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Towards the Quantification of Blanket Bog Ecosystem Services to Water

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2021–2030

Towards the Quantification of Blanket Bog Ecosystem Services to Water

(2015-NC-MS-5)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Queen's University Belfast and University College Dublin

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DISCLAIMER

This report is based on research carried out/data from June 2016 to April 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Blanket bogs cover approximately 13% of Ireland. Despite their widespread occurrence, the ecosystem services they provide to water remain poorly characterised. This knowledge gap undermines the ability of decision-makers to address wider economic impacts of activities that damage blanket bogs, while the lack of research on relatively undamaged catchments often results in measures aimed at restoring damaged ecosystems having poorly defined performance targets.

The Environmental Protection Agency-funded project Towards the Quantification of Blanket Bog Ecosystem Services to Water (QUBBES) aimed to better characterise blanket bog hydrological processes and how they are affected by human disturbance. This involved the generation of hydrological, biological and water quality data to characterise the processes giving rise to (1) stream flow, (2) stream water quality and (3) biodiversity in catchments covered by blanket bog. Following screening of 1406 catchments for indications of disturbance, three of the least degraded (i.e. relatively intact) examples were selected for further field-based research.

Hydrological results showed that peat water tables, monitored over winter periods, occurred within 10 cm of the ground surface for over 95% of the time, while flow balance data suggested that runoff acted as the dominant water loss mechanism, giving rise to frequent high-discharge events. This contrasted with the summer period, when groundwater levels demonstrated greater dependence on physical setting, but were usually lower, reflecting increased storage capacity. Summer levels proved lower in more degraded areas, while differences during winter were less. Although summer stream hydrographs reveal the runoff regime’s continuing sensitivity to rainfall, discharge rates proved lower for comparable rainfall intensities than in winter. Flow balance data demonstrated this to be due to increased evapotranspiration, facilitating greater storage.

Water quality monitoring demonstrated an inverse relationship between stream flow and specific electrical conductance. Although data suggested that sustained discharge of more mineralised water, derived from the peat substrate, contributed to flow throughout the year, more variable contributions of shallower bog water could explain variations in runoff quality.

Relationships between specific electrical conductance and flow contrast with those observed for colour/dissolved organic carbon, the loads of which increased with increased stream discharge. However, the load per unit of flow varied between individual events, suggesting non-linear inputs of carbon.

Spatially distributed numerical modelling of rainfall runoff responses from two intact catchments failed to reproduce extended hydrograph recession limbs until supplemental reservoirs were added that contributed to flow following exceedance of a threshold. The approach is consistent with the findings of field hydrological measurements, and suggests that peat substrate groundwater contributions to runoff are continuous, and can account for up to three-quarters of base flow during prolonged dry periods. This is supplemented by additional peat groundwater, which contributes to quick flow upon exceedance of local storage capacity. Peat groundwater contributions to base flow were found to be less significant in more degraded areas.

A habitat mapping and condition assessment survey of the study sites provided a tool for quick assessment of the habitat condition status of blanket bog. However, there was no consistent correspondence between the findings of hydrological monitoring and modelling and the survey results. The distribution of some habitats corresponded well with modelled outputs, notably in hydrologically sensitive habitats and degraded habitats. However, more typical intact blanket bog communities could not be distinguished on the basis of water table fluctuations.

Taken together, the findings of field investigations suggested that bog habitat condition influences stream flow and water quality, with more intact areas having more stable flow and water quality regimes, and with more stable hydrogeological regimes in peat ensuring more consistent contributions of bog water to stream flow, while maintaining terrestrial biodiversity.

The partially damaged nature of all the QUBBES catchments complicated the economic analysis of ecosystem services. However, detailed studies on smaller catchments, examining the legacy of forestry on thick (> 1 m) peat, revealed that forestry resulted in poorer runoff water quality and a more flashy stream flow regime. Economic analysis, based on these findings, suggests that subsidised activities in drinking water catchments, such as forestry and grazing, which generate conventional marketable products like timber and meat, can result in supplemental treatment costs owing to higher colour/dissolved organic carbon. These factors, when combined with impacts to wider ecosystem services, such as loss of carbon sequestration capacity and increased greenhouse gas emissions, make for a stronger economic case for blanket bog conservation and restoration.

1 Introduction

1.1 Background

Originally covering 897,556 ha, or approximately 13% of the Irish landscape (Hammond, 1981), blanket bog forms an integral element of the natural environment in many areas of Ireland. Despite its widespread occurrence, ongoing national surveys under Section 17 of the EU Habitats Directive (Council Directive 92/43/EEC) (EU, 1992) reporting requirements have revealed a significant proportion of Irish blanket bogs to be in poor ecological condition, primarily owing to damage caused by human activity. Causes of damage include pressures that have affected blanket bogs over the past 100 years, notably cutting and associated drainage for fuel, the planting of commercial forestry, and agriculture; this last category includes overgrazing and the creation of new enclosed areas of agricultural land. In addition, more recent activities have placed further pressures on this habitat, including developments such as the installation of wind turbines and associated access routes.

By contrast, recent recognition of the wider benefits that blanket bogs may bring to society through ecosystem services has given rise to a number of programmes aimed at restoring damaged sites across Britain and Ireland. These programmes have recognised the importance of establishing appropriate hydrological conditions for supporting these specialised ecosystems. Many programmes have focused on the installation of dams in artificial drainage channels to raise water tables, while also controlling land use activities. Implementation of these activities has often come at considerable expense, yet hydrological target conditions were poorly defined. Characterising processes operating in relatively intact blanket bogs provides a basis for more confidently defining these conditions.

This report aims to describe research completed between 2016 and 2020 to provide a better understanding of Irish blanket bog hydrology. The findings of the work provide a basis for quantification of ecosystem services provided by blanket bogs to water. More specifically, investigations focused on the characterisation of hydrological processes operating in relatively intact catchments, covering between 1 km^2 and 3 km^2, using a combination of conventional hydrological approaches and more innovative investigative methods; conditions in these areas were compared with those in adjacent, more degraded, areas. The use of high (temporal)-resolution physical hydrological data along with the results of water quality monitoring and botanical data have allowed researchers to (1) better constrain how water behaves in catchments containing blanket peat and (2) investigate linkages between hydrology, water quality and ecology. These findings have provided a basis from which to begin quantification of the wider economic importance of relatively intact blanket bogs compared with more conventional land use activities in blanket peat-covered areas. Figure 1.1 summarises the process followed over the course of the research programme and described in subsequent chapters. Further details are available for each aspect in the full report associated with this research.

1.2 Site Screening and Site Selection

An assessment of peatland cover made by the Irish Peatland Conservation Council in 2009 estimated that approximately 28% of blanket bog in Ireland remained relatively intact (IPCC, 2009). To better assess the extent of unmodified bog, Quantification of Blanket Bog Ecosystem Services to Water (QUBBES) project personnel undertook a screening of 1406 blanket bog catchments, followed by a more detailed study of the 341 catchments (24%) covering areas greater than 1 km^2 and least impacted by human activity. Of the areas reviewed, 11 catchments displayed no ostensible evidence of disturbance. Multiple-criteria analysis permitted further shortlisting of the 11 sites by considering (1) feasibility for site instrumentation (and landowner consent), (2) occurrence along the climatic gradient of blanket bog occurrence, (3) distance from the project base (Belfast) and (4) ground conditions reflecting contrasting geological and hydrogeological settings. This led to the selection of three test catchments (Figure 1.2). Table 1.1 provides further details of intact areas and adjacent, more degraded, areas, selected to facilitate comparisons in hydrological regimes owing to greater levels of anthropogenic damage. These areas are referred to as “intact” and “degraded” catchments, respectively.

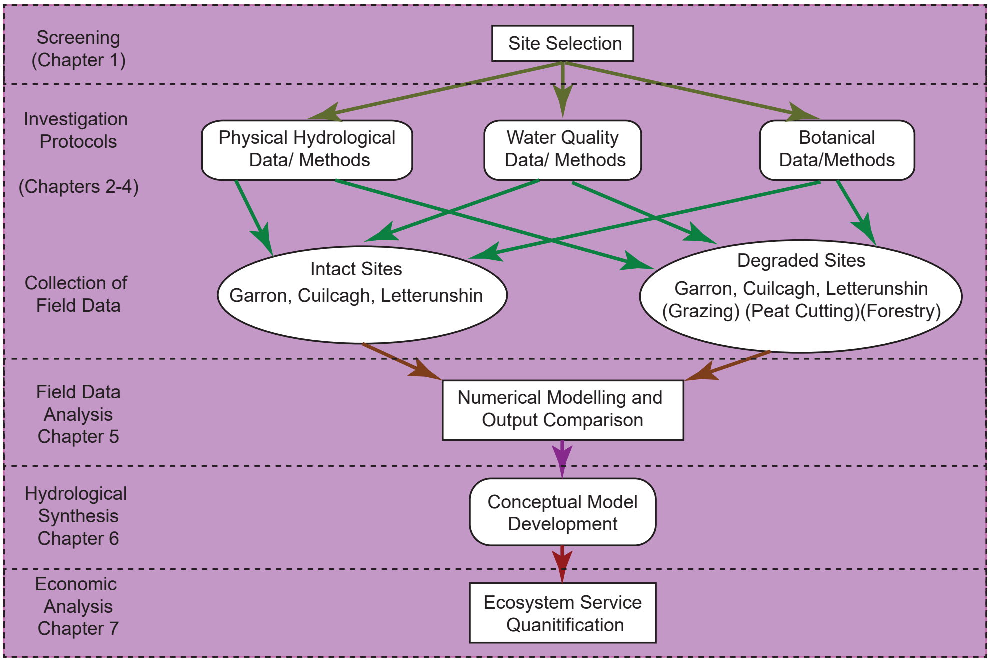


Figure 1.1. Summary of the approach followed in the project to quantify ecosystem services provided by blanket bogs to water.

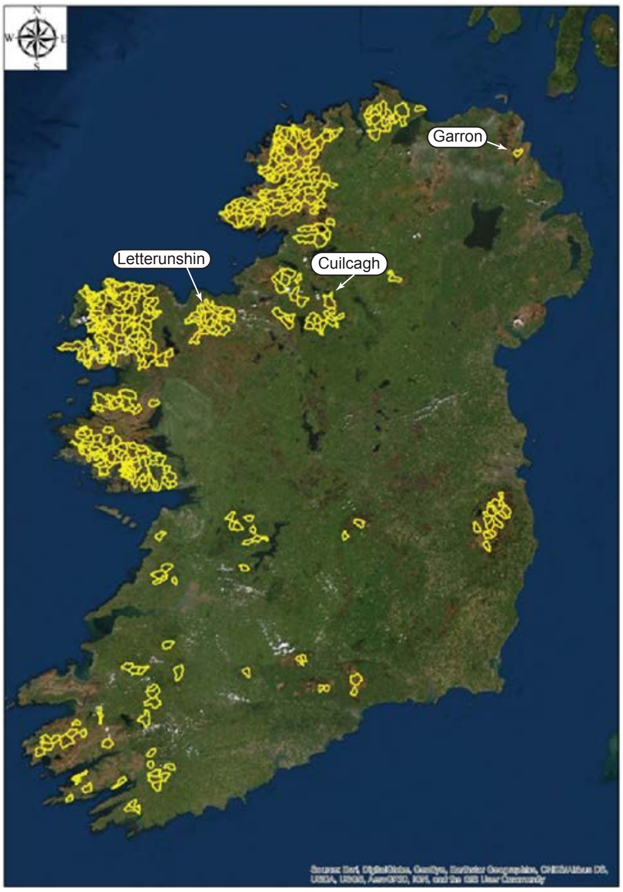


Figure 1.2. Map showing the location of the three QUBBES blanket bog test research catchments. Outlines of the 341 catchments with lower levels of anthropogenic damage are shown in yellow.

