrology, changes in which that will invariably affect the bogs dependent ecology, particularly the Western Soak and Shanely's Lough soak systems which, as described by Van der Schaff (1999), require large catchment areas to keep them sufficiently wet.

## 10.2. Increased high bog infiltration

The effects of subsidence on bog hydrology can be analysed through the water balance (chapter 9) as the water balance is a measure of the rate of flux through a hydrological system. A raised bog wetland in natural unaltered conditions will have a low infiltration rate, meaning recharge to an underlying groundwater body will be slow, in the order of 40 mm/ year.

Van der Schaff (1999) calculated that c. 8 mm/ year, or 0.02 mm/ day, infiltrates from peat in the high bog to the underlying mineral subsoil. This infiltration rate was calculated, using piezometric levels in peat, in areas where peat overlies lacustrine clay and not in areas where peat overlies till subsoil or sand. The water balance and recharge calculation, described in chapter 9, also computes an infiltration rate of 0.02 mm/ day where peat overlies lacustrine clay.

The infiltration rate calculated by Van der Schaff (1999) was correct – but marginal drainage, has induced an increased infiltration rate in particular areas of the high bog. Infiltration rates through the high bog were discussed in chapter 9 and they are significantly higher in the western and central

regions of the bog – where (1) lacustrine clay is absent and till underlies peat and (2) where there are sand lenses between peat and lacustrine clay. The peat in these areas infiltrates water into subsoil that is drained by marginal drains – the FB2 drain (FB2 Flume location), the TD2 drain (EPA Weir location) and drains CT3 and CT4 (both drain into the Restoration Flume) in the Restoration Area. The water balance analysis indicates that infiltration in Clara West is between c. 90 and 140 mm/ year in the central and western regions of the high bog. The high infiltration rates are associated with areas where peat is releasing water from storage, due to an increase in effective stress, to the regional groundwater table.

It is therefore apparent that the peat-till connection does not impose a high infiltration rate on its own – rather, it is marginal drainage inducing a head loss in the mineral subsoil that has increased the downward flux of water from peat to till, which is significantly more permeable than the lacustrine clay, due to the increased vertical hydraulic gradient between the ground surface and base of peat.

The water balance from the Bog Weir indicates that subsurface cracking in the peat substrate greatly increases the infiltration rate through the peat profile. Peat cracking appears to be associated with the occurrence of sand lenses underlying peat substrate. However, the sand lense is underlain by lacustrine clay implying infiltrated water will be held in storage beneath the ground surface and move laterally if there is a connection with the face-bank – i.e. the peat is effectively 'karstified'; water from the peat pipe catchment discharges from the high bog in this way.

Peat cracking is not just confined to areas where there is sand underlying peat – it also occurs at peat-till interfaces. Such a crack, which has reached the surface, occurs on the high bog south of the Western Soak. Figure A1, from a face-bank adjacent to drain TD2, is a photo displaying a crack at the base of peat overlying till subsoil and it may be observed the crack occurs where a large cobble sits at the interface between the upper till unit ($k$ of c. $10^{-4}$ m/ day) and lower till unit ($k > 10^{1}$ m/ day). The crack in figure A1occurs over a localised plane of weakness – which is possibly why cracking features, are associated with sand lense areas. In chapter 5, a zone of high hydraulic conductivity between the Western Mound and Shanely's Lough was described (section 5.8) – this hydraulic conductivity is most probably associated with subsurface cracking and may in fact be considered to be a form of macro-scale porosity than permeability. In any case, infiltration to mineral subsoil is high in such areas.

Thus, high bog infiltration has increased by over 50% since the eco-hydrological work of the 1990s and the increased infiltration is associated with areas where there is (1) a high subsidence rate, > 10mm/ year, in zones of linear ground level decrease and (2) high settlement rates, > 1 mm/ year/ m in zones of linear ground level. The bog system is now highly unstable and it is losing water. The high bog will continue to subside if infiltration is not reduced to c. 40 mm/ year and this will be the subject

of numerical modelling prediction scenarios to ascertain how to reduce leakage in the high bog (chapter 11).

## 10.3. Change in high bog catchment areas

The Clara West high bog has subsided significantly, > 1.0 m in local areas and by > 0.5 m c. 600m from the high bog boundary, since the eco-hydrological work carried out in the early 1990's. Such dramatic changes will invariably affect hydrological processes on the surface of the bog.

### 10.3.1. Topographic changes

The high bog topography has altered since the original ground level survey in 1991. This is clearly indicated on the ground with the development of bog pools since 2002 (Chapter 1). To visualise the changes in the surface topography of the high bog, figures E2 – E5 in Appendix E illustrates the high bog topography, on a 100 m grid, in the subsidence analysis area for the years 1991, 2002, 2008 and 2011.

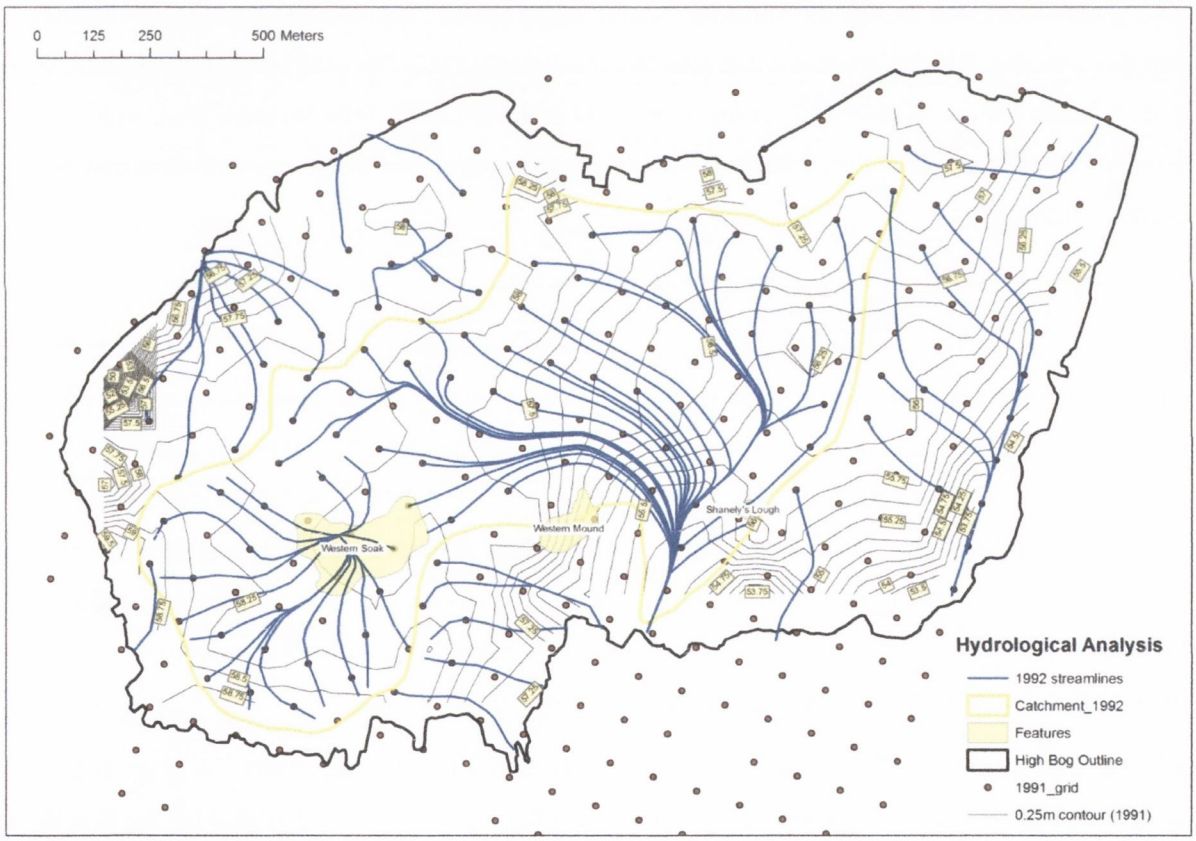


**Figure 10.1.** High bog topography (1991) and flow lines

A gentle topographic gradient can be observed to dip from the Western Soak to the Western Mound in 1991 in Figure 10.1. A clear topographic divide, trending west-east between the two features is present and a topographic high is present to the south of the Western Mound. Surface water, in 1991, flowed northwards from the topographic high and into the Western Soak. Water also flowed from the southeast of the Western Soak and water in the Western Soak itself flew westwards, and around the

Western Mound. This local catchment divide, which can be assumed to include the Western Mound, kept water in the central areas of the high bog in 1991. It can also be observed in figure 10.1 that in 1991 there was a gentle topographic gradient, c. 0.3m/ 200 m, supplying water to Shanely's Lough from an area that is now dominated by 'new bog pools.

Viewing the 2002 topographic map in figure E3, it can be observed that topographic changes on the high bog surface have begun – as shown and described in the 1991-2002 subsidence analysis in chapter 7. The topographic divide has moved northwards so that the topographic contours dip in such a way that water between the Western Soak and Western Mound flows north – northwest around the Western Mound, east of the Western Soak and water southeast of the Western Soak flows southeast, as it did in 1991. The surface level gradient to Shanely's Lough has not changed.

In 2002 the 1991 topographic divide between the Western Soak and Western Mound had begun to shift northwards. Viewing figures E3 and E4, it can be observed that the divide is still propagating northwards, so much so that water from the eastern boundary of the Western Soak is no longer flowing eastwards, and around the Western Mound, like it did in 1991 and 2002, but by 2008 water from this area was flowing southeast and into face-bank drain FB2. The area of 'new' bog pools, west of the Western Mound is therefore getting wetter, but at the expense of the Western Soak and Shanely's Lough, which in 1991, received water from the central area of the bog, which is now being diverted southwards.

### 10.3.2. Change in catchment area and water balance

In chapters 4 and 9, the high bog surface water catchments were discussed and their water balances were calculated. Figure 10.2 illustrates the position of the high bog catchments described in chapter 4 and also the high bog catchment area mapped in 1991 by Van der Schaff (1999) using the OPW 100 m bog grid survey – the 1991 catchment area is c. 0.94 $m^2$. The high bog catchment area(s) now, as estimated using the 2008 LiDAR survey data, is substantially different. As discussed in Chapter 4, there are now four distinct catchment areas on the high bog; whereas in 1991/ 1992 it was one area. However, it must be remembered that a catchment area is drawn where runoff is measured at its outlet – water balance interpretation is again important.

The Bog Weir catchment area is c. 0.31 $m^2$ – less than one third of the area of the 1991 high bog catchment. The change in catchment size is reflected in the water balance calculated for the Bog Weir where runoff has decreased and downward infiltration has increased. Van der Schaff (1999) estimated that c. 35 % and c. 1 % of total rainfall became runoff and infiltration through the peat substrate respectively, whereas the Bog Weir water balance calculates that 20 % and c. 14 % of effective rainfall becoming runoff and infiltration respectively. There has been a dramatic change in the rate of infiltration since 1991 – water that became surface water runoff, and effectively 'wetted' the bog surface and was stored and release in e acrotelm, is now infiltrating downwards.

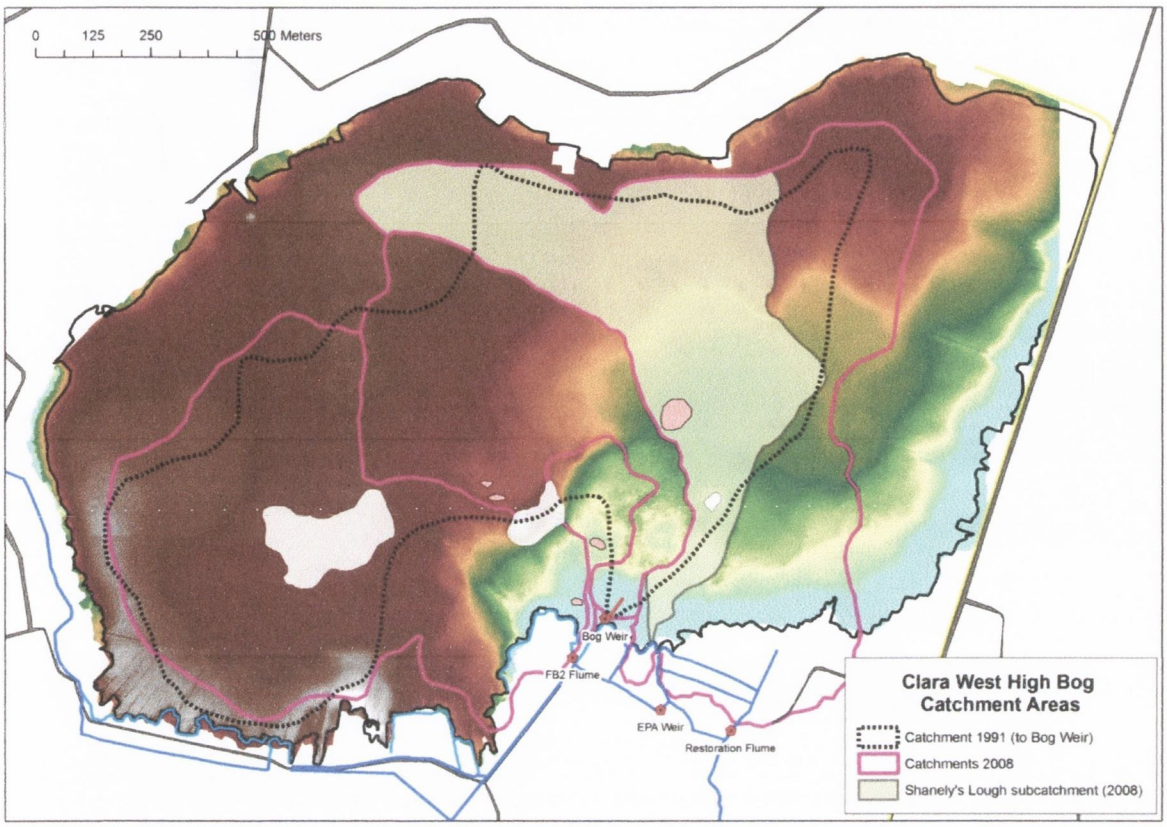


**Figure 10.2.** Change in high bog catchment area

However this does not mean the catchment area, which encompassed the Western Soak and Shanely's Lough in 1991, has necessarily reduced by > 60 %. Runoff from the high bog catchment area in 1991 discharged from the high bog via two drains – one drain close to where the current Bog Weir is located and from a second drain which was subsequently blocked in the early 1990's (weir locations are on figure 10.2). The pattern of the 'second' drain is picked up by the LiDAR DTM – runoff still discharges from the area; but not through a distinct drain, but via a system of cracks on the high bog boundary. The high bog surface water from this area, which encompasses Shanely's Lough, now drains into the Restoration Flume.

Comparing the 1991 high bog catchment area to the current delineated catchment areas, it can be deduced that the eastern region of the 1991 catchment area has not changed much – the drain, which is now blocked, can no longer be instrumented, meaning the eastern part of the 1991 high bog catchment area is reduced simply because there is now only one drain where runoff can be measured. Shanely's Lough is still receiving water from the high bog as it did in 1991 – though it is now clear that the volume of water moving eastwards from the Western Soak and Western Mound area has reduced significantly.

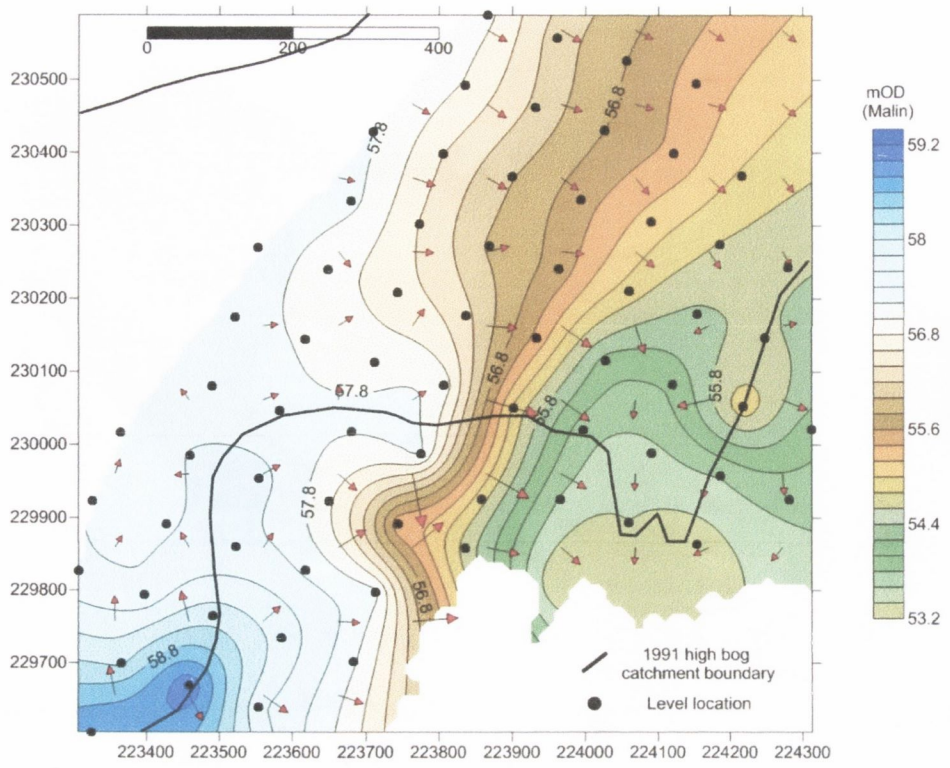


**Figure 10.3.** Topographic contours and 1991 high bog catchment area in subsidence analysis area

The central and western **region** of the 1991 catchment area has changed significantly – areas where there has been a linear rate in ground level decrease (chapter 7). There are now three catchments – the Bog Weir catchment, the Peat Pipe catchment and the FB2 Flume catchment. Figures 10.3 and 10.4 illustrate the ground level topography of the high bog in 1991 and 2011 respectively – in the subsidence analysis area. In 1991 there was a catchment divide, west of the Western Mound, which essentially kept water within the central area of the bog before it flowed eastwards around the Western Mound. However, this catchment divide has been breached and water now flows southwards, west of the Western Mound.

The Western Soak, which was part of the 1991 high bog catchment area, is now encompassed within the FB2 surface water catchment (figure 10.2). The soak is situated within a subtle hollow on the high bog and its southern boundary is bounded by a subtle ridge that effectively 'keeps' water within the soak area. Surface water leaves the Western Soak area by flowing eastwards towards the Western Mound, before water flows southwards, draining from the high bog and into drain FB2. In 1991, this surface water would have flowed northwards, around the Western Mound. The ridge, or 'water-divide', in 1991 is evident on figure 10.3 – it has disappeared in figure 10.4.

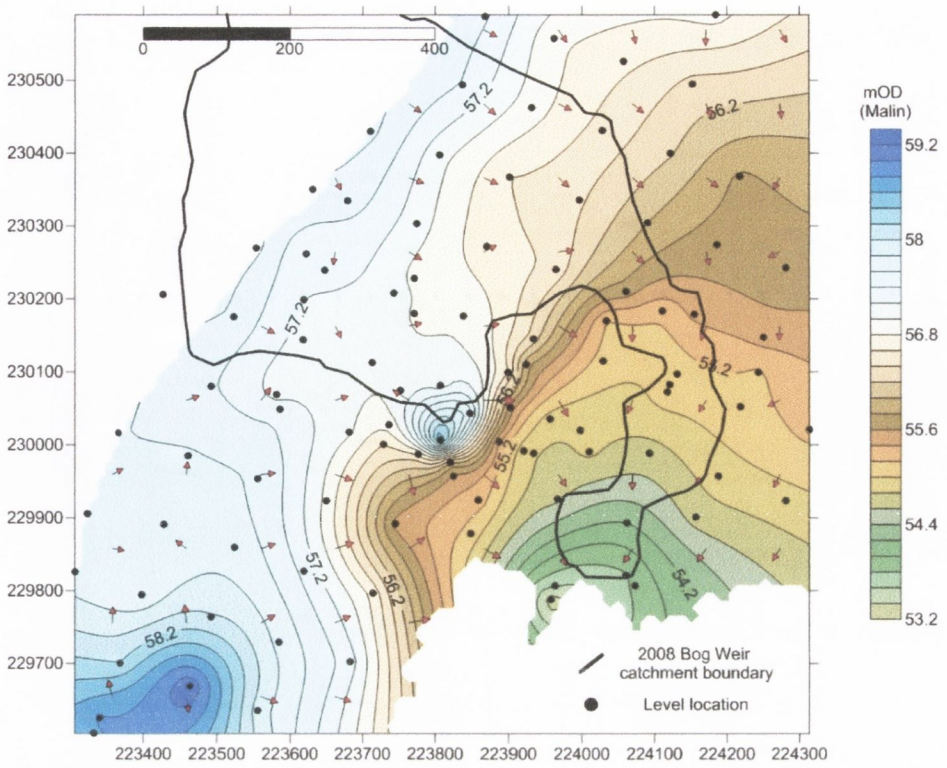


**Figure 10.4.** Topographic contours and 2011 high bog catchment area in subsidence analysis area

Ten Heggler et al (2002) speculated that if subsidence continued, the water divide would be breached and surface water flow that flowed eastwards to the Shanely's Lough area in 1991 would be diverted and a significant proportion of it would flow southwards, west of the Western Mound – this prediction has been realised. The integrity of the Western Soak has been compromised – and the ridge is the reason why the soak area is still wet. As there is not as much water flowing eastwards from the Western Soak area as there was in 1991, the Shanely's Lough catchment area has also been reduced. Overall, the 1991 high bog catchment area has been reduced by approximately 40 %, resulting in the Western Soak now being a distinct catchment area. This reduction is also apparent from the Bog Weir water balance calculation, where runoff is c. 40 % smaller than it was in 1991/ 1992.

### 10.3.3. Changing catchment divide between 2008 and 2011

The water balance calculations in chapter 9 for the high bog surface water catchment were based on catchment areas delineated from the 2008 LiDAR survey. It became apparent during catchment delineation that raised bog systems, which are highly sensitive to gradient changes, can only be accurately delineated using a high resolution topographic survey. As such, the catchment areas used to calculates rates of flux in the water balance may not be wholly accurate. The 2008 and 2011 topography in the subsidence analysis area are presented in Appendix E (note: 2008 topography is based on a 100 grid for comparison purposes). Comparing the figures it is noticeable that the topographic divide between the Western Soak and the Western Mound, described above, has again shifted northwards.

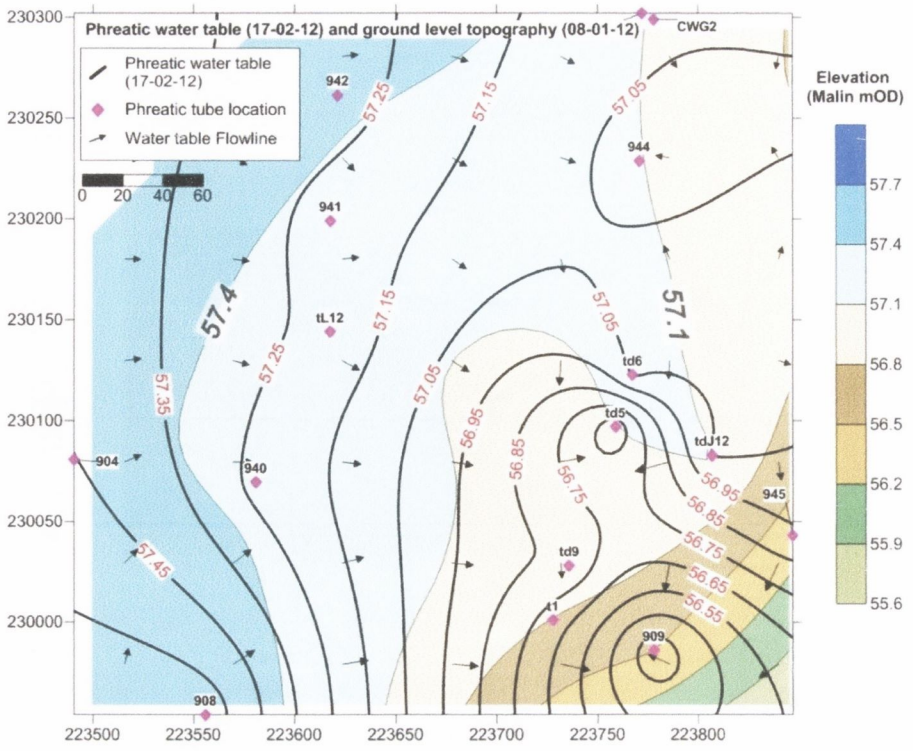


**Figure 10.5.** Topographic contours and 2011 high bog catchment area in subsidence analysis area

If the topographic divide has moved northwards, the catchment area supplying water to the Bog Weir has reduced. If the catchment area, for example, reduces by 10 %, infiltration in the Bog Weir catchment area reduces to 0.32 mm/ day or 11 % of total rainfall; and runoff increases to 23 % of total rainfall. This scenario is highly likely and an infiltration rate of 0.32 mm/ day is the same as the recharge rate calculated for the EPA Weir. Figure 10.5 illustrates the 'shifting' topographic divide area. Also illustrated on the figure is the phreatic water table in February 2012. The phreatic water table mimics the measured ground surface in that water flows south-eastwards in the vicinity of piezometer Tl12. Surface water flows eastwards towards piezometer td5, which marks the water table divide, and flows southwards from piezometer td9. The topographic/ water table divide is continuing to shift/ move north/ north-eastwards.

## 10.4. Hydro-ecological changes

The ecological communities, or ecotopes, on the Clara West high bog were described in Section 4.3 and it was noted that ecotope mapping can be used to assess hydrological conditions on the bog surface. The 'wet' ecotopes, namely central, subcentral and active flush, indicate whether the ecology present on the high bog is in a good condition or not – i.e. whether the bog is 'active'. Of particular importance is the presence of central ecotopes and active flushes. Both ecotopes are characterised by well formed acrotelm layers and in the case of active flushes, which constitute the soak systems, vegetation that is nutrient-rich relative to its surroundings. The presence of such ecotopes is dependent

on particular hydrological conditions being maintained – conditions related to topographic slope and the length of the surface water flow path supplying water to the ecotope assemblage.

### 10.4.1. Ecotope changes

Since the ecological work of the early 1990's (Kelly, 1992; Van der Scahff & Streefkerk, 2002) the area of 'wet' ecotopes on the high bog surface has decreased. Table 10.1 lists the area ($km^2$) of high bog mapped as 'wet' ecotope in 1992 (Kelly, 1993) and 2009 (Fernandez, 2009) and the percentage change in area within this period.

Table 10.1. High bog 'wet' ecotope area in 1992 and 2009 and the percentage change

| | Area ($km^2$) | | | | Area ($km^2$) | | |
|---|---|---|---|---|---|---|---|
| Whole bog | **1992** | **2009** | **Change** | 1991 catchment | **1992** | **2009** | **Change** |
| **Wet** | 1.07 | 0.79 | 26% | **Wet** | 0.81 | 0.64 | 20% |
| **Dry** | 1.39 | 1.67 | 20% | **Dry** | 0.23 | 0.44 | 92% |

Figures 10.6 and 10.7 illustrate the area of high bog covered by 'wet' ecotope in 1991 and 2009 respectively. In 1991/ 1992, the majority of the high bog catchment area (delineated to the Bog Weir so to enable comparison) was mapped as 'wet' ecotope, implying water was contained within the area, thereby maintaining saturated conditions. The flowlines on figure 10.6 are drawn based on the 100m OPW bog grid and it can be observed that long flow path lengths supply water to the Shanely's Lough soak system and that the Western Soak system is in a zone of water convergence. Water from the Western Soak area then flows eastwards towards Shanely's Lough.

