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EcoMetrics – Environmental Supporting Conditions for Groundwater-dependent Terrestrial Ecosystems

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2021–2030

EcoMetrics – Environmental Supporting Conditions for Groundwater-dependent Terrestrial Ecosystems

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EPA Research Report

Prepared for the Environmental Protection Agency

by

Trinity College Dublin

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Executive Summary

This research project evaluated and developed methods for the assessment and definition of appropriate ecohydrological metrics to help policymakers conserve and/or restore wetlands. The project was split into four main work packages, one each focusing on raised bogs, turloughs and calcareous fens, and the fourth being an overarching work package on the use of remote sensing (RS) techniques to monitor changes in the ecohydrological health of wetlands.

The RS study used existing habitat and vegetation mapping techniques and began with a pixel-based approach to mapping vegetation communities across raised bogs. The study was further extended to include segment-based learning, which considers textural information in addition to spectral information, and a mapping vegetation communities (MVC) algorithm was developed. In total, 29 classes of vegetation communities were mapped temporally inside 13 wetlands using the MVC algorithm, with an average accuracy of 84%. To gain higher spatial resolution than that provided by the 10 m Sentinel-2 satellite data, an unmanned aerial vehicle (i.e. a drone) was employed. RS-based monitoring of wetlands was improved by a nested methodology that incorporated georeferenced land cover maps, which were scaled at the drone resolution level and upsampled to Sentinel-2 imagery level through interpolation.

Four fens were instrumented and monitored over a 2-year period, with both their hydrology and hydrochemistry in relation to their different vegetation habitats being investigated. The fens were selected to exhibit a range of different water quantity (drainage) and water quality (nutrient) pressures. The results provided a conceptual model of the groundwater that feeds the fens at discrete points, helping to maintain high water levels even during drought periods in the summer. Groundwater also supplies relatively high concentrations of nutrients, which appear to be picked up by the fen vegetation, thereby leaving lower nutrient concentrations in the surface water runoff from the wetlands. Threshold water level envelopes required for healthy fen vegetation have been defined across all fen habitats (PF1, PF2 and PF3), with the mean annual water level always being above the surface. The setting of water quality thresholds is more challenging and is an area that needs further research, particularly with respect to the link between the wider supporting catchment area and groundwater quality. At the fens studied, the generally higher levels of nutrients in the groundwater feeds (compared with the water quality in the fen) did not appear to be causing any ecological stress to the fen ecosystems, so groundwater threshold values cannot yet be defined with any confidence.

The ecohydrology of two raised bogs, Clara bog and Abbeyleix bog, was intensively studied over a 2-year period as part of a parallel EPA-funded project (Regan *et al.*, 2020). This indicated that active raised bog occurs where water tables are within 100 mm of the ground surface for approximately 90% of a given year. The study also showed that the maintenance of high water levels in the peat may not only be a function of the rainfall onto the bog and the hydraulic conductivity of the peat, but may also be linked to the hydraulic head in the underlying regional groundwater.

This study also investigated a 28-year hydrological record of four turloughs in the west of Ireland (1989–2017) with respect to their ecohydrological metrics. Flood duration and depth, as well as global radiation and temperature (as a proxy for the time of the year when the floodwaters first recede) threshold envelopes, were defined for these vegetation communities. It was suggested that duration may be the key variable that could be used to determine future impacts of damage to such ecosystems. The multidisciplinary research study (Waldren *et al.*, 2015) on 22 turloughs also recommended that phosphorus should be directly measured in turlough flood waters at least once per year, as part of a wider monitoring strategy.

In summary, this project produced the following findings which should be taken forward by policymakers:

- The nested drone–satellite RS methodology should be adopted as a tool for continuous monitoring of wetland health.

- Water level duration envelopes can be clearly associated with required hydrological conditions for the ecological health of different wetland vegetation communities and can be defined.
- Water quality dynamics within such wetlands are more complex than water level dynamics, involving the accumulation and internal cycling of nutrients, so clear thresholds cannot be confidently defined based on the current research; this requires more targeted studies.

1 Introduction

1.1 Background

Wetlands, both those found in proximity to surface water and those depending on groundwater inputs, provide important regulating ecosystem services (such as water purification, carbon capture and storage, and flood protection). They also provide rich habitats for biodiversity, including many protected species. However, many of the world's wetland ecosystems have experienced significant degradation, with negative impacts on biological diversity and on people's livelihoods. Many wetlands have been removed, while others are under threat as a result of proximal land degradation, water quality pollutant impacts and/or water supply pressures (caused by drainage, etc.). In the past 100 years, two-thirds of Europe's wetlands have been lost and those that remain are often heavily degraded, meaning that they are among Europe's most threatened ecosystems (EC, 2007).

Wetland habitats in Ireland occur across a distinct biogeographical climatic gradient, resulting in a diverse array of ecosystems, ranging from upland and low-lying ombrotrophic bogs and groundwater-fed fens to ephemeral karst groundwater lakes (turloughs). Despite an estimated 10% decrease in the area covered by wetlands since 1990, Ireland still contains one of the highest concentrations of wetlands in western Europe. Key habitats, such as raised bog, which have been almost completely lost in other EU Member States (NPWS, 2018), and turloughs, which are characteristic of Ireland's extensive karstic limestone terrains, are highly valued and are priority wetland sites for conservation. Similarly, base-rich fens are one of the most threatened habitats in Europe (Kooijman, 2012), making conservation of the remaining examples paramount.

Research has clearly shown that the ecology of groundwater-dependent terrestrial ecosystems (GWDTEs) is fundamentally reliant on the supporting hydrogeology (Kilroy *et al.*, 2008). Hence, understanding the ecohydrogeological connectivity and environmental supporting conditions of wetland systems is critical for the successful management of wetlands, and for meeting legislative commitments, such as the implementation of the Water Framework Directive (WFD) and the Groundwater Directive. A wetland water supply mechanism (WETMEC) approach, based on a series of hydrological conceptual models with an ecological overlay, has been used in the UK (Whiteman *et al.*, 2009) and Ireland (Kimberley and Coxon, 2013) to represent the dominant pathways of water movement from the groundwater body (GWB) into the GWDTE and assess potential ecological responses to changes in groundwater quality and quantity. However, although it is understood that groundwater is important in maintaining the environmental supporting conditions required to sustain wetland habitat and/or species, there are currently no user-friendly metrics available for assessing the status of the GWDTE and GWB that take into account water demand/availability and/or nutrient levels.

Ireland's geological environment, dominated by Carboniferous limestone bedrock in the central lowlands that combines with a maritime climatic setting on the Atlantic seaboard, has created conditions that are relatively unique for wetland habitats. Over the past 20 years, significant advances have been made in Ireland in terms of understanding the ecosystem functioning of turloughs, raised bogs and fens, which has led to new insights into (1) their eco-hydrological functioning, (2) their dependence on groundwater as an environmental supporting condition and (3) their ecological sensitivity to anthropogenic pressures from land use activities in their catchment areas. This research project has continued the focus on the three different wetland types: calcareous fens, raised bogs and turloughs. More details are given at the start of Chapters 4 (fens), 5 (raised bogs) and 6 (turloughs).

The first major international agreement on the conservation and wise use of wetlands was the Ramsar Convention (1971). This prompted the EU to adopt first the Birds Directive (79/409/EEC) in 1979 and then the Directive on the Conservation of Habitats, Flora and Fauna (92/43/EEC), more commonly known as the Habitats Directive, in 1992. The two designations are collectively known as the Natura 2000 network. Habitats listed in Annex I of the Habitats Directive, which include raised bogs, *Cladium* fens, petrifying springs and turloughs, are all priority habitats that are natural habitat types in danger of disappearance. Member States must maintain or restore these natural habitats to favourable conservation status and are obliged to monitor the status of the habitats under Article 11 of the Directive. Conservation status is assessed holistically and is based on the range, area, structures and functions, and threats/pressures to the existing and future prospects of the habitat. In 2000, the WFD (2000/60/EC) marked a significant advance in environmental legislation and water management. The WFD is receptor orientated and takes an ecological approach to water management and water quality standards, which are based on ecological quality and used to assign status to surface water and groundwater bodies. The WFD recognised that groundwater and surface water represent two components of an interconnected hydrological system; as a result, an improved understanding of this connection across a catchment is increasingly viewed as a prerequisite to more effectively managing water resources. The WFD has progressed water management from being focused on local pollution control to ensuring ecosystem integrity as a whole, and deterioration and improvement of "ecological quality" is defined by the response of the biota, rather than by changes in physical or chemical variables (Hering *et al.*, 2010). As the WFD provides a framework for integrated river basin management, it offers a platform to address wetland-related issues (EC, 2007). An assessment of terrestrial ecosystems that depend directly on groundwater as part of the classification of GWBs is required under Annex V of the Directive. Sites considered ecologically important in European conservation policy are integrated into the WFD, courtesy of the Natura 2000 network, which groups sites designated as Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) under the Birds Directive and Habitats Directive, respectively. Natura 2000 sites that contain GWDTEs are therefore integrated into WFD river basin management planning and their conservation is approached on a catchment basis. Under the EU Groundwater Directive (2006/118/EC), a "daughter" directive of the WFD, a GWB can be classed as being at either poor or good status based on quantitative and chemical elements, and threshold values (TVs) for abstraction and chemical concentrations have been established and are used by the Environmental Protection Agency (EPA). If such pressures on a GWB result in "significant damage" to the GWDTE, the GWB will be classified as being at "poor status" under the WFD and will require mitigation measures (Kilroy *et al.*, 2008). However, the degree to which pressures in the GWB have an impact on the environmental flows of the GWDTE receptors is unclear. A poor Habitats Directive conservation status may not necessarily be the result of hydrogeological impacts, meaning that poor GWDTE condition does not always equate to poor GWB status (Schutten *et al.*, 2011; UKTAG, 2012).

Looking to the future, the new European Green Deal (EC, 2020) proposes a transformative Biodiversity Strategy to tackle the biodiversity crisis by protecting and restoring nature, including through improving and widening the existing network of protected areas and by developing an ambitious EU Nature Restoration Plan for ecosystems across sea and land. Similarly, the United Nations (UN) Decade on Ecosystem Restoration (2021 to 2030) aims to scale up the restoration of degraded and destroyed ecosystems to help to fight the climate crisis and enhance food security, water supply and biodiversity. Such research feeds into the implementation of the new EU Biodiversity Strategy for 2030 as well as those of the ongoing Habitats Directive and WFD as discussed above. Such research also supports Europe's leadership and endeavours to implement many UN Sustainable Development Goals (SDGs), especially SDG6 ("Clean water and sanitation"), SDG13 ("Climate action"), SDG14 ("Life below water") and SDG15 ("Life on land").

1.2 Aims and Objectives

Twenty-one ecosystems on the WFD Register of Protected Areas (Annex I habitats under the Habitats Directive) were identified by the Irish National Parks and Wildlife Service (NPWS) as being directly dependent on groundwater (EPA, 2005), including turloughs, fens and raised bogs. The nature of groundwater dependency in these wetlands differs distinctly with respect to quality, level and contribution/duration (and combinations thereof), and these have been identified as key metrics of environmental supporting conditions for GWDTEs. New and refined approaches are needed to assess the status of

GWDTEs facing pressures associated with the quality and/or quantity of groundwater from the supporting GWB. The aim of this research project was therefore to advance the methods of assessing and defining appropriate ecohydrological metrics to achieve WFD objectives as applied to GWDTEs in Ireland. The project was split into four main work packages, three of which focused on raised bogs, turloughs and fens, respectively, by identifying appropriate metrics that characterise the environmental supporting conditions for these wetlands. This was achieved by evaluating existing data and, where required, some additional field study. In addition, there was an overarching work package that focused on the use of remote sensing (RS) techniques to further identify GWDTEs and to assess changes in their ecohydrological health over time.

The objectives of the project were to:

- understand/define environmental supporting conditions for the water bodies that support turloughs, raised bogs and fens;
- define metrics that characterise these environmental supporting conditions;
- trial these metrics across a range of GWDTEs in different conditions;
- develop RS approaches to identify turloughs, raised bogs and fens;
- develop RS approaches to assess the ecological health of turloughs, raised bogs and fens.

2 Overview of Wetlands Studied – Fens, Raised Bogs and Turloughs

2.1 Study Areas

2.1.1 Fens

The main fieldwork of the project was carried out on four fens: Ballymore fen (County Westmeath), Scragh bog (fen) (County Westmeath), Tory Hill fen (County Limerick) and Pollardstown fen (County Kildare) (Figure 2.1). All four sites are SACs. These calcareous fens were chosen to reflect a range of different apparent pressures, from being in a relatively pristine state to being affected by water quality (nutrient pollution) and/or water quantity (drainage) pressures, as set out in Chapter 4.

Figure 2.1. Fen, raised bog and turlough study site locations.

2.1.2 Raised bogs

The raised bogs used for the field study in the parallel EPA-funded project (Regan *et al.*, 2020) were Clara bog SAC and Abbeyleix bog (non-designated) 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. In addition to this fieldwork, five bogs were used for the RS studies (see Chapter 3), which were Clara bog, Killyconny bog, Knockacollar bog, Mongan bog and Monivea bog; these are all SACs (see Figure 2.1).

2.1.3 Turloughs

A detailed multidisciplinary project on 22 turloughs was carried out for the NPWS by members of the project team between 2006 and 2009 (see Waldren *et al.*, 2015). For this project we focused on four of the turloughs examined in the previous project (Blackrock, Lough Coy, Garryland and Caherglassaun turloughs) on, as these furloughs had also received continued hydrological monitoring in the intervening years, linked to additional studies by Trinity College Dublin (TCD) and the south Galway flood alleviation scheme. In addition to this fieldwork, five turloughs were used for the RS studies (see Chapter 3), namely Blackrock, Knockaunroe, Turloughmore, Roo West and Lough Aleennaun (see Figure 2.1).

2.2 Meteorological and Hydrometric Instrumentation

2.2.1 Meteorological data

Data for meteorological parameters were generally collected by weather stations (Campbell Scientific) installed at each wetland site. Hourly measurements of air temperature and humidity, rainfall, barometric pressure and net radiation were recorded by data loggers. From these data, potential evapotranspiration was calculated according to the Penman–Monteith method (FAO, 1998). Actual evapotranspiration was calculated on a daily basis using a cumulative soil moisture balancing approach for the catchments. For those sites with no weather station, meteorological data were collected from the nearest Met Éireann weather station.

2.2.2 Hydrometric instrumentation and data

The main hydrometric monitoring instrumentation installed as part of this project was at the four fens: Ballymore fen, Scragh bog, Tory Hill fen and Pollardstown fen. Fen piezometers were installed at depths of 3–8 m across different transects across the fens to measure the groundwater pressure head at specific depths and to retrieve water quality samples. Holes were drilled to the depth just before the transition from peat layer to subsoil, while recording the soil logs of the different layers. The tops of each piezometer were accurately located using a differential global positioning system (GPS) (Trimble 4700) and water levels were monitored manually using a dip meter at every field visit. At certain piezometers, pressure transducers (divers) were included to give a full-time series of the water level fluctuations. Phreatic tubes were also installed at the same locations to measure the free water table (and retrieve water quality samples). The combination of piezometers and phreatic tubes enabled information to be gathered on downward or upward hydraulic gradients within the peat, which will help to provide insight into the source of typical chemical compositions of the fen pore water (see Figure 2.2).

Instrumentation was also installed in the wider catchment areas of the research sites to gain information about the quality (and level) of the groundwater feeding the fens. Piezometers were installed as deep as possible, down to the interface between subsoil and bedrock, using a rotary drilling rig provided by Geological Survey Ireland (GSI). In addition, a number of pre-existing boreholes that reached into the bedrock (which typically served as current or previous private domestic water supplies) were also used as monitoring locations (see Figure 2.2).

To collect the flow data for water discharging from Ballymore fen, a flume was installed in the natural outlet (Figure 2.3). Discharge measurements were made more reliable with a stilling well fitted with an OTT Orpheus Mini (integrated pressure sensor and data logger for water level measurement). Stilling wells were already in place in the outlet of Scragh bog (managed by the Office of Public Works – OPW) and Tory Hill fen, which had also been installed with OTT Orpheus Minis.

Similar hydrometric instrumentation (piezometric transects and water discharge measurement gauging stations) was installed in the raised bogs, the details of which are set out in Regan *et al.* (2020). For the turloughs, water level data were also collected using pressure transducer divers with inbuilt dataloggers that were installed as part of previous and other ongoing projects. Detailed 1 m digital elevation models (DEMs) for each turlough were established by light detection and ranging (LiDAR), from which depth–volume relationships were then developed for incorporation into the hydrological/hydraulic models of the karst system with its groundwater surface water interactions (see Morrissey *et al.*, 2020).

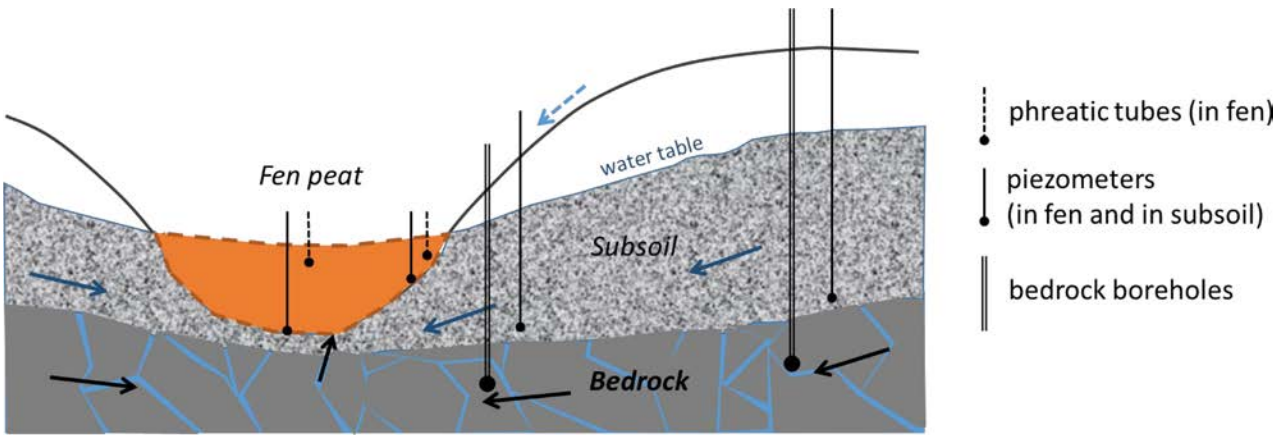

Figure 2.2. Schematic diagram of hydrometric monitoring transects across the fen sites, showing locations of phreatic tubes (in fen), piezometers (in fen and in subsoil) and boreholes into the bedrock.

(a)

(b)

Figure 2.3. (a) Flume and level data logger installed at the outlet to Ballymore fen (Co. Westmeath) and (b) level logger (diver) being downloaded to field laptop.

2.3 Water Quality Analysis

Water samples collected were first tested in the field for electrical conductivity, dissolved oxygen, pH and temperature (Figure 2.4). The samples were then stored and taken back to the laboratory at

Figure 2.4. Water quality field sample collection equipment for the fens.

TCD for analysis of different nutrients (nitrogen and phosphorus) [dissolved reactive phosphorus (DRP), total phosphorus (TP), total ammonia (NH_3), nitrite (NO_2^-), total oxidised nitrogen and total dissolved nitrogen (TDN)], major ions [alkalinity (bicarbonate – HCO_3^-), sulphate (SO_4^{2-}), chloride (Cl^-), calcium (Ca^{2+}), sodium (Na^+), magnesium (Mg^{2+}) and potassium (K^+)], total and dissolved organic carbon and additional metals [ferrous iron (Fe^{2+}), total iron (Fe), manganese (Mn)], using a mixture of spectrophotometry and inductively coupled plasma atomic emission spectroscopy (ICP-AES) methods. Note that DRP refers to the measurement of reactive phosphorus in samples that were filtered through 0.45-μm filters in the field.

2.4 Remote Sensing

The satellite data used on the project were mainly taken from Sentinel-2 and also Landsat 8 satellites. The Sentinel-2 Multispectral Instrument Level 2A (S2-MSIL2A) produces bottom-of-atmosphere (BOA) reflectance in cartographic geometry. The granules, also called tiles, are 100 × 100 km^2 ortho-images in UTM/WGS84 projection. The L2A-BOA product is atmospherically corrected and ready to use (Gatti and Bertolini, 2013), and was accessed from https://scihub.copernicus.eu/. Landsat 8 carries two push-broom instruments: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) in UTM/WGS84 projection. Atmospherically corrected, ready-to-use data can be accessed from http://earthexplorer.usgs.gov/. The RS data used were resampled to 10 m for Sentinel-2 bands and to 30 m for Landsat 8.

The drone used in this study was a DJI Inspire 1™ (DJI, Shenzhen, China) with a high-definition 4K resolution, 12-megapixel (MP) red–green–blue (RGB) camera (see Figure 2.5). The maximum battery lifetime of this drone is 15 minutes, which allows it to capture approximately 12 ha of area flying at a height of 100 m above the ground (although the exact area that can be captured depends on the location, wind speed, distance of take-off and landing point). The spatial resolution flying at a height of 100 m is 1.8 cm.

Figure 2.5. Drone being launched over Clara bog (Co. Offaly).

3 Remote Sensing

3.1 Introduction

Vegetation and habitat monitoring is key to assessing the overall health and dynamics of a wetland. Multiple vegetation surveys, such as the NPWS bog and fen surveys of SAC/Natural Heritage Area sites, and local authority wetland surveys of undesignated sites, were carried out in previous years to map and understand the extent of vegetation on these wetlands. These manual surveys, however, are usually time-consuming and resource-demanding. Furthermore, it is unlikely that such an effort will be repeated regularly to update the resultant data and maps. Hence, there is a growing recognition of RS techniques as a cost-effective and viable alternative (or accompaniment) to field-based ecosystem monitoring. This study aimed to identify and monitor the environmental conditions of the wetlands using machine learning (ML) techniques.

3.2 Satellite Image Analysis

3.2.1 Introduction

The current state-of-the-art technique in terms of RS of wetlands usually involves analysing the spectral response of objects on the ground to different wavelengths (Mahdavi *et al.,* 2018). This study seeks to map the within-site distribution of key ecological communities present in wetland habitats. Vegetation communities present within an ecosystem can be defined and delineated to ecotope level (Fernandez *et al*., 2014; Regan *et al*., 2019). Satellite imagery-derived vegetation indices can be effectively used for assessing the vegetation status of an ecosystem. Vegetation has a higher response in the near-infrared (NIR) region, with the normalised difference vegetation index (NDVI), the soil-adjusted vegetation index (SAVI) and the atmospherically resistant vegetation index (ARVI) stated in the literature to be the most effective vegetation indices (Wiegand *et al.*, 1991). The NDWI, for example, gives an indication of the wetness of the surface inferred as soil moisture, which is not directly derivable from the optical bands. These indices can therefore be used to provide a clearer picture of vegetation and water extent in an area. Topography also plays a vital role in analysing an ecosystem, which can be accurately determined using LiDAR to produce a DEM. It gives an accurate idea of the elevation difference present between various plant communities.

The study was carried out using data from two open-source satellites, Sentinel-2 and Landsat 8, as detailed in section 2.4.

The vegetation indices used in this study are:

(1) NDVI

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R}) / (\mathrm{NIR} + \mathrm{R}) \tag{3.1}$$

where R is red. NDVI indicates the amount of vegetation, distinguishes vegetation from the soil and minimises topographic effects, etc.

(2) SAVI

$$\mathrm{SAVI} = ((\mathrm{NIR} - \mathrm{R}) / (\mathrm{NIR} + \mathrm{R} + \mathrm{L})) \times (1 + \mathrm{L}) \tag{3.2}$$

where L is a soil correction factor.

(3) ARVI

$$\mathrm{ARVI} = (\mathrm{NIR} - \mathrm{RB}) / (\mathrm{NIR} + \mathrm{RB}) \tag{3.3}$$

where RB is a combination of the reflectance in the blue (B) and R channels, $\mathrm{RB} = \mathrm{R} - \gamma(\mathrm{B} - \mathrm{R})$, and γ depends on the aerosol type.

(4) Soil moisture: NDWI

$$\mathrm{NDWI} = (\mathrm{NIR} - \mathrm{SWIR}) / (\mathrm{NIR} + \mathrm{SWIR}) \tag{3.4}$$

Values range from –1, very low moisture level, to 1, very high moisture level.

Hence, there are a total of five extra layers (i.e. NDVI, SAVI, ARVI, NDWI and DEM) along with satellite bands, which are fed into the algorithm as input characteristics. Therefore, for the Sentinel-2 dataset there are 14 layers in total and for Landsat 8 there are 17 layers in total.

