

Ecohydrology, Greenhouse Gas Dynamics and Restoration Guidelines for Degraded Raised Bogs

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- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

**Ecohydrology, Greenhouse Gas Dynamics and
Restoration Guidelines for Degraded Raised Bogs
(2014-NC-MS-2)**

EPA Research Report

Prepared for the Environmental Protection Agency

by

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Contents

Acknowledgements	ii
Disclaimer	ii
Project Partners	iii
List of Figures	vii
List of Tables	ix
Executive Summary	xi
1 Introduction	1
1.1 Background	1
1.2 Protection and Legislation	1
1.3 Ecosystem Services	1
1.4 Aims and Objectives	2
2 Site Selection, Instrumentation and Monitoring	3
2.1 Study Areas	3
2.2 Site Selection	4
2.3 Field and Airborne LiDAR Topographic Survey	6
2.4 Greenhouse Gas Measurement	6
2.5 Meteorological Monitoring	7
2.6 Hydrometric Network	7
2.7 Dissolved Organic Carbon	8
2.8 CO ₂ Evasion and Dissolved Inorganic Carbon	8
3 Ecohydrology	9
3.1 Introduction	9
3.2 Ecotope Distribution	9
3.3 Water Table Dynamic	10
3.4 Acrotelm Hydraulic Properties	11
3.5 Peat Hydraulic Conductivity	12
3.6 Hydraulic Head and Gradient	15
3.7 Groundwater–Surface Water Interaction	15
3.8 Subsidence	18

3.9	Water Balances	20
4	Carbon Balance	21
4.1	Net Ecosystem Exchange of CO ₂	21
4.2	Methane	23
4.3	Fluvial Carbon	23
4.4	Net Ecosystem Carbon Balance	26
4.5	National Raised Bog Carbon Exchange	27
5	Hydrological Restoration	28
5.1	Surface Drainage	28
5.2	Marginal and Groundwater Drainage	29
5.3	Groundwater Modelling	30
5.4	Hydrological Restoration	31
6	Restoration Guidelines	32
7	Summary, Conclusions and Recommendations	34
7.1	Ecohydrology	34
7.2	Greenhouse Gas Emissions	34
7.3	Restoration	35
7.4	Climate Change and Adaptation	36
	References	38
	Abbreviations	40

List of Figures

Figure 2.1.	Peatland distribution map of Ireland and location of Clara Bog and Abbeyleix Bog	3
Figure 2.2.	(a) Clara Bog and (b) Abbeyleix Bog ecotopes, with locations of GHG and hydrological monitoring locations	5
Figure 2.3.	Study area at Clara central ecotope	6
Figure 3.1.	Relative probability plot of ecotope and slope distribution	10
Figure 3.2.	Water table duration curves for ecotopes at Clara and Abbeyleix (2015–2017)	12
Figure 3.3.	Storativity curves for (a) <i>Eriophorum</i> cutover, (b) sub-marginal, (c) sub-central and (d) <i>Sphagnum</i> cutover	13
Figure 3.4.	Mean annual potentiometric surface at the base of peat, variation in hydraulic conductivity and decrease in head (1991–2013) at Clara Bog	14
Figure 3.5.	Potentiometric surface in deep peat at Abbeyleix Bog	16
Figure 3.6.	Mean potentiometric surface in till groundwater body and regional groundwater catchment at Clara Bog and monitoring locations	17
Figure 3.7.	(a) Time series of head and stage fluctuation at the marginal drain between February 2017 and 2018; (b) hydraulic gradient between stage and peat head; (c) fluctuation in stage and EC at low and high flows	17
Figure 3.8.	Decline in ground surface at Clara West between (a) 1991–2017 and (b) 2009–2017	18
Figure 3.9.	Correlation between difference in ground level and mean piezometric head measured at the base of peat between 1991–1993 and 2009–2012	19
Figure 3.10.	Hydrogeological cross-section through groundwater flow line	20
Figure 4.1.	(a) Monthly R_{eco} , (b) monthly GPP and (c) cumulative NEE for Clara ecotopes and the bare peat site between July 2015 and June 2017	21
Figure 4.2.	(a) Monthly GPP, (b) Monthly R_{eco} and (c) cumulative NEE for Abbeyleix ecotopes and cutover bog sites between January 2016 and December 2017	22
Figure 4.3.	Variability in CH_4 daily flux at Clara marginal and central ecotopes	24
Figure 4.4.	Annual CH_4 flux for each ecotope averaged over all collars in Abbeyleix ecotopes and cutover sites	24
Figure 4.5.	DOC concentration and discharge between November 2016 and October 2017 at (a) surface stream and (b) marginal drain	25
Figure 4.6.	Carbon balance for each ecotope including NEE, CH_4 flux, aquatic losses as DOC and DIC, and open water CO_2 evasion	26

Figure 5.1.	Schematic showing the controls on water level around a dammed drainage channel	28
Figure 5.2.	Hydrus models of hydrogeological transect at Clara following (a) current steady state conditions and (b) simulated drain blocking	30

List of Tables

Table 2.1.	Biotic and abiotic characteristics of ecotopes	4
Table 3.1.	Median slope and interquartile range (IQR) for 53 SAC raised bogs	10
Table 3.2.	Summary of water table characteristics for ecotope and cutover bog plot sites	11
Table 3.3.	Summary of hydraulic conductivity tests in peat and till deposits	14
Table 4.1.	Summary NEE for Clara and Abbeyleix	23
Table 4.2.	Carbon balance for two catchment areas at Clara Bog between November 2016 and October 2017	26

Executive Summary

This report presents the results of an integrated scientific study on two raised bogs, Clara Bog and Abbeyleix Bog, which are considered to be representative of lowland peatland conditions encountered in Ireland. Such peatlands are important ecosystems that support a unique biodiversity and are important for global climate regulation. However, their range and function across Ireland and Europe have decreased greatly in the past number of decades. This requires attention in the form of further advances in best practice management for damaged systems. The restoration of raised bog habitats, and their key ecosystem services, such as carbon sequestration, is fundamentally controlled by peatland ecohydrological processes. The integrated measurement of these processes with the fluxes of the two primary greenhouse gases (GHGs) emitted from bog systems, carbon dioxide (CO₂) and methane (CH₄), and fluvial carbon export form the basis of this study. Site selection was directed by detailed ecological mapping of each bog system, enabling an upscaling of results to habitat level and an estimation of national-level GHG emissions from raised bogs designated as European sites.

The flux of CO₂ and CH₄ between the raised bog and the atmosphere in this study is consistent with fluxes reported internationally. In areas where *Sphagnum* spp. dominate the bog surface (central and sub-central ecotopes), the average net ecosystem exchange is in the order of $-50 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$, decreasing to approximately $-10 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ during the second year of study at Clara as a result of substantially reduced rainfall. While central and sub-central ecotopes are consistent sinks (and sources of CH₄, in the order of $10 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$), sub-marginal ecotope reverts to a CO₂ source in a year with lower-than-average rainfall. Marginal ecotopes are persistent sources of CO₂ (and near CH₄ neutral), with fluxes in the order of $100\text{--}300 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$, similar to areas with no vegetative surface (bare peat). When upscaled to the level of the bog habitat, both Clara and Abbeyleix emit CO₂ to the atmosphere. Assigning ecotope emission factors to the network of European sites in Ireland, it is estimated that raised bogs emit approximately 80% more CO₂ than they

sequester. This is because of the limited distribution of *Sphagnum* spp. as a consequence of past management practice, primarily drainage activities. The export of dissolved organic carbon (DOC) was also found to be a significant part of the bog carbon balance. The magnitude of this flux is found to nearly double when peat is drained on the bog margin at Clara and reverts the bog into a significant source of carbon. DOC is thereby considered to be as significant a pathway for carbon loss as the CO₂ land-atmosphere exchange.

Peatlands are considered resilient to gradual changes in climate. However, ecosystem stability can be lost when critical environmental thresholds are passed. This study finds that the water table dynamic is the critical driver of GHG emissions and further confirms that peatland carbon and water cycling are strongly coupled. Engineering solutions required to restore the hydrological balance of degraded raised bogs must reinstate a functioning acrotelm and this study finds that the optimum topographic condition for this is having slope gradients below 0.6%. Water losses can be compensated with greater proportions of lateral flow, demonstrated at Abbeyleix, but it is difficult to engineer this situation in management. To maximise regeneration potential, restoration works must restore the surface water slopes (the hydraulic gradient) that ensure maximum water table depths of 0.2m beneath the ground surface. At Clara, deeper groundwater (the piezometric head) is also an important condition that controls near-surface ecohydrological processes. The drainage of this groundwater, on account of the site's particular hydrogeology, has increased seepage rates through the bog. In this scenario, management necessitates a regional approach to bog ecohydrological management. This was further informed by a groundwater modelling exercise that demonstrated that a three-dimensional approach to restoration is required in areas with complicated hydrogeological regimes such as Clara. To assess the restoration potential of degraded raised bog systems, and the level of management required to address the degradation, a simplified set of guidelines is provided as a summary in this report.

1 Introduction

1.1 Background

Ireland's peatlands, occurring as raised bogs, blanket bogs or fens, host specialised plant and animal communities, which contribute to global biodiversity and carbon regulation. However, exploitation has reduced the habitat distribution and damaged the ecohydrological functioning of remaining areas. In the past 100 years, wetland cover has reduced by up to half globally and by up to two-thirds in Western Europe (Owen, 2007). As a result, peatlands are now among Europe's most threatened ecosystems and the conservation and restoration of remaining areas is an international concern. A peatland system of particular importance is "active", or peat-forming, raised bogs. These habitats have disappeared almost entirely in temperate climates as a result of land reclamation for agriculture and forestry, fuel production and urbanisation. Despite these losses, Ireland contains one of the highest concentrations of wetlands in Europe and approximately 60% of the remaining raised bog habitat area in the European Union (EU). However, mechanised commercial peat extraction, combined with marginal turf cutting, has resulted in the loss of > 80% of the original raised bog area. As a result, despite peatland covering over 20% of the Irish landscape, only 9% of the original raised bog area is considered to be suitable for conservation and less than 1% of this area is actively forming peat (NPWS, 2017).

1.2 Protection and Legislation

In Europe, the protection of biodiversity is primarily afforded by the EU Birds Directive (Council Directive 79/409/EEC) and Habitats Directive (Council Directive 92/43/EEC). These two designations are collectively known as the Natura 2000 network. The overall aim of the Habitats Directive is to maintain or restore the favourable conservation status of habitats and species of community interest. Between 1997 and 2002, Ireland nominated 53 raised bog sites as Special Areas of Conservation (SACs) and a further 75 raised bog sites as Natural Heritage Areas (NHAs) under the Wildlife (Amendment) Act 2000. In Ireland, the Natura 2000 network contains most of the national

resource of the two relevant habitat types listed in the Habitats Directive: (1) active raised bog (ARB) and (2) degraded raised bog still capable of natural regeneration (DRB). Additional protection is afforded by the Water Framework Directive (Council Directive 2000/60/EC), which integrates Natura 2000 sites that are considered to be groundwater-dependent terrestrial ecosystems. The groundwater body that supports the wetland is classed as being at either good or bad status depending on the condition of the ecosystem, thereby protecting both the water and wetland systems.

European and national legislation therefore places a collective obligation on Ireland and its citizens to maintain habitats and species in the Natura 2000 network at favourable conservation condition. The government and its agencies are responsible for the implementation and enforcement of regulations that will ensure the ecological integrity of these sites. However, despite designation, a number of SAC and NHA sites have deteriorated in the past few years, with almost 40% of mapped ARB lost between 1990 and 2013 (NPWS, 2017). This has also led to infringement action being brought against Ireland by the European Commission in 2011 on account of failures to comply with Article 6(2), (3) and (4) of the Habitats Directive (NPWS, 2017). Thus, there is an imperative legal basis for the conservation of raised bog habitats within EU Member States, while requiring any losses to be reduced through restoration programmes. An understanding of the processes that give rise to changes in hydrological supporting conditions that degrade bog ecosystems forms the cornerstone of effective conservation and restoration measures.

1.3 Ecosystem Services

Peatland covers just 3% of the global land surface; however, peatlands are the earth's largest natural terrestrial carbon store, exceeding the total volume of carbon stored in vegetation (Page and Baird, 2016), and they annually sequester 0.37 gigatonnes of carbon dioxide (CO₂) a year (Yu *et al.*, 2010). Carbon storage and sequestration are therefore globally significant ecosystem services provided by peatlands and they

are now considered highly significant in global efforts to combat climate change (IPCC, 2013). However, the unsustainable management of peatland ecosystems significantly alters their ecohydrological characteristics. At present, human activity is either draining or mining ~10% of global peatlands, transforming them from long-term carbon sinks into sources as a result of alterations in hydrology converting stored carbon to CO₂ and an increased export of dissolved compounds in runoff (Joosten, 2009; Leifeld and Menichetti, 2018). Carbon capture projects are essential for reducing emissions, and restoration of degraded peatlands can contribute to this sector. Considering the urgency to arrest the current rise in global air temperatures, the Intergovernmental Panel on Climate Change (IPCC) urges that all emission reduction options are used, including those of peatland conservation and restoration. This necessitates hydrological management of degraded systems to maintain and/or restore the peat-accumulating plant communities that give rise to the peatland carbon sink function, in addition to other valuable peatland ecosystem services, such as water regulation and halting biodiversity loss.

1.4 Aims and Objectives

The protection and restoration of peatlands is vital in the transition towards a low-carbon economy and will contribute to savings in greenhouse gas (GHG) emissions. However, effective management of damaged and degraded peatlands requires a quantification of the ecohydrological processes that create and maintain ARB and carbon sink conditions. To quantify these ecohydrological conditions and fluxes in CO₂ and methane (CH₄), two raised bogs in the midlands of Ireland were chosen for study and

experimental analysis. These sites cover a range of ecological and management conditions typically encountered in Irish lowland peatland sites and they are thereby considered representative of the peatland status in Ireland and other peatlands found in temperate climates.

Thus, the aims of this project were to:

1. quantify the ecohydrological conditions and GHG emissions from two contrasting raised bogs;
2. assess the impact of drainage and restoration on GHG emissions;
3. assess the implications for management and the re-establishment of degraded peatlands to carbon sink ecosystems; and
4. provide guidelines for the restoration of other degraded raised bogs.

To address these aims, each site was equipped with an ecohydrological and climate measuring network, with the following objectives:

1. measure hydrological conditions and GHG fluxes at vegetation classes/ecotopes plot sites covering a range of habitat conditions;
2. evaluate the spatial variability of GHG fluxes related to ecotopes and drainage;
3. measure dissolved organic carbon (DOC) and CO₂ evasion at main runoff outlets;
4. compute water and carbon balances for each site; and
5. hydrologically model the impact of arterial drainage on bog hydrology.

2 Site Selection, Instrumentation and Monitoring

2.1 Study Areas

The raised bogs chosen for study were Clara Bog SAC and Abbeyleix Bog in the Irish midlands (Figure 2.1). Both sites retain considerable areas of uncut peatland, with >400 ha and >100 ha at Clara Bog and Abbeyleix Bog, respectively. Clara is a bog complex that is divided into two separate units, with the majority of the ARB area found on the uncut western side, while the eastern side has a dense network of blocked surface drains and a much reduced expanse of ARB. A >200-year-old road separates the two units and peat extraction occurred at the southern boundary of both bog units until a ban was introduced in 2010 (NPWS, 2017). While Clara contains one of Ireland's largest expanses of ARB, it has decreased considerably in

the past few years, despite the absence of surface peat drainage. However, a dense marginal drainage network was developed on the southern side of Clara West, concurrent with previous turf-cutting activities.

At Abbeyleix, the uncut bog had been extensively drained (in anticipation of commercial peat extraction) and it has a dense network of surface peat drains, similar to Clara East. Restoration of the site, via drain blocking, occurred in 2009, while the cutover bog surrounding the uncut bog has been left abandoned since the 1960s. Localised regeneration of ARB has occurred on the uncut bog and limited areas of ARB have developed naturally on the cutover bog, with no management measures. Accordingly, study sites were set up to investigate hydrological and GHG processes

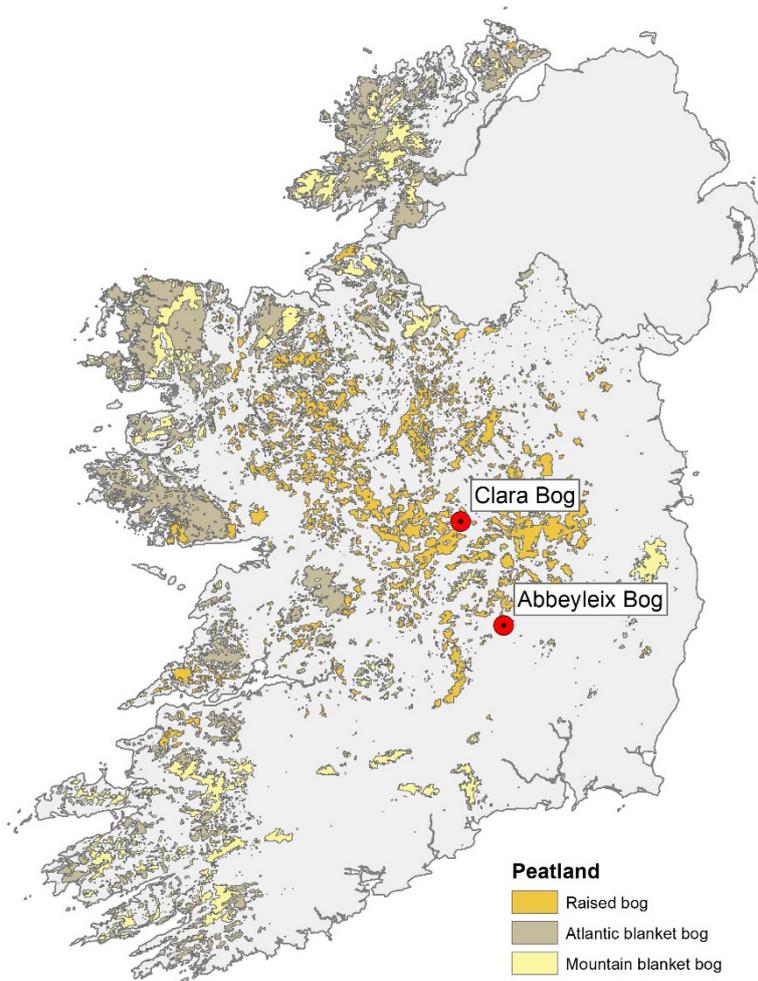


Figure 2.1. Peatland distribution map of Ireland (after Connolly and Holden, 2009) and location of Clara Bog and Abbeyleix Bog.

across ecological gradients at both bogs, enabling an analysis of the effect of (1) management practice and (2) hydrological and hydrogeological regimes on ARB distribution and associated GHG emissions.

2.2 Site Selection

The vegetation of ombrotrophic peatlands is dominated by bryophytes from the genus *Sphagnum* (Robroek *et al.*, 2009). While there is considerable variation in the distribution and diversity of *Sphagnum* spp. on raised bogs, the vegetation succession can be grouped into an “ecotope” classification and mapping scheme. Ecotopes are vegetation communities with similar characteristic water table depths, fluctuations and hydrochemistry (Van der Schaff and Streefkerk, 2002). They thereby classify the ecological quality of habitat areas and represent a hydro-sequence from dry to permanently saturated zones. This has great value as a monitoring tool, as areas of ARB can be delineated and temporal mapping allows the natural or anthropogenic changes in the location and quality of vegetation/habitats to be measured. This is beneficial to practical site management and for impact assessment purposes. The mapping scheme has been adopted as the main monitoring tool for Irish raised

bogs (NPWS, 2017) and a time series of ecotope maps is now available for most Natura 2000 raised bogs, including Clara and Abbeyleix Bogs.

