08 - THE ROLE OF HYDROLOGY IN RESTORING IRELAND'S RAISED BOGS: A REVIEW OF A NATIONWIDE STUDY.

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Abstract
Hydrology and peatlands are inextricably linked as peatland ecosystems require water-logged conditions for peat-forming plant communities to survive. However, the hydrology of most Irish peatlands has been modified through drainage, which has lowered water tables and impacted ecosystem health. Raised bogs have proven particularly susceptible, with areas of peat-forming vegetation reduced nationally to less than 1% of the area that once existed. In many protected areas, peat-forming vegetation, lost since the 1990s, needs to be restored to comply with the EU Habitats Directive (HD). Degradation of these areas not only represents destruction of a priority habitat, but compromises environmental sustainability through losses of sequestered carbon, changes to hydrological responses in downstream watercourses, and an overall deterioration in the chemical and biological health of receiving waters. Restoration aims to address these issues but requires a detailed understanding of hydrological supporting conditions needed for peat-accumulating vegetation to re-establish; these include gentle topographic gradients, to slow the rate of overland flow, and maintenance of water tables very close to the ground surface.

To comply with the HD, the Department of Arts, Heritage and the Gaeltacht engaged RPS, working in collaboration with Queen's University Belfast, to develop sustainable solutions that satisfy both EU and local community requirements. Assessment of the hydrological condition of 53 special areas of conservation (SACs) using LiDAR data and ecological surveys enabled identification of areas with suitable hydrological conditions, where restoration measures could be best targeted to maximise the extent of peat-forming vegetation. At the same time these interventions aim to minimise the risk impacts such as flooding of adjacent land. Overall, the approach aims to ensure that the diverse range of stakeholder interests are accommodated and a sustainable network of raised bogs is maintained. This approach helps satisfy environmental, economic and social strands of the sustainability matrix.

1. INTRODUCTION

Peatlands with near natural hydrological conditions are not only important habitats in their own right, but also perform additional functions such as maintaining biodiversity, acting as carbon sinks, regulating water quality and possibly attenuating hydrological responses in downstream watercourses during high rainfall/storm events to reduce the occurrence and magnitude of floods (Renou-Wilson et al. 2011). As peatlands are such a prominent feature of the Irish landscape, covering approximately one sixth of the land area (Hammond, 1981), the ecosystem services they provide can have a significant economic value. Furthermore they can act as a significant social resource, offering important benefits including provision of a resource for leisure and recreation, a source of knowledge, and a means of preserving cultural heritage.

Peatlands form in areas where saturated conditions have permitted organic matter to decay at a slower rate than it develops, leading to the accumulation of peat (Holden et al., 2004; Holden, 2005). Peat accumulation can continue provided suitable hydrological supporting conditions are maintained; however, most Irish peatlands have been modified to some degree for economic and social purposes. These include sourcing of peat for domestic fuel, reclamation for agriculture, commercial peat extraction for fuel and horticulture, and more recently wind energy developments (Renou-Wilson et al. 2011). Current degradation and loss of peat-accumulating areas is unsustainable as the ecosystem services associated with peatlands may no longer be provided.

Raised bogs have been particularly impacted by past human activity. It is estimated that 50,000 hectares of uncut raised bog ("high bog") remain (NPWS, 2013), out of an original area of 310,000 hectares (Hammond, 1981). Of this, less than 4% can still be considered peat-forming, as the hydrological function of every raised bog in Ireland has been impacted to some extent (DAHG, 2014a). Areas where peat formation still occurs are known as Active Raised Bog (ARB) and constitute a priority habitat under the Habitats Directive (92/43/EEC) (HD). Due to the relatively large area of ARB remaining in Ireland, compared to other European countries, Ireland has an important international obligation to protect this habitat (Cross, 1990; O'Connell, 1998). In response to this obligation, Ireland nominated 53 raised bog sites for designation as Special Areas of Conservation (SAC) between 1997 and 2002. In addition a further 75 raised bogs sites were designated for protection under national legislation as National Heritage Areas (NHAs). This resulted in the designation of approximately 18,000 ha of uncut raised bog (Figure 1.)