For analysis of the RS data, various ML tools have proven to be useful (Lu and Weng, 2007) and there are many state-of-the-art segmentation and classification algorithms available. Full use of the advantages of the different algorithms should be taken to achieve a better segmentation effect (Yuheng and Hao, 2017). Hence, in this study, a combination of segmentation algorithms has been deployed. Classification accuracy has been tested using various classifiers, namely support vector machine (SVM), bagged tree and subspace *k*-nearest neighbour (KNN). SVM can be tuned using the value of optimisation parameter, i.e. the kernel used, and hence overfitting can be avoided. Bagged tree and subspace KNN are ensemble classifiers that are formulated to learn from a set of classifiers rather than a single classifier. The final result either is the average of the results from all the classifiers or is obtained using majority voting. An ensemble learner is robust and requires fewer resources for tuning the parameters. Here, a comparative study on the performance of the classifiers was carried out using freely available Landsat 8 OLI and Sentinel-2 Multispectral Instrument (MSI) data for monitoring ecological conditions and mapping ecotopes present inside the wetlands.

3.2.2 Pixel-based classification of wetlands

Wetland boundary delineation

Delineation of the wetland extent was carried out using three algorithms in conjunction:

1. Entropy filtering. This measures the relative change in entropy for the detection of edges. All the areas with potential objects are thus highlighted.
2. Canny edge detection. Initially, the intensity gradient is measured according to which background pixels are removed, i.e. only thin lines depicting edges remain. The algorithm uses two thresholds (upper and lower) to accept the pixels as the edge.
3. Graph cut segmentation. This divides every pixel into the foreground (source) and background (sink), based on probability and neighbourhood information. Two key steps then follow; the first step is constructing the graph and the second step is producing a minimum cut (min-cut) of the graph (i.e. max-flow – maximum flow).

As the ecosystem and surrounding areas contain distinct vegetation, the NDVI image is used as the base image (Bi) for defining the bog boundary for the Sentinel-2 dataset and band 8 (panchromatic) for the Landsat 8 dataset. An example of this sequential process is shown in Figure 3.1 for Clara bog.

Ecotope identification and classification

The applicability of pixel-based, supervised classification was tested on a raised bog. The classifier

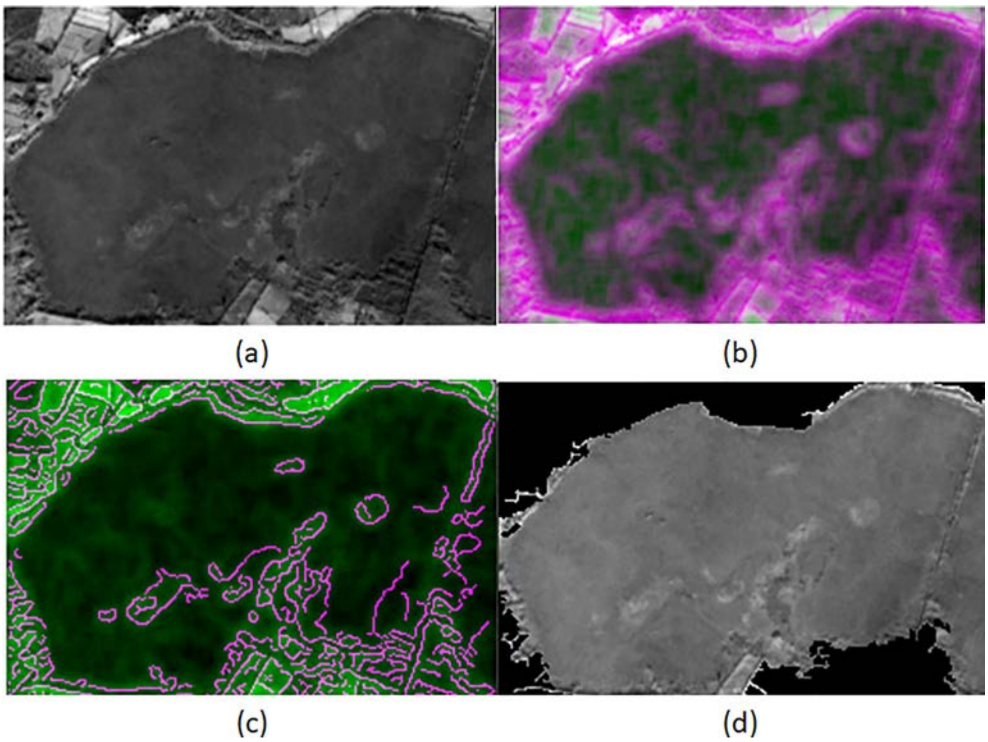

Figure 3.1. Sequential process for wetland boundary delineation. (a) Original Clara bog image, (b) entropy filter image, (c) Canny edge image and (d) boundary-delineated image.

is first trained on a subset of available data and then tested on a new location (test) to predict the classes (ecotopes) present. This involves a direct transfer of pixel-based knowledge from the training area to the testing area. The following classifiers are used for this purpose:

1. SVM. These are supervised learning models with associated learning algorithms that analyse data used for classification and regression analysis. Given a set of training data, a SVM training algorithm builds a model that assigns new data to one of the two categories, making it a non-probabilistic binary linear classifier (Cortes and Vapnik, 1995).
2. Bagged tree. This is an ensemble, supervised classifier approach, which combines several ML techniques into one predictive model to decrease the variance, hence tuning the prediction into an expected outcome (Thoma, 2017).
3. Subspace KNN. Similar to bagging, subspace KNN is an ensemble method to reduce the correlation between estimators (Ho, 1998).

In this study, five major classes were considered, namely submarginal, subcentral, marginal, central and active flush, as these are the key ecological classes indicating bog condition (Regan *et al*., 2019). The result achieved was then verified using a field-derived ecotope map from the NPWS (Figure 3.2).

The results obtained using the algorithms were validated using field-derived ecotopes and are shown in Figures 3.3–3.5. This study primarily highlights the condition of the raised bog during the summer season. TA signifies the scope of transferring the knowledge gained from the first half (train) to identify ecotopes in

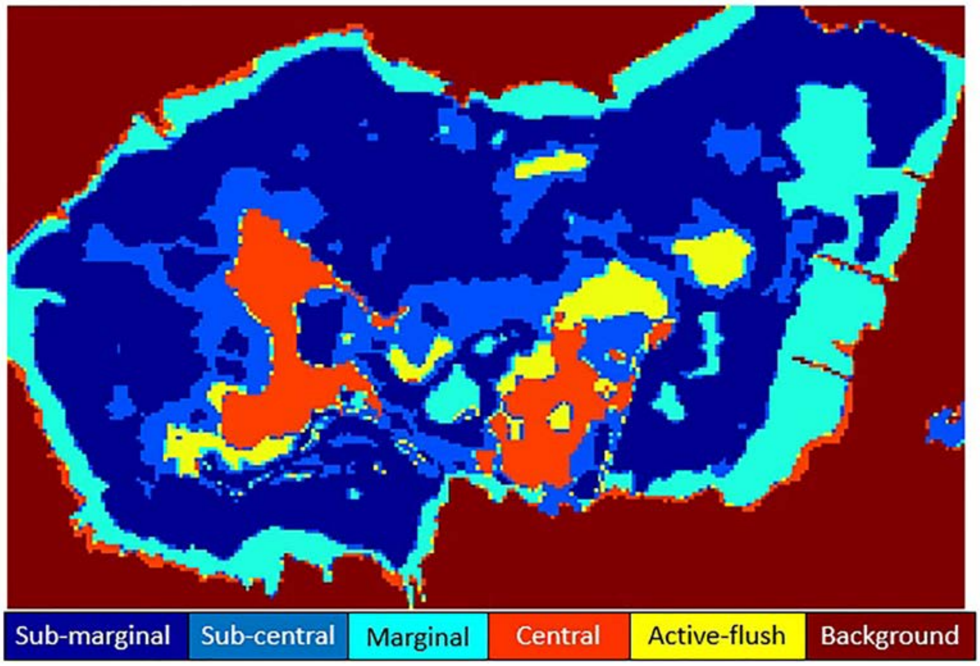

Figure 3.2. Clara bog ground truth with five ecotopes (derived from NPWS, 2020).

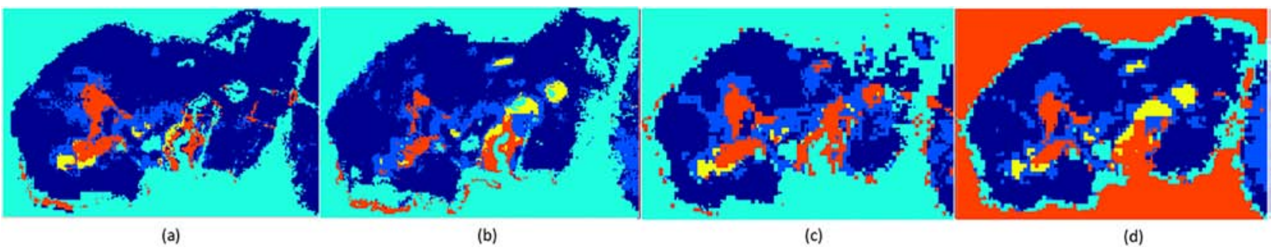

Figure 3.3. SVM-classified image: (a) Sentinel-2 Case 1, (b) Sentinel-2 Case 2, (c) Landsat 8 Case 1 and (d) Landsat 8 Case 2.

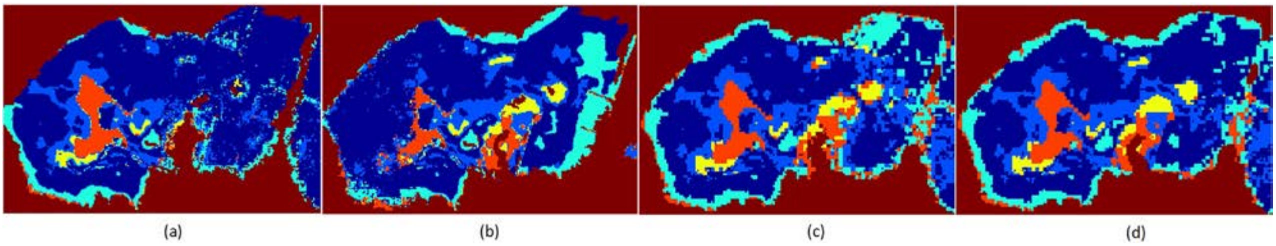

Figure 3.4. Bagged tree-classified image: (a) Sentinel-2 Case 1, (b) Sentinel-2 Case 2, (c) Landsat 8 Case 1 and (d) Landsat 8 Case 2.

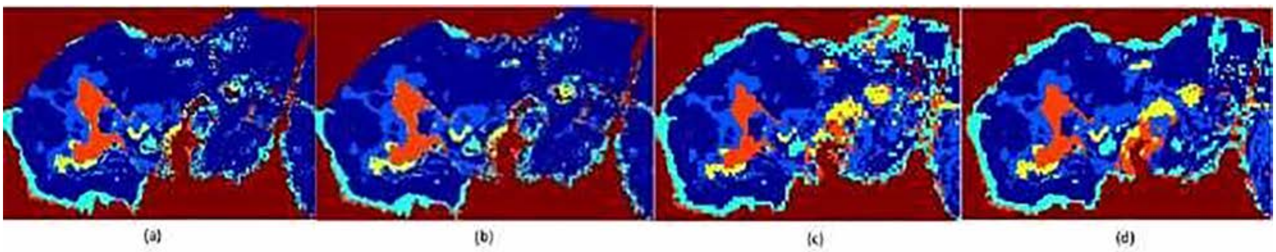

Figure 3.5. Subspace KNN-classified image: (a) Sentinel-2 Case 1, (b) Sentinel-2 Case 2, (c) Landsat 8 Case 1 and (d) Landsat 8 Case 2.

the second half (test). Table 3.1 states the accuracy achieved using the aforementioned methodology.

The final classification accuracy was similar whether the RS data were taken from the Sentinel-2 or Landsat satellite and was also unaffected by the resolution of the images. The study initially described a competent way to delineate boundaries using a series of edge detection techniques. Vegetation indices, along with soil moisture and DEM information, were used as features to train the classification algorithms. The bagged tree classifier proved to be the best for classification of the raised bog, providing better accuracy than either SVM or subspace KNN. This is because the ensemble classifier reduces variance and avoids overfitting. Transfer of knowledge directly from the training location to the test location was not achieved effectively because of limitations in data resolution and the number of input training pixels. The study suggests that transfer of knowledge is effective between similar ecosystems when there is a distinct difference in the distribution of various ecotopes and with little mixing of the pixels. For more details of this work, see Bhatnagar *et al.* (2018).

Table 3.1. Accuracies for all the cases (Clara bog)

Classifier	MA (%)	TA (%)	kappa
Sentinel-2 Case 1			
SVM	73.96	32.40	0.1302
Bagged tree	83.63	53.46	0.3424
Subspace KNN	81.65	52.95	0.3370
Sentinel-2 Case 2			
SVM	71.71	36.36	0.2050
Bagged tree	83.38	65.23	0.5013
Subspace KNN	62.02	36.50	0.1922
Landsat 8 Case 1			
SVM	77.82	26.76	0.1305
Bagged tree	87.27	53.87	0.3883
Subspace KNN	87.22	51.97	0.3635
Landsat 8 Case 2			
SVM	72.92	29.06	0.1711
Bagged tree	85.55	52.69	0.3539
Subspace KNN	85.00	52.71	0.3549

MA, model accuracy (as determined against the training data); TA, test accuracy (as determined against the testing data).

3.2.3 Segment-based classification of wetlands

Sentinel-2 satellite data were used to map vegetation communities in the wetlands. This was done by performing supervised classifications using the bagged tree and image segmentation using maximum a posteriori (MAP) probability. The Sentinel-2 satellite-level 2A BOA reflectance images were used for multiple dates over 2 years (2017 and 2018) and the results were verified using field-derived vegetation maps. An overview of the workflow is shown in Figure 3.6.

As a first step, the boundary delineation algorithm described in section 3.2.2 was applied using NDVI as the base image to separate wetlands from non-wetland areas. Then ecotope identification and classification algorithm were developed based on the graph cut and bagged tree classification algorithms, using the following steps:

1. preliminary classification, using multiple classifiers:
   (a) two-kernel based: SVM classifier and subspace KNN, and
   (b) two ensemble classifiers: bagged tree and random forest (RF);
2. likelihood estimation;
3. data and smoothness function;
4. energy minimisation using α-expansion;
5. forming discrete segments.

See Bhatnagar *et al.* (2020a) for more details on this.

3.2.4 Case studies of segment-based classification of raised bogs, fens and turloughs

Case study 1 – Clara bog

The key ecotopes in Clara bog are based on a vegetation classification system developed by the NPWS (Fernandez *et al.*, 2014) to characterise the different conditions of a bog from the ecologically pristine active raised bog (ARB) down to a degraded status as follows: the central ecotope, subcentral ecotope, active flushes and soaks, submarginal ecotope and marginal ecotope. Actively accumulating peat conditions occur within the central and subcentral ecotopes, which are generally located at the centre of the bog. Along with the central and subcentral ecotope areas, active flush areas have focused surface water flow with typically perennially wet conditions that are dominated by bog mosses (Schaaf and Streefkerk, 2002; Mackin *et al.*, 2017). In contrast, marginal and submarginal ecotopes are characterised by drier vegetation communities.

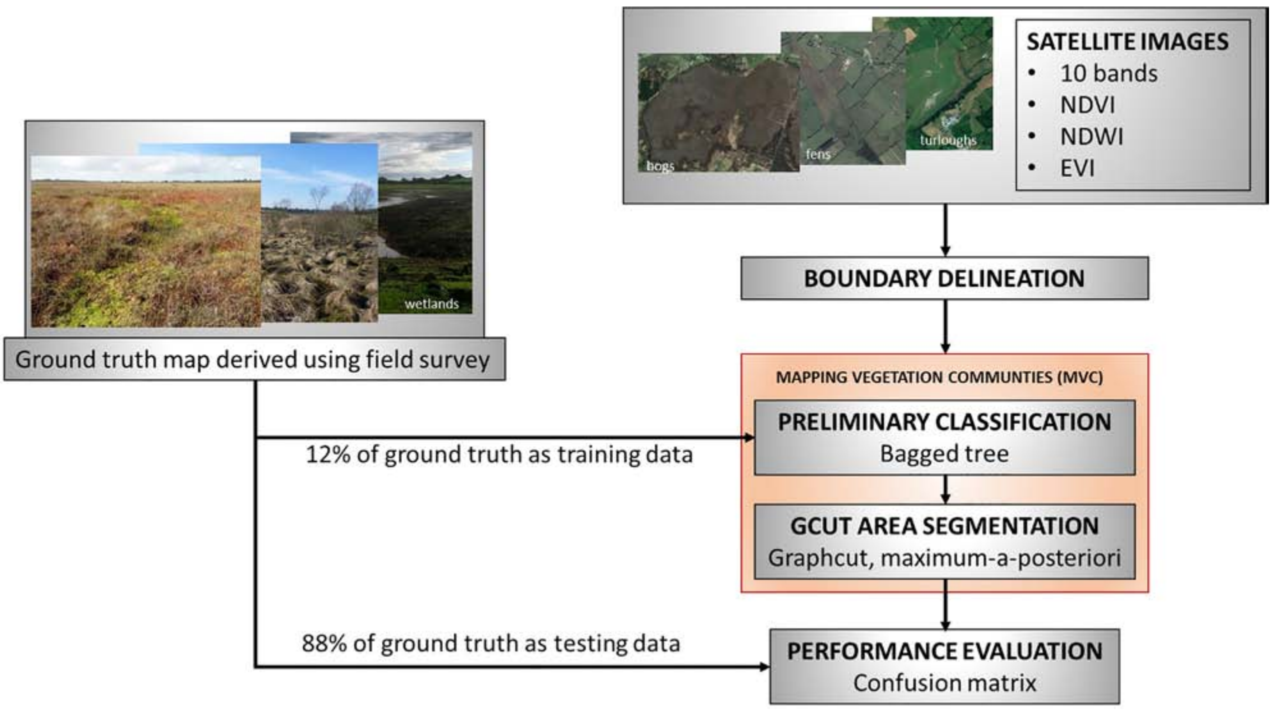

Figure 3.6. Overall methodology used to map vegetation communities in wetlands using segment-based classification. EVI, enhanced vegetation index.

The results obtained for Clara bog for 2017 and 2018 using the mapping vegetation communities (MVC) algorithm are presented in Figure 3.7.

The overall accuracy (OA) for Clara bog ranges from 81% to 87% for all the seasons. For all seasons the crucial wet ecotopes, such as central and subcentral, were picked out accurately.

Case study 2 – Scragh bog

Occupying a narrow basin, which naturally drains northwards, this site is surrounded by intensively managed fields. The northern two-thirds of the site occur on an undulating floating scraw, with the main habitat being transition mire. The centre of the site is the most calcareous part, with an area of extremely wet *Schoenus* fen, and stands of *Cladium mariscus*. There are scattered small trees and shrubs across the transition mire. The south-eastern part of the site is wooded, with fen carr and bog woodland, corresponding to Annex habitat 91D0, some of which has an open canopy over raised bog vegetation. The peat substrate found here is generally alkaline. The transition mires are associated with open waters and quaking bogs. This community reflects the actual succession from fen to bog (Kimberley and Coxon, 2013). This fen also consists of non-peat-forming marsh communities, which are generally quite nutrient rich.

The results obtained for Scragh bog for 2017 to 2018 using MVC algorithm are presented in Figure 3.8. For the fen, the OA ranges from 82% to 84% for all the seasons, and for all seasons the crucial vegetation communities, such as rich fen community and transition mire, were picked out accurately.

Case study 3 – Blackrock turlough

Blackrock turlough under dry conditions comprises 12 vegetation communities, which have been agglomerated into four broad vegetation communities that exist in a turlough by Waldren *et al.* (2015). The first broad community is formed by grouping the *Poa annua–Plantago major* community and *Eleocharis acicularis* community. The second broad community consists of *Carex nigra–Ranunculus flammula* communities and *Agrostis stolonifera–Glyceria fluitans* communities. The third broad community consists of *Agrostis stolonifera–Ranunculus repens* communities, *Agrostis stolonifera–Potentilla anserina–Festuca rubra* community, *Potentilla anserina–Potentilla reptans* communities, and *Filipendula ulmaria–Potentilla erecta–Viola* spp. community. *Lolium* grassland is classified as another community (broad community 4) in this study. Communities such as woodland and scrub were not included as part of the broad communities and were analysed separately. The results obtained for Blackrock turlough for 2017 and

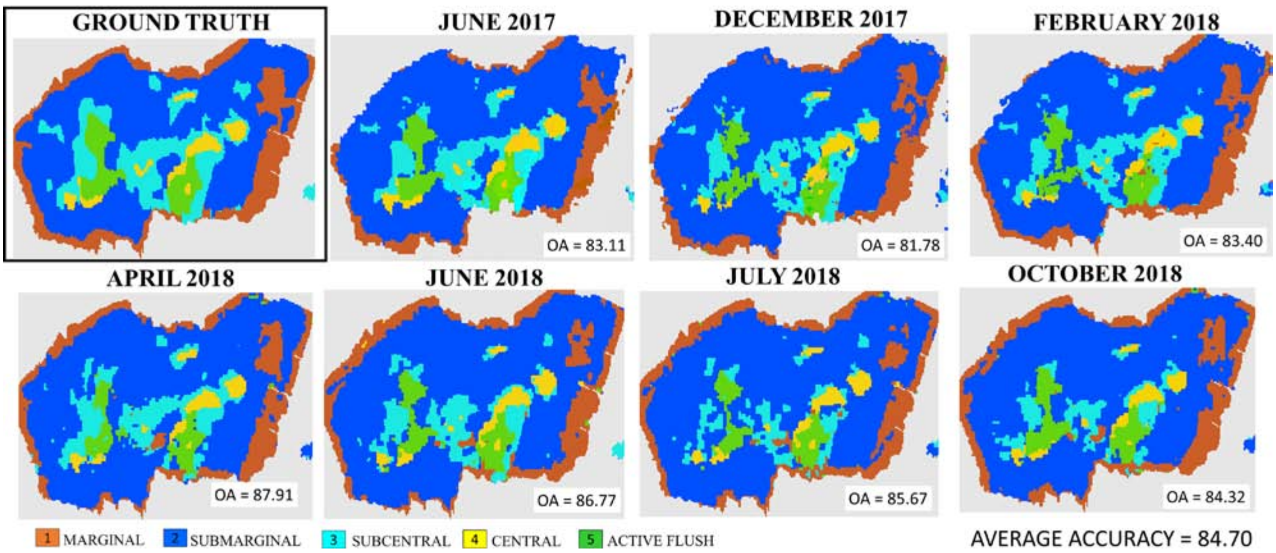

Figure 3.7. Vegetation communities in Clara bog for June 2017 to October 2018, detected using the MVC algorithm (derived from NPWS, 2020).

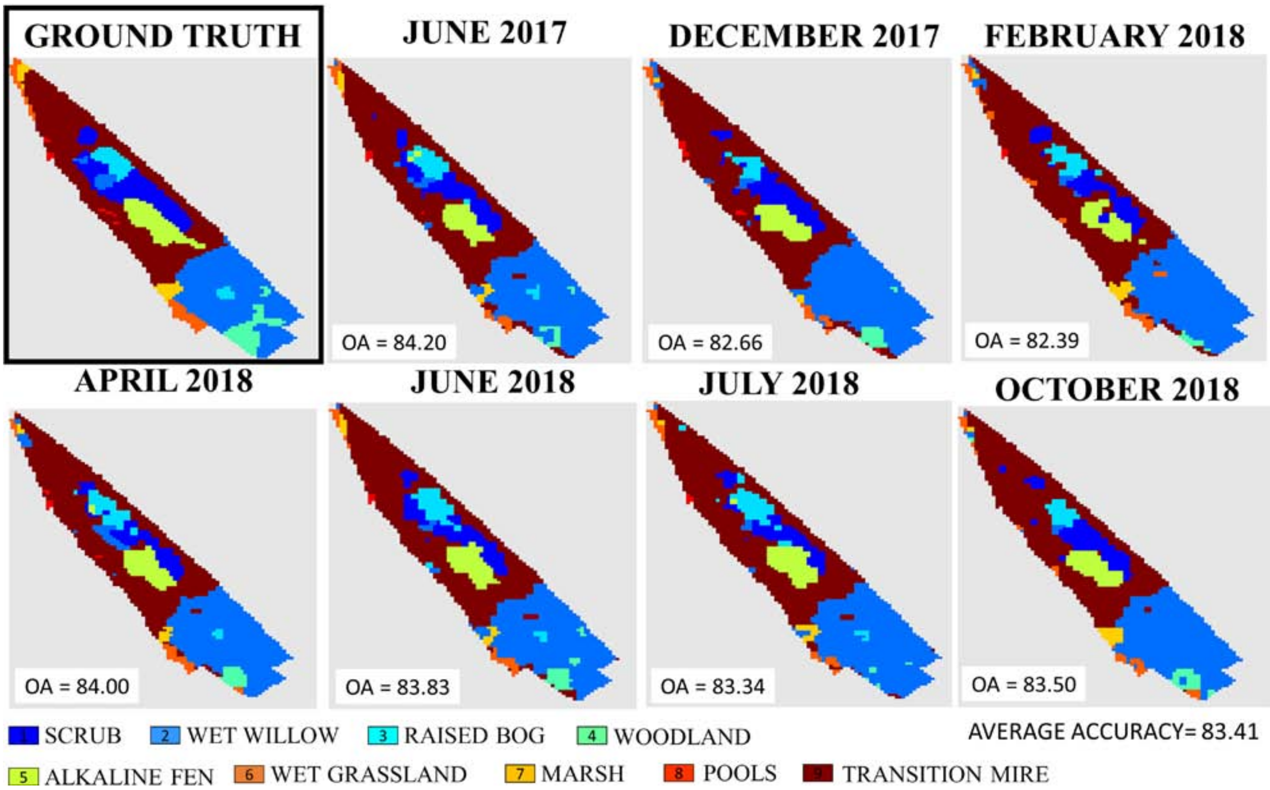

Figure 3.8. Vegetation communities in Scragh bog for June 2017 to October 2018. Ground truth map (NPWS, 2005).