A number of ecotopes have been classified for raised bogs and a full description is available in Schouten (2002); this is summarised in Table 2.1. However, four primary ecotope types, namely marginal, sub-marginal, sub-central and central, are the most common and widely distributed. Central and sub-central are considered to be ARBs and sub-marginal can constitute DRBs; on the other hand, marginal is damaged and is considered incapable of regenerating to ARB or DRB. The differentiation is broadly based on the percentage of *Sphagnum* spp. cover and the presence of micro-topography, such as hummock, hollow and pool structures, which are created by the mosses themselves (Rydin, 1993).

Sites for GHG measurement were selected based on ecotope maps (Figure 2.2) and reconnaissance surveys with ecologists from the National Parks and Wildlife Service (NPWS). At Clara, the four primary ecotopes are represented and were selected for study; an additional area on bare peat (i.e. no vegetation cover/exposed peat surface) in cutover bog was also selected. The central ecotope is absent at Abbeyleix

Table 2.1. Biotic and abiotic characteristics of ecotopes (after Schouten, 2002)

Ecotope	Abiotic characteristics	Biotic characteristics
Facebank	No hummocks and hollows Acrotelm usually absent	Few or no peat-forming plant communities Vegetation dominated by <i>Calluna vulgaris</i>
Marginal	No hummocks and hollows Acrotelm usually absent or poorly developed (<0.05 m)	Few or no peat-forming plant communities Vegetation dominated by <i>Calluna vulgaris</i> and <i>Trichophorum cespitosum</i>
Sub-marginal	Some differentiation between hummocks and hollows Hollows inundated during small fraction of the year Acrotelm absent or thin (<0.05 m)	Hollows dominated by <i>Narthecium ossifragum</i> and <i>Sphagnum tenellum</i>
Sub-central	A micro-topography of hummocks, hollows and lawns, but no pools Lawns are dominant Acrotelm depth variable from 0.10 m to locally well-developed 0.40 m	Lawns dominated by <i>Sphagnum magellanicum</i>
Central	A micro-topography of hummocks, hollows and pools Acrotelm moderately to well developed Depth of up to 0.5 m	Pools, and hollows dominated by <i>Sphagnum cuspidatum</i>
Active flush/soak	Wet to extremely wet conditions In the wettest parts, lawns; in some parts pools and hollows and large, flat hummocks Acrotelm well developed > 0.4 m	<i>Sphagnum cuspidatum</i> and <i>Sphagnum recurvum</i> lawns with <i>Carex rostrata</i> <i>Myrica gale</i> and <i>Betula pubescens</i> scrub/woodland with <i>Sphagnum palustre</i> in drier places <i>Molinia caerulea</i> tussocks in some areas

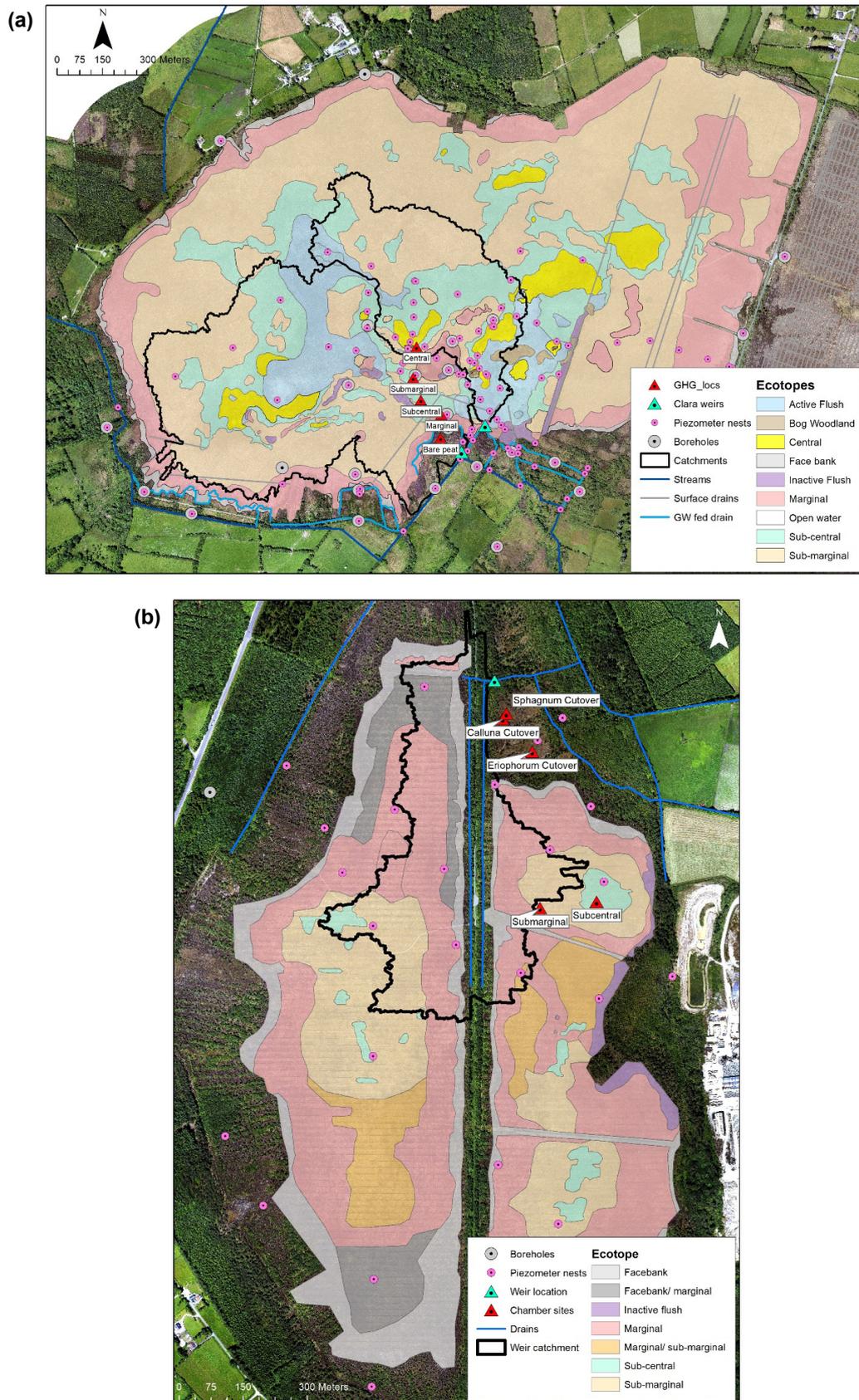


Figure 2.2. (a) Clara Bog and (b) Abbeyleix Bog ecotopes, with locations of GHG and hydrological monitoring locations. Note: ecotope mapping for Abbeyleix Bog conducted by Bord na Mona in 2014 and for Clara Bog by The Living Bog in 2017, and permission was granted to the project team for use in this project.

and so sub-marginal and sub-central areas were chosen; another three locations on cutover bog were chosen as well based on differences in the plant ecology. There is currently no ecotope classification developed for cutover bog, and the three sites were classified as (1) *Sphagnum* cutover, which contains plant species similar to those of a sub-central ecotope; (2) *Calluna* cutover, which contains a low diversity of plant species characteristic of a well-drained peat soil (mainly *Calluna vulgaris*); and (3) *Eriophorum* cutover, which contains a moderate cover of *Sphagnum* spp. (<50%).

2.3 Field and Airborne LiDAR Topographic Survey

Airborne light detection and ranging (LiDAR) surveys of both bogs were available for study and were processed to 1 m resolution digital terrain models (DTMs). Surveys of Clara Bog were carried out in December 2008, February 2012 and June 2017 and of Abbeyleix Bog in July 2014 and June 2017. At Clara, the 2008 and 2017 surveys were calibrated using field-measured Trimble R6 Differential Global Positioning System (DGPS) data from reflective 1.2 × 1.2 m marker boards in 10 contrasting areas across the peatland surface. The root mean square error of the DGPS and LiDAR surveys were determined to be ±0.014 m and ±0.02 m, respectively, giving a combined accuracy of 0.034 m. Prior to LiDAR technology, ground elevation

surveys were carried out at Clara on a 100 m grid by the Office of Public Works in 1991 and 2002.

2.4 Greenhouse Gas Measurement

The closed static chamber method of GHG flux measurement was deployed in this study, following methods outlined in Wilson *et al.* (2016). The chambers (60 × 60 × 30 cm equipped with a fan) were constructed with transparent polycarbonate and opaque polystyrene for CO₂ and CH₄ measurements, respectively. To account for spatial heterogeneity at each site location, six 600 × 600 mm stainless steel collar plots were systematically positioned and inserted into shallow peat to a depth of 130 mm, providing a representative sample of the microforms and vegetation communities; three and five collars were inserted at the bare peat site (Clara) and *Calluna* cutover site (Abbeyleix), respectively. At each site location, boardwalks were placed to permit easy collar access and prevent ebullition due to trampling. In wet areas (central, sub-central) the platforms were raised above the ground surface and supported by scaffold pylons that were installed onto underlying mineral subsoil (till) (Figure 2.3).

Ecosystem respiration (R_{eco}) and net ecosystem exchange (NEE) were measured with transparent chambers over a range of different light levels. When light transmitted into the chamber was zero, the CO₂ flux was assumed to be equal to R_{eco} . Chambers were



Figure 2.3. Study area at Clara central ecotope.

vented for equilibration and cooled with icepacks, which maintained the chamber temperature within 1°C. CO₂ measurements were carried out every 2–4 weeks during the growing season (March–September) and reduced during the winter season (October–February). CO₂ concentration was recorded in the field every 15 seconds for a period of 105 seconds using an EGM-4 infra-red gas analyser (PP Systems). CO₂ flux was calculated from the slope of the linear increase in CO₂ flux over time. CO₂ flux measurements were carried out between July 2015 and July 2017 (71 field days) and between January 2016 and August 2017 (63 field days) at Clara and Abbeyleix, respectively.

CH₄ measurements were conducted monthly using opaque chambers. The chambers were closed for 35 minutes and samples were collected in headspace vials after 5, 15, 15 and 35 minutes. Gas samples from Clara were analysed by Teagasc using a Bruker Scion 456 gas chromatograph (GC) instrument. Gas samples from Abbeyleix were analysed in the Trinity College Dublin (TCD) laboratory using an Agilent GC coupled with a flame ionisation detector. At Clara, samples were collected over 20 field days between July 2015 and August 2018; at Abbeyleix, samples were collected over 17 field days between April 2017 and January 2018.

2.5 Meteorological Monitoring

Campbell Scientific weather stations were placed on the uncut bog at Abbeyleix and Clara. Hourly measurements of air temperature and humidity (CS215 probe), rainfall (ARG100 tipping bucket rain gauge), barometric pressure (PTB110 Barometer, Oyj) and soil temperature at 5 and 10 cm (PT100 temperature probe) were recorded using a CR1000 data logger. Photosynthetically active radiation was measured hourly using an LPO2 pyranometer (Hukseflux Thermal Sensors) and corrected for photosynthetically active radiation measured during the transparent chamber experiments.

2.6 Hydrometric Network

Hydrometric monitoring networks were set up at both bogs. At each site location, a 6-inch-diameter polyvinyl chloride (PVC) stilling well was inserted 2 m into the peat substrate, with the tube sealed at its base and screened in the shallow peat/vegetation layer. The

absolute levels of the stilling wells were assumed to be constant because the greatest strain in bog surface fluctuations occurred in the top 50 cm (Price, 2003). Continuous hourly water table measurements were recorded using OTT Orpheus Mini vented-pressure level transducers (with an estimated accuracy of 1 mm). Soil temperature loggers (LogBoxAA data loggers, Novus) were installed at each site, with sensors placed 50 and 100 mm from the ground surface.

At Abbeyleix, 28 piezometer nests, at the base and mid-section of the peat profile, were installed across the bog complex. Six monitoring boreholes were installed by the Geological Survey of Ireland in till substrate deposits surrounding the bog area. Previous studies at Clara West (Van der Schaaf, 1999; Van der Schaaf and Streefkerk, 2002; Regan, 2013) installed a comprehensive network of piezometer nests (64) across the bog and 11 monitoring boreholes in the till and bedrock units surrounding the bog complex. At Clara, continuous hourly water level measurements were recorded at three deep peat piezometers in the site location areas (central, sub-marginal, marginal), in a drain bordering the uncut bog and at two borehole locations, inside and outside the bog, using Schlumberger Diver loggers (with an estimated accuracy of ±0.5 cm and 0.2 cm resolution). At Abbeyleix, 11 divers were deployed to measure the piezometric head in eight deep peat piezometers, including the five site locations, and three till piezometers.

Thin V-notch weirs were used to measure bog surface runoff at both Clara and Abbeyleix. A flume at a marginal drain at Clara, which receives base flow/mineral groundwater, was maintained and monitored from a previous study (Regan, 2013). At all locations, an OTT ecoLog 500 vented-pressure level transducer (with an estimated accuracy of 1 mm) was used to record stage time series at 1-hour intervals.

To quantify hydrological properties of the vegetative layer and near-surface peat, microcosm experiments were carried out at Abbeyleix at sub-central, sub-marginal, *Eriophorum* cutover and *Sphagnum* cutover sites. The microcosms were 0.5 m² in area and consisted of 1-mm-thick aluminium sheets inserted ~0.8 m into the underlying peat. Phreatic tubes and shallow piezometers to the base of the microcosm were installed inside and outside the installations. This

was in order to quantify the storage properties of the plot areas and the water input from shallow lateral flow.

2.7 Dissolved Organic Carbon

The DOC of runoff was measured at the weir and flume at Clara between October 2016 and November 2017 and at the Abbeyleix weir during 2016 (weekly) and between January and November 2017 (12-hour intervals). Sigma autosamplers were deployed to collect hourly water samples at Clara within selected time intervals and DOC was analysed using an Elementar vario TOC select in the TCD School of the Environment. The DOC concentration of Abbeyleix samples was determined by developing an ultraviolet (UV) absorbance calibration curve using the TOC select analyser. All DOC samples were filtered in the field using an 0.45 µm cellulose syringe filter after rinsing the syringe and filter with 20 mL of the sample. Samples were then acidified to pH 2 using

10% hydrochloric acid (HCl) to preserve them and stored under refrigeration at 4°C and analysed within 2 months.

2.8 CO₂ Evasion and Dissolved Inorganic Carbon

Instantaneous CO₂ evasion, from running and standing water, and dissolved inorganic carbon (DIC) measurements were carried out at the two main runoff outlets at Clara as well as at the weir measuring bog runoff, one stream gauging site and two blocked surface drains at Abbeyleix. CO₂ evasion was measured using a CPY-4 transparent chamber (PP Systems) fitted to a small floating raft (floating chamber) and an EGM-4 gas analyser. The DIC was calculated using a headspace method (Gelbrecht *et al.*, 1998), which measures the change in partial pressure of CO₂ from *in situ* water samples using the EGM-4 gas analyser.

3 Ecohydrology

3.1 Introduction

The ecohydrology of raised bog systems is conceptualised as two main “storages” with differing responses to rainfall inputs (Johnston *et al.*, 2015). The bulk of the bog peat tends to be a low-permeability medium (catotelm), which rests on or in a regional groundwater body that may have a variable hydraulic connection with the wetland above. In contrast, the near surface (<50 cm) consists of a layer of growing vegetation (acrotelm), dominated by *Sphagnum* spp. mosses, and is considered an “active” layer with storage properties that respond much differently to rainfall than the peat beneath.

The stability of the acrotelm is dependent on the dynamics of the water table relative to the ground level. Persistently high water tables are maintained when there is (1) a shallow topographic gradient limiting discharge velocities and favouring increased recharge, (2) a sufficient build-up of poorly humified organic materials to provide storativity in the upper peat and (3) minimal downwards infiltration/seepage and fluid flow at depth (Regan *et al.*, 2019). Runoff and water storage processes occur primarily in the acrotelm, as the porous structure of the *Sphagnum* provides a permeable layer for water transmission.

The much more heavily damped response of the deeper groundwater has received much less attention, but it has far less resilience; hence, damage resulting from disturbance to the regional groundwater can have far greater consequences (i.e. subsidence in the peat) than impacts on the near surface resulting from, for example, local drainage (Johnston *et al.*, 2015). Water flow and storage processes in peatlands are strongly controlled by the hydrogeological properties of peat (Price, 2003) and particularly the hydraulic conductivity (*K*) profile, which controls the rate of subsurface drainage (Beckwith *et al.*, 2003). While permanently saturated, an intact catotelm does not readily transmit water and acts as a barrier to vertical and lateral flow.

Accordingly, the ecohydrological research in this study sought to (1) examine the association between ecotope type and topographic gradient; (2) determine water table thresholds for ARB; (3) determine the role

that regional hydrogeology plays in supporting water table dynamics; and (4) quantify the bog water balance and changes that occur as a result of drainage.

3.2 Ecotope Distribution

Surface slope is a key factor in sustaining a high water table within a functioning acrotelm. Previous work at Clara and Raheenmore Bogs found that shallow topographic gradients in the order of 0.3% are optimal to maintain an active acrotelm layer (Van der Schaaf and Streefkerk, 2002). To investigate this threshold further, 1 m DTMs and ecotope surveys, conducted between 2010 and 2017, of the 53 raised bog SACs were made available for analysis by the NPWS. Polygon ecotope shapefile data were extracted to a 1 m point grid. Surface slope was calculated at a 1 m resolution from the LiDAR DTM raster using ArcGIS ArcMap v.10.3. The 1 m DTM was then smoothed at 2, 5, 10, 15, 20, 30 and 50 m resolutions to reduce noise due to the random height differences between adjacent cells. Mean gradient reduces with increased smoothing resolution between 1 and 10 m, but remains relatively constant at resolutions > 10 m; a grid smoothing resolution of 10 m was therefore applied to all bogs and extracted to the ecotope point vector data (<4 million points).

A relative probability distribution of central, sub-central, sub-marginal and marginal ecotopes is shown in Figure 3.1. The distribution of the topographic slope is not normally distributed for all ecotopes, with median slopes skewed to lower gradient areas. The median slope for central, sub-central, sub-marginal and marginal ecotopes is shown in Table 3.1. The distribution of central and sub-central slopes is very similar, with median sub-central slopes only marginally higher than median central slopes (<10%). The median sub-marginal slope is 0.71%, which is >100% higher than the median sub-central slope and ~20% higher than the 75% sub-central slope confidence interval. The results indicate that at slopes >0.6%, ARB transitions to DRB. The upper sub-marginal slope confidence interval (75%) indicates that at slopes >~1.2%, DRB is generally no longer supported and bog vegetation becomes damaged (i.e. marginal

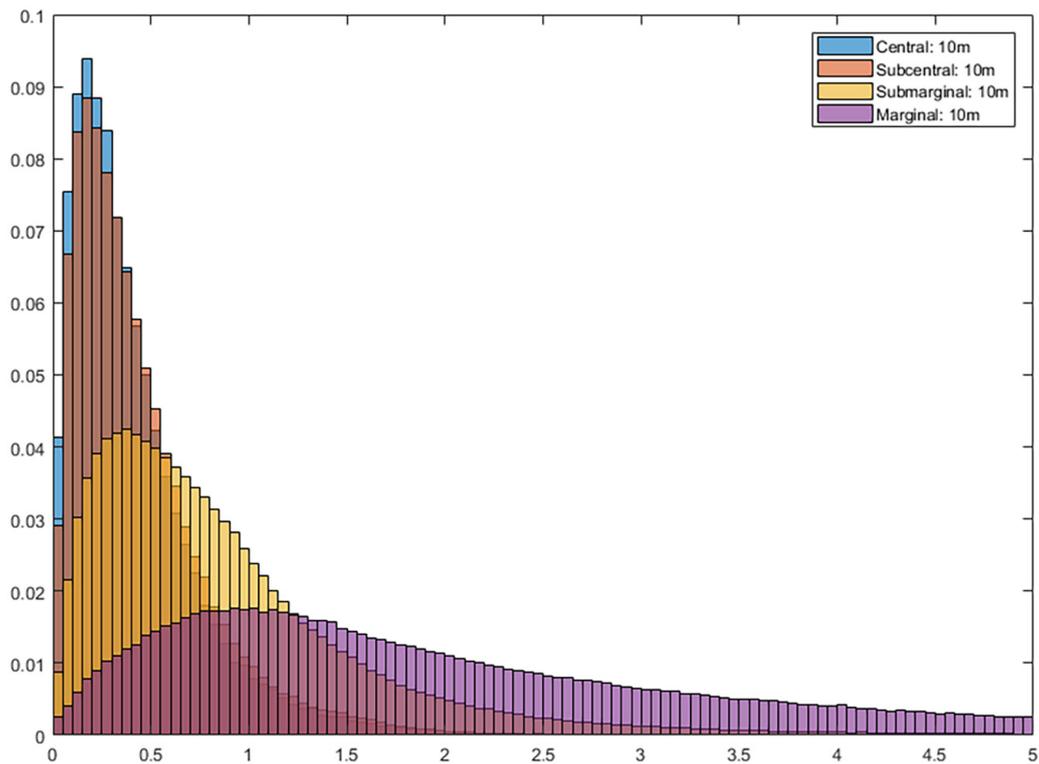


Figure 3.1. Relative probability plot of ecotope and slope distribution.