Table 1.1. Summary table of catchment characteristics for QUBBES test catchments

	Catchment		
Characteristic	**Letterunshin**	**Garron**	**Cuilcagh**
Area intact (ha)	160.3	140.8	239.1
Area degraded (ha)	214.5 (incl. 160.3)	183 (incl. 140.8)	138.2
Bedrock	(Dinantian) Upper Ballina Limestone formation	Palaeogene (Tertiary) Upper basalt formation	(Dinantian) Orthoquartzitic sandstone, with mixed sandstone and shale units (reaching into Lower Namurian)
Aquifer classification	Regionally important karst	Moderately productive fissured	Locally important, moderately productive
Peat substrate subsoil	Till derived from metamorphic rocks. No outcrop visible	Till (diamicton)	Till derived from Namurian sandstones and shales
Permeability	Moderate	Low	Low
Effective rainfall (mm/year)	1105	n/a	1381
Recharge (mm/year)	44	n/a	55
Maximum elevation (mAMSL)			
Intact	Between 140 and 150	431.5	660
Degraded	Between 140 and 150	334	Between 370 and 380
Minimum elevation (mAMSL)			
Intact	Between 110 and 120	298	Between 300 and 310
Degraded	Between 100 and 110	278.5	Between 220 and 230
Nearest surface water hydrometric monitoring point	Easkey_030 RS35E010020	n/a	Swanlinbar River RS36S010100
WFD surface water status	Good	n/a	High
Causes of degradation			
Intact	Grazing	Drainage, grazing	Burning, grazing
Degraded	Grazing or forestry, burning	Drainage, heavier grazing	Grazing, peat cutting, drainage
Stocking density (LU/ha)	0.44	0.075	0.57
Nearest Met Office/Met Éireann weather station	Cloonacool, Co. Sligo (no. 3135)	Ballypatrick Forest, Co. Antrim	Cuilcagh Mountains, Co. Cavan (no. 2037)
Station elevation	204	156	290
30-year average precipitation (mm/year)	1598	1313	1999
30-year average evapotranspiration (mm/year)	493	n/a	614
30-year average rain days (>0.2 mm/day)	259	n/a	238
30-year average wet days (>1 mm/day)	218	n/a	198
Other hydrological comments	Widespread piping at headwaters	Piping feeding stream	Localised calcareous springs

LU, livestock units; mAMSL, metres above mean sea level; n/a, not available; WFD, Water Framework Directive.

2 Hydrological Investigations

2.1 Introduction

Water forms a fundamental abiotic component of wetland ecosystems (Mitsch and Gosselink, 2000). In the case of blanket bogs, the hydrological regime influences a variety of ecosystem services, including biodiversity and the generation of the organic acids that are present in stream waters draining peatlands (Worrall *et al*., 2007). This chapter examines the hydrological processes operating in the QUBBES catchments and how they may influence runoff rates; the next chapter considers how these may affect water quality and aquatic ecosystems. More specifically, this chapter aims to:

- describe the hydrometric network installed in each of the three research catchments;
- present the results of hydrological monitoring over the period of field monitoring;
- use these findings to generate catchment flow balances;
- consider how findings compare with existing concepts of blanket bog hydrology.

2.2 Hydrometry and Instrumentation

Prior to the start of the QUBBES project, no hydrometric instrumentation existed in any of the study catchments. All test catchments were equipped with rain gauges, piezometers to measure groundwater fluctuations, and runoff gauging points at catchment outlets. Letterunshin and Garron were also equipped with autonomous weather stations to facilitate the measurement of evapotranspiration (Et). Collectively, using these automated sensors with these facilities aimed to characterise the monitoring of representative hydrological processes by permitting the measurement of flow balance elements.

2.3 Flow Balance Elements

The flow balance acts as a cornerstone in peatland hydrological studies by providing a means to account for the relative importance of the various elements of the water cycle in a catchment. When calculating flow balances in the QUBBES catchments, topography was used to define both surface water and groundwater catchment boundaries. For each catchment, the balance was considered as:

$$\text{Precipitation} - (\text{evapotranspiration} + \text{runoff}) \\ = \text{increase in groundwater storage}$$

2.3.1 Precipitation

Precipitation acts as the sole input of water in the flow balance for each of the three QUBBES catchments. Air temperature records suggest that snow acted as a significant precipitation input during approximately 1% of the monitoring period; otherwise, rainfall proved the dominant precipitation mechanism. Moreover, comparison of site-specific records with official Met Éireann and UK Met Office records suggests that conditions monitored onsite proved representative of longer-term conditions.

2.3.2 Evapotranspiration

Data collected from weather stations at both Garron and Letterunshin permitted the calculation of hourly potential Et rates using a modified version of the Penman equation, while mini-lysimeters, installed by Cassidy (2018), allowed these Et rates to be compared with those calculated using the Penman–Monteith equation (PME) (Zotarelli *et al*., 2010) for the Garron test site over the dry period of June/July 2018. The findings suggested that Et rates varied by vegetation category, but that in both cases the rates calculated by weather station software overestimated Et, with the deficit at Garron proving considerably greater. No site-specific Et data existed for Cuilcagh.

2.3.3 Groundwater

In the absence of significant areas of open water, storage in blanket bog-covered catchments occurs primarily as groundwater within peat, with storage change reflected by head fluctuations. According to measurements reported by Cassidy (2018), the specific yield of the uppermost 50 cm of peat (where almost all fluctuation occurs) varied between 25% and 60%. The decline in head with time reflects the loss of groundwater from the peat. The results of groundwater level monitoring at all three QUBBES catchments revealed broadly similar (scalar) trends in groundwater fluctuations, with median water table levels proving lower in summer (1 April to 30 September); however, responses to rainfall proved rapid throughout the year. Overall groundwater fluctuations indicate that summer water tables remain within 20 cm of the ground surface over the majority of intact areas, whereas winter levels are typically within 10 cm of the surface in intact catchments, but up to 32 cm below ground in more degraded catchments.

Measurements in the uppermost metre of peat at intact Garron and intact Letterunshin catchments suggest that hydraulic conductivity (K) may vary between 3 m/day and 0.006 m/day, whereas that at Letterunshin ranges between 2 m/day and 0.04 m/day (Campbell, 2017). Comparison with more degraded catchments shows minimum K values to be consistently lower in degraded areas in all three sites. Conversely, K testing suggests that values for deeper peat drop to as low as 1.7×10^{-5} m/day, and point to significant anisotropy in peat at the metre scale, with flow being overwhelmingly horizontal ($K_h/K_v > 3000$).

In addition, piloting of groundwater tracing techniques at Garron suggested that flow velocities in peat varied between 0.51 and 0.001 m/day (Anderson and Flynn, 2019). Simultaneous monitoring of tracer concentrations and heads suggested that water levels need to increase to reach a threshold to generate an increase in flow velocity, i.e. changes in head and velocity did not occur simultaneously.

2.3.4 Runoff

Reaching consensus on the influence of blanket peat on runoff rates has been complicated by a lack of studies on the rainfall runoff processes in undisturbed catchments, with bogs routinely compared to sponges that dampen flood responses (Pearsall, 1950). Hydrographs generated from all three QUBBES catchments revealed intact and degraded site runoff to be sensitive to rainfall. By contrast, extended dry periods reveal prolonged tailing in stream hydrographs and departures from idealised log-linear recessions, often cited in hydrology texts (e.g. Shaw *et al*., 2010). Higher Q_{10}/Q_{90} ratios for all sites suggest that degraded areas have flashier responses, although results must be considered with caution owing to the variability of topographic conditions and poorer flood rating for these areas. Overall, comparison of discharge rates between seasons suggests that rainfall/runoff responses are dampened more in summer than following equivalent precipitation events in winter.

2.4 Flow Balance

Compilation of the elements of the water budget has permitted flow balances to be generated for the three test catchments, albeit with a lower level of confidence for Cuilcagh owing to the absence of an onsite weather station. In all cases, Et proved the most uncertain element of the balance. Figure 2.1 summarises the seasonal variability in flow balance for the intact Garron catchment and reveals runoff to be the principal water loss mechanism over the winter. By contrast, estimates indicate that Et accounts for just below half of all summer water losses. More limited data suggest a comparable regime at Cuilcagh. At Letterunshin, although winter conditions prove comparable, with runoff acting as the dominant water loss mechanism, conditions in summer show that actual Et approaches the potential rate, calculated using the PME.

2.5 Conceptual Model Modifications

The data collected suggest that the sponge model, in which blanket bogs buffer runoff against extreme precipitation, may have some validity for summer periods. This has been corroborated by field data showing that, immediately following dry periods, rainfall can generate prompt rises in groundwater levels, yet these are not reflected in increased runoff. Nonetheless, it must be emphasised that this phenomenon was observed only following prolonged dry summer periods, accompanied by high levels of Et; otherwise, rainfall generated increases in runoff. Groundwater monitoring data show that available storage capacity is significantly less during winter periods. As a consequence, the ability of blanket bogs to buffer against intense rainfall is significantly reduced, and the utility of the sponge model becomes more questionable.