2018 using the MVC algorithm are presented in Figure 3.9.

Using the proposed generalised methodology, up to 18 vegetation communities were mapped in various wetlands, illustrating its wide applicability. The mapping of the different vegetation communities can be used to infer the ecological health of the wetland, making habitat surveys simpler and more effective for

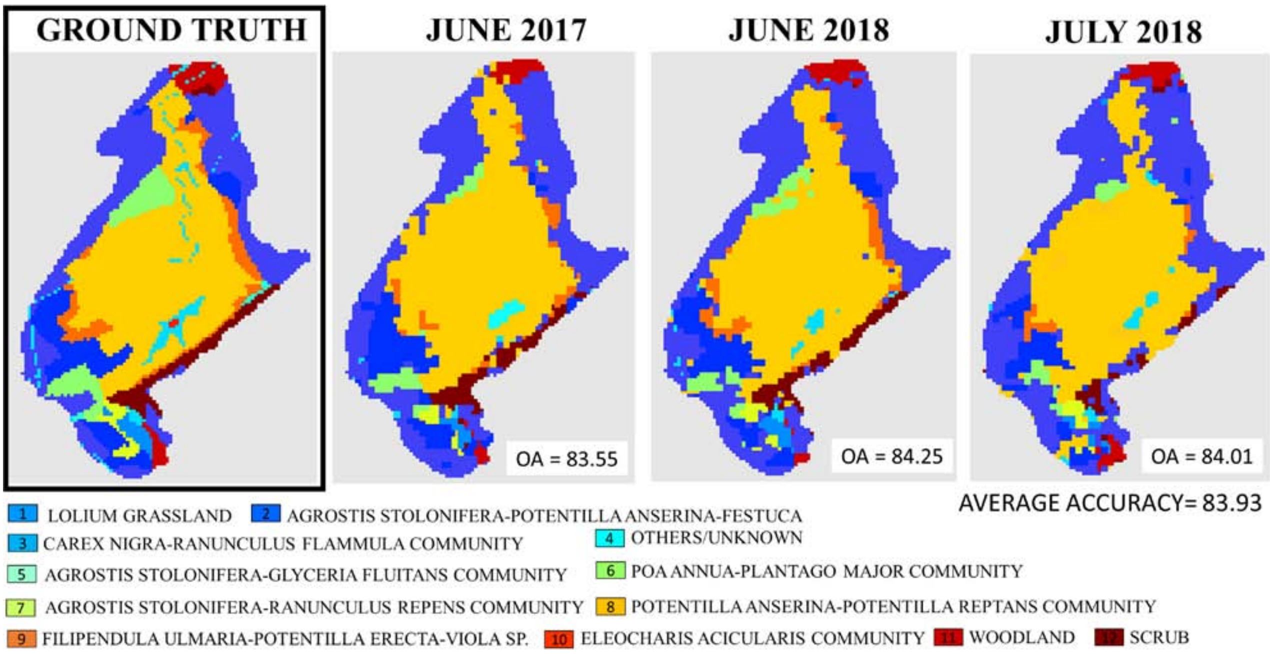

Figure 3.9. Vegetation communities in Blackrock turlough for 2017 and 2018.

ecologists. The average accuracy of all the wetlands mapped in this study is shown in Figure 3.10. The size of vegetation communities played a role in the overall classification accuracy. If the size of the vegetation community was less than 30 pixels (0.3 ha), the precision of mapping decreased, leading to a decrease in OA. This is a limitation of the method, particularly if vegetation communities of high conservation value only occur with limited spatial extent, or in mosaics of limited extent. These wetlands vary significantly in shape and size, making it challenging to identify small vegetation communities using pixels at 10 m resolution; hence, the wetlands with bigger areas and bigger sample pixel sizes have better OAs. Finally, temporal studies carried out on the wetlands using the satellite data over a short 2-year period did not indicate any major ecological changes, thereby indicating their effectiveness. The highest accuracies of about 87% for the raised bog, 84% for the fen and 84% for the turlough were achieved.

3.3 Drone Image Analysis

3.3.1 *Introduction*

The use of drones for different types of vegetation classification has increased over the last decade as a result of the technological development of affordable and lightweight drones. With drones, a very high and flexible spatial resolution can be achieved, which is not possible with satellite imagery due to their fixed orbits. Many techniques are available for analysing drone data and the state-of-the-art techniques in drone image analysis consist of both ML and deep learning (DL) techniques. ML algorithms have been used for vegetation segmentation (e.g. Zimudzi *et al.*, 2019), while wetlands have been classified using ML convolutional neural network (CNN) models (Cui *et al.*, 2019; Hoeser and Kuenzer, 2020). However, it is not clear which technique – the traditional state-of-the-art ML or the advanced DL – is better for identifying vegetation communities. Hence, in this study, both ML and DL techniques have been employed for classifying the vegetation in the different communities on the Clara raised bog wetland, as described in section 3.2.4. The images were captured individually with 70% frontal and 80% sideways overlap at an average speed of 3 m/s. The height of the flight was ~100 m and the spatial resolution of the images captured was 1.8 cm.

3.3.2 *Segmentation using machine learning*

The drone images used for this study have intensity and colour information. Textural features were also subsequently calculated by converting the RGB images into greyscale images. The graph cut segmentation technique was used in this study, based on max-flow min-cut. Based on the texture and colour intensity, a total of 13 bands were used for further

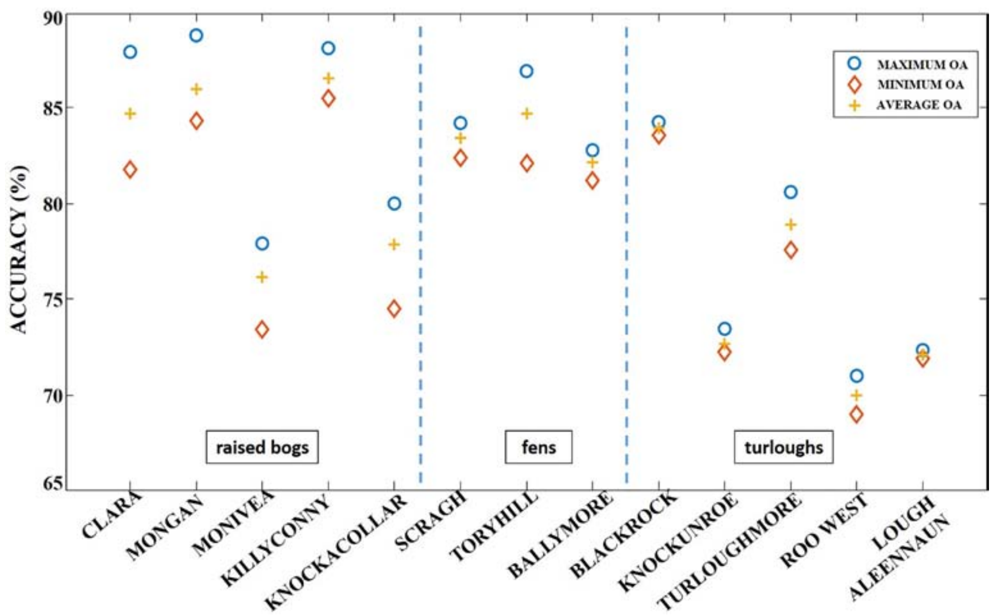

Figure 3.10. Maximum, minimum and average accuracy (%) for all 13 wetlands mapped using RS.

classification of the drone images. Multiple different classifiers were compared in this study (decision trees, naïve Bayes, discriminant analysis, SVM, KNN and RF); ultimately, RF was found to be the best classifier. Once the drone images were classified, they were segmented using the graph cut MAP (energy minimisation) technique. For more details on this, see Bhatnagar *et al.* (2020b).

3.3.3 Segmentation using deep learning

Semantic segmentation using various CNN architectures was applied to identify and label the ecotopes present on Clara bog, namely:

- VGG16 base model with SegNet architecture;
- ResNet50 base model with SegNet;
- VGG16 base model with UNet;
- ResNet50 base model with Unet;
- PSPNet.

For more details on this, see Bhatnagar *et al.* (2020b).

3.3.4 Comparison of machine learning versus deep learning

Figure 3.11 depicts the segmentation results from both ML and DL techniques for a drone image (sized 512 × 1024 pixels) taken of Clara bog. The segmentation was carried out for four ecotope classes present in the drone image captured in the spring season. A key challenge associated with RGB images is the change in light intensity, particularly in a temperate climate such as in Ireland, where sunlight levels are rarely constant for long. Therefore, in this study, all the images with significantly different light conditions were removed.

The best ML algorithm for the given dataset was shown to be the RF classifier used with MAP graph cut segmentation, which reached an OA of 85.1% after addition of textural features. In comparison, for the given dataset, the DL ResNet50 base model with both UNet (OA = 91.5%) and SegNet (OA = 89.9%) architecture performed slightly better. Furthermore, the DL method does not require any colour correction or the addition of extra textural features. However, DL requires a large number of initial labelled training data compared with the ML algorithm, which is also much faster (~30 times) than CNNs. Therefore, for such a specific application as the wetland mapping application, it was considered that the ML approach is more suitable. This would be particularly useful for any unsurveyed wetland, where the minimum amount of information on the vegetation communities is required to produce accurate maps.

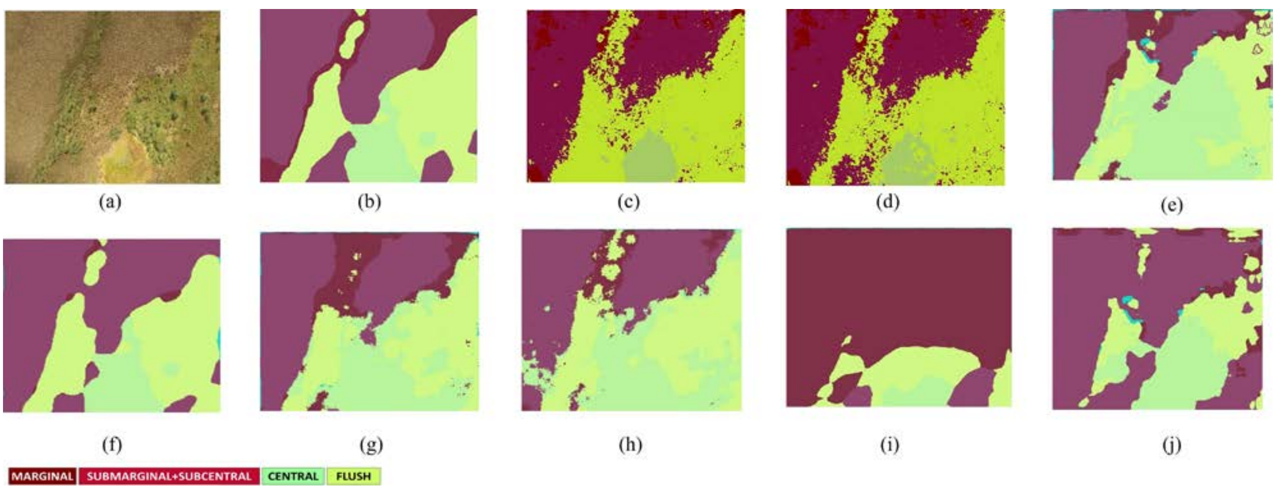

Figure 3.11. Segmentation results from ML and DL techniques on a drone image of Clara bog. (a) Original drone image, (b) ground truth labelled image, (c) ML (RF + graph cut) segmentation using RGB features, (d) ML (RF + graph cut) segmentation using RGB and textural features, (e) DL semantic segmentation using SegNet and VGG16 model, (f) DL semantic segmentation using SegNet and ResNet50 model, (g) DL semantic segmentation using UNet with VGG16 model, (h) DL semantic segmentation using UNet with ResNet50 model, (i) DL semantic segmentation using PSPNet (Cityscapes) and (j) DL semantic segmentation using PSPNet (ADE 20k).

3.4 Nested Drone–Satellite Approach

3.4.1 Introduction

Ecological field surveys, carried out manually to define ground truth maps, inevitably contain some errors due to misclassifications and interpolations between vegetation types. Such ground surveys take multiple days to cover a large land area compared with drone surveys, which are, therefore, more time, and resource-efficient. A proposed method developed in this project uses partial drone surveys of the region of interest to be used as training data to improve the classification of satellite images. This proposed process is described in the flow diagram presented in Figure 3.12.

3.4.2 Drone imagery

The design of the flight path to capture all the main vegetation communities within the area of flight needs to be carefully preplanned. The key details of the processing of the drone imagery were covered in section 3.3 with image preprocessing, involving colour correction (Figure 3.13), image mosaicking and georeferencing (Figure 3.14). The image classification is carried out using the RF classifier, trained on 70% of the drone images, with the remaining 30% used for testing the algorithm. To complement the Sentinel-2 satellite images, the classified drone images were upsampled from the centimetre scale to 10 m using the nearest-neighbour interpolation technique. These

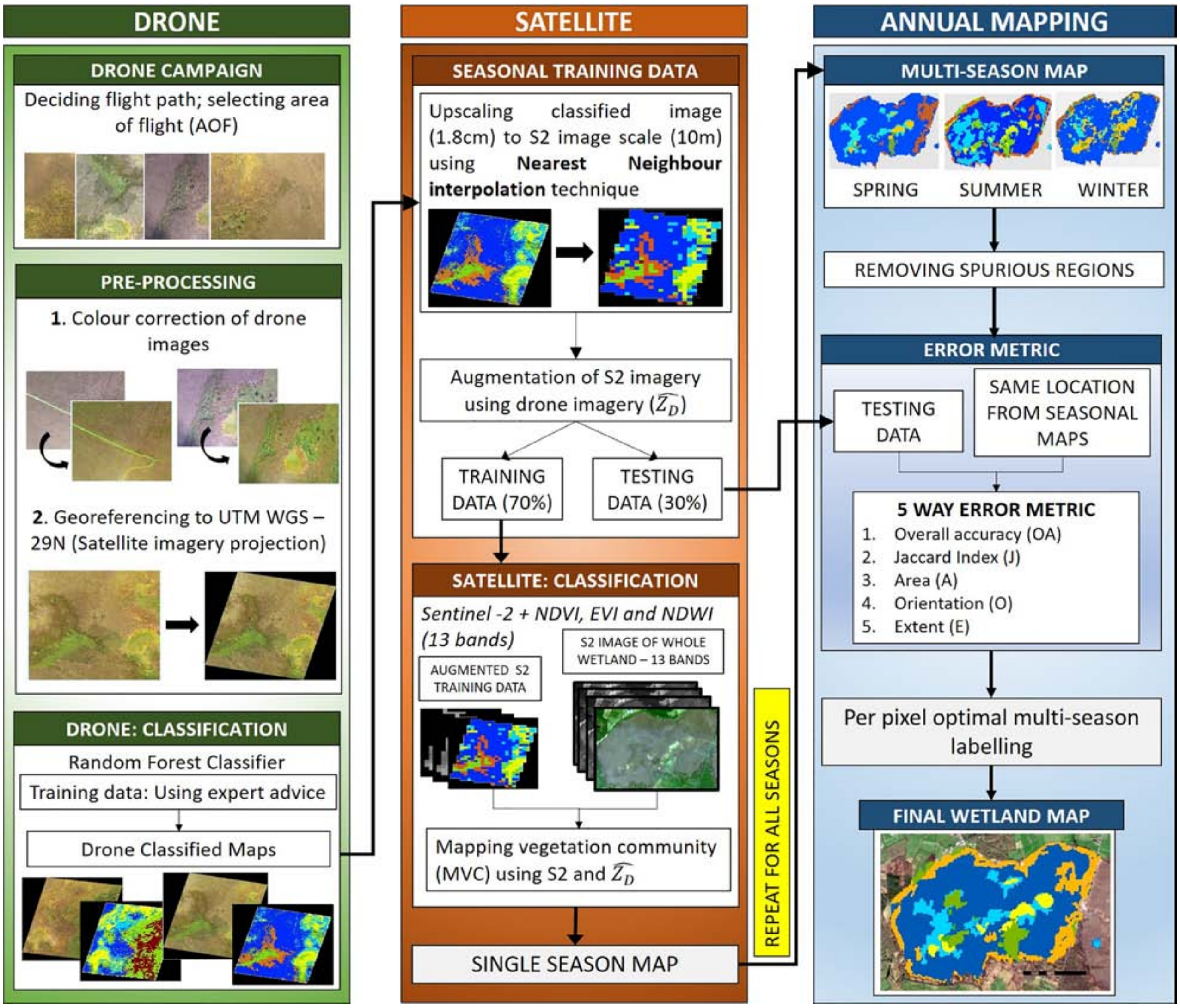

Figure 3.12. Methodology flow chart for the nested drone–satellite approach to wetland mapping. Reproduced from Bhatnagar *et al.* (2021a); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

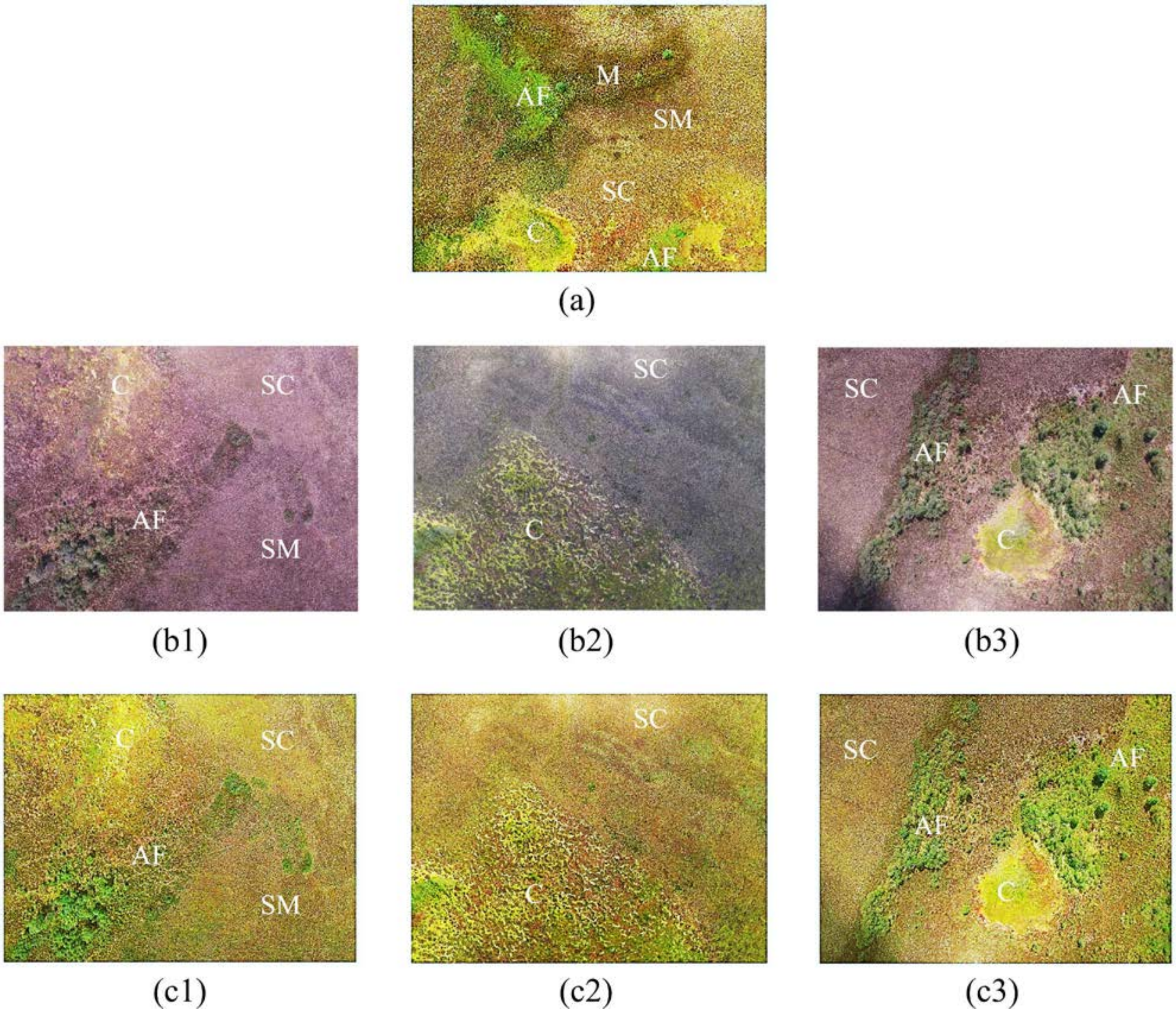

Figure 3.13. Colour-correction using *N*-dimensional probability density function algorithm. (a) Target image, (b1, b2, b3) original drone images and (c1, c2, c3) colour-corrected drone images. Ecotopes: AF, active flush; C, central; M, marginal; SC, subcentral; SM, submarginal.

upsampled images ($\check{Z}_D$) then act as the new training data, which were used with the satellite imagery for overall classification. The drone flights were planned using the PIX4Dcapture software for use on a mobile ephone.

3.4.3 Satellite imagery

Using the labelled training data created by the drone imagery (as detailed in the previous section), the satellite image was segmented. A cloud-free satellite image, captured at a time close to the date of drone survey, was selected. The Sentinel-2 satellite imagery was augmented using the drone imagery, with the Sentinel-2 imagery resampled to 10 m spatial resolution to match the upsampled resolution of the drone data using a Spatial Analyst tool in ArcMap. The classification of satellite imagery was then carried out using the combination of ensemble bagged tree classifier, along with graph cut segmentation, as detailed in section 3.2.3. The Sentinel-2 satellite imagery augmented with the drone images was used for training purposes.

To correctly monitor any natural changes in the wetland over time, such as vegetation growth over the seasons, the steps should be repeated multiple times per year to obtain seasonal maps of the wetland (Figure 3.15). The final map can then be created by performing a multi-seasonal majority voting for every pixel.