Table 3.1. Median slope and interquartile range (IQR) for 53 SAC raised bogs

Ecotope	Median (%)	IQR (25%)	IQR (75%)
Central	0.320	0.174	0.540
Sub-central	0.348	0.190	0.587
Sub-marginal	0.708	0.387	1.168
Marginal	1.803	0.988	3.270

ecotope/dry conditions). Where marginal ecotope occurs on slopes suitable for ARB, it indicates that water is drained via a hydrological pathway that is not a topographic flow.

3.3 Water Table Dynamic

A notional threshold for the sustainability of *Sphagnum* spp. is generally considered to be a mean water level within 10–15 cm of the surface. The low threshold is a consequence of water loss occurring primarily via evapotranspiration and being replaced directly by precipitation or capillary transport from the free water table (Robroek *et al.*, 2009). However, it should be noted that “ground level” on a bog, particularly in *Sphagnum*-dominated areas, is itself notional, as the surface of a peatland can rise and fall, sometimes dramatically, in response to rainfall or mild drought,

while maintaining a fairly constant water level relative to the surface (Dise, 2009). This oscillation of the peat surface, which can be as high as 30 cm (Howie and Hebda, 2018), is related to changes in storage and gas volume (Price, 2003) and is an important mechanism for hydrological self-regulation in bogs. Measurements at Abbeyleix found that this fluctuation is in the order of 3 and 4 cm for sub-marginal and sub-central areas, respectively; at Clara, similar observations were made, except for central areas, where oscillation was as high as 10 cm. The results from this study are referenced to summer (lowered) ground levels.

A summary of water table characteristics from > 2 years of monitoring is shown in Table 3.2 for each of the ecotopes and cutover bog plot sites. At Clara, the median water table was 0.002, 0.012, 0.037 and 0.163 m below ground level for the central, sub-central, sub-marginal and marginal ecotopes, respectively; at

Table 3.2. Summary of water table characteristics for ecotope and cutover bog plot sites

	Water table depth (MBGL)			Quartile		Slope (%)	Catchment (m ²)
	Median	Min	Max	IQR (25%)	IQR (75%)		
Central	0.002	0.105	-0.114	0.029	-0.029	0.11	1431
Sub-central	0.012	0.138	-0.147	0.033	-0.005	0.92	25,000
Sub-marginal	0.037	0.180	-0.014	0.067	0.018	1.79	2000
Marginal	0.163	0.349	0.025	0.221	0.109	5.50	10
Bare peat	0.535	0.730	-0.086	0.614	0.372	1.50	775
*Sub-central	0.038	0.166	-0.032	0.059	0.024	0.18	150
*Sub-marginal	0.033	0.172	-0.026	0.062	0.018	0.60	5
* <i>Sphagnum</i> cutover	0.146	0.314	0.066	0.176	0.121	0.18	400
* <i>Eriophorum</i> cutover	0.007	0.219	-0.023	0.036	-0.003	0.67	75
* <i>Calluna</i> cutover	0.219	0.446	0.121	0.256	0.192	0.84	1

Note: *Abbeyleix sites; negative number is water level above ground level.

IQR, interquartile range; MBGL, metres below ground level.

Abbeyleix these values were 0.038 and 0.033 m below ground level for the sub-central and sub-marginal ecotopes, respectively. *Calluna* cutover at Abbeyleix records a median deep water table (> 0.15 m), whereas *Eriophorum* and *Sphagnum* cutover record median water tables of 0.007 and 0.146 m, respectively. The relatively deep water table at *Sphagnum* cutover is the result of the *Sphagnum* cover being dominated by hummock species, which have deeper water tables than lawn and pool species, such as *Sphagnum cuspidatum*.

While fixed thresholds give an indication of the resilience of a receptor species, in this case *Sphagnum*, to water table drawdown, the hydrological regime is much more complex. The significance in violating fixed thresholds, such as a 0.1 m water table depth, must incorporate an element of time/duration of exceedance. Accordingly, water table duration curves for ecotope water table time series are shown in Figure 3.2. At the Clara central site, a 0.1 m water table depth is exceeded 99% of the recorded time series, and at the Clara sub-marginal and sub-central sites it is exceeded between 88% and 98% of the time. The large catchment area at the Clara sub-central site maintains a high water table despite a steep slope. Water tables at (summer) ground level are exceeded 50% of the time series at central, 32% at Clara sub-central and between 3% and 4% at Clara sub-marginal and Abbeyleix sub-central, respectively. The shallow slope at the Abbeyleix sub-central site differentiates it from the sub-marginal sites; furthermore, duration curves for the Abbeyleix sub-central and sub-marginal

sites diverge at water table depths of ~0.06 m and are reflected in the interquartile range (IQR) (0.035 and 0.044, respectively). The Clara sub-marginal site also has an IQR of 0.049 and its duration curve diverges from Abbeyleix sub-central at ~0.04 m. These results indicate that there is a subtle hydrological transition from sub-central to sub-marginal ecological conditions, and it appears to be related to duration exceedance levels at ~0.04–0.06 m below the summer ground level surface.

At the cutover bog sites, the *Eriophorum* cutover duration is similar to that for Clara sub-central; however, ARB has not developed. The *Sphagnum* cutover is representative of a hummock complex and, in a lawn/pool area where topographic elevation differences are in the order of 0.1 m, the duration curve would probably resemble a sub-central ecotope. While the slope at the *Eriophorum* cutover is high (0.67%) and low at the *Sphagnum* cutover (0.18%), the presence of old drainage channels in the *Sphagnum* cutover site may have stimulated *Sphagnum* regeneration through infilling and secondary rewetting, while the absence of a vegetative layer (i.e. acrotelm) at the *Eriophorum* cutover may limit ARB regeneration.

3.4 Acrotelm Hydraulic Properties

The Abbeyleix microcosm experiments were used to quantify storage properties of the acrotelm and shallow peat layer in degraded areas. Storativity is calculated from measured increases in the water table in response to rainfall event(s) using methods outlined

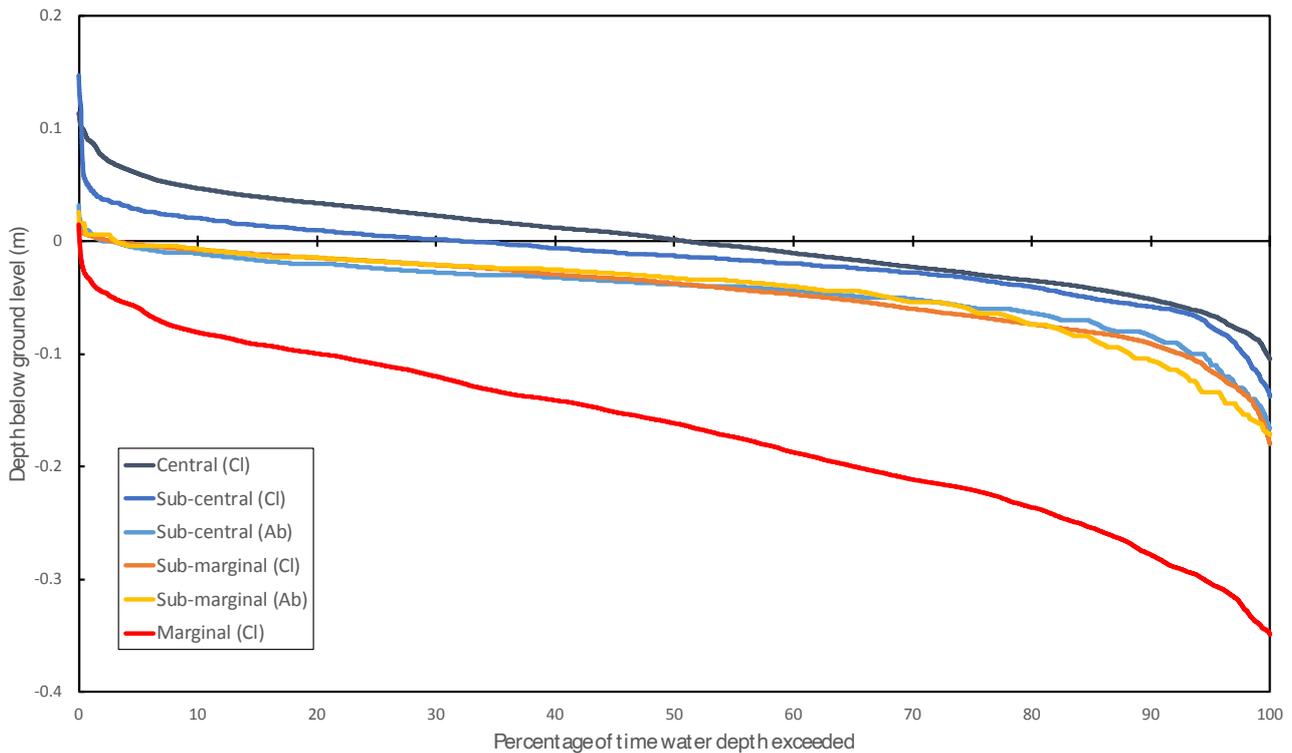


Figure 3.2. Water table duration curves for ecotopes at Clara and Abbeyleix (2015–2017).

in Fetter (2001), and, in this study, discrete rainfall events (>3-hour intervals) and depths (>1 mm) were used. Lateral inflows and outflows were assumed negligible, as water table measurements were shielded by the microcosm; evapotranspiration was also assumed to be negligible during a rain event. Storativity values reported in the literature find ranges of 0.23–0.34 (unitless) for young undecomposed *Sphagnum*, 0.11–0.17 for slightly humified peat, 0.11–0.13 for moderately humified peat and 0.02–0.1 for strongly humified peat (Price *et al.*, 2003; Menberu *et al.*, 2016). At Abbeyleix, storativity values below the ground surface were found to range between 0.24 and 0.35 for sub-central and *Sphagnum* cutover and between 0.1 and 0.13 for sub-marginal and *Eriophorum* cutover (Figure 3.3), similar to values in Price *et al.* (2003) and Menberu *et al.* (2016).

In addition to this, the microcosm experiments enabled an assessment of the importance of lateral flow to maintaining and restoring ARB conditions, by comparing the changes in storage inside and outside the microcosms. During dry periods, particularly in the spring/early summer, the water table dropped more rapidly inside than outside the microcosms for the locations with acrotelm present (sub-central and *Sphagnum* cutover), which was not observed in

locations lacking an acrotelm. This indicates that the higher storage and transmissivity of acrotelm improves drought resilience. Further, a rapid decrease in storage (<24 hours) following rain events was recorded at the *Eriophorum* cutover, indicating sheet/overland flow conditions, and this explains the significant difference between apparent storativity inside and outside the microcosm ($p=0.051$) at levels of 1 cm below ground level and above. At degraded locations where acrotelm is lacking, there is the potential for more rapid losses of water during storm events because overland flow is the predominant flow path compared with the shallow sub-surface flow in ARB.

3.5 Peat Hydraulic Conductivity

Field-based rising head piezometer tests (or slug tests) were used to determine horizontal hydraulic conductivity (K), or permeability, using Hvorslev's (1951) method at Clara and Abbeyleix. Measurements were conducted in piezometers installed to the base of peat (mean depth of 7.7 and 8.5 m at Clara and Abbeyleix, respectively), at the mid-section of the peat column profile (mean depth of 4.5 and 4.0 m at Clara and Abbeyleix, respectively) and in inorganic deposits (till) surrounding and underlying (Clara) the bog complexes. Slug tests in peat piezometers were

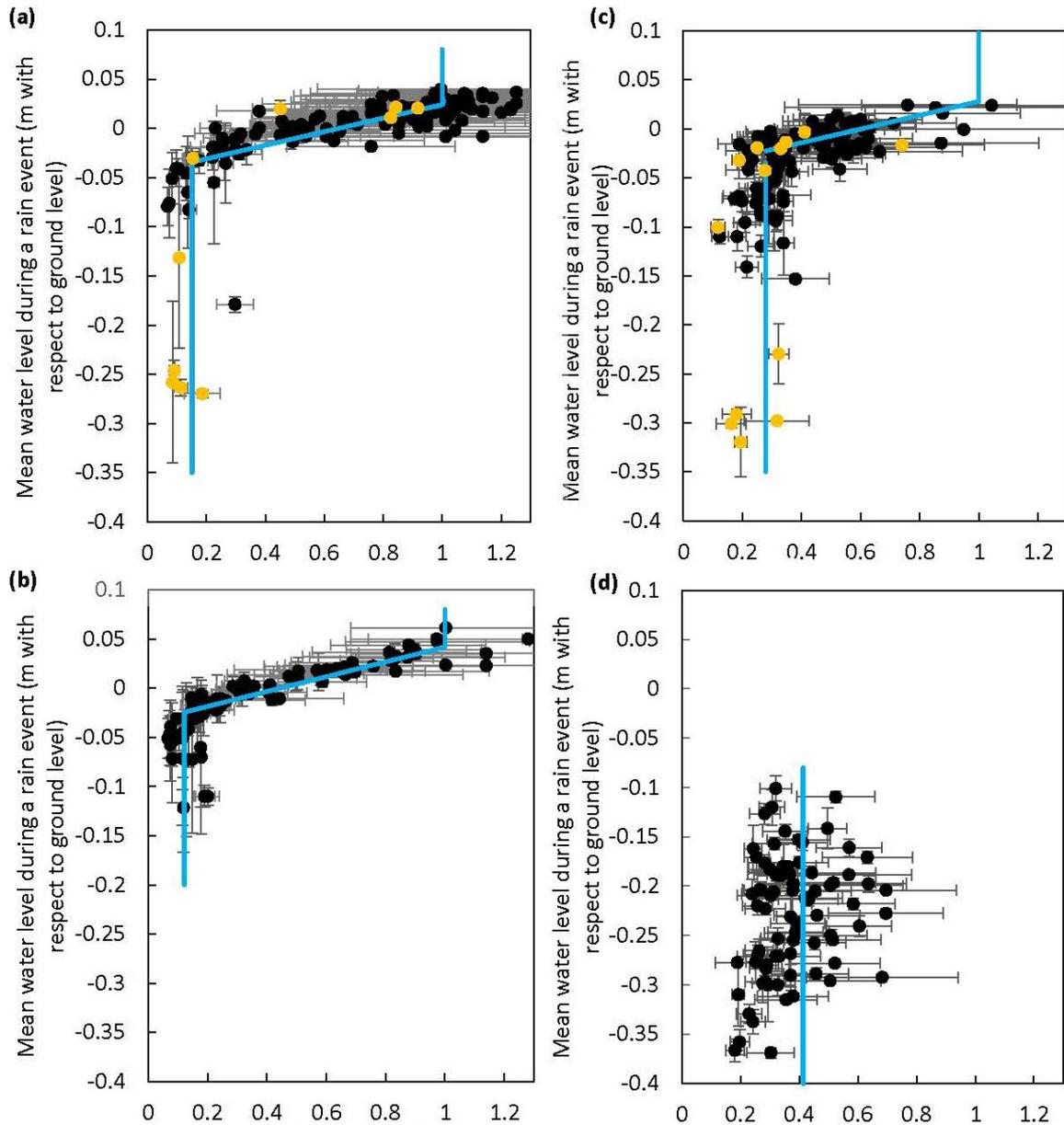


Figure 3.3. Storativity curves for (a) *Eriophorum* cutover, (b) sub-marginal, (c) sub-central and (d) *Sphagnum* cutover. The blue lines are the idealised storativity curves. The horizontal error bars are the error in the storativity based on the measurement limitations of the water table and rainfall. The vertical error bars represent the total change in the water table across a storm event.

controlled in order to contain water level decreases within 10 cm of the static water level. Log-linear rates of water level recovery were observed in the majority of tests, indicating steady-state conditions and minimal alterations of effective stresses following water extraction.

Results of the K tests are presented in Table 3.3. Median K is an order of magnitude higher for both deep-peat and mid-peat at Clara compared with Abbeyleix. While the IQR for mid-peat is similar at both sites (10^{-3} – 10^{-2} m day $^{-1}$), there is a much stronger

spatial and geometric variation in deep-peat K at Clara than at Abbeyleix (Figure 3.4) and this is reflected in the IQR for Clara spanning two orders of magnitude (10^{-4} – 10^{-2} m day $^{-1}$) compared with one order of magnitude (10^{-4} – 10^{-3} m day $^{-1}$) at Abbeyleix. The variation in deep-peat K is wider when the full data sets are considered, with a six orders of magnitude range (10^{-6} – 10^{-1} m day $^{-1}$) at Clara compared with three orders of magnitude (10^{-6} – 10^{-3} m day $^{-1}$) at Abbeyleix. However, fewer measurements were made at Abbeyleix (12) compared with Clara (36).

Table 3.3. Summary of hydraulic conductivity tests in peat and till deposits

	<i>n</i>	Median	Min	Max	IQR (25%)	IQR (75%)
Clara <i>K</i> (m day⁻¹)						
Mid-peat	23	1.15×10^{-2}	1.00×10^{-5}	6.73×10^{-1}	1.94×10^{-3}	9.61×10^{-2}
Basal peat	36	2.22×10^{-3}	6.31×10^{-6}	2.12×10^{-1}	7.99×10^{-4}	1.05×10^{-2}
Till	16	1.02	2.24×10^{-5}	16.5	4.77×10^{-3}	4.36
Abbeyleix <i>K</i> (m day⁻¹)						
Mid-peat	10	5.03×10^{-3}	5.99×10^{-4}	3.59×10^{-2}	1.39×10^{-3}	1.17×10^{-2}
Basal peat	12	9.22×10^{-4}	8.99×10^{-6}	2.25×10^{-3}	1.14×10^{-4}	1.04×10^{-3}
Till	24 ^a	4.40×10^{-1}	3.25×10^{-4}	1.08	4.70×10^{-2}	5.45×10^{-1}

^aEight boreholes with repeated *K* tests.

IQR, interquartile range.