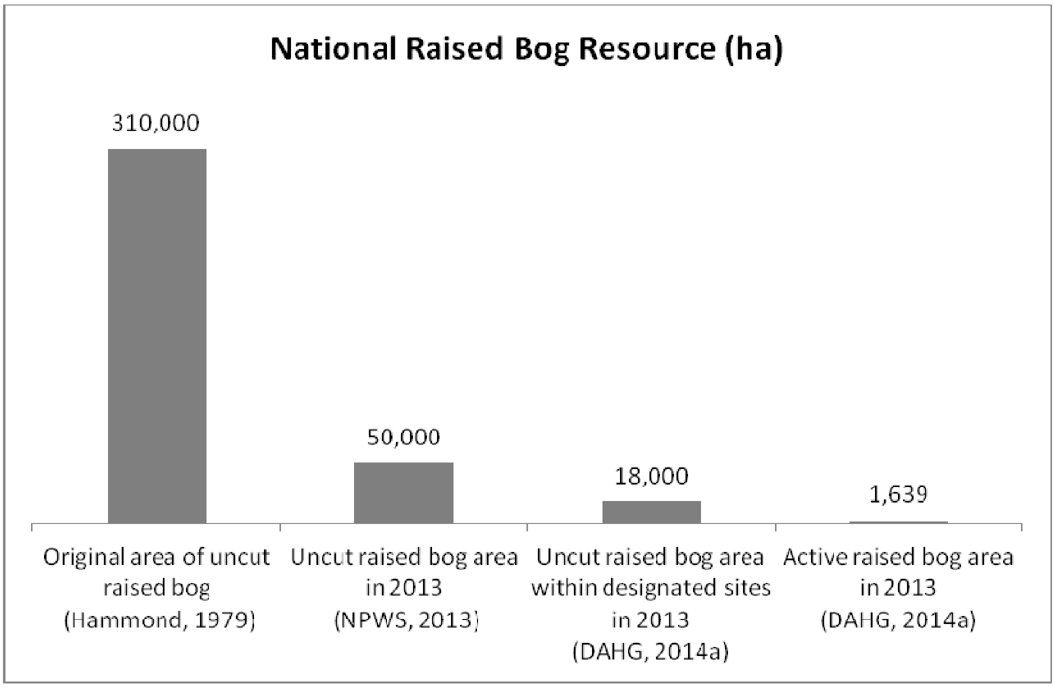

Figure 1: *Raised Bog Resource in Ireland (adapted from DAHG, 2014a)*

Despite the legal protection afforded to raised bog SACs and NHAs significant losses of ARB habitat have continued since designation (Fernandez et al. 2014). These on-going losses have prompted the European Commission to initiate infraction proceedings against Ireland which have the potential to result in daily fines of €25,000. To address this issue and avoid impending financial penalties, the Department of Arts, Heritage and the Gaeltacht and the National Parks and Wildlife Service engaged the services of RPS working in collaboration with key peatland experts, including personnel from The

Queen's University of Belfast, to develop sustainable solutions that would satisfy the requirements of the HD, but also consider the economic and social impact that designation would have on local communities.

2. ACTIVE RAISED BOG

The HD Interpretation Manual defines ARB as areas where peat formation still occurs and these areas are characterised by very wet, acidic conditions, deficient in nutrients that leads to a unique range of plant communities thriving (EC, 2013). *Sphagnum* moss species are particularly abundant on ARB and act as the main contributor to peat accumulation. In Ireland, ARB is mapped employing the ecotope concept, as defined by Kelly & Schouten (2002), which defined ecotopes based on an amalgamation of vegetation community complexes and physical characteristics. Ecotopes corresponding to ARB include central and sub-central ecotopes and are named after their idealised setting on an intact bog (Van der Schaff & Streefkerk, 2002). Table 1 outlines the physical and ecological characteristics of central and sub-central ecotopes. In addition areas of significant flow, such as flushes and soaks, are considered ARB habitat should they have significant *Sphagnum* moss cover.

Table 1: *ARB ecotopes (adapted from Fernandez et al., 2014)*

Ecotope	Physical Characteristics	Characteristic Plant Species
Central	• Surface: very soft & quaking • Micro-topography: highly varied • Pools: frequent to dominant • Lawns of *Sphagnum cuspidatum* typical • All wet vegetation types frequent.	• *Sphagnum cuspidatum* • *Rhynchospora*/algal hollows absent. • *Cladonia* dominated areas are absent.
Sub-Central	• Surface: soft & sometimes quaking, occasionally hard. • Micro-topography: some. • Pools: occasional • Lawns common & usually dominated by *Sphagnum magellanicum.*	• *Sphagnum magellanicum* • *Sphagnum papillosum* in small amounts. *Trichophorum* is scarce. • *Sphagnum austinii* present as a relic from when area was central ecotope.

