Catchment Science and Management –
The Role of Geoscience and Groundwater

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(Irish Group)

Proceedings of the 41st Annual Conference

Online, 26th and 27th April 2021

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(IRISH GROUP)

Presents

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Introduction

Founded in January 1976, the IAH-Irish Group has grown from 10 members to over 150 and draws individuals from professional backgrounds ranging from academic to state agencies to private consultancies. The IAH committee consists of: President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, Conference Secretary, plus a conference sub-committee.

Regular activities of the Irish Group include our annual two-day conference (currently held in Tullamore), an annual weekend fieldtrip, and a series of monthly lectures and technical meetings. Funding for the association is derived from membership fees and the annual conference. We welcome the participation of non-members in all our activities. Other activities of the IAH (Irish Group) include submissions to the Irish Government on groundwater, the environment and matters of concern to members, organising the cataloguing of the Burdon library and papers which are now housed in the Geological Survey of Ireland Library, the invitation of a guest expert speaker to give the David Burdon Memorial Lecture on a topic of current interest in the field, and informing the broader research community by contributing to the Geological Survey of Ireland's Groundwater Newsletter.

The Irish Group also provides bursaries to students undertaking postgraduate degrees in hydrogeology and pays the annual subscriptions of a few members in other countries as part of the IAH's Sponsored Membership Scheme. If you would like to apply for a student bursary, details can be found on the IAH (Irish Group) website shown below. IAH are encouraging members to highlight their local IAH Group to their colleagues/ students and to invite anyone they feel may be interested to join.

The IAH (Irish Group) is also a sponsoring body of the Institute of Geologists of Ireland (IGI).

For more information please refer to:	www.iah-ireland.org
Future events:	www.iah-ireland.org/upcoming-events/
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	www.iah.org/payonline

2021 IAH (Irish Group) Conference "**Catchment Science and Management – The Role of Geoscience and Groundwater**"

On behalf of the organising committee, I would like to 'virtually' welcome you all to the 41st annual IAH Irish Group Conference. Thank you for your continued support and involvement in the activities of the IAH Irish Chapter.

Once again, we are holding the conference online in 2021, given the on-going restrictions with the Covid-19 pandemic. We have maintained the format from last year of two half-days and, this year, we've added some short presentations by early career hydrogeologists. The main sessions will each be followed by live Q&A, and questions can be submitted by attendees through Zoom.

The theme of the conference this year is "Catchment Science and Management – The Role of Geoscience and Groundwater". Catchments are the basis of a significant amount of high quality and critical work that is being undertaken currently to improve environmental outcomes, such as characterisation, investigation, Water Framework Directive implementation and drinking water source protection. The conference aims to publicise this work to water scientists and engineers, particularly hydrogeologists, catchment scientists, environmental scientists and environmental technicians. It will highlight the importance of taking a wider catchment-based perspective, draw attention to new topics of interest, and demonstrate the range of areas where hydrogeologists, and those in related fields, can apply their skills and knowledge.

On our first day, session one, *Catchments and the Environment,* will take a broader perspective and includes talks on the Framework for Integrated Land and Landscape Management developed by An Fóram Uisce (Gretta McCarron, An Fóram Uisce), Nature-based Catchment Management (Patrick Morrissey, EPA) and a karstic lake habitat (Cilian Roden, Consultant). Session two, *Investigating and Assessing Catchment Water Quality,* consists of presentations on the 3rd WFD Cycle River Basin Management Plan (Marie Archbold, EPA), the Agricultural Catchments Programme (Per-Erik Mellander, Teagasc), local catchment assessment (Eoin McAleer, LAWPRO), and the CatchmentCARE Project (Caoimhe Hickey, GSI).

Half-day number two kicks off with a session on *Insights on Water Flow in Catchments*, with talks on the role of groundwater in catchment functioning (Alan McDonald, BGS), blanket bogs and streamflow (Ray Flynn, QUB), and characterising flows in a western karst terrain (Suzanne Tynan, Consultant). The final session is titled *Managing Drinking Water with a Catchment Based Approach*, and the speakers will present on the recast Drinking Water Directive (Lorraine Gaston, Irish Water), mitigation actions using the pollutant transfer continuum (Patrick McCabe, NFGWS), novel catchment modelling methods to support Irish Waters lead mitigation programme (Gerry Baker, Arup) and catchment management in a karst environment (Coran Kelly, Tobin).

Following the conference, we will be sending out a survey to all registrants and we are keen to hear your feedback, thoughts, ideas and suggestions.

The organising committee wishes to express their gratitude to all of those attending this year's and previous year's conferences, particularly the speakers. We hope you find the conference interesting, educational and thought provoking.

Philip Maher
IAH (Irish Group)
Conference Secretary

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH-Irish Group throughout the year and helped to organise the conference:

Donal Daly

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‘Catchment Science and Management – The Role of Geoscience and Groundwater’

International Association of Hydrogeologists – Irish Group
41st Annual Groundwater Conference – Online Event
Monday 26th April – Tuesday 27th April 2021

Programme Day 1, Monday 26th April

13.00 *Conference Login Open*

SESSION I: Catchments and the Environment

13:30 Welcome & Introduction - Philip Maher (EPA), Conference Secretary, IAH (Irish Group)

13:40 **Gretta McCarron** (An Fóram Uisce): *A Framework for Integrated Land and Landscape Management (FILLM), a systems-based approach to environmental management.*

14:00 **Patrick Morrissey** (Environmental Protection Agency): *Nature-based Catchment Management – opportunities to restore our waters whilst also achieving multiple benefits.*

14:20 **Cilian Roden** (Roden Ecology): *Marl lakes on karstic limestone bedrock – a special Irish habitat?*

14:40 Q&A

15:00 Introduction & Chair: Lindsay Connolly (ARUP)

Early Career One-Minute Poster Presentations

15:20 Break

SESSION II: Investigation and Assessing Catchment Water Quality

15:35 Introduction & Chair– Laura McGrath (Tobin Consulting Engineers)

15:40 **Marie Archbold** (EPA): *The scientific evidence-base underpinning the 3rd Cycle River Basin Management Plan.*

16:00 **Per-Erik Mellander** (Teagasc): *The Agricultural Catchments Programme: a decade of agro-environmental studies.*

16:20 **Eoin McAleer** (LAWPRO): *Local Catchment Assessment: From Deskstudy to Referral.*

16:40 **Caoimhe Hickey** (GSI): *CatchmentCARE: Community actions for resilient ecosystems.*

17:00 Q & A

17:30 End of Day 1

'Catchment Science and Management – The Role of Geoscience and Groundwater'

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Programme Day 2, Tuesday 27th April

09:20	*Conference Login Open*

SESSION III: Insights on Water Flow in Catchments

09:30	Introduction & Chair – Alison Orr (Arup)
09:35	**Alan McDonald** (BGS): *Investigating the role of groundwater in catchment functioning in the Eddleston research catchment, Scotland.*
09:55	**Ray Flynn** (QUB): *Blanket bogs and streamflow – the under-appreciated role of groundwater.*
10:15	**Suzanne Tynan** (Tynan Environmental): *Characterisation of flows in a western karst terrain, using combined hydrological and hydrogeological methods.*
10:35	Q&A
11:00	Break

SESSION IV: Managing Drinking Water with a Catchment Based Approach

11:15	Introduction & Chair – Paul Wilson (GSNI/BGS)
11:20	**Lorraine Gaston** (Irish Water): *The Recast of the Drinking Water Directive – Challenges and opportunities for protecting our sources.*
11:40	**Patrick McCabe** (NFGWS): *Determining mitigation actions using the pollutant transfer continuum.*
12:00	**Gerry Baker** (ARUP): *Novel catchment modelling methods to support Irish Waters lead mitigation programme.*
12:20	**Coran Kelly** (Tobin Consulting Engineers): *Challenges and opportunities for catchment management in a karst environment – insights from a work in progress in the Rathcroghan Uplands, Co. Roscommon.*
12:40	Q & A
13:10	Closing Address – Niamh Rogan (EPA), Secretary, IAH (Irish Group)
13:20	**End of conference**

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SESSION I

A FRAMEWORK FOR INTEGRATED LAND AND LANDSCAPE MANAGEMENT

Gretta McCarron

An Fóram Uisce (the Water Forum), Limerick Road, Nenagh

ABSTRACT

Ireland's natural environment is an inheritance for present and future generations. Protecting and managing this inheritance is particularly demanding in the context of the climate crisis, stressed water resources, declining biodiversity and the Covid-19 pandemic. Getting the balance between our current and future food and economic needs, and achieving environmental sustainability, if not regeneration, is an existential challenge. While there are different ways of meeting this challenge, undoubtedly one way is developing and utilising a systems approach that takes account of all relevant aspects in an integrated manner.

Commonly, there is a tendency to treat each component of the environment as siloes, dealt with by particular specialists and organisations. While this is understandable and will have continuing benefits, it is not adequate and will not ensure that our inheritance is maintained and enhanced.

We live in an interconnected world. More specifically, all the components of our natural environment – air, water, ecosystems, soils, rocks, land, landscapes – are interrelated and interlinked. Therefore, management of these components, in the context of society's needs for nourishing food, good health and economic wellbeing, must take account of the linkages and must be undertaken in a cohesive, holistic and integrated manner. Otherwise, our natural environment will continue to decline, and our protection efforts will not be either efficient or effective.

An Fóram Uisce (2021) is proposing the adoption of a systems approach in the form of a Framework for Integrated Land and Landscape Management that enables inclusion of all the relevant aspects in a cohesive and unified manner.

The Framework for Integrated Land and Landscape Management (FILLM) builds on and is a reframing of the Integrated Catchment Management (ICM) approach used in water resources management. However, it is broadened to include the other components of our natural environment, while retaining catchments as the appropriate landscape units. In the process, FILLM becomes the overarching framework for environmental management as a means of connecting several directives and activities, for instance, the Water Framework Directive, Urban Waste Water Treatment Directive, Habitats Directive, Floods Directive, Drinking Water Directive, climate change adaption and mitigation, soil conservation, spatial planning, and sustainable food and timber production. In addition, it is a means of achieving the UN Sustainability Goals for 2030.

Ultimately, it is the implementation of measures and actions that are key to attaining the various environmental outcomes for water, air and ecosystems. Acceptance and use of the FILLM approach by policy makers, public bodies with an environmental remit and local communities encourages consideration of co-benefits, identification of synergies and can facilitate trade-offs where synergies are not feasible. Therefore, the approach helps ensure optimum results for the efforts and resources used.

INTRODUCTION AND RATIONALE

Our natural capital in Ireland, the foundation of our social, economic and health wellbeing, is being challenged on several fronts by human activities. Our water quality is not improving as required by the EU Water Framework Directive (WFD) and is slightly disimproving, biodiversity is declining and the increasing greenhouse gas (GHG) emissions and associated climate crises is the biggest environmental treat facing Irish society. At the same time the population is increasing. Hence maintaining safe, secure and stable water supplies and managing our wastes is challenging, and there is a need for a sustainable and resilient food production system.

These issues are interconnected. For instance, the changing climate regime has consequences for our water resources (quantity and quality), for ecosystems, for food production and for our health and wellbeing. Declining ecosystems and soil quality impinge on carbon sequestration and our resilience to cope with climate generated impacts. We also have many positive features, unspoilt areas, high quality food production and many catchments with good quality water resources, all of which are beneficial to people as well as the economy. Measures and actions are needed to protect our environment where it is satisfactory and mitigate the impacts where it is under threat or is unsatisfactory. It is now clear that many of the necessary measures and actions undertaken or planned for one component of the environment have co-benefits for other components because of the connectedness of nature. Therefore, there is an opportunity to adopt a systems approach to environmental management that takes account of all the environmental components and requirements in an integrated manner as a means of delivering effective and efficient outcomes for the environment and Irish society.

There has been a tendency in the past to consider and manage all the environmental components – water quality and quantity, air and climate, habitats and biodiversity, landscape, soils and geological materials – as separate entities, usually with specific public bodies having responsibilities for them. This is now being replaced by a view that a more holistic and integrated approach that links all the components (Figure 1), as well as the interaction with human activities, is needed.

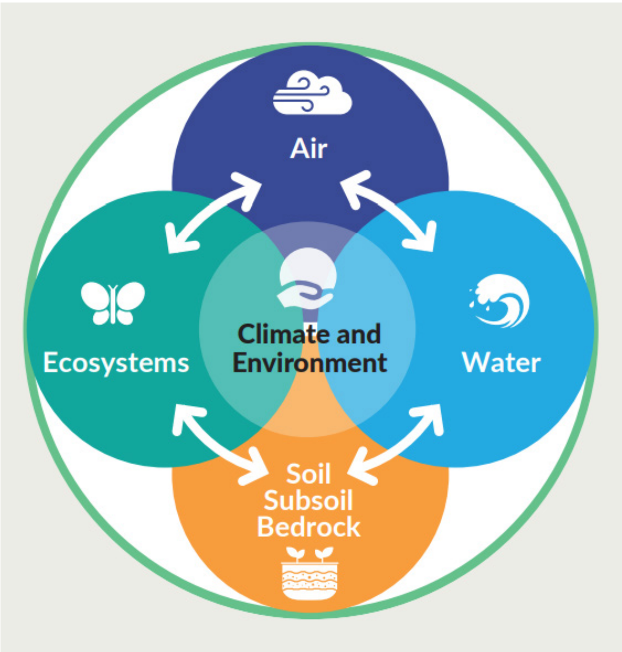

Figure 1: *Illustration of the 'whole of environment' components and linkages (Copied from An Fóram Uisce, 2021)*

Many of the key issues we now face are complex problems involving multiple pressures acting in combination, and therefore require action with multiple sectors. The adaptation of systems thinking[1] and the systems approach in environmental management allows for ecosystems, geosystems and atmospheric systems, as illustrated in Figure 2, to be considered holistically.

Deliberations and recommendations at both international and national level such as the UN Sustainability Goals, the EU vision of 'living well within the limits of our planet', the EU Green Deal and the seven key environmental actions recommended by the Environment Protection Agency (EPA) suggest that such a different approach to environmental management is required to achieve successful outcomes.

Suggested requirements include:

- Policy coherence and policy integration, that potentially require transformative change at government level and within and between public bodies.
- Taking a whole systems approach which requires a multi-disciplinary, multi-objective and multi-stakeholder framework supporting a balanced evaluation of all relevant issues.
- Making the linkages between the environmental components and human activities and taking account of the benefits (co-benefits), disbenefits and trade-offs.
- A spatial planning system that takes account of all environmental components in a holistic, cohesive way. Reduced compartmentalisation of planning and actions within the various environmental components is needed, as cross-component planning can deliver benefits in terms of cost-efficiency and environmental effectiveness.
- Connecting the requirements and implementation of the various Directives, such as the WFD, Habitats, Birds, Floods, Drinking Water, Marine Strategy Framework, Nitrates and Urban Waste Water Treatment and of policies such as Common Agricultural Policy (CAP), European Landscape Convention, climate change and forestry.
- A means of delivering on and balancing multiple objectives, while managing synergies and trade-offs in a transparent way.
- An evaluation of land suitability for various activities, including food production and provision of environmental services.
- Taking a collaborative place-based approach working across all relevant sectors in partnership at local and national level.

INTEGRATED CATCHMENT MANAGEMENT

The EU Water Framework Directive (WFD)[2] is the corner-stone of European water policy. It has provided the structure for integrated water resource management across the European Union over the last 20 years. The central concept to the WFD is **integration** as this is seen as key to the management and protection of water within river basin districts. This includes integration of, for instance:

i) All water resources combining fresh surface water and groundwater, wetlands and coastal water resources at the catchment scale;
ii) Environmental objectives for water bodies;
iii) Water uses, functions and values;
iv) Disciplines and expertise;
v) Stakeholders and civil society;
vi) Measures to achieve the objectives; and
vii) The different decision-making levels (local, regional and national) that influence water management.

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[1] Richmond, B. (1994). Systems Dynamics/Systems Thinking: Let's Just Get On With It. In: International Systems Dynamics Conference. Sterling, Scotland

[2] https://ec.europa.eu/environment/water/water-framework/index_en.html

The Integrated Catchment Management (ICM) approach was developed as the means of enabling the required integration. This is acknowledged in the River Basin Management Plan for Ireland 2018-2021[3] as follows:

"*A new approach to implementation known as 'integrated catchment management' is being used to support the development and implementation of the RBMP, using the catchment (an area that contributes water to a river and its tributaries, with all water ultimately running to a single outlet) as the means to bring together all public bodies, communities and businesses.*"

Traditionally, the vision and definition of a catchment was based on it being an area formed by topography that contributes water to a river and its tributaries, with all water ultimately running to a single outlet. While this is accurate from a hydrological perspective, catchments can be defined and considered in a far broader and relevant way, as follows (Daly, 2017):

A catchment is a multi-functional, topographically-based, dynamic, multiple-scale socio-biophysical system; defined by over ground and underground hydrology; connecting land, water, ecosystems, geosystems, atmospheric systems and people; and used as a basis for environmental analysis, management and governance.

By utilising this concept and understanding of catchments, they become appropriate and effective landscape units for environmental management and land-use planning, as highlighted below:

- They connect water 'from the mountains to the sea' via over ground and underground pathways. In the process, all human activities in catchments are connected.
- They connect many habitats from mountainous to riverine to estuarine to coastal, particularly aquatic habitats.
- In terms of their landscape and history, catchments of both local and national rivers and streams are recognised generally, to a greater or lesser degree, by local communities as part of their 'sense of place'. Features such as streams, associated habitats, holy wells, etc. are used by local communities for their enjoyment and wellbeing providing cultural ecosystem services. The intrinsic and relational connections provided by cultural ecosystem services create a unique appreciation of local nature among catchment communities for water features, habitats, fishing, etc.
- Catchments are being used internationally and in Ireland[4] as the framework for natural capital (ecosystems, geosystems, atmospheric systems) accounting, and particularly for assessing ecosystem services (see Figure 2).
- Local government boundaries are not suitable for water and biodiversity management, catchments are.

ICM comprises a stepped process which has been applied in the development of Integrated Catchment Management plans as set out in Figure 3.