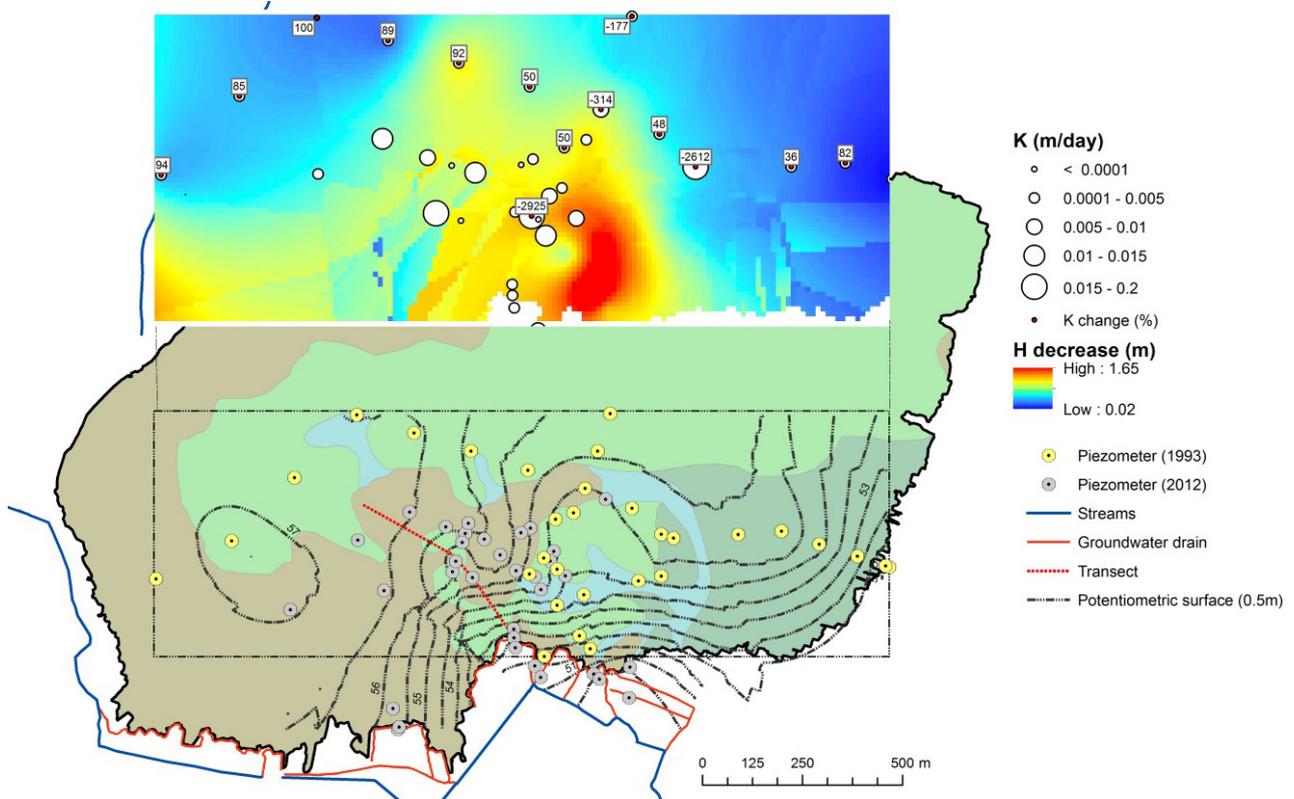


Figure 3.4. Mean annual potentiometric surface at the base of peat, variation in hydraulic conductivity and decrease in head (1991–2013) at Clara Bog.

Nevertheless, while *K* results are in the range typically found in peat (e.g. Letts *et al.*, 2000; Beckwith *et al.*, 2003), the *K* values $> 10^{-2} \text{ m day}^{-1}$ in deep-peat at Clara are far higher than typically reported in other peatland studies.

The *K* results from the inorganic substrates were highly variable, spanning six (10^{-5} – 10 m day^{-1}) and four (10^{-4} – 10 m day^{-1}) orders of magnitude at Clara and Abbeyleix, respectively. This is indicative of the

heterogeneous composition of the deposits, with higher *K* values $> 10^{-2} \text{ m day}^{-1}$ associated with gravel-dominated sequences, such as the esker at Abbeyleix, and lower *K* values $< 10^{-3} \text{ m day}^{-1}$ associated with clay-dominated till matrices. The median *K* at Clara (1.02 m day^{-1}) is an order of magnitude higher than that at Abbeyleix ($10^{-1} \text{ m day}^{-1}$), while the IQR spans three orders of magnitude at Clara compared with one at Abbeyleix. While this is partly attributable to

a greater density of borehole installations at Clara, including seven installed beneath the peat within the bog itself, it is also a reflection of the more variable conditions at Clara and localised areas of high/enhanced permeability ($> 2 \text{ m day}^{-1}$). It was not possible to install a borehole beneath the peat at Abbeyleix. However, cores through the peat column reveal peat to overlie marl in the east of the bog, while a sand sequence underlies peat in the west. While the sand is a permeable layer and hydrological pathway for groundwater flow, it is underlain by stiff clay (till) with reduced permeability. In contrast, till protrudes through low-permeability clay ($< 10^{-6} \text{ m day}^{-1}$) at Clara, including high- K till units. In these areas, peat is in hydraulic contact with the underlying local aquifer system. Examination of the deep-peat K finds that, where peat rests on till, the K IQR spans four orders of magnitude (10^{-5} – $10^{-2} \text{ m day}^{-1}$), while it is within one order of magnitude ($10^{-3} \text{ m day}^{-1}$) in areas underlain by lacustrine clay.

3.6 Hydraulic Head and Gradient

Little research has been conducted on the importance of hydraulic head (piezometric) and vertical hydraulic gradients in peat and underlying substrates and/or bedrock in maintaining water tables in raised bogs.

Potentiometric surface maps for water levels in deep peat are shown in Figures 3.4 and 3.5 for Clara and Abbeyleix, respectively. At Clara, a groundwater mound occurs in the west of the bog and the hydraulic gradient is towards the bog margin. The hydraulic gradient is steep within 200 m of the bog boundary with evidence of internal and sub-surface drainage. At Abbeyleix, the groundwater mound occurs in the central area of the bog and, while locally drawn down by the bog road (old railway line) that runs through the centre of the site, groundwater flows through the peat towards the bog margins.

The potentiometric surface of regional groundwater heads is shown in Figure 3.6 for Clara. A groundwater mound is found in the west of Clara and hydraulic gradients are steep to the east on account of marginal drains lowering the groundwater table. This has resulted in an elongated north–south groundwater catchment underlying the bog area. The artificial drainage system was formed in the period 1995–1997 by continued peat extraction – post the hydrological study conducted in 1991–1993 by Van der Schaaf

(1999). Measurements of piezometric head at boreholes A and B in 1991–1993 (Figure 3.6), located close to the bog’s southern boundary and 400 m within the high bog area, respectively, reveal that the mean head at these locations was $0.5 (\pm 0.1)$ and $0.8 (\pm 0.15)$ m higher than it was between 2010 and 2012, although no significant changes in head are measured outside the catchment area. At Abbeyleix, a high groundwater head is measured in the esker ridge east of the site and groundwater flows westwards, dropping 10 m from the esker to the west of the bog (gradient ~ 0.006).

3.7 Groundwater–Surface Water Interaction

The marginal drainage network on the southern side of Clara West is shown in Figure 3.6. Electrical conductivity (EC) measurements along multiple points in the drains show that they are groundwater fed; EC values $> 200 \mu\text{S cm}^{-1}$ are synonymous with groundwater originating from the calcareous till and limestone deposits in the region. A piezometer nest, measuring stage and piezometric head at the base of the peat and at the base of the till was installed at a location with continuous groundwater input (location F; Figure 3.6) to determine temporal differences in the vertical hydraulic gradient of local groundwater flow. The in-channel exchange of groundwater was further assessed by measuring EC continuously with a YSI Exo Sonde, enabling measurement of the relative contributions of groundwater and surface water flow from the natural bog during runoff generation.

Over the duration of the time series, there was a consistent upwards gradient from the base of the till to the drain, with piezometric heads 0.2–0.8 m greater than stage level (Figure 3.7a). Artesian conditions are characteristic of the cut bog area in general, with four piezometers in the till unit all measuring consistent upwards directions in hydraulic gradient. While peat is generally considered to isolate regional groundwater flows from surface drainage, there is an upwards direction in hydraulic gradient from piezometric head at the base of the peat to the drain (Figure 3.7b), except between November and December 2017, when there is predominant recharge to the regional aquifer. Figure 3.7c shows the temporal fluctuation in EC at the drain between July and October 2017. There is a close inverse correlation between stage

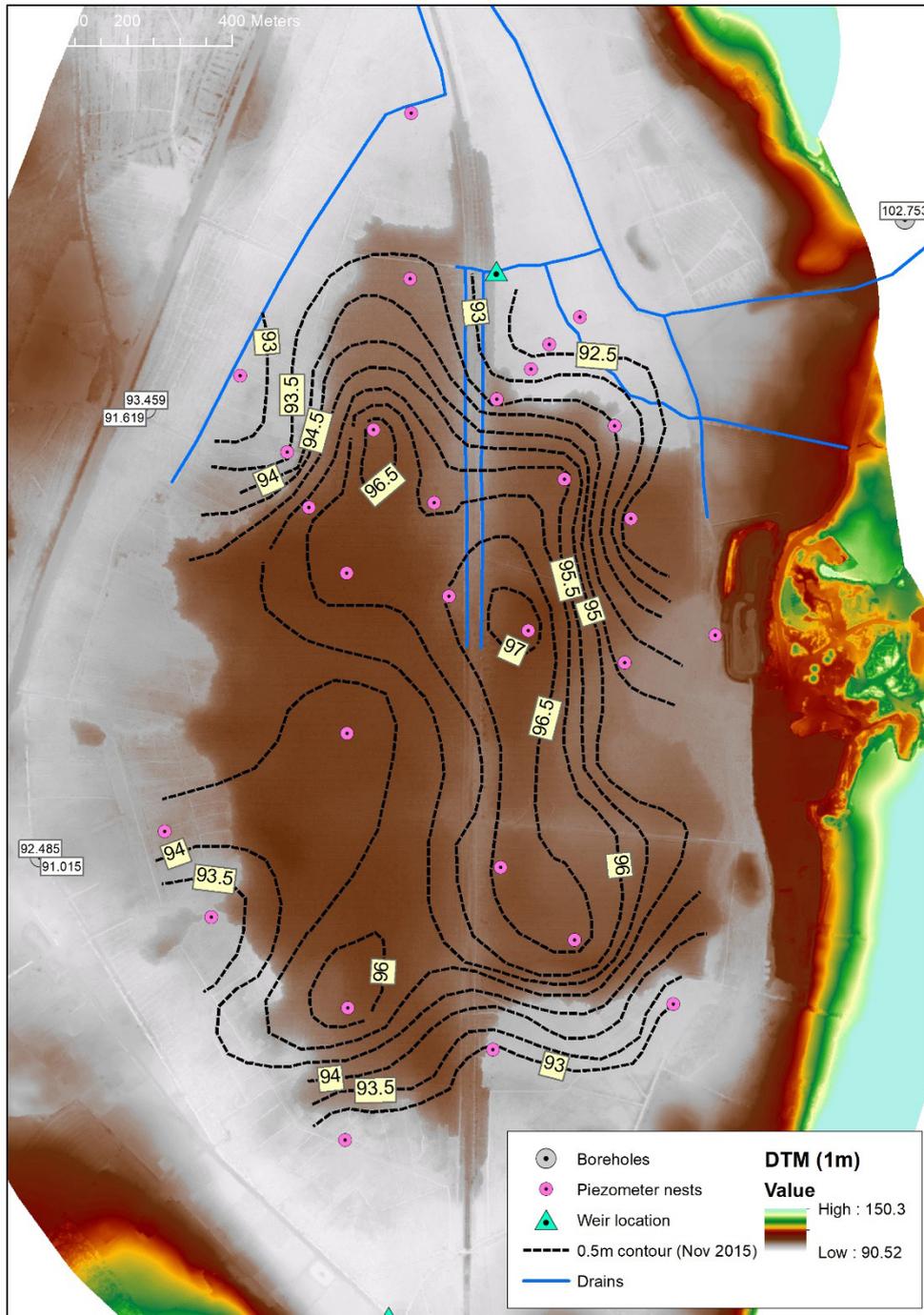


Figure 3.5. Potentiometric surface in deep peat at Abbeyleix Bog. Note: regional groundwater levels in surrounding boreholes in till subsoil (shallow and deep piezometers; downwards gradients) are also shown.

water level and EC value, with EC values increasing to $\sim 350 \mu\text{S cm}^{-1}$ at low flows as the stage recedes, while decreasing rapidly, to values as low as $\sim 50 \mu\text{S cm}^{-1}$, in response to rainfall. Thus, the drain is continuously receiving groundwater (with high EC), but when it rains it also receives direct runoff from the bog of low-EC water, thereby suppressing the net EC values of the

mixing waters. The sharp reductions in EC from July to September, when the difference between stage elevation and peat head is still negative (i.e. upwards gradient), are a result of rapid channelised runoff from the bog via ephemeral flow channels.

In contrast to Clara, piezometers in the cutover bog at Abbeyleix show a predominant downwards hydraulic

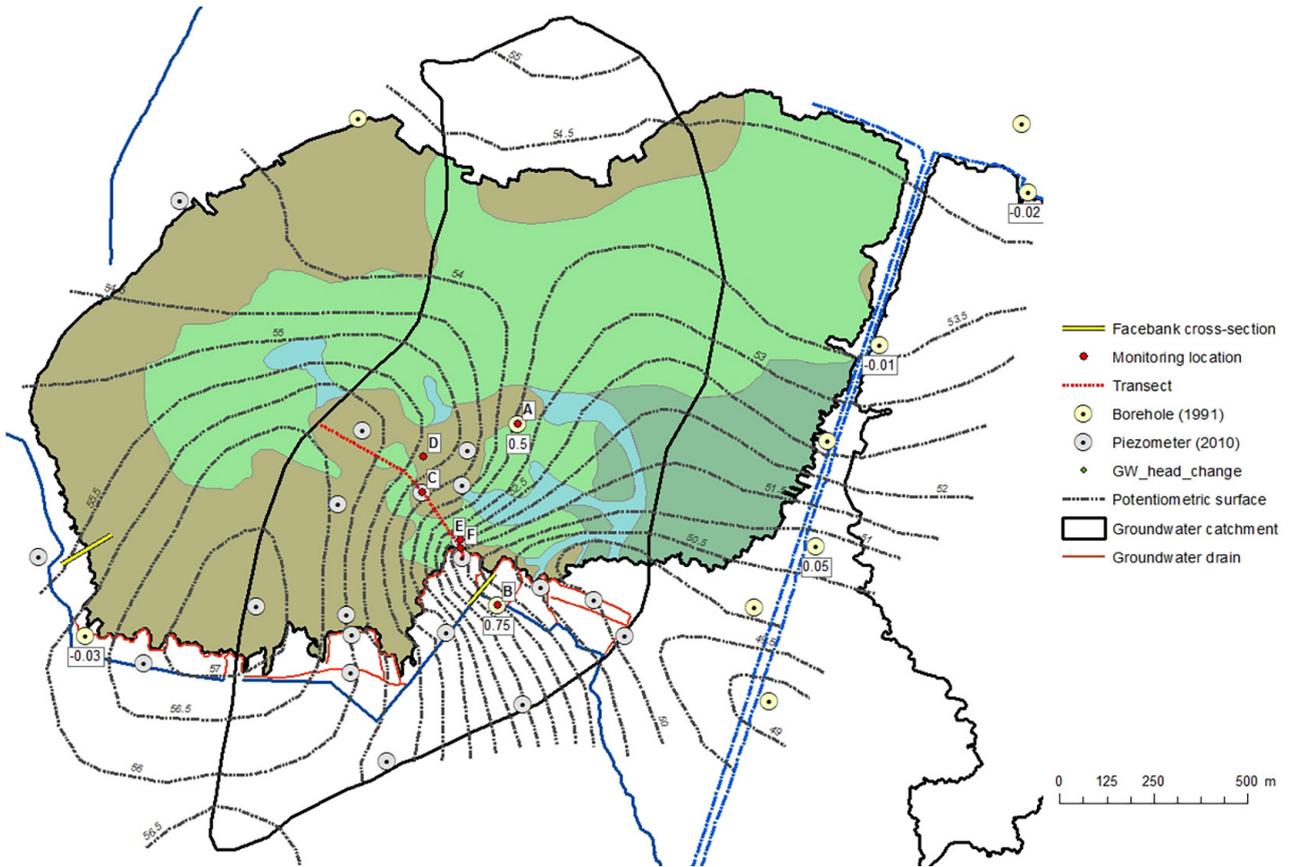


Figure 3.6. Mean potentiometric surface in till groundwater body and regional groundwater catchment at Clara Bog and monitoring locations.

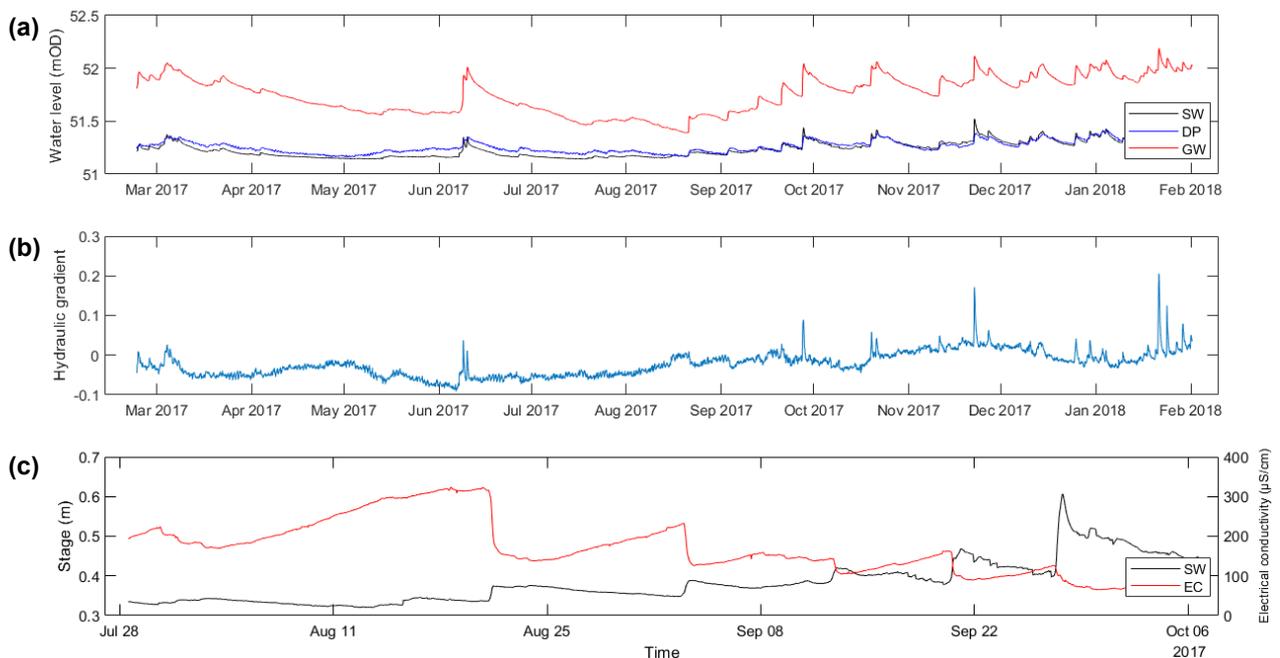


Figure 3.7. (a) Time series of head and stage fluctuation at the marginal drain between February 2017 and 2018 (SW = stage; DP = head at base of peat; GW = head at base of till); (b) hydraulic gradient between stage and peat head; (c) fluctuation in stage and EC at low and high flows.

gradient direction between phreatic water levels and hydraulic head in the peat. Abbeyleix also does not have a significant groundwater-fed drainage network. In the cutover bog area north-west of the site, two drainage channels, which drain into the stream that flows from the east of the site and through an area of alluvial woodland and cutover bog to the north-east of the site, contain groundwater with EC consistently $>200 \mu\text{S cm}^{-1}$ (Figure 3.5). However, flow rates in the drains are negligible with little fluctuation in stage, in contrast to the observed water level and EC dynamics in the groundwater-fed drain at Clara.