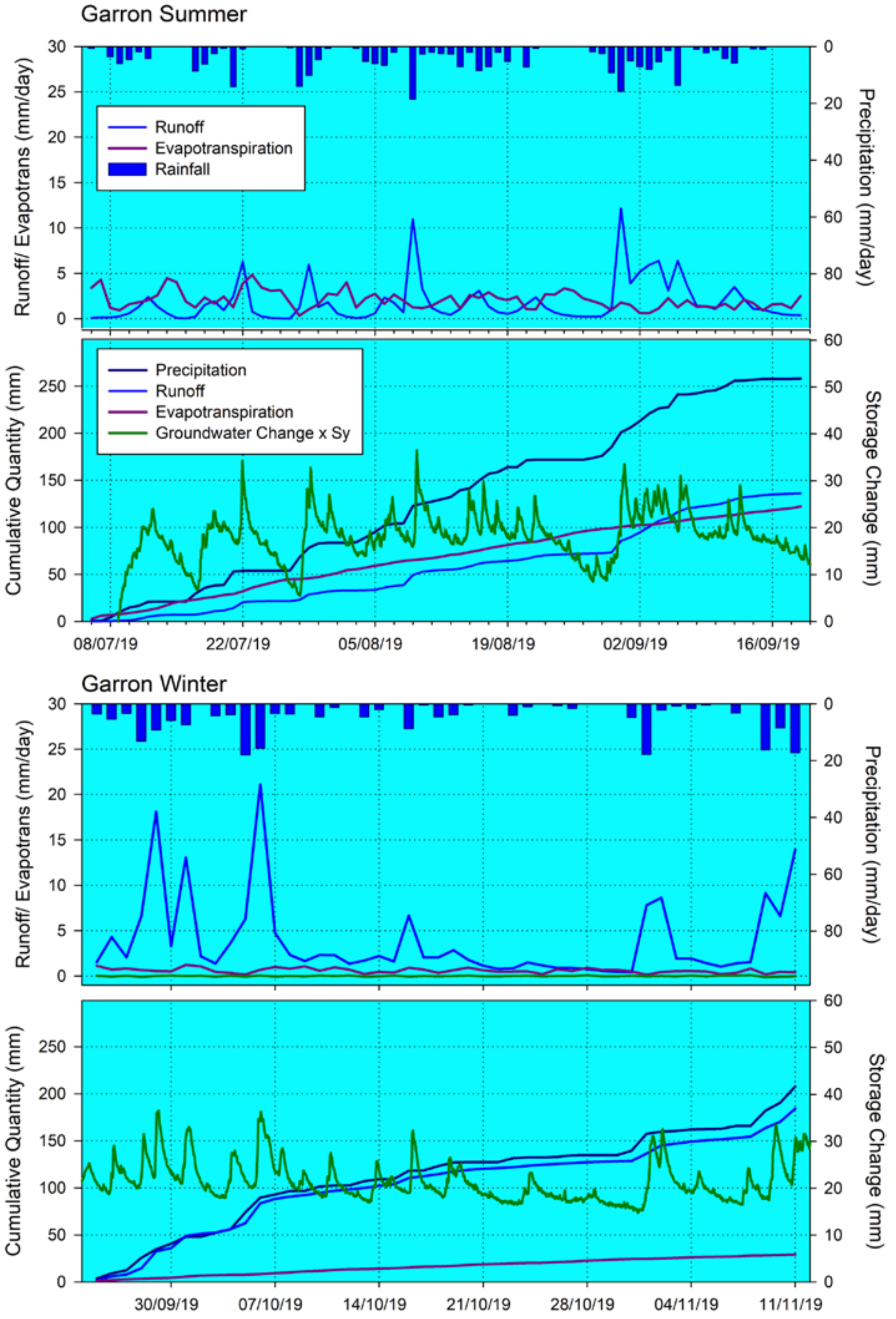


Figure 2.1. Example of flow balance outputs for the intact Garron test catchment, County Antrim. Runoff dominates water losses during the winter period, whereas evapotranspiration plays a more significant role in summer.

3 Water Quality and Hydrochemistry

3.1 Introduction

Water quality constitutes a fundamental abiotic influence on blanket bog ecosystems. This chapter explains how it was used to better characterise runoff-generating processes in streams, draining both the intact and degraded catchments at the three test sites. More specifically, this chapter will:

- provide an overview of the results of water quality monitoring;
- compare water quality from intact and degraded areas;
- employ results to better understand hydrological processes through mixing analysis.

3.2 Monitoring Data

3.2.1 Continuous monitoring

Specific electrical conductance (SEC) monitoring of runoff in all three catchments showed that SEC varied significantly throughout the hydrological year, while base flow quality also differed substantially between sites. By contrast, monitoring data revealed that quick-flow water quality signatures during peak discharge were similar in all three catchments, with SEC being significantly lower than base flow and resembling rainfall more strongly.

Attempts to better understand the relationship between flow and SEC reveal a strong log-linear relationship at lower flow rates, as well as with calcium content in samples collected for laboratory analysis. Comparable patterns are apparent in data collected from intact and degraded catchments at all three QUBBES test sites, although interpretation is complicated by superimposition of multiple events. By contrast, relationships with dissolved organic carbon (DOC) suggest more complex, non-linear (hysteric), behaviour.

3.2.2 Event analysis

Over the course of 2018 and into early 2019, ISCO automated samplers permitted approximately monthly collection of water samples taken at 7-hour intervals over 1 week from intact and degraded catchments, to monitor changes in water quality during hydrological events. Figure 3.1 presents typical responses and shows increases in concentrations of major cations, which decline with increasing discharge. By contrast, DOC concentrations increase with rising flow. Loads, calculated using water quality data, suggest that major ion levels remain reasonably constant during events, while DOC increases with higher discharge, albeit in an inconsistent manner between events.

3.3 Stable Isotope Sampling/Analysis

High-frequency sampling of stream runoff and rainfall at Garron for isotopic analysis of hydrogen and oxygen in water revealed significant differences in isotopic content during 2018, with both rainfall and runoff becoming heavier (less negative) as the year progressed. The isotopic signatures of samples of rainfall and base flow collected during the dry period of May 2018 to July 2018 were used to generate the signature observed in runoff; they suggest that, at the time of peak flow during February 2018, between 20% and 30% of waters were less than 2 days old. By contrast, application of this approach to data collected later in the monitoring period (May 2018 to September 2018) showed that, although significant isotopic variation occurred in rainfall of comparable intensity, a corresponding change in the runoff's isotopic signature was not observed.

3.4 Pairwise Runoff Sampling

Pairwise analysis of runoff involved the near-simultaneous collection of samples from the outlets of intact and degraded catchments at each site on a monthly basis from February 2019 to January 2020. The results revealed increased mineralisation of waters in runoff from the Letterunshin degraded catchment, but no significant change in DOC; this trend is not apparent from the Garron data. These conditions are suspected to be a consequence of drainage promoting mineralised water discharge at Letterunshin (degraded) and the less damaged nature of the Garron (degraded) site.

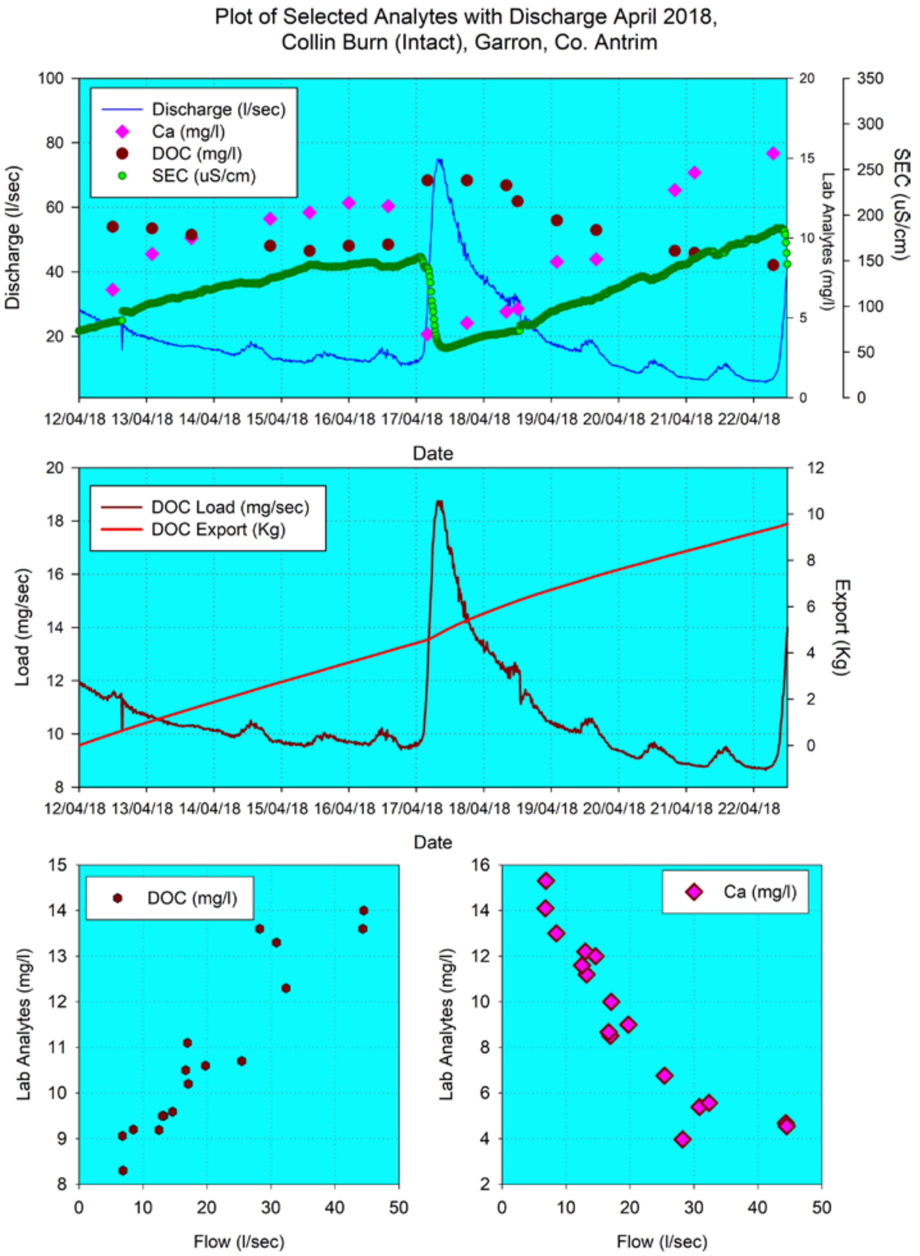


Figure 3.1. Hydrograph and chemograph for the April 2018 event, Garron test catchment.

3.5 End Member Mixing Analysis

End member mixing analysis (EMMA) provides a means of distinguishing contributions to runoff from different water sources (Shaw *et al*., 2010). Using this approach, QUBBES project researchers calculated the contributions to runoff of poorly mineralised bog waters and more mineralised substrate waters. The concentrations of inorganic cations, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), were remarkably consistent in all three catchments, despite variation in the degree of mineralisation of their substrate waters, suggesting that the assumption that the composition of source waters is constant is valid. Monitoring of peat groundwater quality revealed relatively minor variations in SEC (±30 µS/cm).

In addition, monitoring of the water level of peat reveals little variation in head relative to the hydraulic gradient between the peat substrate and the river, suggesting that the hydraulic gradient does not change significantly, and that drivers for mineralised water inputs remain effectively constant throughout the year.

Table 3.1 summarises the results of EMMA calculations for the three QUBBES test catchments. Despite the consistent SEC and aqueous organic carbon contents observed during low-flow conditions,

Table 3.1. Calculated recharge rates to peat substrate for the intact QUBBES test catchments

Catchment	Substrate groundwater SEC (µS/cm)	Typical peat groundwater SEC (µS/cm)	Calculated peat groundwater colour (mg/l)	Observed range of peat groundwater colour (mg/l)	Observed dry weather base flow (l/s)	Recharge (mm/year)
Cuilcagh[a]	130	60	300	150–320	4.5	29.5
Letterunshin[a]	650	60	380	80–400	3	27
Garron	500	50	135	100–450	2.5	30

[a] Assumed substrate SEC based on comparable units.

application of a comparable fixed concentration in quick-flow conditions failed to reproduce the colour levels observed. Instead, by employing a fixed contribution of substrate groundwater, catchment-averaged colour concentrations could be determined from runoff data. Calculated colour levels fall within the range observed in the analysis of peat groundwater samples collected over the same period.