3. HYDROLOGICAL SUPPORTING CONDITIONS

Hydrology plays a pivotal role in supporting ARB, which requires the water table in the peat to remain within 10cm of the surface, except for very short periods of time (Kelly & Schouten, 2002). Conventionally raised bogs are considered to have two hydrologically discrete units (Ingram, 1978). The upper living layer of a bog is described as the acrotelm, while the lower anaerobic and more decomposed layer is defined as the catotelm (Figure 2). Van der Schaff (2002) refined this concept to consider all relatively undecomposed peat (to Von Post Level 4) as acrotelm. The acrotelm has a much higher hydraulic conductivity than the catotelm and therefore most flow occurs through this layer. Raised bogs require slow losses of water for a high water table to be maintained. As vertical infiltration through a raised bog is typically inhibited due to the lower hydraulic conductivity of the catotelm at depth, discharge of effective rainfall (total rainfall minus actual evapotranspiration) occurs predominantly by lateral flow through the acrotelm. To maintain the high water table required to support ARB in such permeable media requires very gentle topographic (and thus hydraulic) gradients. Where topographic gradients are sufficiently gentle, losses by overland flow occur very slowly helping to maintain a stable and high water table. On steeper slopes acrotelm cannot persist and lateral losses are dominated by more intense overland flow events.

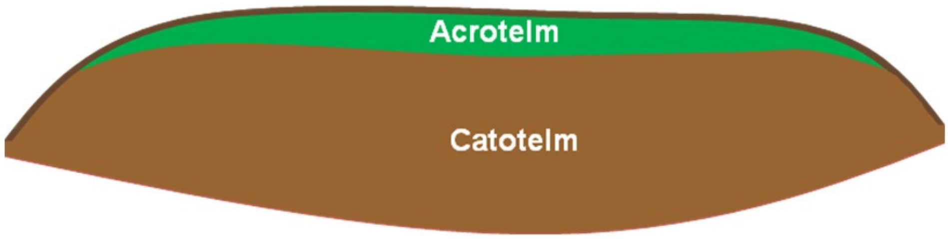

Figure 2: *Schematic illustration of Acrotelm and Catotelm layers of an intact raised bog*

Activities such as peat extraction, afforestation and agricultural reclamation all involve drainage which can affect high bog topography and thus topographic and hydraulic gradients; drainage leads to a decline in water table levels, and consequent oxidation, subsidence and compaction of peat. In highly compressible raised bog peat the decline of pore water pressure within the peat results in settlement which increases with closer proximity to drains. As a consequence drainage causes changes to surface slopes and increases the rate at which water is discharged laterally from the bog. As a result ARB vegetation, requiring a high and stable water table, can no longer be maintained. Despite degradation, some areas impacted by drainage can be restored to ARB. Areas of uncut raised bog where peat-formation no longer occurs, but where there is a reasonable expectation that peat-forming conditions may be restored through appropriate restoration measures, are defined as Degraded Raised Bog (DRB) under the HD.

Bog hydrological processes are further complicated by their inter-relationship with surrounding deposits. Although raised bogs are typically assumed to be largely isolated from regional groundwater, research has shown that many raised bogs display significant groundwater dependency. For example, Regan & Johnston (2010) demonstrated that deep drains along the margins of Clara Bog, Co. Offaly permitted discharge of groundwater from deposits underlying the peat to drains, thus locally lowering the groundwater head in the peat substrate. This has resulted in greater vertical losses of water in areas of the bog where the substrate does not adequately isolate the peat from more permeable substrate units. The increased loss of water through the peat to depth has resulted in significant subsidence on the surface of the bog, up to 600m away from the location of upwelling groundwater. This has resulted in significant changes to surface flow patterns which has led to widespread drying of parts of the uncut bog along with secondary re-wetting of much smaller areas (Flynn et al., 2013).