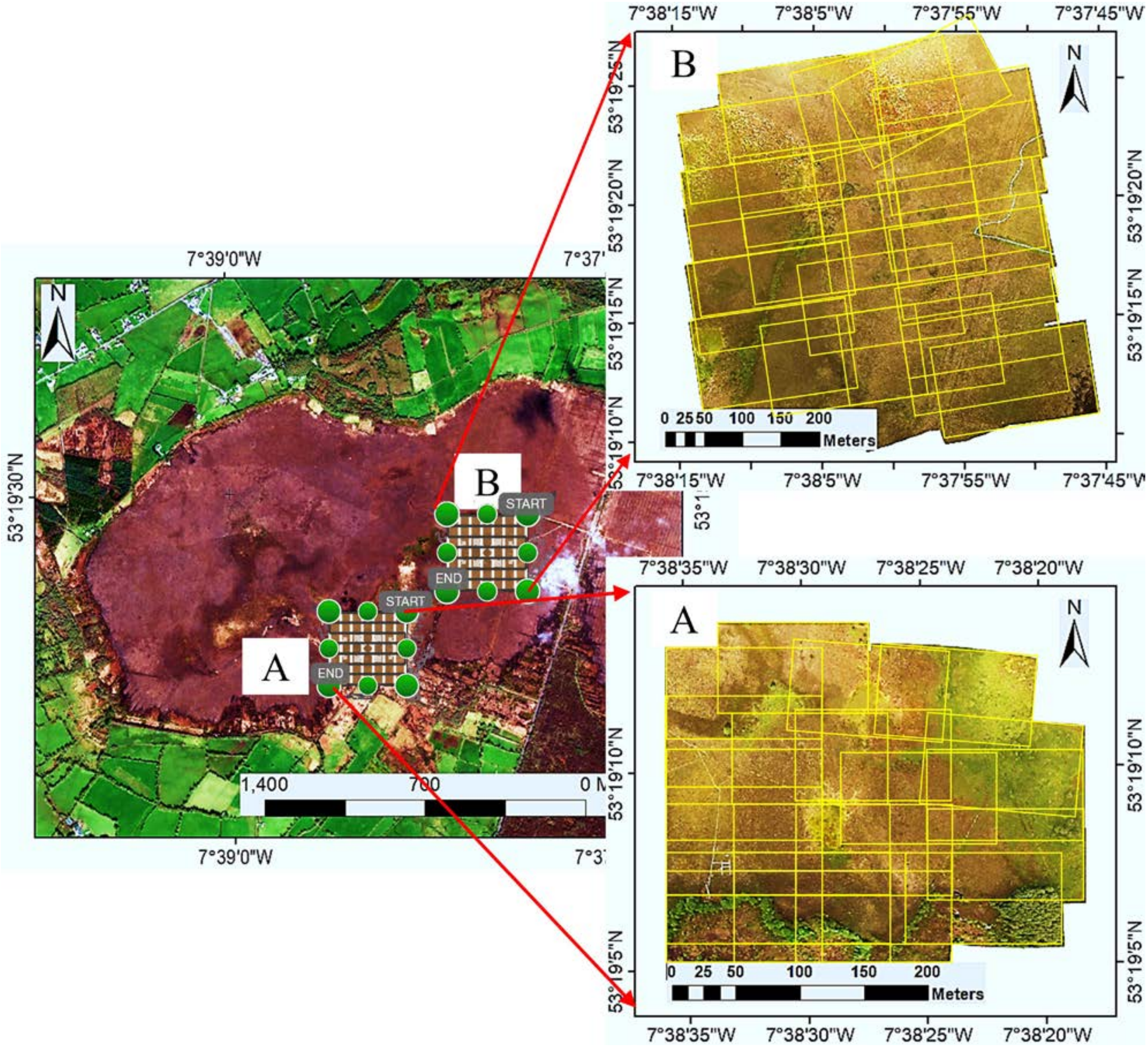

Figure 3.14. Area covered in the Pix4Dcapture mission at Clara bog. Images A and B are mosaics of 20 drone images.

3.4.4 Case study: Clara bog

As previously indicated, Clara bog was used to test the methodology. A maximum of 87.2% OA was achieved for the summer imagery, which was close to the OA achieved in spring (86.6%) when compared against the reference image ground truth (see Figure 3.5), as used in Bhatnagar *et al.* (2020a). An overall mapping accuracy of 87% was achieved for the final map, which is higher than using only Sentinel-2 satellite imagery (see section 3.2.4) and achieved without using any field survey information. This strengthens the case of the applicability and robustness of the methodology. Just 3% of the area surveyed by drone was found to be sufficient to create ecotope maps of the whole of this wetland, although the extent of the surveyed area required is dictated by the number of ecotopes to be classified and the contiguity of these ecotopes. The methodology could potentially replace the need for a week-long field survey or a complete drone survey taking multiple days with an hour-long drone survey of the chosen wetland.

This study successfully demonstrates the suitability of using limited drone images for augmenting satellite imagery for improved overall classification of vegetation communities or ecotopes within the wetlands. Overall, the study demonstrates the advantages of using inexpensive drone imagery combined with open-access satellite data to effectively

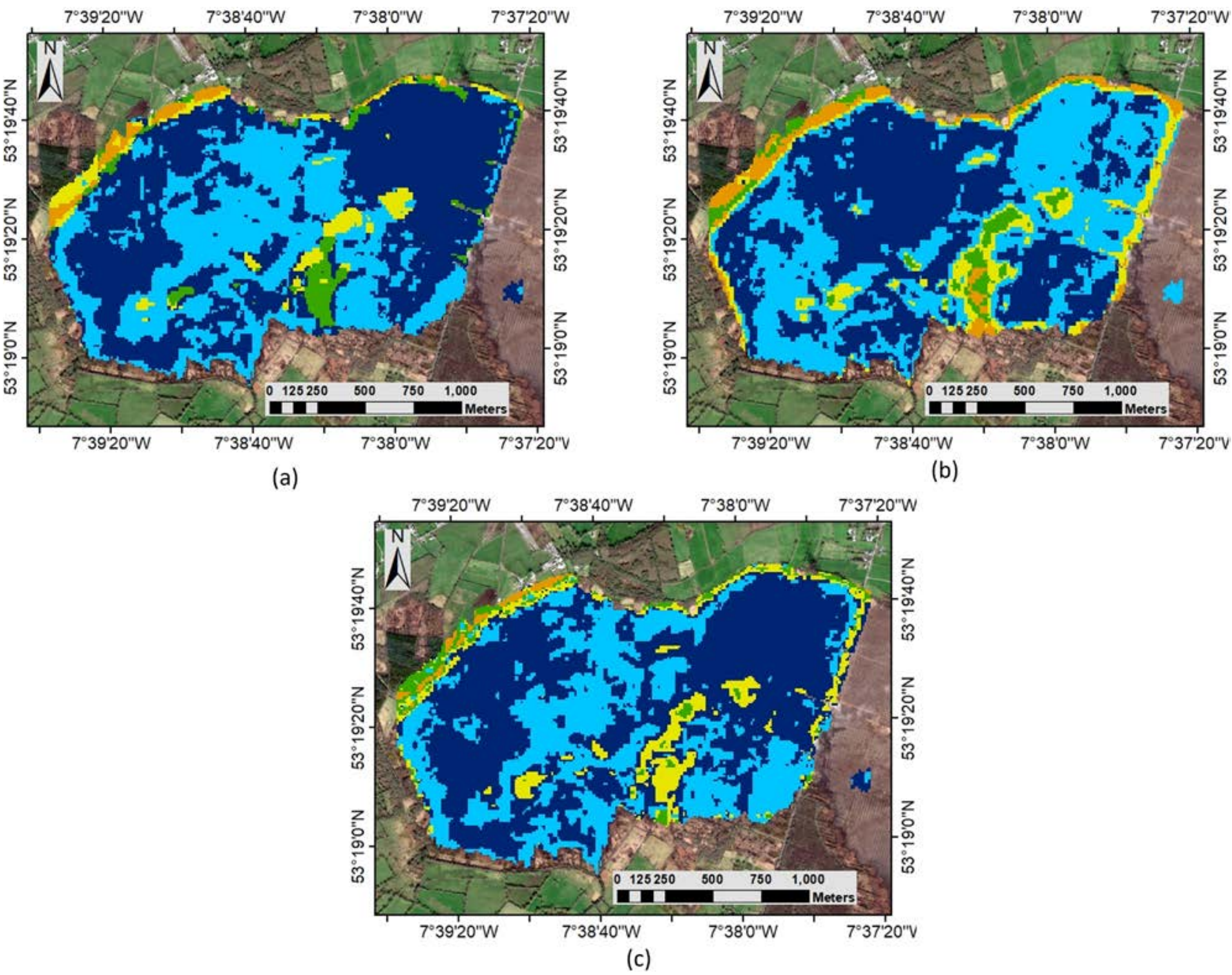

Figure 3.15. Clara bog K-means unsupervised clustering ($K=5$) of Sentinel-2 satellite imagery. (a) Spring, (b) summer and (c) winter.

classify wetland areas with high accuracy without the need to carry out expensive field surveys or extended complete drone surveys. Once classified, these RS approaches can then be used relatively easily to continuously monitor the conditions of the wetlands over time, particularly in response to climatic changes and/or more localised anthropogenic impacts, such as nearby drainage or land use change, thereby helping the agencies given limited budgets for conventional field surveys. For more details on this, see Bhatnagar *et al.* (2021a).

4 Fens

4.1 Introduction

Fens are largely groundwater fed, being located in topographic hollows or below springs or seepages of water that has been in contact with mineral ground (Proctor, 2010). Like bogs, fens accumulate peat, and historically in Ireland the term "bog" (from the Irish for "soft") has been used interchangeably for any wetland area (e.g. Scragh bog). The composition of the fen vegetation reflects the chemical composition of the dominant water supply and the duration of a mean water level. The combination of these factors dictates what type of fen develops and its hydrological regime (McBride *et al*., 2011). A "poor" fen has very low concentrations of nutrients with floristic similarities to a bog, while a "rich" fen has relatively high concentrations of mineral nutrients and a more diverse plant and animal community. The most recent estimate for the extent of Annex I fen habitat in Ireland is 27,257 ha (NPWS, 2019), of which 46% is alkaline fen, 26% is *Cladium* fen, 28% is transition mire and 0.05% is petrifying spring. The area of poor fen, a non-Annex I habitat, has not been estimated. Poor fen is typically found within blanket bog environments and is also referred to as flushes or transitional laggs. However, there are significant gaps in knowledge of the fen resource because of inadequate information on fen ecology and fen types in the NPWS database; this will be resolved with the completion of the National Fen Survey, which is due to be extended from 2021 to 2024.

Cladium fens and petrifying springs are priority habitats that require the highest level of conservation within Member States (Foss, 2007). The understanding of the ecohydrology of fen systems in Ireland has been greatly aided by detailed research at Pollardstown fen, located on the shoulder of a large glacial outwash plain, the Curragh, where springs are the source of the wetland water. Slow seepage rates (1–6 mm/day) have resulted in the formation of "petrifying springs" that have created suitable habitat for a characteristic species of fens: the diminutive mollusc *Vertigo geyeri*. The fen's phreatic water level (± 5 cm) is controlled by groundwater levels in the Curragh Aquifer and, although a nominal TV was identified, the fen water table responds non-linearly to fluctuations in the aquifer water table (Johnston *et al*., 2015), meaning that the ability of the water level to rebound following any disturbance is limited and the system has poor resilience to environmental change. Dewatering of the Curragh Aquifer in the late 2000s to facilitate the Kildare town bypass disturbed the fen water level; although the water level has recovered, indications are that *Vertigo geyeri* has not.

Of the 71 fens designated as SACs, 20 are located adjacent to arterial drainage schemes managed by the OPW. As fens are directly connected to the groundwater table, they can be subject to hydrochemical/nutrient loading pressures. Base-rich fens, such as alkaline and *Cladium* fens, can also be threatened by acidification as a result of eutrophication, especially with phosphorus (Kooijman, 2012). Water supply should be calcium rich, but nutrient poor. Kimberley and Coxon (2013) reviewed the 44 calcareous fens designated as SACs for nitrate and phosphate TVs and found that there are currently insufficient data to determine meaningful TVs for Irish calcareous fens. Thus, there is an urgent need for more ecohydrological field research across the range of different fen types found in Ireland, and the results from this project contribute towards this.

4.2 Site Description, Instrumentation and Monitoring

The aim of this work package was to study calcareous fens representing a range of different conditions, with at least one fen wetland considered to be under water quantity pressure (i.e. either damaged or under pressure from drainage or abstraction), one site considered to be under water quality pressure (i.e. under pressure from nutrient pollution) and at least one site that is considered to still be in a relatively pristine (intact) state. An extensive review of fens in Ireland was undertaken with information gathered from the Intergovernmental Panel on Climate Change peatland sites database (IPCC, 2009), the SAC database from the NPWS (NPWS, 2019) and wetland survey reports for Kildare, Louth, Monaghan and Wicklow prepared by Foss (2007). Fens were ranked against a scoring

Table 4.1. Site specifics for the four fens chosen for detailed study

	Fen			
Site details	**Pollardstown**	**Tory Hill**	**Scragh bog**	**Ballymore**
County	Kildare	Limerick	Westmeath	Westmeath
Area (ha)	266.1	76.9	23.9	43.1
Designation	SAC	SAC	SAC	SAC
	National Nature Reserve	National Nature Reserve	National Nature Reserve	
Condition	Degraded	Degraded	Intact	Near intact
Damage, threats and pressures	Drainage	Drainage	Fertiliser application	Diffuse pollution
	Grazing	Infilling	Roads	
	Dumping	Grazing	Diffuse pollution	
	Gravel quarry			

system of a range of different criteria, including designation status (SAC, Natural Heritage Area or none), Annex I Habitat type (7210 – calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae* and 7230 – alkaline fens), underlying geology, geomorphology, water chemistry (base-rich/poor), damage, previous research data, threats and pressures (water quality and/or quantity). The specifics of the four fens chosen for the 2-year field study are listed in Table 4.1.

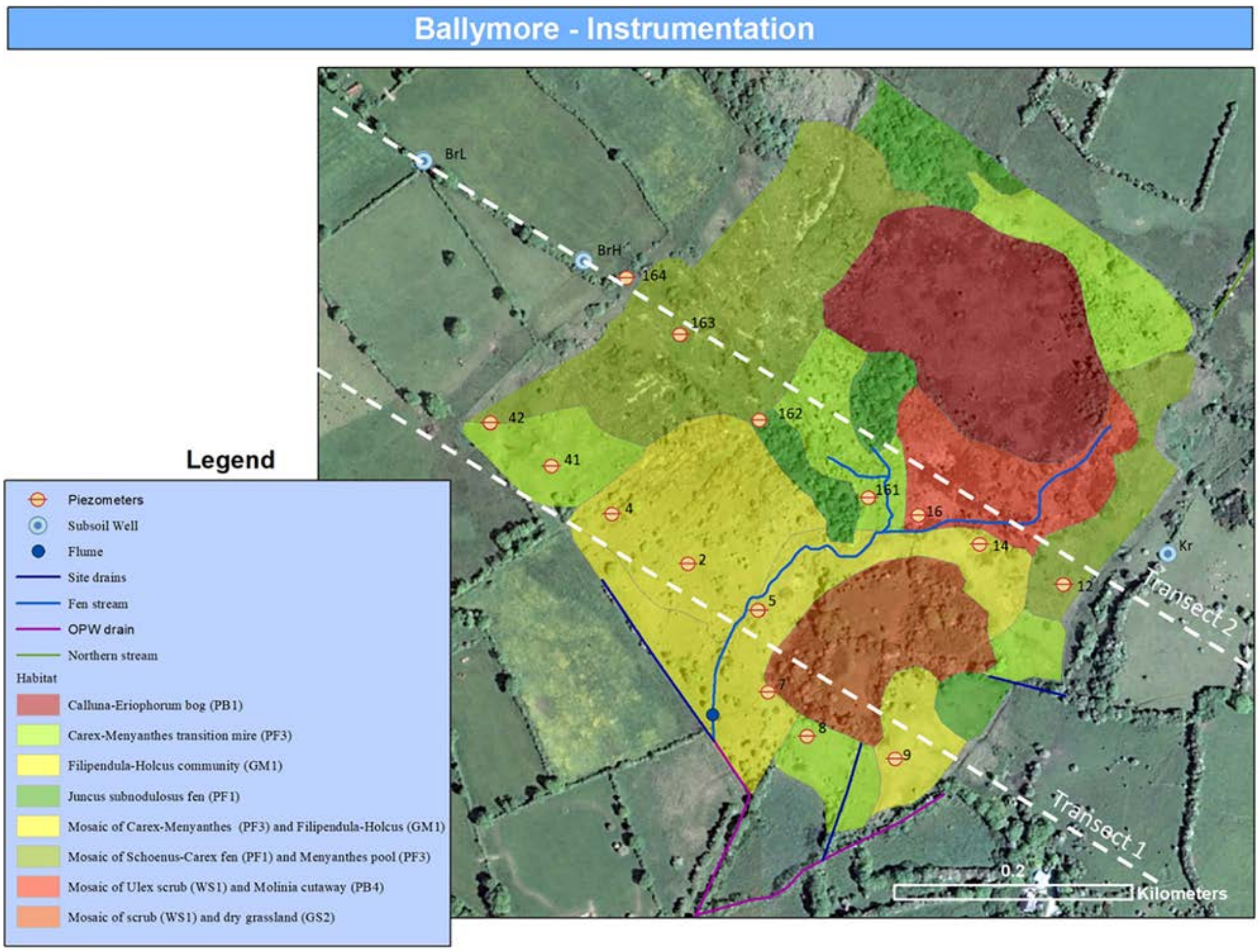

Figure 4.1. Habitat map of Ballymore fen also showing the location of instrumentation transects (Regan and Connaghan, 2017).

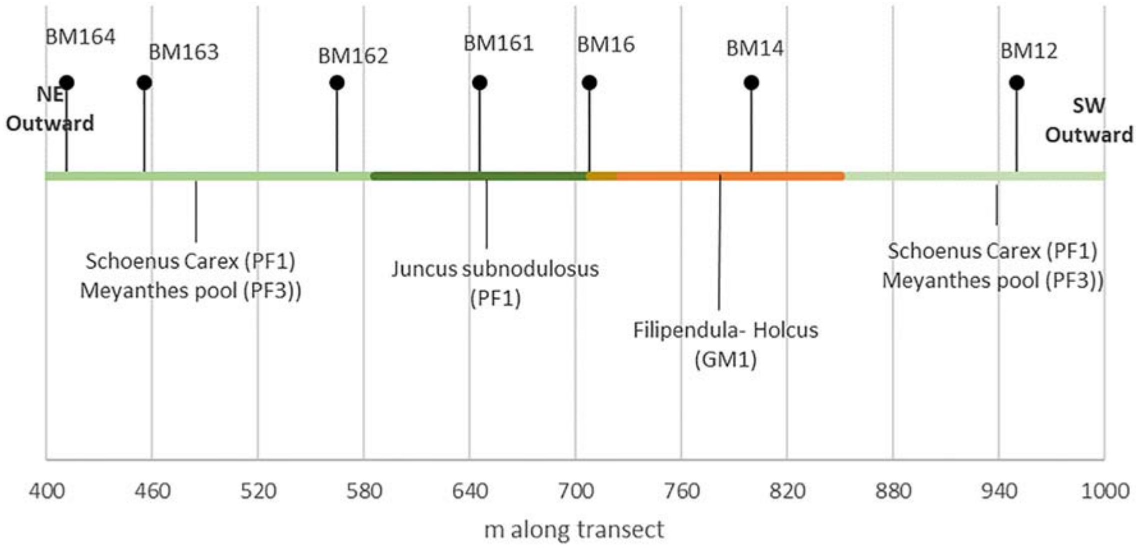

Figure 4.2. Transect 2 across Ballymore fen showing different vegetation community habitats in relation to monitoring locations (BMs).

The latest vegetation surveys for the four fens were obtained from the NPWS, with Ballymore fen shown as an example in Figure 4.1 and the habitat map for Scragh bog (fen) previously shown (see Figure 3.8). These fens were instrumented using piezometer and phreatic tube transects across each site (described in section 2.2), as shown for Ballymore fen in Figures 4.1 and 4.2. Geological/geomorphological cross-sections were also derived for the fens from a mixture of GSI mapping and soil log data recorded during piezometer installation during this project and data from past projects. For example, Ballymore fen (see Figure 4.3) is surrounded by calcareous drift and occupies a wide and deep depression that may have been a lake in the past, as indicated by the presence of lake marl. Most of the basin consists of a peat layer underlain by

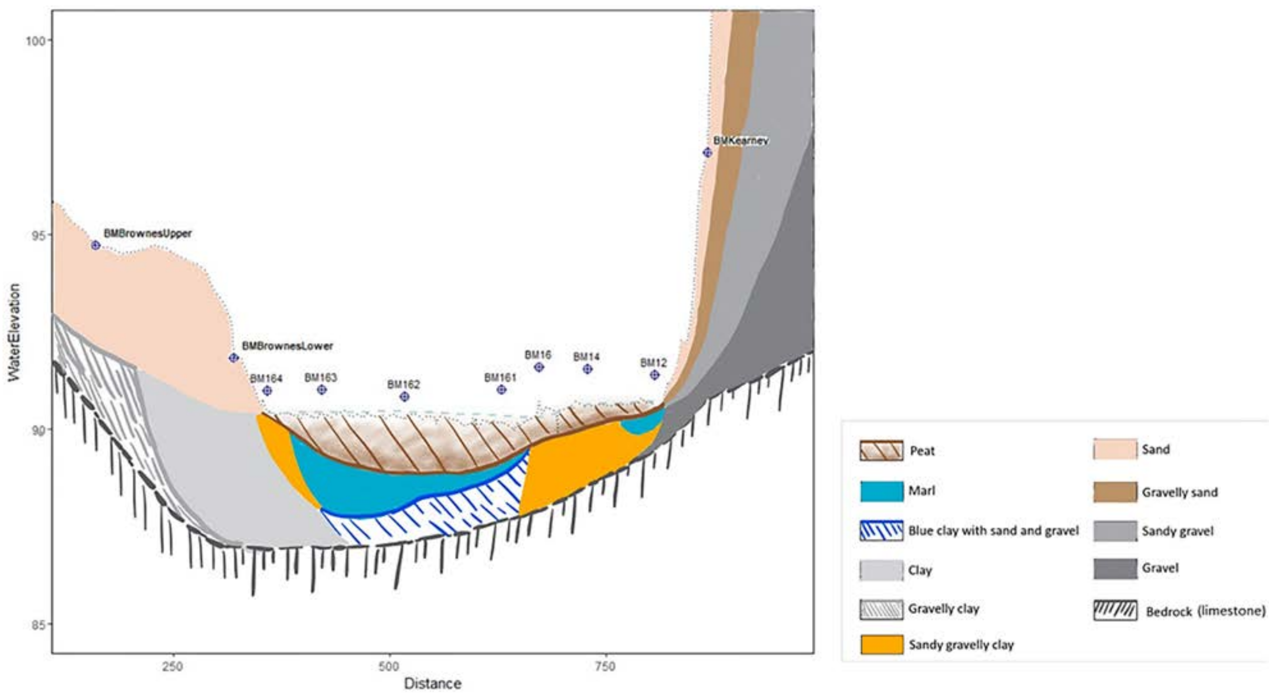

Figure 4.3. Geology/geomorphology transect 2, Ballymore fen (based on Regan and Connaghan, 2017) in relation to monitoring locations (BMs).

Carboniferous limestone. The peat is separated from the bedrock by sandy clay and marl.

4.3 Hydrology

The hydrometric instrumentation on the fens allowed full water balances to be compiled for the sites over a 2-year period. For example, the outflows from Ballymore and Scragh bog fens are shown in Figure 4.4, which reveals sharp responses to rainfall, particularly in the winter months. Equally, water level loggers in the different fens (as well as spot water level measurements taken in the phreatic tubes every sampling trip) enable the water level fluctuations across the years to be displayed for all monitoring sites (see Figure 4.5). These reveal that there were more ordovfluctuations in the fens not affected by drainage (i.e. Ballymore, Scragh bog and Pollardstown) than in Tory Hill, as expected, and that the variation in water levels between the summer and winter periods fluctuated by only 200–300 mm in most cases. However, it should be noted that more pronounced water level fluctuations were measured at the margins of Pollardstown fen during previous research in the vicinity of the "petrifying springs" habitat where the mollusc *Vertigo geyeri* is found (Kuczynska, 2008).

From the data of rainfall onto each fen, evapotranspiration from the fen (calculated from meteorological parameters according to the Penman–Monteith equation), catchment size (and outflows), and annual water balances have been calculated, which allow a more accurate estimation of the catchment area that feeds recharge into the fen, as well as enabling additional flows into the fens to be quantified at different times of the year. For example, at Ballymore, the water balance calculations suggest higher groundwater inputs into the fen during the winter, and this was confirmed with a rising trend of electrical conductivity recorded in the sediments of the fen. Relatively, though, the groundwater contribution was actually lower during the winter as a result of high contribution of surface water to the system (from rainfall). During periods of high effective rainfall (winter), the relative groundwater contribution to the outlet of the fen dropped to a low of 33%, whereas during low effective rainfall (summer) the relative contribution was much higher, up to 87%. This same general pattern, although more muted, was found at Scragh bog and Tory Hill. This means that groundwater is being stored in the fens during periods of high effective rainfall. Furthermore, the fact that phreatic water levels did not drop below the invert of the outlet of any of the fens, even during the significant drought in 2018, is evidence of the resilience of the fens supported by groundwater flows during this time.