However, in 2009, the 1991 high bog catchment area has fragmented and the area of bog covered by 'wet' ecotope has also fragmented – reducing by c. 20 % within the original catchment area and reducing by c. 26 % across the entire high bog area. The areas where 'wet' ecotope has disappeared are located mainly in the northern regions of the original catchment area, and in fragmented areas surrounding, west and northwest of the Western Mound.

Tables 10.2 and 10.3 list the area of high bog, whole bog and 1991 catchment area, covered by 'wet' ecotopes and 'dry' ecotopes in 1991, 2005 and 2009 respectively. It can be observed that the area of central ecotope has decreased between 1991 and 2008, though it has increased between 2005 and 2009. This increase may be a real one. Figure 10.9 illustrates the area of high bog where 'wet' ecotope has increased since 1991. Ecological mapping can never be exact and the small fragments of 'wet' ecotope increase may be a consequence of this. However, it can be observed that 'wet' ecotope area has increased in the north-eastern area of the high bog. Drains were blocked in this area in the mid 1990s (per comm. with NPWS) and this increase in central ecotope is most likely a result of local drain blocking inducing locally wet areas on the high bog surface.

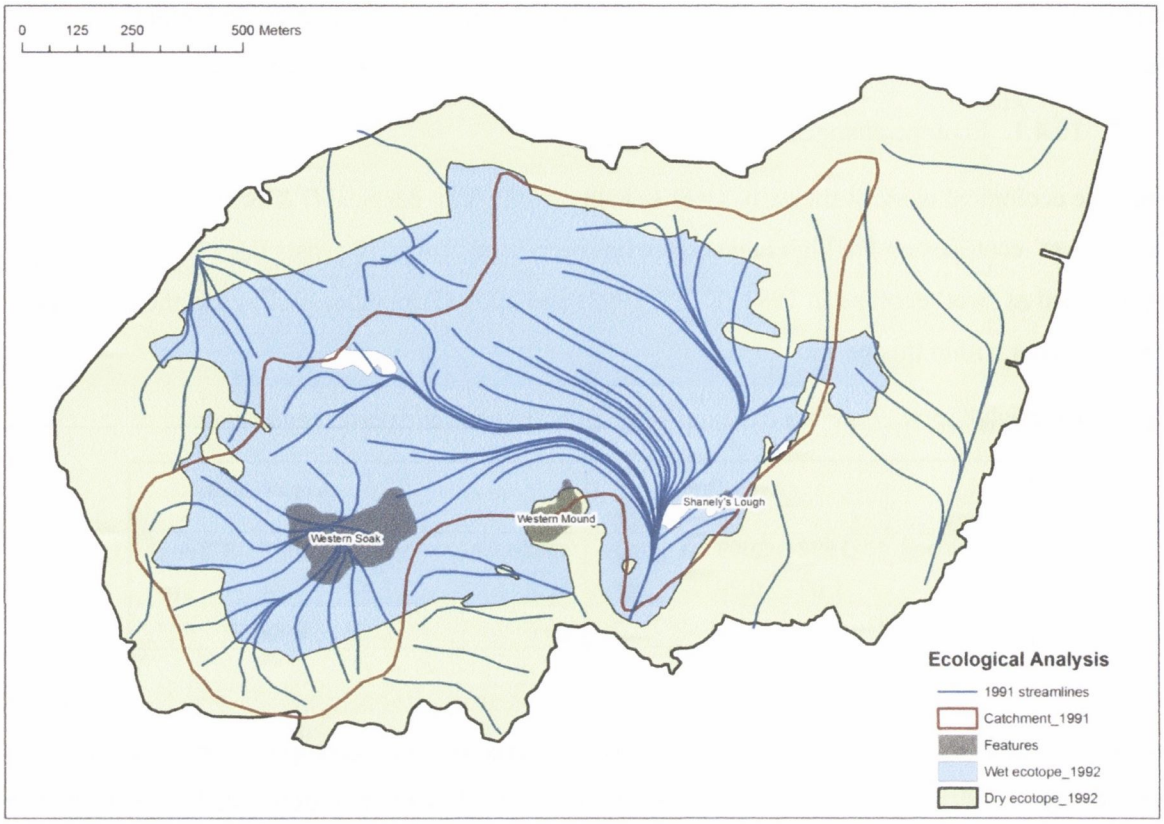


**Figure 10.6.** Area of high bog covered by 'wet' ecotope in 1991/ 1992 (after Kelly, 1993)

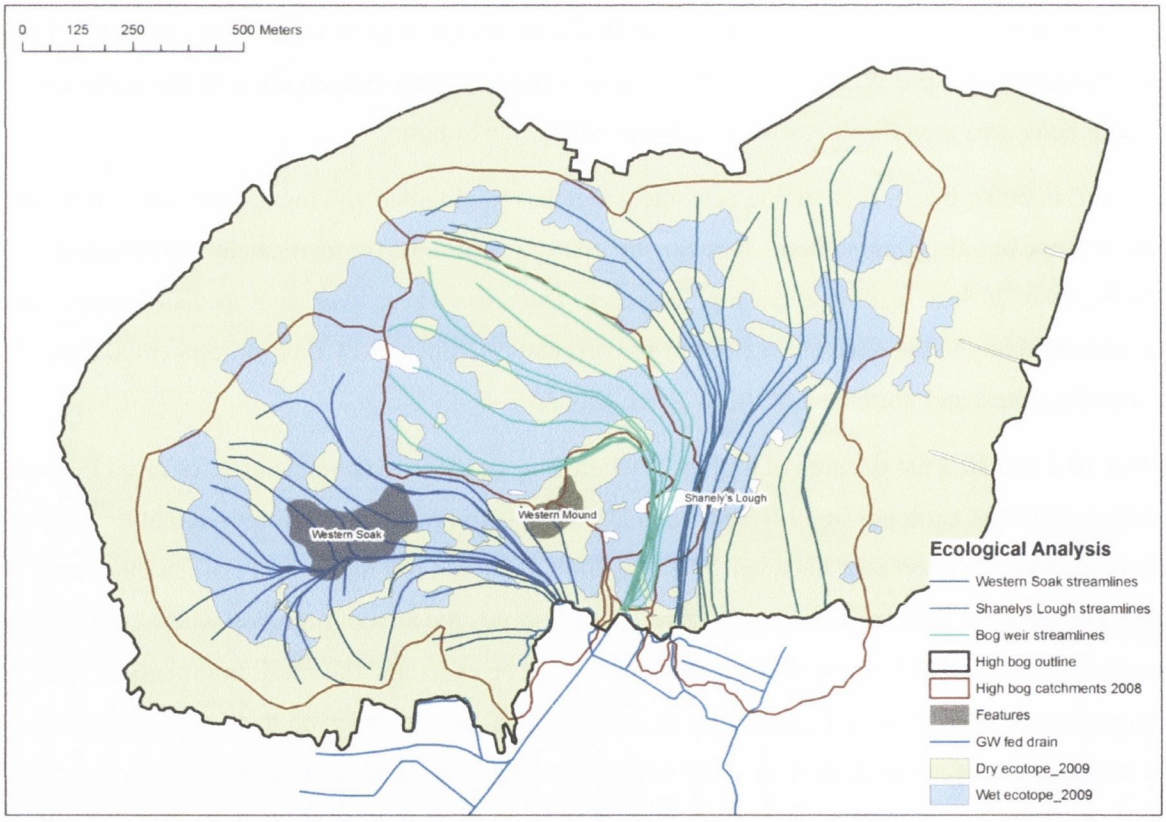


**Figure 10.7**. Area of high bog covered by 'wet' ecotope in 1991/ 1992 (after Fernandez, 2009)

However, overall, the area of central ecotope is decreasing, and from Table 10.2 it can be observed that areas of subcentral ecotope have continued to decrease since 1991 and areas of submarginal ecotope have continued to increase since 1991 – submarginal is effectively replacing subcentral. Figure 10.8 illustrates the area of high bog where 'wet' ecotope has disappeared since 1991. Bogs are susceptible to fires and in 2002 a fire affected the northern and norheastern area of the high bog (per comm. with NPWS). Fires, when they are allowed to persist, damage ecotopes, and there can be a long recovery time in vegetation regeneration, particularly those associated with an acrotelm, even if the hydrological processes remain the same. Fire may therefore explain the loss of wet ecotope in the northern area of the high bog.

However, the loss of 'wet' ecotope surrounding, west, northwest and east of the Western Mound is a consequence of high bog subsidence. Interestingly the area of active flush has remained relatively the same, implying changes in slope, which central and subcentral ecotopes is most sensitive to, is the dominant feature controlling hydro-ecological processes on the high bog surface.

Table 10.2. High bog area covered by 'wet' ecotope in 1992, 2005 and 2009

| Whole bog | Area ($km^2$) | | | 1991 catchment | Area ($km^2$) | | |
|---|---|---|---|---|---|---|---|
| **Wet** | **1992** | **2005** | **2009** | **Wet** | **1992** | **2005** | **2009** |
| Central | 0.15 | 0.09 | 0.11 | Central | 0.14 | 0.08 | 0.13 |
| Subcentral | 0.73 | 0.43 | 0.51 | Subcentral | 0.51 | 0.43 | 0.36 |
| Active Flush | 0.18 | 0.16 | 0.17 | Active Flush | 0.16 | 0.15 | 0.15 |

Table 10.3. High bog area covered by 'dry' ecotope in 1992, 2005 and 2009

| Whole bog | Area ($km^2$) | | | 1991 catchment | Area ($km^2$) | | |
|---|---|---|---|---|---|---|---|
| **Dry** | **1992** | **2005** | **2009** | **Dry** | **1992** | **2005** | **2009** |
| Facebank | 0.07 | 0.06 | 0.06 | Facebank | 0.00 | 0.00 | 0.00 |
| Marginal | 0.45 | 0.56 | 0.52 | Marginal | 0.02 | 0.03 | 0.04 |
| Submarginal | 0.85 | 1.11 | 1.07 | Submarginal | 0.21 | 0.35 | 0.39 |
| Inactive Flush | 0.02 | 0.02 | 0.02 | Inactive Flush | 0.00 | 0.01 | 0.01 |

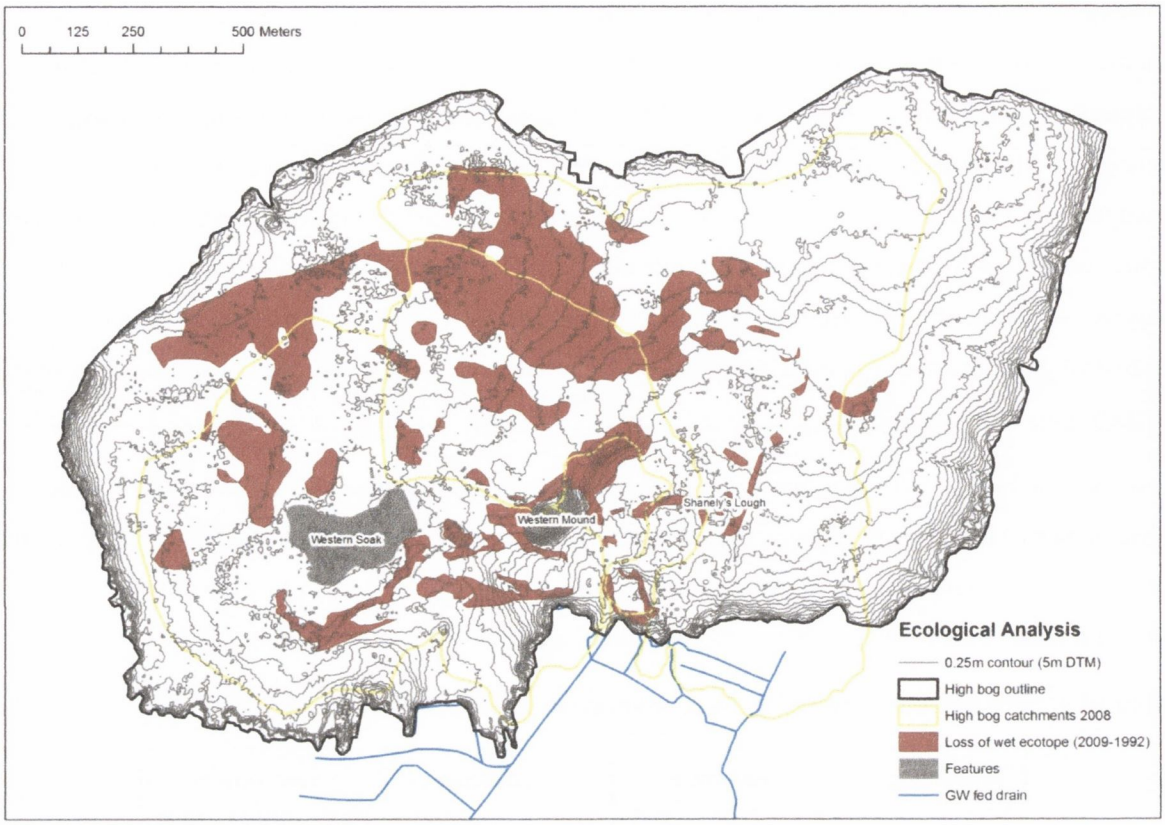


**Figure 10.8.** Area of high bog where 'wet' ecotope has disappeared since 1991

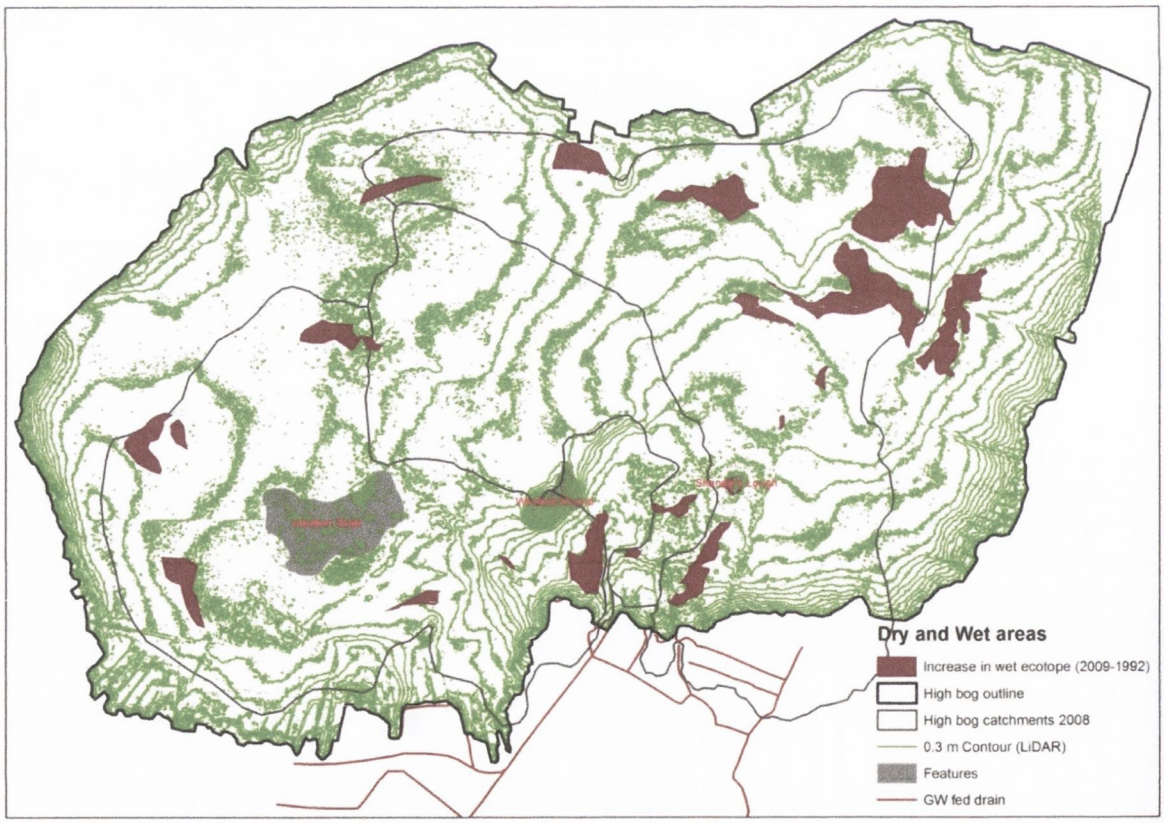


**Figure 10.9.** Area of high bog where 'wet' ecotope has increased since 1991

### 10.4.2. Slope changes

In Section 4.3, the slope gradients on the high bog were discussed. To maintain central and subcentral ecotopes, mean slope gradients < 0.3 % must be **maintained**. Active flushes can survive with higher slope gradients, in the order of 0.5 %, but the flow path lengths must be sufficiently long (> c. 400 m). Figure 10.10 illustrates the slope gradients of the high bog in 1991 and Figure 4.18, in Section 4.3, illustrates the slope gradients of the high bog in 2008. Though the gradients were calculated using different grid resolutions (100m grid in 1991; 10m grid in 2008), it is clear slope gradients have changed significantly. Figure 10.11 illustrates the difference in slope gradients between 1991 and 2008 (analysis computed using 100 m grid).

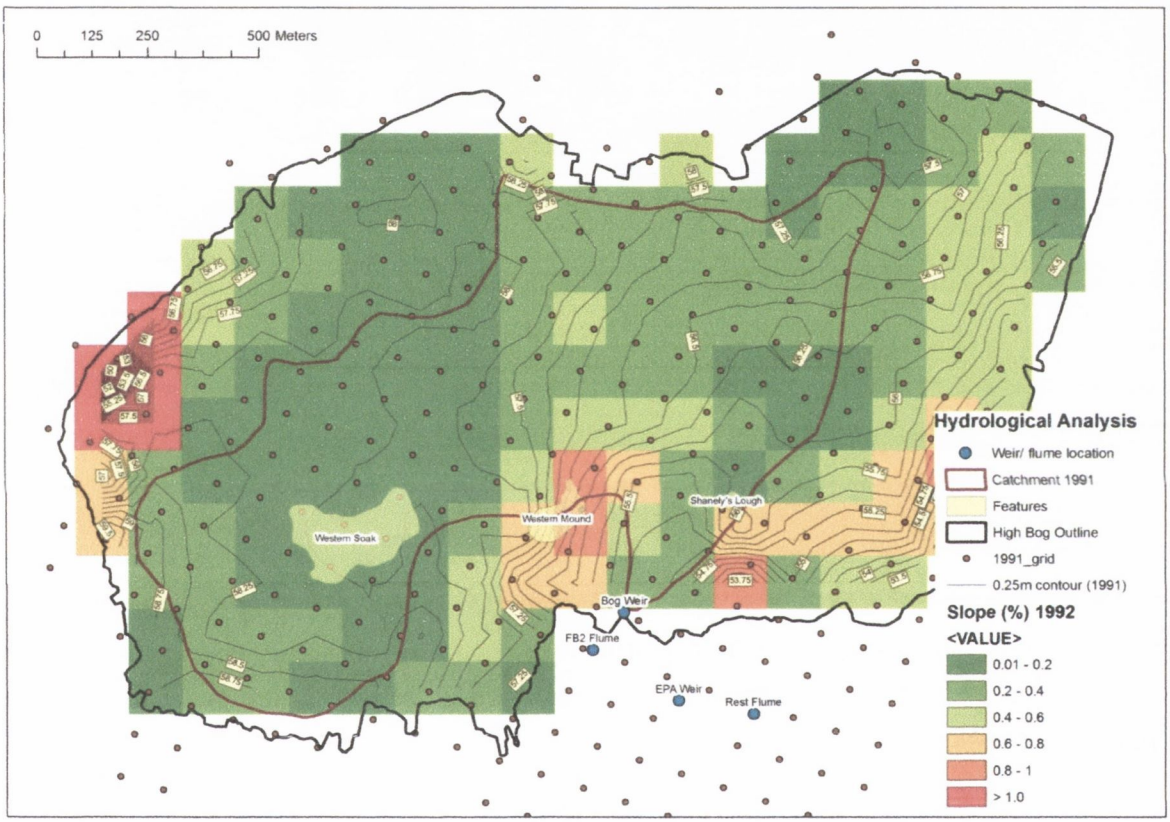


**Figure 10.10.** Slope gradients of high bog in 1991

It can be observed from Figure 10.11 that slope gradients have increased, and decreased, around the margins of the high bog and surrounding the Western Mound. Bog subsidence is highly differential (Chapter 7) and it is unsurprising that there is such variability in the slope gradient change. There has been little change in slope gradient in areas west and north of the Western Soak and in areas north and northeast of Shanley's Lough. Changes in slope gradient are concentrated in the areas surrounding the Western Mound – agreeing with subsidence analysis in Chapter 7 and water level decrease analysis in Chpater 8. It can be observed that the largest levels of slope increase, > 0.6 % since 1991, occurs southwest of the Western Mound – this increase in slope has changed the high bog topographic boundaries described in Section 10.3.

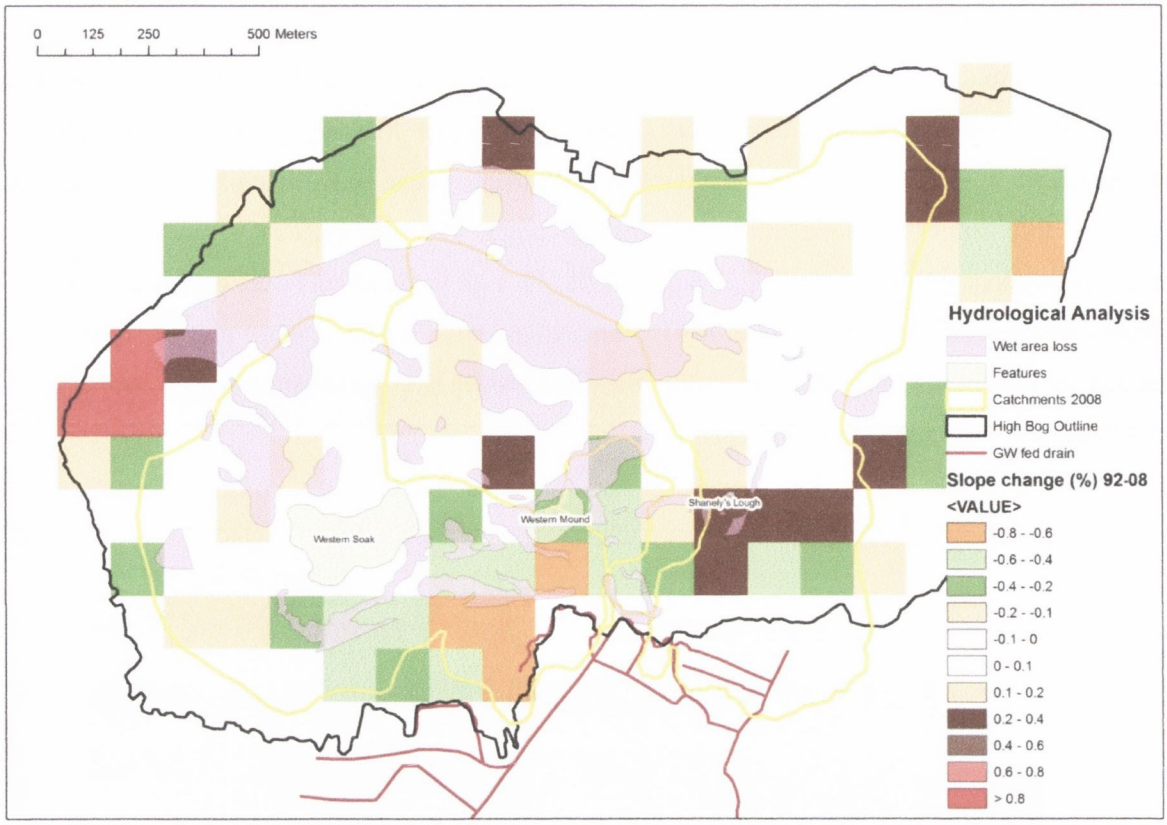


**Figure 10.11.** Difference in high bog slope gradients between 1991 and 2009. Note. Negative values imply increase in slope gradient

### 10.4.3. Flow path changes

In section 4.3, the flow path lengths supplying surface water to the high bog 'wet' ecotopes was described. Tables 4.8 and 4.10 summarised the flow path lengths to the 2009 'wet' ecotope areas in the Western Soak and Shanely's Lough catchment area respectively. By means of comparison, Tables 10.4 and 10.5 summarise flow path lengths to ecotopes in the Western Soak and Shanely's Lough area in 1991.

The mean flow path lengths to subcentral, central and active flush ecotopes in the Western Soak catchment area in 2008/ 2009 was c. 130 m, 170 m, and 320 m. In 1991, the respective flow path lengths were c. 100 m, 180 m and 270 m. Considering the errors involved with ecotope mapping and flow path length estimation, the flow path lengths in the Western Soak area have not changed much since 1991. However, central and subcentral ecotopes are largely maintained in areas with low slope gradients, which effectively means zero flow path lengths – though the flow regime to the Western Soak has not changed, subsidence has still altered slope gradients resulting in the disappearance of 'wet' ecotopes in peripheral areas to the Western Soak.

The mean flow path lengths to subcentral, central and active flush ecotopes in the Shanely's Lough catchment area in 2008/ 2009 was c. 250 m, 430 m, and 730 m. In 1991, the respective flow path lengths were c. 130 m, 380 m and 640 m. Viewing figures 10.7 and 10.8, it is clear that the Shanely's

Lough soak system is more dependent on long flow path lengths than the Western Soak system is. The results in Tables 10.4 and 10.5 indicate that flow path lengths to central and active flush ecotopes has reduced by c. 10 % since 1991. Additionally, the analysis does not include flow from the Western Soak area (which contributed flow to the Shanely Lough area in 1991), meaning the reduction in flow path length is greater than 10 %.

Table 10.4. Flow path lengths in Western Soak Area in 1991 high bog catchment

| | Active Flush | Central | Subcentral |
|---|---|---|---|
| **Max** | 465 | 340 | 130 |
| **Min** | 65 | 70 | 50 |
| **Mean** | 267 | 185 | 100 |
| **S.D.** | 109 | 69 | 29 |
| **n** | 18 | 13 | 5 |

Table 10.5. Flow path lengths in Shanely's Lough Area in 1991 high bog catchment

| | Active Flush | Central | Subcentral |
|---|---|---|---|
| **Max** | 925 | 610 | 300 |
| **Min** | 347 | 260 | 60 |
| **Mean** | 640 | 380 | 130 |
| **S.D.** | 159 | 115 | 97 |
| **n** | 20 | 15 | 5 |

## 10.5. Conclusions

The Clara West high bog had one surface water catchment in 1991. Differential subsidence has altered high bog topography since 1991 and this has resulted in the fragmentation of the 1991 high bog catchment area. The high bog can now be divided into four catchment areas. In 1991, the Western Soak and Shanely's Lough soak systems were encompassed within the same catchment area. Between 1991and 2008, the catchments fragmented, resulting in the soak systems now being isolated from each other. Overall, the 1991 high bog catchment area has been reduced by approximately 40 %. This reduction is also apparent from the Bog Weir water balance calculation, where runoff is c. 40 % smaller than it was in 1991/ 1992. Since 2008, the high bog catchment boundary between the Western Soak and the Bog Weir has reduced further still – possibly by 10 %; further indication that the bog system is far from reaching an equilibrium/ steady state.