Overall, the results suggest that, even during prolonged dry periods, bog water can contribute half or more of base flow in all intact catchments. By contrast, calculations suggest that, although contributions of mineralised water to runoff discharging from intact and degraded catchments remain reasonably constant, contributions made by bog water to base flow in degraded catchments proved lower at Letterunshin and Garron.

4 Vegetation and Eco-hydrological Studies

4.1 Introduction

Vegetation is the most important functional species group in peatland ecosystems. Plant communities greatly contribute to biodiversity at the ecosystem and landscape levels. However, plants shape their own habitats in an exceptional way and, conversely, they are affected directly by management and disturbances. Several vegetation communities occur within any blanket bog, and their arrangement is unique owing to differences in hydrology, hydrochemistry and local topographic features. In effect, variations in peatland vegetation are the result of many environmental factors, including the origin of the water that feeds the peatland, acidity levels (pH), the availability of the major plant nutrients (nitrogen and phosphorus), water table level, micro-topography and edaphic properties, such as the depth of peat (Wheeler and Proctor, 2000). Seasonal variations in moisture levels (reflecting the status of a bog) have also been correlated with the vegetation composition (Renou-Wilson *et al*., 2018). The objectives of the vegetation studies were as follows:

- map habitats and vegetation communities within the three intact and three degraded sites;
- characterise and contrast the habitats and vegetation composition and associated environmental abiotic parameters;
- identify “active/non-active” blanket bog habitats and “pass/fail” condition assessment;
- establish interactions between vegetation profiles and hydrological data;
- appraise the use of vegetation surveys as a quick assessment tool to predict the condition of blanket bog and its hydrological profile.

4.2 Field Surveys and Methodologies

In this study, we developed a field survey level of assessment that allowed us to gather details that would help identify linkages between the vegetation and the abiotic environment, especially hydrology. Thus, the Fossitt vegetation classification scheme (Fossitt, 2000) was used as the primary level of our field survey and, where natural blanket bog (PB2 and PB3) was identified, we further refined these categories using the communities as per the National Survey of Upland Habitats (NSUH) (Perrin *et al.*, 2014). To allow for a quick correspondence between “schemes”, a list of habitats/communities found in our study sites is provided in Appendix 1. Evident topographical and geographical features visible on aerial photos, together with evident homogeneous mosaics of vegetation communities (with associated uniform nanotopes), allowed for the initial mapping of the sites into potential vegetation map “units”, known as polygons. In order to further appraise the status of each polygon, additional relevés ($n = 170$) were surveyed to further describe the vegetation composition habitats/communities covering > 10% of the polygon, as well as nanotopes and other useful indicators (positive and negative) of habitat quality. Relevés were located close to the hydrological monitoring piezometers where present in the polygon. A full description of the methodologies can be found in the QUBBES project final report.

4.3 Characterisation of the Habitat/Community Types and Abiotic Parameters

Geographic information system (GIS) maps of the dominant habitats/communities within each polygon were constructed for each site, revealing both inter- and within-site heterogeneity, which is typical of blanket bogs. Based on the area covered by these dominant habitats/communities within each polygon, a weighted proportional representation was calculated. All three intact bogs were dominated by blanket bog habitat, with, on average, 75% (±0.05%) of the site (defined as catchment boundary) classified as “7130/7130*” blanket bog habitat under the EU Habitats Directive classification scheme (Table 4.1). Cuilcagh and Garron are typical PB2 “Upland blanket bog”, whereas Letterunshin is a PB3 “Lowland blanket bog” owing to its lower ericoid cover, deeper peat and more “grassy” profile, forming a mosaic with “wet heath”. However, black bog-rush (*Schoenus nigricans*) is conspicuously absent, perhaps because the site is in the north-west region, but relatively “easterly” of the western seafront, at just below 150 m

Table 4.1. Fossitt (and NSUH blanket bog categories) and Annex I dominant habitat types and cover at each study site

Study site	Fossitt habitat code	Annex I habitat code	Cover (%)
Letterunshin natural	PB3 (of which BB3/ BB4/BB5)	7130*	7 (1/6/0)
	HW3	(7150)^{a}	64
	HH3	4010	25
	PF2	–	1
	GS3/GS4	–	1
Letterunshin degraded	PB3 (of which BB3/ BB4/BB5)	7130	43 (2/20/20)
	HH3	4010	17
	WD4	–	39
Cuilcagh natural	PB2 (of which BB3/ BB4/BB5)	7130*	71 (20/40/11)
	HH1	4030	3
	PF2	–	18
	GS3/GS4	–	6
Cuilcagh degraded	PB2 (of which BB3/ BB4/BB5)	7130	90 (1/73/15)
	HH3	4010	4
	PF2	–	2
	GS3/GS4	–	1
Garron natural	PB2 (of which BB3/ BB4/BB5)	7130*	82 (6/19/57)
	HH3	4010	13
	PF2	–	2
	GS3/GS4	–	1
Garron degraded	PB2 (of which BB3/ BB4/BB5)	7130	51 (0/24/27)
	HH3	4010	33
	PF2	–	11
	GS3/GS4	–	3

Note: blanket bog habitats are shaded dark blue.
See Appendix 1 for habitat description.

^{a}Reported under 7130*.

"–" denotes no data.

above sea level. However, using the NSUH scheme, large areas of Letterunshin included *Rhynchospora alba* hollows vegetation community (HW3), which appeared as a mosaic between small pools and other intact bog vegetation. These areas could thus also be classified as *Rhynchosporion* depression habitat (type 7150), which is a habitat under the EU Habitats Directive. However, HW3 is a community that is ecohydrologically integral to some blanket bog habitats and thus should also be accounted for as "7130*" blanket bog habitat (being intact and deemed "active"). It is debatable whether or not Annex I vegetation communities within a wider Annex I habitat can be unambiguously reported in the Article 17 conservation status assessment report. The other main habitats found were "wet and dry heath" (HH3/HH1), which are also Annex I habitats (4010/4030), increasing further the conservation value of these large habitat complexes. Within the degraded subsites, the proportion of average blanket bog habitats fell to, on average 61% (±0.2%), with Cuilcagh, in contrast, showing an increased proportion of blanket bog habitat in the degraded part (90%). Thus, Fossitt habitat mapping of peatland sites where no obvious land use change (large cutover of eroding areas) occurred would not be sufficient to identify the status of the site. Moreover, the more refined NSUH scheme revealed the heterogeneity of Irish blanket bogs, showing contrasting habitat profiles, varying in range of habitat types, sizes and assemblages (Table 4.1).

4.4 Condition Assessment of Blanket Bogs

A multi-criteria analysis of relevés data was developed to reveal qualitative information about the status of each blanket bog in terms of its proportion of active (i.e. peat-forming) habitat and its "condition assessment". The five criteria can be divided according to plant functional type cover and environmental parameters and are as listed below (see the full method in the QUBBES project final report).

Plant functional type cover per relevé:

1. *Sphagnum* cover $<20\%$ = non-peat forming = fail;
2. bare peat $>5\%$ = fail.

Environmental parameters recorded at each relevé:

3. peat depth <0.5 m = fail;
4. nanotopes (pools, patterning, hummocks, lawns) absent = fail;
5. intense anthropogenic impacts (overgrazing, turf cutting, active drains) = fail.

The peat depth survey revealed that in all three intact sites peat depth was >0.5 m in more than 95% of the area. This value decreased to less than 60% in the degraded areas at two sites only: Letterunshin and Garron. The Cuilcagh degraded site exhibited similar peat depth as the intact site. Thus, peat depth alone is not a good indicator of intact blanket bogs. Combining the results, this study confirmed that the blanket bog habitats BB3/BB4/BB5 were consistently associated with relatively deep peat (> 1.5 m), whereas in all other non-blanket bog habitats (HH3 and PF2) peat was shallower (depth < 1.0 m). Of interest from a carbon function perspective, the *Rhynchosporion* depression habitat (HW3, Letterunshin) was associated with the highest proportion of very deep peat (> 3 m).

Weighted percentage cover of plant functional types provided a very good profile of the blanket bogs' physiognomy, which was independent of the "habitat" classification schemes. Together with specific ecological variables (ericoid cover) and the nanotopes survey, the results delivered an initial dichotomy of degraded versus intact areas. For example, while all intact sites showed *Sphagnum* percentage cover as > 20% and can be thus assessed as "peat forming", their physiognomy differed significantly owing to other factors such as the varied morphology of the ericoid shrubs and nanotopes such as *Sphagnum* hummocks. Our studies confirmed that nanotopes (their presence, extent and type of surface patterning) increase in complexity toward the north-west of Ireland. Thus, nanotopes may be used as an indicator of "status" only in the more western blanket bogs, and may not be a good indicator for eastern bogs such as Garron.

Taking all criteria together, Cuilcagh and Letterunshin topped the table in terms of "intactness", with more than 90% of relevés having *Sphagnum* cover > 20% and therefore being considered dominantly "active" or "peat forming" (see Table 4.2 and Figure 4.1). Garron intact had the lowest proportion of "active" blanket bog (*c.* 75%) and only two-thirds of all relevés "passed". This was due to the presence of negative indicators at the site, including lower *Sphagnum* cover, bare peat and the presence of drains. However, the presence of drains is not necessarily a negative indicator for "peat forming", and the analysis of our degraded sites showed that management alone (drainage and/or grazing) should not be a used as a direct proxy of ecosystem services of blanket bogs. For example, Cuilcagh degraded is not in a "good" conservation condition, but comprised large tracks of old cutover bog that were regenerating (high *Sphagnum* cover).

4.5 Interactions between Vegetation Profiles and Hydrological Data

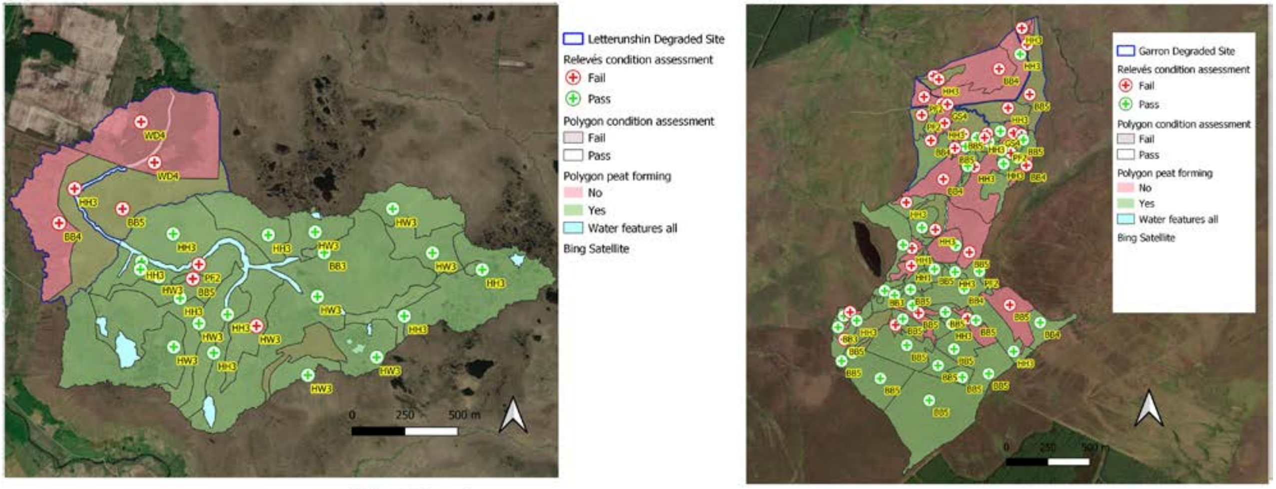
The main habitat types identified across each site were further analysed and compared with hydrological data including water colour (which positively correlates with DOC) and water table fluctuations measured at specific locations. At Letterunshin, the two main dominant habitats were HW3 (*Rhynchospora alba* community) and the HH3 wet heath habitat. HW3 displayed the lowest colour values across all sites regardless of seasons (see the final report), and the HH3 wet heath habitat displayed significantly darker coloured water in all sampled seasons and was also associated with the highest values across all intact sites. The water colour within the degraded area (polygon associated with conifer plantation) was significantly higher than that within the natural habitats.