3.8 Subsidence

Peat undergoes subsidence when drained primarily because of consolidation and organic matter oxidation. The difference in ground surface elevation between 1991 and 2017 at Clara West is shown in Figure 3.8a. Ground level declines are greatest in the south-central area of the bog adjacent to the groundwater-fed drain, with levels $>1.0\text{ m}$ measured over 170 m from the bog margin. The decline in ground level reduces to levels less than 0.5, 0.2 and 0.1 m within 450, 650 and 900 m from the southern boundary, respectively.

In the period 2008–2017, ground level declines $>0.1\text{ m}$ are concentrated around the central and northern regions, and appear to have stabilised in the southern region of the bog (Figure 3.8b). Rates of subsidence have been calculated using time series measurements of ground level. The mean rate in the 1991–2002 period is $21.8 \pm 19.8 \text{ mm year}^{-1}$, decreasing to between 4 and 6 ($\pm 4\text{--}6$) mm year^{-1} in the post-measurement periods. Where peat overlies till, the mean rate was $28.4 \pm 23.2 \text{ mm year}^{-1}$, compared with $15.5 \pm 14.7 \text{ mm year}^{-1}$ where the underlying subsoil is lacustrine clay. Mean rates reduce significantly in the period post 2008 to $\sim 6 (\pm 4) \text{ mm year}^{-1}$ in both till and lacustrine clay areas.

In addition to the decline in regional groundwater head, there has also been a decline in hydraulic head in deep peat piezometers between 1991–1993 and 2010–2013 (Figure 3.4). The decline in piezometric heads at the base of peat is also found to be linearly associated with peat subsidence (Figure 3.9). A decrease of up to 1.65 m is observed towards the southern bog boundary and $>0.6\text{ m}$ within 500 m of the bog boundary; no changes have occurred in the east of the bog. The decrease in head is associated with

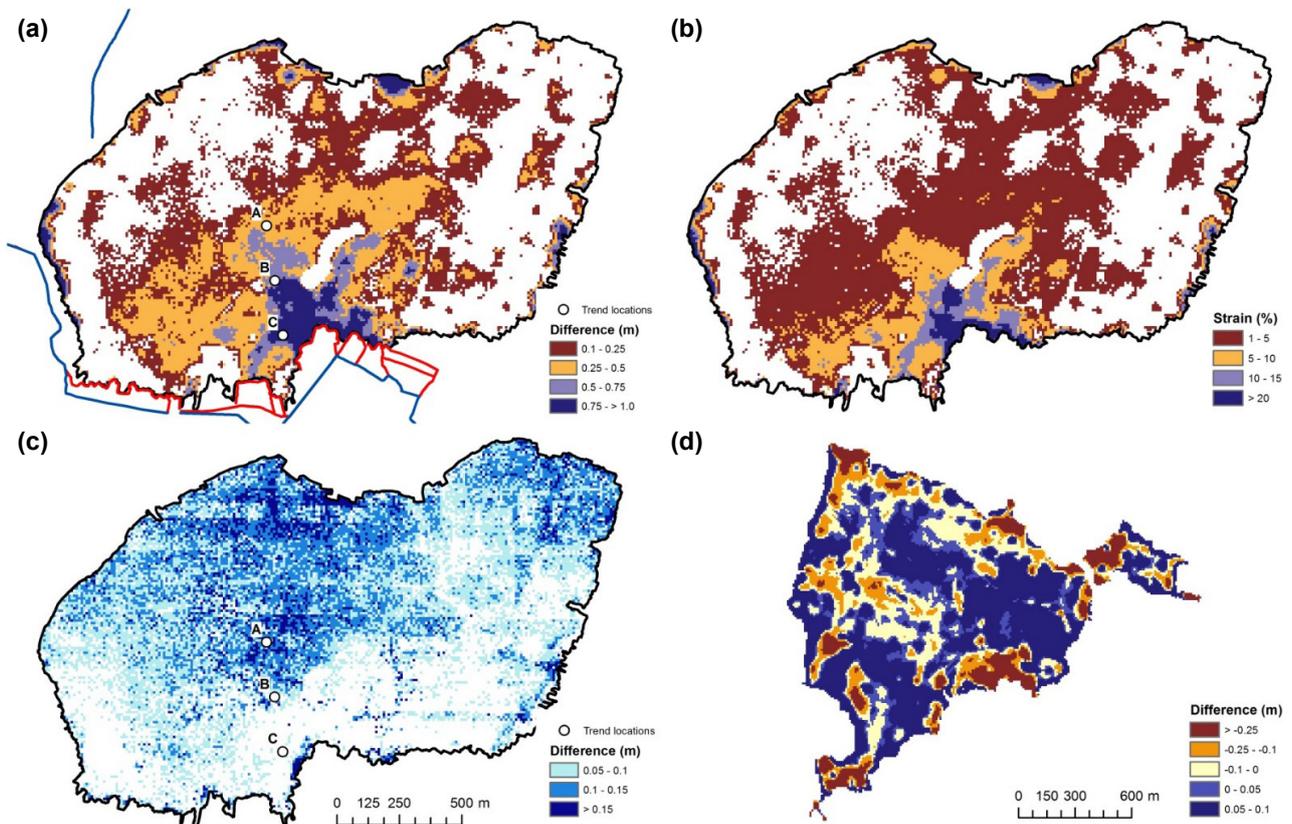


Figure 3.8. Decline in ground surface at Clara West between (a) 1991 and 2017 and (b) 2008 and 2017.

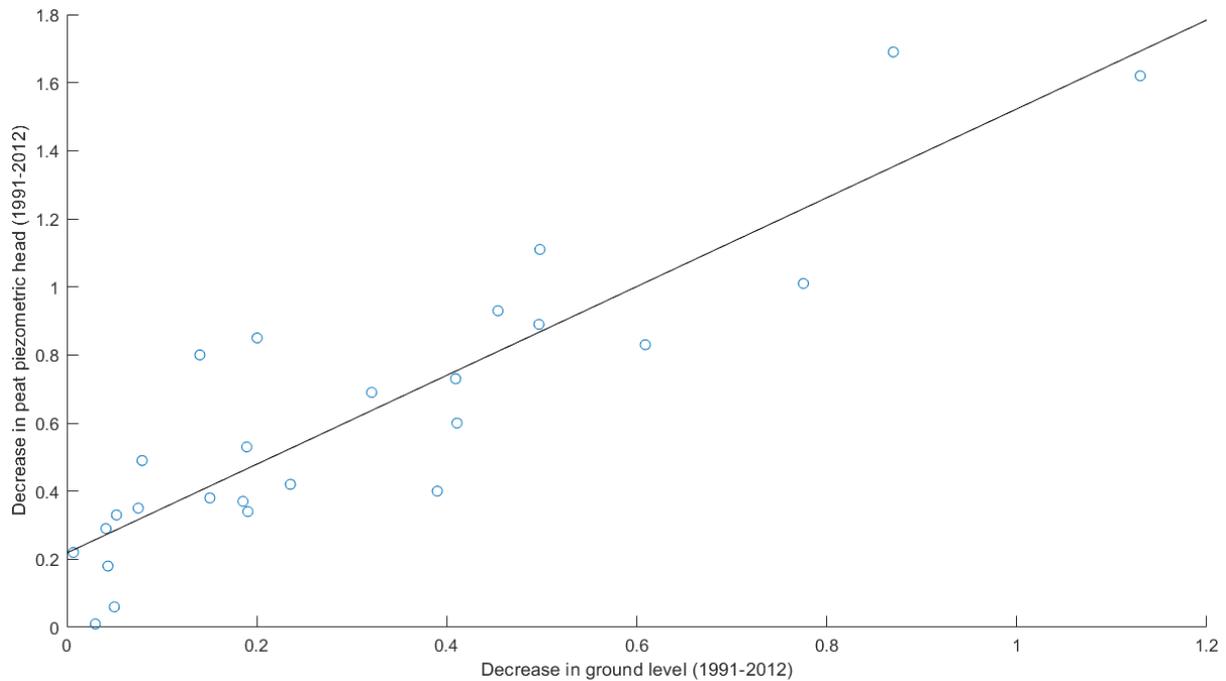


Figure 3.9. Correlation between difference in ground level and mean piezometric head measured at the base of peat between 1991–1993 and 2009–2012.

drainage patterns in the south-east and south-west of the bog, where peat is underlain by till and sand deposits (Figures 3.4 and 3.6). Subsidence appears to have stabilised around the southern areas of the bog, but is propagating into central and northern regions of the bog, which are largely underlain by till. Bio-oxidation processes are generally reported as the primary mechanism driving subsidence of peat soils. However, at Clara, compression seems to be the dominant consolidation mechanism, induced by the decrease in piezometric head at the base of peat (on account of drainage of the till aquifer via the groundwater-fed channel) and a resultant increase in effective stress (Figure 3.10).

Typically, consolidation results in a reduction in water content, which is reflected by an increase in organic matter content and a corresponding decline in K (Moore *et al.*, 2015). This can result in a negative feedback in a peatland's water balance, limiting downwards water loss. However, the deformation of peat can also result in the development of cracks and fissures, resulting in reduced resistance to flow and an increase in seepage losses to deposits underlying the peat (Schouwenaars, 1993). Comparison of K measured from piezometer test responses indicates that there have been no significant changes in peat properties in areas experiencing limited (<1%)

subsidence. These conditions contrast with changes in peat properties in areas experiencing subsidence in excess of 5% of the 1991 peat thickness (Figure 3.4); these areas display marked increases in hydraulic conductivity by up to two orders of magnitude. In this area, there is a concentration of high- K basal peat, indicating that the units are connected. Concurrently, decreases in K by one order of magnitude are found in the same region of the bog, indicating compaction and loss of pore volume.

In contrast to Clara, minimal subsidence has been measured at Abbeyleix; however, ground elevation records are only available from 2014 onwards. Nevertheless, evidence of past subsidence can be deduced from the current surface topography of the raised bog, as it diverges from the parabolic dome shape of natural raised bogs (likewise Clara). Subsidence >0.03 (± 0.03) m is measured between 2014 and 2017 at facebank locations in the north-west of the site and close to the old railway track bisecting the bog; however, this is negligible >50 m inside the bog from the bog and drain margins. In contrast to Clara, there is little groundwater drainage at Abbeyleix and low-permeability till subsoil underlies shallow sand deposits (west) and lacustrine clay deposits (east), meaning that marginal drainage has not impacted on bog hydrology in the way it has at Clara.

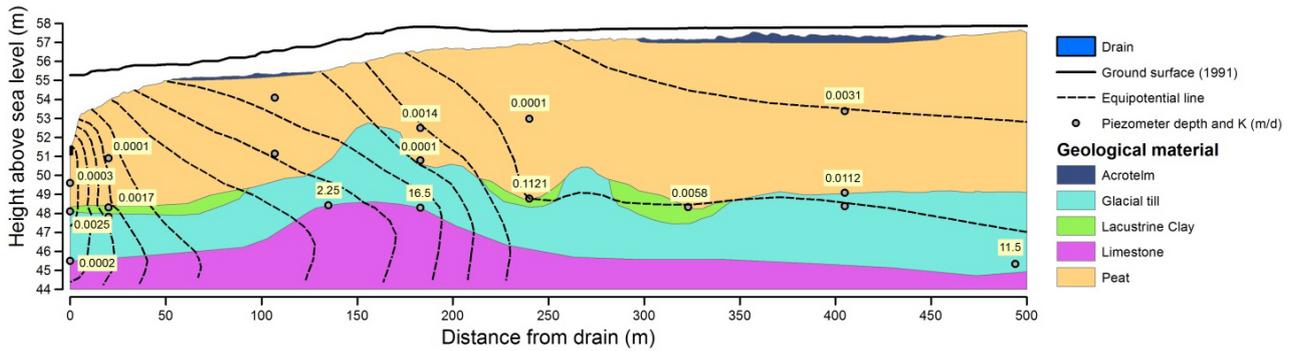


Figure 3.10. Hydrogeological cross-section through groundwater flow line.

3.9 Water Balances

The water balance is a key measure on which to assess the sustainability of a wetland ecosystem – particularly in a bog system where downwards infiltration to the regional groundwater table should be minimal. The K of saturated peat is highly variable. However, it generally decreases exponentially with depth, from high values ($<10 \text{ m day}^{-1}$) close to the surface to low values at depth ($<10^{-3} \text{ m day}^{-1}$). Therefore, the flux of groundwater through peat is generally considered negligible in water balance studies (Van der Schaaf, 1999; Letts *et al.*, 2000), with minimal downwards losses/seepage to underlying substrates and bedrock. However, the local presence

of elevated K in areas underlying Clara Bog indicates that macropores must form a significant groundwater flow pathway. The calculation of runoff, precipitation and evapotranspiration budgets for the hydrometric stations at Clara reveals that downwards infiltration varies between 60 and 140 mm year^{-1} where peat overlies glacial till and reduces to less than 40 mm year^{-1} where peat has a low K and is underlain by low-permeability lacustrine clay. Marginal drainage has also altered the hydraulic properties of peat at Clara and, by implication, its water balance. At Abbeyleix, downwards infiltration is found to be minimal and the water balance is dominated by surface water flow and evapotranspiration.

4 Carbon Balance

4.1 Net Ecosystem Exchange of CO₂

At Clara and Abbeyleix Bogs, NEE was modelled on an hourly basis to account for the expected diurnal variations. Field measurements of CO₂ flux were used to build collar-specific empirical models of gross primary production (GPP) and R_{eco}. Hourly measurements of field variables were input into these

empirical models to calculate hourly GPP and R_{eco}, which were then summed to calculate NEE.

The seasonal trends in modelled monthly GPP and R_{eco} were similar among all ecotopes and cutover bog sites, increasing in the summer and decreasing in the winter (Figures 4.1 and 4.2). The ecotopes show different seasonal trends in cumulative NEE

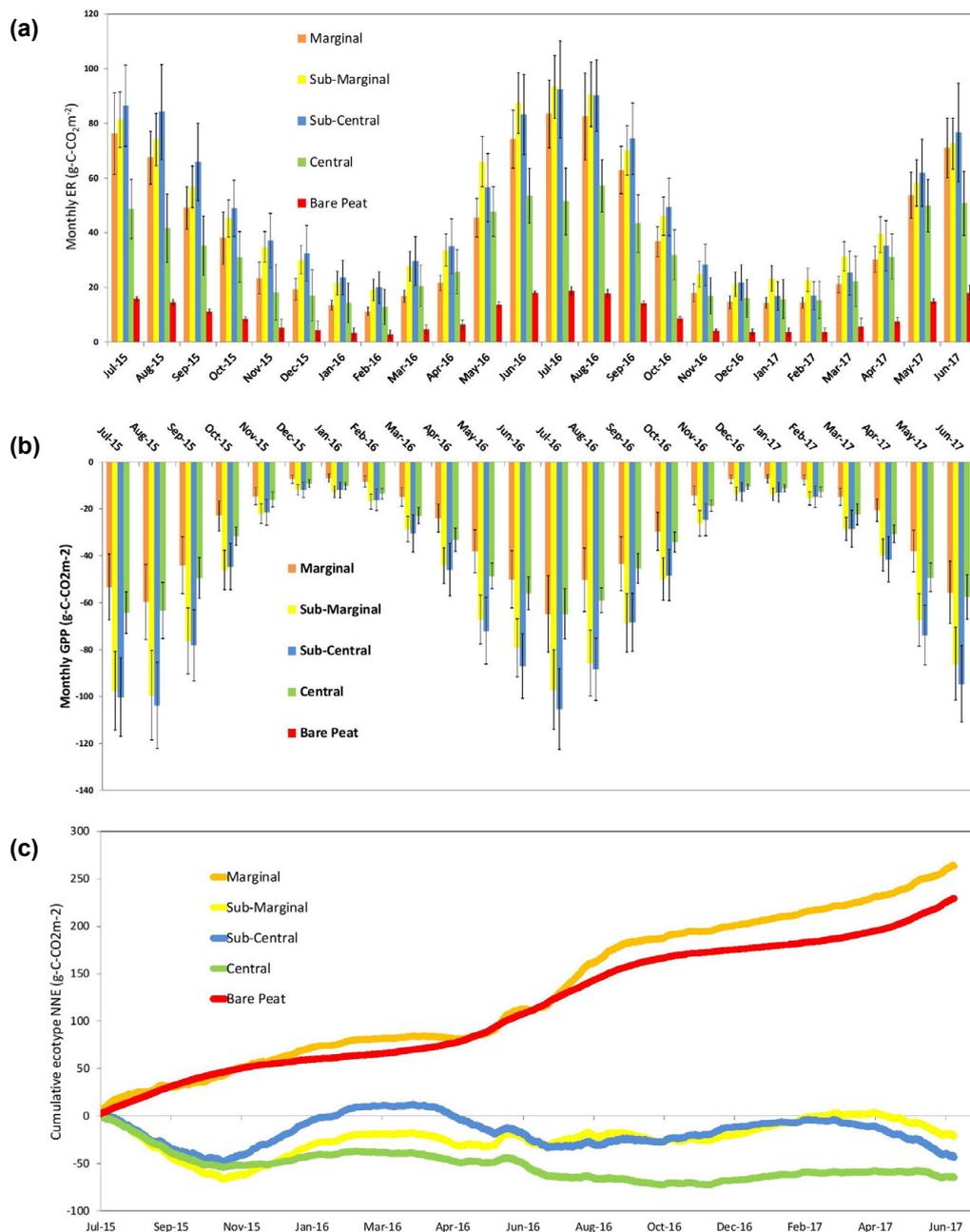


Figure 4.1. (a) Monthly R_{eco}, (b) monthly GPP and (c) cumulative NEE for Clara ecotopes and the bare peat site between July 2015 and June 2017. Note: values are the average of all collars in the ecotope.

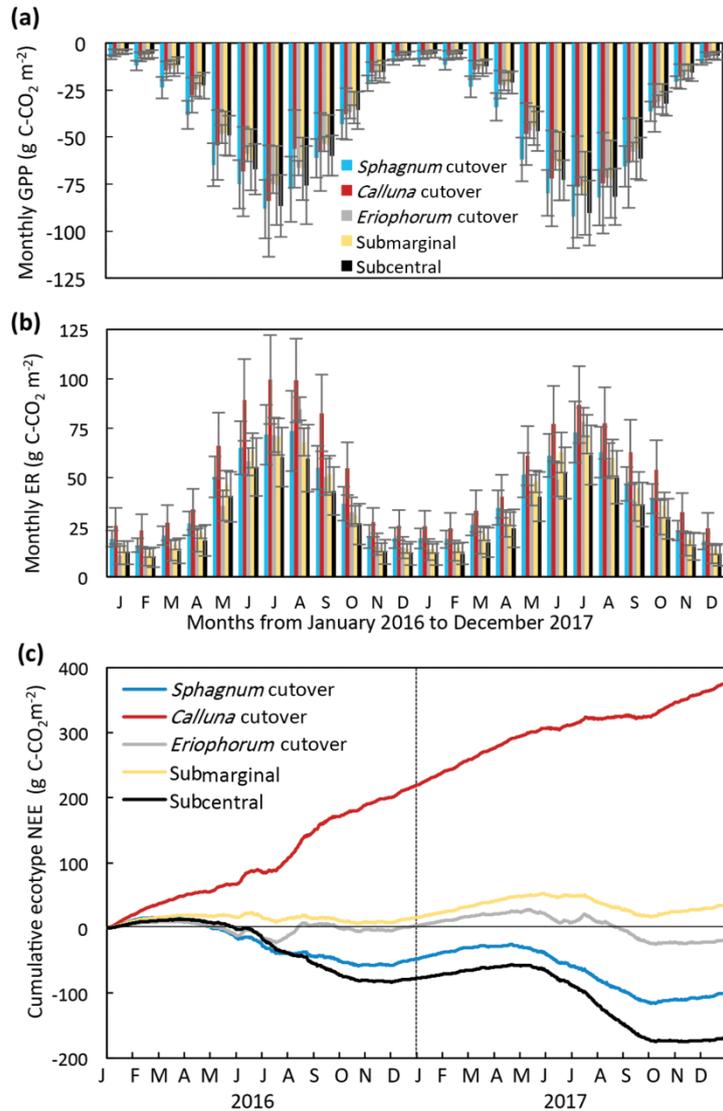


Figure 4.2. (a) Monthly GPP, (b) Monthly R_{eco} and (c) cumulative NEE for Abbeyleix ecotopes and cutover bog sites between January 2016 and December 2017. Note: values are the average of all collars in the ecotope.