The fragmentation of the 1991 high bog catchment has resulted in hydro-ecological changes to the high bog. The area of high bog supporting 'wet' ecotopes has reduced by 26 %, over the entire high bog surface, and by 20 %, within the 1991 high bog catchment area, since 1991. Areas of high bog supporting subcentral ecotopes have declined in ecological surveys in 2005 and 2009, and are being replaced by 'dry' submarginal ecotopes. Central ecotope areas have increased between 2005 and 2009, due to local restoration activities, but overall it has declined since 1991. The decrease in 'wet'

ecotope areas is a result of local fire affects, but most changes are a direct consequence of ground level subsidence. Slope gradients have increased, and decreased, on the high bog since 1991. A large slope gradient increase > 0.6 % in the area of the Western Mound has fragmented the original 1991 high bog catchment area. Though the area of active flush has remained relatively static since 1991, flow path lengths have decreased by c. 10% in the Shanely's Lough area. Changes in active flush ecotope may take longer to manifest themselves on the high bog compared to central and subcentral ecotopes which are controlled largely by slope gradient.

# 11. Groundwater Flow Modelling

## 11.1. Introduction

Groundwater flow models are tools that attempt to better the understanding of a groundwater system. The premise is that groundwater flow models can perform calculations and simulations that are too difficult to perform using analytical equations. Their real strength is therefore in predicting future groundwater flow behaviour in response to induced flow changes, natural or artificial, in the groundwater system. The validity of a groundwater model, and any model that attempts to interpret reality and indeed, the future, depends inherently on the knowledge of the systems geohydrology and the data available in which to calibrate it. No model is perfect and computed models of a hydrogeological system must always be interpreted with caution and analysed in tandem with observations and measurements made from the field.

## 11.2. Why develop a groundwater flow model for Clara West?

Runoff, recharge and infiltration rates of flux have been calculated, analytically, and used to compute water balances and solve for infiltration/ recharge rates for the Clara West hydrogeological system (chapters 6 and 9). There is a good understanding on how the bog system and marginal drainage is interacting with regional groundwater flows (chapter 4-6) – so what benefit is there to constructing a complicated groundwater flow model for the Clara hydrogeological system?

### 11.2.1. Purpose

Groundwater flow models are used to predict aquifer response, in terms of hydraulic head and fluxes into and out of an aquifer, to natural and human-induced stresses (Healy, 2010). They may therefore be used as forecasting tools in decisions related to groundwater resources and environmental management – i.e. they predict the consequence of a proposed action (Anderson & Woessner, 1992). However, a groundwater model also provides valuable insights into the groundwater systems sensitive hydraulic parameters and enables a visualisation on how the system works on a whole, in two and/ or three-dimensions.

A three-dimensional groundwater flow model for the Clara hydrogeological system has therefore been constructed so to (1) examine the hydraulic linkage between the till subsoil 'aquifer' and the bog body, (2) investigate the impact of marginal drainage on the hydraulic gradient and head in the till aquifer and bog body and (3) predict how the groundwater table, in each of the geological units, will behave following the removal of marginal drains and application of restoration works – and so feed into a conservation management plan for the bog systems long-term sustainability.

As such, the model serves two main purposes:

(1) Enables a better understanding of the interaction between the hydrogeological units in the system and the drainage system and why the flow system behaves in a particular way and;

(2) Allows a prediction to be made on groundwater flow patterns following restoration works. In particular, the high infiltration/ recharge rate (chapters 5 and 9) through the Clara West high bog is inferred to be a result of a lowered potentiometric surface in the high bog peat and underlying till groundwater body. Raising the groundwater table should, theoretically, reduce this infiltration rate. A numerical model will provide this information.

#### 11.2.2. Uncertainties

Modelling is typically limited by uncertainties due to sparse and inaccurate data related to the geohydrology of the system – e.g. (1) the geology of the system is poorly defined, (2) there is poor characterisation of key hydraulic parameters such as hydraulic conductivity and (3) there is a lack of water level data in the various hydrogeological units to calibrate the model – i.e. there is poor model control. In addition to uncertainties in the actual geohydrology of the system, the stresses affecting the groundwater system, and often the basis for constructing a groundwater model, are often unclear. However, in this case, the stresses affecting groundwater flow in the Clara region are relatively clear – the marginal drains are providing an artificial outlet for groundwater discharge (peat is effectively being dewatered). There is a clear cause and effect relationship – artificial groundwater discharge has lowered the regional groundwater table resulting in subsidence of the high bog.

#### 11.2.3. Conceptual justification

The Clara West high bog and surrounding area is well instrumented with piezometers measuring water level in the various geological units; and a c. two-year water level monitoring period provides a good record on water level fluctuations (section 5.2). The hydraulic conductivity of peat and subsoil units is also well characterised (chapter 5). The groundwater catchments can be drawn relatively accurately and though uncertainties will invariably remain the geology, particularly the unconsolidated/ subsoil geology, is relatively well constrained.

There was therefore a good database in which to develop a groundwater flow model – i.e. the basis of any good model is a good, underlying, conceptual model; which is dependent on the quality of the field measurements and interpretations. The modelling results are therefore used in conjunction with results measured in the field to ascertain (1) whether Clara Bog is groundwater dependent and (2) to characterise the linkage between the high bog and the regional groundwater system – field results and model results, carried out and interpreted in isolation, cannot answer this question alone.

### 11.3. What is a groundwater flow model?

A model has many definitions but it may simply be defined as a representation of a real system or process – it should represent observations made in the field. A conceptual model is a hypothesis of how a system or process operates - which may then be quantified mathematically.

### 11.3.1. Mathematical models

A mathematical model represents processes as equations, physical properties as constants or coefficients in the equations and measures of state or potential in the system as variables (Konikow & Bredehoeft, 1992). A mathematical model therefore simulates groundwater flow indirectly through use of a governing equation(s) that may be solved analytically or numerically – i.e. a model is a conceptual description or approximation that describes physical systems using mathematical equations; they are not exact descriptions of physical systems or processes.

Groundwater flow models effectively solve for the distribution of hydraulic head in an aquifer. Most groundwater models are deterministic mathematical models – i.e. a given input will always produce the same output; there is no variability ($y = f(x)$). Such models are based on conservation of mass, momentum, and energy and describe cause and effect relations. Deterministic groundwater models require the solution of partial differential equations (Konikow, 2001). Various established solution techniques based upon either finite difference or finite element approximations, or a combination of both, are available for solving the governing equations of the model. The accuracy of the solutions, or model predictions, is dependent upon the reliability of the estimated model parameters and the accuracy of the prescribed boundary conditions (Mays, 2012).

### 11.3.2. Limitations of a mathematical model

Analytical models can be employed to obtain groundwater flow solutions, though the parameters and boundaries used in such models are highly idealised and do not account for the complex, three-dimensional, heterogeneous hydrogeological setting. Heterogeneity, or variability in aquifer properties, is characteristic of all geologic systems and invariably influences groundwater flow (Konikow, 2001). Numerical techniques may then be employed to account for such heterogeneity and yield approximate solutions to the governing equations(s) through the discretion of space and time (Konikow & Bredehoeft, 1992). Numerical models essentially 'relax' the idealized conditions of analytical models and are therefore more realistic and flexible solutions - though they always remain an 'approximation' of groundwater flow. Numerical models are therefore used when boundary conditions are complex and where there is significant variability in hydraulic parameters within the groundwater system.

## 11.4. Mathematics underlying a groundwater flow model

### 11.4.1. Basic assumptions

The process of groundwater flow is generally assumed to be governed by the relations in Darcy's law and the law of conservation of mass (Konikow, 2001). Figure 11.1 depicts an idealised cube of porous material in which to derive a groundwater flow equation – the cube is large enough to be representative of the properties of the porous medium and yet is small enough so that the change in head within the volume is relatively small (Anderson & Woessner, 1992).

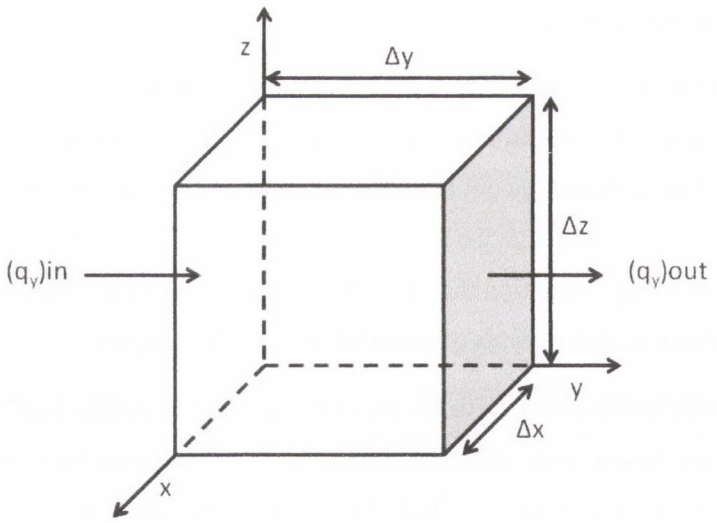


**Figure 11.1.** Elemental control volume for flow through porous media (after Freeze & Cherry, 1979)

The law of conservation of mass for steady-state flow through a saturated porous medium requires that the rate of fluid mass flow *into* any elemental control volume be equal to the rate of fluid mass flow *out* of any elemental control volume (Freeze & Cherry, 1979). A general equation for the conservation of mass, for the representative volume of porous media, may therefore be expressed as:

$$\begin{aligned}(rate\ of\ mass\ inflow) - (rate\ of\ mass\ outflow)\\ + (rate\ of\ mass\ production/consumption)\\ = (rate\ of\ mass\ accunulation)\end{aligned} \qquad \text{Equation 11.1}$$

The conservation of mass equation is essentially a water balance equation. The flow of water through the cube in figure 11.1, referred to as a representative elementary volume (REV), is expressed in terms of the discharge rate (**q**), which is a vector and whose magnitude is expressed in terms of three components: $q_x$, $q_y$ and $q_z$.

However, **q** cannot be measured directly (Anderson & Woessner, 1992). Head ($h$) can be measured directly and Darcy's law is used to calculate specific discharge through the flux planes in figure 11.1 - Darcy's law describes the rate of flow of water through a porous media and is related to the properties of the water, the properties of the porous media and the gradient of the hydraulic head and may be written as:

$$q_y = -K_y \frac{\partial h}{\partial y} \qquad \text{Equation 11.2}$$

where $q_y$ is the specific discharge along the y axis (volumetric flux per unit cross-sectional area rather than a 'speed' of groundwater flow), $K_y$ is the hydraulic conductivity of the porous medium along the y-axis and $h$ is the hydraulic head. The same equation is applied to the x and z axes in three-dimensions.

11.4.2. Groundwater flow equation

When Darcy's law is combined with the equation of continuity, the following general equation for transient flow through a non-homogeneous anisotropic saturated porous medium can be deduced:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - R^* \qquad \text{Equation 11.3}$$

where $K_x$, $K_y$ and $K_z$ are components of the hydraulic conductivity tensor (i.e. a force projected along a vector; assumed to be collinear to the x, y and z axes). $S_s$ is specific storage (the volume of water released from storage per unit change in head per unit volume of the aquifer); $R^*$ is a general sink/source that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time. To stimulate outflow $R^* = -W^*$ (after Anderson & Woessner, 1992).

Equation 11.3 is not concerned with hydrogeological units, *per se*, but rather it distributes head, hydraulic conductivity and storage in three-dimensions - it allows for both vertical and horizontal components in a groundwater system and may be used to describe groundwater flow in two and three-dimensions (Anderson & Woessner, 1992). If the aquifer is relatively thin compared to its lateral extent, it may be appropriate to assume that groundwater flow is areally two-dimensional (Konikow, 2001).

The groundwater flow equation 11.3 can then be simplified to represent two-dimensional horizontal flow in confined and unconfined aquifers:

$$\frac{\partial}{\partial x}\left(KD_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(KD_y \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} - R + L \qquad \text{Equation 11.4}$$

where $D$ is saturated aquifer thickness, $S$ is the storage coefficient, $R$ is a sink/source term that is defined to be intrinsically positive so to represent recharge and $L$ represents leakage through a confining layer. If equation 11.4 is applied to an unconfined aquifer, groundwater flow is assumed to be horizontal and the horizontal hydraulic gradient is assumed to be equal to the slope of the water table.

## 11.5. Numerical groundwater models

It is possible to solve the groundwater flow partial equations 11.3 and 11.4 analytically – however, this involves assumptions of homogeneity, simple boundary conditions and one or two-dimensional flow.

11.5.1. Requirement

Groundwater/ hydrogeological systems are invariably complicated and assuming a highly idealised system that is isotropic and homogeneous does not adequately describe its behaviour and flow

dynamics. As such, if analytical solutions are deemed too simplistic and inadequate, the partial differential equations, 11.3 and 11.4, must be solved numerically. Numerical models do not have the same limitations as analytical models, where the geology is highly schematised, and can be used to solve complicated groundwater flow problems. Whereas analytical solutions solve for head ($h$) at any point in a flow domain, numerical solutions solve for $h$ at fixed nodal points in the flow domain, which are connected to each other by a series of elements.

### 11.5.2. Numerical techniques

All numerical methods have their roots in polynomial approximation theory (Pinder & Celia, 2006) and the two major classes of numerical methods utilised by computer models to solve the groundwater flow equation are finite difference methods and finite element methods. The finite difference method consists of a rectangular element shaped discretisation of the aquifer and the finite element method consists of a triangular discretisation.

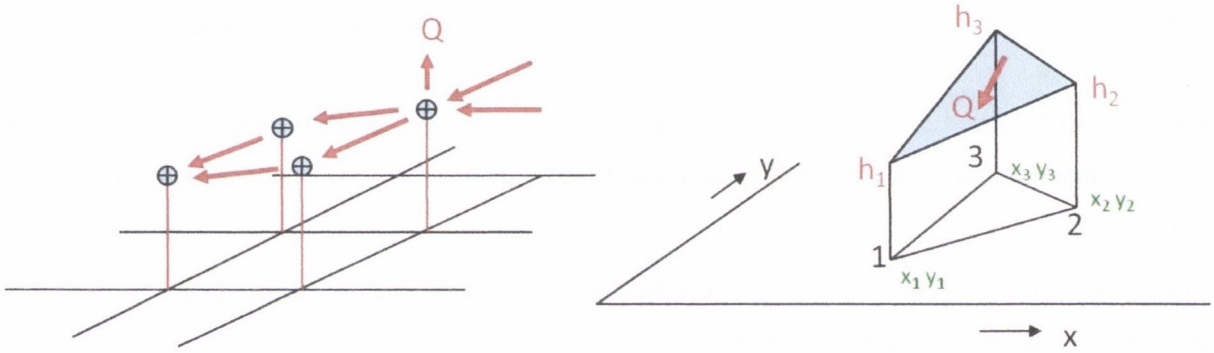


**Figure 11.2.** (A) Finite difference method, (B) Finite element method (after Hemker, 2011).

Both finite difference and finite element methods divide the model area, by a grid, into a large number of small cells or elements, and solve the water balance equation for each of the smaller parts (Hemker, 2011) – continuous variables are replaced with discrete variables that are defined at grid blocks/ node points (Konikow, 2001). Figure 11.2 schematises two-dimensional steady state flow modelled in a finite difference and finite element model. In each method, the continuous partial differential equation, which defines hydraulic head in the groundwater system, is replaced by a finite number of algebraic equations that defines the hydraulic head at specific points (Konikow, 2001). The size of the cells or elements, which are joined by nodes/ specific points, should be relatively small in all areas where the hydraulic properties are known in detail, where strong spatial variations in groundwater flow occur or are anticipated, and where accurate model results are required (Janssen & Hemker, 2011).

The mathematical background for the finite difference and finite element models are fundamentally different (Janssen & Hemker, 2011). Finite difference methods approximate the first derivatives in the partial differential equations as difference quotients – i.e. the differences between values of variables

at adjacent nodes, both in space and time, with respect to the interval between those adjacent nodes. Finite element approaches are more difficult mathematically and are assumed functions of the dependent variables and parameters to evaluate equivalent integral formulations of the partial differential equations (Konikow, 2001).

In both numerical approaches, the discretisation of the space and time dimensions allows the continuous boundary-value problem for the solution of the partial differential equation to be reduced to the simultaneous solution of a set of algebraic equations (Konikow, 2001).

### 11.5.3. Choosing a numerical model code: MicroFEM

*Requirements*

It is important to choose an appropriate numerical model and code that best suits the hydrogeological system being analysed. The model should be able to simulate (1) the observed groundwater flow patterns in the aquifer (s) - whether they are confined or unconfined, (2) the inferred model boundary conditions and (3) the measured field hydraulic parameters.

The numerical model must compliment the conceptual model of the system so that they may be used in tandem when interpreting the various processes at work, and ultimately, predicting future groundwater flow behaviour – though the groundwater model is an approximation, it should provide answers/ solutions not possible in idealised analytical solutions.

The Clara West hydrogeological system is complicated by a range of differing lithologies and their interaction with an artificial drainage system. To model such a system the model grid/ nodal distribution must be flexible as (1) the geological units vary in their extent, both in terms of thickness and areal distribution, and (2) the model boundaries are irregular enclosures. As leakage and downward seepage are important quantities to measure in the Clara West hydrogeological system, the model must be able to calculate these quantities so rates of flux can be estimatedand assigned to the different geological/ hydrostratigraphic units. Additionally, it is useful to model top boundary conditions such as drainage out from the system if recharge or effective precipitation is to be modelled in the system.

*Numerical code*

Considering the requirements necessary to model the Clara Wesy hydrogeological system, a finite-element model is considered most appropriate as a major advantage of finite-element methods is the flexibility of the finite element grid, which allows a close spatial approximation of irregular boundaries of the aquifer or particular parameter zones within the aquifer which demand closer analysis.

The finite-element code used to generate a numerical model for the Clara West hydrogeological system is MicroFEM – this program can model confined, unconfined and leaky multiple aquifers at

steady state and transient groundwater flow. It is possible to create a flexible grid in MicroFEM and model features include flexible methods of zone-selection and formula-assignment for input hydraulic parameters such as transmissivities, aquitard resistances, well discharges and boundary conditions for each model layer. Depending on the type of model employed, this can be extended with layer thicknesses, storativities, spatially varying anisotropy, top-system and user-defined parameters.

## 11.6. The conceptual model

### 11.6.1. Purpose

The purpose for constructing a numerical model for the Clara West hydrological system was discussed in section 11.1 – a numerical model permits (1) an improved understanding of the observed groundwater flow behaviour in the Clara West groundwater system and (2) a prediction of flow behaviour following restoration/ management works.

However, before constructing a numerical model a conceptual model must first be formulated so that there is a good understanding of the groundwater flow system and its interaction with the local drainage system – as this determines the grid design, boundary conditions and dimensions of the numerical model. In many ways, a conceptual model is the most important part of a modelling exercise as it requires an accurate understanding of the groundwater flow dynamics of the system.

As such, a conceptual model of the Clara West hydrogeological system essentially serves to simplify the flow behaviour in each of the hydrogeological, or hydro-stratigraphic, units. If the conceptual model is an accurate representation of the observed field situation, the numerical model will serve as an accurate representation of the measured field conditions.

### 11.6.2. The problem

The problem is clear - the Clara West high bog is losing water and subsiding as a result of peat consolidation. Peat is consolidating because water is being released from storage due to a decrease in pore water pressure associated with a decrease in the potentiometric surface in the peat and till 'groundwater' bodies. The result is an infiltration rate from peat to mineral subsoil in areas of the high bog where there is an underlying 'permeable' layer that serves as a subsurface drainage pathway for the water released from the peat substrate.

The conceptual model, based on field data, must therefore define the drainage pathways by which the bog is losing water and clearly indicate (1) the defining hydro-stratigraphic units, (2) the components of the water budget/ local hydrological cycle, (3) the surface and subsurface flow patterns and (4) the interaction between subsurface flows and the marginal drainage system in the areas of cutaway bog.

In short, an accurate conceptual model of the flow-system behaviour of the Clara West hydrologic system using observed and measured field data will allow the system to be analysed more readily – the calibrated steady state numerical model can then be used to validate the assumptions made in the

conceptual model. If the assumptions are validated, the steady state model can be applied as a prediction model that can simulate the future behaviour of the groundwater system following restoration works to restore the high bog system to a condition that may be considered to be favourable – i.e. 'active' raised bog and the preservation of the ecotopes deemed most worthy of scientific conservation.

### 11.6.3. Conceptual hydrological model

The geological/ physical framework of the Clara West region was discussed in chapter 3 and the hydrogeological framework and groundwater flow patterns were discussed in chapter 5. Water balances and recharge rates were calculated and discussed in chapter 9. Using this data, a conceptual Clara West hydrological model, which simplifies the hydrological and geological information, is formulated and is illustrated in figure 11.3.

*Model boundaries*

Model boundary conditions are critical in groundwater flow models and it is equally important that the hydrogeological conditions are properly defined in the conceptual model – boundary conditions in themselves. The hydrogeological components of the conceptual model are summarised as follows:

*Hydro-stratigraphic units*

The Clara West system contains five geological units that transmit water: (1) The acrotelm, which hosts the high bog phreatic water table, (2) the main bog body, or catotelm peat, where water infiltrates downwards and recharges underlying subsoil units (3) localised sand lenses, (4) till subsoil which hosts the regional groundwater table and (5) limestone bedrock, where water moves in a system of conduits/ fractures, and the regional groundwater table is coincident with the potentiometric surface in the till body. A confining unit, lacustrine clay, separates the peat from till, though this is absent where till mounds protrude above the clay unit. An upper clay unit in the till subsoil is also a confining layer but more permeable than lacustrine clay.

*Recharge and infiltration*

Recharge ($R$) refers to the volume of water that crosses the water table and becomes part of the groundwater system. However, in the Clara West hydrogeological system, infiltration ($I$), which is the downward movement of water through the peat profile that recharges the groundwater table hosted in the till body, is considered separately. Infiltration rates, from water balance analysis, vary enormously based on what the underlying subsoil unit is – and the same phenomenon is found in subsidence analysis. In the conceptual model, infiltration 'recharges' the groundwater table in till quickly where lacustrine clay is absent – but slowly where lacustrine clay is present.

Additionally, water that infiltrates downwards through cracks in the peat substrate, as indicated by the water balance from the Bog Weir, suggests a degree of lateral movement in the bog body - if the

'true' groundwater system is that of the till and limestone 'aquifer', where the regional groundwater table is hosted, water that infiltrates through the high bog peat, but does not enter the till body, does not constitute 'true' recharge in the model. Thus, while most infiltrated water moves vertically downwards, recharging the groundwater table in till, a proportion of this water moves laterally where cracks exist, particularly in areas where there are sand lenses present.

*Sub-surface drainage patterns*

The hydrogeological cross-sections described in Chapter 9 indicate that there are two main subsurface drainage pathways for groundwater flow within the bog body – (1) where peat is underlain by a till protrusion and (2) where peat is underlain by a sand lense and/ or peat crack. Lateral movement in groundwater flow occurs where either of these two situations are present beneath the high bog – the hydrogeological analysis shows this to be true (Chapter 5).

*Groundwater-surface interaction*

The drains in the Clara West drainage system receive groundwater flow from the till 'aquifer'. Base flow analysis estimates that runoff from the till groundwater body is between 0.29 and 0.39 mm/ day. In low-flow steady state periods, c. 70 to 90 % of drain runoff is mineral groundwater. Runoff from peat, originating from the high bog, is estimated to be between 0.03 and 0.08 mm/ day. The runoff from peat is higher than would be expected in natural conditions and the runoff is considered to be water released from peat storage due to peat consolidation. The runoff components in the marginal drains are mostly derived from waters originating from within and beneath the high bog. Thus, measured runoff components give a measure of leakage rates through the high bog, which can be used in steady state model calibration.

### 11.6.4. Summary

The conceptual diagram summarizes, and simplifies, the hydrogeological components of the Clara West hydrologic system. In figure 11.3, a groundwater fed drain separates high bog on one side from cutover bog on the other. The effects of the drain are illustrated by means of drawing the potentiometric surface in the till groundwater body and the phreatic water table in the high bog acrotelm and upper, oxidised, peat layer in cutover bog. The drain essentially draws down the potentiometric surface, thereby increasing the hydraulic gradient beneath the high bog – by inference the potentiometric surface in peat is also drawn down. The potentiometric surface drawdown is much like what happens when pumping from a well pulls down the surrounding groundwater table – the process is the same; the drain is discharging groundwater the same way a well discharges groundwater, but at a constant rate.

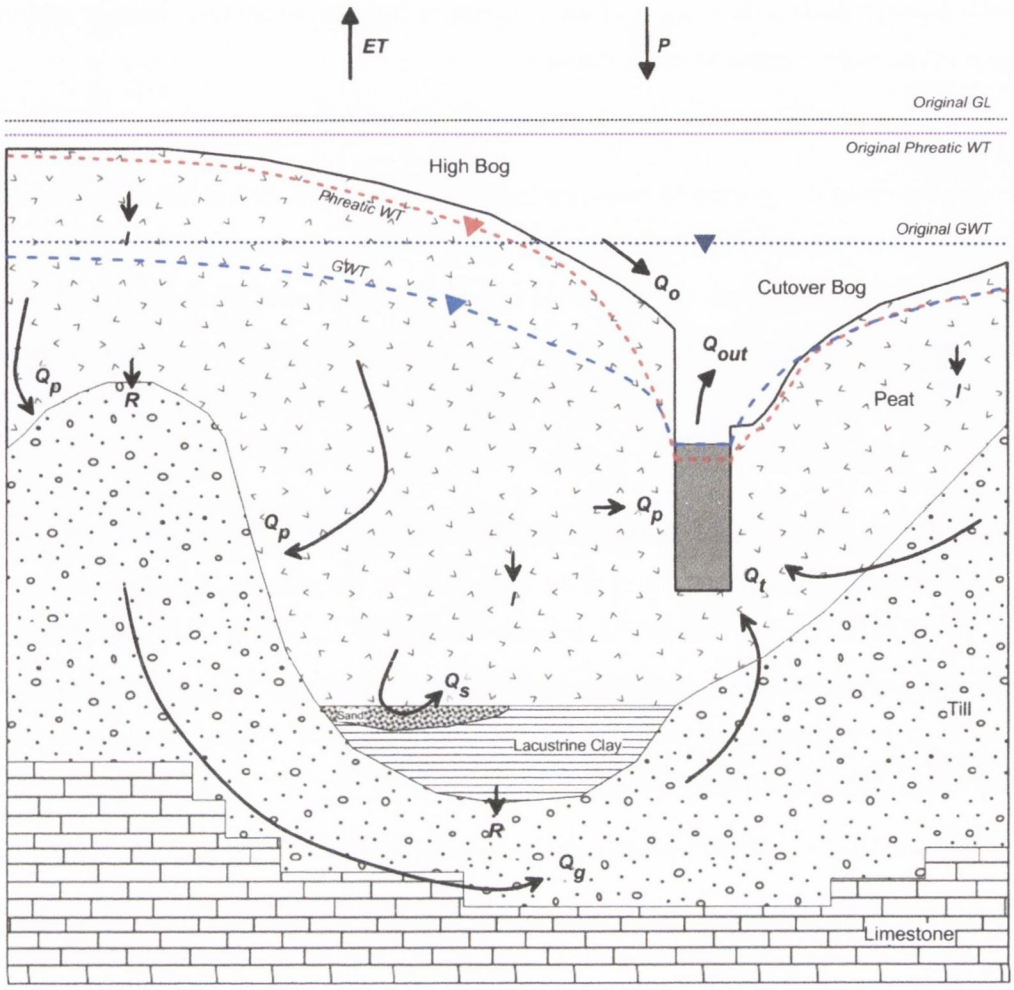


**Figure 11.3.** Conceptual Clara West hydrological model (not to scale). See Appendix H, Figure H1, for annotation.

Also illustrated in figure 10.3 is the assumed original or 'natural' phreatic water table and potentiometric surface in the till groundwater body. There is a flat gradient; whereas now it increases in the vicinity of the drain – this increased hydraulic gradient extends deep into the high bog. The open area between the 'original' surface ground level and the 'current' ground level can be assumed to be peat volume loss due to subsidence.