4.4 Hydrochemical Results

Spot samples taken across two different transects per fen at different depths (from the phreatic tubes and piezometers in the fens and groundwater monitoring points in the wider catchment) every 2 months were analysed for nutrients and major ions. In general, this revealed significant differences between the water quality of the phreatic water in direct contact with the

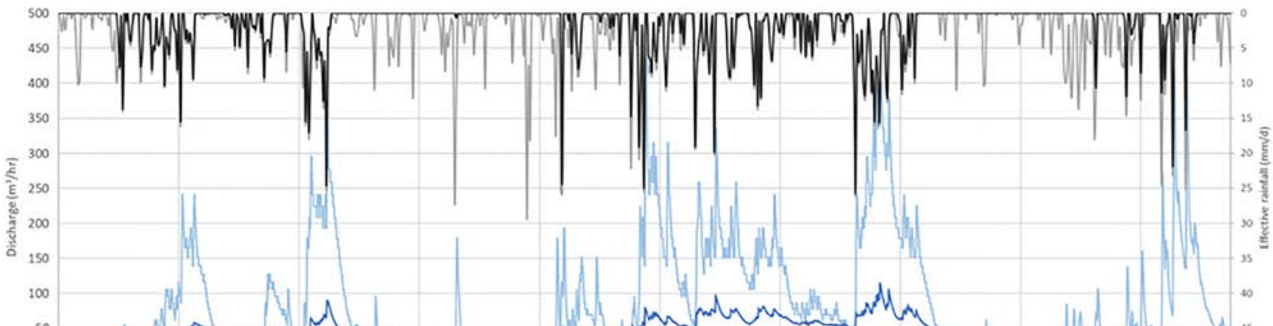

Figure 4.4. Ballymore and Scragh bog outlet discharges versus rainfall across a 2-year monitoring period.

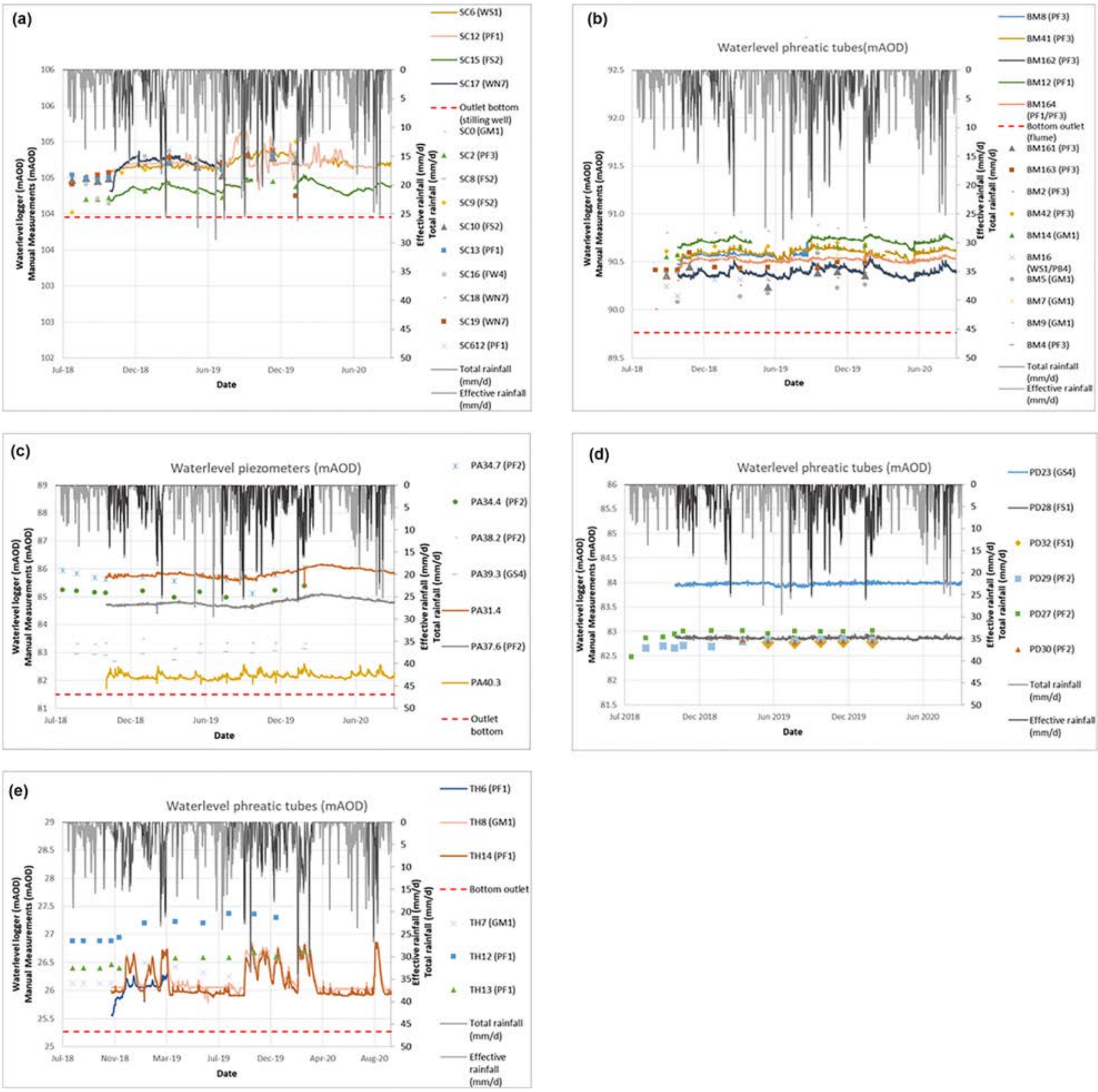

Figure 4.5. Water level fluctuations in the fen research sites as measured at the phreatic tube sampling positions, both manually at each site visit (the individual points) and continuously by pressure transducer dataloggers located in the sample points at selected locations. (a) Scragh bog, (b) Ballymore, (c) Pollardstown site D, (d) Tory Hill and (e) Pollardstown site A. mAOD, metres above ordnance datum.

vegetation, the water in the depths of the sediment at the interface between the top of the till and bottom of the peat (from the piezometers) and the groundwater feed in the aquifer (from the deep subsoil piezometers and boreholes). This is shown, for example, for Scragh bog in terms of DRP, ammonia and total oxidised nitrogen in Figure 4.6. Interestingly, the spot samples also showed that the nutrient concentrations at the different sampling locations did not seem to fluctuate very much across the seasons. As a further example, water quality results and hydraulic gradients across one transect through Scragh bog are compared between summer and winter and the results for DRP are shown in Figure 4.7. These results show generally higher concentrations of DRP in the water sampled at the base of the peat (in piezometers) at both times of year (although it was slightly higher in the summer) than in the groundwater samples taken in the borehole or the water samples taken from the phreatic wells. Equally, for ammonia the concentrations are much

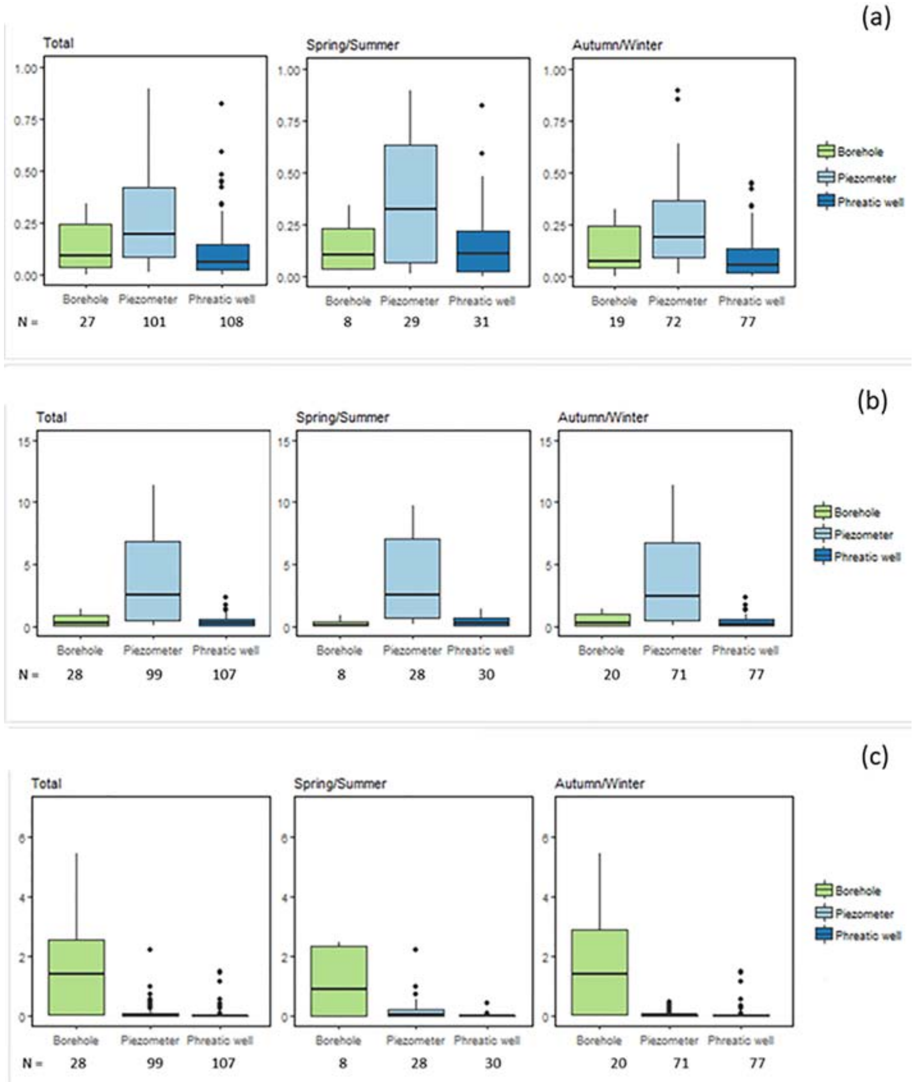

Figure 4.6. Concentrations of (a) dissolved reactive phosphorus (mg/l as P), (b) total ammonia (mg/l as N) and (c) total oxidised nitrogen (mg/l as N) as sampled from a number (N) of phreatic wells and piezometers inside the fen and groundwater-feed piezometers and boreholes in the surrounding catchment of Scragh bog.

higher in the deeper water sample positions in the more anaerobic conditions at the base of the peat sediments. Nitrogen in the form of nitrate is much higher in the incoming groundwater feed than in the fen itself. Other consistent patterns were that higher concentrations of dissolved organic carbon were found in the fens than in the surrounding catchment groundwater (this was expected because of the high rate of decomposition in the upper layer of the peat) and that sulfur, nitrogen and iron species clearly indicated more reducing conditions in the deeper peat (as monitored with the piezometers) than in aerobic conditions in the aquifer and phreatic (surface) level of the fens.

4.5 Conceptual Model of Calcareous Fens

The hydrological and hydrochemical results from the four fens have revealed a consistent picture with respect to the importance of the groundwater feed and the interrelationship between vegetation at the surface of the fen and the underlying substrate. A representative conceptual model of lowland calcareous

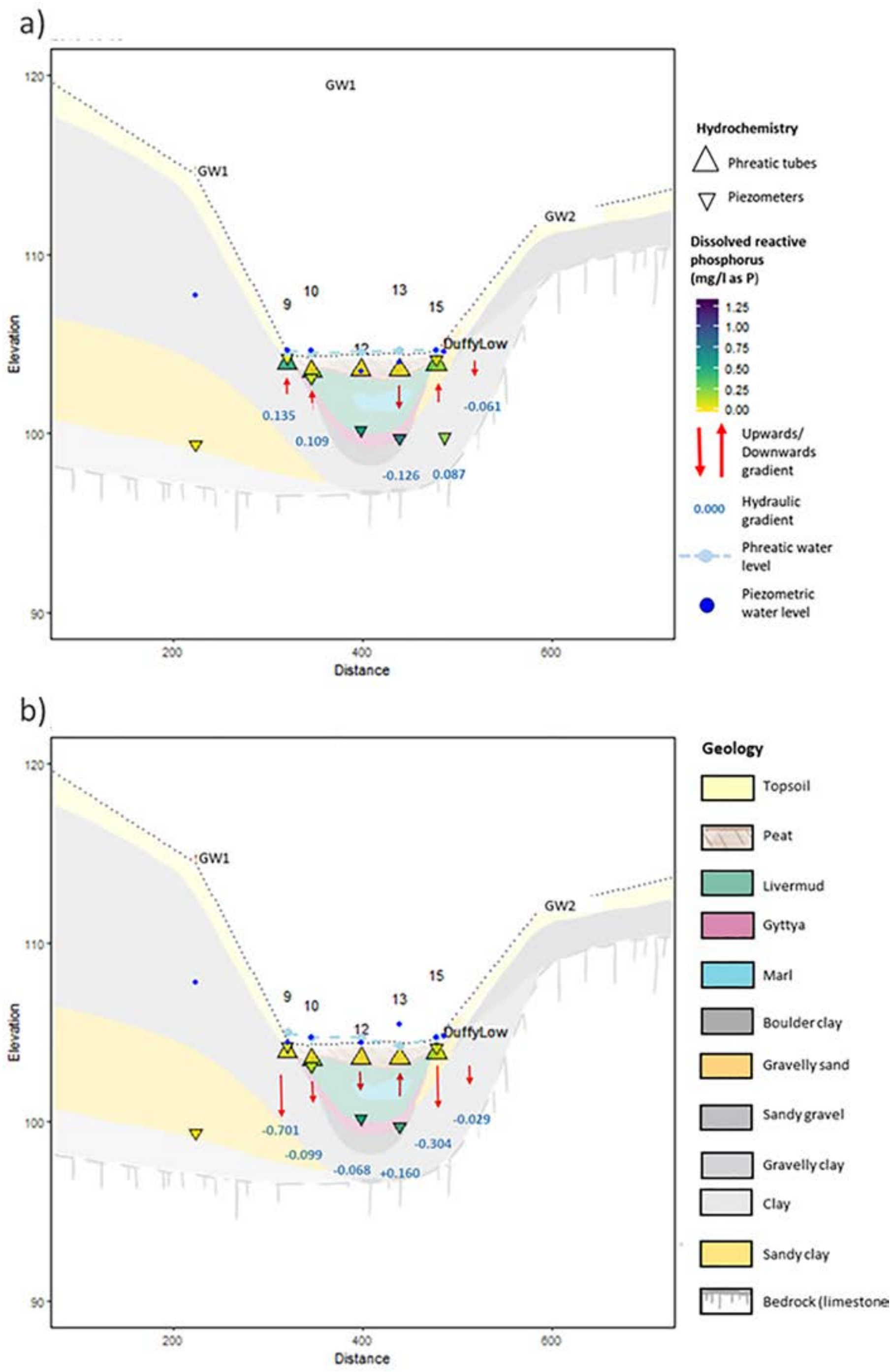

Figure 4.7. Dissolved reactive phosphorus concentrations measured from water samples taken from sampling points at Scragh bog (fen) transect 2, comparing (a) summer (5 August 2019) and (b) winter (4 February 2020) periods.

fens in Ireland has been developed (Figure 4.8), indicating the groundwater pathways supplying the wetland and the controlling nature of the wetland soils and substrates modifying that hydrology. The underlying bedrock is typically fractured or fissured Carboniferous limestone. Over the bedrock, glacially derived subsoil, including tills and outwash gravels, usually provides the topography that hosts the conditions for the fen to develop. Organic soils or peat then accumulate, often on a lacustrine clay, depending on the topography and drainage. The fen vegetation develops on the surface and at the margins of these wetland soils, influenced by the pathways taken by the water supply. The substrate soils are rarely areally

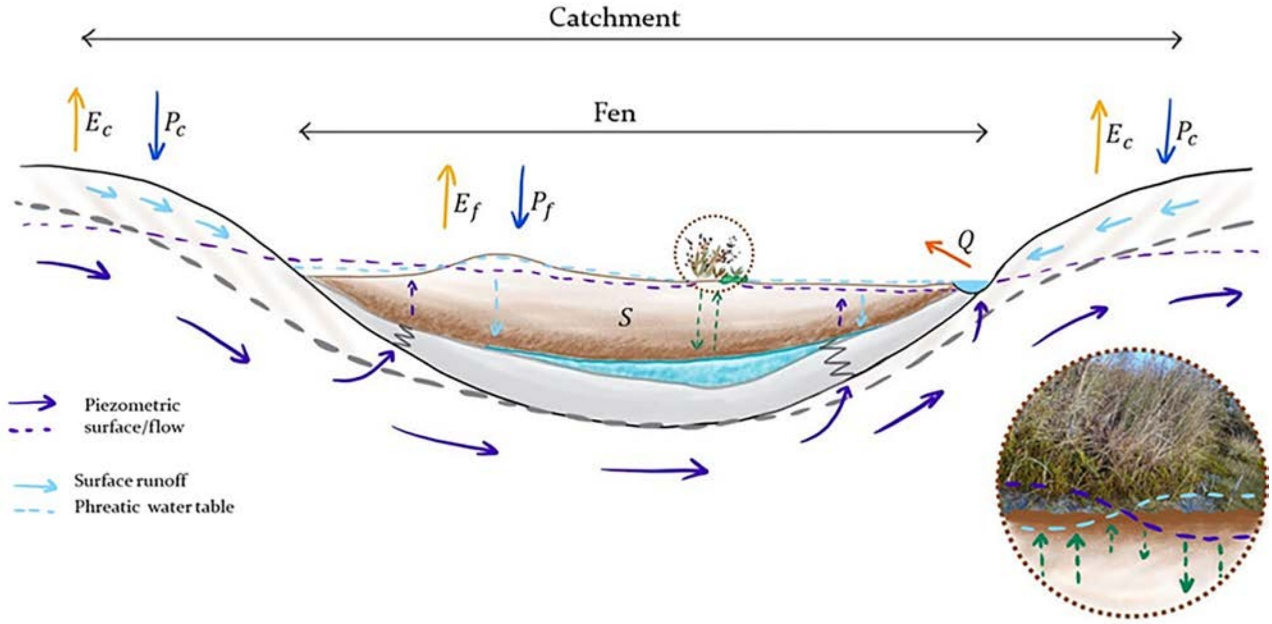

Figure 4.8. Conceptual model of Irish calcareous fens. Ec, evapotranspiration from the catchment; Ef, evapotranspiration from the fen; Pc, precipitation onto the catchment; Pf, precipitation onto the fen; Q, outflow from the fen; S, storage of water in fen.

uniform, allowing discrete inflow pathways to persist as the piezometric level of the regional groundwater is above the substrate or the margins of the fen, creating the seepages and springs feeding the fen. As the fen develops, the piezometric level may become established above or below the fen surface, but it will seasonally and climatically fluctuate. Thus, the model presents separate but connected hydrological regimes – the one in the catchment surrounds the fen and feeds the other within the fen itself. The characteristics and dynamics of the connections between the two dictate the sustainability of the supported vegetation. Surplus water from groundwater inflow and direct rainfall on the fen, i.e. runoff, is typically routed via natural or artificial drainage to an outlet, discharging to the natural surface water stream network. The morphology of this on-fen surface drainage can also influence the nature of the fen vegetation and its sustainability.

The dynamics between the piezometric surface and the phreatic water table in the fen also play a role in nutrient cycling utilising the fen vegetation and fluctuating hydraulic gradients. Upward flows, displayed in Figure 4.8, may bring nutrients to the surface, where the fen vegetation can access the nutrients for growth, thereby acting to reduce (or “treat”) the levels of nutrients in the phreatic water. When the vegetation dies down in the winter, natural degradation processes can then release both organic and inorganic soluble forms of nutrients back into the water column. Seasonal hydraulic/hydrological fluctuations may then cause small gradients to support a downward nutrient flux to the sediments underlying the peat. Diffusion and dispersion act to further spread out the concentrations throughout the different fen sediment layers.

Thus, the derived model for a lowland calcareous fen is one of a dynamic water balance for the dependent vegetation between groundwater (the chemistry of which is modified by the pathways involved) and direct rainfall.

4.6 Ecometrics for Fens

Each of the vegetation habitats at the fen sampling locations can be associated with a Fossitt habitat code (Fossitt, 2000), which include PF1 (rich fen and flush), PF2 (poor fen and flush) and PF3 (transition mire and quaking bog). These locations were then further divided into habitats that either passed or failed the fen assessment criteria, based on the vegetation surveys. The habitats that passed the criteria are termed “good” fen habitat, whereas the failed habitats are termed “poor” in the following section.

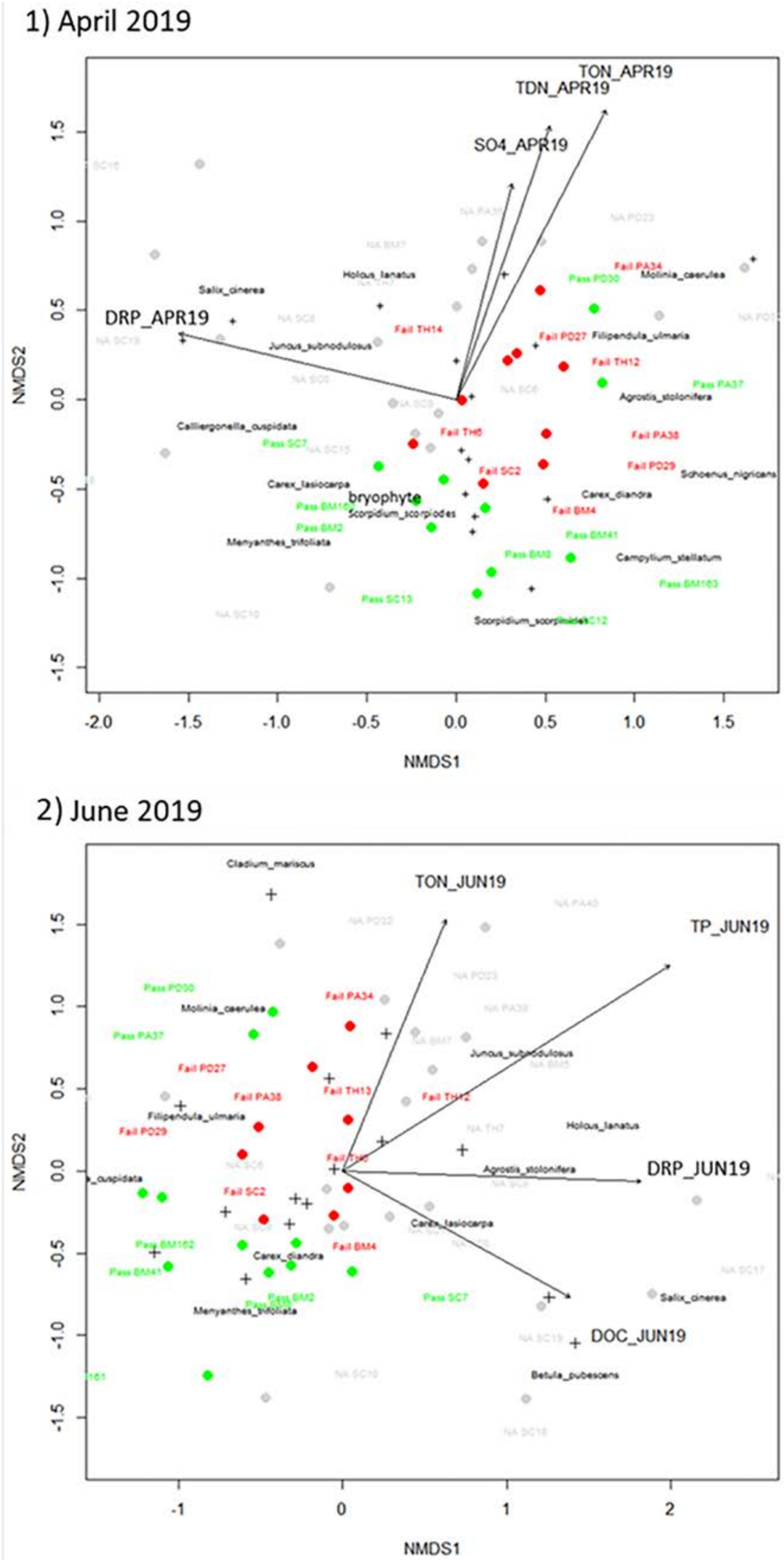

Figure 4.9. Non-metric multidimensional scaling ordination of dimensions 1 and 2 with vegetation cover and Fossitt habitats plotted as vectors (maximum *p*-value = 0.2) in good, poor or non-fen (NA) habitats in April 2019 (top) and June 2019 (bottom). The phreatic water sampling locations with their specific quality are shown in green for good, red for poor and grey for non-fen (NA) habitats. The names of the species with the highest abundances (10%) are also plotted.

Under this categorisation, a non-metric multidimensional scaling ordination technique was used to produce plots that assess the relationship between surface water hydrochemistry, vegetation distribution and fen sampling points, using all data across the research sites (see Figure 4.9 as an example). This shows that the different hydrochemical parameters (nutrients, dissolved organic carbon, etc.) do not appear to be positively associated with fen habitats that have vegetation in either good or poor ecological condition. Higher concentrations of these components found in a fen site do, however, seem to be associated with non-fen habitat rather than with designated fen habitats (in good- and/or poor-quality condition). Furthermore, these plots also show that good quality habitats have a lower association with concentrations of those hydrochemical parameters than the poor quality fen habitats. Hence, this might suggest that the fen habitat-specific vegetation is much more effective in the uptake, recycling and storage of nutrients than the vegetation in non-fen and poor-quality habitats. These plots were then used to inform the statistical analysis of the key water quality parameters linked to different vegetation habitats.