Combining the relevés with the hydrological data, we determined a general increasing gradient of colour in the runoff water associated with dominant habitats in the following order:

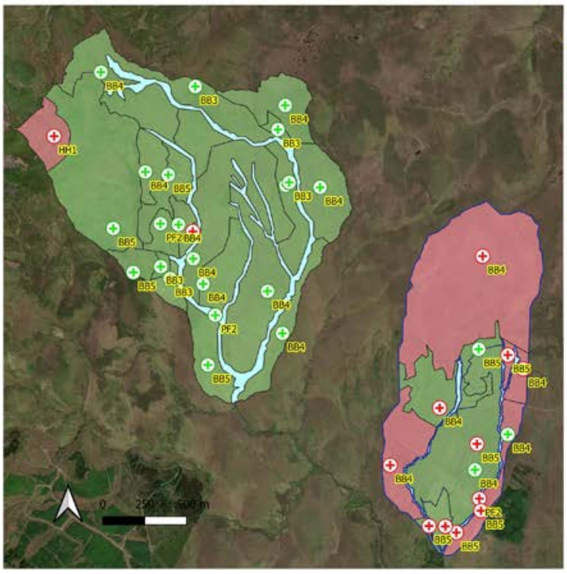
> HW3 (*Rynchosporion* hollows) > PF2 > BB3/BB4/BB5 > HH3 (wet heath) >> degraded habitats

Table 4.2. Condition assessment results as percentage of relevés having active/inactive blanket bog and overall passed/failed status

	Blanket bog habitat		Condition assessment	
Site	% active	% inactive	% passed	% failed
Letterunshin natural	95.9	4.1	91.3	8.7
Letterunshin degraded	39	61	12.5	87.5
Cuilcagh natural	93.3	6.7	74.2	25.8
Cuilcagh degraded	42.1	57.9	21.4	78.6
Garron natural	74.6	25.4	65.2	34.8
Garron degraded	51.3	48.7	9.5	90.5



(a) Letterunshin (b) Garron



(c) Cuilcagh

Figure 4.1. Distribution of relevés and their dominant habitat, and condition assessment results (green cross = pass; red cross = fail). Overall results at polygon level (using the largest dominant habitat results): active (peat forming in green) and condition assessment (failed in hashed red).

From a functional aspect of those habitats (and how they contribute to ecosystem services related to water), the darker colours associated with wet heath habitats mean that it is critical to identify this habitat type within a larger area where other blanket bog habitats may appear intact. From an ecosystem services viewpoint, the occurrence of hydrologically sensitive habitat such as "*Rhynchosporion alba*" and "flushes" communities appears significant not only in terms of biodiversity but also in terms of water quality downstream from the bog.

Analysing the water table level (WTL) data duration curves, all intact habitats (blanket bog and non-blanket bog) displayed a median around –10 cm below the surface, even during the summer seasons (Table 4.3), with values closer to the surface in winter seasons. The maximum WTL values pointed to a gradient

Table 4.3. Average minimum and maximum water table levels at each site

Site	Average minimum WTL (cm)	Average maximum WTL (cm)
Letterunshin natural	–9	–31
Letterunshin degraded	–12	–63
Cuilcagh natural	–6	–28
Cuilcagh degraded	–6	–62
Garron natural	–5	–38
Garron degraded	–6	–41

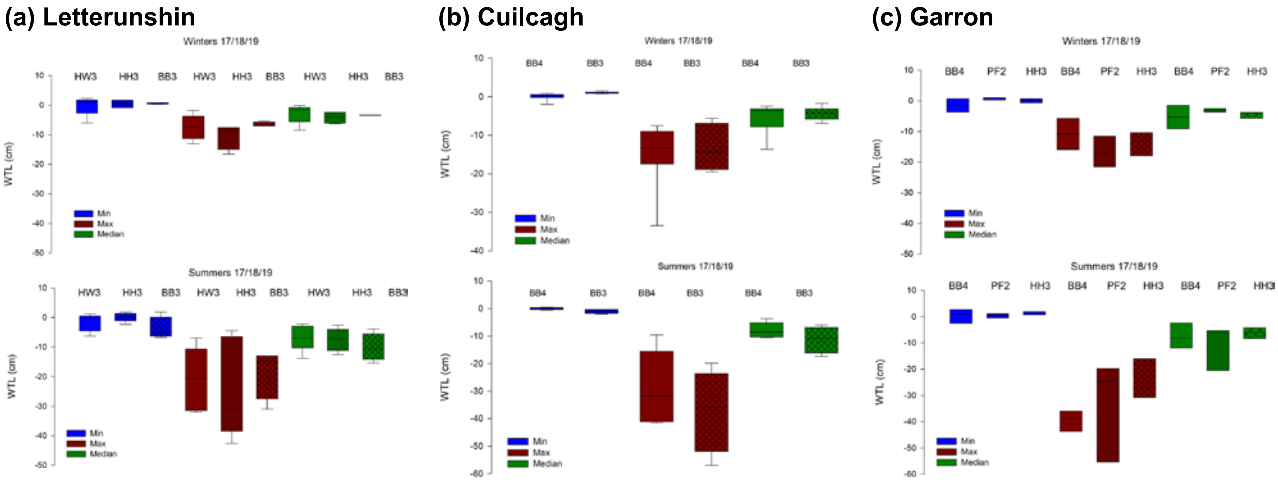
of intactness, with Garron exhibiting the deepest maximum averages in summer, which supported the overall condition assessment status of the site.

A combined analysis of identical dominant habitat types and associated WTL duration curves revealed a fairly consistent profile across all intact sites (Figure 4.2). Both BB3 and BB4 habitats displayed similar median profile across all three sites, but summer values varied, with deeper WTL recorded with BB3. WTL fluctuations were mostly associated with BB3, but this may be an artefact of the topography, as the BB3 habitat was found on slopes in Letterunshin. Thus, while the habitat can provide a good idea of median WTL and potential increased fluctuations (BB3), there will be variations owing to other geographical factors. This corroborates with the description of blanket bog by Lindsay (1995), which implies that a wide range of ecohydrological processes operate on blanket bogs. WTL fluctuations (deepest WTL in summer) were recorded in non-blanket bog habitats, namely PF2 “fen and flush” habitat in Garron and HH3 “wet heath” at the other sites. This analysis confirmed the need to identify these habitats within the larger blanket bog, as these may be associated with both greater WTL fluctuations and darker colouring of the runoff water.

4.6 Conclusion

The results from our habitat field survey (based on homogeneous polygons) have confirmed the considerable variation in habitats/communities forming larger blanket bog ecosystems. Our adapted vegetation and environmental surveys have been found to predict the general status of a blanket bog, including the “active” proportion of a bog – be it intact, degraded or regenerating. This is critical if we aim to value or ascertain the impact on ecosystem services.

While the hydrological data confirmed the “intactness” of the sites, this study did not elucidate more refined relationships between the typical blanket bog habitats and hydrological profiles (water quality and WTL) except for (1) hydrologically sensitive vegetation communities such as *Rhynchospora alba* (HH3) and (2) associated habitats such as wet heath. The latter is probably related to its likely successional development into a degraded blanket bog habitat. Even where a distinct water gradient may exist, an individual assemblage of species may occupy different positions along it owing to other environmental factors, thus making it difficult to analyse direct relationships between habitats and water table regimes when comparing sites. Thus, it is recommended that future research includes the long-term monitoring of hydrology and hydrochemistry in the main three blanket bog habitats (BB3/BB4 and BB5) at all three sites, and also in the wet heath and associated intact habitats (flushes).



(a) Letterunshin **(b) Cuilcagh** **(c) Garron**

Figure 4.2. Water table level box plots (minimum, maximum and median) associated with dominant habitats at all sites during winter and summer periods.

5 Hydrological Modelling

5.1 Objectives

Hydrological modelling provides a means of testing hypotheses as well as providing insight into processes that may be operating within the peat and may otherwise be difficult to observe. The objective of this chapter is to provide an indication of the capacity of lumped modelling, using the Danish Hydraulic Institute's (DHI's) MIKE NAM (Nedbør-Afstrømnings-Model; Hørsholm, Denmark), and integrated catchment modelling, using Infoworks integrated catchment modelling (ICM) (Innovyze, 2014), to simulate rainfall runoff responses. In addition, GIS-based modelling of the surface hydrological processes, using a modified version of the Mackin *et al*. (2017) model, examined relationships between hydrology and vegetation.

5.2 Rainfall Runoff Modelling

Runoff responses in peatlands have proven difficult to accurately model owing to the very close interaction between groundwater and surface water. Similarly, some peat properties may exceed those for other geological media, thus providing anomalous (but accurate) model calibration values, which appear incorrect, based on previous model experience, e.g. possible elevated storage capacity (or specific yield). To better assess the capacity to reproduce hydrological conditions in space and time, a range of approaches were investigated.

5.2.1 MIKE NAM

The DHI's MIKE NAM allowed lumped rainfall runoff modelling to be carried out for Garron and Letterunshin. Figure 5.1 provides an example of outputs for Garron and shows a relatively close correlation to the observed discharge, with regression analysis indicating an r^2 of 0.885 over the monitoring period. Despite good model fits for peak flow, NAM proved poor for simulating the prolonged recessions observed in all catchments, thus failing to fully account for the hydrological processes operating within the peat.

5.2.3 Distributed rainfall runoff modelling

Despite being computationally more intensive, integrated catchment modelling can account for the topographic variation across QUBBES catchments. Initial simulations using Infoworks ICM failed to adequately simulate runoff responses.