Runoff components and flow pathways are also illustrated in figure 10.3. Runoff to the marginal drain consists of: (1) overland flow from the top of the high bog/ acrotelm and surface of the cutaway area ($Q_o$), (2) subsurface discharge ($Q_t$) which includes groundwater flow from peat ($Q_p$), till/ limestone ($Q_g$) and sand ($Q_s$) and (3) lateral flow through peat ($Q_p$), which includes flow that moves through peat cracks. Discharge out of the drain, and out of the groundwater system is denoted as $Q_{out}$.

Arrows in the figure indicate the direction and flow path lengths of groundwater flow. Groundwater flow through the till body, which possibly infiltrates into limestone, flows upwards towards the drain, is relatively long, as too is the lateral movement of groundwater flow in peat by the till mound which induces the lateral flow which is ordinarily downward vertical infiltration/ recharge. The rotating arrow in the sand lense, which is not connected physically to the drain in the figure, indicates that

groundwater is moving laterally, outside of the conceptual diagram, to another drain or upstream/ downstream of the drain illustrated in the figure.

## 11.7. Model Design

Model design describes the process of transforming the conceptual model outlined in section 11.6 into a numerical model by means of (1) accurately designing the groundwater system boundaries, geohydrology and initial boundary conditions (in transient models) and (2) inputting the recharge rate, hydraulic fixed-head conditions and preliminary aquifer hydraulic parameters and confining layer resistances.

### 11.7.1. Boundary conditions

Boundary conditions are mathematical statements specifying the dependent variable (head) or the derivative of the dependent variable (flux) at the boundaries of the problem domain (Anderson & Woessner, 1992). In the case of MicroFEM, boundary conditions are set as a function of hydraulic head. Setting the correct boundary conditions in model design is critical if model outputs can be used and analysed with any degree of certainty as the model boundaries in steady state simulations (i.e. mean water level) effectively determine flow behaviour.

The model boundaries are selected based on the perceived behaviour of the groundwater flow system, by means of field measurements. The better the study site is understood on the ground the more accurately the model and its boundary conditions can be designed so to best mimic 'reality' – i.e. the conceptual model sets the geometry of the model dimensions and grid design.

*Types of boundaries*

There are two broads types of boundary considered in groundwater flow systems – physical boundaries and hydraulic boundaries. Physical boundaries are features that permanently alter groundwater flow and can be (1) geological features such as a fault or an impermeable body of rock or (2) hydrological features such open water bodies like a river or lake. Hydraulic boundaries are groundwater divides and streamlines and are in many ways 'artificial' boundaries as they are derived from inferred assumptions of groundwater flow in a groundwater system.

Two main types of hydraulic boundary may be defined: (1) Dirichlet, or constant head, conditions for which the hydraulic head is given and 'fixed' with the model boundary and flux is calculated by the model, and (2) Neumann or no-flow conditions for which the derivative of head across the boundary is given – the flux across the boundary is zero within the model system. Streamlines and groundwater divides are defined by no-flow boundary conditions and fixed head conditions are generally assigned to model boundaries where there is the need to define a specific flux to a discharge interface such as a spring or stream/ drainage channel.

Thus, knowledge of groundwater systems boundary conditions informs the geometry of the model domain to be generated. As boundary conditions are rarely linear features in map view, an advantage of finite element grid design is that the elements in the model grid can be adjusted so that the node with information on hydraulic head is situated on the perceived streamline, groundwater divide or drain/ stream location.

*Model boundaries*

The Clara West hydrogeological system is reasonably well understood – understood well enough to draw a conceptual model and permit the creation of a groundwater flow model. In chapter 1, the geographical location of Clara was described and it was noted that Clara Bog is situated between two rivers – the Brosna River, situated c. 1.7 km north of the high bog and the Silver River, situated c. 2.4 km south of the high bog. Initially the Brosna River and the Silver River were to be used as the models northern and southern boundary conditions – thereby serving as physical fixed head boundaries, which are generally more reliable boundaries then hydraulic boundaries, which are often in a state of flux, whether through natural water table fluctuations or due to stress conditions that shift the groundwater divide. However, in the early stages of model design it was apparent that there was not enough geological or hydrogeological data, north or south of the bog, to allow the calibration of a regional scale model of the bog system, particularly as the problem is a relatively localised one.

The groundwater model was refined to focus on the area of the system encompassed within the groundwater catchment area inferred from the mapping of the potentiometric surface in the till groundwater body (chapter 5) – i.e. a local groundwater system within a larger scale regional system. Figure H2, appendix H, illustrates the boundaries set in the model. The southern, western, northern and north-eastern boundaries in the model are defined by the groundwater catchment divide measured in the field – i.e. no flow boundaries. The south-eastern section of the model, highlighted in blue in figure H2, is a constant head boundary defined by the southerly flowing bog road drain (chapter 4). The drain was included in the model, at the expense of the south-eastern groundwater catchment divide inferred from field measurements (Chapter 5), so to facilitate more 'room' in the model domain for a stimulated ground water table rise following restoration work in the restoration Area - this will be discussed in Chapter 12. Within the model domain itself, the drains that form the Clara West drainage system are inserted as constant head boundaries, thereby serving as internal hydraulic boundary conditions within the model domain.

*Fixed head values*

Fixed heads, using stage values from drain water level monitoring (section 4.2), were applied to the drains in the Clara West hydrologic system. In chapter 4, the surface water flow regime in the Clara West drainage system was described and the instrumentation to monitor surface water levels, both continuously and periodically, was discussed, the data from which is presented in appendix B. As the

model attempts to represent a steady state situation of the Clara West groundwater system, mean stage values were used to define the fixed head values in the drains. The base of the drains in the drainage system were levelled (chapter 4) and knowing the relative gradients of the drains and the mean water levels from stage measurements, fixed head values were applied to nodes along the entire stretch of the model drain segment(s) – the head values therefore vary spatially as the gradients of the respective drains are highly variable. Figure 11.4 illustrates the model boundaries and grid network input into the groundwater flow model/

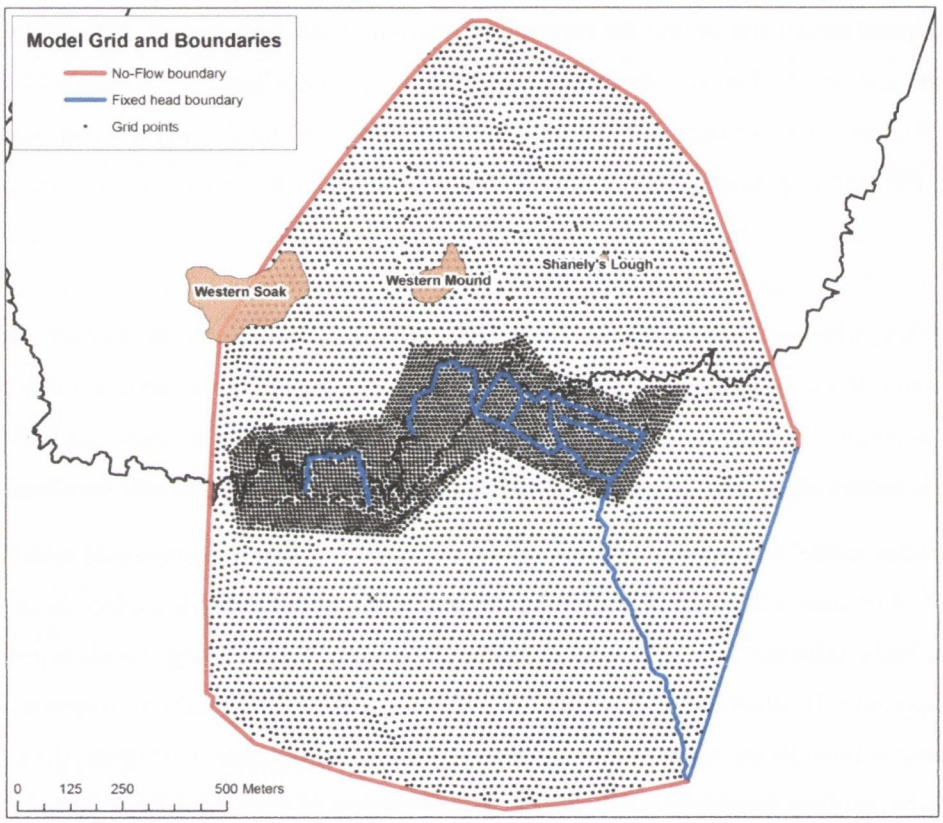


**Figure 11.4:** Overview grid design groundwater model Clara Bog West (with insight grid design drainage area)

### 11.7.2. Grid generation

The model grid domain was constructed based on the boundary condition definitions set in section 11.7.1 and the model grid generated is displayed in figures H3 and H4 (appendix H). In MicroFEM there are two options available for grid generation: (1) FemGrid which is an irregular boundary grid which can accurately model irregular geometries, such as river channels in regional groundwater studies and (2) FemMesh which is a high spacing contrast grid which can be used in more localised studies where irregular boundaries are not required and where there is a specific area of interest, such as in a construction and dewatering study. FemGrid was utilised in the Clara West groundwater model.

A finite element grid consists of a series of triangular elements that are joined together at specified nodes. Such a triangular network permits flexibility when entering details into the model. This nodal

framework defines the discretized modal domain. In grid generation a number of fixed node positions (i.e. nodes that remain fixed within the model, regardless of calculations performed in the model; though they can be adjusted following grid generation if necessary) were chosen so to define the position of the model boundary, drain system and additionally at selected locations within the model domain at known piezometer locations, the positions of which are used in model calibration. Following the selection and input of fixed node positions, a nodal spacing was assigned to the gird – i.e. the distance between two neighbouring nodes. This process generates the triangular elements that distinguish a finite element model.

The nodal or network spacing is important as the model calculates heads and flux between neighbouring elements – the more elements there are, the more computations the model must iterate when performing a specified calculation. Therefore a balance between the optimum spacing for adequate head calculation and an efficient time for the calculation iteration is necessary. In general, finer spacing of elements is applied to the area(s) of interest, where hydraulic head information is available, and courser element spacing is applied elsewhere in the model.

Following a process of trial and error two element spacing distances between nodes was decided upon and generated in the Clara model – 20 m throughout the whole model domain with a finer spacing of 10 m in the Clara West drainage system where there are groundwater fed drains close to the high bog (figure H4). In total, there are 8683 nodes and 17092 elements, meaning it is a highly discretised model – but not overtly so and calculations can be performed quickly, which is particularly important in model calibration.

### 11.7.3. Model layout

*Geo-hydrology set-up*

MicroFEM works with a system of aquifers and aquitards to represent the groundwater system. Various top-system packages are available in MicroFEM to simulate precipitation, evapotranspiration and drainage. The drainage top-system is head dependent and is entered in the model in terms of a drainage resistance and a drainage level. Fully phreatic conditions, where all recharge infiltrates downwards, and leaky aquifer conditions, where a proportion of water flows out of the groundwater the system and the remainder infiltrates into the system, can be simulated using the top-boundary drainage system, which is assigned the label $H_0$ in the model.

The aquifers units themselves are confined and are assigned transmissivity values (units in $m^2$/ day) accordingly. Separating the aquifer units are aquitards which are assigned resistance values (units in days; section 5.6). However, the aquitard units are not 'real' aquitards in the conventional sense, where they are physical, near impermeable, barriers to groundwater flow, but rather they are simply layers introduced to separate 'aquifer' units by means of a resistance, whether the 'aquitard' exists in reality or not. Groundwater flow therefore seeps downwards through the aquitard layer, the rate of

which depends on the resistance value assigned to the layer/ node of interest. Transmissivity and resistance values can be applied to specific nodes and the model can then interpolate transmissivity values between the intervening nodes.

Figure 11.5 illustrates a schematisation of the model system layers/ geohydrology. Based on the conceptual model, five 'aquifer' units have been identified and inserted as model layers – (1) the acrotelm, (2) the peat body or catotelm, (3) the sand lense/ stringers, (4) the till and (5) limestone bedrock. The base of the limestone layer is considered impermeable in the model, so to provide a physical boundary to downward seepage. Each aquifer unit is separated by an aquitard, even though in reality there is only one unit, lacustrine clay, which can be considered a true aquitard. However, whether aquitards in the model exist as physical entities in reality is not important as a resistance between aquifer units is required in order to simulate heads measured in the field.

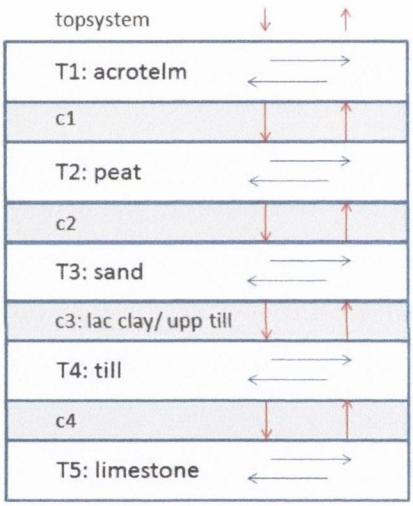


**Figure 11.5.** Schematised geohydrology/ model layer system

*Groundwater flow equation*

MicroFem solves the basic two-dimensional groundwater flow equation (equation 11.4) for confined aquifers described in section 11.4. The model accommodates for three-dimensional groundwater flow by employing (1) a two-dimensional triangular finite element method for the lateral flow components and (2) a one-dimensional finite difference method for vertical flow components (after Hemker et al, 2004). To solve for leakage, or vertical flux ($v$) through the aquitard, the following equation is applied to nodal areas in the model domain:

$$v = \frac{\partial h}{c} \qquad \text{Equation 11.5}$$

MicroFem therefore uses a sequence of aquifers and aquitards with horizontal/ lateral flow in the aquifers and vertical flow in the aquitards – i.e. it is essentially a quasi three-dimensional model.

Figure 11.4 illustrates the basic principles of this flow methodology, with horizontal flow lines in the aquifer units and vertical flow lines in the aquitard units. The inflow flow line in the top system represents recharge or precipitation and the outflow is discharge out of the groundwater system (e.g. evaporation or surface water runoff).

As the model is calibrated to an assumed steady state situation the storage coefficient is neglected - as storage is assumed to be at a minimum in steady state conditions. The variables in equation 11.4 to be solved are head ($h$), recharge ($R$), hydraulic conductivity ($K$) and leakage ($L$). Recharge is input directly, hydraulic conductivity and leakage indirectly and hydraulic head is solved for each of the model nodes when the hydraulic parameters of transmissivity and resistance are applied to each node in the aquifer and aquitard layers. Measured hydraulic heads are never input as a known quantity to non-fixed nodes in the model domain – measured heads are only used in the calibration and verification process (section 11.7.8).

### 11.7.4. Hydraulic parameter input

The hydraulic parameters required by MicroFEM are transmissivity and resistance. Transmissivity and resistance values are not measured directly in the field, but can be calculated when the thickness and hydraulic conductivity of the geological unit is known - the hydraulic conductivity of the geological substrate will also vary with depth, particularly in peat (section 5.6). A neat function of MicroFem is the ability to generate user defined parameter files based on the hydrological requirements for the model in question. In this case, the thickness of the geological units, using field information and thickness contour maps (Appendix A), was input as parameters file(s), and using contour maps of hydraulic conductivity, based on field measurements (chapter 5), transmissivities were calculated and applied to the model nodes. The same method was employed to calculate various resistance parameters. The resultant parameters values were later refined during model calibration (section 11.7.3.7). It is also important to note, that while hydraulic parameters are assigned to nodes, finite element computation is based on transmissivities of the elements (Hemker, 2011).

*Layer 1*

The first aquifer in the modelled groundwater system is that of the acrotelm - where most hydrological processes on the surface of the bog occur (chapter 2). Van der Schaff (1999) defined the acrotelm as 'a transmissivity-controlled aquifer, because its hydraulic gradient is determined by the shape of the catotelm and thus virtually constant in time'. The acrotelm is not a confined aquifer in the conventional sense as it hosts the phreatic water table. However, the phreatic water table, in healthy conditions, remains close to the surface of the bog with minimal fluctuations in water level. Van der Schaff (1999) found that a storage coefficient can be used to describe flow behaviour in the acrotelm body and that to describe lateral flow through the body it is more appropriate to think of flow in terms of transmissivity rather than water released as overland flow.

The acrotelm is the living layer in an active bog and is only present in particular areas where the ground level gradient permits sufficiently wet conditions to be maintained. Acrotelms are associated with central, sub-central and flush ecotopes (chapter 4 and 10) and the 2009 ecotope survey (Fernandez, 2009) was used to mark areas in the model domain where acrotelms are present on the high bog surface. The transmissivity of the acrotelm is highly variable, in both space and time, as at high phreatic water levels transmissivity increases considerably (> 1000 $m^2$ / day) while at low phreatic levels transmissivity is < 10 ms/ day (Van der Schaff, 1999). Taking steady state conditions into account, a generic transmissivity value of 2 $m^2$/ day (T1) has been applied to the acrotelm 'aquifer' modelled in layer 1. Where the acrotelm is absent, transmissivity is zero (figure H5; appendix H). As layer 1 is the upper boundary in the groundwater model, and is technically unconfined, the resistance c1 has been set to zero, reasons for which are explained in section 11.7.8.

*Layer 2*

The second aquifer layer in the model is that of peat – or the decomposed catotelm peat body. The hydraulic characteristics of peat were discussed in section 5.6 and though peat is a geological medium that transmits water very slowly, subsidence has altered the rate of flux through the peat column (as indicated by the settlement rates discussed in chapter 8) and the peat body must be considered an 'aquifer' in the model system. Though lateral flow rates are low (c. 1 mm/ year; chapter 2) the leakage rates are highly important and one of the goals of the model is to analysis the proportions of water that seeps from peat to till subsoil compared to peat-lacustrine clay subsoil.

Transmissivity

The measured hydraulic conductivities of peat are presented in tables 5.4 and 5.5 and are discussed in Chapter 5. It was found that the hydraulic conductivity of deep peat, which is generally in the order of $10^{-4}$ to $10^{-7}$ m/ day, increases significantly, in the order of $10^{-1}$ to $10^{-3}$ m/ day, in the area between the Western Mound and the Western Soak. It is this area where the bog ground level is continuing to subside (chapter 7). Another area of localised elevated hydraulic conductivity (> $10^{-2}$ m/ day) is also found south of the Shanely's Lough area. Similarly, this area has undergone significant (> 0.4 m) subsidence since 1991. To calculate transmissivity peat depths were introduced as an aquifer thickness file and hydraulic conductivity as a parameter file and the values multiplied. Measured hydraulic heads from the base of peat were used in model calibration (section 5.3) and the input transmissivity was adjusted accordingly (e.g. increasing/ reducing transmissivities by 5 % etc).

Figure H8 (appendix H) illustrates the resultant peat (layer 2) transmissivity and figures H6 and H7 illustrate areas of the model where transmissivity is greater than 0.01 $m^2$/ day and less than 0.001 $m^2$/ day respectively. The results are similar to what is found in the field – the high transmissivity areas are found in the region of high bog between the Western Soak and Western Mound, and also in the region of Shanely's Lough. Interestingly, elevated transmissivity also had to be applied to the area

north of Shanely's Lough, in the area of 'new' bog pools, where there is a perceived elevated infiltration rate, and close to the high bog margin, southeast of the Western Mound. The high transmissivities in areas such as the bog boundary and in the area of the Western Mound are mostly probably a consequence of subsurface peat cracking – which still constitutes as increased transmissivity in the model aquifer layer.

Resistance

Resistance between the acrotelm and the peat body (i.e. c2) was estimated simply by dividing the peat thickness by its estimated hydraulic conductivity - and then adjusting locally during calibration of the deep peat heads (section 5.6). Figure H10, H11 and H12 appendix H, illustrates areas of (1) low resistant peat (c < 1500 days), (2) high resistant peat (c > 3000 days) and (3) highly resistant peat (c > 6000 days).

Low resistant peat underlies most of the model area outside of the high bog as peat is shallow or absent in these areas, but the layer by default is still included in the model. Highly resistant peat (i.e. > 6000 days) is found in the Restoration Area, and is a consequence of the system being drained. The majority of the high bog is resistant peat (> 3000 days) and the areas of low resistant peat (< 1500 days) are found on the Western Mound and the subsurface mound located south of the Western Soak, in the region of piezometer 908. Highly resistant peat is also found on the high bog, adjacent to drain FB1 (deep peat piezometer 907 took near 7 months to reach equilibrium; section 5.3), and south and east of the Western Mound. The resistance near the Western Mound is in accordance with the inference that head in peat at piezometer 909 is isolated from the till body (section 5.3) and the very low hydraulic conductivity measured at piezometer 937. The highly resistant peat along the north-western boundary of the high bog is possibly a consequence of the peat underlain by lacustrine clay in these areas.

*Layer 3*

The sand lense(s) underlying peat and overlying lacustrine clay in the area east of the Western Mound and south of Shanely's Lough is a thin unit no thicker than c. 0.3 m (Chapter 3). It is also relatively localised and occurs adjacent to the old lake basin (Figure A2). However, it is an important substrate unit in the Clara West hydrogeologic system as (1) it is associated with subsidence south of Shanely's Lough and (2) is a pathway for subsurface drainage from the high bog. The sand unit has therefore been included as a model aquifer in the groundwater model system.

At the time of model generation it was inferred that the sand lense was largely one unit that trended north-south into the Restoration Area. Subsequent analysis and acquirement of additional information indicates that it is actually number of sand lenses, or stringers, representing an old drainage system that flowed north-eastwards into the old lake basin, marked by the marl unit (Figure A2). However, the sand lense area marked in the model domain (figure H13) is still valid, as it marks approximately

the same area as the sand distribution in figure A2. Model calibration of head in peat (layer 2) also found that the whole 'sand area' is one of low hydraulic head, meaning its exact location is not overtly important.

Compared to the well instrumented peat and till geological substrates, assigning field hydraulic parameters to the sand lense unit is difficult (section 5.6) as there is no accurate field measurement of hydraulic conductivity in which to estimate transmissivity or resistance. Piezometers installed in the sand lense suggest hydraulic conductivity is low, but this is unreliable. However, analysing the piezometer level data from piezometer nests 92 and 937, water levels in deep peat and sand are within 10 cm of each other, implying downward movement of water but little resistance.

Taking a generic hydraulic conductivity value of 0.005 $m^2$/ day, a generic resistance, c3, of 12.5 days is applied across the model domain. Applying a transmissivity value required more thought as simply multiplying aquifer thickness by hydraulic conductivity results in a transmissivity value that has little impact of groundwater flow – but the low hydraulic heads in the area suggests substantial subsurface drainage. In the model calibration of heads from the base of peat a high transmissivity of 20 $m^2$/ day was required to account for heads in peat in these areas. It is inferred that there is possibly subsurface peat cracking in the sand areas inducing this high transmissivity – a similar deduction as made to account for the high infiltration rates deduced from the Bog Weir water balance .

*Layer 4*

The forth model aquifer layer is that of the till mineral subsoil. Most of the Clara West groundwater instrumentation has concentrated on measuring water level and hydraulic parameters from the till subsoil body as the regional groundwater table is hosted in the till subsoil unit and marginal drainage has served to lower this groundwater table under the high bog.

As discussed in section 11.6, a purpose of the model is to better the understanding of the hydraulic connection between the till groundwater body and the high bog and Clara West drainage system. The till body is well instrumented with piezometry (chapter 3) meaning the layer 4 has ample information in which to be calibrated with.

Transmissivity

Section 5.6 in chapter 5 discussed the range of hydraulic conductivity values measured in till and the results are presented in table 4.4 and 4.5. The results were variable and it is found that till subsoil generally becomes more permeable with depth due to the prevalence of more sand and gravel units than is found in the upper margins of the subsoil body, where the lithology is generally more clay rich, thereby reducing its relative permeability. To account for this apparent division into 'low permeability' till, < $10^{-3}$ m/ day, and 'high permeability' till, > $10^{-3}$ m/ day, the upper till unit is considered to be the aquitard overlying the lower till unit, an aquifer.

Model calibration of heads from the till body found that heads in the groundwater systems are sensitive to the value of transmissivity chosen for layer 4. In contrast to the methods utilised for determining transmissivity in layer 2, where peat thickness and hydraulic conductivity were combined, a generic transmissivity value of 8 $m^2$/ day was found to adequately calibrate computed heads against measured heads in layer 4. An increased transmissivity value of 15 $m^2$/ day was necessary to account for the observed groundwater heads in the south-western region of the model domain (figure H41; appendix H). This area is an elevated area of the model region, an elevated area known locally as 'The Island'. The high transmissivity value required here is possibly a result of the recharge value being too low (i.e. recharge is locally high in this area). However, this does not affect the model results.

Resistance

Till subsoil is overlain by lacustrine clay across much of the model domain except for the southern region of the model domain where lacustrine clay is absent and in localised pockets underneath the high bog, where till protrudes above the lacustrine clay so that it lies directly underneath peat substrate. Lacustrine clay is a highly impermeable material with hydraulic conductivity values in the range of $10^{-7}$ m/ day. The lacustrine clay unit is therefore inserted as the aquitard c3. Where the lacustrine clay is absent, the upper till unit with low permeability characteristics serves as the aquitard with resistance c3. The model is not concerned with substrate thickness, but resistance, so it is easy to group lacustrine clay and upper till as the one aquitrad as they are the confining layer to the same unit, the aquifer in layer 4.

Figure H15, appendix H, illustrates the resistances applied to layer 4. Resistance increases where the clay layer becomes thicker towards the centre of the old lake basin in the eastern region of the model area. Resistance is between 7500 and 17500 days in this area. Lacustrine clay is relatively thin in the western half of the model area and a lower resistance value of 5000 days is applied. Where the lacustrine clay is absent a resistance value of 1000 days is applied to the upper till unit beneath the high bog and a resistance value of 100 in the area south of the high bog is applied. Again, this is possibly a result of a lower recharge value being set outside of the high bog area.