1. Identify key stakeholders. This local participation identifies issues of concern, encourages practice change and raises awareness of the issues and actions that are needed to attain environmental protection or improvements.
2. Create a community vision and potentially a community 'plan' for the catchment capturing local cultural ecosystem services and connecting people with their local stream, river, lake, coastal water, spring or borehole.
3. Getting the science right is achieved through catchment characterisation, using desk studies and field assessments to identify the causes and sources of pollution, critical source areas (CSAs), pollution load reductions and possible management strategies and mitigation options.
4. Identify and evaluate management strategies and mitigation options.

[3] https://www.housing.gov.ie/water/water-quality/river-basin-management-plans/river-basin-management-plan-2018-2021

[4] https://www.incaseproject.com/about-the-project

5. Select and agree appropriate measures, develop an implementation schedule and monitoring and set up engagement and communications strategies.
6. Implement the catchment action plan and communicate progress.
7. Evaluate progress, make necessary adjustments and communicate revised action plans.

The process requires close collaboration between relevant public bodies and a combination of 'bottom-up' and 'top-down' approaches. It involves awareness-raising, engagement and consultation with local communities. It presents a 'new' vision of a healthy, resilient, productive and valued water resource that supports vibrant communities.

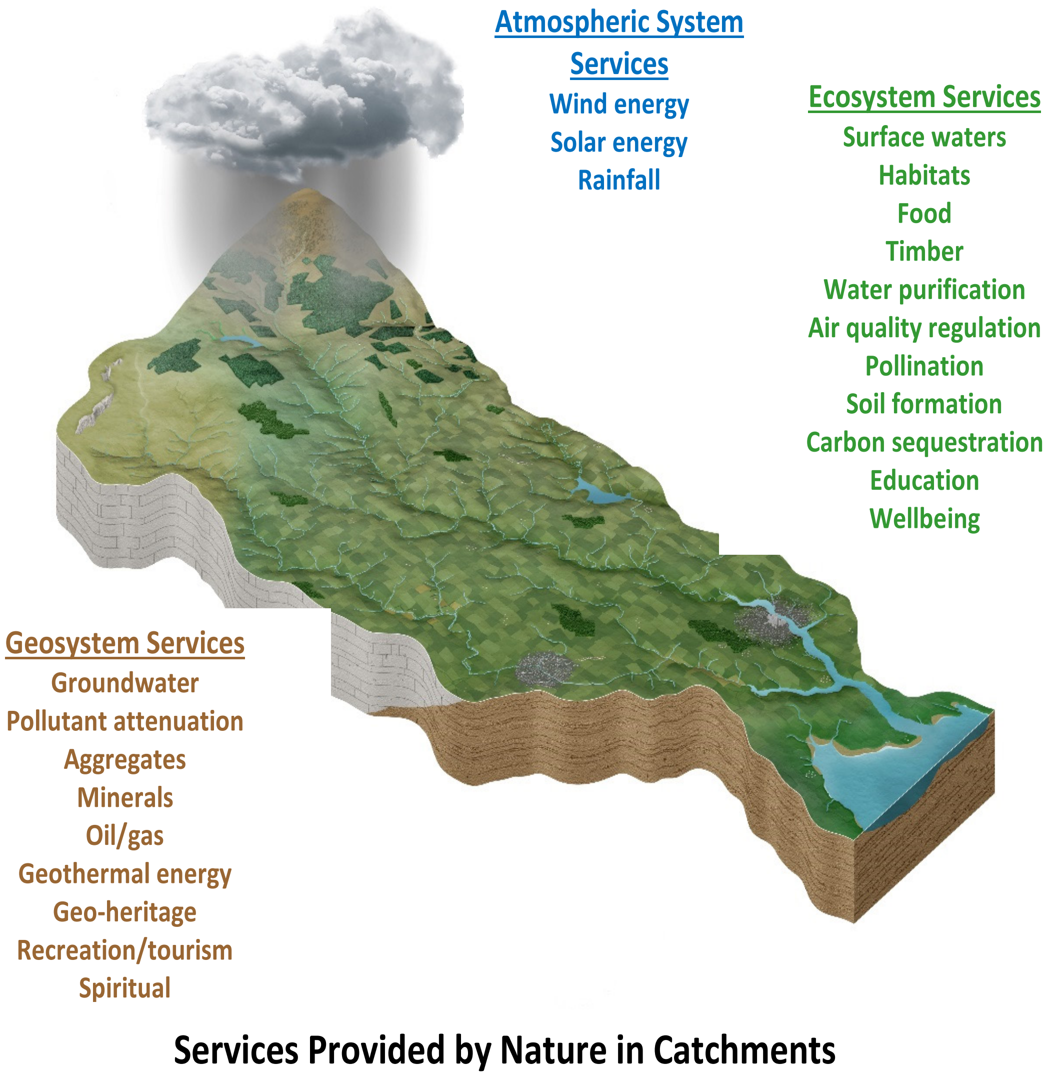

Figure 2: *Schematic diagram of a catchment highlighting the three natural capital systems and the potential benefits provided by nature to people living in catchments. (Copied from An Fóram Uisce, 2021)*

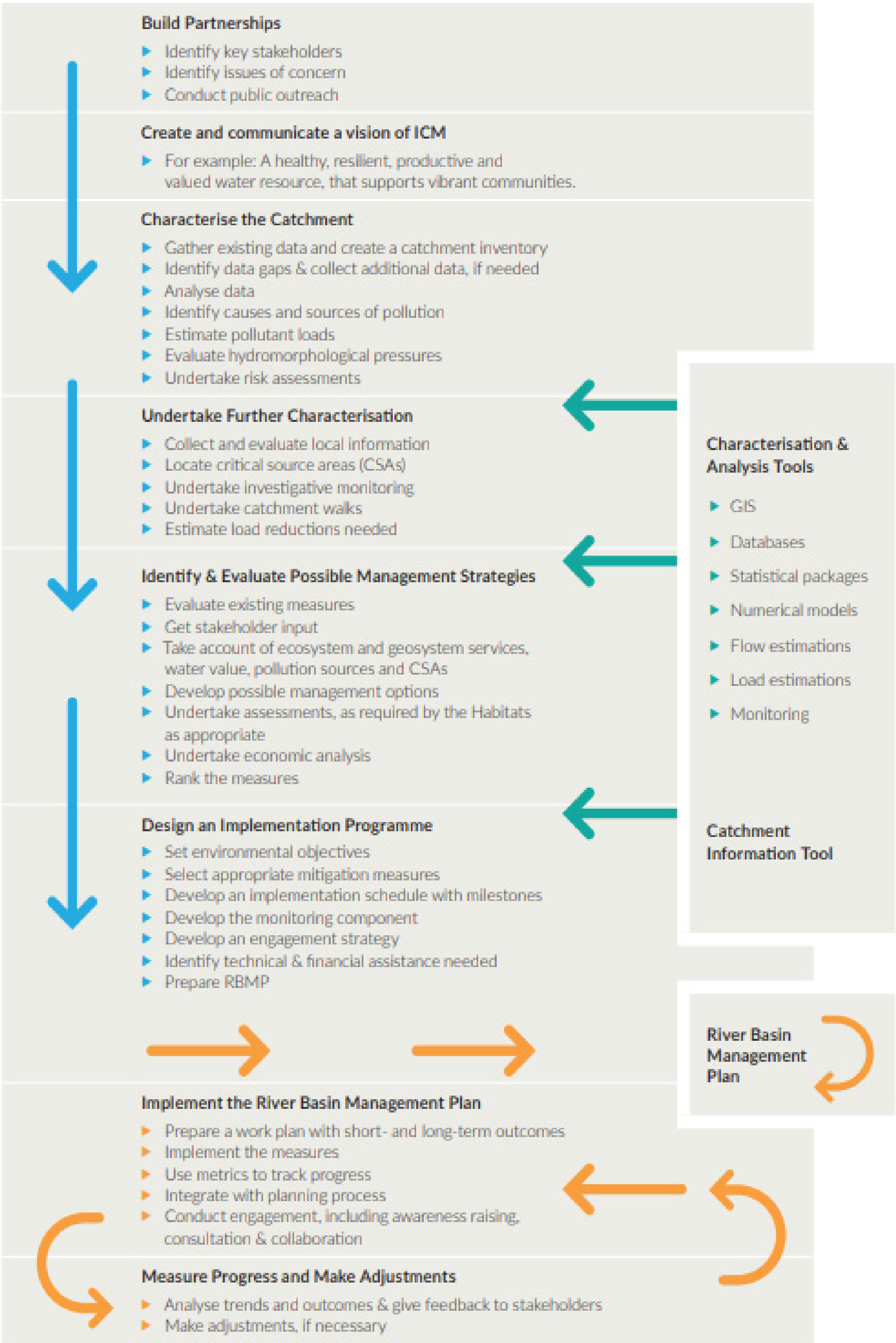

Figure 3: *Steps in the integrated catchment management process (Adapted from Daly, et al., 2016)*

REFRAMING ICM AS FILLM

In reviewing ICM and considering how our environmental objectives for water could be achieved, An Fóram Uisce concluded that there was scope for broadening it to include public participation, biodiversity and ecosystems, greenhouse gas emission reduction and carbon sequestration more explicitly and comprehensively, thereby connecting all the environmental components shown in Figure 1. In the process, this makes ICM a more powerful and relevant means of protecting and enhancing our environment and of achieving co-benefits from measures. ICM, as illustrated in Figure 3, has been rebranded as the Framework for Integrated Land and Landscape Management (FILLM) as shown in Figure 4. This amended approach addresses catchments as the landscape/spatial units in a holistic systemic-perspective, simultaneously focusing on the atmospheric system, the ecosystem and the geosystem. In this way, it aims to trigger a virtuous dynamic within and between all three systems in a coherent drive towards environmental enhancement.

When Figures 3 and 4 are compared, it is clear that the stages of FILLM are mirrored by the Steps of ICM, illustrating the close connections between the two. In addition, FILLM includes consideration of stakeholder engagement, GHG emission reduction and carbon sequestration at all stages. Also, the FILLM process can be used not only where water is the main receptor being considered (e.g. WFD implementation), but also where both terrestrial and aquatic ecosystems are the main receptor, such as Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) (for Habitats Directive implementation).

WHY USE THE FILLM APPROACH?

- It provides a basis for a shared vision of land utilisation and management that includes all stakeholders, all human activities and all environmental components.
- It acknowledges ICM as an essential approach for successful water resources management and WFD implementation, and reframes it, as a critical driver for wider environmental protection and enhancement. For instance, FILLM is recommended as a structured approach for integrated ecosystem management.
- It makes environmental management more understandable and appealing to local communities because many householders and farmers 'see' the surrounding landscape as a mosaic of topographical, physical, ecological, cultural and infrastructural features and functions with no clear boundaries between them, particularly those that are the natural capital or components of an area.
- It provides the opportunity and encouragement for policy coherence and integration in land, landscape and nature management in a context where there are multiple environmental and socio-economic needs.
- It encourages different relevant disciplines and organisations to collaborate in the pursuit of mutually beneficial objectives.
- It takes account of situations where pressures that are seen to impact on one element of the environment in a catchment often impact on others, e.g. intensive farming can impact not only water quality, but also biodiversity, and can increase carbon and ammonia emissions unless actions are taken to mitigate impacts.
- It enables environmental management actions to be optimised in terms of cost-effectiveness and environmental benefits, takes account of trade-offs and helps avoid conflicts.
- It encourages a multifunctional approach to land-use, encompassing all the particular ecosystem, geosystem and atmospheric system services in a catchment area.
- It facilitates greater integration of resource use, including nutrient cycling, spatial distribution of 'natural' and productive land, and renewable energy generation and biofuels.
- It encourages identification of those situations in which management practices that achieve benefits for one environmental issue could conflict with the delivery of other environmental priorities so that such conflicts can be resolved.

- It enables agri-environmental and forestry environmental schemes to be considered as an integrated process.
- It discourages ‘one-off’ actions to deal with a singular environmental issues without consideration of the potential for ensuring optimum environmental benefits and cost-effectiveness.
- It encourages optimum location of protection and improvement measures, for example, planting of native woodlands as buffer zones alongside streams.
- It enables and encourages greater cooperation between different agencies, industries and civil society to more effectively plan and manage areas of mutual interest and resolve conflicts where “competing” interests (real or perceived) occur.
- It enables consideration of co-benefits from environmental management actions.

TO SUPPORT IMPLEMENTION

An Fóram proposes the following:

1. That the Framework for Integrated Land and Landscape Management (FILLM) becomes the overarching framework for environmental management, as a means of connecting and achieving , for instance, the UN Sustainability Goals for 2030 and the Water Framework Directive, Urban Waste Water Treatment Directive, Habitats Directive, Floods Directive, Drinking Water Directive, the European Landscape Convention, climate change adaption and mitigation, soil conservation, and sustainable food production and land-use planning requirements.
2. That public engagement on a particular component of the environment, such as river basin management planning or ecosystem protection and enhancement or GHG emission reduction, should include consideration of all the environmental components in a holistic manner.
3. That the Programmes of Measures for water resources, biodiversity and climate change adaptation and mitigation should not be considered in a siloed manner, but rather as measures and actions that can achieve more than one objective and benefit as a means of optimising efficiency and effectiveness in terms of resource use and environmental outcomes, and as a means of considering trade-offs where synergies are not feasible.
4. That all relevant public bodies with an environmental remit, such as An Fóram Uisce, Department of Housing, Local Government and Heritage (DHLGH), Department of Agriculture, Food and the Marine (DAFM), Environmental Protection Agency (EPA), National Parks and Wildlife Services (NPWS), Local Authority Waters Programme (LAWPRO), Inland Fisheries Ireland (IFI), Geological Survey of Ireland (GSI) and local authorities, adopt the FILLM approach, including the multi-disciplinary and multi-organisational implications, in their vision and environmental management work as a means of achieving optimum efficiency and effectiveness.
5. That resources are allocated to allow these recommendations to be enabled.

CONCLUSIONS

Utilising the FILLM approach provides the opportunity for policy coherence and integration in land, landscape and nature management in a context where there are multiple environmental and socio-economic needs. It provides a basis for a shared vision of land utilisation and management that includes all stakeholders, all human activities and all environmental components. It encourages different relevant disciplines and organisations to collaborate in the pursuit of mutually beneficial objectives. It takes account of situations where pressures that are seen to impact on one element of the environment in a catchment often impact on others, e.g. intensive farming can impact not only water quality but also biodiversity, and can increase carbon and ammonia emissions unless actions are taken to mitigate impacts. It enables environmental management actions to be optimised in terms of cost-effectiveness and environmental benefits, takes account of trade-offs and helps avoid conflicts.

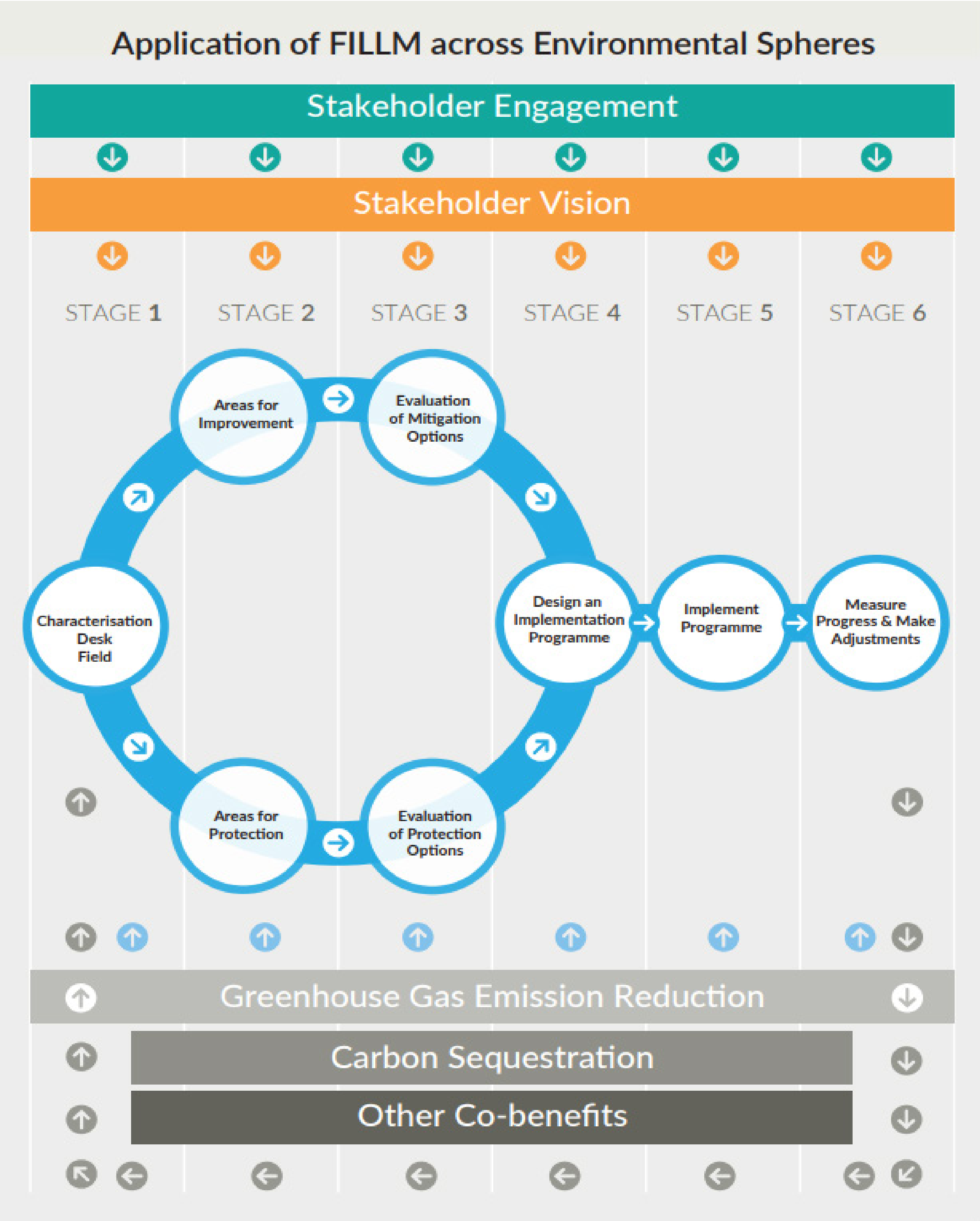

Figure 4. *Stages in the application of FILLM to address all component systems. (Copied from An Fóram Uisce, 2021)*

ACKNOWLEDGEMENTS

This paper is based on the work of Donal Daly and builds on experience gained implementing integrated catchment management in the 2nd WFD Cycle River Basin Management Programme. *The Framework for Integrated Land and Landscape Management* report, was produced and approved by the members of An Fóram Uisce – The Water Forum as a deliverable in its role as the only statutory

body representing all stakeholders with connections pertinent to water resource management. These include consumer, community and water sports groups, business and trade unions, environmental sector, Irish Water consumers, the group water scheme sector and a range of other sectors including education, agriculture, fisheries and forestry. The Forum is chaired by Dr Tom Collins.