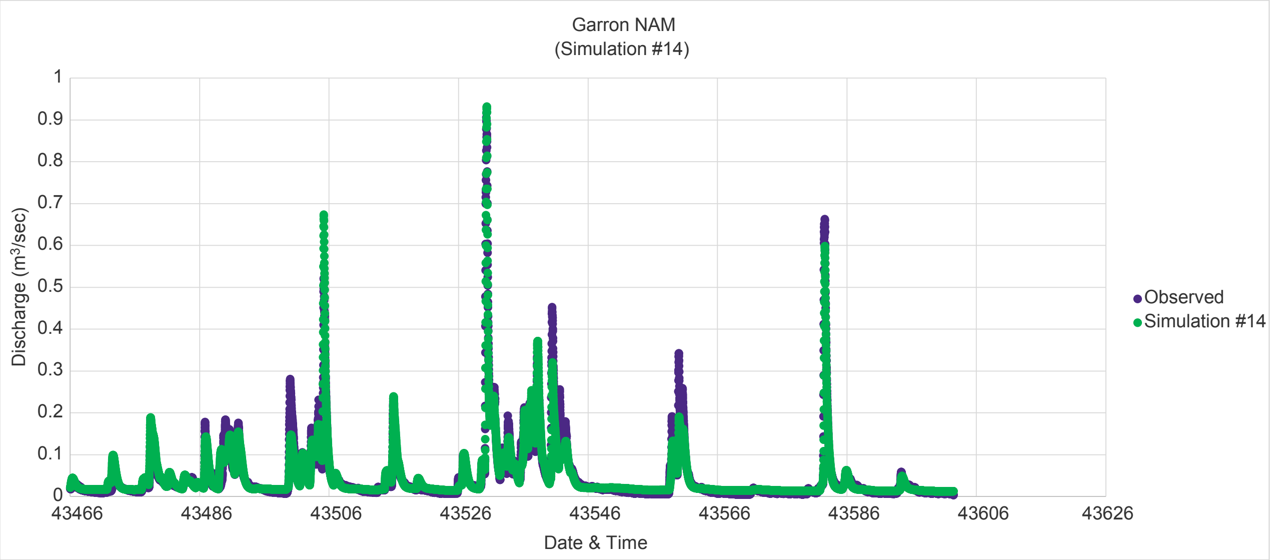


Figure 5.1. Garron catchment model simulation in NAM plotted with observed discharge data.

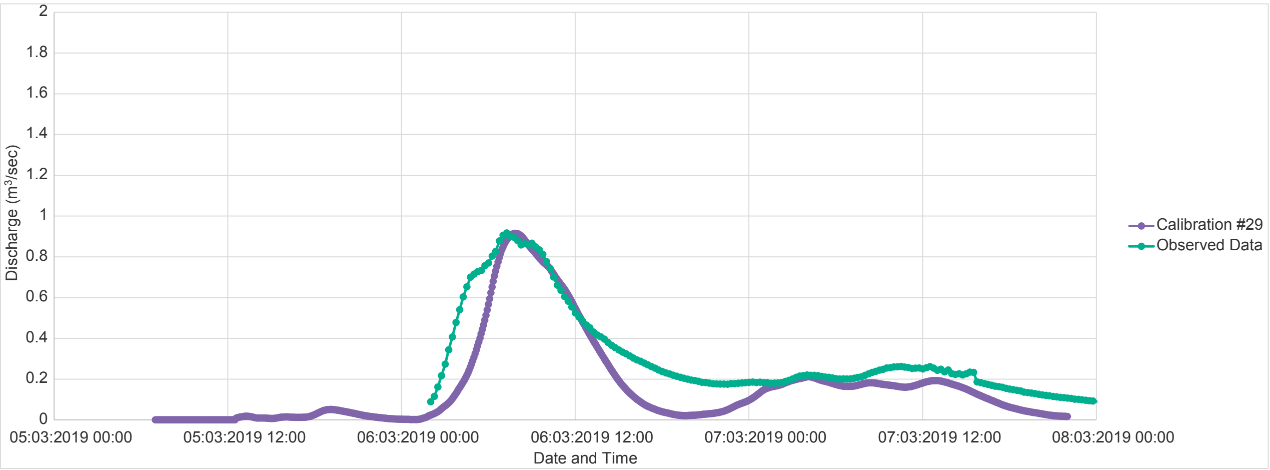


Figure 5.2. Revised modelling output incorporating shallow storage basins within the topography.

Given the findings of the field investigations, a revised modelling procedure was implemented to account for the additional storage and near-surface groundwater contributions from within the catchment. Supplementary basins were added to test model performance with additional storage capacity within the topography.

Overall, the inclusion of basins within the catchment resulted in significant improvements to the modelled outputs (Figure 5.2), suggesting that a fill-and-spill model is operating within the catchment. Outputs from the revised model suggested that, over the duration of the simulation, the model accounted for more water entering storage than observed. Through further calibration it was possible to align the recession limb more closely with the observed data. However, this approach failed to adequately simulate the rising limb of the hydrograph, demonstrating the difficulty in representing flow delivery in blanket bogs. Nonetheless, the use of ICM for distributed modelling shows greater potential for application to ungauged catchments than lumped methods. However, it remains necessary to introduce supplementary elements to align the model with findings from field investigations. The physical basis underpinning this requires further investigation.

5.3 GIS-based Distributed Modelling

A modelling protocol, originally developed for raised bogs (Mackin *et al.,* 2017), was applied to the three study sites, with modifications made to reflect the greater influence of topography on blanket bog hydrology. Modifications were carried out to account for the influence of streams and peat pipes identified at all three test sites. By accounting for the occurrence of these features in the modified flow accumulation capacity (MFAC) method, outputs improved, with results appearing to correlate more closely with observations on the ground (Figure 5.3). The refined modelling protocol was subsequently applied to intact and degraded sites for which light detection and ranging (LiDAR) data were available.

Model outputs compared with vegetation data failed to show consistent direct correspondence. However, there is evidence of broad correspondence between “drier” habitats, such as heath (HH1 and HH3), and the areas modelled as having lowest modelled wetness values, and between “wetter” habitats, such as BB4 and HW3, and the highest modelled wetness values. Comparisons between monitored groundwater levels and MFAC method outputs found a linear relationship between summer (April–September) D_{90} values (depth below ground level is exceeded 90% of the time) and MFAC output values (i.e. higher D_{90} values were correlated with higher MFAC method outputs); this suggests the model can be used to predict wetter and drier areas at the smaller catchment (<2 km^2) scale.

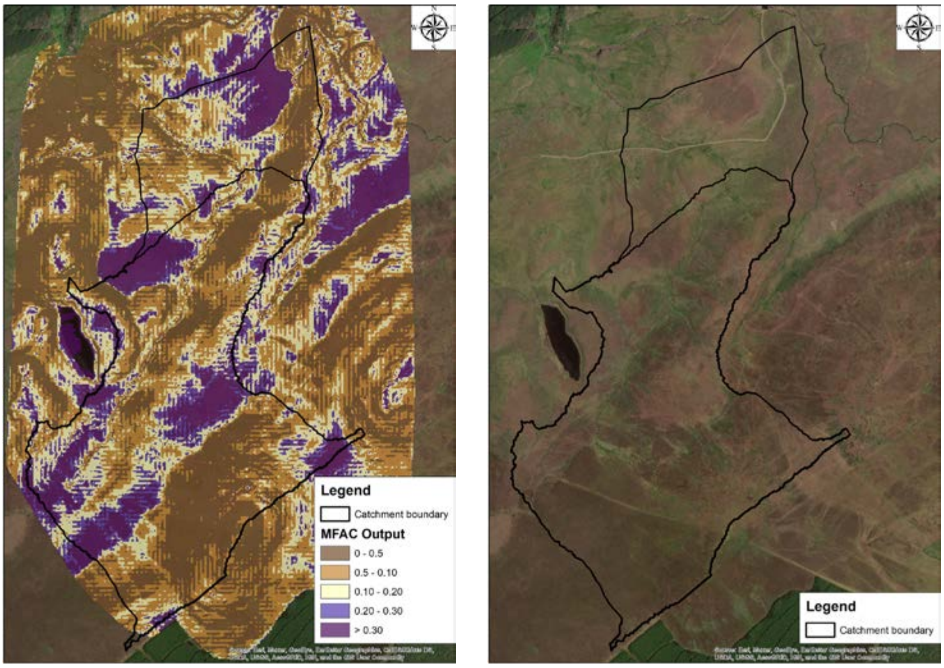


Figure 5.3. Left: final model outputs for Garron intact and degraded catchments; areas of higher model output values in purple indicate areas predicted to have wetter conditions and areas of brown indicate areas predicted to have drier conditions. Right: aerial image of Garron intact and degraded catchments, enabling comparison with model outputs.

6 Reappraisal of the Irish Blanket Bog Ecohydrology

This chapter provides a synthesis of the findings of hydrological, water quality and ecological investigations developed using data collected over the course of the QUBBES research programme. These data have permitted a reappraisal of existing concepts concerning blanket bog hydrology and how this may affect ecological processes and ecosystem services. Figure 6.1 summarises these findings.

Many previous concepts concerning intact blanket bog hydrodynamics were largely speculative and without significant evidence bases. The flashy nature of runoff was linked to saturation excess overland flow, with peat groundwater supporting additional flow. QUBBES monitoring data provide a basis for the reappraisal of this view. Overall, concepts largely neglected the role of the substrate, implicitly regarding blanket bogs as hydrologically isolated systems, largely disconnected from surrounding deposits.

Geochemical and hydrological evidence collected during the QUBBES project showed this not to be the case, and emphasised the important influence of inorganic materials underlying the peat on base flow water. Critically, the occurrence of calcium-enriched waters in base flow could not be explained by contributions from groundwater flowing though peat alone, nor by concentration by Et (as reflected in relative concentrations in groundwater and rainfall). In short, an additional source of more mineralised water proved necessary and pointed to the peat substrate groundwater. Although EMMA showed this to be a small part of catchment flow balances, it proved significant for maintaining stream flow and water quality during drier periods. Moreover, the data suggest that more mineralised water may derive from both inorganic subsoils and deeper bedrock.

By contrast, the presence of high levels of DOC and colour in intact catchment base flow (and their absence in deeper groundwater) suggested an additional bog-derived contribution to flow, even during very low-flow periods, when it could make up the dominant contribution to base flow. This is consistent with hydraulic conductivity measurements, which, when considered with the steep hydraulic gradients across each catchment, demonstrated that peat could maintain contributions to runoff given large volumes

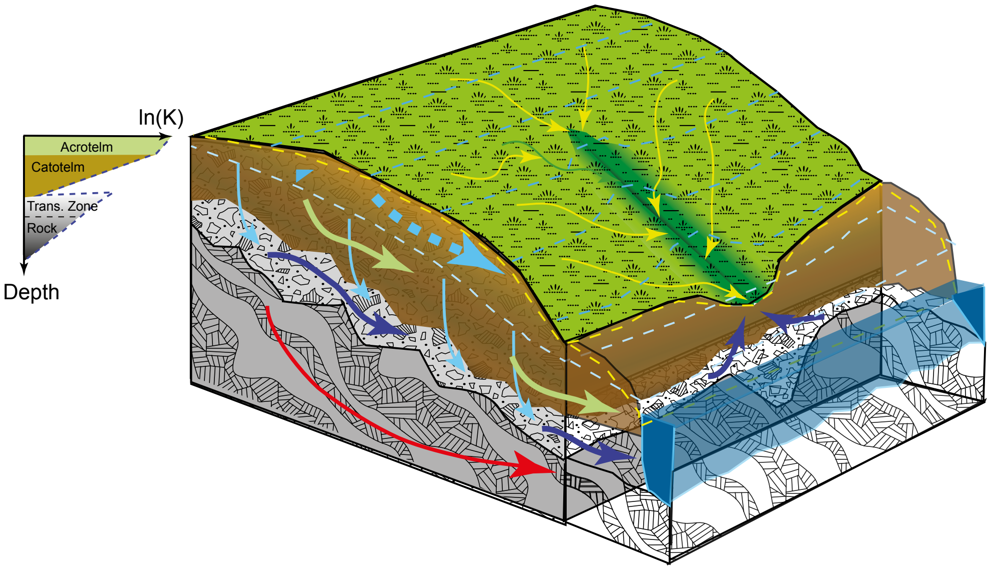


Figure 6.1. Schematic conceptual model of contributions of peat and substrate groundwater to runoff in blanket peat-covered catchments. Consistent discharge from deeper peat and peat substrate (subsoil and bedrock) contributes to stream flow and quality, while more variable discharge in the upper parts of the peat contribute to quick flow and variable DOC fluxes.

of available water in storage, i.e. small changes in water level can maintain runoff for prolonged periods. By contrast, the results of tracer tests showed that groundwater flow (and thus mass transfer) rates could prove highly variable in both space and time. The results demonstrated not only the capacity of water flowing through shallow, more permeable peat to generate the high levels of runoff observed shortly after rainfall events, but also why runoff responses proved lower in summer than in winter for precipitation events of equivalent intensity.