*Layer 5*

The fifth modelled aquifer layer is limestone bedrock, the base of which is considered to be impermeable. The base of the Limestone is set to 30 m above sea level in the model domain and an arbitrary transmissivity value of 2 $m^2$/day has been applied to the unit as it is perceived that most of the groundwater discharge into the Clara West drainage system is derived from the till groundwater body. The hydraulic heads measured in piezometers installed in limestone bedrock indicate that there is little downward vertical flow from till to limestone, particularly close to the Clara West drainage system where water levels in till and limestone are near coincident with each other. A low resistance

of 40 days has therefore been applied to the 'aquitard' layer separating the till aquifer (layer 4) and the limestone aquifer (later 5) across the model domain.

However, during model calibration of hydraulic heads measured in the till aquifer, a zone of 'low' hydraulic heads measured in the field were difficult to account for in the model domain. This particular area is overlain by lacustrine clay > 1.0 m implying the low hydraulic heads in till are a consequence of water being 'pulled' from elsewhere, rather than localised high transmissivity in the till aquifer, which is unrealistic based on the measured hydraulic conductivities. A northwest-southeast trending high transmissivity zone in the limestone aquifer, simulating a conduit/ fracture, has been inserted in an area between the Western Mound and the Western Soak. A transmissivity of 120 $m^2$/ day has been applied to this zone underneath the high bog and a transmissivity of 30 $m^2$/ day has been applied to this zone south of the high bog boundary (Figure H16).

### 11.7.5. Hydraulic parameter input summary

A summary of the hydraulic parameter inputs assigned to each of the modelled layers is provided in table 11.1. It should be noted that transmissivity (T) refers to lateral flow in the aquifer units and resistance (c) refers to vertical resistance in the confining aquitard units.

Table 11.1. Summary of hydraulic parameters input in Clara West groundwater steady state flow model

| | | | |
|---|---|---|---|
| **Layer 1** | | **Layer 4** | |
| Resistance (days) | 0 | Resistance (days) | 100 - 17500 |
| Transmissivity ($m^2$/day) | 0 - 2 | Transmissivity ($m^2$/day) | 8 – 15* |
| **Layer 2** | | **Layer 5** | |
| Resistance (days) | 22 - 10000 | Resistance (days) | 40 |
| Transmissivity ($m^2$/day) | 0 – 0.8 | Transmissivity ($m^2$/day) | 2 - 120 |
| **Layer 3** | | | |
| Resistance (days) | 12.5 | | |
| Transmissivity ($m^2$/day) | 0 - 20 | | |
| *Note: * not including low T areas surrounding drains* | | | |

### 11.7.6. Fixed head application

Fixed head boundary conditions have been assigned to nodes defining the Clara West drainage system (figure H1). Fixed heads have been applied to layers 1, 2, 3 and 4. As described in section 11.7.3, the mean of measured stage in drains in the Clara West drainage system (chapter 4) were used to determine the fixed head values. As the regional groundwater table in the till aquifer is above the base level of the drains in the Restoration Area (section 4.3), the fixed heads derived from stage measurements (table 4.3) were applied to define fixed heads in layer 4. Fixed heads in layers 1, 2 and

3 are below this, as there is an upward movement of water, and are applied fractionally below the layer 4 fixed head elevation using base drain elevations.

There is a steep hydraulic gradient of the potentiometric surface in the till groundwater body in the vicinity of drains which have cut below the regional groundwater table. To account for this in model calibration of heads in layer 4, low transmissivity values between 0.01 and 0.5 $m^2$/ day were applied to the nodes surrounding the fixed head drainage system (see figure H3). Also, during model design, fixed head conditions were removed from drain TD. Drain TD1 is observed to be periodically dry (dry in July – September 2011) and fills following sustained rainfall events. As the model is a steady state model it is reasonable to removed fixed head conditions from drain TD1 – this aided the calibration process. No other groundwater fed drain is observed to be dry in the field and fixed head conditions remain.

### 11.7.7. Recharge and top-boundary condition

Layer 1 in the groundwater model is the acrotelm and it is an unconfined aquifer – there is no confining unit overlying this unit. This implies that there is no head dependent flow at the top of the aquifer and that the aquifer is replenished by recharge from precipitation. By default, MicroFem sets the top-boundary condition as that of a leaky aquifer so that $H_0$ is fixed and $H_1$ is calculated. In phreatic conditions, the head in the top boundary must become a no-flow boundary and this is achieved by setting the resistance in layer 1 to zero (i.e. c1 = 0). By adopting a precipitation system as a top boundary condition the no-flow becomes a fixed-flow top boundary condition – i.e. recharge from precipitation is a specified flux through the upper model boundary, thereby creating the fixed-flow condition. The value entered as $H_0$ plays no role when calculating the model heads and $H_1$ is calculated.

Recharge rates have been calculated for the flow measurements structures installed in the Clara West hydrologic system using baseflow analysis (chapter6 and 7). It is estimated that recharge to the till groundwater body varies between 0.24 to 0.39 mm/ day. The higher recharge rates appear to be associated with high infiltration zones associated with the esker deposit that borders the northern boundary of the high bog. The modelled catchment area was drawn based on the potentiometric surface measured from piezometers in the till groundwater body – but before sufficient runoff data was available to compute the water balances presented in chapter 7. As such, the northern boundary of the model is underestimated – by c. 0.3 $km^2$. However, the model boundary is still valid as the groundwater streamlines do not change – problems may possibly be encountered in transient/ prediction calculations (chapter 12).

A recharge value of 0.3 mm/ day was selected as the precipitation system input value. However, the high bog under the model domain area, particularly in its western section, has undergone significant subsidence (> 0.6 m in local areas) since 2002. Subsidence and settlement rates were calculated and

discussed in chapter 8 and to account for this 'additional' water released from storage in the high bog peat, the recharge value was increased to 0.45 mm/ day in the area of the model domain underlain by the Clara West high bog.

An additional top-system boundary condition was required in the model set-up. During model design and calibration (section 11.7.3.7) it was found that $H_1$ in layer 1, i.e. the phreatic water level in the acrotelm aquifer, was consistently over-estimated – by up to 1.0 m. The 2008 LiDAR survey was input as a grid xyz file in the model domain and assuming the LiDAR generated topography of the high bog is representative of the high bog phreatic water level, analysis of computed phreatic water level versus $H_0$ (the LiDAR topography) necessitated the inclusion of an additional, secondary, top-boundary drainage system. The additional drainage system, which has its own drainage base ($H_0$) and resistance (c = 100 in model) serves to calculate additional fluxes at the model nodes, resulting in a lowering of the phreatic water level in the model, consistent with what is observed in reality.

### 11.7.8. Calibration

*Calibration process*

Calibration of a flow model refers to a demonstration that the model is capable of producing field-measured heads and flows which are the calibration values (Anderson & Woessner, 1992) – i.e. the purpose of model calibration is to show that the model can reproduce head measurements. The process is achieved by finding a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes that match field-measured values within a pre-established range of error (Anderson & Woessner, 1992). In this case, the model must be able to reproduce the head from the model aquifers, layer 2 (peat) and layer 4 (till), measured in the field, within c. +/- 0.5 m. The more field measured heads there are in which to calibrate the model the more time-consuming the process – but it also ensures a more accurate representation of the field situation, particularly if the heads to be calibrated are randomly distributed across the model domain.

A problem encountered in most groundwater models is the lack of head data in which to calibrate it with – partly due to model domain areas in regional studies being quiet large while being represented by a limited number of observation points. However, the Clara West model domain area is relatively small with a large number of measurement points in peat and till and the boundaries of the model are known and are considered relatively accurate. There is therefore sufficient data to calibrate the model using head information from the critical aquifer layers 2 and 4.

There are two main methods to finding model parameters to achieve calibration: (1) manual trial-and-error adjustment of parameters and (2) automated parameter estimation (Anderson & Woessner, 1992). In MicroFEM, automated calibration is possible using an optimization tool which adjusts some selected parts of the model input data (the "parameters") to reduce the differences between the observed and the computed heads - the optimization process is based on searching for the best fit

between a user-specified set of observed heads and the corresponding model heads (Hemker, 2011). The calibration process combined both methods by first getting a best fit (i.e. low residual sum of squares) and by then applying the optimisation tool to refine the calibration.

*Layer 2 calibration*

Field conditions

As noted in section 11.7.8, and described in section 5.5, chapter 5, there is a zone of 'low hydraulic head' in basal peat in an area south of Shanely's Lough and east of the Western Mound. This area is associated with the sand lense (layer 3) and is a zone of subsidence (chapter 7). In model set-up and calibration the resistances and transmissivities were input so to represent the observed field situation. The area where sand underlies peat is underlain by a significant thickness of lacustrine clay– high vertical resistance between layers 2-3 and layer 4 in this area; as marked in the model domain. Thus, while resistance is an important hydraulic parameter, the input resistances were realistic enough that further adjustments were minimal – i.e. the low hydraulic heads in peat required adjustment of transmissivity in layers 2 and 3; the transmissivity of till (layer 4) has little effect in this area.

Figure H13, appendix H, illustrates peat transmissivity and the marked nodes where a transmissivity was applied to the sand lense (layer 3). Peat transmissivities are high in this area of the model, ranging between 0.01 and 0.06 $m^2$/ day. Increasing and decreasing this transmissivity was found to have little effect on hydraulic head in layer 2 – unless unrealistic values, akin to a subsoil aquifer unit, were introduced. However, applying an increased transmissivity to layer 3, in areas where sand was encountered in the field and interpolated to occur, the low heads in layer 2 could be explained. Following a process of trial and error, a transmissivity value of 20 $m^2$/ day was applied to layer 3.

It is possible that this high transmissivity is representative of subsurface cracking in the peat rather than a highly conductive sand layer. Field measurements would suggest the former is the case. It is possible that the sand lense is a 'weak' break in the subsurface geological profile, a former high energy environment, and has effectively induced peat cracking above the layer, increasing the peat permeability, locally. Whatever the scenario may be, the low peat heads in layer 2 require an increased transmissivity in layer 3 – assuming that there is a low vertical resistance between the two layers. The high transmissivity zone in layer 3 has also been extended beneath Shanely's Lough and in the area of piezometer nest 70 so to account for the heads observed in layer 2 in these regions.

Calibration results

Table H1, appendix H, lists the mean of measured deep peat hydraulic heads and the heads as calculated following calibration and optimisation in the model. The residuals refer to the differences between respective heads. All of the heads are within +/- 0.5 m, except those at piezometers 66 and 70 where residuals are marginally < 0.55 m, and the calculation is considered a good best fit model.

Figure 11.6 plots the calculated and observed heads. An $R^2$ value of 98% (based on 49 measurements) is calculated, implying an excellent correlation between the two sets of heads. The outliers 66 and 70 are still within a reasonable range, the 'large' residual at 66 being a result of its proximity close to a drain (FB2) and 70 being in an area of the bog with particularly low heads in both peat and till.

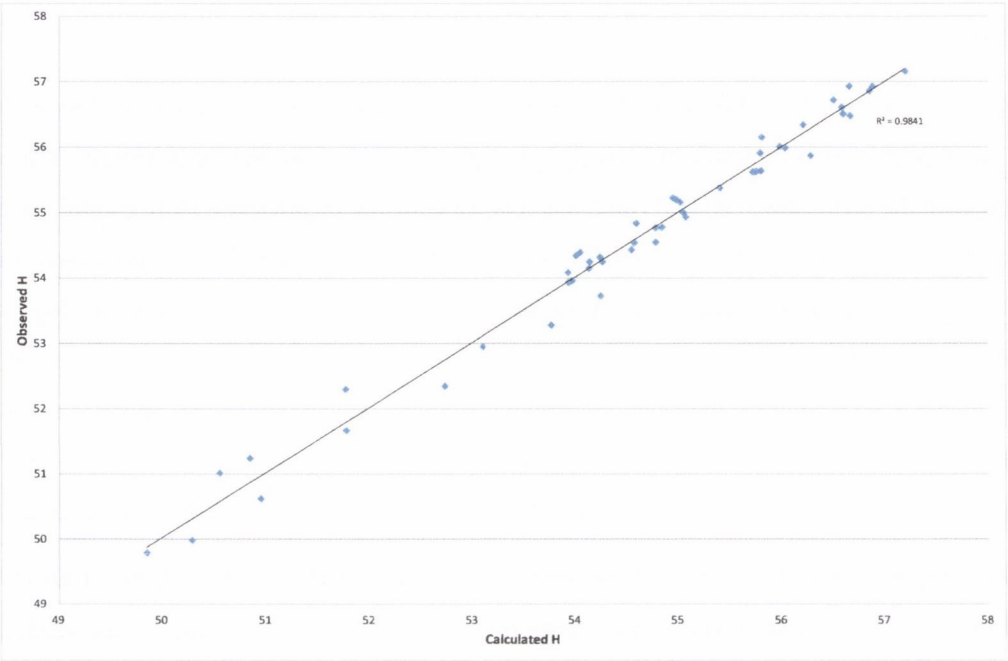


**Figure 11.6.** Plot of measured field (observed) heads versus computed model (calculated) heads in layer 2 (peat) aquifer.

Figure H17, appendix H, plots the residuals of table 1 in the model domain. The size of the 'discs' is relative to the size of the residual at the calibrated head location. To achieve 'acceptable calibration' it is necessary to have both low residuals (< 0.5 m) and a spatial scatter in residuals (i.e. random distribution of plus and minus residuals). From figure H17, it can be observed that there is a reasonably good scatter of residuals where the model head is higher than observed (dark green) and where the model head is lower than observed (light green) – implying the calibration and optimisation process in layer 2 has been effective.

*Layer 4 calibration*

Field conditions

The hydraulic conductivity of the till aquifer (layer 4) is variable but dividing the till body into two units, an upper till 'aquitard' and lower till 'aquifer', for the purposes of the model, allows a relatively high transmissivity value to be assigned to layer 4. Similar to layer 2 calibration, the vertical resistance in layer 4 (c3) is an important hydraulic parameter, but the resistances input in the model domain did not require much alteration and transmissivity in layer 4 was a stronger/ more sensitive control on calculated heads. Following a process of trial-and-error a transmissivity of 8 $m^2$/ day was applied to the majority of nodes in the model domain, except in the south western area of the model where a transmissivity value of 15 $m^2$/ day was required to account for the head measured in

piezometer 935. However, the transmissivity input parameter is remarkably consistent in the model, in contrast to that applied to the peat (layer 2) aquifer, which by nature, is a far more heterogeneous geological material due to its compressible structure. The transmissivity value of 8 $m^2$/ day is also consistent with that calculated in section 5.6 when estimating, analytically, the flux rate to the marginal drainage system.

Similar to the low hydraulic heads measured in peat in the area between the Western Mound and Shanely's Lough, a low hydraulic head in subsoil piezometer CLCD3 was difficult to account for. A transmissivity value in the order of 100 $m^2$/ day was necessary to calibrate the modelled head so that it was similar to the measured head – such a localised zone with very high permeability is unlikely to be found in the till subsoil. The elevated transmissivity value was therefore applied to the limestone bedrock, layer 5, underlying the till unit.

In the model domain a generic transmissivity value of 2 $m^2$/ day has been applied to layer 5. A localised zone, representing a probable conduit/ fissure/ fault in the limestone, has been inserted to account for the low groundwater head in CLCD3 and a transmissivity value of 120 $m^2$ /day has been applied. The conduit is found in the same area as the sand lenses underlying peat and in the model it is assumed to follow the drainage pattern of the brook stream (figure h1; appendix B). A lower transmissivity value of 30 $m^2$/ day is applied outside of the high bog, in the Restoration Area, and this value was required to account for heads measured in the subsoil piezometers 920, 926 and 927.

In chapter 6, it was found from hydrochemical and stable oxygen isotope analysis that groundwater, sampled from till substrate, contains a deeper groundwater component – groundwater derived from limestone. The same inference was made following baseflow separation at the Restoration Flume. Thus, there is indirect evidence that a limestone conduit/ fissure underlies the restoration area, and most probably extends northwards through the high bog, in the region inserted in the model (figure H16), explaining the low hydraulic head measured in CLCD3.

Calibration results

Table h2, appendix h, lists the mean measured hydraulic heads from the till aquifer and the heads as calculated following calibration and optimisation in the model. The residuals are all within +/- 0.5 m, and the calculation may therefore be considered to be a good best fit model. Figure 11.7 plots the calculated and observed heads. Similar to layer 2, an $R^2$ value (based on 20 measurements) of 98% is calculated, implying an excellent correlation between the two sets of heads. Figure h18, appendix X, plots the residuals of table h4 in the model domain. There is a reasonably good scatter of residuals where the model head is higher than observed (dark green) and where the model head is lower than observed (light green) – implying the calibration and optimisation process in layer 4 has been effective. Optimising T4 in the model system increased the transmissivity from 8 to 8.04 $m^2$/ day – a negligible amount.

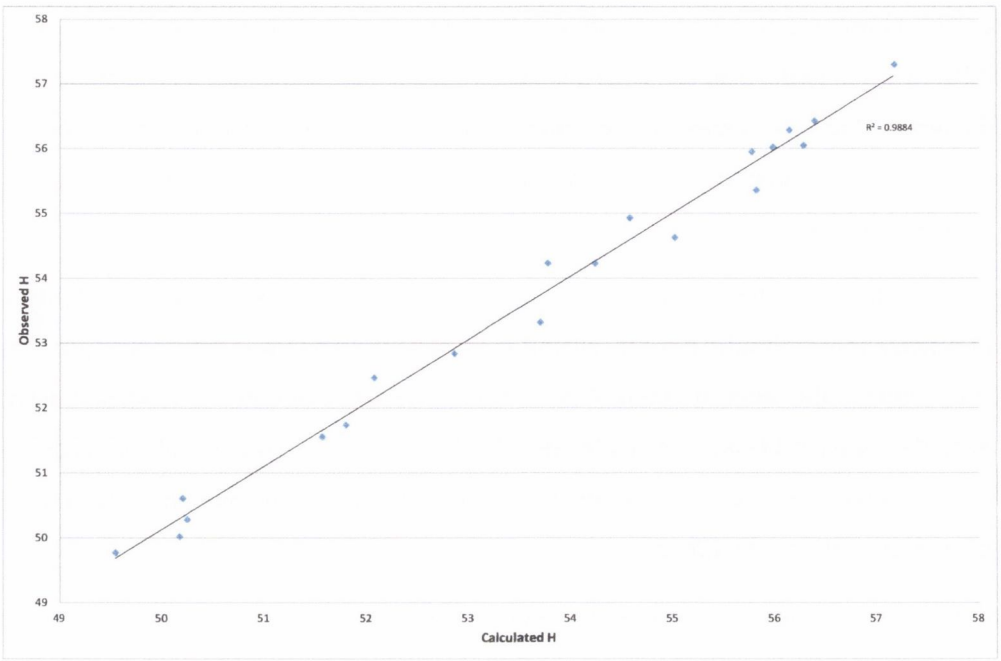


**Figure 11.7.** Plot of measured field (observed) heads versus computed model (calculated) heads in layer 4 (till) aquifer.

### 11.7.9. Sensitivity Analysis

Sensitivity analysis is a procedure through trial and error, to find hydraulic parameter(s) that are most sensitive to change in the calibration process. Its purpose is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Anderson & Woessner, 1992). There are three basic hydraulic parameters that will influence flow behaviour in the model system: recharge rate/ effective rainfall, resistance and transmissivity. In many ways the calibration process itself is a sensitivity analysis as once the model set-up is complete and the aquifer layers are assigned T and c parameter values, it becomes clear, quite quickly, where the 'problems' lie.

*Layer 2*

The magnitude of changing a parameter in a particular model layer is a measure of how sensitive the model system is to that parameter. Model calibration will invariably have much uncertainty associated with it and using field data for hydraulic parameter input attempts to reduce the uncertainty. The hydraulic head in layer 2 is controlled by both the transmissivity and resistance in the layer. Broad zones of 'low, high and very high' resistance were entered in the model to account for the varying resistance. In section 11.7.4, high hydraulic conductivity zones were described in the high peat and these zones are high transmissivity zones in the model domain. There is a large difference between low transmissivity areas (< 0.001 $m^2$/ day) and high transmissivity area (T > 0.01 $m^2$/ day), as there is between high resistance zones (> 6000 days) and low resistance days (< 1500 days), and varying the values of these zones by an order of magnitude is of no practical as it is not realistic – e.g. varying the T and/ or c values by +/- 10 % makes little difference to the layer 2 head output; it is not logical to

vary the values by, e,g., 100 %. However, it was found that the zone of low hydraulic heads could only be accounted for by applying a transmissivity to the sand lense aquifer in layer 3 – a sensitive parameter, but localised, and trial-and error determined a T value of 20 m2/ day to be most appropriate; c3 makes little difference here.

*Layer 4*

Hydraulic head in the till unit (layer 4) is sensitive to change. Table h4, appendix H, lists the residuals from analysis when transmissivity is set to 4, 8 and 12 $m^2$/ day respectively. Transmissivity at 8 $m^2$/ day is the calibrated model and it can be observed that errors increase when this value is increased or decreased by 50 %. Though the changes are not large, there is no random scatter of residuals at lower or higher values of transmissivity, as there is when it is calibrated to 8 $m^2$/ day. The transmissivity in layer 4 also impacts on the head in layer 2 (table 3), with the standard deviation of the head 2 residuals increasing when the T4 value increases or decr3ases by 50 %.The resistance of the aquitard, c4, will also influence head in layer 4. The resistance is either very big (> 6000 days) or relatively small (< 1000 days) and varying the values of these zones by an order of magnitude, such as by +/- 10 %, makes little difference on head computation.

Similar to layer 2, low hydraulic head in the area between the Western Mound was not sensitive to changes to c4 or T4, but rather to changes in transmissivity, applied locally, to the limestone unit, layer 4. The transmissivity in this zone needs to be high; > 100 $m^2$/ day, to account for the heads measured in this region and a trial-and-error process determined the input transmissivity value.

### 11.8. Summary

A numerical groundwater flow model was required for the Clara West hydrologic system so to (1) better understand the hydraulic connection between the bog body and regional groundwater table/ flow system and (2) predict changes simulated restoration/ engineering works would have on hydraulic gradients in model aquifers and the effects that raising the hydraulic gradient would have on infiltration and recharge rates.

On this basis, a steady state groundwater flow model was generated for the Clara West drainage system. The model consists of five hydro-stratigraphic, or aquifer, units, namely acrotelm, peat, sand, till and limestone that are separated by aquicludes. Hydraulic parameter input consists of transmissivity values assigned to nodes in the aquifer layers and resistance values assigned to aquiclude nodes. Model boundary conditions consist of fixed-head conditions, based on steady state water levels, being applied to drain segments, which form internal boundary conditions and form the south-eastern model boundary condition. The remaining model boundary area is assigned no-flow boundary conditions, as the model is designed based in the measured regional groundwater catchment from the till aquifer. Recharge is the top-boundary condition and a top-boundary drainage system is applied to the model domain to account for surface-water runoff.

Hydraulic parameter input was based on known field conditions and measured field hydraulic values such as hydraulic conductivity. Model calibration used mean hydraulic heads from deep peat and till units and sensitivity analysis found that transmissivity in peat and till was most sensitive to change. Calibration necessitated the inclusion of a high transmissivity zone in both the sand (layer 3) and limestone (layer 5) aquifer layers, in order to account for low hydraulic heads measured between the Western Mound and Shanely's Lough.

## 12. Clara West Groundwater Flow Model

### 12.1. Steady State Model

The calibrated steady state model outputs can be used to assess the validity of the conceptual model by means of analysing (1) the potentiometric surface and flow lines in the aquifer layers of most importance and (2) the various fluxes through the groundwater system by means of analysing the models water balance.

#### 12.1.1. Contour maps and cross sections

In chapter 5, the potentiometric surface at the base of peat and in the till aquifer, drawn based on field measurements, were discussed. The model is calibrated to (1) mean hydraulic heads measured from the peat and till hydrogeological units and (2) heads in the Clara West drainage system that have been fixed based on drain gradients and mean measured stage levels. If the hydraulic parameter input in chapter 11 is correct, the generated potentiometric surfaces should be comparable with that measured in the field.

The benefit of generating potentiometric water level maps in a computer programme is that flow lines, which trace the path of an imaginary particle of water as it flows through an aquifer, can be generated based on the computed heads in the aquifer layer and therefore provide more information on where the water is flowing, and if drains, as is the case in Clara, are having an impact on groundwater flow movement. Also, as contour maps are two-dimensional representations of a three-dimensional surface, a model computer programme can generate three-dimensional views of aquifers and the potentiometric surfaces of heads of most interest.

Groundwater flow movement in layers 2 (peat) and 4 (till) are of most interest as (1) water released from storage in layer 2 is inducing ground level subsidence and (2) steep hydraulic gradients due to drains being cut below the potentiometric surface in layer 4 have reduced head level in layer 2. However, layers 3 (sand) and 5 (limestone) are important also - layer 3 influences the groundwater flow in layer 2 and layer 5 influences groundwater flow in layer 4.

*Layer 2*

Figure I23, appendix I, illustrates the model generated potentiometric surface in layer 2, the peat 'aquifer'. The contours are similar to those generated from field measurements (Appendix C):

- Groundwater flow in the peat layer converges into an area between the Western Mound and Shanely's Lough – similar to that described in section 5.5.
- The groundwater table steeps sharply at the high bog boundary due to the pore pressure drop induced by the drains marking the high bog boundary.

- Groundwater is at its highest in the Western Soak by the western boundary of the model domain and flows eastwards, following a steep hydraulic gradient – similar to that described for the field situation in section 5.5.

In section 5.5 the influence of the underlying sand lense(s) was discussed. It is the sand lense, or subsurface peat cracking associated with the sand lense, that is inducing a drawdown of the groundwater table in deep peat. Ground level subsidence in this area (chapter 8) and the decrease in hydraulic head in deep peat since 1991 (chapter 9) are evidence of a water level drawdown due to subsurface drainage. To aid the visualisation of where groundwater in the peat is flowing, a three-dimensional image of the layer 2 potentiometric surface is presented in figure I19, appendix I. The drop in hydraulic head in the central region of the bog (north-central area of the image) is the sand lense area with high transmissivity inserted in the model domain (section 11.7).

**Figure 12.1.** Potentiometric surface and flow lines in layer 2 (peat aquifer). Contours are at 0.5 m intervals.

Figure 12.1 illustrates the layer 2 potentiometric surface with computed model flow line directions. It can be observed that the flow lines are not always perpendicular to the potentiometric contour lines, particularly in the sand lense area, and this is a consequence of anisotropy in the aquifer layer due to the variable transmissivities and resistances introduced in model design to calibrate the model effectively – i.e. peat in layer 2 is not an isotropic medium. Differing transmissivity zones, indicating

different hydraulic conductivity zones as mapped in the field (section 5.6) refract the flow line direction, complicating the groundwater flow direction, which is again complicated by subsurface drainage in sand lense areas.