An Fóram Uisce - The Water Forum was established as a statutory body in June 2018 to facilitate stakeholder engagement and debate on issues relating to water as a resource, water quality, rural water concerns, issues affecting customers of Irish Water and issues associated with the implementation of the Water Framework Directive.

For further information, contact gretta@nationalwaterforum.ie **www.thewaterforum.ie** Twitter: **@AnForamUisce**

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NATURE-BASED CATCHMENT MANAGEMENT – RESTORING OUR WATERS WHILST ALSO ACHIEVING MULTIPLE BENEFITS

Patrick Morrissey, Emma Quinlan, Darragh Cunningham and Jenny Deakin

Environmental Protection Agency

ABSTRACT

Hydromorphological pressures present a significant challenge which must be addressed in order to meet our environmental objectives and restore our waters. 28% of 'At Risk' water bodies are impacted by this pressure type which is the 2nd most prevalent significant pressure type for "At Risk" river water bodies. Physical modification alters the natural functioning of a water body, which in turn can impact habitat and often affects the natural sediment regime. Nature-based Catchment Management provides a methodology to implement measures to address this pressure type which mimics natural processes to achieve multiple benefits. There is a need to shift our approach towards measures for multiple benefits at the catchment scale given that the whole of the environment is linked. NbCM measures fit perfectly within the catchment based approach of targeting interventions to both meet our environmental objectives and restore our waters.

Key words: hydromorphology, nature-based catchment management, river restoration, natural water retention measures, nature-based solutions, river basin management plan, water quality, significant pressures

INTRODUCTION

The objective of the WFD is to prevent any further deterioration in status of surface waters, groundwater and water dependent ecosystems, and to restore polluted water bodies to at least good status. The EPA is responsible for assisting the Minister with the preparation of the River Basin Management Plan (RBMP), undertaking initial characterisation (i.e. assessments of pressures and impacts) of all water bodies, advising the Minister on draft environmental objectives and identifying where exemptions may be required. The Unit also advises the Minister on the Programme of Measures (PoMs) to mitigate against impact from pressures on water bodies and supports the technical implementation of the River Basin Management Plan, including reporting on progress with implementation.

During the 2nd Cycle Characterisation process, hydromorphological pressures were identified as the 2nd most prevalent significant pressure type for "*At Risk*" river water bodies. The pressure relates to damage to habitat and natural river/lake processes through physical modifications caused by for example, channelisation, land drainage, dams, weirs, barriers and locks, overgrazing, embankments and culverts. Mitigating hydromorphological pressures through river restoration, is becoming increasingly acknowledged as a key focus of integrated catchment management and WFD implementation. The 2nd cycle River Basin Management Plan (RBMP) for 2018-2021 set out a national hydromorphology work programme which included tasks to improve assessment methods, carry out condition assessments, set hydromorphological standards, and develop a programme of restoration measures.

The EPA leads the implementation of the national hydromorphology work programme, and is supported by a national Hydromorphology Working Group. This is one of two working groups set up to assist with the work programme. The development of the MQI-Ireland (see below) condition assessment tool means we now have the scientific tools to assess the hydromorphological pressures. This will form the basis for targeting the right measure in the right place to facilitate restoration of natural river processes, addressing hydromorphological pressures while providing multiple benefits.

However, there is currently no national framework in place for the effective implementation of river restoration in Ireland. There is also no governing body for the regulation of works within our rivers at present. Development of a restoration framework is therefore a key step in delivering an evidence-based approach to prioritised restoration of our surface waters.

A second related piece of work, which was also set out in the RBMP was recently completed by the national Natural Water Retention Measures working group. The group was co-chaired by EPA and OPW and was tasked with assessing the potential for implementing Natural Water Retention Measures in Ireland, as part of a suite of measures to address water quality, reduce flooding and achieve other environmental outcomes. The group produced a recommendation to the National Technical Implementation Group (NTIG) and the output of their work will feed into the development of the PoMs for the 3rd Cycle RBMP. It was recommended as part of this work to refer to these measures as Nature-based Catchment Management rather than the former NWRM as many measures are not primarily focused at flood prevention or mitigation.

HYDROMORPHOLOGY AS A SIGNIFICANT PRESSURE

The physical conditions (or hydromorphology) of a waterbody is key to sustaining healthy aquatic ecosystems. However, modification to these conditions ranks as the second most significant pressure in surface water bodies nationally see Figure 2. Hydromorphological modification has been identified as a significant pressure in one-third of all river waterbodies considered 'At risk' of not achieving their environmental objective.

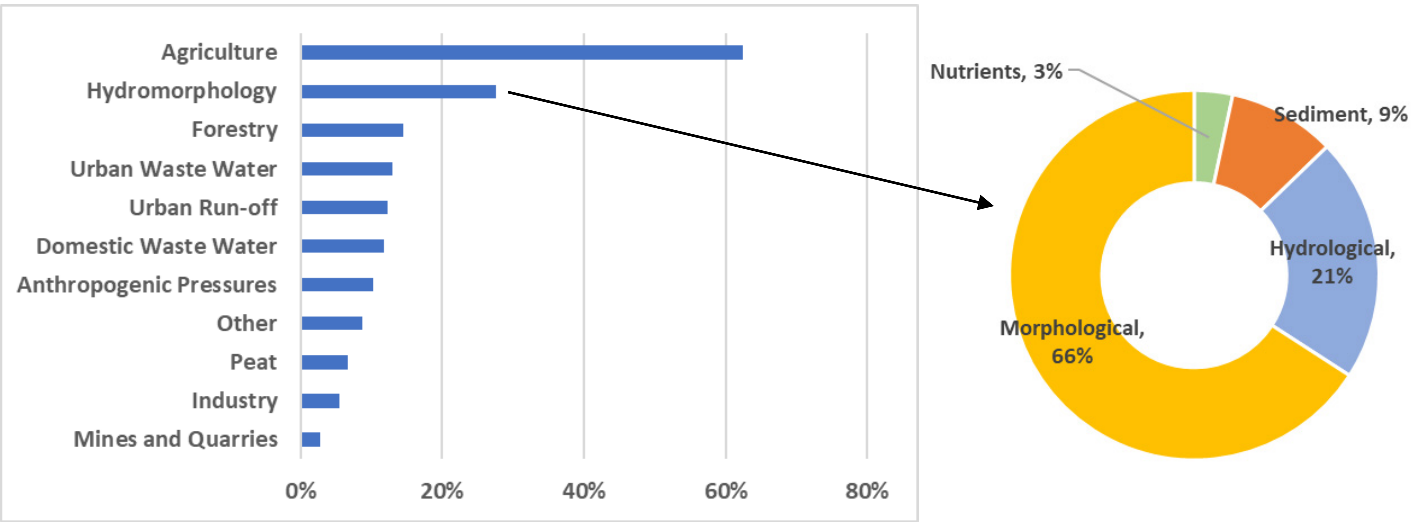

Figure 1: Proportions of At Risk water bodies impacted by a specific significant pressure in 3rd Cycle characterisation – insert shows impacts associated with hydromorphological significant pressures

In many of these waterbodies (~80%), hydromorphological modification is not the only significant pressure as shown in Figure 2 – dark red colour identifies surface waterbodies where additional significant pressures have been identified.

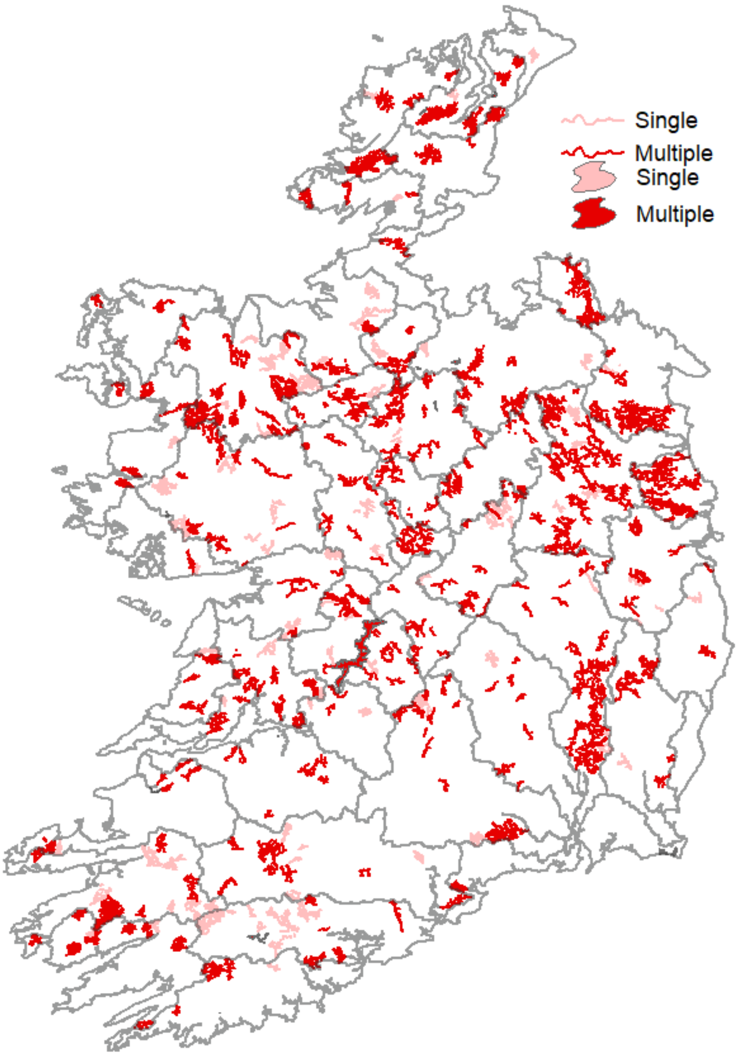

Figure 2: Surface water bodies where hydromorphological modification is a significant pressure either alone or in combination with other pressures (Oct. 2020).

Physical modification alters the natural functioning of a water body, which in turn can impact habitat. Examples of pressures, identified within rivers, include straightening, widening or deepening of channels, land drainage, traditional flood protection, abstraction and development along the river corridor. In-channel barriers such as dams, weirs and culverts can not only impede physical processes but impact the movement of fish (see Figure 2).

While fine sediment (i.e. sand, silt, clay) plays an important role in aquatic ecosystems, levels higher than expected for the natural geological setting can be a significant issue, particularly if associated with nutrients and/or toxic pollutants. This has become evident from LAWPRO's local catchment assessment findings.

NATURE-BASED CATCHMENT MANAGEMENT MEASURES

Nature-based Catchment Management Measures (NbCMs) are multi-functional measures that aim to protect water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and characteristics of water bodies using natural means and processes (EU, 2014). The main functions of these measures are to reduce flood risk, improve water quality, and create habitats. In carrying out these functions these measures can also provide multiple co-benefits such as climate regulation, climate change adaptation, improved soil management, and the creation of amenities. It must be noted that the concept of NbCM is not a new one and many of these measures already exist and are being actively implemented within different sectors plans and policies in Ireland. NbCM should be used as part of the overall Integrated Catchment Management (ICM) approach. Many measures are ineffective when deployed in isolation without other supporting measures. The ideal solution will be at the catchment scale usually taking the form of a suite of measures designed to complement each other across the landscape. The key benefit of these measures lies in the multiple benefits that they bring, key benefits include:

- improving water quality
- regulating water storage and delivery
- flood risk reduction
- sequestering carbon
- supporting and enhancing biodiversity
- improving amenity value (e.g. angling and walking)
- health benefits (e.g. mental health benefits/improved air quality)
- aesthetic quality (e.g. visually desirable features such as ponds)
- cultural benefits (i.e. tourism and recreational value of rivers)
- climate change resilience (e.g. increased buffering to extreme rainfall events)

The NWRM working group compiled a comprehensive list of measures suitable for use in Ireland which are categorised into 5 sectors (see Appendix 1). It must be noted that many of these measures are cross cutting between sectors e.g. riparian buffers are relevant in the agricultural, forestry and urban sectors etc.

NbCM measures in action: GLAS scheme

The Green Low-Carbon Agri-Environment Scheme (GLAS) was an agri-environment scheme contained within the Rural Development Programme 2014-2020. It followed the Rural Environmental Protection Scheme (REPS) and the Agri Environmental Options Scheme (AEOS). GLAS aimed to encourage farmers to promote biodiversity, protect water quality, and also to help combat climate change. Figure 3 below illustrates the successful implementation of arable margins coupled with low emission slurry spreading.

Figure 3: Arable Margins (BSBI: Botanical Society of Britain & Ireland and Plantlife)

Activities which are mandatory for farmers to qualify for the scheme (subject to other requirements not listed here) are almost all equivalent to a NbCM so in a sense the GLAS scheme is already incentivising NbCM in Ireland. Table 1 gives a comparison between GLAS scheme activities and their equivalent NbCM; with the exception of low emission spreading, all have an equivalent measure.

Table 1: GLAS scheme measures compared to NWRM

GLAS Scheme Activity	Equivalent NWRM
Planting new hedgerows	Buffer strips and hedges
Arable margins	Buffer strips and hedges
Minimum Tillage	Low till agriculture
Catch Crops	Crop Rotation, Intercropping
Low Emission Slurry Spreading	-
Wild Bird Cover	Meadows and pastures

Targeted measures for maximum benefits

In order to identify NbCM measures which had the greatest multiple benefits with the least effort (scale & cost) the NWRM working group assessed each of the measures using potential matrices. This approach allowed a setting by setting examination of measures that have the greatest benefit with the least effort. The cumulative list of measures scored under the assessment criteria were then ranked allowing the highest potential measures to be identified: It became clear that many of these measures are similar in terms of their underlying principle or corresponding benefit and this list could therefore be condensed within grouped headings as follows:

- Removal of dams and other longitudinal barriers
- Buffer strips & riparian margins
- Wetlands
- Re-wetting organic soils/ Enhanced Peatland Rehabilitation
- Engineered basins, ponds & ditches
- Floodplain restoration
- River re-meandering

Innovative NbCM measures – engineered ditches

Engineered ditches (equivalent to peak flow control structures within the EU NWRM study) are designed to reduce flow velocities in networks of traditional agricultural or forestry drainage ditches. Whilst this measure is essentially a variation of ponds and basins as described above, additional information is provided here given the linear nature of their construction. The principle is to re-engineer existing ditch cross-sectional areas to incorporate flow control structures and, where practical, widen and flatten the ditch to further reduce flow velocities (Environment Agency, 2012). Flow control structures are designed to retard flow temporarily during storm events thereby contributing to sediment control and a reduction in the size of flood peaks – see Figure 4. Numerous variations of this principle have been trialled including: willow hurdles, sediment traps, sedge wetlands, willow wetlands, check dams, bunds with orifice outlets and wooden leaky barriers (Quinn et. al., 2007). Engineered ditches will have a limited lifespan before maintenance is required as sediment will eventually accumulate upstream of the flow barriers. Many of these methods have been trialled at the Nafferton Farm study led by researchers from Newcastle University and have shown this measure to be very effective at removal of sediment, nutrients and in dampening the peak discharge to watercourses (Quinn et. al., 2007). A similar study led by the University of Leeds was also undertaken at Allerton Farm and showed similar improvements can be achieved. Given the vast network of drainage ditches present across the country, this measure has the potential to provide enormous benefit if rolled out nationally in a targeted manner.

Figure 4: Engineered ditch as part of a study at Newcastle University

TARGETING MEASURES

The EPA has been developing tools which allow NbCM measures to be targeted to achieve the best benefits. Below the key tools for targeting NbCM measures in the 3rd Cycle RBMP and beyond are summarised.

MQI Ireland

An example of tool development includes the Morphological Quality Index for Irish rivers (MQI-Ireland tool) that was implemented nationally along ~60,000km of river channel. The tool was developed by a team led by the EPA, adapting international best-practice from the original Italian-derived method. Technical input and advice were provided by a Technical Working Group comprised of several Irish geomorphological experts. The tool provides an overview of the hydromorphological condition of rivers, at reach scale, i.e. 1-10km. MQI-Ireland is desk based, utilising remote sensing and GIS, and comprises of four components: reach segmentation (i.e. breaking the river network into homogenous sections); data capture of hydromorphological pressures; generating hydromorphological condition indicators and; calculating hydromorphological condition assessment scores based on these indicators. MQI-Ireland output aids screening as to whether there is full functionality of hydromorphological processes within a reach and whether there are significant hydromorphological pressures impacting this functionality. The latest output of the MQI-Ireland tool shows that approximately 42% of the total river channel length is of less than Good hydromorphological condition. The key hydromorphological pressures driving the MQI score for impacted reaches within 'At Risk' water bodies with hydromorphological modification identified as a significant pressure are:

- Historic channel modification
- Channel modification mainly relating to drainage schemes

PIP maps

High risk areas for phosphorus loss typically have poorly draining soils and dominant overland flow pathways. These characteristics are reflected in the nutrient attenuation factors for the hydrogeological flow pathways developed in the Pathways project (Archbold et al., 2016). Pollutant Impact Potential (PIP-P) maps for Phosphorus have been generated to help target local catchment stream walks to areas where the potential impact may be higher. The PIP-P map is made of three layers that are combined to visualise the movement of P losses across the landscape. Overland flow paths overlaid on the PIP-P critical source area maps together with focussed delivery points will indicate indicative locations for measures to break the pathway for P transport (based on research from the EPA DiffuseTools Project). Targeted measures in these areas in 'At Risk' water bodies in which phosphate or sediment is the significant issue and farming is the significant pressure will yield the best benefit for water quality together with associated multiple benefits.