(Figures 4.1c and 4.2c). The *Sphagnum* cutover and the sub-central ecotope at Abbeyleix were net CO_2 sinks (negative slope) from March to October 2016 and from April to October 2017 and CO_2 sources the rest of the year, showing an overall similar pattern to other studies of intact peatlands (e.g. Gažovič *et al.*, 2013). Similarly, at Clara, central, sub-central and sub-marginal ecotopes were net CO_2 sinks from the start of measurements in July 2015 to October 2015, from April 2016 to October 2016 and again from April 2017 to the end of measurements in June 2017. By contrast, the *Calluna* cutover at Abbeyleix and bare peat and marginal ecotope at Clara are strong CO_2 sources, particularly during summer months.

The estimated yearly NEE for Clara and Abbeyleix is summarised in Table 4.1. At Clara, central and sub-central ecotopes are sinks in both measurement years. However, CO_2 uptake reduces by c. 75% at central in Year 2, which corresponds to a rainfall reduction of c. 45% (1304 and 707 mm of rainfall measured in Years 1 and 2, respectively). Similarly, sub-marginal was a moderate sink in Year 1, but a small source in Year 2, while marginal was a significant source in both years, increasing by c. 35% in Year 2. In contrast, sub-central remains a moderate sink in both measurement years. This may be related to the large catchment area to the site and subsidence-altering topographic gradients. Upscaling the NEE to the level of the bog habitat indicates that it is a

Table 4.1. Summary NEE for Clara and Abbeyleix

Clara (g C-CO ₂ m ⁻² year ⁻¹)			Abbeyleix (g C-CO ₂ m ⁻² year ⁻¹)		
Site	Year 1	Year 2	Site	Year 1	Year 2
Central	-51.4 ± 103	-13.5 ± 99	Sub-central	-77 ± 45	-92 ± 51
Sub-central	-19.9 ± 72	-23.6 ± 71	Sub-marginal	16 ± 79	19.6 ± 80
Sub-marginal	-23.4 ± 65	2.3 ± 64	<i>Sphagnum</i> cutover	-47 ± 43	-53 ± 42
Marginal	112.9 ± 72	150.6 ± 68	<i>Eriophorum</i> cutover	3 ± 61	-22 ± 76
Bare peat	108.4 ± 28	120.8 ± 24	<i>Calluna</i> cutover	219 ± 50	156 ± 61
Habitat	1.8 ± 15	47.8 ± 16	Habitat	131.84 ± 29	96.66 ± 26

Note: habitat-scale fluxes do not include cutover bog sites. Negative numbers indicate plant uptake. Year 1 is the measurement period July 2015 to June 2016 and Year 2 is the measurement period July 2016 to June 2017 at Clara; Year 1 is calendar year 2016 and Year 2 is calendar year 2017 at Abbeyleix.

small source in Year 1 ($1.8 \pm 15 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$), increasing in Year 2 in response to dry conditions ($47.8 \pm 16 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$). While this is a generalisation, and does not include other NPWS mapped ecotopes, it is considered indicative of the bog's CO₂ source/sink function. At the bare peat area, it is a significant source in both years.

At Abbeyleix, the sub-central ecotope and *Sphagnum* cutover site were CO₂ sinks in both Years 1 and 2. The increase in sequestration in the second measurement period is related to a higher water table because of a >12% increase in rainfall (746 and 840 mm of rainfall measured in Years 1 and 2, respectively). In contrast, the sub-marginal ecotope was a moderate source in both years and *Calluna* cutover was a significant source in both years, decreasing by c. 30% in Year 2 in response to increased rainfall. *Eriophorum* cutover was a marginal source in Year 1 and reverted to a moderate sink in Year 2. Upscaling the NEE to the level of the bog habitat, and using marginal ecotope data from Clara, indicates that it is a significant source in Year 1 ($131.84 \pm 29 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$), decreasing in Year 2 in response to wetter conditions ($96.7 \pm 51 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$).

4.2 Methane

The average CH₄ emissions for central, sub-central, sub-marginal and marginal ecotopes at Clara between 2015 and 2017 were 10.6 ± 5.4 , 8.7 ± 2.8 , 6.0 ± 2.1 and $1.1 \pm 0.5 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$, respectively, and are strongly correlated with water table depth. CH₄ emissions are the highest and most variable at the central plot sites on account of the presence of vegetation such as *Eriophorum*. In the central area, daily fluxes vary between $> 1 \text{ mg C-CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ and

$> 150 \text{ mg C-CH}_4 \text{ m}^{-2} \text{ day}^{-1}$, whereas in the marginal area flux never exceeds $10 \text{ mg C-CH}_4 \text{ m}^{-2} \text{ day}^{-1}$ (Figure 4.3). This is consistent with the CH₄ flux from intact peatlands generally being quite high and indicative of stable ecosystem conditions, with the high variability in flux related to micro-topography and diversity of vegetation.

The annual CH₄ fluxes for Abbeyleix are shown in Figure 4.4. The CH₄ emissions are highest for the *Eriophorum* cutover ($14.2 \pm 4.8 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$) and sub-central ecotopes ($12.6 \pm 7.9 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$), which have the highest mean annual water table. The annual CH₄ flux at the sub-central ecotope is highly variable, with a range of $1.2\text{--}19.3 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$ between collars. The annual CH₄ flux is lowest for the *Calluna* cutover ecotope ($2.7 \pm 1.4 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$).

4.3 Fluvial Carbon

The DOC at Clara was measured at runoff outlets from two catchments (Figure 2.1). The eastern catchment receives only surface water runoff (natural stream on the high bog), whereas the western catchment receives both surface runoff and groundwater drainage (marginal drain in cutover bog – see Figure 3.7). The DOC concentration in the surface runoff catchment varied between 24 and 48 mg L⁻¹, with a monthly mean of 36 mg L⁻¹, and between 18 and 48 mg L⁻¹ in the groundwater-fed catchment, with a monthly mean of 27 mg L⁻¹. Over the course of the measurement period (the 2016–2017 hydrological year), the annual flux in the surface stream was $6.4 \pm 0.42 \text{ g C m}^{-2} \text{ year}^{-1}$ and $15.4 \pm 0.63 \text{ g C m}^{-2} \text{ year}^{-1}$ for the marginal drain, reflecting the considerably higher discharge in the marginal drain. The temporal dynamics of the DOC concentration are shown in Figure 4.5. The

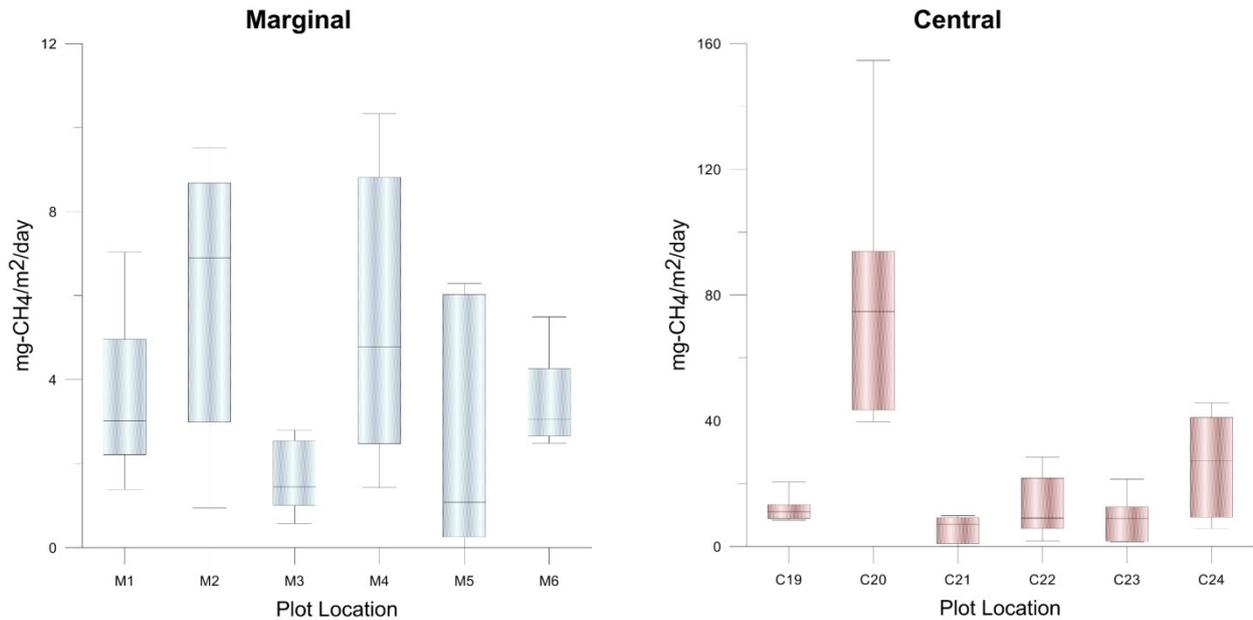


Figure 4.3. Variability in CH₄ daily flux at Clara marginal and central ecotopes.

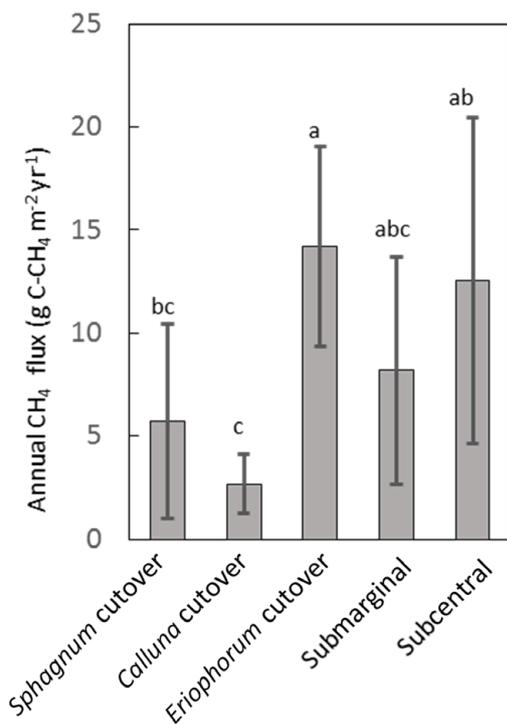


Figure 4.4. Annual CH₄ flux for each ecotope averaged over all collars in Abbeyleix ecotopes and cutover sites.

concentration follows a seasonal trend in the surface stream – it is generally higher in the summer months with increased air and soil temperature. In the marginal drain, the temporal pattern is much more closely linked with stage and groundwater level and thereby controlled by discharge.

The mean ($n=12$) instantaneous CO₂ evasion rates from the surface runoff catchment and groundwater influenced catchment at Clara were 0.05 and 0.24 mg C-CO₂ m⁻² s⁻¹, respectively. DIC in the drainage water was substantially less, with mean concentrations of 0.22 and 0.23 mmol L⁻¹ from the surface runoff catchment and groundwater influenced catchment, respectively. Over the course of the measurement period (the 2016–2017 hydrological year), the annual flux of open water CO₂ evasion and lateral flux of DIC (when combined with measured discharge) in the surface stream were 0.34 ± 0.10 g C m⁻² year⁻¹ and 0.66 ± 0.16 g C m⁻² year⁻¹ for the marginal drain, respectively. The much larger CO₂ evasion rates from the groundwater-fed marginal drain can be attributed to the greater level of supersaturation of CO₂ in this drainage water. The source of this is likely to be both geogenic (i.e. calcium-rich mineral groundwater from depth) and “old” biogenic carbon-saturated water from peat compaction (i.e. bog subsidence).

At Abbeyleix Bog, the DOC concentrations for the runoff measured at the weir showed a seasonal trend for both years – it was higher between June and November (46.0 ± 3.0 mg L⁻¹) and lower between December and May (34.5 ± 2.3 mg L⁻¹) – but no trend was observed with respect to discharge. Annual losses of DOC were 8.0 ± 1.6 and 12.8 ± 2.5 g C m⁻² year⁻¹ for 2016 and 2017, respectively. The average DIC concentration at the weir (based on a limited number of seven samples) was 4.6 ± 1.1 mg L⁻¹, which

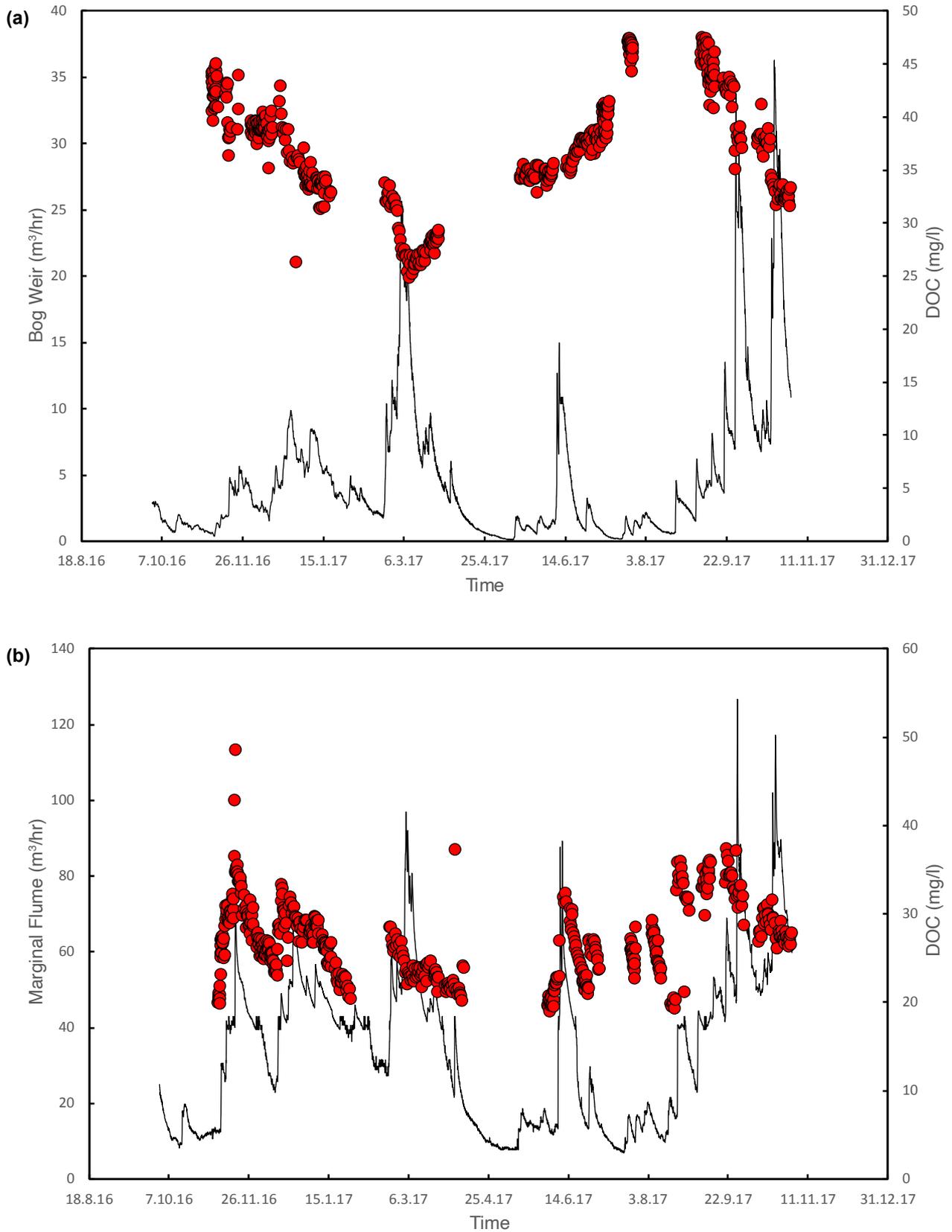


Figure 4.5. DOC concentration and discharge between November 2016 and October 2017 at (a) surface stream and (b) marginal drain.

showed no significant trend with respect to season, temperature or discharge, so it was assumed to be constant throughout the 2-year study period. This yielded annual losses of DIC of 1.1 ± 0.2 and $1.5 \pm 0.3 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively.

Open water CO_2 evasion was measured for two blocked drains on the raised bog and just upstream of the weir. The average CO_2 evasion rate from the two blocked drains ($n=15$) was $5.1 \times 10^{-3} \pm 2.9 \times 10^{-3} \text{ mg C-CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and was somewhat higher at the weir ($n=8$) at $9.2 \times 10^{-3} \pm 3.2 \times 10^{-3} \text{ mg C-CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Again, based on this limited data set, there was no significant trend in evasion rate with respect to season, temperature or (at the weir site) discharge. The CO_2 evasion rate was thus assumed constant and extrapolated to give an annual carbon loss as CO_2 evasion of $162 \pm 91 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ and $290 \pm 100 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ for open water blocked

ditches and the active drain network of the weir, respectively. The open water areas in the drain network contributing to the weir were $\sim 0.9\%$ of the total catchment area, to give a carbon loss of $2.7 \pm 0.9 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ for the weir catchment area as a whole.

4.4 Net Ecosystem Carbon Balance

The NEE, CH_4 fluxes and aquatic losses of carbon were compiled to calculate the carbon balance for the hydrological catchments at Clara (Table 4.2) and for ecotope and cutover sites at Abbeyleix (Figure 4.6). At Clara, average seasonal values of CO_2 and CH_4 flux were applied to ecotopes mapped within the respective catchments. Each catchment area is near-neutral with respect to CO_2 , but each is a source of CH_4 , DOC and DIC. The net carbon balance from the groundwater influenced catchment is nearly twice that of the surface

Table 4.2. Carbon balance for two catchment areas at Clara Bog between November 2016 and October 2017

Flux	Groundwater	Surface	Unit
CO_2	-0.27	0.07	$\text{g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$
CH_4	7.16	6.64	$\text{g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$
DOC	15.39	6.39	$\text{g DOC m}^{-2} \text{ year}^{-1}$
DIC	0.66	0.34	$\text{g DIC m}^{-2} \text{ year}^{-1}$
Net	22.93	13.44	$\text{g C m}^{-2} \text{ year}^{-1}$

Note: negative number indicates a sink; DIC includes open water CO_2 evasion.

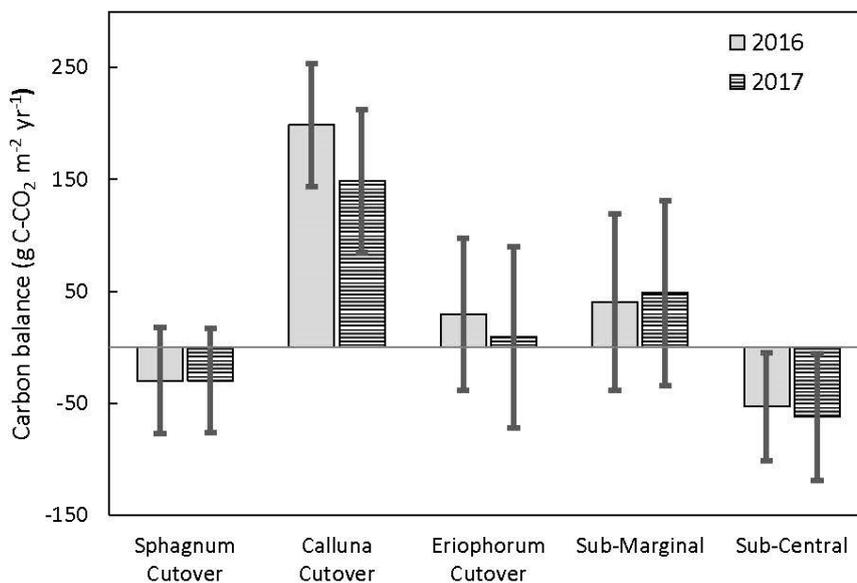


Figure 4.6. Carbon balance for each ecotope including NEE, CH_4 flux, aquatic losses as DOC and DIC, and open water CO_2 evasion.

catchment, illustrating the impact of marginal drainage on the carbon balance of an “uncut” bog (i.e. without surface drainage). Moreover, the marginal drain has caused subsidence, which has resulted in the significant loss of ARB and peat mass, a component of the Clara carbon balance that was unaccounted for.