It may be observed in figure 12.1 that groundwater flow in the peat 'aquifer' is towards the drains. In the western area of the map, groundwater flow from the Western Soak moves laterally towards drain FB2 and in the Western Mound area groundwater flow is towards drain FB3. In the central area of the map, in the area north, and, between the Western Mound and Shanely's Lough, groundwater flow is towards the Restoration Area drains CT3 and CT4. The gradient is also shallower is this area, similar to Figure C16. The flow movement in this area is a direct consequence of the drainage pathway provided by the sand lense in the model – which corresponds with observations made from field data (section 5.5).

*Layer 4*

Figure I24, appendix I, illustrates the model generated potentiometric surface in layer 4, the till 'aquifer'. Similar to layer 2, the contours are similar to those generated from field measurements (figure C15; appendix C):

- Groundwater flow in the till body flows in an easterly direction from the Western Mound in the western area of the model before rotating northwest of Shanely's Lough, where groundwater flow is then in a south to south-easterly direction.
- South of the Restoration Area, groundwater flow is in a west to north-westerly direction.
- All of the potentiometric surface contours converge towards the Clara West drainage system, where drainage pulls, down the groundwater table, resulting in the steep hydraulic gradient of the potentiometric surface that is clearly evident in figure 12.2, particularly at drain FB2.

To aid the visualisation of where groundwater in the till body is flowing, a three-dimensional image of the layer 4 potentiometric surface is presented in figure I16 and it can be observed that the gradient of the potentiometric surface increases greatly at the drains.

The modelled potentiometric surface is similar to the field inferred potentiometric surface (section 5.5) with one notable difference south of the Restoration Area. The field measured potentiometric surface, which has been used in groundwater catchment delineation, indicates a steeper converge of the potentiometric surface towards drain TD2, whereas the modelled surface indicates most groundwater flow in this area is into the Brook Stream, leaving the Restoration Area – i.e. the field inferred groundwater flow direction is northeast towards the Restoration Area/ drain TD2, whereas the modelled groundwater flow direction is east/ northeast towards the Brook Stream. However, the potentiometric surface under the high bog and in the Restoration Area coincides with field observations and the modelled layer 4 potentiometric surface is still valid.

In section 11.7.3 the influence of layer 5, the limestone aquifer, was discussed. A high transmissive unit in the limestone, possibly a conduit or fracture type structure, was necessary in model calibration to account for low layer 4 heads underneath the high bog and in an area of the Restoration Area (section 11.7.3.6). In figure 12.2 and I22, an inflection in the potentiometric surface, northeast of the Western Mound and northwest of Shanley's Lough, is a consequence of the inclusion of the high transmissive limestone unit – implying drainage. Whether such an inflection exists in reality is unknown, however, the flow path directions are presumably still the same. Figure 12.2 illustrates the layer 4 potentiometric surface with computed model flow line directions. It can be observed that the flow lines are near always perpendicular to the potentiometric contour lines, implying the till unit is isotropic, which is not the case in reality but a T4 value of $8m^2$/ day calibrated the model and is presumably representative of the real transmissivity in the till aquifer.

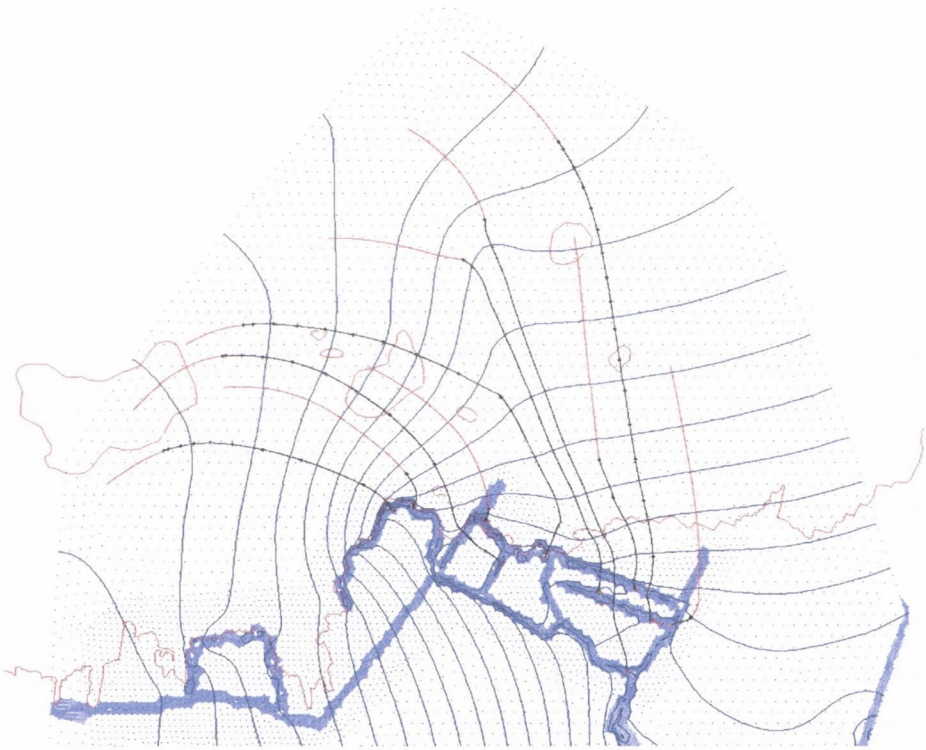

**Figure 12.2**. Potentiometric surface and flow lines in layer 4 (till aquifer). Contours are at 0.5 m.

It may be observed in figure 12.2 that groundwater flow in layer 4 is towards the drains. In the western area of the map, groundwater flow from the Western Soak moves laterally towards drain FB2 and in the Western Mound area groundwater flow is towards drains FB3, CT1 and CT3. In the central area of the map, in the area north, and, between the Western Mound and Shanely's Lough, groundwater flow is towards the Restoration Area drains CT3, CT4 and the Restoration Drain itself. The flow line direction mirror the flow line hydrogeological cross-sections discussed in section 9.2 (figures G1-G7; appendix G). The computed model flow lines are therefore in accordance with the inferences made in section 9.2. Thus, the model supplements evidence that drains in the Restoration

Area are outlets for groundwater discharge derived from the western area of the high bog, where significant subsidence has occurred since 1991 (section 8.3) – not just drains adjacent to the high bog boundary, such as drain FB2.

### 12.1.2. Cross-sections

To visualise how groundwater is moving through the model domain it is useful to analyse groundwater movement using cross-sectional profiles – in both two-dimensions and in three-dimensions. On figure I22 the position of five flow line locations are illustrated and cross-section profiles illustrating the potentiometric surface in each aquifer layer and section profiles illustrating the thickness of the aquifer and aquitard units with flow lines of a particle of water either in layer 2 or layer 4 are presented in figures I1 to I15, appendix I. Three-dimensional views of the layer 2 and layer 4 potentiometric surface are also included in appendix I; including a three-dimensional view of the flow line of a particle of water.

*Cross-sections in 2D*

Flow line 1 trends from west-northwest to east-southeast from the Western Soak to drain FB2 – similar to the hydrogeological profile through flow line 1 in Chapter 10 (Figure F8; Appendix F). In the profile section (Figure 12.3 and Figure I1) it can be observed that the potentiometric surface in layer 4 and layer 5 are coincident, but layer 5 is above that of layer 4 at the drain, indicating discharge from deeper groundwater. Layers 4 and 5 are also above that of layer 2 in the vicinity of the drain. While the potentiometric surface in layers 4 and 5 dips deeply, and smoothly, towards the drain, the potentiometric surface in layer 2 oscillates, and this is due to the variable resistance and transmissivity encountered within the peat substrate – it is also a function of sub surface drainage pulling down the groundwater table in layer 2 in localised locations. The section profile (figure I2) illustrates that the flow line of a water particle in till, in the Western Soak area, moves laterally in layer 4 before seeping into layer 5 and discharging into marginal drain FB2. The water particle in peat (figure I3) moves flow vertically downwards before moving laterally in layer 4 and seeping in to layer 5 before discharging into drain FB2 – there is no lateral movement in the layer 2 aquifer.

Flow line 2 trends from northwest to southeast through the Western Mound to drain CT3 – similar to the hydrogeological profile through flow line 2 in Chapter 10 (Figure F9; Appendix F). The observations made from flow line 1 can also be applied to flow line 2 – deeper groundwater from limestone discharges in the marginal drain and the potentiometric surface in later 2 is uneven due to anisotropy in the layer 2 aquifer. The section profiles in figures I4 and I5 are also similar to that of flow line 1 with the addition that the Western Mound (mound area in layer 4) is creating a local barrier to groundwater flow – similar to field observations (Chapter 5). The water particle flow line in peat, figure I6, also appears to be drawn down at the Western Mound area, fitting in with the conceptual model of the system.

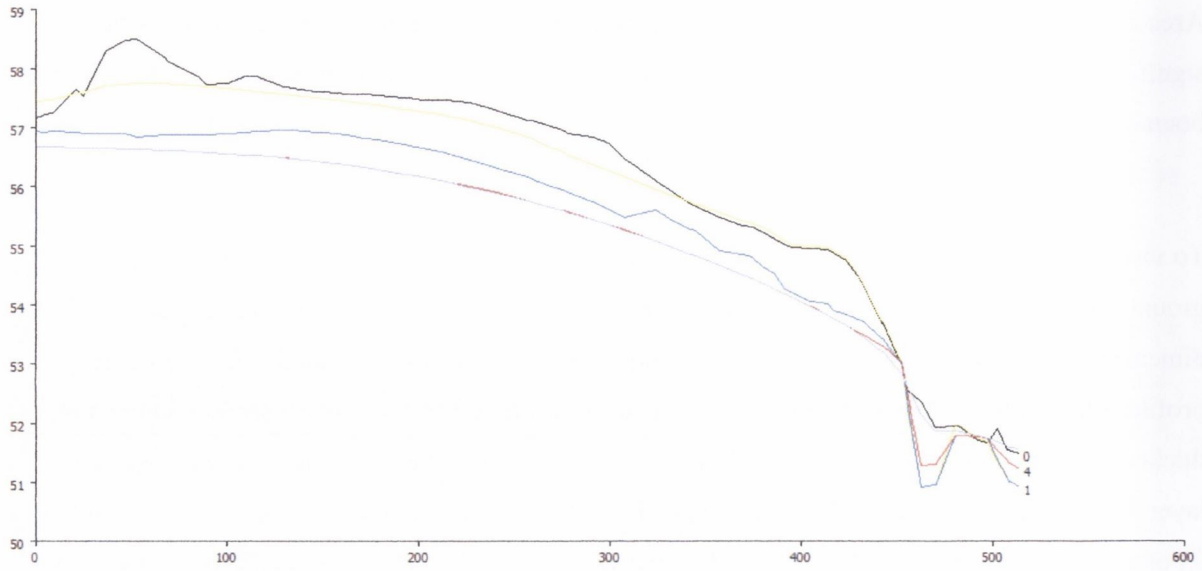


**Figure 12.3.** Topographic profile and modelled potentiometric surfaces through flow **line1**

Flow line 3 trends from north-northwest to south-southeast from the Shanely's Lough area to drain CT4 – similar to the hydrogeological profile through flow line 3 in Chapter 10 (Figure F10; Appendix F). In contrast to flow line 1 and 2, the potentiometric surface in layer 2 is c. 1.0 m higher than the potentiometric surface in layer 4 and 5 – the difference is c. 0.5 m in flow lines 1 and 2. The difference is an effect of the greater resistance between the two layers in this area – groundwater flow/ gradient in layer 4 has less of an influence here than in the western area of the map where lacustrine clay is absent – the high resistance material in layer 4 (c4). Similar to flow lines 1 and 2 is the potentiometric surface in layer 5 being above that in layer 4, implying deeper groundwater discharge into drain CT3 – similar to the inference made from hydrochemical analysis in section 6.7. The section profiles again indicate vertical downward movement of groundwater flow in layer 2 and lateral movement in layer 4. The presence of a thick sequence of lacustrine clay (c4) ensures a longer residence time of water seeping downwards in this area – i.e. groundwater in layer 4 will have come from outside this area.

Flow lines 4 and 5 are oriented northeast-southwest and northwest-southeast respectively through the Restoration Area. Observations are similar to flow lines 1 and 2 in that drainage is complicating the potentiometric surfaces, with the layer 5 potentiometric being above that in layer 4, which in itself is above layer 2, indicating an upward gradient of flow and discharge of groundwater in the Restoration Area – exactly the scenario that is encountered from field measurements.

Section profile figures I14 and I15 (also Figure 12.4) illustrate the effects of sand and till outcrop beneath the high bog peat and the flow line movement of a water particle in layers 2 and 4 respectively. In figure I14, the water particle flows laterally at the base of peat (layer 2). This profile, north to south, is through the sand lense area described in chapters 5 and 8 (note: flow line is not directly parallel to section line; flow lines of water particles are based on those in figure I24). This

flow line amounts to a drainage pattern and the water particle moves upwards and discharges outside of the high bog (the section doesn't adequately draw the drainage ditches like the profile sections do). In figure 12.4, the water particle flows laterally towards a till protrusion - the Western Mound. It then seeps downwards and flows laterally in till body, before it flows upwards and discharges into the marginal drain FB2.

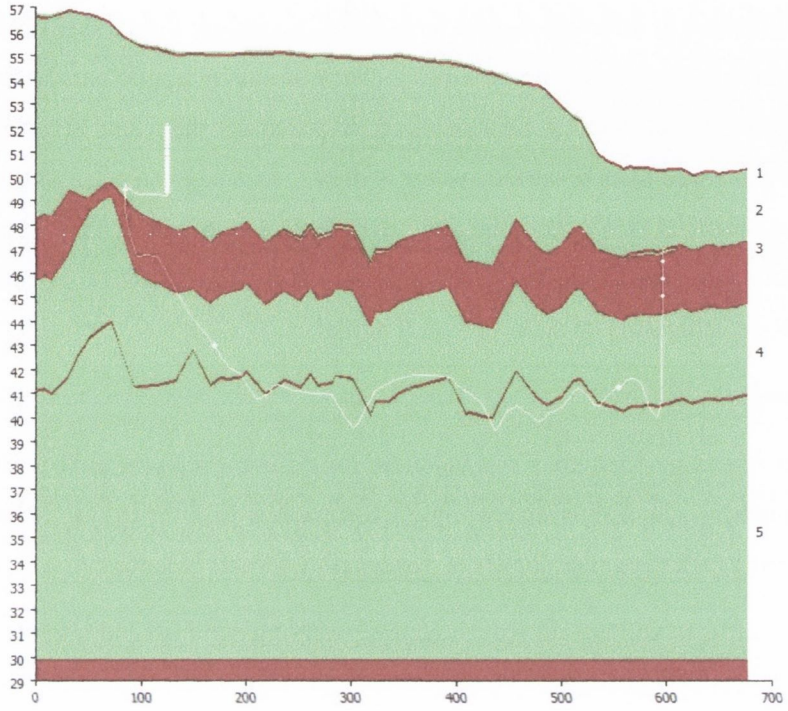


**Figure 12.4.** Flow path of water particle in layer 4; Western Mound area (N-S orientation)

*Cross-sections in 3D*

The observations made from the 2D cross-section drawings may also be viewed in three-dimensions. A three-dimensional image of the potentiometric surface and the flow lines from layer 2 in figure 12.2 is illustrated in figure I19, appendix I. Where sand beneath peat is absent, the downward flow direction of water through the peat profile is near vertical (front-most flow line in figure I19) and moves vertically upwards outside the high bog area where a drain is inserted. However, where sand is present, downward flow direction is not vertical, but rather slopes downwards, creating the peat groundwater basin observed in figures I19 and I20. Similar to figure 12.2, lateral movement at the base of layer 2 is inferred in this area.

A three-dimensional image of the potentiometric surface and the flow lines from layer 4 in figure 12.1 is illustrated in figure I16, appendix I. Where lacustrine clay underlies the high bog, it takes longer for the water particle to discharge to a drain, whereas, where till underlies the high bog, the water particle discharges more quickly to the drain, and this is inferred from the 3D flow lines where the longer

residence times are indicated by long downward vertical flow lines, whereas shorter residence time have shorter downward sloping flow lines.

### 12.1.3. Water balance

A water balance is the most powerful check on the validity of any groundwater model (Hemker, 2011) and a key result from any modelling exercise. A groundwater flow model water balance can be used to (1) calculate infiltration to different aquifer units and (2) compute flows/ flux rates across model boundaries. The water balance therefore provides a check on the hydraulic parameter input as computed fluxes may be considered to be unrealistic. Importantly, the water balance gives information about discharge rates to surface water bodies or recharge rates across the water table (Anderson & Woessner, 1992). The computed water balance can therefore be used to check the baseflow calculation described in section 6.8 and the recharge and infiltration calculations described in section 7.3 – i.e. a verification of the conceptual model.

*Water balance computation*

Tables I1 to I14 in Appendix I list the water balances for different regions/ areas of the Clara West groundwater flow model. The following terminology is used to describe flows, into and out, of the various 'aquifer' units (after Hemker, 2012) in the generated water balances:

- Leakage – refers to vertical flow through the overlying aquitard and into the top of the underlying aquifer. Leakage may enter or leave the aquifer depending on the relative difference in heads between the source aquifer and the source reservoir on the other side of the leaky layer (Anderson & Woessner, 1992).
- Lateral flow – refers to groundwater that flows laterally in or out the water balance area, except for boundary flow.
- Boundary flow - consists of all groundwater that flows laterally across the model boundaries (because of the fixed-head boundary conditions). Discharge is outflow in the water balance computation and refers to water that moves upward across the water table and discharges directly to the surface or unsaturated zone (Anderson & Woessner, 1992).
- The total inflow, the total outflow and their difference - the water balance error. When the errors are low (< 0.005) it means that the heads are computed accurately. An error of around 1% is usually considered acceptable (Anderson & Woessner, 1992).

The water balance computation is typical of what is produced in numerical groundwater models in that water enters and leaves the model in two ways – through the boundaries, as determined by the boundary conditions, or through sources and sinks within the interior of the model grid (after Anderson & Woessner, 1992). Sources and sinks, which are represented by $R$ in equation 11.4 (section 11.4), essentially represent the volume of water that flows between the aquifer units in the model domain.

Recharge, which is the volume of water that crosses the water table and becomes part of the groundwater flow system, is considered a source. The Clara West drainage system has been assigned fixed head boundary conditions, within the model domain, and they are considered internal sinks for groundwater flow. In the Clara West steady state model there are no wells discharging or recharging water to the groundwater system. Recharge and internal fixed head boundaries are therefore the source and sink(s) within the model domain grid.

*Computed water balances*

Chapter 9 presented and discussed water balances calculated for each of the flow measurement structures in the Clara West hydrological system and recharge, based on baseflow analysis, was calculated for each of the flow structures in chapter 6. Analysing the computed model water balances provides a check on whether what is calculated by the model is representative of reality, assuming what has been calculated in the field is accurate.

Model area

The water balance for the model domain is presented in table I1, appendix I. The water balance indicates that 39 %, or 14 mm, of net recharge infiltrates into the till aquifer and that 73 % of total boundary flow (i.e. the fixed heads in the Clara West hydrologic system) is groundwater flow from the till aquifer (layer 4). However, analysing the whole model domain is not appropriate or beneficial in this instance as approximately half of the modelled area is located outside of the area of interest – the Clara West high bog and cutaway area.

Catchment areas

An analysis of local groundwater catchments that underlie the Clara West high bog, as described in chapter 9, is a more logical approach in interpreting computed flux rates from the calibrated steady state model. Figures J44, J45 and J46 in appendix J highlight the nodal areas where water balances have been computed for the FB2 Flume, Restoration Area Flume and EPA Weir respectively. As these local catchments do not encompass an entire drainage basin, as interpreted in the model, there will be a degree of error associated with the water balance computation as there will be lateral inflows and outflows from outside the chosen catchment area that will alter the net inflow-outflow calculations. However, analysing the boundary outflow, or discharge, calculation in the water balance and leakage inflow calculation allows an assessment of relative infiltration rates through the high bog and the proportions of water in the drainage system that may be attributed to the model layers/ aquifers.

FB2 Flume water balance

Tables I3 and I4 in appendix I present the steady state water balance for the FB2 Flume groundwater catchment in terms of flow rate and flux rate respectively. Table 12.1 summarises table I4 into (1)

leakage/ infiltration rates into each of the model aquifers and (2) flux rates in the drains with fixed heads in the catchment area.

Table 12.1. Summary of (1) leakage rates and (2) runoff rates in FB2 groundwater catchment area

| | Leakage | | |
|---|---|---|---|
| | mm/ day | mm/ year | % Re |
| Recharge: | 0.27 | 99 | |
| Peat Inf.: | 0.26 | 95 | 61 |
| Sand Inf.: | 0.26 | 94 | 60 |
| Till Inf.: | 0.25 | 93 | 60 |
| Lst Inf.: | 0.14 | 52 | 33 |

| | Runoff | | |
|---|---|---|---|
| | mm/ day | mm/ year | % Ro |
| Total Q: | 0.39 | 141 | |
| Acrotelm: | 0.01 | 5 | 4 |
| Peat: | 0.00 | 1 | 1 |
| Sand: | 0.07 | 25 | 18 |
| Till: | 0.30 | 109 | 77 |

*Note: Re refers to recharge and Ro refers to total runoff in drains with fixed-head boundary conditions. Inf. Refers to infiltration into the subject layer.*

The recharge rate of 0.27 mm/ day is the flux of water that infiltrates into the groundwater system – the remaining water (16 mm/ day; table I4) flows out of the system either as evaporation or surface water runoff and is not accounted for in the model (note: this is not necessarily an estimate of overland flow but is a consequence of introducing a secondary top-boundary drainage system to reduce the head calculated in the layer 1/ acrotelm aquifer (section 11.7).

Approximately 95% of recharge infiltrates into the peat body and 93% of recharge infiltrates into the till body, meaning the remaining 2% flows laterally once it enters the peat and sand 'aquifers'. In reality, the flow attributed to sand (layer 3) is drainage through peat as no sand layer is present within the FB catchment area – in model design all layers are distributed across the domain of the model. 53% of recharge infiltrates into limestone from till, meaning the remaining c. 31% of infiltrated water flows laterally once it enters the till aquifer body.

Runoff calculations in table 12.1 refer to boundary flow in the drainage system encompassed within the catchment area. Approximately 19% of total runoff is from the peat and sand 'aquifer' and 77% is from the till aquifer – c. 0.07 and 0.30 mm/ day respectively. The analytical water balance in section 7.5, calculated peat and till derived runoff as 0.05 and 0.24 mm/ day respectively – which is very similar to that computed in the model water balance. A proportion of the till runoff also comes from limestone. As the model is calibrated to a steady state situation, 77 % of runoff being of till/ limestone in origin is realistic and similar to the baseflow calculation described in section 6.9.

Infiltration through the peat was calculated as 0.17 mm/ day, which is marginally lower than the model infiltration rate of 0.26 mm/ day. However, the analytical infiltration rate was based on the surface water catchment area that extends outside of the model area into zones with increased resistance, thereby reducing 'overall' infiltration when applied to the whole catchment area. The model water balance is in very close agreement with the analytical water balance.

Restoration Flume water balance

Tables I5 and I6 in appendix I present the steady state water balance for the Restoration Flume groundwater catchment in terms of flow rate and flux rate respectively. Table 12.2 summarises table I6 into (1) leakage/ infiltration rates into each of the model aquifers and (2) flux rates in the drains with fixed heads in the catchment area.

Table 12.2. Summary of (1) leakage rates and (2) runoff rates in Restoration Flume groundwater catchment area.

| Leakage Summary | | | |
|---|---|---|---|
| | **mm/ day** | **mm/ year** | **% Re** |
| Recharge: | 0.23 | 85 | |
| Peat Inf.: | 0.21 | 77 | 51 |
| Sand Inf.: | 0.21 | 75 | 50 |
| Till Inf.: | 0.19 | 70 | 46 |
| Lst Inf.: | 0.20 | 72 | 47 |

| Discharge Summary | | | |
|---|---|---|---|
| | **mm/ day** | **mm/ year** | **% Ro** |
| Total Q: | 0.58 | 211 | |
| Acrotelm: | 0.03 | 11 | 5 |
| Peat: | 0.01 | 4 | 2 |
| Sand: | 0.09 | 33 | 16 |
| Till: | 0.45 | 163 | 77 |

*Note: Re refers to recharge and Ro refers to total runoff in drains with fixed-head boundary conditions. Inf. Refers to infiltration into the subject layer.*

Approximately 75% of recharge infiltrates into the peat body and 70% of recharge infiltrates into the till body, meaning the remaining 5% flows laterally once it enters the peat and sand 'aquifers'. There is a higher resistance at the surface in the Restoration Flume catchment than compared to the FB2 Flume catchment – which is why less water infiltrated downwards; similar to the observation made in chapter 9. Approximately 72% of recharge infiltrates into limestone from till, however, there is groundwater inflow from outside the catchment area (as can be interpreted from table I6) contributing to this leakage rate.

Approximately 2%, 16% and 77% of total runoff is from the peat, sand and till 'aquifers' respectively – c. 0.01, 0.09 and 0.45 mm/ day respectively. In chapter 9, the analytical water balance calculated peat and till derived runoff to be 0.03 and 0.34 mm/ day respectively. It is possible that the analytical balance hasn't accounted for runoff from sand due to the difficulty in identifying it, hydrochemically, or that it has underestimated peat runoff which may be grouped with sand runoff. The runoff from till is relatively similar – it is possible that the contribution from limestone in the analytical calculation has underestimated the contribution from limestone, which seems to be a significant aquifer in this area. Also, the groundwater catchment areas, as delineated in the model (figure H2) and in the field (figure E2 and E5) are not coincident – there is less groundwater entering the Restoration Flume location according to the model water balance (section 9.5) and this adds to the discrepancy.

Infiltration through the peat was calculated as 0.07 mm/ day, which is lower than the model infiltration rate of 0.21 mm/ day. However, the analytical infiltration rate was based on the surface water catchment area that extends outside of the model area into areas that has not subsided and underlain by lacustrine clay (section 7.4), thereby reducing 'overall' infiltration when applied to the whole catchment area. Overall, the model water balance is in close agreement with the analytical water balance.

EPA Weir water balance

Tables I7 and I8 in appendix I present the steady state water balance for the EPA Weir groundwater catchment in terms of flow rate and flux rate respectively. Table 12.3 summarises table I8 into (1) leakage/ infiltration rates into each of the model aquifers and (2) flux rates in the drains with fixed heads in the catchment area.

Approximately 90% of recharge infiltrates into the peat body and 86% of recharge infiltrates into the till body, meaning the remaining 4% flows laterally once it enters the peat and sand 'aquifers'. The EPA Weir catchment is similar to the FB2 catchment in that most water infiltrates downwards. Approximately 74% of recharge infiltrates into limestone from till, though this is complicated by lateral flows from outside the catchment area.

Approximately 2%, 17% and 72% of total runoff is from the peat, sand and till 'aquifers' respectively – c. 0.01, 0.06 and 0.25 mm/ day respectively. In section 7.5, the analytical water balance calculated peat and till derived runoff to be 0.03 and 0.32 mm/ day respectively - similar to that computed in the model water balance. The discrepancies, which are minor, may be attributed to the groundwater catchment areas being not coincident with that mapped in the field – similar to the Restoration Flume there has less groundwater entering the EPA Weir location according to the model water balance. Infiltration through the peat was calculated as 0.26 mm/ day, which is near exactly the model infiltration rate of 0.25 mm/ day. Overall, the model water balance is in close agreement with the analytical water balance.