Additional tools

EPA catchment Unit are currently developing national sediment risk maps which will provide another tool for targeting measures to tackle sediment as an impact of significant pressures again whilst also achieving associated multiple benefits. In addition, the EPA are also overseeing a national project which is developing a draft framework for implementing both river restoration and NbCM. This will allow targeting of such measures to suit the position with the catchment and the specific setting in which measures are to be implemented. It is anticipated that this project will be completed by the end of 2021. There are also other existing EPA tools available which can also be used to target NbCM measures in such a strategic manner. Rivers impacted by significant abstractions fall under the hydromorphology pressure category. Low flow and e-flow assessments based on the Qube model allow a cumulative assessment of abstractions and discharges and quantification of climate resilience to target measures required to achieve environmental objective. Assessments of hydromorphological condition of lakes and transitional and coastal (TRAC) water bodies are carried out using Lake MiMAS and TRAC- HQI respectively and these tools again allow quantification of pressures leading to focussed areas for measures.

CONCLUSION

Hydromorphological pressures present a significant challenge which must be addressed in order to meet our environmental objectives and restore our waters. In addressing this pressure, there is a need to shift our approach towards measures for multiple benefits at the catchment scale given that the environment is linked even if many of our interventions are not. The need for an integrated catchment approach – i.e. a conceptual understanding of how catchments work – is fundamental if we are to address the significant issues present in many of our waters. NbCM measures fit perfectly with the ICM approach and overlap with river restoration measures so it is important that we integrate both together to achieve the best outcomes.

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APPENDIX 1

River Restoration

- Basins and ponds
- Wetland restoration and management
- Floodplain restoration and management
- Re-meandering
- Stream bed re-naturalization
- Restoration and reconnection of seasonal streams
- Reconnection of oxbow lakes and similar features
- Riverbed material renaturalisation
- Removal of dams and other longitudinal barriers
- Natural bank stabilisation
- Elimination of riverbank protection
- Lake restoration
- Restoration of natural infiltration to groundwater

Forest

- Forest riparian buffers
- Maintenance of forest cover in headwater areas
- Afforestation of reservoir catchments
- Targeted planting for 'catching' precipitation
- Land use conversion
- Continuous cover forestry
- Water sensitive driving
- Appropriate design of roads and stream crossing
- Sediment capture ponds
- Coarse woody debris
- Urban forest parks
- Trees in urban areas
- Peak flow control structures
- Overland flow areas in peatland forests

Agriculture

- Meadows and Pasture
- Buffer strips and hedges
- Crop Rotation
- Strip cropping along contours
- Intercropping
- No till agriculture
- Low till agriculture
- Green Cover
- Early sowing
- Traditional terracing
- Controlled traffic farmig
- Reduced stocking density
- Mulching
- Re-wetting drained organic lands

Urban

- Green Roofs
- Rainwater Harvesting
- Permeable surfaces
- Swales
- Channels and rills
- Filter Strips
- Soakaways
- Infiltration Trenches
- Rain Gardens
- Detention Basins
- Retention Ponds
- Infiltration basins
- Detention Basins

Peat

- Drain blocking
- Artificial wetlands
- Wetland lakes
- Bunding
- Spagnum inoculation
- Land re-profiling
- Clearance of inappropriate vegetation on peatlands

Figure A1: NbCM measures grouped into various settings [Note: many measures cross between multiple settings and are not limited only to the areas shown here]

MARL LAKES ON KARSTIC LIMESTONE BEDROCK
A SPECIAL IRISH HABITAT

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ABSTRACT

The Irish Carboniferous limestone lowlands are characterised by an abundance of lakes of high alkalinity, often called marl lakes. These lakes have an unusual flora and vegetation of cyanobacterial crusts and charophyte algae with few flowering plants or angiosperms. Water clarity is great with plant growth down to 12 m depth. Total phosphorus concentrations are low, often less than 0.01 mg/l. A little reported feature of many lakes is a shallow water zone of cyanobacterial crust that extends to a depth of 2m. Lough Carra in Co. Mayo is regarded as the best example of an Irish marl lake. It has many unusual features including rare flora, fauna and vegetation. It is however under threat due to eutrophication. Symptoms include decreasing water clarity and a decline in charophyte and cyanobacterial crust vegetation. We show that habitat decline can be correlated both with increasing total phosphorus and increasing water colour. Current Irish Water Framework Directive standards are insufficiently rigorous to protect marl lakes. We conclude by postulating that biogenic erosion of limestone is caused by the cyanobacterial crust and suggest that eroded limestone is a marker of former marl lake ecosystems now destroyed by excess nutrients.

INTRODUCTION

The many lakes of the Central Irish Plain are more unusual than many Irish people realise. Firstly there are few other lowland areas in Atlantic Europe with such a variety of lakes. Secondly many of these lakes are a distinctive type called marl lakes which have water alkalinity greater than 100 mg/l. This reflects lake basins resting on Carboniferous limestone. The limestone itself was karstified in pre-glacial times but now is largely buried under glacial deposits. In places where the deposits are absent glacio karstic landscapes emerge, most famously in the Burren in Co. Clare. Of course, the limestone lakes are also places where glacial deposits do not cover the landscape and many midland lakes have unusual flowers reminiscent of the Burren, growing on their limestone shores. Conversely the Burren contains a suite of marl lakes very similar to others found from Meath to Mayo and south to Limerick. It is these lakes we discuss in this paper. The paper summarizes work we have done on marl lakes since 2011 (see the included references for a more detailed account of both ours and others work). Our work complements the surveys of the EPA and others, but is distinctive in that we used diving/snorkelling techniques to study the underwater vegetation of the lakes and we paid close attention to the lakes' cyanobacterial crusts and charophyte algae (advanced large algae with well-developed stems and whorls of branches, rarely identified to species level in many lake studies).

THE DISTINCTIVE FEATURES OF IRISH MARL LAKES

The most obvious feature of Marl lakes is their great water clarity. Very clear water in turn allows plants to grow to great depths (referred to as the euphotic depth) such as Lough Rea in Co. Galway and Coolorta Lough in Co. Clare where euphotic depths >10 m were measured. Previous estimates, largely based on grapnel samples, appear to underestimate the euphotic depth of marl lakes (*e.g.* Free *et al*., 2006). A thoughtful ecologist would quickly infer that such unusual water clarity is only possible if phytoplankton concentration is low, which consequently implies low nutrient concentrations. Data from the EPA and other sources (Roden et al. 2020a) confirms this inference; many marl lakes have total phosphorus (TP) concentrations of less than 0.01 mg/l.

The flora and fauna of Marl lakes are unusual, comprising mainly charophytes and extensive cyanobacterial crusts (not unlike stromatolites) with few flowering plants (angiosperms), unlike most other typical lowland European lakes. Many species ranging from charophytes (e.g. *Chara curta, Chara denudata, Chara rudis, Chara tomentosa*, which together comprise much of the lakes' vegetation), to crustaceans (e.g. White-clawed Crayfish *Austropotamobius pallipes*) and insects (e.g. *Ochthebiuis nilssoni*) are rare or absent from neighbouring countries. They are (or were) also the location of some of the country's finest Brown Trout *Salmo trutta* fisheries (e.g. Lough Mask and Lough Corrib) .

The typical vegetation of a marl lake in good ecological condition is dominated by cyanobacterial (blue green algal) crusts in shallow water giving way to extensive charophyte communities at depth. A typical depth zonation of plant communities occurring in many marl lakes is as follows:

- Cyanobacterial crusts with some small charophytes growing on rock and gravel *(see figure 3*). (0-2 m)
- Communities dominated by *Chara curta* (and occasionally with *Chara tomentosa*). These communities often extend into areas with sparse beds of *Phragmites* or *Schoenoplectus*, and other angiosperms may occur. (2-4 m)
- *Chara rudis* communities occur at mid-depth, both as monospecific beds or with a diverse array of angiosperms including *Hippuris vulgaris, Nuphar lutea, Myriophyllum verticillatum/spicatum,* large *Potamogeton* species or *Elodea canadensis*. (3-5 m)
- Below the *Chara rudis* community, *Chara virgata* can form extensive swards which extend to 8m below the surface.
- The deepest macrophyte vegetation units consist of either *Nitella flexilis, Chara denudata* or *Chara contraria (See figure 4*). These communities can extend to 12m depth.
- Mats of purple red cyanobacteria grow below this zone close to the base of the euphotic zone.
- In places, underwater springs rich in CO_2, support a little-known community of mosses.

The extent and probable ecological importance of the shallow-water crust in marl lakes is rarely referred to by ecologists. It is often confused with marl, an inorganic calcium carbonate rich deposit, but is in fact a living crust of cyanobacteria which binds precipitated calcium carbonate (*see figures 7-10*). Pentecost (2009) noted its existence in marl lakes in Ireland, and referred to Austrian and German researchers who found a comparable layer in alpine lakes. Modern researchers, e.g. Pentecost (2009) and Doddy et al. (2019a), have shown the crust is dominated by *Schizothrix* sp. Roden et al. (2020a) and Roden & Murphy (2013), using a snorkel survey, emphasised the extent and frequency of the cyanobacterial crust in Irish marl lakes. While it is mostly found on hard limestone rocks, it can, in some lakes, cover clay and gravel bottoms in shallow water as well as plant stems. It can reach thicknesses of 50 cm (e.g. Lough Muckanagh, Co. Clare) but in polluted areas is overgrown by mosses, green algae and even *Chara vulgaris* (Roden & Murphy, 2013, Doddy 2019a, b).

Even less understood is the ecology of underwater springs. Lough Bane in Co. Westmeath has a wonderful example at about 3m depth supporting an assemblage of mosses and uniquely, water cress (*Nasturtium sp.*). A serious study or exploration will require SCUBA and the involvement of hydrogeologists.

A constant but rarely emphasised feature of marl lakes is the relative scarcity of vascular plants. Praeger (1934) noted the near absence of flowering plants in marl lakes such as Lough Carra and

Lough Corrib, perhaps showing that the lakes were dominated by cyanobacterial crust in shallow water.

Plant distribution and zonation vary with varying euphotic depth. Thus, lakes with euphotic depths of less than 6m are characterised by the growth of *Chara rudis* and angiosperms to the base of the lake's euphotic depth. In contrast, when euphotic depth exceeds 7m, these species are replaced by *Chara virgata*, *Chara contraria* and *Chara denudata* at depth. In addition, angiosperms are uncommon or absent in lakes with euphotic depths >7m. Extreme examples of this phenomenon are the small doline lakes of the Burren such as Loughs Coolorta, Ballyeighter *(See figure 2)*, Gealáin, Travaun and Aughrim (Roden, 2001). Such lakes, dominated by charophytes and cyanobacterial crust, have few flowering plants and great water clarity.

The exceptional nature of the lakes is recognized in the E.U. Habitats Directive where marl lakes are included in the category *Hard oligo-mesotrophic lakes with Magnopotamion or Hydrocharition-type vegetation* (3140). Many Irish examples are designated as Special Areas of Conservation.

LOUGH CARRA, AN EXCEPTIONAL MARL LAKE

An excellent example of an Irish marl lake is Lough Carra in Co. Mayo. Its name in Irish is not simply Loch Carra but Fionn Loch Carra or *fair* or *white* Lough Carra, a reference to the reflection of light off the many hectares of calcium carbonate enriched cyanobacterial crust.

It is a large complex lake of 18 km^2, with eight separate deep holes of 15-20m depth separated by extensive shallows of 1-4m depth. It is divided into a southern basin running north-east to southwest linked by the narrow Castle Carra basin to a smaller northern arm running in the same direction. Several streams enter the northern and southern basins, but not the Castle Carra basin. A series of circular depressions at the south-west end of the northern basin appear to be dolines which may act as water sources or sinks.

The Castle Carra basin has great water clarity and excellent examples of cyanobacterial crust and charophyte vegetation; the other basins have cloudier water and fewer charophytes. Nevertheless the ecology and vegetation of the entire lake is of great interest and ecological importance.

The cyanobacterial crust is very extensive in Carra, covering huge areas of shallow water. It is remarkably thick in this lake with crust-depth sometimes exceeding 10cm (*see figures 7 and 8*). Beds of *Chara curta* are also very extensive, this species may be an Irish speciality as it is hardly known outside Ireland, so much so, that Irish and British botanists recently had to persuade their European colleagues that it actually is a distinct species. Its abundance in Ireland may reflect the absence of erosion by winter ice in our lakes. Equally common is *Chara rudis*, again much more abundant in Ireland than in western Europe. This is also the case for *C. tomentosa* and *C. denudata*,(which is all but unknown elsewhere in Europe). Such a list of aquatic rare flora justifies the assertion that Irish marl lakes are the aquatic counterpart of the well-known Burren.

We know less about the fauna of marl lakes but recently entomologists have discovered the aquatic beetle *Ochthebiuis nilssoni*, otherwise recorded only from Sweden and Italy, living in the cyanobacterial crust of Lough Carra as well as some Burren lakes. Lough Carra also has, or had, a very large population of brown trout- a fish in much of Europe associated with upland or alpine rivers (we often overlook how unusual it is to have such fisheries in the lowlands).

Unfortunately Lough Carra is also of scientific interest as it provides a good example of a lake in transition to eutrophy. In some basins, large vascular or flowering plants such as *Elodea canadensis, Myriophyllum verticillatum* and *Potamogeton* species form the lower-most vegetation unit rather than charophyte dominated communities. Equally plant colonization now only extends to 5 or 6 m in some basins. In addition *Myriophyllum verticillatum* forms dense stands which break the surface in water depths of 6m. Such beds are a new and increasing nuisance in the lake. Another development is equally striking; at three river mouths a distinctive vegetation has developed which is characterised by mineral sand replacing limey marl and an abundance of mosses, growing on the visibly decaying cyanobacterial crust. These developments are a recent event, to judge by earlier accounts of the lake.

Praeger (1906) gives us a first view of Lough Carra. He was struck by its clear "*pale pellucid green*" water. The lake was nearly devoid of plants, other than at depth, where he dredged *Chara rudis* from 20 feet (6-7m), suggesting the lower zones of *Chara virgata* and *Chara denudata* possibly extended to more than 12 m. Instead pale two inch deep crust was everywhere (to Praeger's disappointment as he hoped to find flowering plants). Stream mouths (now choked with reeds) only contained a few starved plants. While this description hardly applies to Lough Carra today, lakes in the south of the Burren still fit his description.

In 1977, Hester Heuff and Jim Ryan found a largely unchanged lake from Praeger's assessment in 1906, but a detailed survey by King and Champ in 1996 showed changes including huge banks of *Myriophyllum verticillatum* and the appearance of *Chara tomentosa*. Very significantly they noted that water transparency had declined by 40% in the previous 20 years. In the early years of the 21st century work led by Ken Irvine of Trinity College Dublin, showed a striking increase in lake sediment phosphorus, while Chris and Linda Huxley showed a great increase in the extent of reed beds since the 1970's. Our own work in 2011 described changes in the underwater vegetation of the lake (see Huxley and Huxley 2015, for a review of the lake's ecological changes). During this time the brown trout fishery declined dramatically (Thomas Byrne, pers. com.). Clearly Lough Carra (and many other Irish marl lakes) are in a state of ecological flux, but what is driving these changes?

DRIVERS OF ECOLOGICAL CHANGE IN MARL LAKES

Factors that influence lake ecology have been widely investigated (e.g. Free et al., 2006) and it is generally agreed that decreasing euphotic depth is driven by eutrophication due to increased total phosphorus (TP), leading to increased phytoplankton and decreased light penetration. When we examine Irish marl lakes we see good inverse correlations between TP and euphotic depth, and between TP and charophyte vegetation cover. Increasing TP leads to darker lakes with fewer charophytes and more vascular plants. A reasonable explanation of these results is that unmodified marl lakes are characterised by a specialized vegetation of charophytes and cyanobacterial crust with few angiosperms. As eutrophication reduces euphotic depth and increases nutrient availability, angiosperm cover increases, while charophyte cover decreases. The end point of this process includes lakes such as Summerhill Co. Monaghan/Fermanagh or Cullaunyheeda, Co. Clare with few if any charophytes and abundant generalist or nutrient tolerant vascular plants such as *Elodea canadensis*. Similarly, the experimental and observational work of Doddy et al. (2019a, 2019b) on the decline of the cyanobacterial crust with increasing concentrations of phosphorus and nitrogen shows a similar destruction of an unusual vegetation community.

Less often noted is the equally important relationship between water colour, euphotic depth and charophyte abundance. Our data suggest that lakes with euphotic depth greater than 6m have colour less than 20 Hazen units and the two variables are strongly correlated. Given that increased colour directly reduces light penetration, this finding is not surprising but it does emphasise the role of water colour independent of phosphorus enrichment. As large numbers of cut-over bogs in Ireland are near marl lakes, leaching of coloured water into marl lakes is an environmental problem.

As TP or colour independently affect marl lakes an index of environmental stress can be devised based on the product of these factors. This index yields correlations both with lake euphotic depth and charophyte vegetation cover (*see figures 5 and 6*). Charophyte cover shows a step change from above 55% to near 0% at an index value of about -0.5. This change reflects the complete collapse of charophyte vegetation when TP or colour exceed certain values and indicates a radical change in the lake ecosystem resulting in dark water and extinction of charophytes and cyanobacterial crust.

At present, the EPA regards .02 mg/l TP as the boundary for lakes in good condition under the Water Framework Directive. Our data however suggests that marl lakes are very sensitive to TP and a value of at most 0.01 mg/l is considered necessary for marl lakes to be classified as being in good condition.

DO CYANOBACTERIAL CRUSTS ETCH LIMESTONE?

Our appreciation of the unusual nature of marl lakes is still evolving. Our recent extensive snorkel surveys have suggested an unexpected aspect of marl lake ecology; the possibility that lake geomorphology is partly shaped by its vegetation. It is well established that cyanobacteria can erode limestone bedrock in many different habitats. Doddy and Roden (2018) have shown that rock pools in the Burren are eroded by their flora of unicellular cyanobacteria and many examples are known elsewhere (see Doddy and Roden, 2019, for references). In lakes such as Lough Carra or Muckanagh Lough, very thick (up to 20 cm) cyanobacterial crust covers all exposed bedrock from the surface to a depth of 2-4m, including what appear to be large boulders. *Figures 7-9* show however that these "boulders" are often either hollow or contain a small core stone surrounded by soft clay. As the cyanobacterial crust covers and protects most bare rock below the surface, it is difficult to ascribe this erosion to waves or currents. A more likely possibility is the build-up of carbon dioxide and hence carbonic acid through decay at the base of the cyanobacterial crust, which no longer grows by photosynthesis due to a lack of light.