At Abbeyleix, the *Calluna* cutover site was a substantial carbon source of $234 \pm 52 \text{ g C m}^{-2} \text{ year}^{-1}$ and $175 \pm 61 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively. Two of the ecotopes were, on average, C sinks both years – the *Sphagnum* cutover ($-29.8 \pm 42 \text{ g C m}^{-2} \text{ year}^{-1}$ and $-30.0 \pm 40 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively) and the sub-central ($-53.0 \pm 37 \text{ g C m}^{-2} \text{ year}^{-1}$ and $-62.4 \pm 46 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively). Environmental drivers of the annual carbon balance and CH_4 flux were analysed by comparing the data from each of the 29 collars in the study sites. There is a significant ($p=0.015$) but weak ($r^2=0.20$) negative linear correlation between the 2-year average annual carbon balance and the average mean annual water table (MAWT). Conversely, the annual CH_4 flux has a significant ($p<0.001$) positive linear correlation ($r^2=0.51$) with the average MAWT.

4.5 National Raised Bog Carbon Exchange

In Ireland, 53 raised bogs have been designated as SACs (European sites) and each has been mapped for ecotopes. According to recent figures from the NPWS, the total high bog extent is c. 10,684 ha, of which 173 ha, 910 ha, 351 ha and 3477 ha are mapped at central, sub-central, sub-marginal and marginal, respectively. Using the average C-CO₂ emission values from both Clara and Abbeyleix, these fluxes are upscaled to the scale of the European site network. Central, sub-central and sub-marginal ecotopes are marginal sinks sequestering c. -105, -198 and -565 tonnes C-CO₂ year⁻¹. In contrast, marginal ecotope emits c. 4581 tonnes C-CO₂ year⁻¹, meaning that the raised bogs in Ireland that are designated as European sites emit c. 80% more CO₂ than they take in. Similarly, upscaling CH₄ emissions from ecotopes at Clara results in 473 tonnes being released from the raised bog SAC network per year (equates to c. 13% of the total C-CO₂ emissions from the SAC network). The DOC will also be a significant carbon emission pathway from all bogs, particularly heavily degraded systems with large areas of cutover bog and marginal drainage.

5 Hydrological Restoration

Raised bog ecosystems that have been degraded as a result of drainage require engineering measures to restore the hydrological conditions necessary for a self-regulating acrotelm (see section 3.3). The hydrodynamic functioning of the acrotelm is topographically controlled and initial restoration measures must identify areas where suitable geomorphological conditions exist to support *Sphagnum* regeneration and growth. However, where these conditions exist, and an acrotelm is not supported, it indicates that hydrogeological pressures are impacting on the peat's capacity to maintain saturated conditions at the ground surface. Management of degraded sites must therefore determine if ecological degradation is primarily a consequence of shallow surface drainage or linked to groundwater pressures in the wider regional landscape.

5.1 Surface Drainage

The depth to which *Sphagnum* can efficiently access water via capillary action is relatively shallow. A lowering of the water table by as little as 0.2 m is sufficient to break the capillary water stream and reduce the percentage of capillary water by over 95% (Clymo and Hayward, 1982). Surface drainage thereby impacts on capillary action and relatively small elevation differences (0.1 m or less) are required to maintain the water table sufficiently close to the bog surface to be accessible for uptake by the *Sphagnum* carpet.

The effect of drainage is to increase peripheral water slope gradients to drain outlets, thereby lowering the

water table in the surrounding acrotelm. Dewatering processes remove the capacity of the acrotelm to self-regulate the water table level and can promote hydrological and structural changes that result in acrotelm desiccation. Drains on bog systems are therefore spaced so that the water table between them is kept suitably low. These drains are the primary routes for anthropogenic water loss and generally consist of drain spacing between 10 and 25 m, depths of <1.0 m and widths of <0.5 m. Abbeyleix and Clara East are examples of this managed situation. Discrete dams are required to retain water in these channels in order to restore the hydrological conditions necessary for a self-regulating acrotelm.

Immediately upstream of a dam, the water table is determined by the natural changes in water level within the acrotelm (dH_n) (Figure 5.1). Further upstream, the water table is controlled by the water level in the drainage channel. Immediately downstream of a dam is the worst case scenario; the water table is therefore the sum of the water level and the height difference between dams (dH_d). To ensure viable conditions for *Sphagnum* regeneration, the water table must be maintained within 0.2 m of the peat surface. Thus:

$$dH_d + dH_n \leq 0.2 \text{ m} \quad (5.1)$$

Assuming a limit of 0.10 m for dH_n , this gives:

$$dH_d \leq 0.1 \text{ m} \quad (5.2)$$

Dams are therefore necessary for every 0.1 m drop in elevation gradient. Slope values in the order of 0.3% are the threshold that seems to differentiate between active peat-forming conditions, as indicated by the distribution of central and sub-central ecotopes, and a

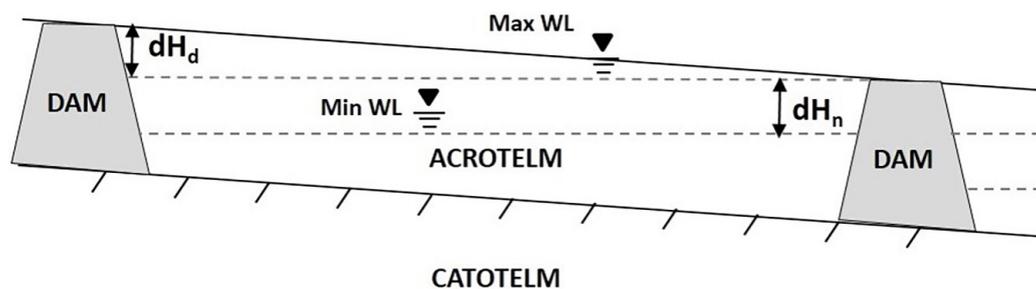


Figure 5.1. Schematic showing the controls on water level around a dammed drainage channel.

progressive decrease to inactive conditions on slopes in the order of 0.7%, as indicated by the distribution of a sub-marginal ecotope. Thus, if more than 10 dams are required over a distance of 100 m, it implies that the water slope gradient is greater than 1% and acrotelm restoration is improbable.

A slope criterion is therefore used to assign areas where there is the potential for acrotelm restoration. However, the water balance studies at the Abbeyleix mesocosm experimental sites show that lateral flow from the catchment area can also sustain high water tables. This demonstrates that the water losses in high gradient areas can be compensated by increased accumulation of lateral flow, which necessitates catchment areas being large enough to provide the difference in the water balance that keeps the acrotelm suitably wet over the course of a given year.

5.2 Marginal and Groundwater Drainage

The acrotelm is considered to be the active layer in conservation terms and has attracted research in determining criteria for its sustainability (Johnston *et al.*, 2015). While the K of peat at depth is generally low, evidence suggests that deeper peat can have permeabilities as high as near-surface peat (Baird *et al.*, 2017) and interconnected macropores at depth can act as significant flow pathways (Regan *et al.*, 2019). The diagenesis of vegetation into peat substrate in ombrotrophic environments generally assumes the presence of low-permeability substrates to impede downwards drainage and maintain saturated conditions. However, groundwater can also prove critical in raised bogs underlain by permeable inorganic deposits, with reversals in hydraulic gradient demonstrated to maintain groundwater levels in prolonged drought periods (Siegel *et al.*, 1995; Reeve *et al.*, 2000).

Continued subsidence at Clara is a consequence of marginal drainage. In contrast to Abbeyleix and the eastern Clara Bog complex, Clara West is underlain by a significant area of glacial till and sand-lens deposits with hydraulic conductivities orders of magnitude higher than lake clay deposits. Drainage of the till subsoil has been shown to lower piezometric heads significantly within this groundwater body and, in the absence of a natural geological and hydraulic barrier, peat has consolidated because of the lowered

piezometric heads within the peat itself. This impacts on surface hydrology by increasing the rates of downwards seepage through the peat column, as measured in the bog's water balance. Concurrently, differential deformation of the bog surface alters peripheral water slope gradients and promotes ecological desiccation where slope gradients have increased.

To illustrate the lateral effect of marginal drainage, a hydrogeological cross-sectional profile through a groundwater flowline (Figure 3.6) is shown in Figure 3.10. The drawdown of piezometric heads in the peat is evidenced by the hydraulic gradient of the equipotential lines towards the drain. The drain laterally draws down the water table within an extent of approximately 50 m. From this point, ARB is mapped on the bog surface (or acrotelm) in an area of shallow topographic gradient. However, where the peat rests on the till mound, a drawdown in piezometric head is observed and no ARB (i.e. acrotelm) is mapped on the bog surface. Topographic gradients are high in this area ($>0.5\%$) and it is also where large levels of subsidence have occurred (>0.1 m). Thus, the lateral effect of drawdown by the groundwater-fed drain extends beyond the bog margin and as far as 250 m inside the bog area, where the till mound occurs. Further inside the bog, ARB re-appears where there are shallow equipotential gradients.

The restoration of organic soils that have undergone subsidence is particularly challenging because of changes to hydraulic gradients and water storage capacity (Price, 2003). While the hydraulic conductivity of peat generally decreases with compaction, it can also increase significantly in localised zones in the form of subsurface cracks and fissures. The introduction of subsurface preferential pathways means that any management designed to arrest subsidence and restore water levels must reinstate/increase groundwater pressures and reduce hydraulic gradients between peat and substrate to restore the bog's hydrological balance. To achieve this, the discharge outlets for groundwater flows emanating from beneath the bog system must be removed. However, while regional piezometric heads can conceivably raise hydrostatic pressures in this manner, it is not possible to remove the pathways of preferential flow. The presence of these features may permanently impact on peatland ecohydrology, particularly in periods of low antecedent rainfall,

as water is continually drained via the preferential pathway.

5.3 Groundwater Modelling

To raise water levels in bogs impacted by regional groundwater drainage, restoration must be concentrated on marginal drainage. To simulate the impact of blocking a drain on the water table and groundwater flow dynamic at Clara Bog, a two-dimensional steady-state numerical simulation was constructed through the groundwater flow line/transect illustrated in Figure 3.10. The finite element model HYDRUS, which simulates variably saturated transient water content and volumetric flux using a numerical solution to the Richards equation (Šimůnek *et al.*, 2007), was applied in order to account for shallow unsaturated conditions found in degraded areas of the bog transect. The layers in the model set-up consisted of an acrotelm, where it is mapped in the field, peat

divided into “mid” and “deep” sections, lacustrine clay and glacial till, divided into a lower permeable unit and upper low-permeability unit. The hydraulic properties of all materials were based on the field *K* experiments and inverse parameter optimisation was used to refine input hydraulic parameters such as the van Genuchten water retention properties and residual and saturated water content. Recharge was estimated from water balance calculations and set as a constant top boundary condition (30 mm year^{-1}), the catchment boundary (eastern part of domain) was set as a no-flow boundary, the bottom boundary was set to free flow, and the drain and bog margin was set as a variable seepage face boundary.

The model was run to simulate the measured field hydraulic parameters of water level and hydraulic conductivity. Optimisation of these parameters (15 in total) was used to calibrate the model and regression analysis between model and input (field) parameters gave a strong correlation ($r^2 > 0.8$). The graphical

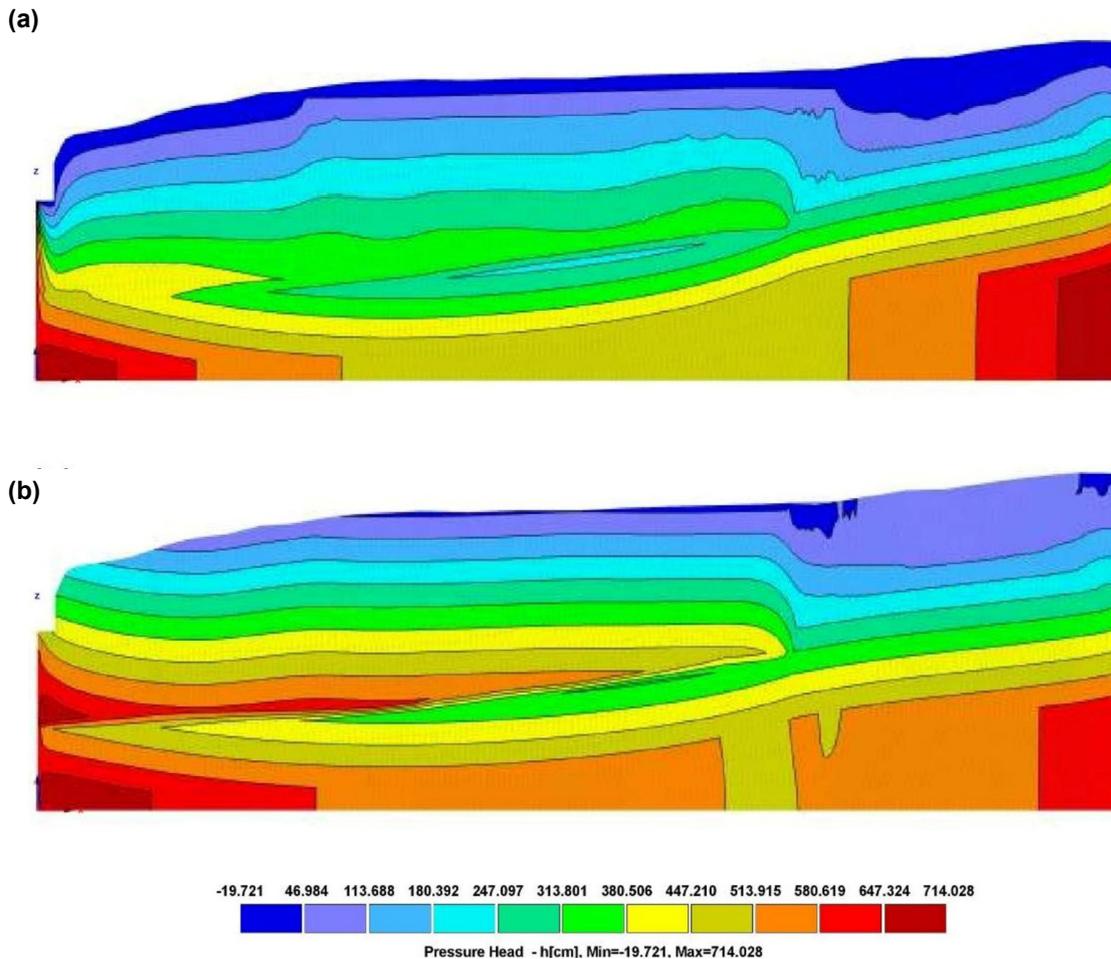


Figure 5.2. Hydrus models of hydrogeological transect at Clara following (a) current steady state conditions and (b) simulated drain blocking.

results of the simulation are shown in Figure 5.2a, which reveals a strong upwards hydraulic gradient at the drain and converging equipotential lines within the bog body, which occurs where peat K is high and highly permeable till underlies peat. The drawdown induced by the drain and highly permeable material is affecting the water table and indicates preferential flow via a connected macropore pathway. Where the water table is shallow, it broadly corresponds with where acrotelm is mapped in the field. In Figure 5.2b, the drain boundary condition is changed to a no-flow boundary, and replicates a situation where the drain invert and the peat seepage-face are blocked with a very low-permeability material, such as clay. The result is that the water table rises close to the face bank (cut-bog margin), but inside the bog body the water table is still drawn down. This indicates that while the groundwater seepage can be blocked locally (on the section), it is not enough to raise the water pressure within the bog – i.e. it is being drawn down regionally (along the whole drainage section). This means that a landscape approach to restoration is required. Furthermore, drain blocking is not sufficient to raise regional pressure heads; infilling the entire stretch of drain that intercepts regional groundwater flow is necessary.

5.4 Hydrological Restoration

The restoration of degraded peatland conservation sites is a legal requirement under the EU Habitats Directive and is the first step towards the sustainable management of the peatland as a natural resource. This process can be difficult, as a lowering of the water table induces peat consolidation, oxidation and sub-surface cracking (Price, 2003). The degree to which it can re-expand is limited by the peat materials' lack of porosity and damage can be irreversible, at least within human timescales, which has implications for the perceived success of peatland restoration strategies. However, rewetting of degraded bog systems via the blocking of drainage ditches has

been shown to return vegetation trajectories towards the recovery of a *Sphagnum*-dominated ecosystem (González *et al.*, 2014).

Restoring the hydrology of peatlands can be expensive because of the cost of implementing the various restoration techniques. It is therefore important to select areas of bog where works should be prioritised based on the probability of re-establishing hydrological conditions favourable to long-term acrotelm regeneration. In areas where the slope is greater than 0.7%, the potential for acrotelm development and recovery is limited and should be considered low priority in restoration design. However, in areas with large catchment areas, lateral flow can sustain high water tables.

The hydrogeological setting of the peatland must be considered. While it is not generally possible to instrument a site with boreholes akin to a research project, inferences can be made based on topography, geological mapping and drainage regime. In situations where peat rests on permeable subsoil, the bog is vulnerable to marginal drainage. Where this occurs, the piezometric head, both in peat and underlying mineral substrates, is an important environmental supporting condition. The decline of these heads with drainage induced the considerable subsidence measured at Clara. In addition to this, consideration needs to be given to the spatial monitoring of the long-term trends in regional groundwater dynamics. In this study, a progressive reduction in regional piezometric head was measured in a monitoring station close to the centre of the bog system, but not in the peripheral areas adjacent to the bog. Without the central monitoring unit, it would not be possible to confidently conclude that drainage is continuing to deplete the groundwater body/aquifer system underlying the bog system. While installing such structures is difficult, the information provided is critical, with regard to both insights into peatland hydrology and informing peatland management and assessing the effects that groundwater withdrawal has on ecosystem functioning.