4. DEGRADED RAISED BOG

In order to reverse negative trends affecting areas of ARB and to begin to plan restoration, RPS, working in collaboration with QUB, undertook an assessment of the Irish national raised bog network to identify those areas most likely to support peat accumulating vegetation following restoration. This programme of work focused on eco-hydrological investigations to determine current condition and restoration potential, not only of each raised bog SAC and NHA, but also 130 non-designated bogs which may potentially be of conservation interest. Consequently, to define the areas with the greatest potential for targeted restoration measures, eco-hydrological investigations aimed to define the extent of DRB within each raised bog. This focused on comparing hydrological conditions of the areas currently supporting ARB habitat with areas where ARB habitat does not exist at present. DRB could then be defined as areas that have similar hydrological conditions as areas with ARB but where supplemental pressures are preventing ARB vegetation from being maintained e.g. drainage, forestry or recent vegetation burning.

5. RAISED BOG TOPOGRAPHY

Eco-hydrological investigations have revealed that above a critical slope, (typically ranging between 0.3% and 0.6% for most Irish raised bogs), ARB cannot be maintained (with the exception of flush areas where there is sufficient focused flow to maintain saturated conditions and thus high water tables). Using detailed topographic information for each bog, obtained from LiDAR surveys, topographic conditions were correlated with the distribution of ARB using a semi-empirical approach that employed a modified version of the topographic wetness index (Beven & Kirby, 1979). The method permitted identification of trends in surface topography that correlated to differences in ecological conditions and indicated clear regional difference in local surface slope and ecological conditions. A general trend of increasing surface slope with increasing effective rainfall was identified. An example of this is summarised in Figure 3. Analysis of surface slope at Ballynafagh Bog SAC in Co. Kildare indicates that the median local surface slope was 0.16% within the area of central ecotope, increasing to 0.23% within sub-central ecotopes. By contrast slopes within central and sub-central ecotopes were significantly steeper within Carrowbehy/Caher Bog SAC in Co. Roscommon/Co. Mayo at 0.57% and 0.94% respectively. This reflects the influences of higher rainfall rate and frequency encountered further west in Ireland, which can sustain a high water table on steeper slopes; this in turn enables ARB habitat to be maintained on steeper slopes than further east.

Carrowbehy/Caher Bog SAC

Ecotope	Median Slope (%)
Central	0.57
Sub-central	0.94

Ballynafagh Bog SAC

Ecotope	Median Slope (%)
Central	0.16
Sub-central	0.23

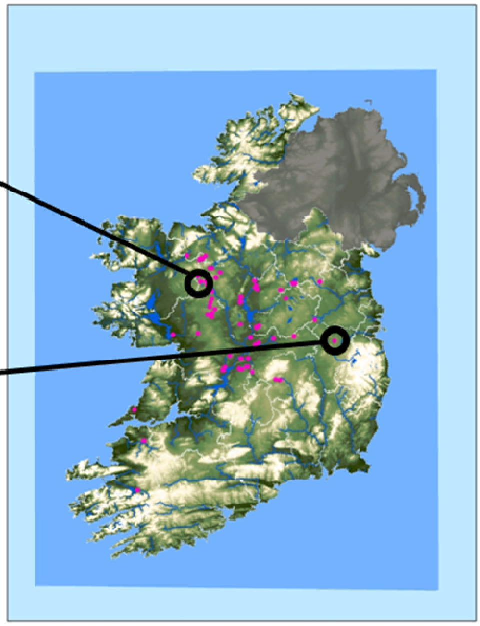

Figure 3: *Example of variation in physical characteristics between two bogs with different meteorological conditions*

Using this approach it has been possible to map, on a site by site basis, areas where restoration is likely to be most successful and therefore provide an estimate of the area of DRB habitat. This is illustrated by Figure 4 which outlines an example of surveyed ecotopes along with the predicted maximum extent of ARB, should restoration works be carried out.

This approach was applied to all 53 raised bog SACs, 75 NHAs and 130 non-designated sites of potential conservation interest and enabled a comprehensive review to determine the importance of each raised bog in the designated network. As a result of this review 39 NHAs were proposed for de-designation, including parts of 7 NHAs, while 25 non-designated sites were proposed for designation as NHAs. Overall this has led to the establishment of a much more sustainable network of NHAs, which has a larger area of ARB and DRB and fewer turf-cutters requiring compensation (DAHG, 2014b). In addition this process provided significant additional benefits, including the setting of challenging, yet realistic, national and site-specific conservation objectives for ARB habitat.