Erosion beneath the cyanobacterial crust might also explain the very characteristic "egg box" weathering seen along the shores of many marl lakes, especially Lough Corrib and Lough Mask. *Figure 10* shows this weathering occurs up to 2 m below the lake surface. Removing the crust reveals very sharply edged pinnacles and ridges, suggesting recent erosion. While the most often observed examples of egg box weathering are now above lake level, it should be remembered that the level of Corrib and Mask was lowered in the mid-19th Century. What is now shoreline was formerly within the cyanobacterial zone of the lake and would have been covered by the crust. Certainly egg box weathering is not seen far from lake shores, nor indeed is it seen on the limestone shores of lakes such as Lough Leane in Killarney which are not alkaline enough to support the vegetation of marl lakes. At present the association of egg box weathering with growing cyanobacterial crust is a hypothesis, but if true it has important consequences. Wonderful examples of egg box weathered stone are incorporated in buildings at Portumna Castle on the shores of the now very eutrophic Lough Derg, and in a small Abbey on the shores of the damaged Urlaur Lough, Co. Roscommon. Could such stones be monuments to now vanished marl lake ecosystems and a challenge to future projects for habitat restoration?

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FIGURES

Figure 1. The characteristic scenery of Irish limestone lakes, lots of water, wide skies, flat countryside and distant hills.

Figure 2. A remote Burren lough at Ballyeighter, accessible only on foot or by canoe. In the foreground shallow water with cyanobacterial crust, blue water in the background lies over a deeper depression of about 15 m.

Figure 3. A single charophyte growing amongst stones covered with cyanobacterial crust. The charophyte is about 10 cm high.

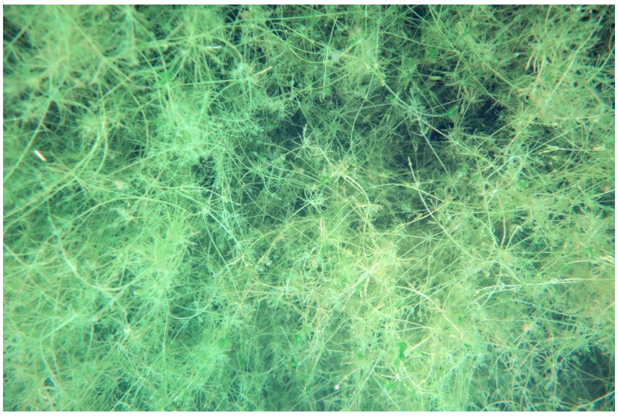

Figure 4. Charophyte “meadow” at about 9 m depth. Note the density of the charophyte plants covering the entire surface. The base of the photo is about 1 m across.

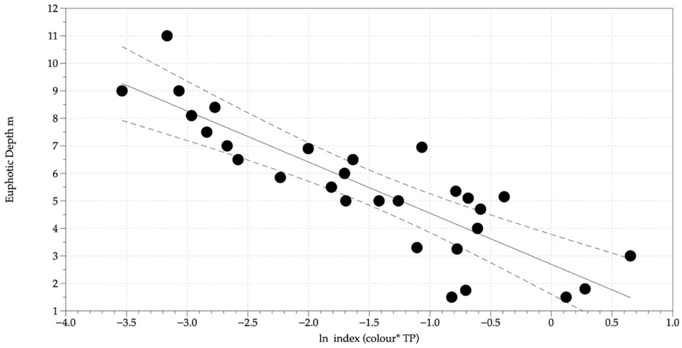

Figure 5 Euphotic depth plotted against the natural log of the environmental quality index (TP × Colour). High euphotic depth is associated with low TP and low colour.

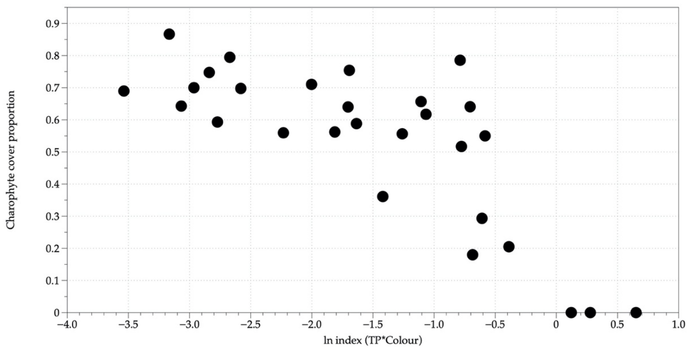

Figure 6.Charophyte cover, as a proportion of total vegetation cover, plotted against the natural log of the environmental quality index (TP × Colour).

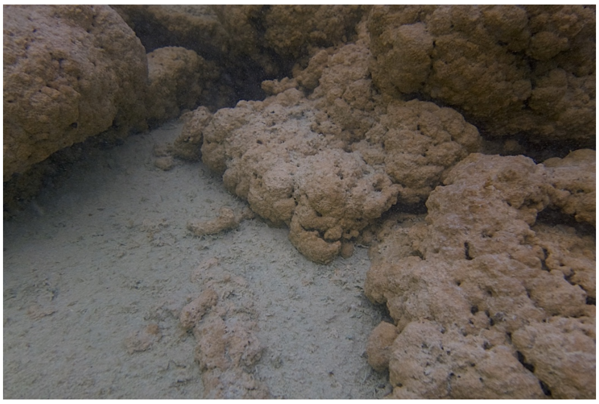

Figure 7. Cyanobacterial crust covering rocks at 1 m depth in Lough Carra.

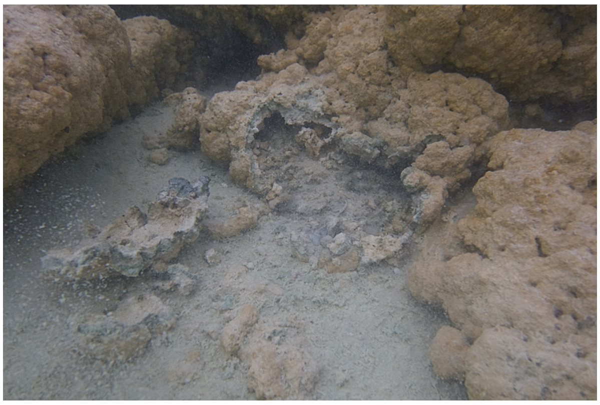

Figure 8. The same scene with crust removed to show hollow space below crust.

Figure 9. “Boulder” in Muckanagh Lough with hollow centre at a depth of 2 m. Note the green band in the crust, this is chlorophyll in the crust forming cyanobacteria.

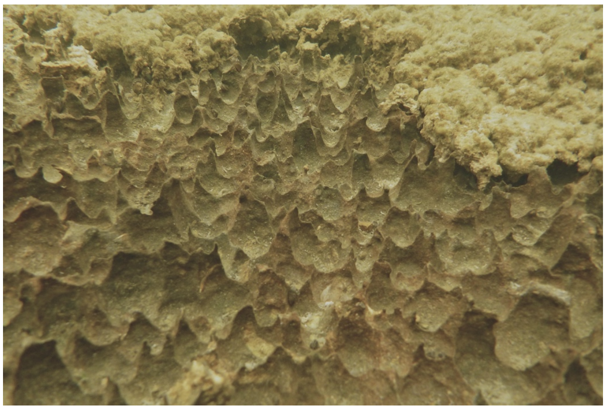

Figure 10. “Egg Box “ weathering on limestone bedrock in Lough Corrib at a depth of 2 m. Note the sharp pinnacles and ridges, rarely seen on egg box weathering exposed above the lake level.

SESSION II

THE SCIENTIFIC EVIDENCE-BASE UNDERPINNING THE 3RD CYCLE RIVER BASIN MANAGEMENT PLAN

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Environmental Protection Agency

ABSTRACT

Approximately half of Ireland's assessed water bodies do not achieve their water quality standards. As part of the 3rd Cycle river basin management planning process, assessments have been undertaken to determine the issues and associated pressures causing these water quality problems. Excess nutrients leading to eutrophication continue to be the biggest issues impacting on our water bodies, driven largely by agriculture. Management strategies need to be strategically targeted to improve and protect our water bodies and Pollution Impact Potential maps for nitrogen and phosphorus are available to help target "the right measure in the right place".

Key words: river basin management plan, water quality, significant pressures, agriculture, measures, nutrients, pollution impact potential maps.

INTRODUCTION

Approximately half of all Irish water bodies do not meet Water Framework Directive (WFD; European Parliament and Council, 2000) objectives and an overview of the results for each water body type for the monitoring period 2013-2015 is shown in Figure 1.

In terms of change since the last assessment period covering 2010-2015 there has been an overall 4.4% **net decline** in water bodies. This was nearly entirely driven by the decline in river water bodies.

High status surface water bodies continue to decline with a loss of 94 high status surface water bodies since 2009 while there was an increase of 115 poor status surface water bodies, across the same period.

Overall these findings indicate that water quality is getting worse after a period of relative stability and improvement (EPA, 2019).

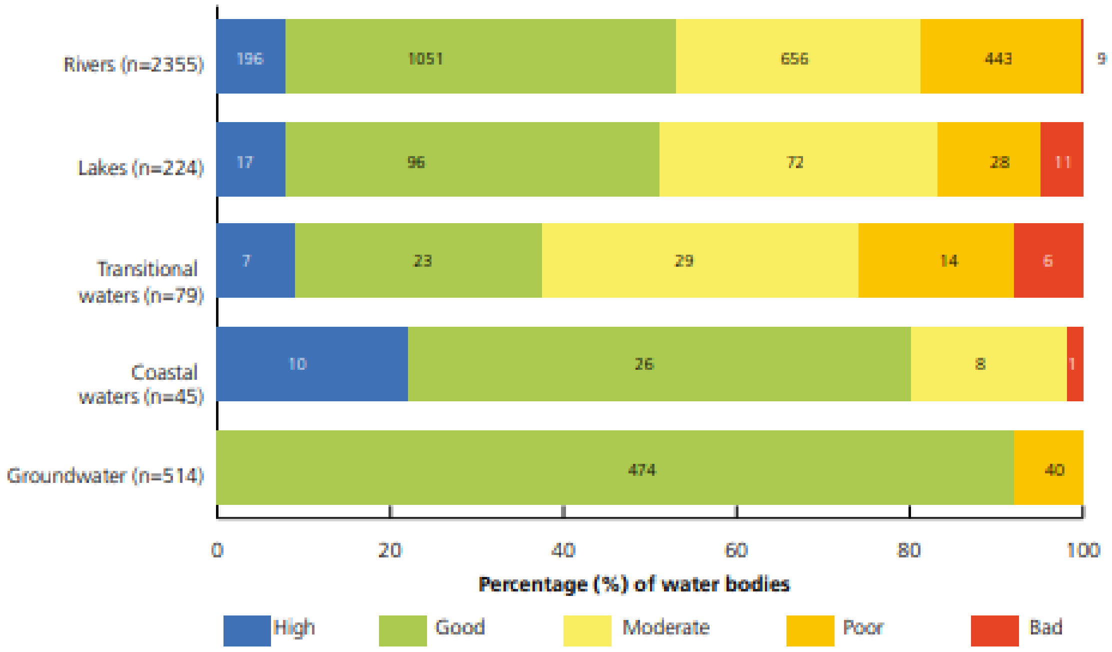


***Figure 1**. Ireland's water quality in 2018 as a percentage of monitored water bodies (EPA, 2019)*

WHAT'S CAUSING THE PROBLEM: CHARACTERISATION PROCESS

The key goal of the characterisation process is to identify water bodies which require action to meet the relevant objectives, and identify the significant issues and pressures impacting on those water bodies. The characterisation process provides important information to inform the development of a programme of measures, and to allow a realistic and achievable River Basin Management Plan (RBMP) to be developed and implemented.

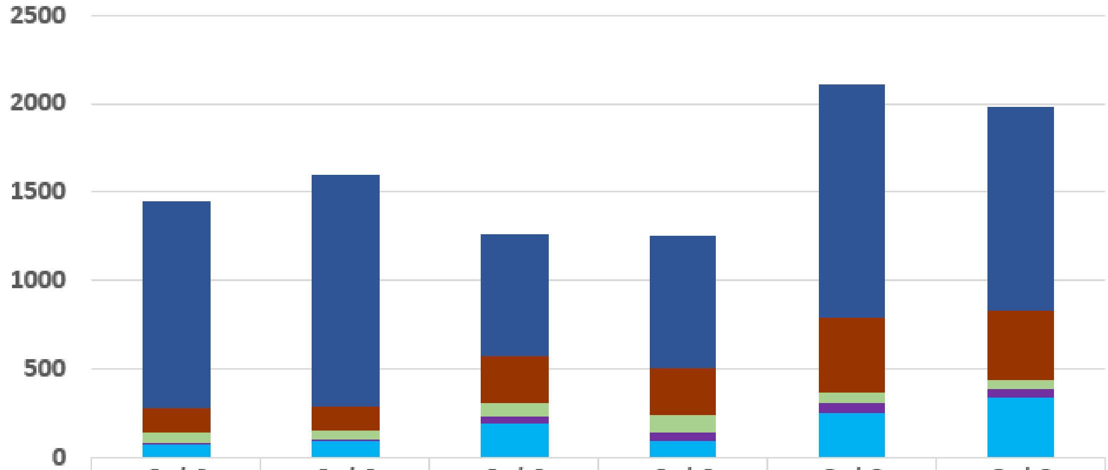
In preparation for the 3rd Cycle RBMP a risk assessment process was undertaken to identify water bodies that were *At Risk* of not achieving their WFD objectives. The risk was assessed on the basis of the monitoring data for the period 2013–2018, including data on status and water quality trends, and the scale of the challenges involved in meeting the environmental objectives of at least good status. Where the monitoring data indicated that there was a risk that the water body environmental objectives would not be achieved, an assessment was then carried out to identify the significant issues and pressures impacting on the water bodies. The outcome of these assessments will inform the setting of objectives for water bodies, and the measures that need to be taken to achieve those objectives in the 3rd Cycle.

WATERBODY RISK

The outcomes of the risk assessment across 4,826 water bodies show that:

- 1,977 (41%) are within the *Not at Risk* category; they are achieving the requirements of the Directive and meeting their environmental objective of good or high-status.
- 1,600 (33%) are *At Risk* of not meeting their environmental objective of good or high-status, and
- 1,249 (26%) are currently in *Review*, which means that the measure is in place but the water quality improvement has not yet been realised, or that there is some improvement but not

enough yet to put it at *Not at Risk*, or, more commonly, that there is currently inadequate monitoring data to determine whether or not the water body is *At Risk*.



	At Risk		Review		Not at Risk	
	Cycle2	Cycle3	Cycle2	Cycle3	Cycle2	Cycle3
River	1178	1309	694	740	1320	1143
Lake	132	139	264	271	422	402
Transitional	56	52	80	102	59	42
Coastal	13	12	34	45	64	55
Groundwater	73	88	193	91	247	335

Figure 2. *Comparison of number of At Risk, Review and Not At Risk water bodies between Cycle 2 and 3.*

A comparison of the 2nd and 3rd Cycle water body risk categories (Figure 2), show that there has been an increase of 148 water bodies considered *At Risk* and a nearly corresponding decrease in the number of water bodies considered *Not at Risk.*

SIGNIFICANT ISSUES AND PRESSURES

Having identified those water bodies *At Risk* of not meeting their environmental objectives, detailed assessments were undertaken to identify the significant issues impacting on our water bodies and the significant pressures preventing the water bodies from achieving the required environmental objectives. Significant pressures are those that either cause or are likely to cause an unsatisfactory water body status and measures therefore need to be taken in order to mitigate the impact(s) of these pressures. These assessments are based on over 140 national datasets comprising information on pressures, impacts and physical settings and consider the linkages and dependencies between the sources of environmental pressures, and the pathways linking those pressures to the receptors, such as rivers, lakes or groundwater. Evidence and expertise from a range of public bodies including the Local Authority Waters Programme, local authorities, Inland Fisheries Ireland (IFI), Forest Service, National Federation of Group Water Schemes, and Irish Water also informed the process.

Significant Issues

Assessment results show that elevated nutrient concentrations (phosphorus and nitrogen) continue to be the most widespread water-quality problem in Ireland (Figure 3) and monitoring results indicates that trends are increasing upwards. In the freshwater environment, elevated concentrations of phosphorus are the primary reason for ecological impact in our rivers and lakes. Nitrogen is a more significant factor in our transitional and coastal waters (EPA, 2019). Physical alterations to habitat (morphological alterations) are also a significant issue especially in our river water bodies along with organic pollution, such as ammonia and biological oxygen demand.