4.6.1 Water level

Boxplots are presented of the phreatic water levels using the new fen quality groupings (good or poor) in Figure 4.10. A clear difference in the behaviour of the phreatic water level can be seen between the poor and good versions of PF1 (rich fen and flush). The poor-quality habitat (all located in Tory Hill fen) had

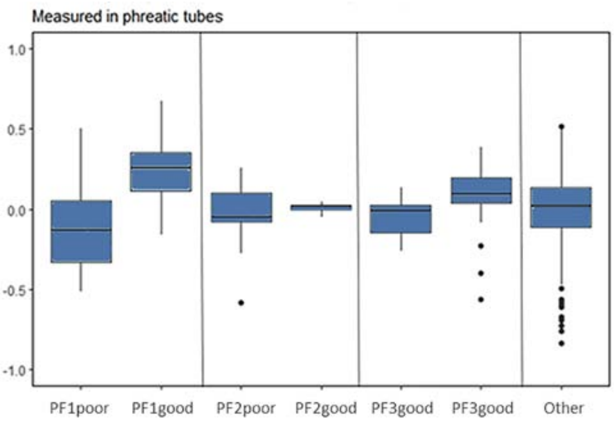

Figure 4.10. Phreatic water level in metres above ground level in good, poor or non-fen (other) habitats.

the lowest median water level of all displayed habitats of 0.175 m below ground level. The good-quality PF1 sites had much higher phreatic water levels (median of 0.231 m above ground level). For PF2 and PF3, the good-quality habitats reveal slightly higher median levels than their poor counterparts, 0.016 and 0.089 m above ground level for PF2 and PF3, respectively. All PF2 habitats (good and poor) were recorded on Pollardstown fen, while the PF3 habitats were found on both Ballymore and Scragh bog.

To further investigate the influence of hydrology on the quality of the vegetation, phreatic tube water levels were plotted against duration for the different quality fen habitats. The results are presented in Figure 4.11. Most of the fen habitats were of good quality and show minimal change in water levels. In most habitats, water levels were above ground level for > 90% of the hydrological year, with some exceptions where the level was found 0.1 m below ground level for short periods of time. Highest levels were recorded in habitat PF1, with some especially high elevations, up to 0.73 m, for < 16% of the year. This habitat seems to require a tighter envelope of water levels always above the ground surface from approximately 0.10 m to 0.40 m depth of flooding all year round (based on 25th to 75th percentile levels). These "flooding" levels were also seen in the PF1 poor-quality habitat; however, here the levels change drastically and are below ground elevation for most of the year (70%), with levels down to 0.43 m below ground level. From this, it can be concluded that the overall hydrological controls for good-quality fen vegetation seem to be reflected in phreatic water levels above ground level with minimal level changes for most (over 90%) of the hydrological year. The only exception to this is at Tory Hill fen – which was chosen for the study because it is known to be affected by drainage (as indicated by the red line in Figure 4.11) – which exhibits much lower water levels during summer periods. Evidence from Ordnance Survey maps shows that this drain has been in existence since at least the late 1830s, at the time with a much more meandering course; at some stage between the 1830s and the 1900s the outflow stream/drain was straightened and substantially deepened. Some areas of rich fen and flush (PF1) at Tory Hill do seem to be resilient to that lower water level regime; however, the vegetation is known to be in poor condition with less species richness, which matches previous findings from the UK (Wheeler *et al*., 2009).

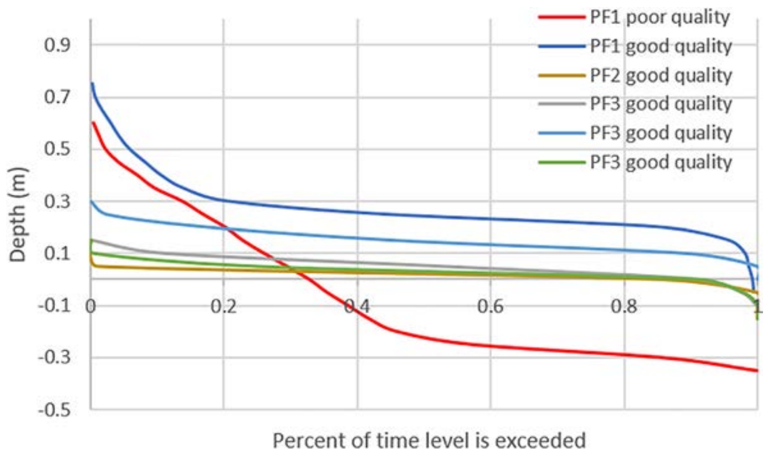

Figure 4.11. Phreatic level–duration curves recorded in good and poor fen habitat. The negative numbers are water levels below ground level.

In general, to support good fen vegetation the overall surface water level needs to be within a range of 0.029–0.277 m above ground level, and these levels should be sustained for at least 60% of the year. These envelope values were calculated by taking the first and third quartiles of the good fen habitats.

4.6.2 Hydrochemistry

In a similar manner to the water level analysis, the water chemistry data from surface water samples taken from the phreatic tubes, piezometers at the base of the peat layer and groundwater-feed monitoring points have been analysed statistically and presented as boxplots according to vegetation habitat types for DRP (Figure 4.12), TP (Figure 4.13), total dissolved nitrogen (Figure 4.14) and ammonia (Figure 4.15).

Hydrochemical controls should enable an internal cycling system in which the fen recycles nutrients (which were released from the breakdown of vegetation) from the phreatic water levels into the sediments below. This is visible by a statistically significant difference in nutrient concentrations between the phreatic water levels (low concentrations) and in both the deeper substrate and surrounding catchment (high concentrations). The median values

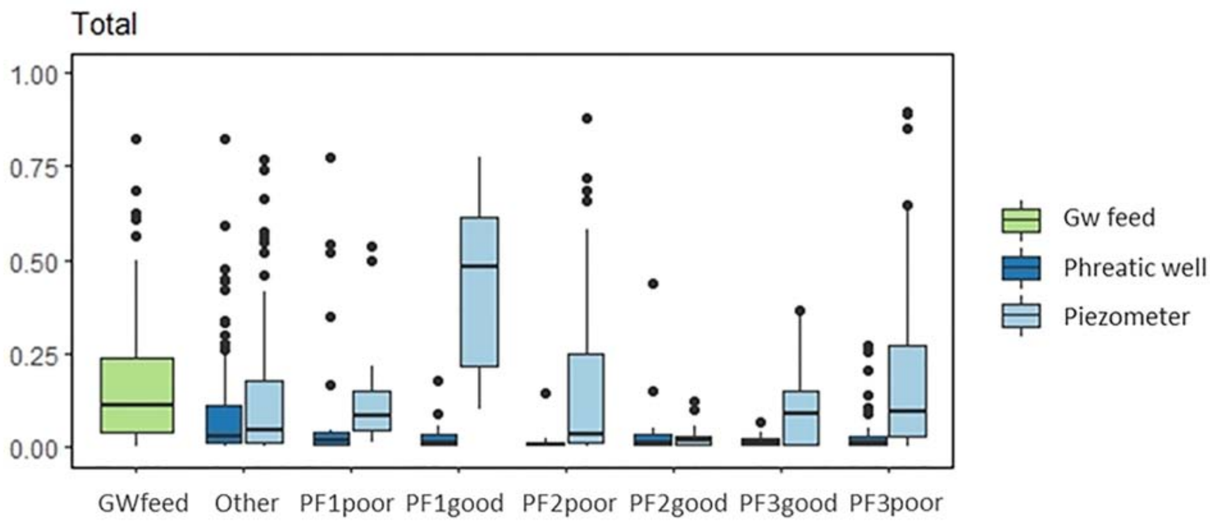

Figure 4.12. Total dissolved reactive phosphorus (mg/l as P) for calcareous fen vegetation Fossitt habitat types PF1, PF2 and PF3 in the fen phreatic tubes and piezometers of good, poor or non-fen (other) habitats, and groundwater (Gw) feed from the wider catchment.

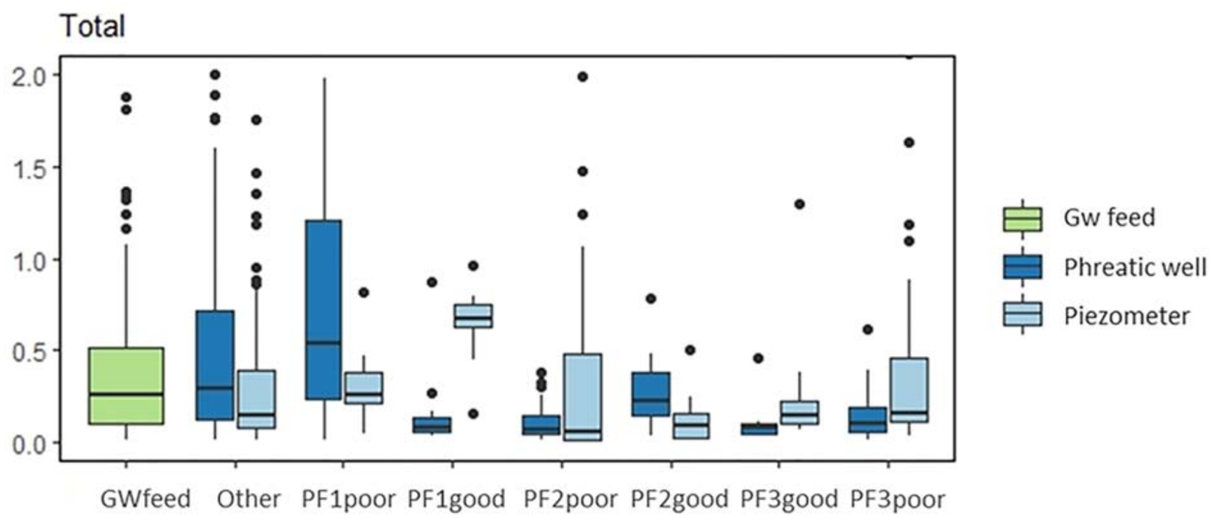

Figure 4.13. Total phosphorus (mg/l as P) for calcareous fen vegetation Fossitt habitat types PF1, PF2 and PF3 in the fen phreatic tubes and piezometers of good, poor or non-fen (other) habitats, and groundwater (Gw) feed from the wider catchment.

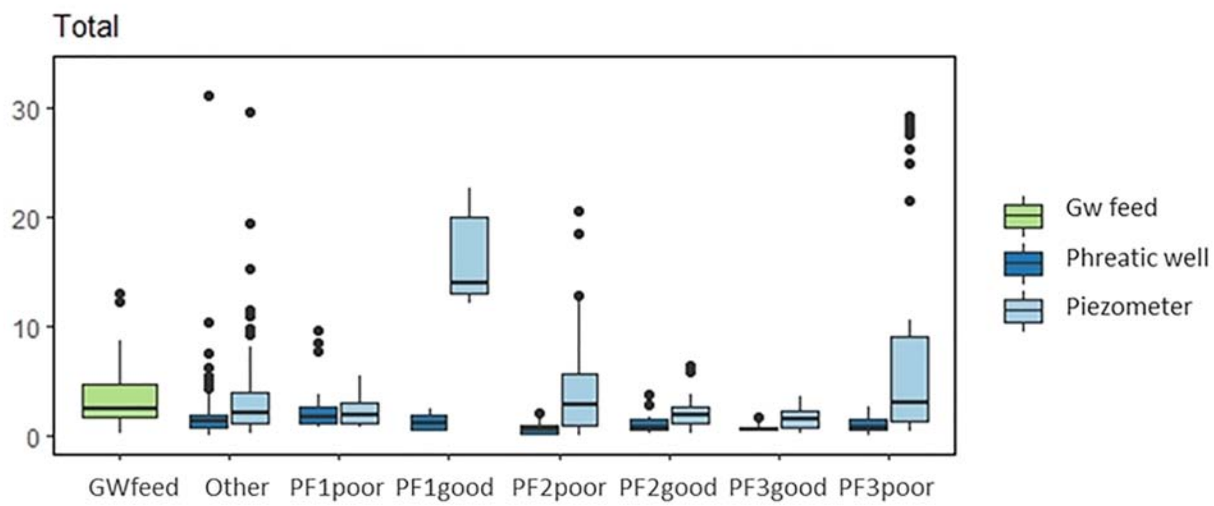

Figure 4.14. Total dissolved nitrogen (mg/l as N) for calcareous fen vegetation Fossitt habitat types PF1, PF2 and PF3 in the fen phreatic tubes and piezometers of good, poor or non-fen (Other) habitats, and groundwater (Gw) feed from the wider catchment.

of nutrients found in the near-surface phreatic zone of good-quality fen habitat were found to be 14 µg P/l for DRP, 110 µg P/l for TP, 0.26 mg N/l for ammonia, 0.01 mg N/l for total oxidised nitrogen and 0.95 mg N/l for total dissolved nitrogen. However, this does not mean that levels found above these medians should necessarily be regarded as nutrient pollution.

These results suggest that the fen vegetation needs a certain level of nutrients to survive. Envelope recommendations for each Fossitt habitat are based on the first and third quartiles in boxplots of phreatic water table concentrations recorded in good fen habitats. However, it is important to note that these values should be viewed as being representative of "remnant" nutrients not taken up by the vegetation or cycled into lower sediments rather than the nutrient feed needed to sustain the fen. These levels are also a reflection of the dilution by rainwater evident from the mixed surface/groundwater at phreatic levels. The reported values in Table 4.2 are, however, representative of typical conditions found in the shallow phreatic zone of good-quality fen habitat.

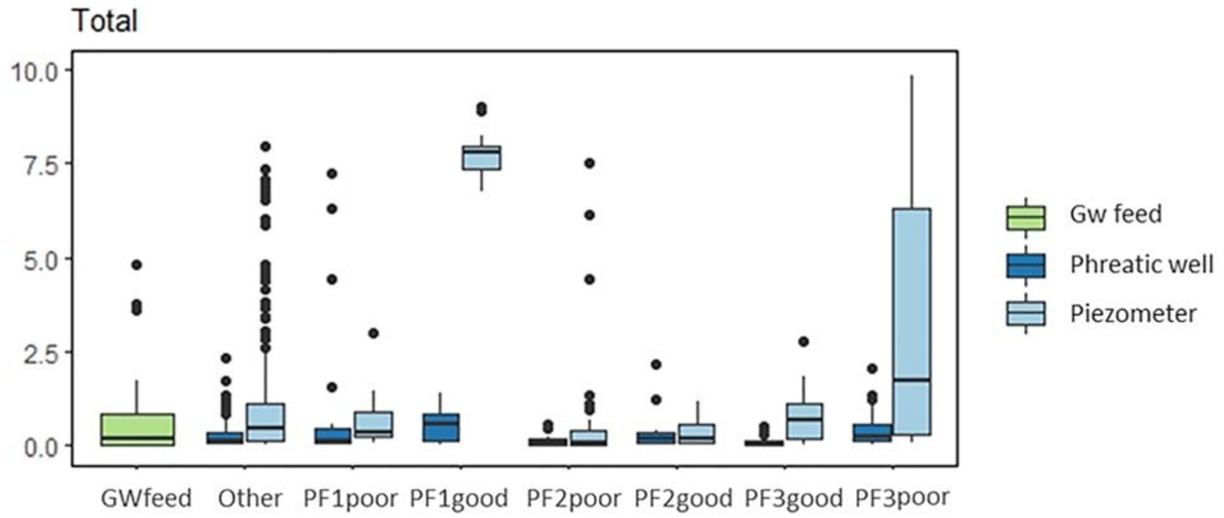

Figure 4.15. Total ammonia concentrations (mg/l as N) for calcareous fen vegetation Fossitt habitat types PF1, PF2 and PF3 in the fen phreatic tubes and piezometers of good, poor or non-fen (other) habitats, and groundwater (Gw) feed from the wider catchment.

Table 4.2. Recommendations of nutrient concentration envelopes within Irish calcareous fens

Fossitt habitat type	Nutrient				
	Dissolved reactive phosphorus (as mg P/l)	Total phosphorus (as mg P/l)	Total ammonia (as mg N/l)	Total oxidised nitrogen (as mg N/l)	Total dissolved nitrogen (as mg N/l)
PF1	0.006–0.037	0.062–0.135	0.116–0.836	0.000–0.010	0.666–2.017
PF2	0.010–0.037	0.152–0.382	0.100–0.354	0.023–0.171	0.695–1.511
PF3	0.010–0.030	0.056–0.191	0.154–0.568	0.000–0.021	0.654–1.502

If the above observations in relation to the specific components of the conceptual model for a “healthy” fen are met, the system has a higher natural resilience against natural environmental stressors such as drought or flooding. Furthermore, the fen acts as a self-cleansing system for nutrients flowing in from groundwater and surface water, whereby they get caught in the wetland’s internal biogeochemical cycles. Ultimately, the build-up of organic material (including nutrients) causes peat formation. In general, groundwater containing elevated nutrient concentrations is effectively supporting the fen vegetation. The maximum values in Table 4.2 should therefore not be used as a TV above which damage will be inflicted on the fen, as no direct link was found between high nutrient concentrations and “poor” fen habitats. These are considered to be remnant concentrations after vegetation uptake, surface water dilution and dispersion rather than the nutrients entering the fen from the catchment. The vegetation was also found to be relatively robust against short- to medium-term changes in nutrient supply from groundwater or surface water through a process of self-recycling/cleansing. Therefore, the threshold metrics should include a time dimension.

The median nutrient concentrations in groundwater monitoring points in the catchment surrounding the fens, which are reflective of the water feeding the fens, were 110 µg P/l for DRP, 260 µg P/l for TP, 0.17 mg N/l for ammonia, 1.00 mg N/l for total oxidised nitrogen and 2.59 mg N/l for total dissolved nitrogen. These levels appeared to cause no problem to the ecology in these four fens (as far as can be determined from the relatively short duration of the research study, at least), so a groundwater threshold can presumably be set at higher levels than this; however, this cannot be defined with any confidence from the results of these field studies.

In summary, these field studies have shown that the natural resilience of Irish calcareous fens can be decreased by significant hydrological changes in the fen catchment (as was found in Tory Hill). Even though the research did not find damage by nutrient pollution, very high levels of pollution can cause the nutrient cycling system to become overloaded. This may result in levels harmful to fen vegetation and the likelihood that species diversity will diminish as the smaller herbs are outcompeted by species typical of other habitats, such as swamps, scrub or woodland. Hence, more targeted research is needed in terms of understanding the complex water quality dynamics within such wetlands, involving accumulation and internal cycling of nutrients, in order to establish pragmatic nutrient TVs.

5 Raised Bogs

5.1 Introduction

Ireland's peatlands, occurring as raised bogs, blanket bogs or fens, host specialised plant and animal communities, which contribute to global biodiversity, carbon regulation and other ecosystem services. However, exploitation has reduced the habitats' global distribution and damaged their ecohydrological functioning. These habitats have disappeared almost entirely in temperate climates as a result of land reclamation for agriculture, horticulture, forestry, fuel production and urbanisation. Despite these losses, Ireland contains approximately 60% of the remaining raised bog habitat area in the EU. However, mechanised commercial peat extraction, combined with marginal turf cutting, has resulted in the loss of over 80% of the original raised bog area. Consequently, despite peatlands 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, 2018). Since the late 1980s, raised bogs in Ireland have been the subject of a series of integrated research projects by scientists and engineers from Ireland, the UK and the Netherlands. This has led to an enhanced understanding of the ecology and the hydrological conditions necessary for their maintenance and restoration, including the development of a unique habitat classification system based on ecotopes (vegetation communities that represent both the ecological condition and hydrological signature of the bog). The maintenance of a hydrologically self-regulating acrotelm[1] is a key supporting condition for active peat accumulation and conservation of the Annex I priority habitat, ARB, under the Habitats Directive.

Functionally, raised bogs are ombrotrophic systems, and water loss occurs primarily through evapotranspiration and is replaced directly by precipitation or capillary transport from the free water table (Robroek *et al.*, 2009). ARBs are thus not groundwater dependent in the traditional sense, in that the wetland system generally does not receive direct transfer of recharge or nutrients from the GWB. Instead, the GWB can act as an indirect support, maintaining upward hydraulic gradients to promote water retention within the overlying peat substrate (Regan *et al.*, 2019). Anthropogenic alteration of the GWB can disturb this equilibrium, reversing gradients and inducing increased water loss in the ecosystem with resultant peat consolidation, oxidation and subsurface cracking (Price, 2003). This has been demonstrated at Clara bog, where a lowering of the regional groundwater has drained the peatland and resulted in losses of ARB in the order of 40% since the 1990s (Regan *et al.*, 2019).

For degraded peatlands to be restored – and there is growing interest in such peatland conservation and restoration as a method of carbon capture to reduce Ireland's net greenhouse gas emissions – careful hydrological management is required 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 biodiversity. Hence, research-based metrics are needed to inform the ecohydrological conditions that need to be maintained in such systems. In parallel with the EcoMetrics project, another research project was being carried out for the EPA, led by the same TCD team; the report resulting from project is entitled *Eco-hydrology, Greenhouse Gas Dynamics and Restoration Guidelines for Degraded Raised Bogs* (Regan *et al.*, 2020). Although much of the focus of that project was on quantifying the greenhouse gas emissions from different areas of the raised bogs, there were also many relevant findings concerning the ecohydrological conditions required to support the optimum areas of ARBs; the results are summarised here.

5.2 Study Sites

As detailed in Chapter 2, the raised bogs chosen for the study were Clara bog SAC and Abbeyleix

1 Acrotelm is the surface layer of peat in a bog that contains living plants.

bog in the Irish midlands (Figure 2.1). Although the Clara site contains one of Ireland's largest expanses of ARB, it has decreased considerably in the past number of 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, through drain blocking, occurred in 2009, while the cutover bog surrounding the uncut bog was abandoned in 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 (Smith and Crowley, 2020).

The study sites were set up to investigate hydrological and greenhouse gas processes 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 greenhouse gas emissions.

A number of ecotopes have been classified for raised bogs (see Schouten, 2002), with four primary ecotope types, namely marginal, submarginal, subcentral and central, being the most common and widely distributed. Central and subcentral are considered to be the Annex I-type ARB and submarginal can constitute degraded raised bogs (DRBs); on the other hand, marginal is damaged and is considered incapable of regenerating to ARB.

Comprehensive hydrometric monitoring networks were installed at both bogs, involving phreatic and piezometer tubes to monitor the groundwater head conditions in the peat and underlying till subsoil, as well as flumes at the main drainage outlets to monitor runoff. To investigate the hydrological properties of the vegetative layer and near-surface peat, microcosm experiments were also carried out at Abbeyleix to quantify the storage properties of the different vegetative areas and the water input from shallow lateral flow.

5.3 Ecohydrology

The ecohydrology of raised bog systems is generally conceptualised as two main types of storage with differing responses to rainfall inputs. The bulk of the bog peat tends to be a low-permeability medium (catotelm), which rests on or in a regional GWB 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 to be an "active" layer with storage properties whose response to rainfall is quite different from that of the peat beneath. The stability of the acrotelm depends 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).

5.3.1 Surface slope

Topographic slope and climatic regime are the primary factors controlling the water table on the surface of Irish raised bogs and largely determine ecotope type. Mean slope gradients at central, subcentral, submarginal and marginal ecotopes were determined to be 0.32%, 0.35%, 0.71% and 1.8%, respectively, from the study of 53 raised bog SACs across the midlands of Ireland (see Figure 5.1).

5.3.2 Water table

Water table depth 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 (see Figure 5.2). A subtle transition from subcentral to submarginal conditions, and thereby ARB to DRB, occurs when this water table duration threshold drops below approximately 90%. Ecological damage, the result of desiccation of the acrotelm, is thereby reflected in water table depth 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.