Tracer testing also shed further light on storm flow generation. Localised time lapses between water table rises and increases in groundwater velocity pointed to storage deficits that must be satisfied before groundwater may discharge at higher rates. This is consistent with the results of limited geological investigations completed at the Garron site, which suggested that peat occurs in a series of deeper basins connected by thinner units. Declines in water tables in the connecting units, particularly when dropping into less permeable deeper peat, limits lateral groundwater discharge. However, rising WTLs increase the transmissivity of these units to facilitate more rapid discharge of groundwater, reflected in an increase in groundwater velocity (Figure 6.2). This is consistent with the distributed hydrological modelling results, which showed that the basins help generate prolonged hydrograph recession.

The capacity of current ecological mapping methods to reflect these processes has proven patchy. The vegetation mapping and condition assessment results failed to generate a consistent correspondence for any of the sites; nonetheless, some habitats and blanket bog plant communities corresponded well with modelled outputs, notably in hydrologically sensitive blanket bog plant communities, such as flushes.

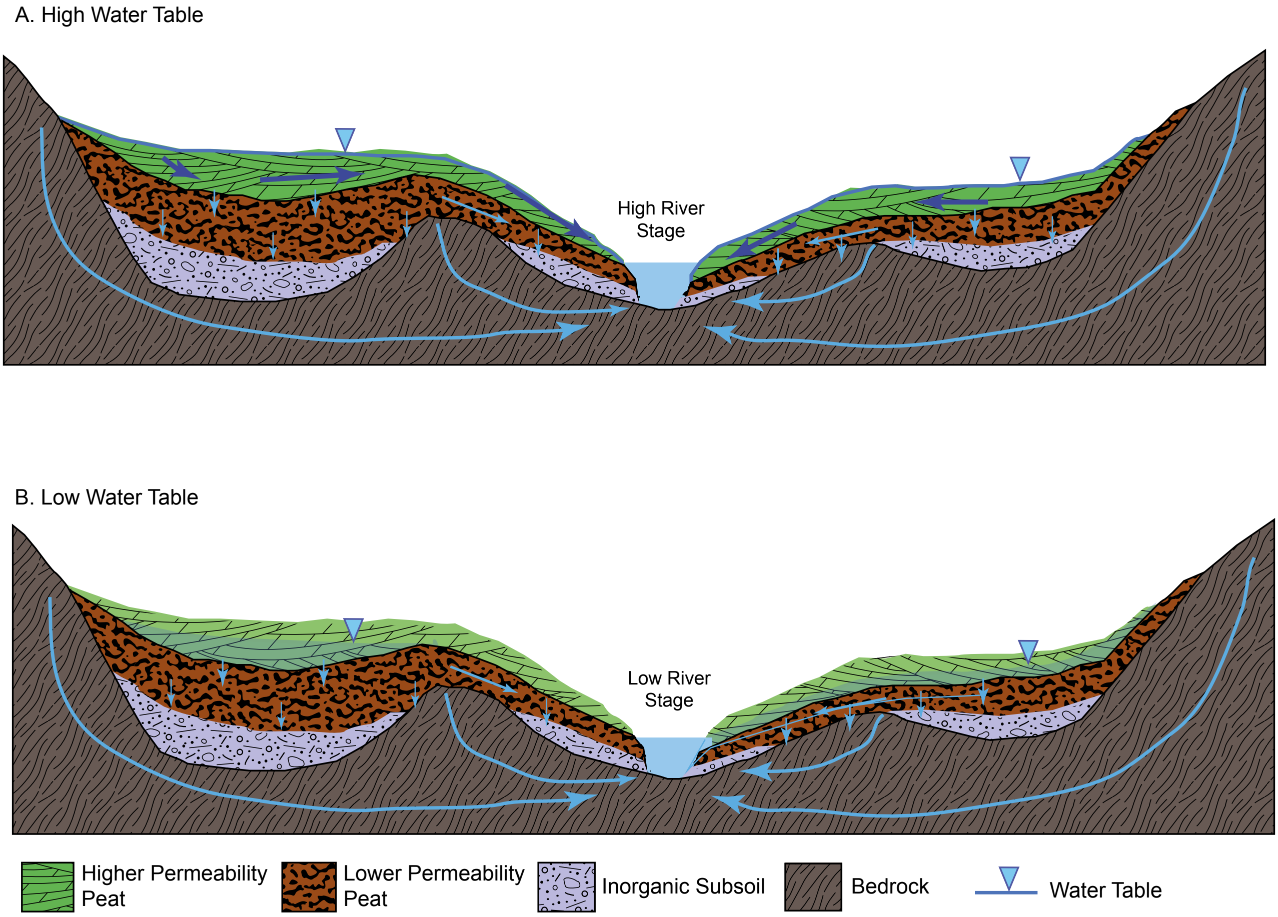


Figure 6.2. Schematic conceptual model of contributions of peat and substrate groundwater to stream flow in blanket peat-covered catchments. (A) Rainfall during period of high water table and limited available storage passes rapidly to streams as runoff; (B) low water tables isolate intervals of more permeable peat, requiring storage deficits to be met before interconnection and discharge as runoff.

Pairwise comparison of stream aquatic ecology *Q*-scores failed to distinguish a significant trend between biota in streams draining intact and degraded sites. This arises in part as a result of the influence of variable water quality and flow regimes and is further complicated by the need to characterise the impact of higher-flow conditions, particularly at degraded catchment outlets. Overall, flow data suggest more stable flow regimes in the intact catchments of Cuilcagh and Garron, while the flow regime at Letterunshin is complicated by additional groundwater discharge (and disproportionate change in water chemistry) arising from extensive artificial drainage.

Runoff from all areas proved flashy. Comparison of regimes at the outlets of intact and degraded areas suggests that more degraded areas experience a wider variation in flow regime. However, further work is necessary to strengthen this conclusion, focusing notably on the upper end of degraded catchment rating curves and accounting for variable topography/drainage.

7 Economic Analysis

7.1 Introduction

Ecosystem services provide a basis for quantifying and valuing environmental processes beneficial for human wellbeing (Millennium Ecosystem Assessment, 2005). These services flow from the stock of natural assets (natural capital) upon which economies and society are built and which form a critical part of natural capital appraisal and accounting, where ecosystem services constitute flows from natural assets (INCASE, 2020).

It has proved difficult to quantify ecosystem services in relation to bogs, despite the fact that particular services are routinely attributed to them, as underpinning data remain poorly defined/lacking and the benefits may vary by location. Xu *et al*. (2018) have identified Britain and Ireland as global hotspots where peatland condition has the greatest immediate economic impact on ecosystem services. This area consumes 85% of all drinking water provided by peatlands globally, the large majority of which is derived from catchments containing blanket bog. Improving peatland condition in the UK and Ireland, and the associated ecosystem services to water, thus has potential to provide economic benefits, including improved water security, reduced water treatment costs and lower flood risk, more quickly than would be the case in areas elsewhere in the world, where blanket bogs are often more remote from large population centres.

7.2 Impacts to Services

Across Ireland, widespread drainage and damage to blanket bogs have resulted in the alteration of natural hydrological processes and the ecosystem services they provide to water. These include the following:

- altered stream flow regime, leading to reduced base flow and possible elevated flooding risk;
- degraded water quality, resulting in increased levels of colour and possibly higher ammonia levels;
- reduced water security, owing to the reduced capacity of peat to store water;
- reduced aquatic biodiversity, resulting from degrading water quality and flow;
- loss of terrestrial biodiversity generated by dieback in peat-forming plants;
- reduction/loss of carbon sequestration capacity owing to increased peat oxidation.

7.3 Pressures

The pressures giving rise to the loss of these services include the following:

- agriculture – overgrazing accounts for damage to 54,000 ha of blanket bog, with a similar area threatened;
- forestry – just over half of all commercial plantations are on peatland, which alters hydrological regimes;
- peat cutting – approximately 36% of blanket bog is cut for fuel (IPCC, 2009), with impacts of cutting extending to uncut peat;
- wind power facilities – wind regimes at the upper end of turbine operational capability make it attractive to locate wind power facilities on blanket bogs; however, the effects of both turbine footprints and access roads need to be considered.

In all cases, these activities have enjoyed, and may continue to enjoy, government support in the form of subsidies, despite causing wider environment impacts. Economic evaluation of these impacts needs to extend beyond individual financial benefits to factor in the costs of degraded ecosystem services and loss of natural capital.

7.4 Quantifying Ecosystem Services

Comparing the economic impact of reduced ecosystem services arising from more conventional economic activity requires baseline data on the services provided by blanket bog under undisturbed conditions. This information requires quantification to allow a value to be assigned. The QUBBES project considered the following services.

7.4.1 Water quality

Water companies need to deliver water to consumers that satisfies aesthetic and health standards. Northern Ireland Water provided historical water treatment data and costs to enable the QUBBES team to better evaluate the economic benefits that may have resulted from peatland restoration in the catchment of the Dungonnell Water Treatment Works in Country Antrim in 2012–2013. Overall, the results from Dungonnell suggest that catchment management measures aimed at improving raw water quality can be economically viable, particularly when factored in with other ecosystem services. This approach has potential for application elsewhere, including the Liffey Catchment, which provides 154 Ml/day to 1.25 million consumers (Xu *et al*., 2018). Given the capacity of improved treatment costs in this catchment to generate cost savings, peatland restoration programmes in this area show particular promise of being financially beneficial. Scaling up savings is estimated to generate annual savings of *c*. €20,000 per year.

7.4.2 Flooding

Degradation of peatland associated with drainage is frequently cited as a cause of more extreme flooding in downstream areas (Pilkinton *et al*., 2015). Pricing these impacts remains uncertain. Discharge monitoring data generated by the QUBBES programme indicated increased flashiness in stream regimes in degraded areas; however, quantification of these changes requires further modelling.