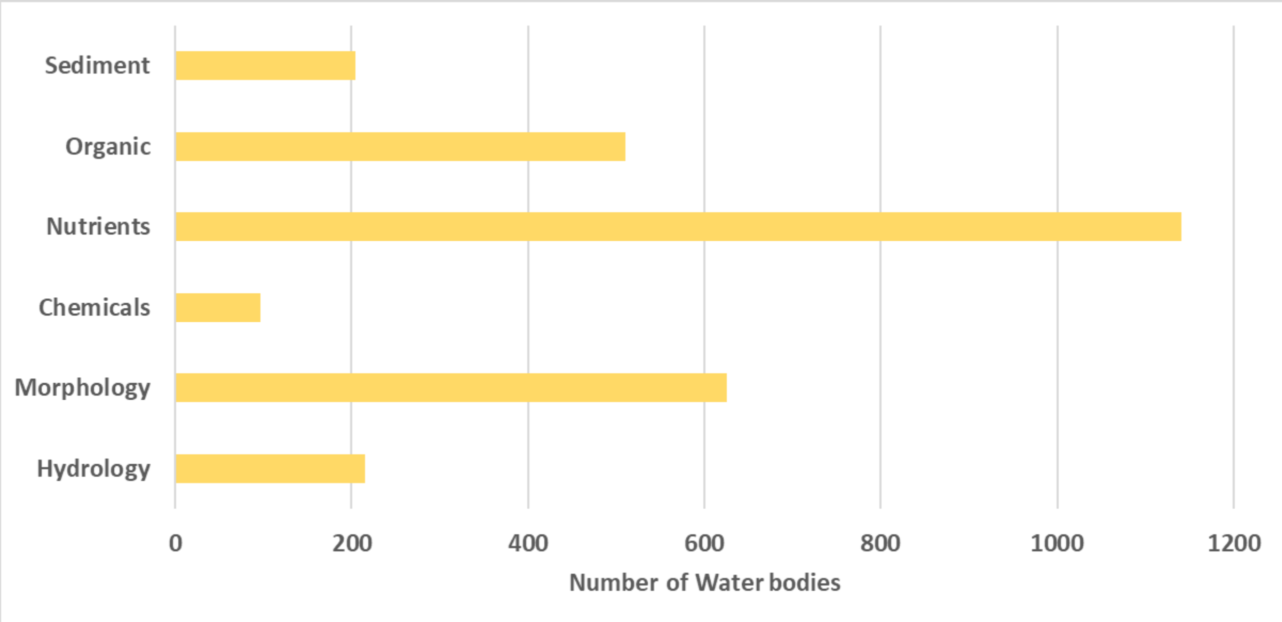


Figure 3. *Cycle 3 Key Significant Issues impacting At Risk Surface Water Bodies.*

Significant Pressures

For the 3rd Cycle, of the 1,600 water bodies that are *At Risk*, 46% are impacted by a single significant pressure, while the remaining 54% are impacted by more than one significant pressure. The breakdown of the significant pressure types and a comparison between the 2nd and 3rd Cycle is shown in Figure 4 and summarised as follows:

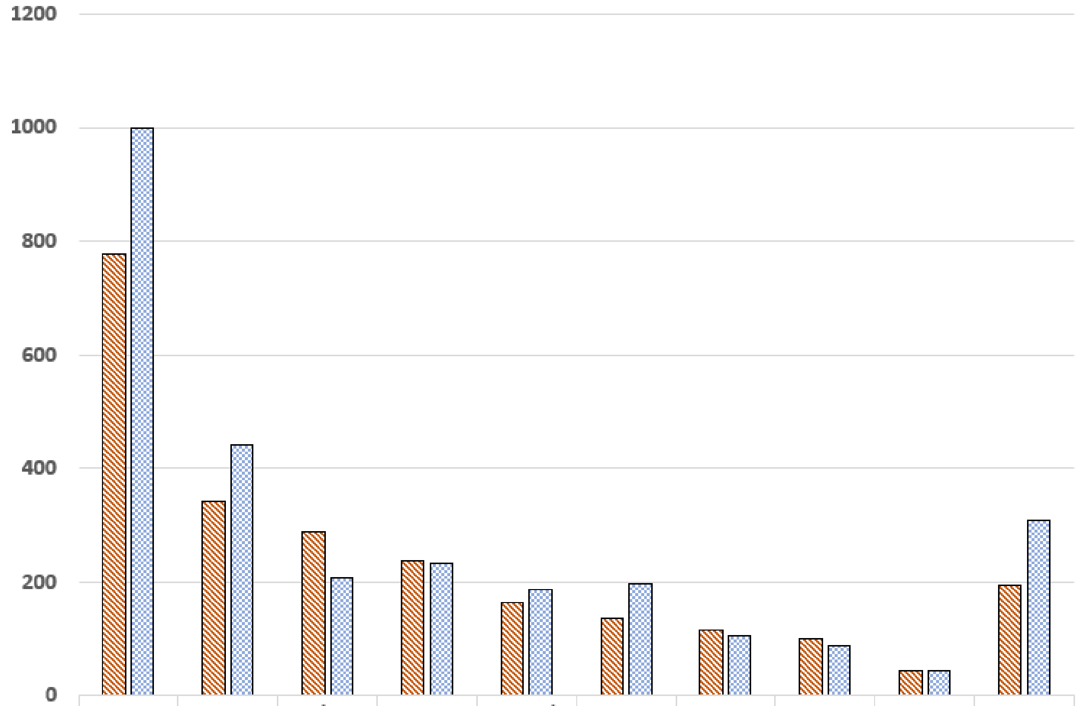
- Agriculture is the highest significant pressure impacting 1000 water bodies, followed by hydromorphology, forestry and urban waste water, which are impacting 442, 233 and 206 water bodies, respectively.

- The number of water bodies impacted by agriculture has increased by 223 water bodies since the 2nd Cycle and this represents the greatest increase in any one significant pressure type.

- The number of water bodies impacted by hydromorphology, urban run-off and domestic waste water treatment systems (DWWTS) has increased by 100, 60, 23 water bodies, respectively since the 2nd Cycle.

- The number of water bodies impacted by urban waste water has decreased by 83 water bodies since the 2nd Cycle and this represents the greatest decrease in any one significant pressure type.

- The number of water bodies impacted by peat, industry and forestry has decreased by 10, 10 and 5 water bodies, respectively since the 2nd Cycle.



	Agriculture	Hydromorphology	Urban Waste Water	Forestry	Domestic Waste Water	Urban Run-off	Peat	Industry	Mines and Quarries	Other
Cycle2	777	342	289	238	165	136	116	99	45	194
Cycle3	1000	442	206	233	188	196	106	88	45	310

Figure 4. *No of water bodies impacted by significant pressures for the 2nd and 3rd Cycle*

HOW CAN AGRICULTURAL MEASURES BE BEST TARGETED?

There has been a 25% increase in water bodies where agriculture is a significant pressure since the 2nd Cycle. By understanding the significant issues impacting the water body we can target "the right measures in the right place".

For example, for nitrogen, the predominance of free draining soils in the south and southeast make these areas particularly susceptible to nitrogen losses from agriculture. Over 90% of the nitrogen loads in these catchments come from agriculture and there is a strong relationship between farming intensity and nitrate concentrations in waters at the catchment scale. There is however, water quality variability within and between sub-catchments. Detailed research work in the Agricultural Catchments Programme has highlighted that soils, weather and farming practices also have a significant influence on nitrate concentrations, at the local scale. This has important implications for targeting "the right measure in the right place". Figure 5 shows the locations where nitrate measures are needed. Measures to stabilise and reduce nitrogen losses and adoption of alternative farming practices that require less nitrogen need to be considered.

The main sources of phosphorus are agriculture and urban waste water. The majority of urban waste water (volumetrically) is discharged in coastal areas, with agriculture the most significant source inland. Figure 5 shows the locations where phosphorus and sediment measures are needed from the agricultural sector. The most susceptible areas for phosphorus losses are poorly draining soils, from which the runoff discharges to watercourses. While many of the catchments in the east and northeast have elevated phosphorus concentrations there are typically areas of poorly draining soils in most catchments. Research has shown that most of the phosphorus loss in catchments typically comes from a relatively small area (the critical source areas), within a relatively short time, during significant rainfall events. It only takes a very small amount (<200g/ha) of phosphorus loss to cause a water quality problem. Pathway interception measures are likely to be most effective to prevent surface runoff reaching watercourses. These types of measures can include buffer zones, engineered ditches, native woodlands, and other nature-based solutions. The best outcomes will be achieved when measures are targeted into the critical source areas (EPA, 2021).

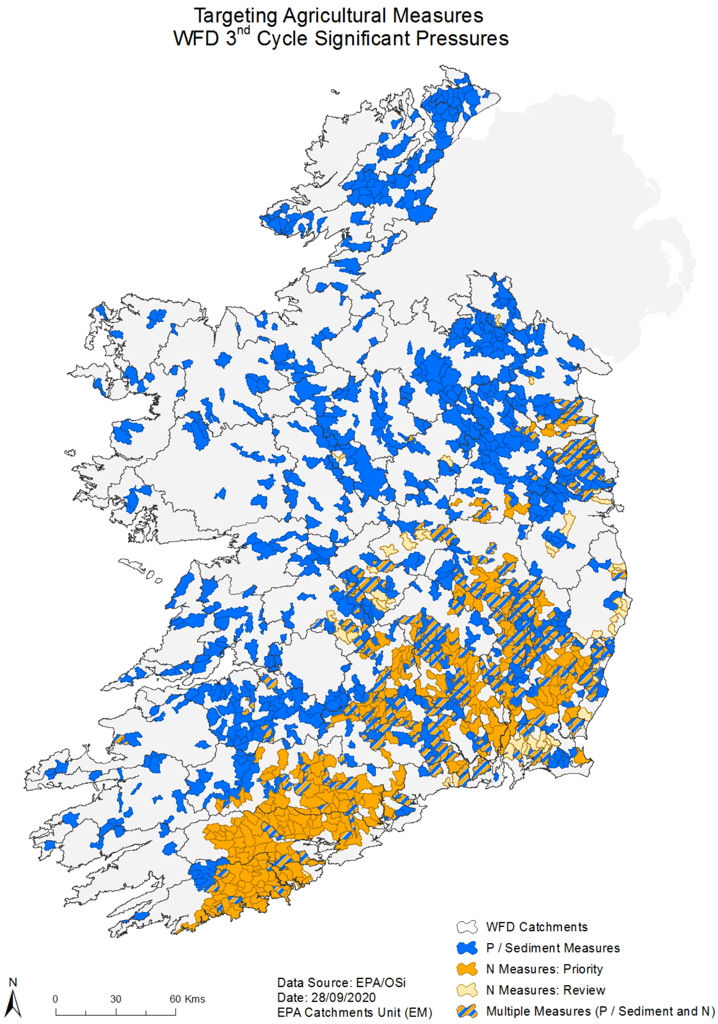


Figure 5. *Water bodies requiring agricultural nutrient and sediment measures for the 3rd Cycle*

CRITICAL SOURCE AREAS AND POLLUTION IMPACT POTENTIAL MAPS

National agricultural nitrogen and phosphorus critical source area (CSA) maps called Pollution Impact Potential maps are available currently to public bodies and are used to help target measures. These maps have recently been updated with DAFM agricultural management data up to 2018 and these updated maps will be publicly available by May 2021.

The new versions of the Pollution Impact Potential maps for phosphorus (PIP-P) maps now include flow delivery paths and delivery points overlaying the CSAs to better reflect the transport of phosphorus in the landscape (Figure 6). The flow delivery paths and points are based on research from the EPA DiffuseTools Project. The components of the maps are as follows:

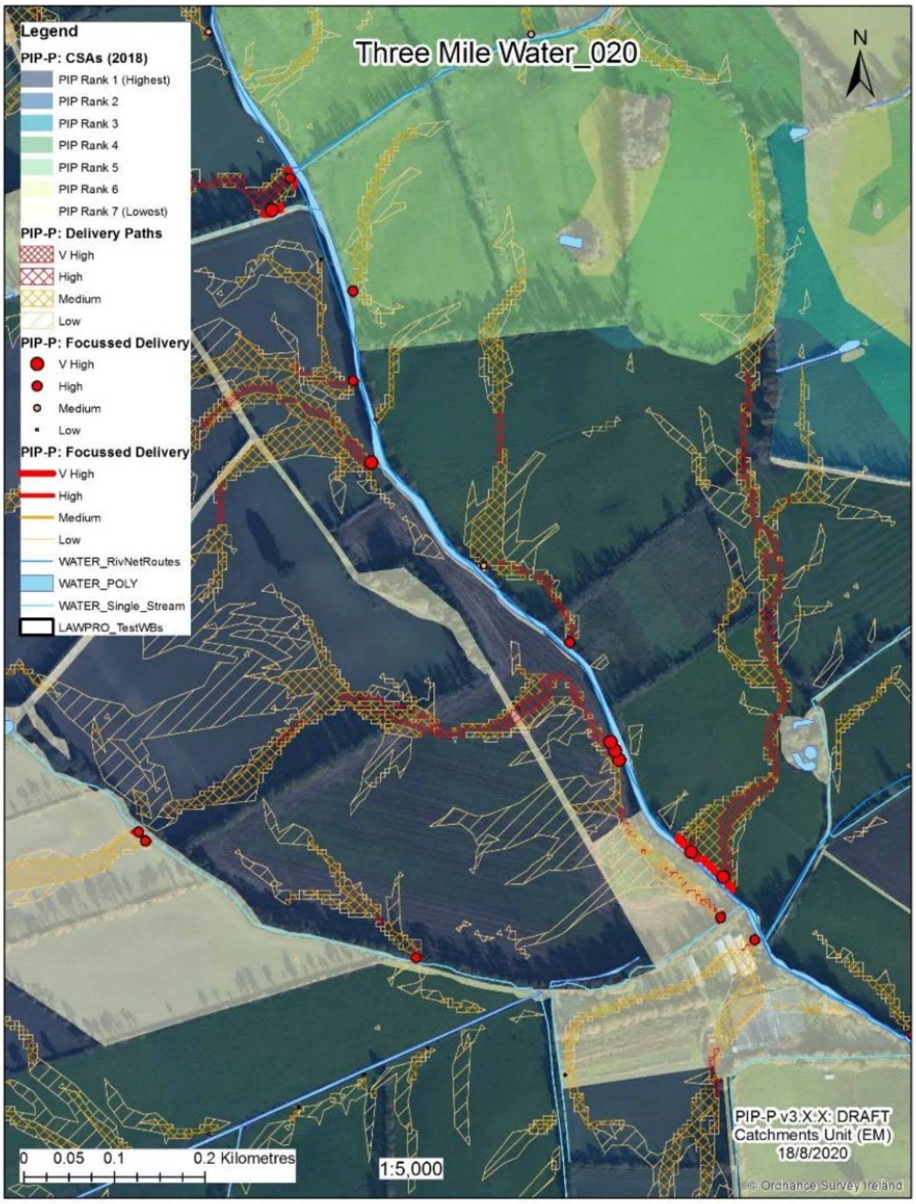


***Figure 6**. Updated Pollution Impact Potential Maps for Phosphorus (PIP-P V3)*

Layer 1 - PIP-P: CSA Map

The blue areas (High PIP Rank 1-3) are the phosphorus critical sources areas (Figure 6). These high risk areas for phosphorus to surface water have moderate/high livestock intensity that coincide with poorly drained areas, meaning that in these areas phosphate is more likely to flow overland to surface waters rather than being retained in the soil and subsoil. For locating the "the right measures in the right place" these High PIP areas should be targeted in *At Risk* water bodies where phosphorus is the significant issue and agriculture is the significant pressure.

Layer 2 - PIP: Focussed Delivery Flow Paths

This layer is a new addition to the PIP-P maps. Focussed Delivery Flow Paths are the areas of converging runoff that results in an increasing accumulation of flow. It is important to consider the available source of phosphorus in these contributing areas when deciding whether to target measures (check the underlying PIP-CSA rank). The red flow paths have the highest surface runoff (Figure 6). Where these cross High PIP areas, expect higher P losses. The map can highlight areas to target phosphorus pathway interception actions e.g. hedgerows.

Layer 3 - Focussed Delivery Flow Points

This layer is also a new addition to the PIP-P maps. Focussed Flow Delivery Points are where Focussed Flow Paths enter a watercourse. The size of the point indicates the relative volume of flow delivered to water. It is important to consider the available source of phosphorus in the upslope contributing areas. The map can highlight areas to target phosphorus pathway interception actions e.g. riparian/buffer zones, woodlands, engineered ditches.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of colleagues in the EPA including members of the Catchments Unit and the broader Water Programme. Furthermore the authors would like to thank all public body organisations, including the Local Authority Waters Programme and local authorities, who contributed significantly by providing data and information for the 3rd Cycle characterisation assessment.

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THE AGRICULTURAL CATCHMENTS PROGRAMME: A DECADE OF AGRO-ENVIRONMENTAL STUDIES

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ABSTRACT

For a sustainable environment and food production, we need efficient ways to manage nutrients and mitigate the losses to water. A clearer understanding of the relative influence of soils, geology, farm practice, landscape and weather, on the propensity for nutrients to be lost to water, is needed to reshape the thinking on future nutrient management. Within the Agricultural Catchments Programme (ACP) comprehensive agro-environmental monitoring and studies of six meso-scale catchments have taken place since 2008. The ACP have contributed to a better understanding of nutrient mobilisation and transfer pathways and highlighted the influence of the physical and chemical environment as well as agricultural and meteorological drivers on diffuse nutrient loss to ground and surface waters. The Environmental Quality Standards were breached for nitrogen and or phosphorus in some of the catchments, but for different reasons and not always clearly linked to the source pressures within the catchment. There are clearly no one-size-fits all solutions for mitigation of nutrient losses to water. A better understanding of the underlying processes is required to identify critical source areas and times, to identify mitigation strategies and build realistic expectations on measures.

Key words: *Agriculture, Soil, Geology, Weather, Nutrients, Water quality.*

INTRODUCTION

To meet the challenge of reducing nutrient loss to waters we need a comprehensive understanding of how agronomic and climate drivers influence nutrient loss, and what the impacts for catchments with different physical settings are. The European Union (EU) Member States are required to monitor the effectiveness of their Nitrates Regulations, of the EU Nitrates Directive (ND). In Ireland the Agricultural Catchments Programme (ACP) was established in 2008 to: i) monitor the effectiveness of the Good Agricultural Practice (GAP) measures, initially for compliance with the ND and since 2014 additionally with the Water Framework Directives (WFD), ii) provide a scientific basis for policy review, and iii) monitor derogation in Ireland. Researchers, advisors, technicians and technologists in the ACP work together on bio-physical and socio-economic research, as well as knowledge transfer in collaboration with over 300 farmers in six river catchments (3 – 31 km^2) in Ireland. By using the "nutrient transfer continuum" (Haygarth *et al*., 2005) as a conceptual framework, an extensive monitoring programme of nitrogen (N) and phosphorus (P) sources and hydro-chemo-metrics have been designed similarly across six catchments (Figure 1). High-resolution monitoring helps understanding how nutrients are lost from agricultural sources, how they can be mobilised and transferred via different hydrological pathways, how they are delivered to water and where there may be a negative impact on water quality and aquatic ecology.

The objective of this paper is to briefly provide an overview of the current conceptual understanding of the key biophysical findings within the ACP.