It should also be noted that the maintenance of high water levels in the peat may not be just a function of the rainfall onto the bog and the hydraulic conductivity of the peat, but may also be linked to the interaction between the water in the peat and the underlying regional groundwater. At Clara bog, the decline of the

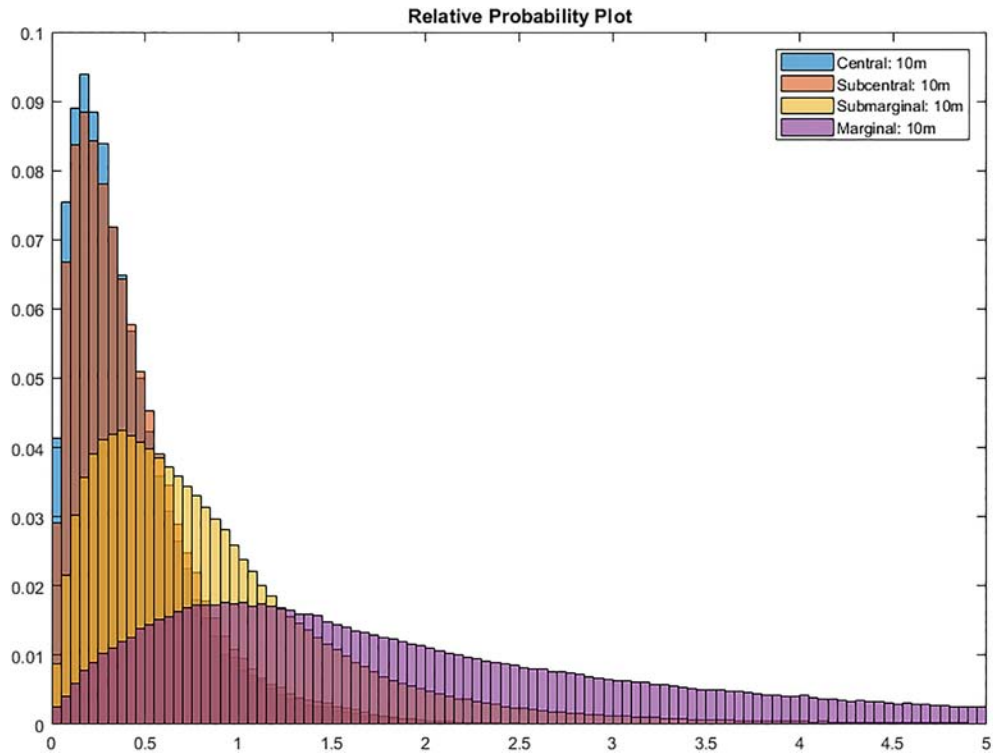

Figure 5.1. Relative probability plot of ecotope and slope distribution from 53 raised bogs (Regan *et al.*, 2020).

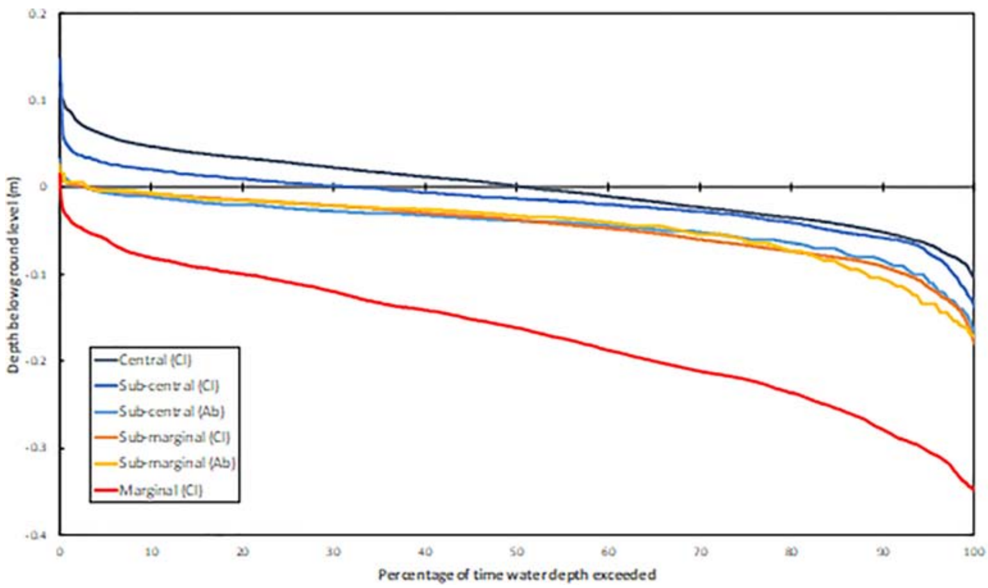

Figure 5.2. Water table depth duration curves for ecotopes at Clara (Cl) and Abbeyleix (Ab) bogs (2015–2017) (Regan *et al.*, 2020).

piezometric head in the peat is shown to have induced considerable subsidence, which is a result of regional groundwater drainage in marginal areas outside the intact bog. In contrast to Abbeyleix bog, there is a strong hydrological connectivity at Clara, as that bog is underlain by mineral subsoil/substrate with a much higher hydraulic conductivity than the lacustrine clay or low-permeability glacial till deposits usually assumed to be beneath raised bogs.

5.3.3 Acrotelm hydraulic properties

The microcosm experiments carried out at Abbeyleix bog were used to quantify the storage properties of the acrotelm and shallow peat layer in degraded areas. By comparing the changes in storage inside and outside the microcosms, the experiments showed the importance of lateral flow to maintaining and restoring ARB conditions. The timing and magnitude of the lateral flow differed considerably between locations with differing ecological conditions (i.e. different ecotopes), indicating that shallow lateral flow is an important determining factor in the ecohydrological trajectory of a recovering bog system. For locations where a *Sphagnum* spp. moss layer was present, a slow continuous net lateral input of water from the upstream catchment area supported the water table during drought periods, which was not observed in locations lacking *Sphagnum*. For more details on this work, see Swenson *et al.* (2020).

5.3.4 Hydrological restoration

From this work, guidelines have been developed on how to approach hydrological restoration of degraded bogs, in particular how to achieve and maintain a functioning acrotelm. The main recommendation from this work is that to maximise regeneration potential, restoration works must restore surface water slopes (the hydraulic gradient) to ensure maximum water table depths of 0.2 m 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 100 m 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 $>0.6\%$, 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 bogs. Further research is required to determine what size a catchment needs to be to sustain ARB conditions in areas with relatively high slopes. This is likely to be both scale and climatically dependent. 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. A lack of significant *Sphagnum* regrowth in the restored areas may suggest that water loss from the bog is not confined to surface drainage and that there may be losses to the subsurface. For more details see Regan *et al.* (2020).

6 Turloughs

6.1 Introduction

Turloughs are ephemeral lakes that form in shallow depressions in karst areas, mainly in the west of Ireland. Such intermittent wetlands act as attenuation devices for excess groundwater and surface water recharge during extended rainy periods, storing large volumes of water, mainly over the winter, when it cannot be accommodated by the underlying groundwater flow system. They generally flood (and drain) from their lowest topographic point, often via estavelles[2] linked to the main karst conduit networks (Naughton *et al.*, 2012). This intermittent flooding of the basin produces a distinct hydrological gradient, which produces a linked vegetation gradient. Such wetlands are designated priority habitats under the EU Habitats Directive and are considered as GWDTEs under the EU WFD. Considerable research has been carried out in recent years on turlough hydrology (Naughton *et al.*, 2012; Gill *et al.*, 2013, 2020), nutrient cycling (Cunha Pereira *et al.*, 2010; McCormack *et al.*, 2016) and ecology (Moran *et al.*, 2008; Cunha Pereira *et al.*, 2011; Porst *et al.*, 2012), shedding light on their ecohydrological interdependencies. Studies on turlough geomorphology and conservation importance have also been conducted, e.g. Coxon (1987) and Sheehy Skeffington *et al.* (2006), and summaries of turlough wetland plant and freshwater habitats and communities are provided in Goodwillie and Reynolds (2003). Some of this research originated as part of an integrated project (Waldren *et al.*, 2015) that was also funded by NPWS, which studied the conservation status (flora, aquatic invertebrates and algae, hydrology and hydrochemistry, soils and conservation status) of 22 turloughs. This EcoMetrics project, led by most of the same investigators from the Waldren *et al.* (2015) study, has synthesised the findings from that project. It then progressed to develop a methodology using a combination of continuous water level monitoring and high-resolution topographic surveying to define the flood conditions experienced across different vegetation communities across turloughs. These were then collated and presented as statistical distributions for the ecometrics of flood duration, flood depth, flood frequency and mean temperature/global radiation at the time of year, in spring, when the flood waters start to recede. This work has been published (see Bhatnagar *et al*., 2021b); a summary of the findings is presented in this chapter.

6.2 Synthesis of the Waldren *et al.* (2015) Study

A multidisciplinary team from TCD carried out detailed investigation of 22 turloughs in the west of Ireland between 2006 and 2008, characterising their ecology, hydrology, water chemistry, soils and land use to determine their overall ecological functioning, from which an assessment of their conservation status was then formulated. The turloughs were selected to be representative of the range of turlough hydrogeological variation found in Ireland, from shallow epikarst to conduit surcharge flow types and with a range of flood dynamics, from those exhibiting short duration (flashy) shallow flooding episodes in winter to those with very long duration flood events across the whole winter. The turloughs were characterised during the project and covered a range of soil types (nutrient status), water quality (from eutrophic to oligotrophic) and land use, and hosted a range of algal and aquatic invertebrate communities and terrestrial vegetation.

The main conclusion from the research was that turloughs exist as a hydrological and ecological continuum and therefore need to be considered on a site-by-site basis, rather than trying to categorise them into specific types. Phosphorus concentrations in the flood water, while varying considerably across the 22 turloughs and at different times of year, did show a strong relationship with algal and aquatic invertebrate communities and terrestrial vegetation. The turloughs with the highest water quality (oligotrophic) usually had the most interesting biological communities, with vegetation dominated by various sedges (*Carex* spp.); several of these turloughs occurred in the vicinity of the Burren National Park. By contrast, turloughs with

2 Orifices in a karst landscape which, depending on hydrological conditions, can act as either a sink or a source of water.

higher nutrient levels (mesotrophic) tended to have vegetation communities dominated by grasses and forbs. Other turloughs had very poor water quality (strongly eutrophic), which was often associated with degraded biological communities. The causes of such poor water quality could often be attributed to sources adjacent to or within the turlough, including fertiliser application, slurry spreading and effluent discharge. Furthermore, the nature of karst catchments in which turloughs are located means that they are potentially very sensitive and susceptible to pollutants being emitted anywhere in their recharge catchment as a result of the rapid transport of such pollutants through well-connected karst features, from swallow holes and sinking streams into conduits to estavelles. Inappropriate agricultural management seemed to be an important pressure in some turloughs, with some evidence that overgrazing had reduced biological diversity in some turloughs over the past decade.

Recommendations were made that biological communities, hydrology and hydrochemistry monitoring should continue on these 22 turloughs to assess future change. Additional studies and active conservation are required on further sites to improve their ecological status. Furthermore, it was recommended more generally that TP should be directly measured in the turlough flood waters at least once (but preferably three times) per year by state authorities. These recommendations do not seem to have been taken up in the intervening years. However, the turloughs in the south Galway chain have continued to be monitored by the TCD team in the Environmental Engineering research group over the intervening years to build up a longer time series of water levels from which more detailed models have been developed and calibrated. There has also been a renewed interest in a flood alleviation scheme in the area, which has meant further monitoring has been sponsored by the OPW, Galway County Council and GSI. These data have been used in this project

6.3 Ecohydrological Metrics for Vegetation Communities in Turloughs

6.3.1 Introduction

The four turloughs selected for study (Blackrock, Lough Coy, Garryland and Caherglassaun) are located in an extensive conduit karst network catchment in south Galway (see Figure 2.1). The turloughs in this interconnected lowland karst network contain waters that are a mixture of soft water from rivers that drain the Slieve Aughty mountains and hard water from the lowland calcareous parts of their catchments, yielding waters of relatively low alkalinity and relatively high colour (due to the presence of humic and fulvic materials in drainage from peat). Sampling of these turloughs in the past has shown fairly consistent concentrations of nutrients both over time and between the four turloughs, with TP ranging from 20 to 50 μg P/l, total dissolved phosphorus from 5 to 30 μg P/l and total nitrogen from 0.25 to 1.2 mg N/l (McCormack *et al.*, 2016). The soil types are very similar between the four turloughs, comprising mineral soils associated with till subsoils. Furthermore, the land use is very similar between the four turloughs, with grazing mainly by cattle (and also some sheep and horses) at relatively low intensity during the summer.

6.3.2 Vegetation communities and hydrological data

Vegetation field surveys were conducted over three field seasons, 2006, 2007 and 2008, across all 22 turloughs (Waldren *et al.*, 2015). From this, 28 vegetation communities were then described from multivariate analyses of the relevés taken across all the turloughs. These turlough plant community species and community identification keys were used in the field in 2008 for identifying and mapping the vegetation types in the four turloughs focused on in this study (Blackrock, Coy, Caherglassaun and Garryland). Fourteen vegetation communities were found in at least one of these four turloughs (Figure 6.1). A more recent assessment of the vegetation distribution across the turloughs was made as part of this EcoMetrics project using RS methods from Sentinel-2 satellite imagery captured in June 2018, as detailed in Chapter 3.

As described in section 2.2.2, continuous water level data were collected using pressure transducers with inbuilt dataloggers at the base of four turloughs between 2007 and 2018. Continuous rainfall data were collected from two rain gauges positioned at 70 metres above ordnance datum (mAOD) and 150 mAOD in the catchment to assess the spatial distribution of rainfall. These data were then related to the Gort Derrybrien

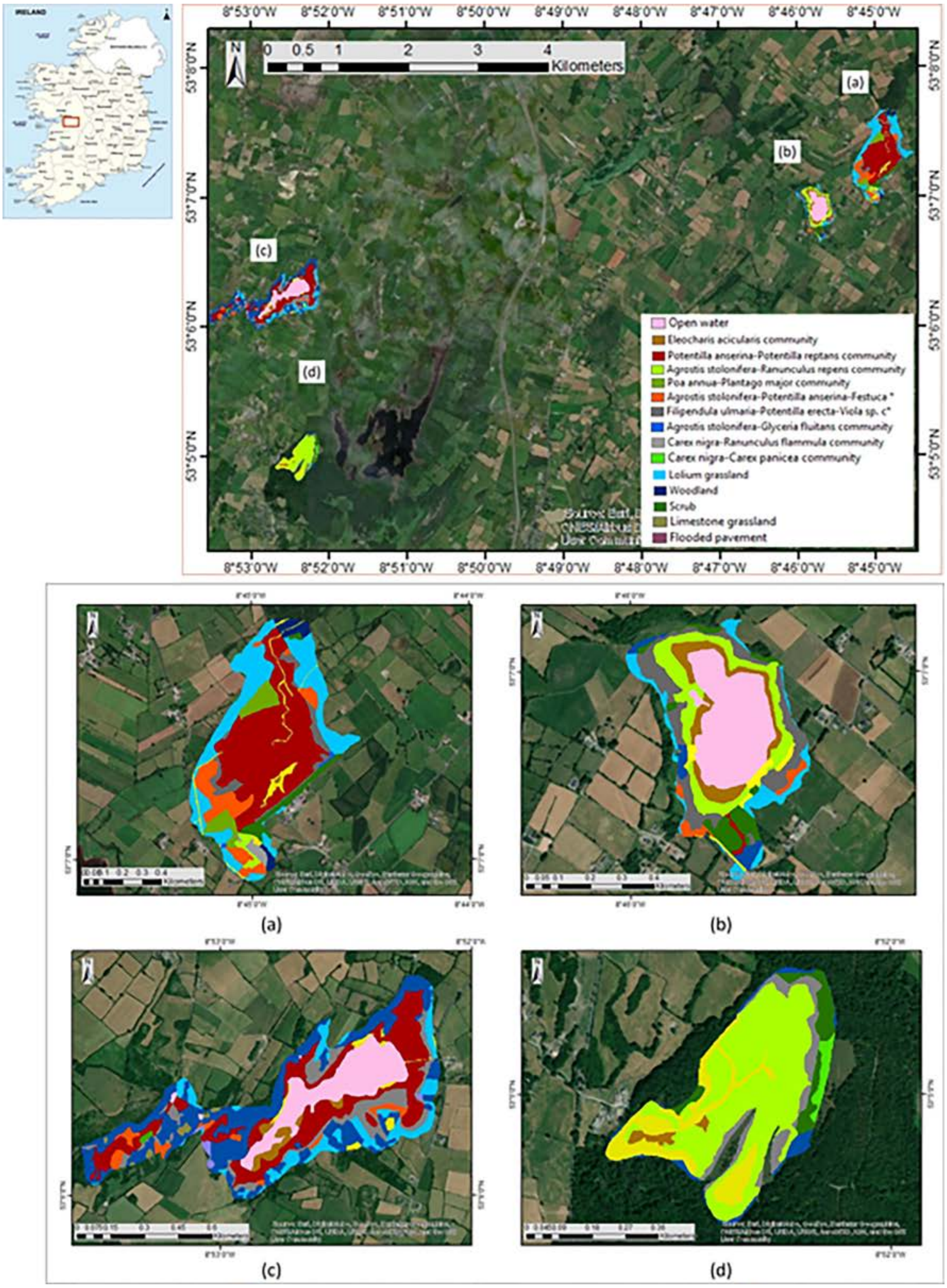

Figure 6.1. Vegetation communities for the four turloughs mapped between 2006 and 2009 in (a) Blackrock, (b) Coy, (c) Caherglassaun and (d) Garryland (from Waldren *et al.*, 2015).

gauge operated by Met Éireann, which provided a longer dataset. Topographical data were derived from LiDAR mapping data for the catchment with a grid spacing of 2 m and a vertical accuracy of ±0.15 m.

A detailed semi-distributed hydraulic model of the karst network has been developed over many years for various applications (ecohydrology, flood alleviation, etc.) and was used to fill in any gaps in the turlough water level data and also to extend the turlough water time series back to 1989, when local rain monitoring started in the region. The model is built using the InfoWorks CS drainage software owing to its ability to model the hydraulics of the karst conduit network in both open channel and pressurised pipe flow. The model is described in detail in Gill *et al.* (2013, 2020), with the most recent update in Morrissey *et al.* (2020).

6.3.3 Hydrological characteristics

The average depth–duration plots for the four turloughs over the last 28 years are shown in Figure 6.2. This shows the flash flood dynamics of Blackrock turlough, which has the steepest topography and is located at the start of the hydraulic network, meaning that it receives a less damped hydraulic signal from the allogenic river inputs than the turloughs lower down the network. Garryland and Caherglassaun, at the lower end of the system, show very similar curves.

The annual flood duration spatial profile across the 28 years is shown for Blackrock turlough, as an example, in Figure 6.3 revealing the difference between hydrological years. In particular, years 1989/1990, 1991, 1994, 1995, 2009 and 2015/2016 can be seen to have much longer flood durations than many of the other years; these were years when there was widely reported significant flood disruption in the winters in this area, compared with the much drier years of 1997, 2006, etc.

6.3.4 Ecohydrological metrics

The key hydrological variables evaluated that were potentially related to the distribution of the different vegetation communities were depth, duration, frequency and timing of flooding. The 28-year water level time series for each of the four turloughs were then used in conjunction with the detailed topographical maps to determine the following metrics for any point across each turlough on a daily basis. These metrics were then associated with the different vegetation communities according to their spatial distribution from the vegetation survey maps and presented as cumulative statistics for the different communities across the four turloughs and across the 28-year period. The communities have been ordered according to the flood duration on the graphs and tables ranging from *Eleocharis acicularis* (experiencing the most flooded conditions in a year) to the flooded pavement community (experiencing the least amount of flooding).

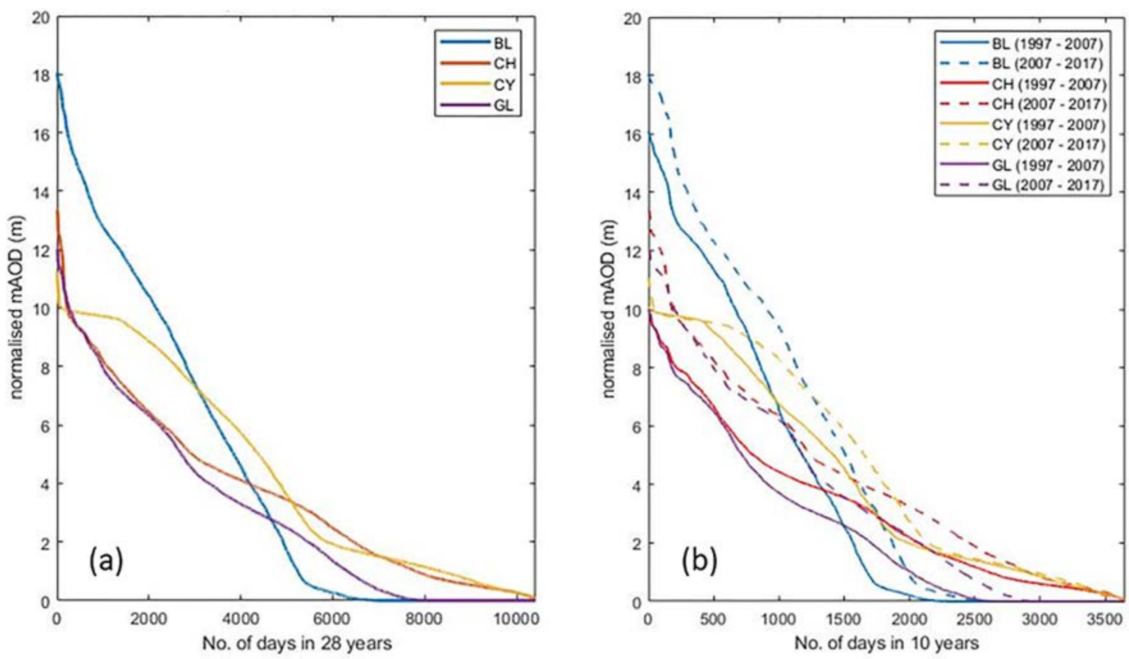

Figure 6.2. Flood depth–duration plots for four turloughs, Blackrock (BL), Caherglassaun (CH), Coy (CY) and Garryland (GL), (a) across the full 28-year dataset and (b) comparing 10-year datasets (1997–2007 and 2008–2017).

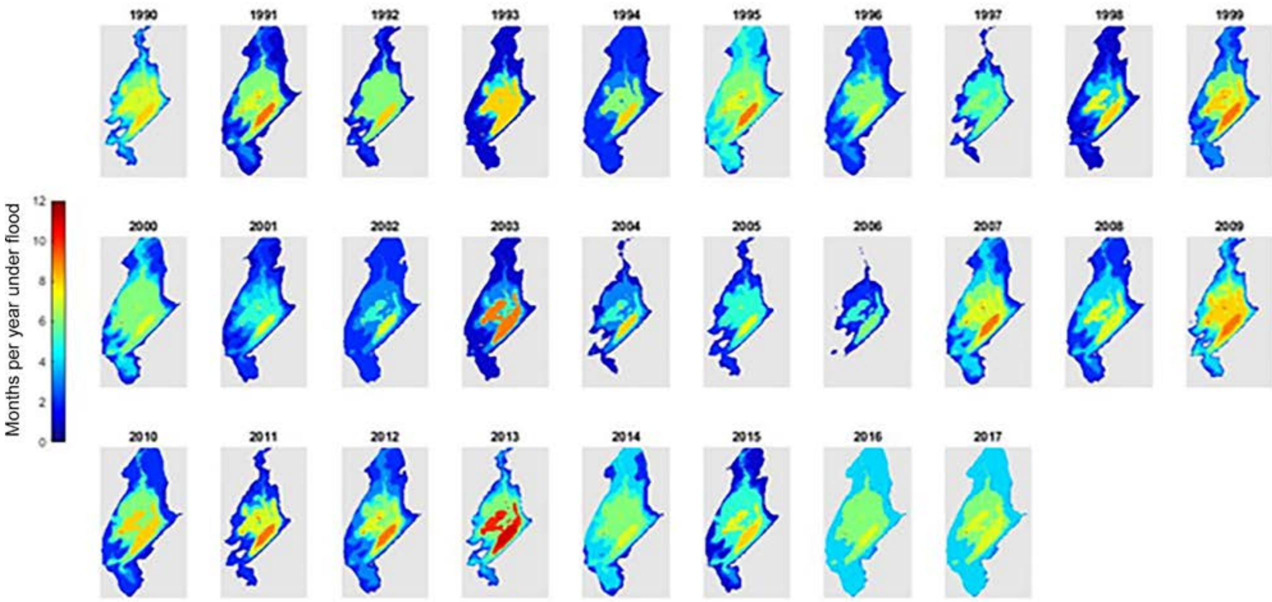

Figure 6.3. Annual mean flood duration spatial profiles for Blackrock turlough. Note that each annual figure represents a hydrological year from October to September with the year written above referring to the last 9 months of each year.

Flood duration and depth

The variations in flood duration and flood depth statistics across the 28 years, averaged among and between the key communities, are shown in the boxplots in Figure 6.4(a) and (b). This shows not only wide fluctuation between different years but also the differences between communities, from *Eleocharis acicularis*, which is found at the base of the turlough, typically experiencing 6 to 7 months of inundation per year, to the limestone pavement community at the top fringes of the turloughs experiencing flooding only 1 to 2 months per year.