6 Restoration Guidelines

The following principles can be used as guidelines for assessing the restoration potential and complexity of restoration design for raised bog ecosystems:

1. Identify areas, using high-resolution topographic data, where suitable geomorphological conditions exist to support *Sphagnum* spp. regeneration and growth and thereby raised bog growth (or peat formation and carbon sequestration).
2. Ecohydrological characterisation and monitoring should ideally prelude restoration activities:
 - (a) Ecotope mapping will define the ecological quality of the bog. Ecological mapping should also be carried out in cut bog.
 - (b) Detailed drain mapping in cut and high bog, including levelling of invert levels and determining the direction of water flow.
 - (c) Baseline hydrological data, along selected transects from high to cut bog, will provide data on what current groundwater behaviour is, and monitoring of discharge at runoff outlets will indicate how well water is stored in the bog catchment.
 - (d) This information can be used to guide restoration design, by informing how high water tables must rise and how much water is lost to runoff and groundwater seepage/ infiltration.
 - (e) Baseline data are also critical for assessing restoration success and in guiding other/ similar projects.
3. Restoration potential is greatest where topographic slopes are less than 0.7%. Damming shallow drains will reinstate mean annual water tables to less than 0.2 m below the ground surface if dams are placed every 0.1 m drop in ground elevation.
4. On high bog, where slopes are greater than 0.7–1.0%, drain blocking will be limited with regard to stimulating the growth of *Sphagnum* spp. (although they will still slow the release of runoff from the bog catchment and reduce the load of DOC entering water courses).
5. A water table deficit in this scenario can be compensated by a large contributing catchment area. However, it is generally not feasible to engineer this situation. Raising the water table and reducing the hydraulic gradient in this instance will require substantial damming of the bog margin.
6. Marginal dams may encounter upwards groundwater hydraulic gradients, which could destabilise dams made wholly out of peat. Topographic slopes will also be high towards the bog's facebank, meaning that open water will concentrate at the dam. Marginal dams thereby require geotechnical investigation and design on slope stability and risk of failure. This will probably be a costly action and should be considered only if necessary for the long-term conservation of the raised bog system.
7. On cutover bog, the same principles (1–5) apply, but the ground surface should be considered to be levelled to contain slopes to <0.5% for maximum restoration potential. The retention of water in ponds and pools can stimulate the growth of *Sphagnum* spp. and the installation of low-lying berms (height <20 cm) that follow topographic contours could potentially accelerate this process.
8. In situations where water losses also occur vertically through the peat profile, damming of shallow drains will have limited impact. In this scenario, groundwater drainage is driving peatland degradation and a landscape approach to management is necessary.
9. To identify bogs that are impacted by groundwater drainage, a number of indicators can be recognised:
 - (a) Bogs that are impacted by groundwater drainage are underlain by permeable subsoil ($K > 10^{-3} \text{ m s}^{-1}$) or inorganic deposits. These deposits can be identified during field surveys, such as in drains and outcrops in cut bog and adjacent land. Similarly, the presence of

- bedrock indicates a hydraulic connection with a deeper groundwater flow system.
- (b) Regional groundwater flow moves through these deposits and can be detected in the bog's marginal drainage system using field measurements of electrical conductivity and pH.
 - (c) If the bog has been subject to an ecotope survey, and ARB is absent from areas with slopes $<0.5\%$, it is probable that there are vertical water losses (although the possibility of nutrient enrichment should also be investigated).
 - (d) The presence of cracks and slump, flush and mound features away from the bog margin indicate peat consolidation and failure as a result of groundwater drainage increasing effective stresses far beyond the bog margin.
10. The restoration of groundwater-drained bogs requires the installation of marginal dams. In contrast to point 6, a marginal dam in this instance would need to block groundwater flow through the underlying subsoil, in addition to groundwater flow through the peat. However, this may not address the drainage, as groundwater flow paths may still discharge to areas of cutover bog if peripheral drainage outlets exist [i.e. drains and areas of shallow degraded peat (<1 m)].
11. Thus, because of the hydrogeological complexity of this situation, the marginal dam may need to be constructed at the boundary of the cut bog and marginal land. Within this, peat or clay material would be required to fill in the space between the high bog and marginal dam, in order to reinstate hydrostatic pressures required to reduce vertical water losses in the high bog itself. Similar to point 6, a hydrogeological and geotechnical study would be necessary to inform engineering design.
12. Management of degraded sites must therefore determine if ecological degradation is primarily a consequence of shallow surface drainage or is linked to groundwater pressures in the wider regional landscape. Restoration design will be significantly different, both in terms of complexity and cost, depending on understanding the mechanisms of water loss from the bog system.

7 Summary, Conclusions and Recommendations

7.1 Ecohydrology

Topographic slope and climatic regime are the primary water table controls on the surface of Irish raised bogs and determine the ecotope type. Mean slope gradients at central, sub-central, sub-marginal and marginal ecotopes were determined to be 0.3%, 0.35%, 0.7% and 1.8%, respectively. Water table duration curves for each ecotope indicate that ARB occurs where water tables are within 0.1 m of the ground surface for approximately 90% of a given year. A subtle transition from sub-central to sub-marginal conditions, and thereby ARB to DRB, occurs when this water table duration threshold drops below approximately 90%. Ecological damage, as a result of desiccation of the acrotelm, is thereby reflected in water table duration curves, with marginal and cutover bog sites with no *Sphagnum* spp. retaining little water within 0.1 m of the ground surface over a given year.

The hydrology of the bog also relies on the maintenance of high water levels in the peat and thus the interaction between the water in the peat and the underlying regional groundwater. At Clara, the decline of the piezometric head in the peat is shown to have induced considerable subsidence that is a result of regional groundwater drainage in marginal areas outside the intact bog. In contrast to Abbeyleix, there is a strong hydrological connectivity at Clara. This is mainly because of the bog being underlain by mineral subsoil/substrate whose hydraulic conductivity properties are a number of orders of magnitude higher than lacustrine clay or low-permeability glacial till deposits found at Abbeyleix and generally found elsewhere.

This study demonstrates that the piezometric head, both in peat and underlying mineral substrates, can be an important environmental supporting condition in raised bog ecohydrology. This information is thereby also necessary to inform peatland management and for assessing the effects that groundwater withdrawal has on ecosystem functioning.

7.2 Greenhouse Gas Emissions

Ecotope CO₂ emission factors were upscaled to the level of habitat using ecotope mapping. At Clara, the NEE in Year 1 was $1.8 \pm 15 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ and $47.8 \pm 16 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ in Year 2, with decreased sequestration in the second measurement period related to a lowered water table due to an almost 45% decrease in rainfall. Overall, despite being a near-intact bog, Clara is a moderate source of CO₂ because of the proliferation of the marginal ecotope. At Abbeyleix, the NEE in Year 1 was $131.84 \pm 29 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ and $96.7 \pm 51 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ in Year 2, with decreased emissions in the second measurement period related to a higher water table due to a > 12% increase in rainfall. Thus, despite restoration of high bog surface drainage, Abbeyleix is a significant source of CO₂.

The CO₂ emission ecotope factors calculated at Clara and Abbeyleix are further upscaled to the total area of Ireland's SAC network (53 raised bogs). Using average CO₂ emission values from both sites, central, sub-central and sub-marginal ecotopes are moderate sinks, sequestering c. -105, -198 and -565 tonnes C-CO₂ year⁻¹. In contrast, marginal ecotope emits c. 4581 tonnes C-CO₂ year⁻¹, meaning the raised bogs in Ireland that are designated as European sites emit c. 80% more CO₂ than they take in. The value of bog restoration is thus not as much about creating a carbon sink as it is about preserving the peat carbon store and reducing emissions.

Emission factors have been calculated for areas of cut and drained bog. At Clara, an area of bare peat was a significant source for CO₂ in both measurement years, at $108.8.4 \pm 28$ and $120.8 \pm 24 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$, respectively. At Abbeyleix, measurement sites in areas of cutover bog dominated by *Sphagnum*, *Eriophorum* and *Calluna* are considered as being broadly representative of wet, transition and dry cutover bog, respectively. In *Sphagnum* cutover, the area was a significant sink in both measurement years, sequestering -47 ± 43 and $-53 \pm 42 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ in 2016 and 2017, respectively. *Eriophorum* cutover was a moderate

source in 2016 ($3 \pm 61 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$) and sink in 2017 ($-22 \pm 76 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$). In contrast, the *Calluna* cutover area was a significant source of CO_2 in Years 1 and 2, at $219 \pm 50 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ and $156 \pm 61 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$, respectively.

The average CH_4 emissions for central, sub-central, sub-marginal and marginal ecotopes at Clara between 2015 and 2017 were 10.6 ± 5.4 , 8.7 ± 2.8 , 6.0 ± 2.1 and $1.1 \pm 0.5 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$, respectively, and are strongly correlated with water table depth. CH_4 emissions are highest and most variable at the central plot sites as a result of the presence of vegetation such as *Eriophorum*. This is similar at Abbeyleix, where annual CH_4 emissions are highest for the *Eriophorum* cutover ($14.2 \pm 4.8 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$) and sub-central ecotopes ($12.6 \pm 7.9 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$). Similar to marginal ecotope at Clara, the annual CH_4 flux for the *Calluna* cutover ecotope at Abbeyleix is $2.7 \pm 1.4 \text{ g C-CH}_4 \text{ m}^{-2} \text{ year}^{-1}$.

Annual losses of DOC at Abbeyleix were 8.0 ± 1.6 and $12.8 \pm 2.5 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively, while at Clara the DOC loss between November 2016 and November 2017 was 6.39 ± 1.8 and $15.6 \pm 2.3 \text{ g C m}^{-2} \text{ year}^{-1}$ for catchments on uncut bog and on cutover bog in a groundwater-fed marginal drain, respectively. The loss of carbon in fluvial pathways was significant at both bogs. This is particularly the case at Clara, where the transfer of carbon from the ecosystem to the stream network is via both surface runoff and groundwater drainage.

At Clara, the net ecosystem carbon balance (NECB) has been calculated for two catchment areas. Both catchment areas are net carbon sources, with emissions of $13.1 \pm 15 \text{ g C m}^{-2} \text{ year}^{-1}$ and $22.3 \pm 18 \text{ g C m}^{-2} \text{ year}^{-1}$ for the surface water and groundwater-fed catchment, respectively. In the groundwater-influenced catchment, the annual carbon loss is almost doubled compared with the carbon balance measured from a surface runoff catchment. This demonstrates the impact of marginal drainage on the carbon balance on an "uncut" bog (i.e. without surface drainage). Moreover, the marginal drain at Clara has caused the subsidence, which has resulted in the significant loss of ARB and peat mass, an unaccounted-for component of the carbon balance. The subsidence measured at Clara has altered the composition and distribution of the bog's vegetation, with impacts on the NECB.

At Abbeyleix, two ecotopes were, on average, carbon sinks across both years: the *Sphagnum* cutover ($-29.8 \pm 42 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and $-30.0 \pm 40 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2017) and the sub-central ecotopes ($-53.0 \pm 37 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and $-62.4 \pm 46 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2017). In contrast, the *Calluna* cutover ecotope was a substantial carbon source of $234 \pm 52 \text{ g C m}^{-2} \text{ year}^{-1}$ and $175 \pm 61 \text{ g C m}^{-2} \text{ year}^{-1}$ for 2016 and 2017, respectively.

Peatlands are considered resilient to gradual changes in climate. However, ecosystem stability can be lost when critical environmental thresholds are passed. This study finds that the water table dynamic is the critical driver of GHG emissions and further confirms that peatland carbon and water cycling are strongly coupled.

7.3 Restoration

Engineering solutions required to restore the hydrological balance of degraded raised bogs can be costly if works are not focused in appropriate areas. A functioning acrotelm is a pre-requisite to the ecosystem and therefore must be tackled first in remediation/management plans. This study describes the design methodology, using slope criteria, for targeted hydrological remediation on bogs subjected to near-surface drainage. The analysis of ecotope distribution from 53 geographically spread uncut bogs finds that ARB is mapped predominantly in low-gradient areas, $< 0.6\%$ within a 95% confidence interval. DRB is found on higher slopes, $< 1.2\%$ within a 95% confidence interval, while damaged conditions are found on slopes $> 1\%$.

Therefore, to maximise regeneration potential, restoration works must restore surface water slopes (the hydraulic gradient) that ensure maximum water table depths of 0.2m beneath the ground surface. Accordingly, restoration work, such as the installation of dams, should be focused in areas where topographic gradients are $< 1.0\%$, with no more than 10 dams installed per 100m stretch of drain. Beyond these thresholds, the restoration of ARB is highly unlikely, as also indicated by ecotope water table duration analysis. In areas where ARB occurs on slopes $> 0.6\%$, it implies that larger catchment areas are locally important in sustaining shallow water tables. This lateral flow component is demonstrated to be significant at both Abbeyleix and Clara. Further

research is required to determine what size of catchment is needed to sustain ARB conditions in areas with high slopes. This is likely to be both scale and climatically dependent.

The maintenance of shallow water tables is dependent on there being minimal downwards infiltration/seepage at depth through the peat profile. At Clara, marginal drainage has resulted in peat drainage and significant subsidence of the bog surface. This has altered the hydraulic properties of the peat and introduced preferential pathways for groundwater flow. Where this has occurred, there are significant localised increases in recharge to the underlying mineral subsoil/substrate. Hence, any management designed to arrest subsidence and restore water levels must reinstate/increase groundwater heads and reduce hydraulic gradients between peat and substrate to restore the bog's hydrological balance. To achieve this, the discharge outlets for groundwater flows emanating from beneath the bog system must be removed. This therefore necessitates a regional approach to bog ecohydrological management, as indicated by the results of the groundwater modelling exercise.

Ecohydrological monitoring is required post restoration, in the short term to ensure hydrological conditions are re-established and in the long term to assess the regeneration of peat-forming vegetation. Knowledge of a site's local hydrogeology, such as the presence of permeable till or subsoils and discharging mineral groundwater in drains close to the remaining bog, can serve as a good indicator of its connectivity with regional groundwater flows and vulnerability to marginal drainage.

In cutover bogs, surface slope is also a key factor in sustaining a high water table. However, because of the absence of *Sphagnum* and/or bare peat surface, consideration should be given to the importance of localised water storage features on the ground surface, such as berm structures. Evidence at Abbeyleix suggests that the presence of old and disconnected drainage ditches in areas of shallow gradient cutover bog have aided *Sphagnum* regeneration by providing storage for surface water. This is similar to processes that occur during natural peatland development, where the presence of pools on the bog surface is a prerequisite for the development of bog microforms and peat accumulation. However, old drains can be functional long after the cessation

of peat extraction, which would continue to drain the peat and compromise surface water storage. Further research is required to examine the importance of localised water storage for the regeneration of *Sphagnum* moss species in drained raised bogs proposed for restoration.

7.4 Climate Change and Adaptation

It is unknown how resilient raised bogs are to current models on projected climate change. The results from this study show that raised bog vegetation is very sensitive to changes in the water table. While changes in the water table at Clara are attributed to land management activities, climate controls the hydrological baseline conditions that allow peat formation and ecosystem stability in undisturbed settings. Increases in atmospheric CO₂ and temperature can potentially increase the growing season of vegetation and thereby their productivity and carbon assimilation capacity. However, such a positive feedback process is compromised by persistently lowered water tables during drought conditions, which inhibits *Sphagnum* growth and increases CO₂ emissions as a result of the decomposition of the surface vegetative layer and shallow peat. Similarly, warmer temperatures can increase the rates of microbial decomposition and cause an increase in the DOC.

Climate change may therefore impact on the peatland carbon sequestration function, result in the destabilisation of stored carbon and increase nutrient and DOC emissions. However, further research is required to examine how expected increases in mean annual temperature and changes in the seasonality of precipitation, with more rain in the winter and less in the summer predicted, could alter the critical environmental variables in Irish bogs and their vegetation successions. This is particularly the case of cutover and mined peatlands, which are already unstable systems with large CO₂ and DOC emissions.

The deployment of large-scale and land-based climate change mitigation measures is encouraged by the IPCC in order to reach the long-term temperature goals of the Paris Agreement. Considering the land area covered by peat soil in Ireland, peatland restoration can simultaneously contribute to both climate change mitigation and adaptation. While climate change may negate the impacts of restoration

activities implemented to address land management pressures, land management decisions that protect peatlands from further damage will increase ecosystem resilience and help slow climate change

and mitigate the impacts. Peatland restoration and protection should therefore form an integral part of a national climate adaptation and mitigation strategy.

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Abbreviations

ARB	Active raised bog
DGPS	Differential Global Positioning System
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DRB	Degraded raised bog still capable of natural regeneration
DTM	Digital terrain model
EC	Electrical conductivity
EU	European Union
GC	Gas chromatograph
GHG	Greenhouse gas
GPP	Gross primary production
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile range
K	Hydraulic conductivity
LiDAR	Light detection and ranging
MAWT	Mean annual water table
NECB	Net ecosystem carbon balance
NEE	Net ecosystem exchange
NHA	Natural Heritage Area
NPWS	National Parks and Wildlife Service
R_{eco}	Ecosystem respiration
SAC	Special Area of Conservation
TCD	Trinity College Dublin

AN GHNÍOMHAIREACTH UM CHAOMHNÚ COMHSHAOIL

Tá an Gníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaoil a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaoil a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: Déanaimid córais éifeachtacha rialaithe agus comhlionta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.

Eolas: Soláthraimid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spríodhírthe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.

Tacaíocht: Bimid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaoil atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaoil inbhuanaithe.

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaoil:

- saoráidí dramhaíola (*m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistriúcháin dramhaíola*);
- gníomhaíochtaí tionsclaíocha ar scála mór (*m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta*);
- an diantalmhaíocht (*m.sh. muca, éanlaith*);
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe (*OGM*);
- foinsí radaíochta ianúcháin (*m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha*);
- áiseanna móra stórála peitрил;
- scardadh dramhuisece;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdarás áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhírú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídionn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaoil.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uisce idirchriosacha agus cósta na hÉireann, agus screamhuisecí; leibhéal uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaoil

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil (*m.sh. tuairisciú tréimhsiúil ar staid Chomhshaoil na hÉireann agus Tuarascálacha ar Tháscairí*).

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis ceaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhar breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainnaint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaoil in Éirinn (*m.sh. mórfheananna forbartha*).

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéal radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as tairmí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaoil ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaoil (*m.sh. Timpeall an Tí, léarscáileanna radóin*).
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosaint agus a bhainistiú.

Múscaill Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an gníomhaíocht á bainistiú ag Bord Iáinimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltáí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair inní agus le comhairle a chur ar an mBord.

Ecohydrology, Greenhouse Gas Dynamics and Restoration Guidelines for Degraded Raised Bogs



Authors: Shane Regan, Michael Swenson,
Mark O'Connor and Laurence Gill

Identifying Pressures

The range and function of raised bogs across Ireland and Europe has decreased greatly in the past few decades. This requires attention in the form of further advances in best practice management for remaining and degraded systems. Effective management therefore requires a quantification of the ecohydrological processes that create and maintain active bog and carbon sink conditions. Accordingly, the aim of this report was to:

- quantify the ecohydrological conditions and greenhouse gas (GHG) emissions from two contrasting raised bogs with different management histories;
- assess the impact of drainage and restoration on GHG emissions;
- assess the implications for management and the re-establishment of degraded peatlands to carbon sink ecosystems; and
- provide guidelines for the restoration of other degraded raised bogs.

The GHG results are consistent with international studies and show that the net ecosystem exchange of carbon dioxide (CO₂) in areas of active bog is in the order of $-50 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ and switches to CO₂ emissions in the order of $100\text{--}300 \text{ g C-CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ when drained. Upscaling fluxes using ecological mapping finds that even relatively intact bogs are sources of CO₂ to the atmosphere because of a limited distribution of *Sphagnum* species. The water table dynamic is the critical driver of GHG emissions and further confirms that peatland carbon and water cycling are strongly coupled. The export of dissolved organic carbon was also found to be a significant part of the bog carbon balance and as significant a pathway for carbon loss as the CO₂ land-atmosphere exchange.

Informing Policy

The development of ecotope CO₂ emission factors in this research finds that Natura 2000 sites in Ireland emit approximately 80% more CO₂ than they sequester. Raised bogs, and peatlands in Ireland generally, are therefore considered significant sources of CO₂ and must be accounted for in GHG land use inventory reporting. The value of bog restoration is thus not as much about creating a carbon sink as it is about preserving the peat carbon store and reducing emissions. It is important that peatland restoration and protection forms an integral part of a national climate adaptation and mitigation plan. Meeting conservation objectives of favourable conservation status for the Natura 2000 network is therefore entwined with land management climate mitigation strategies.

Developing Solutions

Engineering solutions required to restore the hydrological balance of degraded raised bogs, and their carbon sink function, can be costly if works are not focused in appropriate areas. Restoration must reinstate a functioning acrotelm and this study finds that the optimum topographic condition for this is having a slope gradient below 0.6%. Water losses can be compensated with greater proportions of lateral flow but it is difficult to engineer this situation in management. To maximise regeneration potential, restoration works must restore the surface water slopes (the hydraulic gradient) that ensure maximum water table depths of 0.2 m beneath the ground surface. The findings from this research suggest that, in some instances, particularly areas where peat rests on permeable subsoil, groundwater drainage is also an important drainage mechanism and in these scenarios a regional approach to ecohydrological restoration is necessary.