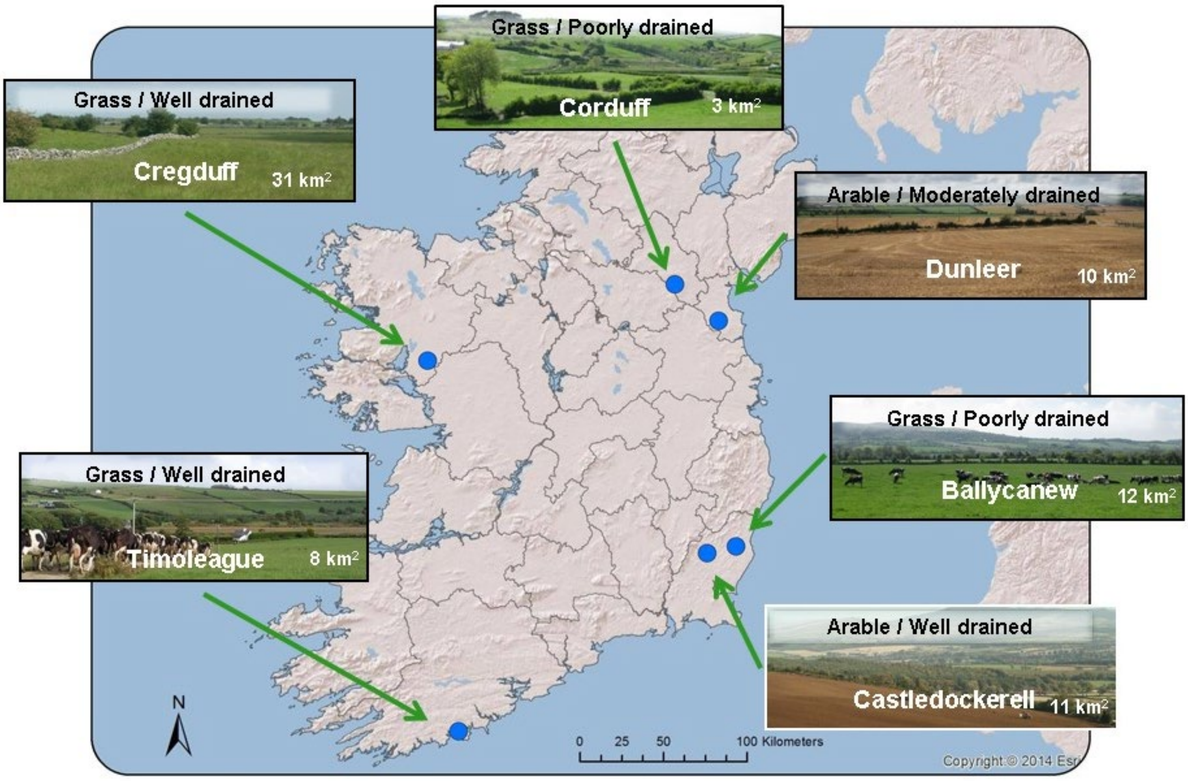

Figure 1: *The six catchments monitored within the Agricultural Catchments Programme since 2009.*

EXPERIMENTAL DESIGN

The ACP monitor and research six meso-scale catchments (3 – 31 km^2). These were selected by a multi-criteria analysis (Fealy *et al.*, 2010) to represent intensively managed agricultural land in different bio-geophysical settings and dominating land use, and thus different types of risk for N and P loss in terms of vertical drainage or lateral runoff risk. The catchment scale was chosen to include monitoring of both surface and groundwater, as well as farming activity and surveys of soil, bedrock and topography. The bio-physical data collection started in 2009 or 2010 and includes:

- **Surface water** in the catchment river outlets: river discharge (Q), Electrical Conductivity (EC), Temperature, Turbidity (Turb) and nitrate-N, Total Reactive P (TRP), Total P (TP) and Total Organic Carbon (TOC) concentrations (every 10-minutes)
- **Surface water** in multiple sites along the river networks: NO_3-N, TP, TDP, TRP, DRP, DOC, EC, pH, Dissolved Oxygen (DO), Oxidation-Reduction Potential (ORP), Turb and metals (monthly)
- **Groundwater** in focused study sites: piezometric water level (every 30 minutes), and NO_3-N, TP, TDP, DRP, DOC, EC, pH, DO, ORP, Turb and metals sampled in multilevel monitoring wells (monthly)
- **Weather** in catchment centre lowland: air Temp, soil Temp, Relative Humidity, Rain depth, Solar Radiation, Wind Speed/direction for estimation of Potential Evapotranspiration (PET) (every 10-minutes) and additionally rain depth at higher ground (every 10-minutes)
- **Aquatic ecology** in multiple sites along the river networks: diatoms and macro invertebrates assessed (every May and September)
- **Soil** analysis at the field scale (every 4 years, maximum sampling unit 2 ha): pH, liming requirement (LR), P, K, and Mg content.

Additionally each catchment has been surveyed for soil type, topography (LiDAR <1m) along with geophysical surveys (EM3/EM37, 2-D resistivity, seismic refraction and GPR on representative fields).

RESULTS AND DISCUSSION

WATER QUALITY CONTROLS

The on-going research within ACP have confirmed that the six headwater catchments (1st and 2nd order) were large enough to encompass the range of hydrological conditions to the main river channels, allowing for normal N and P transformation and mobilisation processes to occur. Despite hydrological and biochemical time lags present within the catchments they were small enough to detect changes caused by agronomy and weather.

Ten-years of sub-hourly monitoring of N and P concentration in the catchment outlets have facilitated analytical methods to identify and quantify nutrient transfer pathways (Mellander *et al.*, 2012a) and provided insights to underlying processes of nutrient loss for the different settings. The high frequency monitoring of river flow and nutrient concentrations allows the full dynamics of nutrient loss to the river over the year to be captured, without being skewed to representative sampling events or periods and provide insights to water quality during both low-flow and high-flow conditions (Jordan and Cassidy, 2011). The approach can also detect subtle changes in nutrient concentrations and mass loads which is needed to reveal influences of large–scale weather systems on loss of terrestrial nutrients to rivers (Mellander *et al*., 2018). The data revealed that both the magnitudes and dynamics of nutrient loss to rivers varied largely across the catchments (Figure 2).

The hydrological flow paths that transfer nutrients are controlled by the physical settings, mainly soil/bedrock permeability and topography, which affects storage and transfer time. Along the pathways there are associated chemical and biological transformation process that influence the timing and location of delivery. The chemical controls are those which affect sorption, speciation and transformations, and the biological controls are those which affect the fixation and uptake of nutrients. Consequently there was not always a clear link between a catchments nutrient source pressure and the nutrient concentration in the shallow groundwater or in the river outlets. The nutrient loss was also reflected by the heterogeneity in soil type, land-use and the meteorological factors which were evident in the ACP meso-scale catchments (Table 1, Figure 2) but not as clear when monitoring larger river basins.

Table 1: *Dominating catchments characteristics, annual average organic N source (2010-2018), organic P source (2008-2014) and annual average hydrochemistry (2010-2019).*

Catchment				**Annual input**			**Annual output**		
Name	**Land use**	**Soil drain-age**	**Size**	**Rain**	**Org P**	**Org N**	**Q**	**TRP**	**NO_3-N**
			[km^2]	**[mm]**	**[kg/ ha]**	**[kg/ ha]**	**[mm]**	**[mg/l]**	**[mg/l]**
Corduff	Grass	Poor	3	1051	12	87	575	0.031	1.37
Dunleer	Arable	Mod	10	869	9	67	419	0.119	5.35
Ballycanew	Grass	Poor	12	1037	11	101	506	0.078	2.62
Castle-dockerell	Arable	Well	11	1015	4	41	528	0.028	7.06
Timoleague	Grass	Well	8	1100	23	166	679	0.065	6.07
Cregduff	Grass	Well	31	1153	10	90	--	0.017	1.33

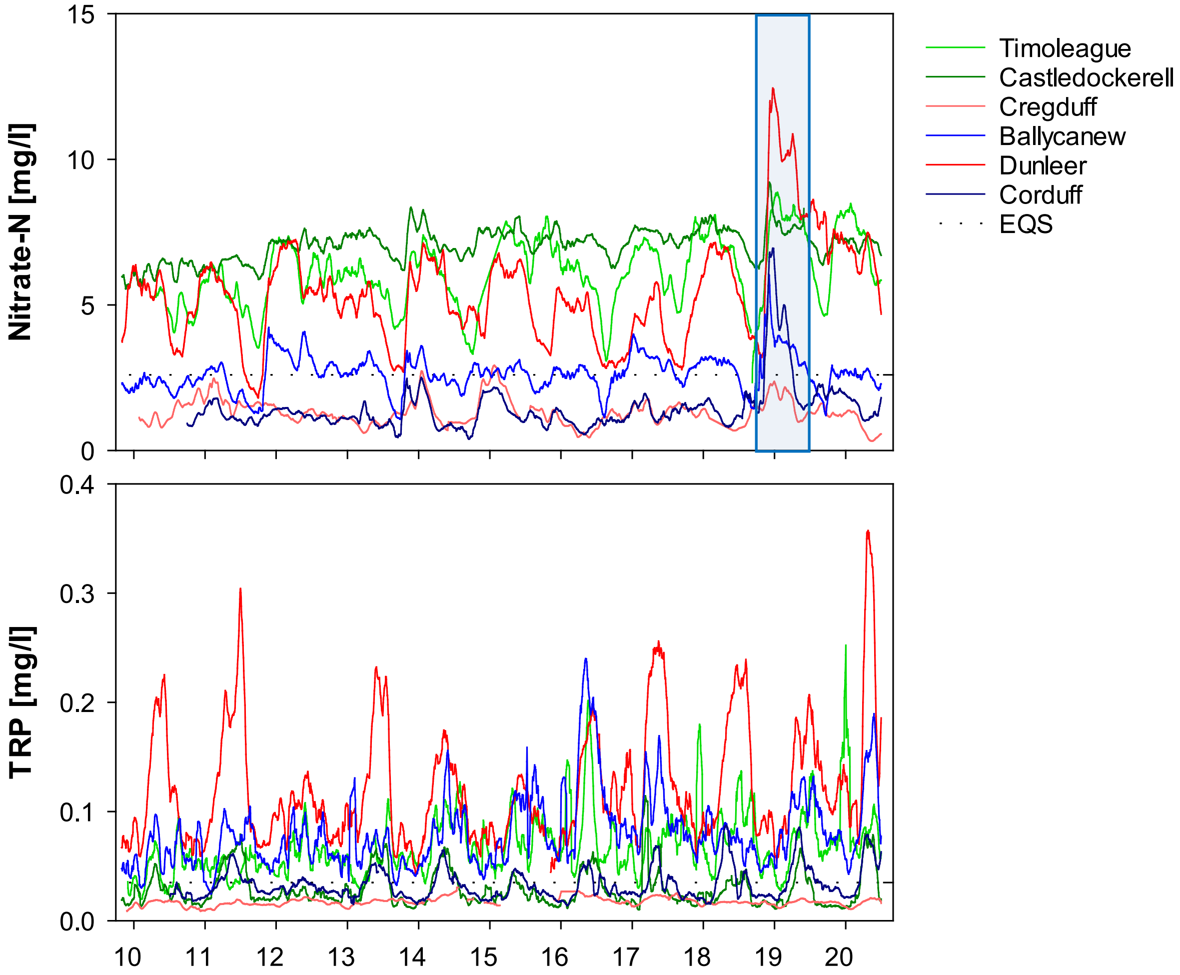

Figure 2: *Ten years (2010-2019) of monthly antecedent moving average Total Reactive P and nitrate-N concentration at a daily time step in the catchments river outlets. EQS = Environmental Quality Standard 2.60 mg/l for nitrate-N and 0.035 mg/l for TRP. Elevated nitrate-N concentrations following a nationwide drought are highlighted in blue in the top panel.*

While the *Dunleer catchment* had the highest P concentrations in the river outlet, due to high sources in the soils and a need to improve the spatial distribution of nutrients (McDonald *et al.*, 2019), there were other catchments where the physical or chemical setting appeared to override the source pressure (Mellander *et al.*, 2015; Shore *et al.*, 2014). For example, the *Castledockerell catchment* had the highest NO_3-N concentration in the stream water but the lowest N-loading source. Also the N removal capacity in groundwater varied highly between and within *Timoleague* and *Castledockerell catchments* (McAleer *et al.*, 2017). Another example is the *Ballycanew catchment*, with poorly drained soils, which had three times higher total P loss for the same river flow than the well-drained and mostly groundwater-fed *Castledockerell catchment*, despite similar source pressure (Mellander *et al.*, 2015).

The influence of chemical controls for mobilisation processes were also identified. These can drive both N and P exports in groundwater-fed catchments (Dupas *et al*., 2017). For example, in both of the two mostly groundwater-fed *Timoleague* and *Castledockerell catchments* half of the total reactive P loss was lost in the river outlet via below ground pathways. However, in the *Timoleague catchment* the soils were iron-rich which favoured P into a soluble form and P was leached resulting in elevated P concentrations in shallow groundwater. In that catchment the total P loss was three times higher than in the *Castledockerell catchment* with Al-rich soils (Mellander *et al.*, 2016). In the *Cregduff catchment*, a karst spring-zone catchment with calcium rich soils, P was instead largely retained and

despite thin soils and numerous karst features the P loss was low and reactive P concentrations remained below the Environmental Quality Standard (EQS) (Mellander *et al*., 2012b; 2013).
Due to the heterogeneity in the controls, there are apparently no one-size-fits-all solutions for the mitigation strategy. Based on the dominating controls (agronomical, chemical and physical), catchments were suggested to be classified into "Source risky", "Mobilisation risky" or "Transfer risky" catchments in order to interpret the response to changing climate (Mellander *et al*., 2018) (Figure 3).

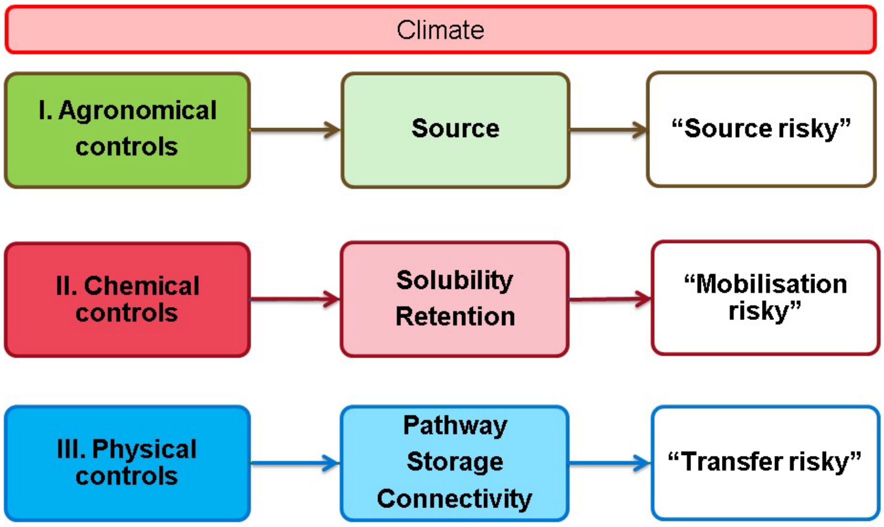

Figure 3: *Simplified catchment climate-chemical indicators. The relationship between different mechanisms for nutrient transfer and the types of risks each mechanism poses, using the nutrient transfer continuum as a conceptual framework. Climate is an over-arching factor which impact all parts of the nutrient transfer continuum.*

TRENDS
During the period 2010-2019 increasing P concentrations trends were found in the *Ballycanew* and *Timoleague catchments* and increasing N concentrations trends in the *Corduff*, *Castledockerell* and *Timoleague catchments (Table 2)*. Trends in stream water quality may however be hidden by counteracting responses for specific months and in different pathways. On-going work is using high frequency water quality data to assess nutrient concentration trends in apportioned transfer pathways (Mellander *et al*., in prep). In the groundwater there was an increasing N concentration in *Castledockerell catchment* but not in *Timoleague catchment* for the period 2010-2017 (McAleer *et al*., in prep). While both agronomical and meteorological factors were identified it was not possible to separate these.

Table 2: *Mann-Kendall trend analysis of the annual total river discharge and the annual average N and P concentrations in the river outlets for the period 2010-2019. "No trend" = Confidence Factor (CF) <90%, "Stable" = CF<90% and Coefficient of Variance<1, "Probably increasing" = 95%≥CF≥90%, and "Increasing" = CF>95%*

CATCHMENT	RIVER DISCHARGE	TRP CONC.	NO_3-N CONC.
CORDUFF	STABLE	NO TREND	INCREASING
DUNLEER	STABLE	NO TREND	NO TREND
BALLYCANEW	NO TREND	INCREASING	PROBABLY INCREASING
CASTLEDOCKERELL	NO TREND	STABLE	INCREASING
TIMOLEAGUE	INCREASING	INCREASING	INCREASING
CREGDUFF	--	NO TREND	STABLE

The influence of weather was clearly seen in 2018 when a nationwide summer drought caused a build-up of a large soil N pool due to poor grass growth and enhanced soil N mineralisation. That pool of N was flushed out and transferred to the stream in the heavy rain events in November, causing elevated NO3-N concentrations in all six catchments (Figure 2 top panel). The long-term shifts in weather patterns and the increased frequency of weather extremes, as expressed by the North Atlantic Oscillation index, was found to influence both N and P concentration in the ACP catchments and in similar sized agricultural catchments in Norway and Brittany (Mellander et al., 2018). The response was different for catchments with different physical and chemical settings and requires consideration and different mitigation strategies.

CONCLUSION

The ACP has provided research for an improved process-based understanding of nutrient loss to water in heterogeneous agricultural landscapes, under changing weather patterns and intensified agriculture. The research provides on-going support for environmental schemes and nutrient management planning. Ireland's landscape is heterogeneous in terms of factors controlling N and P transfer pathways, transformation processes and timing of delivery. In some cases, such factors can override the nutrient source pressures. Weather changes may further override temporal trends of agronomic pressures. Site specific information is required to implement appropriate measures to mitigate nutrient loss to water and both long-term weather shifts and short-term offsets need consideration.

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LOCAL CATCHMENT ASSESSMENT: FROM DESKSTUDY TO REFERRAL

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ABSTRACT

The Local Authority Waters Programme (LAWPRO) catchments team was established in 2018 as part of the 2nd cycle River Basin Management Plan. Incorporating the ethos of Integrated Catchment Management (ICM), the aim of LAWPRO is to restore at least 'Good ecological status' in our most At Risk rivers, lakes, estuaries and coastal waters. The ecological status at a monitoring point is predicated upon hydrological, hydro-chemical and anthropogenic processes occurring at local, sub-catchment and catchment scales. It is the role of LAWPRO to disentangle the complex interaction of pathway and pressure within a catchment/community and put forward the right measure in the right place to improve water quality. The aim of this paper is to provide a short example of the LAWPRO catchment assessment process, focusing on the Ballough River and the logical framework of methods used to narrow down on the significant issues and pressures impacting ecological status. Each investigative method described herein, treated on its own merit, could not provide a defensible conclusion. Taken together however, the stepwise analysis of: background ecology, hydro-morphology, water chemistry and conceptual pathways understanding, coupled with the interplay between macroinvertebrate dynamics and pressure and pathway observed in the field, forms a sophisticated "Story of the Catchment". Communicating this story to the stakeholder, whether that is the environmentalist, the farmer, the agricultural advisor or the institution is the key to achieving improvements in ecological status.