Flood recession timing

The timing of when the flood receded (and hence the potential start of the growing season for each vegetation community) was determined by looking at the mean global radiation and mean temperature (as proxy metrics that can be linked to physiological plant processes), taking an average across 30 days (10 days before the vegetation was first revealed and 20 days after). The global radiation statistics across the 28 years, averaged for each of the key communities when coming out of flood, which generally happens in the springtime, are shown in Figure 6.4(c). This shows that the higher elevation communities are exposed earlier in the year, when the mean solar radiation (and average air temperature) is lower, as expected. However, there are not such clear differences between the different vegetation communities, which is perhaps due to the temperate maritime climate in Ireland, which has less extreme climatic changes across the year than other temperate parts of the world.

Flood frequency

The variations in flood frequency per year among and between the communities are shown in Figure 6.4(d) and illustrate that most communities experience a maximum of only two flood inundations per year.

Finally, a hierarchical spatial clustering analysis was used on the 28-year dataset on the four turloughs on the key ecohydrological variables (i.e. flooding depth, duration, temperature and global radiation) to identify clusters of similar hydrological years. This was used to refine the ecohydrological metrics to reflect what the different vegetation communities experienced in what might be considered more “normal” years. A summary of the flood duration, depth, global radiation when coming out of flood and flood frequency metrics across all four turloughs for the different vegetation communities is presented in Table 6.1. These then indicate suggested threshold envelopes for these

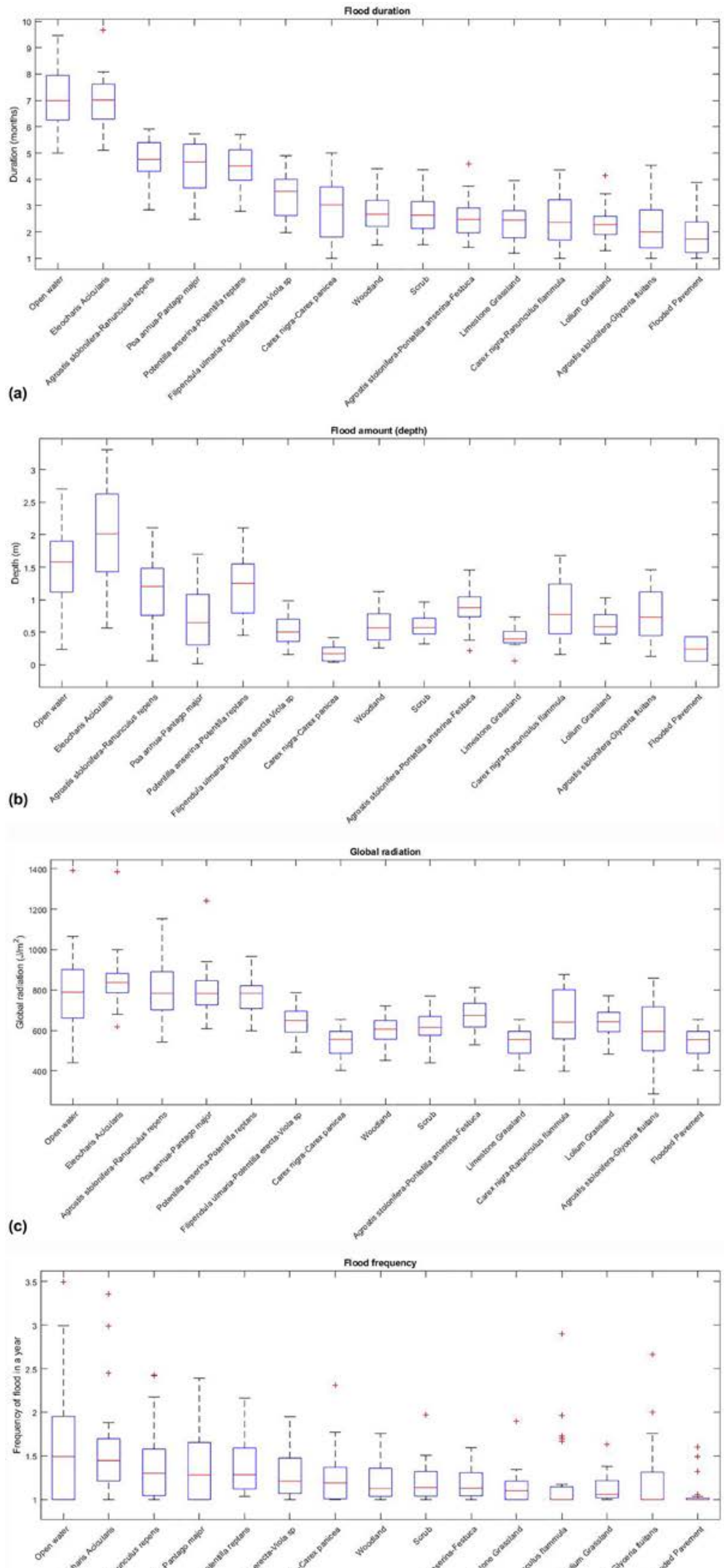

Figure 6.4. The statistical distributions of four different ecohydrological metrics for the range of turlough vegetation communities averaged over the four turloughs. (a) Flood duration, (b) flood depth, (c) global radiation when the flood waters first recede and (d) flood frequency per year.

Table 6.1. Ecohydrological metrics for different turlough vegetation communities averaged across four turloughs

	Depth (m)				Duration (months)				Frequency (per year)				Global radiation (J/m²)			
Vegetation community	Min	Mean	Max	Range	Min	Mean	Max	Range	Min	Mean	Max	Range	Min	Mean	Max	Range
Open water	0.23	1.97	3.31	0.77–2.50	5.11	6.92	9.67	6.40–7.19	1.00	1.57	3.49	1.00–1.87	440	792	1391	600–811
Eleocharis acicularis	0.56	1.52	2.70	0.75–1.85	5.00	7.01	9.46	6.12–6.99	1.00	1.54	3.35	1.02–1.70	618	848	1385	723–807
Agrostis stolonifera–Ranunculus repens	0.06	1.24	2.19	0.55–1.62	2.84	4.57	5.83	4.10–4.87	1.00	1.40	2.42	1.00–1.58	542	795	1152	661–785
Poa annua–Plantago major	0.01	0.71	1.70	0.30–1.22	2.48	4.44	5.72	3.18–5.18	1.00	1.40	2.39	1.08–1.33	608	795	1241	680–732
Potentilla anserina–Potentilla reptans	0.45	1.21	2.11	0.71–1.50	2.79	4.48	5.71	3.25–4.88	1.04	1.39	2.16	1.02–1.52	598	775	966	669–739
Filipendula ulmaria–Potentilla erecta–Viola spp.	0.16	0.52	0.98	0.44–0.80	1.98	3.36	4.90	2.18–4.04	1.00	1.29	1.95	1.00–1.21	492	647	787	570–630
Carex nigra–Carex panicea	0.04	0.18	0.42	0.22–0.47	1.00	2.82	5.00	1.55–4.03	1.00	1.27	2.31	1.00–1.21	403	539	654	490–556
Woodland	0.26	0.59	1.13	0.47–0.81	1.50	2.74	4.40	1.97–3.10	1.00	1.20	1.76	1.00–1.10	452	606	722	550–601
Scrub	0.32	0.60	0.96	0.49–0.65	1.51	2.68	4.37	1.91–3.15	1.00	1.20	1.97	1.01–1.12	439	618	770	556–619
Agrostis stolonifera–Potentilla anserina–Festuca	0.21	0.86	1.46	0.54–0.85	1.42	2.50	4.58	1.60–2.72	1.00	1.18	1.59	1.04–1.10	529	681	813	609–662
Limestone grassland	0.06	0.42	0.73	0.50–0.63	1.20	2.37	3.95	1.76–2.80	1.00	1.14	1.90	1.00–1.14	403	539	654	490–556
Carex nigra–Ranunculus flammula	0.16	0.84	1.68	0.48–1.36	1.00	2.40	4.36	1.03–2.36	1.00	1.22	2.89	1.00–1.40	398	657	876	539–658
Lolium grassland	0.18	0.61	1.00	0.20–0.75	1.18	2.17	4.05	1.34–2.33	1.00	1.14	1.63	1.03–1.10	482	649	772	583–637
Agrostis stolonifera–Glyceria fluitans	0.13	0.78	1.46	0.36–1.13	1.00	2.20	4.54	1.00–2.00	1.00	1.21	2.66	1.00–1.50	286	591	858	465–694
Flooded pavement	0.05	0.24	0.43	0.43–0.43	1.00	1.88	3.88	1.15–2.46	1.00	1.06	1.60	1.00–1.20	403	538	654	490–556

vegetation communities, with flood duration perhaps being the key variable that could be used to determine possible impacts of damage to the ecosystem in future assessments. However, it should be noted that these four turloughs are all on the same connected conduit karst system and therefore have a similar nutrient status. As concluded in the wider Waldren *et al.* (2015) research study, the TP concentration in the flood waters also has a strong relationship with vegetation habitats in turloughs, so it also needs to be included as an ecological metric; however, more data and research are needed on this aspect. It should also be noted that the four particular turloughs studied on this linked conduit network behaved rather differently from the other turloughs in the wider Waldren *et al.* (2015) study, which showed a clear relationship between TP and chlorophyll a concentrations (i.e. algal productivity). In these four turloughs, high phosphorus concentrations corresponded to low chlorophyll a, possibly reflecting suppression of algal growth due to the high water colour as a result of the allogenic inputs of water into the karst network from the adjacent Slieve Aughty mountains, which have a significant peat covering.

7 Conclusions and Recommendations

7.1 Conclusions

Understanding the ecohydrogeological connectivity and environmental supporting conditions of wetland systems is critical for the successful management of wetlands as well as for meeting legislative commitments, such as the implementation of the WFD and Habitats Directive, particularly for those wetlands defined as GWDTEs. The aims of this research project were to advance methods of assessing and defining appropriate ecohydrological metrics to help policymakers, environmental regulators and managers conserve and/or restore such wetlands, as well as achieving WFD objectives as applied to GWDTEs in Ireland. The project was split into four main work packages, with three that focused on raised bogs, turloughs and calcareous fens, respectively, by identifying appropriate metrics that characterise the environmental supporting conditions for these wetlands. The other was an overarching work package on the use of RS techniques to identify GWDTEs and assess changes in their ecohydrological health over time.

One of the key outcomes of these studies of environmental supporting conditions for wetlands – raised bogs, fens and turloughs – is that, although there is wide variation in any one habitat type, there are now clear indications of how appropriate and consistent metrics may be defined. These wetland types, as GWDTEs in landscape form, are essentially areas of temporary water retention, no matter the source of the water (rainfall, groundwater or surface flow). As such, they are dynamic systems, albeit having widely different residence times and which do not necessarily have an "equilibrium condition", not least under a changing climate. The vegetation patterns are themselves also dynamic, reflecting these different and characteristic hydrological regimes, which are defined in terms of both quantity and quality. Even if a long-term state is assumed for a wetland in a relatively unimpacted condition, appropriate metrics to delimit that condition must include a time dimension. For all three wetland types, water level has been found to be a key defining metric for the sustainability of the characteristic vegetation. However, the metric is defined by both water level and a measure of its frequency and duration. The water level, relative to vegetation "ground" surface, is effectively an integrated response to the variety and often localised nature of water sources that may be driving the wetland and its vegetation. Hence, a time-related water level has been shown to be a defining metric.

Water quality is a more difficult characteristic for which to define a single metric, as the localised sources of water often result in localised vegetation responses as a result of the hydrochemistry. Nevertheless, ranges of nutrient concentrations can be defined for different vegetation groups or habitat types in characteristic wetland types. Moreover, uptake and recycling of nutrients by plant communities results in wide variations of water quality across a wetland, which also depends on season. This situation complicates the defining of a single metric, even though it too will have a time dimension. Although metrics may be somewhat easier to define in a raised bog with relatively homogeneous vegetation cover (compared with fens and turloughs), appropriate metrics for nutrients can be defined by a range, at best. The quantification of critical duration and frequency will require longer-term studies than was possible in this study, but a key outcome is that most vegetation communities in these wetlands appear to be relatively resilient to fluctuating inputs. It is therefore recommended that a more appropriate metric for sustainability of these wetlands is a measure of the resilience of the vegetation (or of habitat types) rather than single TVs. More research is also needed on the link between the wider supporting catchment groundwater water quality and quantity metrics and those metrics defined in the wetlands for different vegetation types, particularly with respect to the requirements of the WFD.

The implication of these results is that data collection over a significant period is necessary to define the compliance with appropriate metrics or to indicate their exceedance. In this context, the value of satellite/drone observations has been well demonstrated in this study, together with their efficacy in long-term monitoring, provided good calibration datasets can be established for each wetland type.

7.1.1 Summary of water level metrics

Fens

Four fens were instrumented and monitored over a 2-year period so that both their hydrology and hydrochemistry in relation to their different vegetation types could be investigated. The results of water balance calculations and the hydrochemistry monitoring provided a conceptual model of the groundwater feeding the fens at discrete points. The model suggests that the groundwater helps to maintain high water levels, even across drought periods in the summer, as well as supplying relatively high concentrations of nutrients that appear to be picked up by the fen vegetation; this results in lower nutrient concentrations in the surface water of the fen, which leaves via a stream. The field investigations suggest that a threshold water level envelope of between 29 mm and 277 mm above ground level, which should be sustained for at least 60% of the year, is required for healthy fen vegetation, with the mean annual water level always above the surface. The PF1 (rich fen and flush) habitat seems to require a higher envelope of water levels that are always above the ground surface, from approximately 100 to 400 mm depth of flooding all year round. These envelope values were calculated by taking the first and third quartiles of the healthy fen habitats.

Although envelopes of nutrients in the surface water of the fen associated with healthy fen vegetation can be defined (e.g. DRP concentrations of between 6 and 37 µg P/l for PF1 habitat), these levels should be regarded as the water quality after the fen vegetation has effectively treated the higher incoming nutrient levels in the groundwater. At the four fens studied, the generally higher levels of nutrients in the groundwater feeds did not appear to be causing any ecological stress to the fen ecosystems and hence groundwater TVs cannot yet be defined with any confidence.

Raised bogs

The ecohydrology of two raised bogs, Clara bog and Abbeyleix bog in the Irish midlands, was intensively studied over a 2-year period as part of a parallel EPA-funded project (Regan *et al.*, 2020). Hydrometric monitoring in relation to the different ecotopes across the raised bogs indicates that ARB occurs where water tables are within 100 mm of the ground surface for approximately 90% of a given year. It was also noted that the maintenance of high water levels in the peat may not just be a function of the rainfall onto the bog and the hydraulic conductivity of the peat, but may also be linked to the interaction between the water in the peat and the underlying regional groundwater.

Turloughs

Ecohydrological metrics have been investigated using a 28-year hydrological record of water levels for four turloughs in the west of Ireland. The metrics defined for each vegetation community were flood duration and depth, as well as global radiation and temperature, with the last two used as a proxy for the time of the year when the floodwaters first recede and the vegetation can emerge. These then indicate suggested threshold envelopes for these vegetation communities, with duration perhaps being the key variable that could be used to determine future impacts of damage to the ecosystem in future assessments. These threshold envelopes are presented in Table 6.1.

7.1.2 Remote sensing

The RS research started with a pixel-based approach. Vegetation communities across raised bogs, turloughs and fens were mapped using ensemble classifiers such as bagged tree. As the boundary of such wetlands is often ill-defined, the study initially developed a boundary delineation algorithm using edge detection techniques such as entropy filtering and Canny edge detection. However, the pixel-based approach only considers the spectral properties of the area. Therefore, the study was further extended to include segment-based learning; graph cut MAP segmentation was used. This takes into account the textural information on top of the spectral information. This segmentation process acted as a post-classification smoothing for the wetland maps and was termed the MVC algorithm. A total of up to 18 classes were mapped temporally inside 13 wetlands using the MVC algorithm, with an average accuracy of 84% for the years 2017 and 2018. The algorithm works very well for larger vegetation communities, but because of the restricted spatial resolution (10 m) of Sentinel-2 satellite data, some small communities were not adequately identified. Therefore, to gain high spatial resolution images, a drone (an unmanned aerial vehicle) was employed and a comparison was made between DL and ML methods. The study then extended the ability of RS-based monitoring of wetlands by combining the high spatial resolution images from drones with the global coverage of the satellite data to create seasonal maps of vegetation communities within the wetlands. This nested methodology incorporated georeferenced land cover maps, scaled at the drone-resolution level, and upsampled to Sentinel-2 satellite imagery level through interpolation. A colour correction technique was introduced to improve consistency between drone image capture sessions.

This study has shown that it is possible to monitor the vegetation communities on these wetlands up to a reasonable level of accuracy using freely available satellite data, in particular data from Sentinel-2. Going forwards, this RS classification of vegetation habitats on wetlands should start to be carried out at least once per year to assess if there are any changes, particularly to the key vegetation habitats associated with the different wetland types. For wetlands where no habitat survey has been carried out, or for wetlands where more accuracy is required, the nested drone–satellite approach can be used.

7.2 Recommendations

Table 7.1. Recommendations for implementation and uptake of research findings

Issue	Recommendation	Target organisation	Timeframe
RS expertise to monitor wetlands	The RS techniques developed during this project need to be used by the relevant state/semi-state organisations responsible for the protection and/or restoration of such wetlands. This will require specific expertise to be taken on by these organisations	EPA, NPWS, Bord na Móna	< 1 year
RS monitoring wetlands	A co-ordinated strategy of using RS to assess the ecological health of the GWDTEs needs to be set up and implemented by the relevant state/semi-state organisations responsible for their protection and/or restoration. It is recommended that this is carried out at least once per year on these wetlands going forwards to identify any changes in key vegetation habitats, indicators of ecological health and land use	EPA, NPWS	1 year onwards
Use of nested–drone satellite methodology	More wetlands should be assessed using the nested drone–satellite technique alongside field surveys to build experience and confidence with the method and to build reliable calibration datasets	EPA, NPWS	1–3 years
Continued monitoring of the fens	The fens studied in this project should continue to be monitored for another 3 years to strengthen the findings and evaluate their response over a wider climatological period	EPA, NPWS, DECC	1–3 years
Monitoring of additional fen sites	Additional fens should start to be monitored to add to the database and to help strengthen the findings over a wider range of wetland sites with different pressures, and more focus should be placed on the link between the wider supporting catchment groundwater metrics and those defined in the wetlands for different vegetation types	EPA, NPWS, DECC	1–5 years
Groundwater quality vs surface water quality in fens	More targeted research is needed in terms of understanding the fate and transport of nutrients coming into the fens in groundwater compared with the levels found in the surface water. This will require more extensive analysis of groundwater chemistry in the wider catchments feeding the wetlands	EPA, NPWS, DECC	2–5 years
Dissemination of suggested water quantity ecometrics for fens, bogs and turloughs	The water quantity ecometrics suggested for these wetlands (water level and durations) need to be disseminated and discussed widely between all stakeholders involved in planning and development activities in catchments that host such wetlands. Target TVs also need to be integrated into future wetland restoration activities	EPA, NPWS, DECC, DAFM, LAs, GSI, Bord na Móna	1–5 years
Dissemination of suggested water quality ecometrics for fens	The nutrient water quality envelopes indicative of good quality fen vegetation need to be discussed widely between all stakeholders involved in the planning and development of activities in catchments that host such fens. In particular, the concept of target threshold nutrient values of groundwater feeding the fens also needs to be discussed further, based on the levels recorded in this project with respect to policies being taken in relation to the WFD	EPA, NPWS, DECC, DAFM, LAs, GSI	1–5 years
Monitoring of phosphorous levels in turlough flood waters	As previously recommended in the Waldren *et al.* (2015) study, monitoring of TP levels in turloughs at least once per year is needed to better understand the relationship between vegetation habitats (and wider ecology) and nutrient status	NPWS, EPA, GSI	< 1 year onwards

DAFM, Department of Agriculture, Food and the Marine; DECC, Department of Environment, Climate and Communications; IW, Irish Water; LAs, local authorities.

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Abbreviations

ARB	Active raised bog
ARVI	Atmospherically resistant vegetation index
BOA	Bottom-of-atmosphere
CNN	Convolutional neural network
DEM	Digital elevation model
DL	Deep learning
DRB	Degraded raised bog
DRP	Dissolved reactive phosphorus
EPA	Environmental Protection Agency
EU	European Union
GSI	Geological Survey Ireland
GWB	Groundwater body
GWDTE	Groundwater-dependent terrestrial ecosystem
KNN	*k*-Nearest neighbour
LiDAR	Light detection and ranging
mAOD	Metres above ordnance datum
MAP	Maximum a posteriori
min-cut	Minimum cut
ML	Machine learning
MVC	Mapping vegetation communities
NDVI	Normalised difference vegetation index
NIR	Near-infrared
NPWS	National Parks and Wildlife Service
OA	Overall accuracy
OLI	Operational Land Imager
OPW	Office of Public Works
RF	Random forest
RGB	Red–green–blue
RS	Remote sensing
SAC	Special Area of Conservation
SAVI	Soil-adjusted vegetation index
SVM	Support vector machine
TCD	Trinity College Dublin
TP	Total phosphorus
TV	Threshold value
UN	United Nations
WFD	Water Framework Directive

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol 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 comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

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

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

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe 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 peitril;
- scardadh dramhuisce;
- 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 húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú 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 ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil 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 gComhshaol
- 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 Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

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

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, 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 gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí 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 gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(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 chosc agus a bhainistiú.

Múscailt 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 ghníomhaíocht á bainistiú ag Bord lánaimseartha, 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 comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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EcoMetrics – Environmental Supporting Conditions for Groundwater-dependent Terrestrial Ecosystems

Authors: Laurence Gill, Saheba Bhatnagar, Ella Bijkerk, Shane Regan, Celia Somlai, Owen Naughton,Bidisha Ghosh, Stephen Waldren, Catherine Coxon and Paul Johnston

Identifying Pressures

Wetlands provide important regulating ecosystem services, such as water purification, carbon capture and storage, and flood protection. They also provide rich habitats for biodiversity, including many protected species. Understanding the hydrology of wetland systems is essential for successful management. Many of the world's wetland ecosystems have experienced significant degradation; many have been removed, while others are under threat as a result of proximal land degradation, water quality pollutant impacts and/or water supply pressures (caused by drainage, etc.). Wetland habitats in Ireland present a diverse array of ecosystems, ranging from upland and low-lying ombrotrophic bogs and groundwater-fed fens to ephemeral karst groundwater lakes (turloughs). The ecology of groundwater-dependent terrestrial ecosystems (GWDTEs) is fundamentally reliant on the supporting hydrogeology. The nature of groundwater dependency in these wetlands differs distinctly with respect to quality, level and contribution/duration (and combinations thereof), and these have been identified as key metrics of environmental supporting conditions for GWDTEs. This study focused on raised bogs, turloughs and fens, and sought to identify appropriate metrics that characterise their environmental supporting conditions by evaluating a combination of existing data and, where required, some additional field study. In addition, there was an overarching work package that focused on the use of remote sensing (RS) techniques to monitor changes in the ecohydrological health of wetlands.

Informing Policy

This research project evaluated and developed methods for the assessment and definition of appropriate ecohydrological metrics to help policymakers conserve and/or restore wetlands, particularly with respect to meeting the objectives of the Water Framework Directive and Habitats Directive as applied to GWDTEs in Ireland. The research showed that water level duration envelopes can be clearly associated with required hydrological conditions for the ecological health of different wetland vegetation communities and defined such envelopes for the three wetland types studied (raised bogs, calcareous fens and turloughs). The research also investigated water quality dynamics within such wetlands, revealing that they are more complex than water level dynamics and involve the accumulation and internal cycling of nutrients. Hence, at this stage, clear thresholds cannot be confidently defined without carrying out additional targeted studies and more continual monitoring of such wetlands. Finally, the research developed a new nested drone–satellite RS methodology, which can be adopted as a tool for continual monitoring of wetland health.

Developing Solutions

This research project advanced the methods of the assessment and definition of appropriate ecohydrological metrics that can be applied to GWDTEs in Ireland. It provides a template for co-ordinated field monitoring in parallel to the implementation of RS mapping to assess the ecological health of GWDTEs. This needs to be set up and implemented by the relevant state/semi-state organisations responsible for the protection and/or restoration of GWDTEs. The research findings suggest that the nested drone–satellite RS methodology can be adopted as the ideal solution for the continual monitoring of wetland health. In addition, the study showed that it is possible to monitor the vegetation communities on these wetlands up to a reasonable level of accuracy using freely available satellite data, in particular those from Sentinel-2. Additional fens need to be monitored to add to the database and to help strengthen the findings over a wider range of wetland sites with different pressures. The research recommends that more focus should be placed on the link between the wider supporting catchment groundwater metrics and those defined in the wetlands for different vegetation types. Equally, in terms of water quality, it recommends that more long-term monitoring, particularly of fens and turloughs, is needed before the real impact and source of pollutants can be quantified and targeted.

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