Table 12.3. Summary of (1) leakage rates and (2) runoff rates in EPA Weir groundwater catchment area.

| **Leakage Summary** | | | |
|---|---|---|---|
| | **mm/ day** | **mm/ year** | **% Re** |
| Recharge: | 0.27 | 97 | |
| Peat Inf: | 0.25 | 90 | 61 |
| Sand Inf: | 0.24 | 88 | 59 |
| Till Inf: | 0.24 | 86 | 58 |
| Lst Inf: | 0.20 | 74 | 50 |

| **Discharge Summary** | | | |
|---|---|---|---|
| | **mm/ day** | **mm/ year** | **% Ro** |
| Total Q: | 0.35 | 127 | |
| Acrotelm: | 0.03 | 11 | 8 |
| Peat: | 0.01 | 3 | 2 |
| Sand: | 0.06 | 22 | 17 |
| Till: | 0.25 | 91 | 72 |

*Note: Re refers to recharge and Ro refers to total runoff in drains with fixed-head boundary conditions. Inf. Refers to infiltration into the subject layer.*

Subsoil area water balance

A water balance should ideally be computed for an area where there is an outlet for groundwater flow – i.e. a drainage basin. However, a purpose of the model is to assess whether areas with less resistance subsoil, such as till, underlying high bog peat are zones of high infiltration rates, as indicated by subsidence analysis . Tables I10, I12 and I14 in appendix I are model water balances for areas of the high bog that are underlain by till, lacustrine clay (with underlying sand units) and lacustrine clay (without underlying sand units) respectively. Table 12.4 summaries the recharge rates and infiltration rates to each of the model layers from each of the 'subsoil' water balances.

There is a clear difference in recharge rate to the groundwater system depending on what the underlying subsoil, or resistance, beneath peat is. Where peat sits on till, 64% of the input recharge rate infiltrates into the groundwater system, whereas in lacustrine clay areas with sand and without sand, the recharge rate is far lower at 38% and 13% respectively. This amounts to c. 0.29, 0.15 and 0.12 m/ day infiltrating from the peat column to till subsoil for till, lacustrine clay (with sand) and lacustrine clay (without sand) respectively.

When the infiltration rate is 0.12 mm/ day, or 44 mm/ year, it is considered to be a sustainable recharge rate for the high bog system (Streefkerk & Casparie, 1989)). However, infiltration rates of 0.29, mm/ day, or 105 mm/ year, is extremely high and a rate that must be minimised to arrest subsidence of the high bog (chapter 7). To address this issue, and to model a situation where infiltration through high bog peat is in the order of 40 mm/ year, conservation engineering must be devised and this requires the set-up of a prediction model.

Table 12.4. Recharge and infiltration rates (mm/ day) for areas of high bog underlain by till, lacustrine clay and lacustrine clay with no underlying sand layer

| | | | Infiltration inflow (mm day) | | | |
|---|---|---|---|---|---|---|
| **Catchment** | **Re** | **% T Re** | **Peat** | **Sand** | **Till** | **Lst** |
| **Till** | 0.29 | 64 | 0.294 | 0.294 | 0.296 | 0.164 |
| **Lac (sand)** | 0.17 | 38 | 0.149 | 0.147 | 0.124 | 0.95 |
| **Lac (no sand)** | 0.13 | 13 | 0.119 | 0.119 | 0.115 | 0.023 |

*Note: % T Re refers to percentage of water that infiltrates downwards from input recharge rate – the remainder exits the system.*

## 12.2. Prediction Model

In section 12.1, the groundwater flow patterns in layers 2 (peat) and 4 (till) were described and it was found that the hydraulic gradient of the potentiometric surface in each of the aquifer layers increases substantially as groundwater flows beneath the high bog towards the cutaway/ Restoration Area. This is a result of the drainage system 'pulling' down the groundwater table in each of the model aquifers – the drains have become zones for groundwater discharge. The potentiometric surface contour maps

and water balances for different model catchment areas demonstrate this phenomenon – the bog is losing water due to excess leakage from the peat 'aquifer' and this 'excess' water discharges into the drainage system. The calibrated steady state model confirms the conceptual model described in section 11.6.

### 12.2.1. Conservation strategy

If the high bog is 'losing' water because a drop in regional groundwater table, in the till aquifer, has increased the hydraulic gradient between water level in peat and underlying till subsoil, then raising the regional groundwater table will decrease the leakage rate through peat as the hydraulic gradient between the peat and till 'aquifers' will have been reduced.

To simulate a raised groundwater table in the steady state model, a prediction model is necessary - i.e. a model that can be used to predict aquifer response to a future event or stress on the system. As the drains in the Clara West hydrologic system are zones of groundwater discharge from waters originating from beneath the high bog the most obvious, and logical, approach to simulating a raised groundwater table is to block or remove the drains in the steady state model.

Under the EU Habitats and Water Framework Directives (WFD), wetland ecosystems, particularly groundwater dependent ecosystems in WFD legislation, require management measures to restore them to 'favourable' conditions if the ecosystem is deemed to be, or at risk of becoming, 'damaged'. The effects of subsidence on the eco-hydrology of the Clara West bog system were discussed in chapter 10 and it is clear that a management measure to conserve ecotopes of special scientific interest and areas of active raised bog in the Clara West bog system must be devised.

### 12.2.2. Prediction model design

To simulate a raised groundwater table the internal fixed-head boundaries, i.e. the drains, in the calibrated steady state model were removed. Rather than simply remove the drains from the model domain, the drains were 'filled' with low permeability material as in reality, drains cannot be removed from a system - they can only be blocked. To simulate a 'low permeability' material, a parameter file was created in the prediction model so to raise the level of the drainage system to the surrounding topography and the 'infill' transmissivity was set to 0.0001 $m^2$/ day; simulating a low permeability material such as clay or low permeability till subsoil. The fixed heads, and low transmissivity values assigned to drains in steady state model calibration were removed. To allow an outlet for surface water drainage, which would be required in a realistic management plan, the Brook Stream and Bog Road drain were kept in the model as fixed-head boundary conditions. All other hydraulic parameters and boundary conditions were retained from the steady state model.

It is possible to run a prediction model in steady state - i.e. in this case, remove the drains and simply recalculate the aquifer heads. However, the model was run as a transient model simulation so to (1)

input a storage coefficient value for each of the aquifer layers and (2) track the changes in head over time and to get an estimate on how long it would take the system to reach steady-state following restoration works. A conservative estimate for storativity, $10^{-4}$, was applied to layers 3, 4 and 5. Peat material is more compressible (Price, 1999) and $10^{-3}$ was applied to layer 2. Van der Schaff (1999) and Boelter (1964) attempted to estimate storativity for the acrotelm, and a value of 0.2 is applied based in this work. However, it is found that storativity has relatively little influence on the groundwater table rise in the prediction model. The heads calculated at steady state were used as the prediction/ transient models initial boundary condition (i.e. head at the beginning of a time-dependent simulation) and the input recharge was the same as that set in the steady sae model. The secondary top-boundary drainage system also remained. Following a number of simulation tests it was found that steady state, following management measures, reached after c. 1000 days and all models presented below are run over 1000 days.

*Management scenarios*

To simulate a groundwater table rise in the groundwater system three 'management' scenarios were implemented: (1) blocking the groundwater-fed drainage system, (2) blocking the groundwater-fed drainage system by means of installing a 'dam' in the face-banks by the high bog boundary and inserting a linear trending dam in the Restoration Area and (3) blocking the groundwater-fed drainage system and infilling the Restoration Area with low permeability material which is held inwards by means of a dam type structure.

Drain blocking

In the first management scenario the drains in the prediction model were simply blocked and filled with low transmissivity material. This simple measure has a huge effect on the potentiometric surface in layer 4, with the groundwater table rising from 3.5 m locally to 0.25 m at the model boundaries. The rise in the layer 4 groundwater table is illustrated in figure J25, appendix J, and it can be observed that the model domain area is too small to account for groundwater flow in layer 4 following restoration works and this is discussed in section 12.2.3.

In figure J26, appendix J a simulation of the raised potentiometric surface contours in layer 4 following the removal of the drainage system in the Restoration Area is presented. It is clear from the flow line patterns that groundwater from beneath the high bog, from the area of the Western Soak and Western Mound, still discharges into the Restoration Area following the blocking of the Restoration Area drainage system. The reason being is that there is not sufficient pressure in the Restoration Area to prevent upward flow of water. This is not an acceptable situation if the downward seepage through the high bog peat is to be minimised as the Western Soak area is where ground level subsidence is continuing – i.e. blocking drains on its own would raise the groundwater table but the Restoration

Area would still serve as an outlet for groundwater discharge. As such, the drain blocking, in isolation, management option is discounted.

Dam and drain blocking

An alternative management measure is to infill drains, as the first option, in tandem with installing dams by the face-bank drains and in the Restoration Area. The dam by the face-bank is essentially a sheet pile inserted to the top of the clay aquitard in layer 4 and a lower transmissivity value of $10^{-7}$ $m^2$/ day is applied. A single dam, approximately 10 m x 300 m, is also inserted in the Restoration Area with its base set to the top of clay in layer 4 and a transmissivity value of $10^{-7}$ $m^2$/ day is applied to the conceptual structure. The locations of the dam are illustrated in figure J28, appendix J.

Following the implementation of this management measure a rise in groundwater table in layer 4 (till) occurs, similar to that described for the drain blocking scenario. It can also be observed that the rise is slightly greater south of the Western Mound and again the model domain is too small to retain groundwater that in steady state discharges to the existing drainage system.

The stimulated potentiometric surface of layer 4 is illustrated in figure J27. Flow lines tracking the movement of a theoretical water particle are also illustrated on the figure J28. Similar to the drain-blocking scenario, the drain and dam construction succeeds in raising the groundwater table but groundwater from layer 4, and the other aquifer layers, still discharges into the restoration zone. As such, the management scenario is again not acceptable as groundwater, from the high bog, still finds an alternative path of least resistance and again discharges in the Restoration Area due to the low confining pressure and artesian pressures existing in the zone.

Cutaway infill and drain blocking

The prediction models for management scenarios 1 and 2 both successfully simulated a rise in the potentiometric surface in layer 4 (and the other model layers; not illustrated) – but are deemed inappropriate as groundwater flow lines still discharge into the Restoration Area. Though the rate of leakage, and presumably subsidence, will be reduced in the high bog, the water released into the cutaway area is a management problem as water will, presumably, pool in the cutaway area over time – which is not a desired restoration strategy due to the geotechnical and financial risks involved with an open-water body being contained by a dam structure.

As such, following a trial-and-error prediction model calibration, the management scenario deemed most appropriate, is blocking the drainage system as in scenarios 1 and 2 – but by also infilling the Restoration Area with low permeability material. As the Restoration Area is a topographic low that receives groundwater discharge, the infill must sit within the surrounding landscape – i.e. there must be a shallow gradient from the high bog, onto the infill and onto the landscape south of the cutaway area. The infill therefore follows the encompassing topographic contours. Figure 12.5 illustrates the

simulated infill – the low permeability material is infilled to the surrounding topography of the cutaway area – the 51, 52, and 53 topographic contour lines. The results of this management scenario, renamed the Restoration Model, are discussed below.

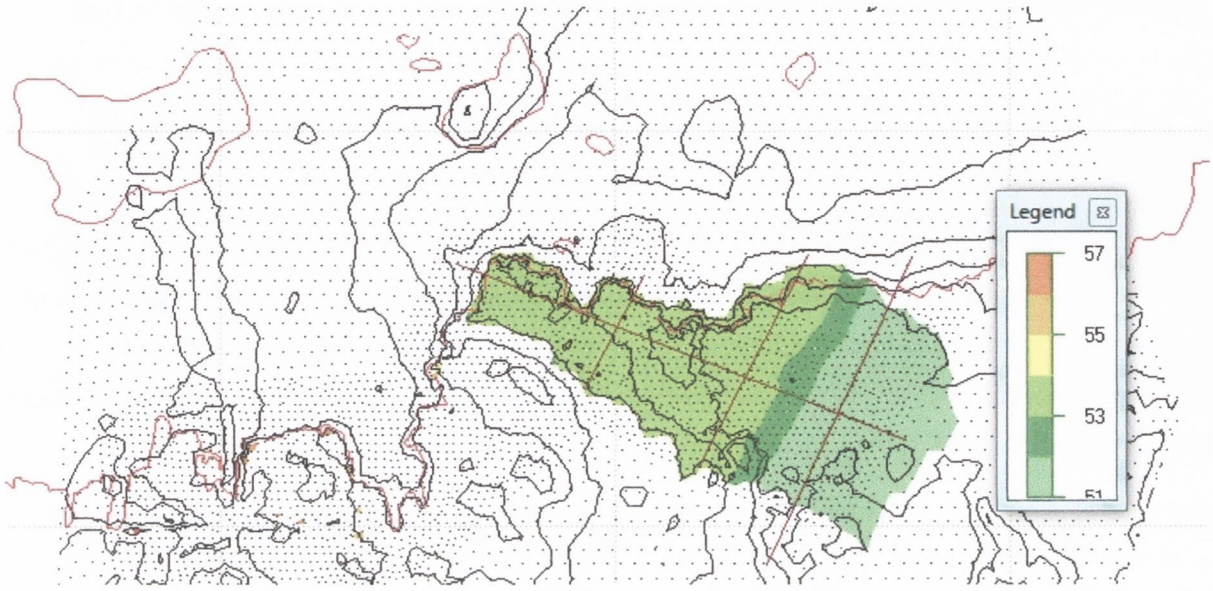


**Figure 12.5.** Location of low permeability infill in Restoration Area. Note: contour lines are topographic lines (1.0 m interval) from 2008 LiDAR survey.

### 12.2.3. Restoration model

In short, the Restoration Model is used to (1) estimate the rise in the potentiometric surface in the model aquifer layers and (2) compute a water balance that enables a calculation of the leakage rate through peat, and to underlying mineral subsoil, following restoration works. A downward leakage rate in the order of 40 mm/ year (Streefkerk & Casparie, 1989) is necessary if the restoration strategy is to be considered useful. Subsidence of the high bog will stop or slow down if this leakage rate is reached.

*Groundwater table rise*

The computed rise in the potentiometric surface in layers 1, 2 and 4 are presented in appendix J, figures J29 to J35, and are discussed below.

Layer 1

The rise in the potentiometric surface in layer 1 (acrotelm), which in reality is a rise in the high bog phreatic level, is presented in figures J29 and J30 for a rise of 0.25 m and 0.5 m respectively. It can be observed that the phreatic water level in the high bog itself does not change much, which is to be expected as water table in the acrotelm is distinct from that in peat and mineral subsoil. However, a rise in water level occurs adjacent to the Restoration Area in an area of high bog south of the area between the Western Mound and Shanely's Lough.

This area, which is east of the Bog Weir in an area of bog woodland, may therefore become dominated by free surface water following restoration works – a conservation strategy, over time, may therefore require the inclusion of shallow drains on the top of the infilled cutaway area to discharge excess surface water, which may otherwise flood on top of the infilled area and surrounding land. A rise in water level is also found at the Western Mound, which is not important as phreatic level is low here, and a moderate rise is observed west of the Western Mound in a 'channel' area of the bog, previously described in Chapter 10 and again unimportant.

Layer 2

The rise in the potentiometric surface of layer 2 (peat) is presented in figures J31 and J32 for a rise of 0.5 m and 0.25 m respectively; and figure 12.6 below. There is a substantial rise in peat head following restoration works – between 0.75 and 1.0 m in areas southwest and northeast of the Western Mound and between the Western Mound and Shanely's Lough.

The head in peat also rises within the rest of the high bog in the model domain – between 0.2 and 0.5 m in the western area of the model and between 0.05 and 0.3 m in the eastern area of the model. The rise of the layer 2 potentiometric surface throughout the model domain underlain by high bog indicates that marginal drainage affected the entire bog system in the steady state model; otherwise only local rises in head would have been simulated.

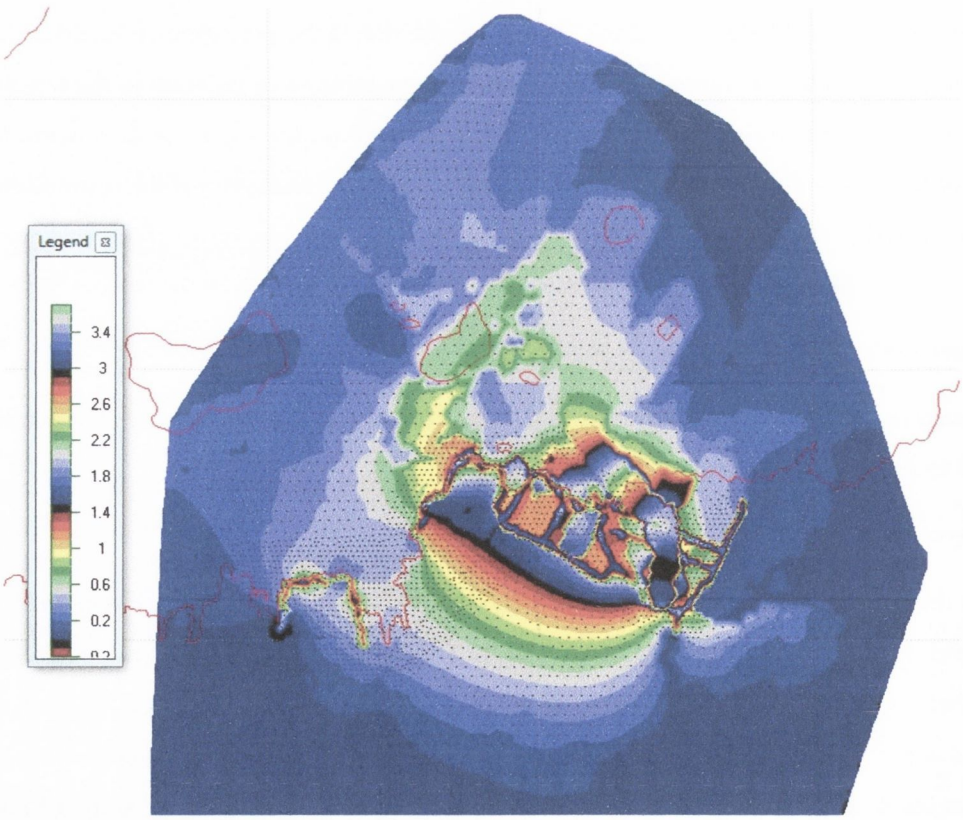


**Figure 12.6.** Rise in potentiometric surface contours in layer 2 (peat aquifer) following restoration works. Contour interval is 0.25 m.

Layer 4

The rise in the potentiometric surface of layer 4 (Till) is presented in figures J33 and J34, and figure 12.7, for a rise of 1.0 m and 0.5 m respectively. The potentiometric surface rises significantly in localised zones in the Restoration Area – by up to 4.0 m. The potentiometric surface also rises substantially under the high bog – between 0.25 and 2.0 m. Significantly the potentiometric surface rise under the high bog extends as far as the models no-flow boundary – by up to 0.5 m and 0.75 m in the western and eastern area of the high bog respectively.

Hydraulic boundaries can be used legitimately to produce a steady-state flow field for calibration purposes. However, they may or may not be acceptable for transient problems or for steady-state predictive simulations (Anderson & Woessner, 1992). Thus, the perceived groundwater catchment area used to delineate the model domain in section 11.7 appears to have been underestimated – the groundwater catchment area is probably 10-20 % bigger than used in the model simulation, which is not unrealistic based on catchment area calculations discussed in chapter 9.

As means of a comparison, figure J48 in appendix J, simulates the potentiometric surface rise when the model boundaries are fixed using steady state heads. A substantial increase in head also occurs in this simulation – but the rise decreases to < 0.1 m at the model boundaries. It is probable that the true rise in head is somewhere in between the simulation scenarios – particularly in the eastern area of the model where groundwater appears o 'pond' at the model boundary. In section 11.7, it may be recalled that while the western boundary is relatively well constrained, there is uncertainty regarding the delineation of the eastern boundary. However, the leakage rates (section 12.1.3) from the two models are relatively similar and the no-flow restoration model simulation is still considered valid – lateral flow rates will differ slightly, but they are not considered in the conservation strategy. Importantly, the rise in the potentiometric surface of layer 2 is constrained within the model domain.

In appendix J, figures J40 to J43, are timelines for the rise in head at piezometer locations 909, CLCD3 (figure 12.8), 920 and CLBH5 are presented. It can be observed that each of the investigation points reach a steady state within c. 1000 days. In section 9.3 the drop in hydraulic head at subsoil piezometers CLCD3 and CLBH5 were described - c. 0.35 and 1.0 m respectively. In figure J41 and J43 it can be observed that the model simulation predicts a rise of c. 0.9 m and 1.5 m at CLCD3 and CLBH 5 respectively – approximately 3 and 1.5 timed that of the measured water level decrease respectively.

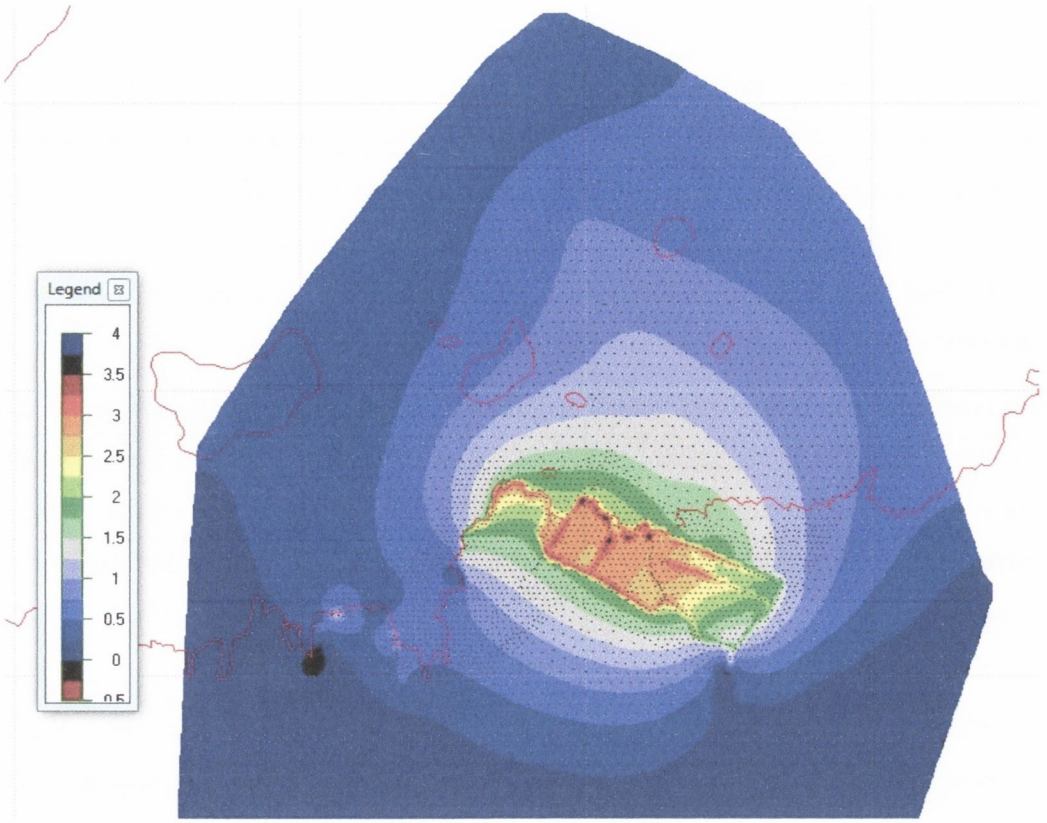


**Figure 12.7**. Rise in potentiometric surface contours in layer 4 (till aquifer) following restoration works. Contour interval is 0.25 m.

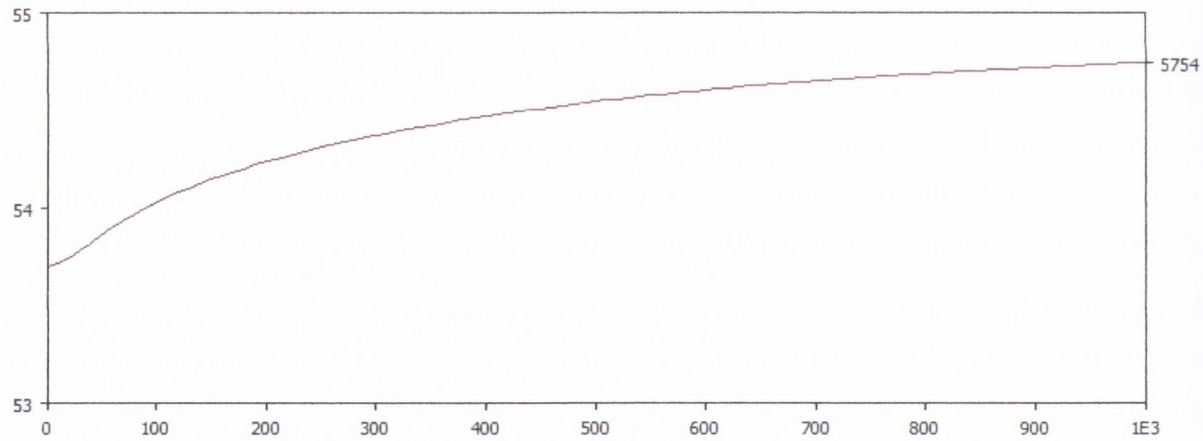


**Figure 12.8**. Rise in GWT (layer 4) at piezometer location CLCD3 following Restoration Area infill. Period is 1000 days.

*Contour maps and cross sections*

The computed potentiometric contours following restoration works for layers 2 and 4, with flow lines, are presented in appendix J and discussed below.

Layer 2

The potentiometric rise in layer 2 has changed the groundwater flow pattern in the aquifer layer compared to the groundwater flow pattern described for the steady state model. The gradient has

decreased in the western area of the map – and is relatively shallow west and north of the Western Mound and east of Shanely's Lough. The 'groundwater' flow basin between the Western Mound and Shanely's Lough described in section 12.1.1 still remains and this is due to the underlying sand lense (layer 3) still providing a subsurface drainage pathway – there was no reason to omit this high transmissive zone in the prediction model. The potentiometric surface still suggests a drainage channel feature - but the gradient has been reduced.

Figure J37 illustrates water particle flow lines from the layer 2 potentiometric surface. It can be observed that a water particle in peat from the western area of the model now discharges south of the Restoration Area – in contrast with the observations made in the other management scenarios. The cutaway infill is effective as confining discharge from subsurface discharge. However, one flow line in the southwest of the high bog still discharges in the cutaway – possibly because the confining pressure is still not great enough. The other observation to note is that water from the area surrounding Shanely's Lough now has a very long flow path length and discharges > 200 m south of the cutaway area. The flow lines illustrated in green indicate very quick movement of water and this is a result of subsurface drainage through the sand – which discharges into the Brook Stream outside the Restoration Area. Subsurface drainage via the sand lense is probably impossible to contain.