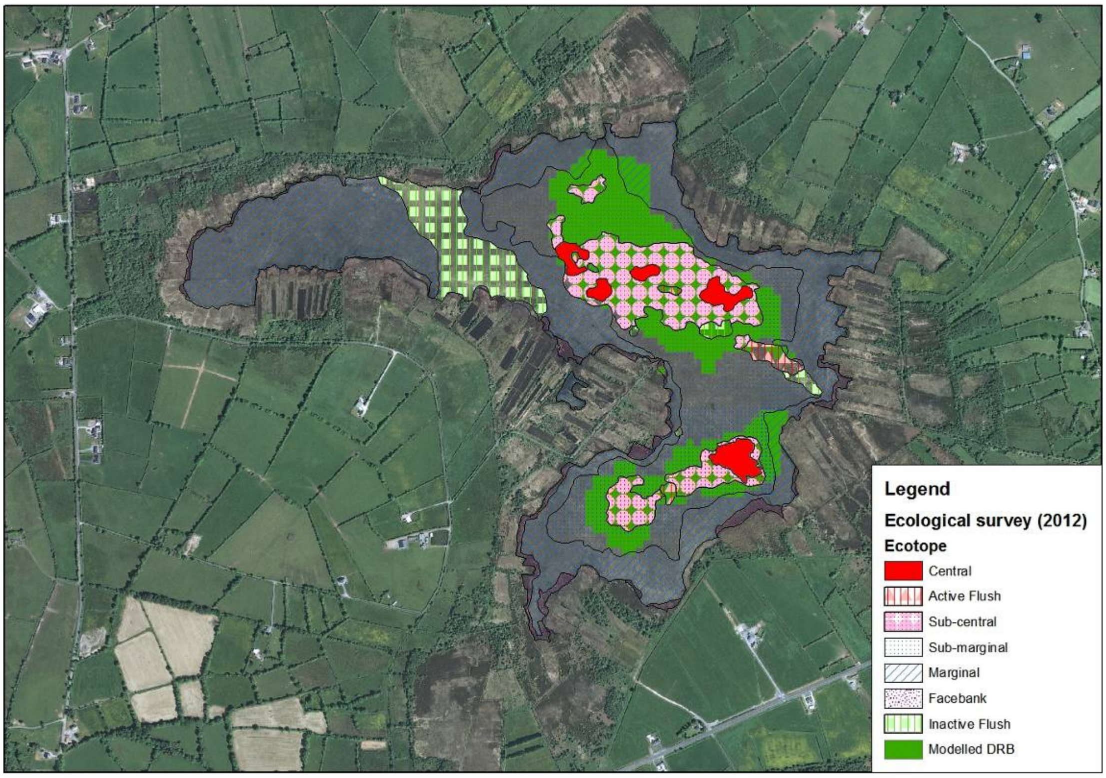

Figure 4: *Ecotope survey of Corbo Bog SAC with modelled DRB. The DRB reflects areas where topographic conditions are considered suitable to support ARB, should restoration measures be implemented.*

6. HYDROLOGICAL RESTORATION PLANS

In order to achieve national and site-specific conservation objectives it is important to define which restoration works would be effective for restoring ARB habitat. As a result detailed hydrological restoration plans are currently being produced for all 53 raised bog SACs. Technically feasible restoration measures have been identified for the various zones of the bog including the high bog, cutover bog and adjacent marginal areas. Although the primary focus of the restoration plan is on hydrological restoration of ARB habitat, it is anticipated that restoration will bring the additional ecosystem service benefits that natural peatlands provide.

Raised bog restoration aims to maintain or improve the quality of existing areas of ARB and/or improve hydrological conditions in areas of DRB to allow peat-formation to occur once again. While hydrological restoration measures are typically focused on areas of high bog, activities need to consider peatland hydrology in a holistic manner. This involves incorporating restoration on cutover areas and measures on the surrounding margins to assist in reducing the hydraulic gradient between the high bog supporting ARB and deeper deposits. These actions may have the ancillary benefit of leading to the establishment of compensatory peat-forming habitat on the margins of the bog, which once established can provide further ecosystem services. In this manner restoration of the entire hydrological unit contributes not only to the objectives of the HD but also aligns with the objectives of the Water Framework Directive (2000/60/EC) and Floods Directive (2007/60/EC). This approach proposed provides significant environmental, economic and social benefits and therefore meets all three strands of the sustainability matrix.