7.5 Restoration

Recent British and Irish climate change mitigation strategies view peatland restoration as a central element of their approach to reducing national carbon footprints. However, restoration efforts should be subject to a cost–benefit analysis. Assessing ecosystem services to water alone underestimates the wider economic benefits of blanket bog. Although the value of benefits such as amenity value and spiritual value are more debatable, the wider environmental impacts of peatland degradation on atmospheric conditions contributing to climate change prove less equivocal. Table 7.1 presents annual carbon dioxide (CO_2) equivalent emissions from peatlands when combined with 2019 valuations for CO_2 employed by the Irish Government in its carbon tax scheme (€26/tonne), and provides a broad indication of the value of carbon emissions avoided as a result of restoration measures. Benefits are likely to become more significant with rising carbon taxes.

Table 7.1. Centre for Ecology and Hydrology emissions factors for peat condition types and potential savings arising from restoration measures[a]

Peat condition category	Drainage status	Total CO_2 equivalent (tonnes/ha/year)[b]	Equivalent value (€26/tonne)	Difference with natural bog (€)
Forest	Drained	9.91	257.66	257.40
Eroded modified bog	Drained	4.85	126.10	125.84
	Undrained	0.69	17.94	17.68
Heather-dominated modified bog	Drained	3.4	88.40	88.14
	Undrained	0.69	17.94	17.68
Grass-dominated modified bog	Drained	3.4	88.40	88.14
	Undrained	0.69	17.94	17.68
Rewetted bog	Rewetted	0.81	21.06	20.80
Near-natural bog	Undrained	0.01	0.26	0.00
Extracted domestic bog	Drained	7.91	205.66	205.40
Extracted industrial bog	Drained	13.84	359.84	359.58

[a]Based on 2019 Irish Government carbon tax costings for 1 tonne of CO_2 (€26/tonne).

[b]Adapted from Evans *et al*. (2017).

8 Conclusions and Recommendations

The results of the QUBBES investigations at the three test sites have improved current understanding of hydrological process operating on Irish blanket bogs. Studies at QUBBES catchments aimed to collect sufficient data to reappraise existing conceptual models of blanket bog hydrology, which in turn underpin numerical models needed to confidently quantify ecosystem services provided by these areas to water. The following points summarise the principal conclusions of this research:

- Blanket bogs can act as sponges, buffering against flooding, but only during periods of high available storage, principally in summer.
- Less degraded blanket bogs better support base flow during prolonged dry periods.
- Runoff regimes from more degraded catchments appear flashier than in intact areas. However, further work is required on (1) populating the upper end of rating curves and (2) hydrological modelling to remove the influence of topography in order to draw firmer conclusions on this issue.
- Tracer test results suggest that changes in peat properties associated with degradation alter pathways to surface water, resulting in increases in intensity of stream discharge.
- High levels of groundwater fluctuation in peat can give rise to elevated colour levels in groundwater. Areas with more stable groundwater levels have lower colour content; the water from these areas thus incurs lower treatment costs.
- A disproportionate amount of organic carbon is exported from catchments during high-flow periods. Consequently, treating water from high-flow events for use as drinking water will result in disproportionately higher water treatment costs for colour removal.
- Substrate geochemistry strongly influences the base flow water quality of streams draining blanket bog-covered catchments. Although the condition of the overlying bog has little influence on the contribution of mineralised water to the stream during low flows, it significantly influences levels of dilution made by bog water to overall base flow. This may affect aquatic biodiversity and stream water status.
- Drainage reduces the capacity of peat to store water, resulting in more intense runoff and less stable base flow, thus elevating flooding risk and placing greater physical–chemical stress on aquatic ecosystems [and their Water Framework Directive (WFD) status]. Further work is necessary to quantify this issue.
- The results of existing vegetation surveys have limited capacity to identify hydrological processes in typical blanket bog vegetation communities, but show linkages in associated habitats such as flushes and heath. These initial results need to be supported by additional monitoring, whereby deployment of piezometers would be informed iteratively through vegetation mapping and restoration potential modelling. Hydrological correlations have to date focused on the relationship between vegetation and water level fluctuations. Qualitative ecological analysis indicates that fluxes through peat, determining the total load of nutrients as well as organic carbon passing a plant community, can be reflected by plant communities, e.g. *Rhynchosporion alba* communities, flushes and wet heath. The results of tracer dilution testing, coupled with water quality/water table monitoring, show considerable potential to better constrain hydrological influences on plant communities. This in turn would (1) allow vegetation mapping to better identify hydrological processes and (2) help identify appropriate restoration targets to ensure that restoration measures comply with the EU Habitats Directive requirements for the restoration of active blanket bog.
- Distributed hydrological modelling provides a means of pulling together the findings of the QUBBES research. This will prove essential for linking ecosystem services with economics, e.g. assessing the change in risk associated with peatland restoration.
- Blanket bog conservation and restoration to promote ecosystem services are financially viable activities on deep peat when compared with other (unsubsidised) economic activity.

8.1 Further Research

Further research is needed to advance current understanding of blanket bog hydrology. The outcome of the QUBBES project has highlighted research deficits in the following areas:

- There remains a need for improved understanding of the linkages between hydrology, geology and vegetation, particularly in degraded areas. This includes characterising periods of higher stream discharge, which have proven critical for underpinning models necessary to assess flood risk.
- Hydrological modelling needs to be further developed to establish better linkages with bog condition. This includes a capacity to upscale findings from test areas to larger catchments.
- The linkage between DOC levels in both groundwater and surface water requires further constraint.
- Further characterisation will prove necessary to establish linkages between hydrological processes and plant communities, notably the need to identify active or peat-forming blanket bog and elucidate the hydrological role or contribution of non-*Sphagnum* species in peat formation.

The benefits of completing this work would include more confident quantification of natural capital and the range of ecosystem services provided by blanket bogs. At the same time, results would build on those generated during the QUBBES project and assist environmental managers in better appreciating the significance of hydrological regimes in damaged and degraded bogs in helping Ireland meet its legal obligations towards achieving a more sustainable society, e.g. linking blanket bog condition to WFD waterbody status.

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Abbreviations

DHI	Danish Hydraulic Institute
DOC	Dissolved organic carbon
EMMA	End member mixing analysis
Et	Evapotranspiration
GIS	Geographic information system
ICM	Integrated catchment modelling
MFAC	Modified flow accumulation capacity
NAM	Nedbør-Afstrømnings-Model
NSUH	National Survey of Upland Habitats
PME	Penman–Monteith equation
QUBBES	Quantification of Blanket Bog Ecosystem Services to Water
SEC	Specific electrical conductance
WFD	Water Framework Directive
WTL	Water table level

Appendix 1

Table A1.1. Adapted classification scheme for this study

Annex code	Annex name	Fossitt code	Fossitt name	Communities/habitat	NSUH code
7130/7130*	Blanket bog	PB2	Upland blanket bog	*Schoenus nigricans – Sphagnum* spp.	BB2
7130/7130*	Blanket bog	PB2	Upland blanket bog	*Eriophorum vaginatum – Sphagnum papillosum*	BB3
7130/7130*	Blanket bog	PB2	Upland blanket bog	*Trichophorum germanicum – Eriophorum angustifolium*	BB4
7130/7130*	Blanket bog	PB2	Upland blanket bog	*Calluna vulgaris – Eriophorum* spp.	BB5
7130/7130*	Blanket bog	BP2	Upland blanket bog	*Eriophorum angustifolium – Juncus squarrosus*	BB6
7130/7130*	Blanket bog	PB3	Lowland blanket bog	*Schoenus nigricans – Eriophorum angustifolium*	BB1
7130/7130*	Blanket bog	PB3	Lowland blanket bog	*Eriophorum angustifolium – Sphagnum austinii*	BB7
7130/7130*	Blanket bog	PB4	Cutover bog		
7130/7130*	Blanket bog	PB5	Eroding blanket bog		
7150	*Rhynchosporion* depressions	PB3	Lowland blanket bog	*Rhynchospora alba* hollow/depression	HW3
7140	Transition mires	PF3	Transition mires		
4010	Wet heath	HH3	Wet heath		
4030	Dry heath	HH1	Dry heath		
NA	NA	PF2	Poor fen and flush		

The table shows equivalent Annex I EU Habitats Directive habitats, Fossitt (2000) and NSUH (Perrin *et al*., 2014) habitat and/or community codes, and descriptions of blanket bogs and associated habitats.

NA, not applicable.

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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Towards the Quantification of Blanket Bog Ecosystem Services to Water

Authors: Raymond Flynn, Francis Mackin
and Florence Renou-Wilson

Identifying Pressures

Blanket bogs are common in many areas of Ireland, contributing to some of our most iconic landscapes. However, although they cover approximately 13% of the country, natural processes sustaining blanket bogs remain poorly understood. This lack of knowledge includes an underappreciation of the natural capital that they contain and the ecosystem services that they provide to society. Failure to appreciate the wider benefits provided by blanket bogs has resulted in many blanket bogs being altered for alternative uses that generate marketable products such as fuel, meat and timber. Some of these activities involve installing artificial drainage, which can negatively affect bog hydrology (or how water behaves). This can have an impact on bog vegetation, flow in streams and water quality. Moreover, damage to blanket bog hydrology can have significant economic knock-on effects, ranging from an increased risk of flooding downstream to higher water treatment costs and reduced water security. However, assigning costs to these effects has been complicated by a lack of information on how blanket bogs behave naturally and how much human activities have altered natural processes.

Informing Policy

The EPA-funded project Towards the Quantification of Blanket Bog Ecosystem Services to Water (QUBBES) aimed to better understand blanket bog hydrology through a 3-year programme in which researchers monitored the flow and water quality in streams draining Irish blanket bogs that are relatively intact. Using the information that has been collected, and comparing conditions with those streams collecting water from areas containing more damaged bog, allows the value of intact blanket bogs to be more confidently determined, while also allowing the economic benefits of conservation and peatland restoration programmes to be better defined. The importance of these issues has proven particularly relevant for Ireland, given its strong dependence on peat-covered areas for water supply. Although not all ecosystem services can be economically costed, providing values to those that can allows for a better understanding of the wider cost of developments on blanket bogs, while also giving us an appreciation of the wider economic value of blanket bogs to society.

Developing Solutions

Information collected during the QUBBES project suggested that, compared with damaged sites, the flow in streams draining the more intact blanket bogs studied displayed greater stability and/or less variable water quality, particularly during prolonged dry periods. More limited data indicated that more degraded areas were associated with higher flood risk. Economic analysis of the wider benefits of blanket bog development proved challenging, as specific information concerning underpinning costs proved hard to come by. However, a case study comparing the effects of development on ecosystem services in a drained and undrained area of bog demonstrated that water coming from the developed area had greater water treatment costs and higher flood risk. The results, when considered with additional losses of greenhouse gases from degrading peat, suggested that failing to incorporate ecosystem services provided by bogs generated an unrealistic picture of economic benefits of conventional developments, and that maintaining/restoring blanket bog to its natural (peat-accumulating) condition may be more viable. This information provides a strong economic case for Irish blanket bog conservation and restoration programmes.

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