Layer 4

The potentiometric rise in layer 4 has changed the groundwater flow pattern in the aquifer layer compared to the groundwater flow pattern described for the steady state model in section 12.1.1. The hydraulic gradient in the western area of the model, beneath the high bog in the region of the Western Soak and the Western Mound, is shallower and the potentiometric surface no longer converges in the cutaway area like it does in the steady state model – groundwater from the till layer is no longer discharging into this area; as indicated by the groundwater level rise in figure J24. The high transmissivity zone in limestone (layer 5) remains in the model and creates the 'kinked' pattern in the potentiometric surface in the north of the model. However, this is a natural feature and not necessarily a drainage pathway as the limestone 'conduit' is overlain by lacustrine clay.

Figure J39, and Figure 12.9, illustrates water particle flow lines from the layer 4 potentiometric surface. The flow patterns are similar to those described for layer 2 – groundwater from western area of the model now discharges south of the Restoration Area and groundwater from the northern and eastern regions of the model discharge east of the Restoration Area. This is in contrast to the flow lines from the steady state model and is a result of the groundwater table rise reducing the hydraulic gradient and changing the flow path direction away from the Restoration Area. However, similar to layer 2, one flow line in the southwest of the high bog still discharges in the cutaway – again, possibly because the confining pressure is still not great enough in this localised area.

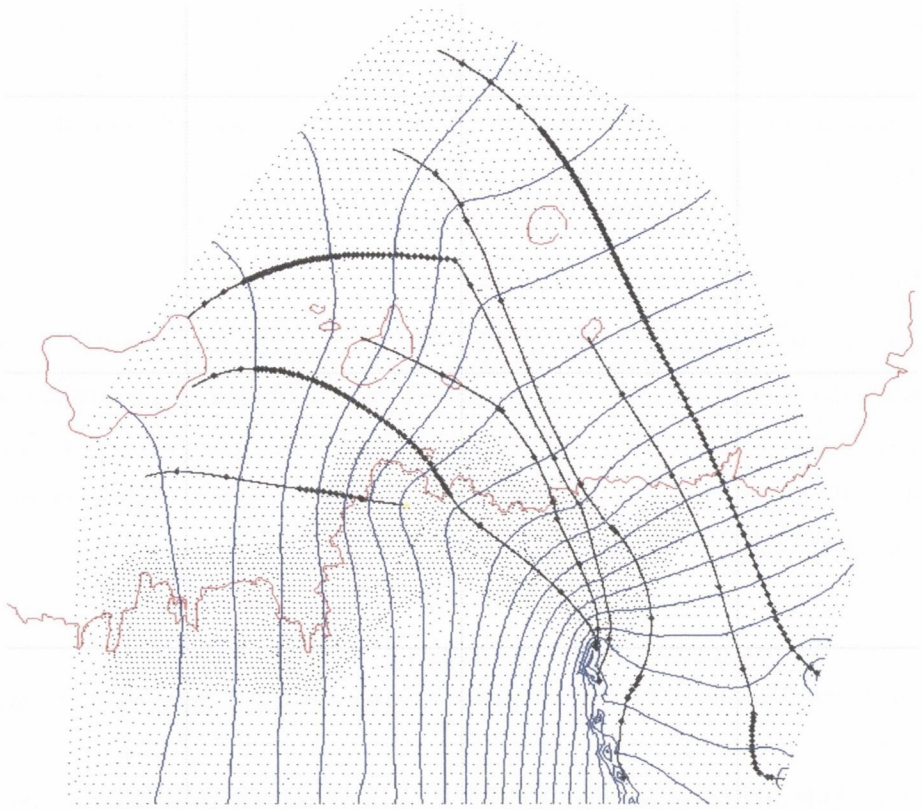

**Figure 12.9.** Potentiometric surface and flow lines in layer 4 (till aquifer) following restoration works. Contours are at 0.5 m intervals.

*Cross-sections*

Profile cross-sections of the potentiometric surface in the aquifer units and aquifer thickness cross-sections with water particle flow lines are illustrated in figures J6 to J20, appendix J – the cross-section/ flow lines are the same lines used in the steady state analysis (section 12.1.2).

Cross-sections in 2D

Cross-sections with the potentiometric surface from the aquifer layers through the five flow lines analysed in the steady state analysis are reproduced in appendix J – following restoration work. The observations made from the potentiometric surface contour maps can also be applied to the cross-sections. The potentiometric surface of layers 4 and 5 has risen in flow lines 1 to 3 compared to the same flow lines in steady state. The potentiometric surface of layers 4 and 5 are now also coincident with each other – similar to observations made of piezometer nests in the field where piezometers measures water level in till and limestone (e.g. BH5 and BH9). In the steady state model the limestone potentiometric surface is above that of till at the drain – implying groundwater discharge is largely from limestone. The difference between the potentiometric surface in layer 2 and 4 has also decreased.

Water particle movement is now largely contained within the groundwater system – as indicated from the flow line analysis following restoration work. The exception is flow line 1, where groundwater in

layer 2 and 4 continues to discharge in the cutaway area – the water particle in layer 2 moves laterally into a till protrusion (figure j8) implying the absence of a confining clay layer is still having an effect. In flow line 2 the flow path of the water particle is at the bottom and upper margins of the till unit, whereas in flow line 3 the flow path is at the base of till, where is discharges outside of the modelled region. This flow line is also near the limestone conduit and may explain this groundwater flow behaviour. The effect of the sand layer is evident in figure J15 and J20. Water particle flow is generally vertical in layer 2, but in areas with sand there is an induced lateral flow from the base of peat – similar to the observation made in steady state analysis.

*Vertical hydraulic gradient*

In Chapter 5, Section 5.3, the measured vertical hydraulic gradient, between deep peat and till hydraulic head was described for piezometer nests on high bog and cutover bog (see table 4.4). Table 12.5 lists the vertical hydraulic gradients as computed in (a) the steady state model and (b) the prediction/ restoration model for the same piezometers (or nodal points in the model) as used in Table 4.4. Table 12.9 lists the difference between the same investigation points.

Table 12.5. Vertical hydraulic gradients for selected piezometers in (a) steady state model and (b) prediction model

| Steady state model | | | | Prediction model | | | |
|---|---|---|---|---|---|---|---|
| **ID** | **Gradient** | **ID** | **Gradient** | **ID** | **Gradient** | **ID** | **Gradient** |
| 906 | 0.005 | 912 | 0.488 | 906 | 0.008 | 912 | -0.210 |
| 907 | 0.067 | TI12 | 0.557 | 907 | 0.045 | TI12 | 0.488 |
| 908 | 0.090 | CLCD3 | 0.166 | 908 | 0.078 | CLCD3 | 0.092 |
| 909 | 0.294 | 915 | -0.006 | 909 | 0.154 | 915 | -0.054 |
| 910 | 0.302 | 920 | 0.267 | 910 | 0.189 | 920 | 0.010 |
| 911 | 0.236 | 927 | -0.270 | 911 | 0.238 | 927 | -0.109 |

Table 12.6. Difference in vertical hydraulic gradient between steady state model and prediction model

| **ID** | **Diff** | **ID** | **Diff** |
|---|---|---|---|
| 906 | -0.003 | 912 | 0.698 |
| 907 | 0.022 | TI12 | 0.070 |
| 908 | 0.012 | CLCD3 | 0.074 |
| 909 | 0.140 | 915 | 0.049 |
| 910 | 0.113 | 920 | 0.257 |
| 911 | -0.002 | 927 | -0.161 |

The computed steady state vertical hydraulic gradients are similar to those calculated manually in table 4.4. Following the simulated restoration works in the prediction model, the vertical hydraulic gradient reduces by 0.11 and 0.14 at piezometers 910 and 909 respectively. In the subsidence and

hydrogeological analysis, 909 and 910 were identified as areas of water loss associated with decreased pore water pressure in the peat substrate. The reduction in hydraulic gradient, following the raising of the groundwater table in till and peat, indicates that hydraulic gradient in an environmental supporting condition in the raised bog.

## 12.3. Conclusions

In section 11.2 the reasons for constructing a numerical model of the Clara West groundwater system were outlined and are discussed according to the results generated from the steady state and prediction model computations.

### 12.3.1. Steady state model

The steady state model was calibrated using field measured heads in peat and till subsoil. The calibration and sensitivity analysis indicate that the transmissivity in layer 4, the till aquifer, was most sensitive to change. Zones of high permeability in peat, as mapped in the field, were necessary to calibrate heads in layer 2. Resistance in layer 2 and layer 4 were also sensitive to change and low resistance in layer 4 was required to account for heads in the western area of the model domain.

To account for locally low heads in peat (later 2) and till (layer 4) the model required the inclusion of two unknown features – a highly transmissive sand unit (field measurements do not measure high permeability) and a highly transmissive limestone unit. The model could not be calibrated without the inclusion of these two interpreted features.

*Linkage between bog body and marginal drains*

The model confirms that the Clara West marginal drains are zones of groundwater discharge for groundwater flow beneath the high bog. This is evident from the potentiometric surface contours generated for the layer 2 (peat) and layer 4 (till) aquifers and the gradients of the aquifer potentiometric surface in cross-section. The model also indicates that deeper groundwater flows, from limestone, are important and contribute to groundwater flow in the drains.

Water balance computations for groundwater catchment areas in the model domain show that groundwater discharge, from till (as heads are fixed; they are not fixed in limestone), to marginal drains is between 0.25 and 0.45 mm /day. This is similar to the base flow calculations in chapter x where estimates are between 0.24 and 0.39 mm/ day.

Runoff from layers 2 and 3, which may be grouped together as peat runoff, is calculated as ranging between 0.06 and 0.09 mm/ day. This is similar to the analytical water balance calculation where estimates of peat runoff are between 0.03 and 0.05 mm/ day. Subsidence analysis estimates water loss from peat as ranging between 0.02 and 0.11 since 1991. The model is consistent with the analytical solutions and confirms that groundwater flow through till is an important drainage route for subsurface drainage in the high bog.

*Impact of marginal drainage on the bog body*

Analysis from selected groundwater catchments (those that are instrumented in the field) show that leakage rates through layer 2 and into layer 4 range between 70 and 93 mm/ year. The analytical water balance for the Bog Weir measures 138 mm/ year. The high leakage rate at the Bog Weir is due to (a) an underestimated model recharge input or (2) local high infiltration zones, such as peat cracks, on the high bog. However, estimates from instrumented marginal drains measure between 25 and 95 mm/ year. The leakage rates generated by the model are therefore considered accurate. The high leakage rates, > 40 mm/ year, are a result of the lowered potentiometric surface in layers 2 and 4.

Leakage rate in the model is controlled by the subsoil unit underlying the peat aquifer – similar to the conclusion made for the rate of subsidence in chapter 7. In areas of high bog where peat overlies till, areas with sand lenses and lacustrine clay, model water balance computations calculate leakage rates of c. 108, 45 and 42 mm/ year to mineral subsoil respectively. However, in areas where there is sand, lateral flow in the sand layer reduces the leakage rate to layer 4. The leakage rate to the sand units amounts to 54 mm/ year, and is locally higher, between 70 and 90 mm/ year. The vertical leakage rates are similar to lateral (boundary flow) flow discharge rates – water moves vertically into the till layer and then moves laterally in the aquifer unit and discharges into the drainage system.

The leakage rates confirms that there are two subsurface drainage pathways where the bog is losing water due to high, > 70 mm/ year, leakage rates: (1) where peat sits on till the leakage rate is high due to (a) the locally high permeability of the peat unit itself and (b) till protrusions inducing lateral flow where normally flow is predominantly downward and (2) where peat sits on sand lenses the leakage rate is high because the sand area induces a drawdown of the groundwater table in peat and lateral flow is increased.

### 12.3.2. Prediction model

The steady state model proves that drains in the Clara West drainage system have a big effect on groundwater flow in the high bog – the high leakage rates are a result of the drains lowering the potentiometric surface in layers 2 and 4, therefore increasing the hydraulic gradient between head in peat and head in till, which has induced water loss from peat storage in areas where peat is associated with low permeability subsoil. The prediction model removed the drains from the system, by means of blocking them with low permeability material and infilled the cutaway bog area, the Restoration Area, with low permeability material – simulating a conservation management plan to restore the bog system hydrology to its 'natural' state.

*Rise in groundwater table following restoration*

Removing the drains removes the outlet for groundwater discharge from flows beneath the high bog. The potentiometric surface in layer 2 (peat) and layer 4 (till) rises considerably once this outlet is

removed. The potentiometric surface in peat rises between 0.1 and 1.0 m under the high bog - < 1.0 m within 200 m of the high bog boundary and < 0.5 m within 600 m of the high bog boundary. The potentiometric surface in layer 4 (till) also rises considerably – between 0.1 and < 2.0 m under the high bog. A water level rise of < 1.0 m occurs within 500 m of the high bog boundary. A rise of < 0.25 m occurs as far as the western margin of the model and < 0.5 m as far as the eastern margin of the model margin.

That the water level rise does not level out indicates the groundwater catchment divide has been underestimated and the rise overestimated. However comparison with the model run with a fixed head boundary condition confirms the model is still valid. The considerable rise in head in layer 2 and 4 are associated with subsidence zones.

*Leakage from the high bog*

Raising the potentiometric surface has decreased the hydraulic gradient – it is more 'horizontal' in the prediction model following the simulation of restoration works. The change in gradient has resulted in a change in leakage rate. In the prediction model the Brook Stream has been retained so to provide an outlet for runoff. The water balance for the groundwater catchment area to this outlet calculates that 26 % of input-recharge infiltrates the groundwater system – in the steady state model this was between 75 and 90 %. The infiltration rate from high bog peat to mineral subsoil is calculated as 46 mm/ year – c. 35 to 50 % lower than the estimates in the steady state model. As downward leakage should ideally be approximately 40 mm/ year in natural, sustainable hydrological conditions, the result indicates the simulated management scenario is successful.

However, while the global leakage rate of the high bog has been reduced to an acceptable level the subsurface drainage associated with till remains. Where peat sits on till in the western area of the high bog model domain, infiltration to the till unit is calculated as 61 mm/ year – c. 45 % lower than in the steady state model. Flow line analysis shows that following restoration work, groundwater discharges outside of the infill area. However, there are still localised flow lines that discharge groundwater in the western margin on the infill area. The infill may need to rise to create a confining pressure in which to prevent upward seepage of water – and reduce the leakage rate from 61 to c. 40 mm/ year. Where peats sits on sand, infiltration from peat to the sand unit is 37 mm/ year and 27 mm/ year from sand to layer 4 (lacustrine clay); implying lateral flow remains, but the infiltration rate is acceptable. Where no sand is present, infiltration from peat to lacustrine clay is 35 mm/ year – c. 40 % lower than where peat sits on till.

Infiltration to limestone (layer 5) also decreases following restoration simulation. In the steady state model infiltration from layer 4 (till) to limestone ranges between c. 50 and 70 m/ year. The potentiometric surface of layer 5 is coincident with that in layer 4 beneath the high bog but rises above it in the vicinity of the drains. In the prediction model infiltration reduces to c. 23 mm/ year and

the potentiometric surface in layers 4 and 5 are everywhere coincident, suggesting hydraulic continuity between the two aquifer units. Marginal drainage there induces discharge of deeper groundwater in the steady state model. Following restoration, water that normally infiltrated into limestone remains within the till aquifer, and this is evident in higher lateral flow rates. The simulated restoration measure successfully raises the regional groundwater table in the till 'aquifer' - which has a positive effect on the groundwater table in peat in the high bog. Surface water runoff on the high bog increases and infiltration through the high bog decreases – with local zones of higher infiltration associated with high permeability peat zones resting on till subsoil.

## 13. Conclusions

The principle aim of this work was to assess the dependency of Clara Bog West on the regional groundwater table. Traditional models of raised bog hydrology assume the bog system is isolated from the regional groundwater system. This study demonstrates that this is not the case. The raised bog is intrinsically linked with regional hydrology, with groundwater pressures in the underlying aquifers maintaining the hydraulic head in the peat substrate. The groundwater dependency becomes apparent when the piezometric level, in peat and groundwater body, is reduced.

### 13.1. Lowering of the water table in peat and till

The regional groundwater table in the till groundwater body has decreased by between 0.5 and 0.7, in local areas since 1991. The piezometric level in basal peat has decreased by > 1.0 m, in local areas, since this time. Hydrological characterisation of the Clara West drainage system and water level monitoring of piezometers installed to the till groundwater body shows that where peat is < 2.0 m thick, and the base of the drain is below that of the potentiometric surface in the till groundwater body, groundwater discharge occurs. These zones for groundwater discharge have drawn down the potentiometric surface in the peat body and till, thereby increasing the vertical and horizontal hydraulic gradients within c. 600 m of the drainage system.

### 13.2. Hydraulic connection

Hydrograph analysis and seepage calculations of piezometer nests on the high bog indicate that where till underlies peat the downward seepage rate is in the order of 0.6 mm/ year in local areas. Piezometric water levels in peat and till bodies are connected in areas where suspected water losses are occurring – adjacent to subsurface till mounds. Base flow analysis estimates that recharge to the till groundwater body is between 0.24 and 0.39 mm/ day (+/- c. 20%), some of which, in the Restoration Area, is deeper groundwater flow from limestone (c. 9% of total baseflow).The base flow recession moves in concurrently with water released from storage in the till deposit under the high bog and under cutover bog. Surface water levels and groundwater levels are hydraulically connected.

### 13.3. Increased high bog infiltration

The Clara West high bog is losing water and subsiding as a result of peat consolidation. Peat is consolidating because water is being released from storage due to a decrease in pore water pressure associated with a decrease in the potentiometric surface in the peat and till groundwater bodies. The result is an enhanced infiltration rate from peat to mineral subsoil in areas of the high bog where there is an underlying 'permeable' layer that serves as a subsurface drainage pathway for the water released from peat substrate.

Infiltration through the high bog is calculated as being c. 140 mm/ year at the bog weir – far higher than that calculated by Van der Schaaf (1999) and approximately three times the 'natural', or

boundary, limit of 40 m/ year (Streekerk & Casparie, 1989). The marginal drain flow structures estimate leakage as being between 25 and 95 mm/ year – low leakage rate associated with areas underlain mostly by lacustrine clay. The high leakage rates at the Bog Weir are a result of subsurface peat cracking associated with a subsurface palaeo-channel – areas of sand lenses.

There are two subsurface drainage pathways where the bog is losing water due to high, > 60 mm/ year, leakage rates: (1) where peat rests on till, the leakage rate is high due to (a) the locally high permeability/macro-pore porosity of the peat unit itself due to cracking and (b) till protrusions inducing lateral flow where normally flow would be predominantly downward and (2) where peat rests on sand lenses, the leakage rate is high because the sand area induces a drawdown of the groundwater table in peat and lateral flow, locally, is increased. Subsurface cracking is also a feature of san lense areas. Significantly, subsurface cracking alters the properties of the catotelm, meaning it is no longer a barrier to groundwater flow.

### 13.4. Peat consolidation

Subsidence analysis shows that the rate of ground level decrease follows two trends of decrease – linear and exponential. Areas of exponential decrease subside rapidly, in the first 10 years, before levelling off, whereas linear rates of decrease continue to subside over time. Modelled runoff from peat/ sand is calculated as being between 0.06 and 0.09 mm/ day. This discharge is similar to the analytical water balance calculation in which estimates of peat runoff are between 0.03 (exponential area of ground level decrease) and 0.05 mm/ day (linear areas of ground level decrease).

Overall, analysis of subsidence estimates water loss from peat as ranging between 0.02 and 0.11 mm/day since 1991. The model results are consistent with the analytical solutions and confirm that groundwater flow through till is an important drainage route for subsurface drainage from the high bog.

### 13.5. Controls on leakage and subsidence

Modelling and subsidence analysis demonstrate that leakage rate is controlled by the subsoil unit underlying the peat aquifer. In areas of high bog where peat overlies till, model water balance computations calculate leakage rates of c. 108mm/ year in areas of bog underlain by till. In areas with sand lenses overlying lacustrine clay, the leakage rate from peat to the sand units is modelled as being between 70 and 90 mm/ year. The vertical leakage rates are similar to lateral (boundary flow) flow discharge rates – water moving vertically into the till layer and then laterally in the aquifer unit to discharge into the drainage system.

Between 2002 and 2011, areas underlain by lacustrine clay in exponential decrease zones decrease by 3 mm / year and 12 mm/ year in linear zones. In areas underlain by till the decrease were 9 mm/ year in exponential zones and 19 mm/ year in linear zones. Subsidence is an order of magnitude bigger in

areas underlain by till – but subsidence propagates into lacustrine areas as the potentiometric surface decrease extends beyond the areas of till-peat interface. In areas underlain by sand the decrease were 6.4 mm/ year/m in exponential zones and 10.4 mm/ year in linear zones.

Peat thickness controls the rate of settlement - between 2002 and 2001, areas underlain by lacustrine clay in exponential decrease zones decrease by 0.4 mm/ year/ m and 1.4 mm/ year/m in linear zones. In areas underlain by till the decrease were 1.4 mm/ year/m in exponential zones and 2.6 mm/ year in linear zones. In areas underlain by sand the decrease were 0.9 mm/ year/m in exponential zones and 1.3 mm/ year in linear zones.

### 13.6. Hydro-ecological impact

The occurrence of 'wet' ecotopes, namely subcentral, central and active flush/ soak systems, and by extension acrotelm development, on the high bog surface is dependent on particular slope and flow path lengths being maintained. Hydrological processes on the surface of the high bog are therefore associated with topographic conditions.

In 1991 the Clara West high bog supported one surface water catchment, which contained both the Western Soak and Shanely's Lough soak systems. Subsidence has fragmented this catchment area into four separate catchment areas. The Western Soak and Shanely's Lough soak systems are now isolated.

Since 1991, the area of high bog supporting 'wet' ecotopes has decreased by c. 26 %, due to (1) local fires and (2) increasing slope gradients. The effect of fire, which damages acrotelm, is limited. Central ecotopes develop on gradients < 0.3 % and subcentral ecotopes develop on gradients < 0.5 % - both ecotopes have declined significantly since 1991. Subcentral ecotopes are gradually being replaced by submarginal ecotopes – the bog is getting drier as there are now more outlets for surface water discharge. Water is no longer contained on the bog as it once was.

The area of active flush has not changed significantly since 1991. However, long flow path lengths maintain active flushes. Flow path lengths to the Western Soak have not changed significantly since 1991, but flow path lengths have decreased by c. 10 % to the Shanely's Lough soak system since 1991. In 1991, water flowed from the Western Soak to Shanely's Lough. However, this water now discharges south of the Western Mound to the FB2 Flume – the volume of water discharging to Shanely's Lough soak system has reduced, and over time the condition of the soak system will degrade.

### 13.7. Restoration

Field measurements and the steady state model shows that drains in the Clara West drainage system have a strong influence on groundwater flow in the high bog – the high leakage rates are a result of the drains lowering the potentiometric surface in peat and till, therefore increasing the hydraulic

gradient between the water table in the bog and the head in peat and head in till, which, in turn, has induced water loss from peat storage in areas where peat is normally associated with low permeability subsoil.

### 13.1.1. Rise in groundwater table

Removing the drains removes the outlet for groundwater discharge from flows beneath the high bog. The potentiometric surface in peat and till rises considerably once this outlet is removed. The potentiometric surface in peat is indicated to rise between 0.1 and 1.0 m under the high bog - < 1.0 m within 200 m of the high bog boundary and < 0.5 m within 600 m of the high bog boundary. The potentiometric surface in till rises considerably – between 0.1 and < 2.0 m under the high bog. A water level rise of < 1.0 m occurs within 500 m of the high bog boundary. A rise of < 0.25 m occurs as far as the western margin of the model and < 0.5 m as far as the eastern margin of the model margin.

### 13.1.2. Reduced leakage

Raising the potentiometric surface decreases the hydraulic gradient – it is more 'horizontal' in the prediction model following the simulation of restoration works. The change in gradient has resulted in a change in leakage rate. In the prediction model the Brook Stream was retained so as to provide an outlet for runoff. The water balance for the groundwater catchment area to this outlet indicates that 26 % of input-recharge infiltrates the groundwater system – in contrast to the steady state model which showed values between 75 and 90 %. The infiltration rate from high bog peat to mineral subsoil is calculated to be 46 mm/ year – c. 35 to 50 % lower than the estimates in the steady state model. As downward leakage should ideally be approximately 40 mm/ year in natural, sustainable hydrological conditions, the result indicates that this simulated management scenario would be successful.

However, while the global leakage rate of the high bog has been reduced to an acceptable level the subsurface drainage associated with till remains. Where peat sits on till in the western area of the high bog model domain, infiltration to the till unit is calculated as 61 mm/ year – c. 45 % lower than in the steady state model. Where peat rests on sand, infiltration from peat to the sand unit is 37 mm/ year and 27 mm/ year from the sand to layer 4 (lacustrine clay). This situation implies lateral flow remains, but with an acceptable infiltration rate. Where no sand is present, infiltration from peat to lacustrine clay is 35 mm/ year – c. 40 % lower than where peat rests on till.

Infiltration to limestone bedrock (layer 5) also decreases following restoration simulation. In the steady state model infiltration from layer 4 (till) to limestone ranges between c. 50 and 70 m/ year. The potentiometric surface of layer 5 is coincident with that in layer 4 beneath the high bog but rises above it in the vicinity of the drains. In the prediction model, infiltration reduces to c. 23 mm/ year and the potentiometric surface in layers 4 and 5 are everywhere coincident, suggesting hydraulic continuity between the two aquifer units and reduced vertical gradients. Marginal drainage induces

discharge of deeper groundwater in the steady state model but, following restoration, water that normally infiltrated into limestone remains within the till aquifer.

The simulated restoration strategy successfully raises the regional groundwater table in the till groundwater body - which has a positive effect on the groundwater table in peat in the high bog. Following restoration simulation the surface water runoff on the high bog increases and infiltration through the high bog decreases – albeit with local zones of higher infiltration associated with high permeability peat zones resting on till subsoil.

In summary, reducing hydraulic gradient results in a decreased downward vertical infiltration rate through the peat profile in the high bog. This demonstrates that the bog is, indirectly, dependent on the regional groundwater table – hydraulic head and hydraulic gradient are environmental supporting conditions for the Clara West high bog.

### 13.8. Recommendations

The research presented was the result of an intense three year study involving field work, groundwater flow modelling and analysis. That there is still work to be done highlights how complicated the Clara Raised bog system is. Further work is required to:

- Quantify accurate evapotranspiration rates – an eddy covariance tower is needed to estimate evapotranspiration form the high bog, particularly as the vegetation/ ecotope distribution is so variable; vegetation type strongly controls evapotranspiration
- Continued topographic surveying – to establish with more data points (i.e. > 4 points on a graph) the mechanisms of subsidence that results in ground level elevation change
- Continued groundwater monitoring of subsoil and peat piezometers and phreatic tubes – to monitor water level fluctuations and catchment boundary alterations
- Continued water balance studies and runoff measurement – the bog is highly unstable and is in an unsteady state of flux meaning the runoff measurement will change each year – a mean value is required and this necessitates a longer period of analysis
- More hydrochemical analysis to more confidently identify end-members and better estimate baseflow runoff
- Stable oxygen isotopic analysis requires more frequent sampling to reduce variability in oxygen 18 values and to confirm if it is a reliable environmental tracer to use in estimating peat runoff released from catotelm storage
- Continued ecotope mapping, coupled with hydrological measurements

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