The main restoration measures that may be considered for improving hydrological conditions for the development of peat forming habitats include:

- Drain blockage (on both high bog and the margins/cutover)
- Clearance of forestry
- Installation of bunds/dams (on both high bog and the margins/cutover)

In general peatland restoration should favour the use of low cost, long-term solutions requiring minimal maintenance. Complex restoration measures that require significant maintenance, or that may display a high risk of failure will be less sustainable as long-term interventions. This approach is based on experience to date in Ireland, as trials of high cost measures such as bunding or large dams on high bog have proven ineffective in substantially increasing the area of ARB. As a result restoration plans focus on simple measures in areas where hydrological conditions are most suitable for peat-formation.

Blocking of drains within the high bog area is the most common restoration measure implemented at raised bogs in Ireland and has been carried out by NPWS, Coillte, Bord na Móna and several environmental non-governmental organisations (ENGOs). Indeed Bord na Móna has carried out extensive drain blocking on several large raised bog complexes that were once drained at regular intervals but were never taken into peat production (Bord na Móna, 2015). The purpose of blocking high bog drains is to raise the water table within the peat, not only within the drain, but also the adjacent areas as illustrated by Figure 5. Typically drain blocking on the high bog involves using peat dams, although plastic dams can be more effective where significant erosion is expected, machinery access is inhibited or sequences of acrotelm occur at depth which may provide preferential flow paths.

a) Before drain blocking **b) After drain blocking**

Figure 5: *Photographs illustrating the effectiveness of drain blocking using peat dams to bring the water table to within 10cm of the surface at Cuckoo Hill Raised Bog, Co. Roscommon*

Drain blocking on cutover areas has been less widespread but has been carried out at a selected number of sites in Ireland, typically in areas under State ownership, or subject to a management agreement with the landowner. The process of drain blocking is similar to that carried out on high bog where peat or plastic dams are inserted into the drain. Other restoration elements including removal of forestry on both high bog and cutover areas, have proven effective in improving hydrological supporting conditions for ARB, particularly when combined with drain blocking measures (Derwin, 2015).

Further active interventions aimed at improving hydrological conditions include the construction of marginal dams, usually less than 1m high, constructed from peat. These aim to promote the retention of water on the cutover areas and when combined with drain blocking can be very effective in promoting the re-establishment of peat-forming vegetation. Nonetheless, measures are more complex than drain blockage. Dams require an appropriate low permeability core to prevent water flowing under the dam, and a series of weirs or sluices to allow water to discharge into a boundary drain in a controlled manner and prevent excessively high water levels that can both hinder *Sphagnum* regrowth and promote dam failure. More specifically, target water levels on cutover behind dams should be between 0-20cm deep to provide the optimum hydrological conditions for *Sphagnum* moss regeneration. As with drain-blocking, retaining water behind a dam does not increase the amount of water being discharged but rather augments storage capacity. As a result run-off is attenuated while helping to maintain a high water table in cutover areas. The measure has been proposed for cutover areas where there is a relatively large flat area behind the dam, to maximise the potential area that will be re-wetted. A successful pilot study employing this measure has been undertaken at Killyconny Bog (Cloghbally) SAC (000006), where a marginal dam was constructed along the margin of the cutover in 2008, the dam continues to operate successfully and has resulted in extensive regeneration of peat-forming vegetation (Figure 6).

Figure 6: *Photograph illustrating the establishment of peat-forming vegetation behind a marginal dam at Killyconny Bog (Cloghbally) SAC*

7. FLOODING

To ensure measures such as drain blocking will not result in flooding/waterlogging outside target areas where restoration works have been proposed, each proposal has been evaluated to determine the anticipated extent of impact. This has involved analysis of topographic data collected using LiDAR to identify low-lying areas, along with existing hydrological barriers such as a drain/watercourse or elevated topography separating the cutover from surrounding land. In addition, where it was unclear what would be the extent of impacts from proposed works it was possible to identify high risk areas requiring further active (engineered) mitigation measures, such as providing a protective marginal dam or alternative drain.

Despite this approach some local communities will continue to express concern that blocking of high bog or cutover drains will result in, or exacerbate, flooding. Restoration projects have been undertaken on both high bog and cutover areas in Ireland without generating adverse impacts such as flooding. There is also evidence that re-establishment of *Sphagnum* vegetation on areas of bare peat has a positive hydrological impact by increasing hydraulic roughness. This has led to changes in overland flow regimes and increase travel times, potentially reducing downstream peak flows (Holden et al., 2008; Grayson et al., 2010). However, the extent to which intact peatlands regulate flows within catchments can be over-stated through inaccurate comparisons of a peatland to a “sponge”. A review carried out by Holden et al., (2004) identified conflicting results on the impact of peat drainage on catchment hydrology from several different studies. In some cases an increase in peak flow downstream was identified following peatland drainage while a decrease was noted elsewhere. Few of these studies clearly provided explanations for their results or explanations backed-up with sufficient evidence. Furthermore the timescale of many of these investigations was inadequate to determine whether there were changes in flow associated with degradation of vegetation or reestablishment of vegetation following restoration. Therefore this topic remains an issue that requires research more appropriate to an Irish setting and which takes into account the impact of restoration at appropriate scales by considering both local flows regimes as well as the impact on flows in downstream watercourses.

In order to build confidence with local stakeholders a focused drainage management plan has been produced as a pilot study for a raised bog SAC in Co. Galway. Through knowledge gained from local stakeholders, it was known that localised incidents of flooding of agricultural land adjacent to the SAC occurred more than once per year over the past 5 years. In order to address these issues, a study was carried out to determine whether drainage maintenance works were required on the main drainage channels surrounding the bog to reduce the risk to an acceptable level for local stakeholders. One of the key problems associated with drainage maintenance in an area close to a water-dependent SAC is the risk that channel deepening will lead to a decline in regional groundwater head that could potentially impact on bog hydrology. In the pilot study it was recognised that there was a clear link between the ecology of the bog and the aquifer underlying the bog, based on the vegetation patterns observed on the high bog. This suggested that drainage works have the potential to have a significant impact on the SAC. To evaluate flood flows expected in the main channels surrounding the bog a range of common flood estimation techniques were used to estimate Index Flows (Q_{MED}) including:

- The Institute of Hydrology Report No. 124 (Marshall & Bayliss, 1994)
- The Flood Estimation Handbook (FEH) Statistical Method (Kjeldsen et al. 2008)
- The Flood Studies Update (FSU) 7 - variable equation (Murphy, 2009)

Due to the small scale of these catchments (<6km^2) the methods generated significant differences in Index Flows. Subsequent surveys of these channels and their dimensions permitted identification of under-sized and inappropriately designed channel structures; these contributed significantly to flooding issues identified. It has therefore been recommended that focused upgrades of a number of channel structures be carried out as part of the restoration plan. Furthermore specific issues such as removal of debris in the channel, as well as rooted in-channel vegetation, are proposed to improve conveyance capacity during times of high flow. Overall general maintenance works on the main channels have been proposed, along with recommendations for long-term monitoring of channel condition and focused remedial works. The recommendations highlight that the risk of flooding will not be completely eliminated, but that the frequency and magnitude of flood events will be significantly reduced through appropriate interventions that improve channel conveyance efficiency, while not detrimentally impacting on the conservation objectives of the SAC.

8. CONCLUSIONS

Hydrology plays a significant role in the restoration of raised bogs. The hydrological condition of raised bogs must be restored to achieve favourable ecological conditions and associated ecosystem services. In order to identify whether restoration is likely to be successful, focused characterisation of existing hydrological conditions is fundamental in determining whether restoration measures will succeed in restoring ARB. This allows for effective restoration plans to be developed which focus on restoring the hydrological conditions necessary for ARB habitat to be maintained. Use of low-cost solutions requiring minimal maintenance, which allow targets for habitat area and quality to be met, while maximising the ecosystem services benefits, often prove to be the most sustainable solutions in peatland restoration. While the main aim of peatland restoration is the improvement of the condition of the habitat, restoration can have significant additional benefits. These include maintaining biodiversity, improving carbon sequestration and water quality in receiving waters and possibly increasing storage capacity to regulate flows in downstream watercourses. Restoration measures focusing on the entire peatland hydrological unit therefore have the potential not only to contribute to the objectives of the HD, but also align with the objectives of the Water Framework Directive and Floods Directive. This sustainable approach meets the environmental, economic and social strands of sustainability.

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