INTRODUCTION

A comprehensive ecological monitoring programme is maintained by the EPA in three year cycles; the rivers programme involves the characterisation of 3192 sub-basins (waterbodies), with sampling at some 2,300 biological and 1500 physico-chemical monitoring points (EPA, 2006). The work of LAWPRO centres on 726 of these waterbodies within 189 priority areas for action (PAA's), nationally. The catchments in which LAWPRO operate are not instrumented research catchments with available high resolution, spatio-temporal data to infer significance. Conversely, empirical data in the 189 PAA's is typically limited and oftentimes absent. In an environment with scarce background information, determining the relative significance of an issue or pressure requires a systematic, logical, 'first principles' approach that utilises multiple strands of desktop and field based information to form a defensible "Story of the Catchment". The development of a hydrological/hydrogeological pathways understanding forms an integral part of the LAWPRO deskstudy and is essential in catchments where diffuse pressures dominate. In a team that is made up of primarily ecologists and agricultural scientists, rather than hydrogeologists, the methodology used to develop the understanding must be simple, but also effective. The pathways understanding serves not only to inform the planning/interpretation of fieldwork, it also serves as a visual tool to explain hydrogeological principles in an understandable way to agricultural stakeholders and the wider public at public meetings and streamside events.

The design of the conceptual pathways model begins at the receptor, typically an EPA monitoring point (s) with an associated topographical catchment area. All available monitoring point information is compiled and interrogated for spatial patterns and temporal trends. Information sources include historical biological (Q) assessments, macrophyte/macroalgal surveys, hydro-morphological survey results and investigative/surveillance chemistry data, if available. Investigative chemistry datasets are typically four samples per year, representing seasonality and include phosphate, nitrate, ammonium and biological oxygen demand (B.O.D), at a minimum. Investigative monitoring involves a greater sampling frequency and can inform pesticide, trace organics and microbial pathogen abundance. Chemical results are compared against ecological water quality standards (EQS) to infer impact. Where a parameter is deemed to impact water quality, further analysis including co-variation of parameters and rainfall analysis is utilised.

The end result of the receptor analysis is a conclusion on the **significant issue** affecting the water quality status at the monitoring point and the timing of when that issue is most impactful. The next step in the process is to establish what **significant pressure** (s) in the waterbody have resulted in the significant issue at the monitoring point. A myriad of potential pressures exist within all catchments including agriculture, urban/domestic wastewater, diffuse urban (e.g. misconnections) and hydro-morphology. At deskstudy stage, when assigning significance, LAWPRO are guided by the 2nd cycle EPA characterisation of pressures (DHPLG, 2018) and discussions with local authorities. Once a defensible conclusion has been made on the significant issue (s) and the significant pressure (s) at the monitoring point, a decision is made as to whether a pathways conceptual model is required, or not. An example of the "not" scenario could be where B.O.D is the significant issue and a wastewater treatment facility is identified as the sole significant pressure. When a conceptual model pathways model is deemed necessary, it is specific to the significant issue at the monitoring point. For example, where excessive stream phosphate is the significant issue and diffuse agriculture is the significant pressure, the pathways conceptual model would focus on near surface overland flow pathways with an emphasis on critical source areas (CSA's) for phosphate loss. In this scenario, the groundwater pathway is of course considered, but not in the context of contaminant transport. Rather, the pathway is considered in the context of how it may affect the significant issue at the receptor. In the case of phosphate, the conceptual model would highlight areas with the potential for rejected recharge, high water tables, areas where there may be excessive drainage or stream reaches where groundwater inflow may provide dilution for the overland, phosphate rich pathway.

The aim of this paper is to provide a short example of the LAWPRO catchment assessment process, focusing on the Ballough River (BALLOUGH_10 and BALLOUGH_20 waterbodies). The Ballough River is one of four rivers in the Rogerstown Estuary PAA, three of which discharge directly to the Rogerstown Estuary. Smothering of sensitive seagrass by opportunistic algae has resulted in Bad status in the estuary. The estuary typology is nitrogen (N) limited; as such, the significant issue in the estuary is the combined N load from each of the contributing rivers. The "Estuary N Story" is the subject of a separate work package and series of referrals. Instead this paper focuses on the ecological status of the Ballough river and the steps taken to try and improve the water quality of the river.

The Ballough River

The Ballough river is split into two waterbodies; the BALLOUGH_010 (18.5km^2) and the BALLOUGH_020 (15km^2). The *Corduff Br* monitoring point is at the base of the river and acts as the end receptor for water quality for both the BALLOUGH_010 and BALLOUGH_20. The BALLOUGH_010 waterbody is unassigned whereas the BALLOUGH_020 has Moderate ecological status (2013-2018) based upon Moderate Invertebrate Status or Potential; heavy siltation was noted by the EPA Biologists at the monitoring point.

The Significant issue

Stream phosphate concentrations from 2007 to 2018 at the *Corduff Br* monitoring point are shown in Figure 1; also shown are plots of cumulative rainfall and B.O.D versus stream phosphate. Annual average phosphate concentrations were exceedingly high, and showed a rising, albeit non-significant five year trend (2012-2018). To place the severity of impact in perspective, the three year baseline concentration of 0.21mgP/L exceeded the EQS by a factor of five; 94% of Irish rivers had lower stream phosphate in 2017 (EPA, 2017). Plotting cumulative rainfall in the seven days prior to sample collection against phosphate revealed a dual pattern. Highest stream concentrations occurred when there was little to no effective rainfall in the preceding week; coupled with contemporaneous dry weather peaks in B.O.D and ammonium, the data reflects a large point source or series of upstream point sources. The analysis revealed a secondary pattern; phosphate increased in response to rainfall when dry weather sources were factored out. While not reaching the heights of the dry weather maxima, a stream concentration of 0.18mgP/L (5 x EQS) after >50mm of weekly rainfall is no less significant, particularly when considered in terms of load.

Analysis showed that B.O.D and ammonium also exceeded surface water thresholds intermittently, reflective of a periodic source or mobilisation factor. While both parameters are considered significant, the effect is deemed secondary when compared to phosphate and sediment. Based upon the receptor analysis and the EPA characterisation (DHPLG, 2018), the following significant issues were put forward for the river at deskstudy stage:

1) Diffuse: sediment and phosphate loss from tillage enterprise.
2) Point: Phosphate, B.O.D and ammonium loss from wastewater and grassland agriculture.

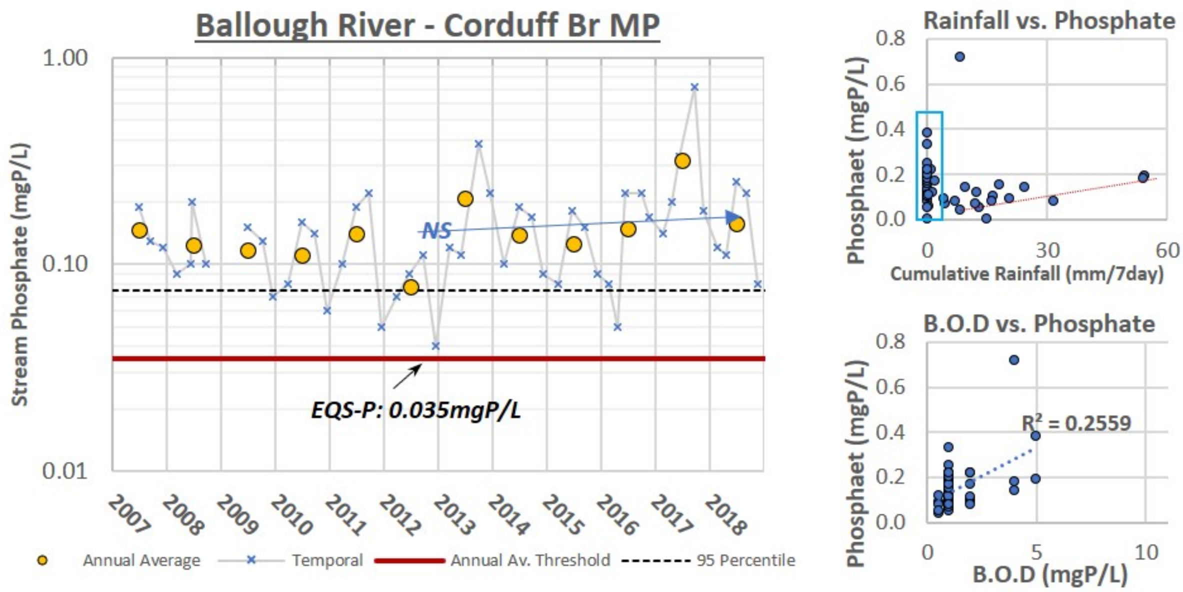

Figure 1. Large centre graph: timeseries of stream phosphate concentrations at the *Corduff Br* monitoring point (2007-2018) Top right graph: Cumulative seven day rainfall prior to sample collection vs. stream phosphate. Bottom right graph: Stream phosphate vs. stream B.O.D (2007-2018).

CONCEPTUAL UNDERSTANDING

Building upon the results of the receptor analysis, a conceptual pathways model was deemed necessary for the Rogerstown Estuary PAA; the model was tailored specifically to the significant diffuse issue and pressure in the PAA, namely: sediment and phosphate loss from tillage enterprise. The regional pathway framework for LAWPRO PAA's are provided by aquifer type. As with almost two-thirds of Ireland's land area (Moe et al., 2010), the aquifer distribution within LAWPRO PAA's are dominated by the Poorly Productive archetype. Typically therefore, the conceptual aquifer considers four groundwater zones: subsoil, transition zone, shallow groundwater (< 30 mBGL) and deeper groundwater (> 30 BGL). Once the catchment is sub-divided into pathway zones by aquifer type, relevant information such as bedrock type/features, soil drainage, subsoil type/thickness and catchment topography are superimposed into each zone. A simple conceptual model, specific to near surface phosphate and sediment loss for the Rogerstown Estuary PAA is shown in Figure 2.

Three conceptual pathways zones are identified in the Rogerstown PAA. The Calp Limestone (Lm aquifer) in pathway Zone 2 is characterised as having reasonably high transmissivity and storativity (effective thickness may extend to 30 mBGL). This higher productivity aquifer separates Zones 1 and 3, both of which are Poorly Productive. Soil drainage throughout the PAA ranges from Poor to Well Drained, with better drainage in the southern half of the catchment. The northern portion of the PAA is characterised by steep topography, becoming more leeward progressing southward.

The Ballough river catchment boundary (illustrated in grey on the conceptual model) straddles three pathway zones. The significant pathways within each zone are described below:

Zone 1: Phosphate loss to shallow groundwater via thin (<0.5m) or absent soils/subsoils.

Zone 2: Sediment and phosphate loss to stream via near surface overland CSA's.

Zone 3: Sediment and phosphate deposition in low velocity reaches.

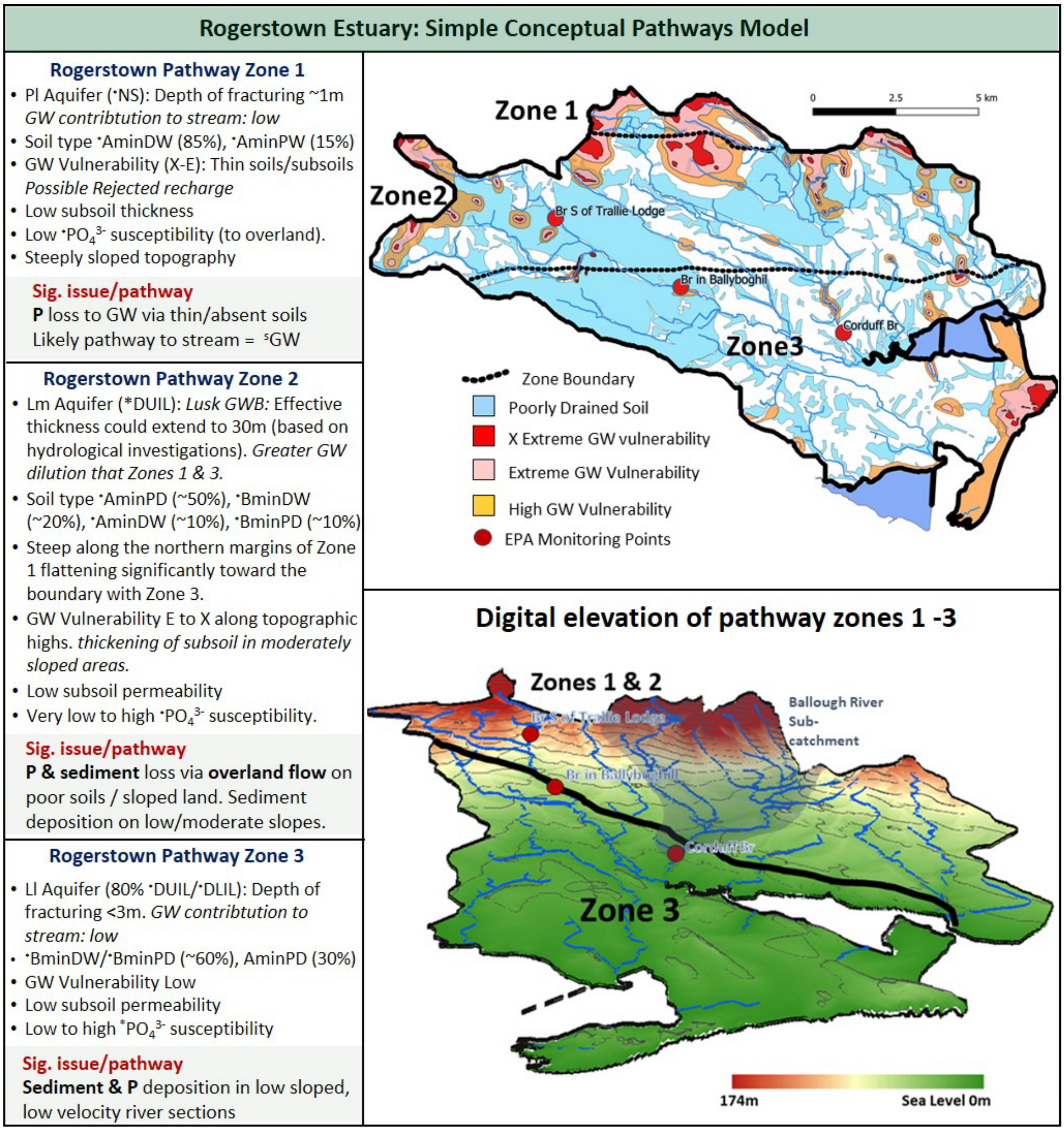

Figure 2. Simple conceptual flow pathways model for the Rogerstown Estuary PAA

**NS: Namurian Sandstone; *DUIL/*DLIL: Dinantian Upper/Lower Impure Limestone; *PO_4^{3-} Susceptibility: EPA Diffuse Tools Near Surface P model ; AminPD / BminPD : Deep Poorly drained mineral soils ; AminDW / BminDW Deep Well drained mineral soils*

LOCAL CATCHMENT ASSESSMENT

Local catchment assessment was split into three phases, as summarised below:

Phase 1: Biological Assessment: Small stream impact score (SSIS) ecological assessments were carried out at 11 locations throughout the BALLOUGH_10 and BALLOUGH_20 waterbodies. SSIS locations were chosen based upon access (proximity to bridges), availability of additional data at the point and suitability to rule out/in tributary impact. The biological assessment was complimented by physico-chemical measurements (dissolved oxygen, electrical conductivity, pH and temperature) and a description of the type and quality of the macroinvertebrate habitat. The physical characteristics of the river including the width and depth of the streambed, siltation level and the channel bed substrate (cobbles, boulders, gravel etc.) were also noted.

Phase 2: Nutrient Load Apportionment: Stream-flow was manually measured at nine targeted locations throughout the BALLOUGH_10 and BALLOUGH_20 waterbodies. The chosen locations complimented a supplementary water chemistry monitoring dataset, maintained by Fingal County Council. The combination of streamflow and baseline average phosphate concentrations allowed phosphate load reduction targets to be assigned and the relative load contribution of waterbody tributaries and tributary reaches to be calculated.

Phase 3: Stream-walks and refinement of pressures

Using the interpretation from *Phases 1 & 2*, stream-walks were undertaken along tributaries and tributary reaches deemed to exert the greatest influence on waterbody status. Stream walks were carried out during both summer and winter conditions.

Photos from the Ballough river assessment are shown below in Figure 3, while Figure 4 overleaf illustrates the specific points along the stream within the BALLOUGH_10 and BALLOUGH_20 where LCA was carried out. In addition, the analysis carried out at each location is described, as are the results of the biological assessment.

Figure 3. Photos from LCA, including flow measurement, sediment cover and macroalgal cover.

Small stream impact score (SSIS) ecological assessments were carried out at 11 locations throughout the Ballough River in June 2019, with sites chosen to characterise the BALLOUGH_10 waterbody and the two main tributaries of the BALLOUGH_20: Woodpark Tributary and Colecot Tributary. The ‘score’ obtained is based on the relative abundance of sensitive vs. tolerant macroinvertebrates that are present at the sampling point; an SSIS score of <6.5 indicates that the stream is Probably Impacted. SSIS is a useful tool when it is considered that the vast proportion of WFD status failures in Irish rivers result from impacted macroinvertebrate populations (Kelly-Quinn et al., 2020). The use of SSIS provided a high level overview of macroinvertebrate populations throughout the river; the headwaters of the BALLOUGH_10 and BALLOUGH_20 all showed impacted stream ecology. The Woodpark tributary in the BALLOUGH_20 was least impacted, while the BALLOUGH_10 waterbody and the Colecots tributary were both highly impacted throughout (all SSIS <2; no sensitive taxa).

While the SSIS score provides a high level indication of impact at each point, it is not heavily relied upon; rather LAWPRO scientists attempt to look past the score and examine the relative change in macroinvertebrate taxa from one location to the next. This information is used to further refine the conceptual understanding of the stream, providing in-stream clues as to the **significant issue, pressure and pathway**.

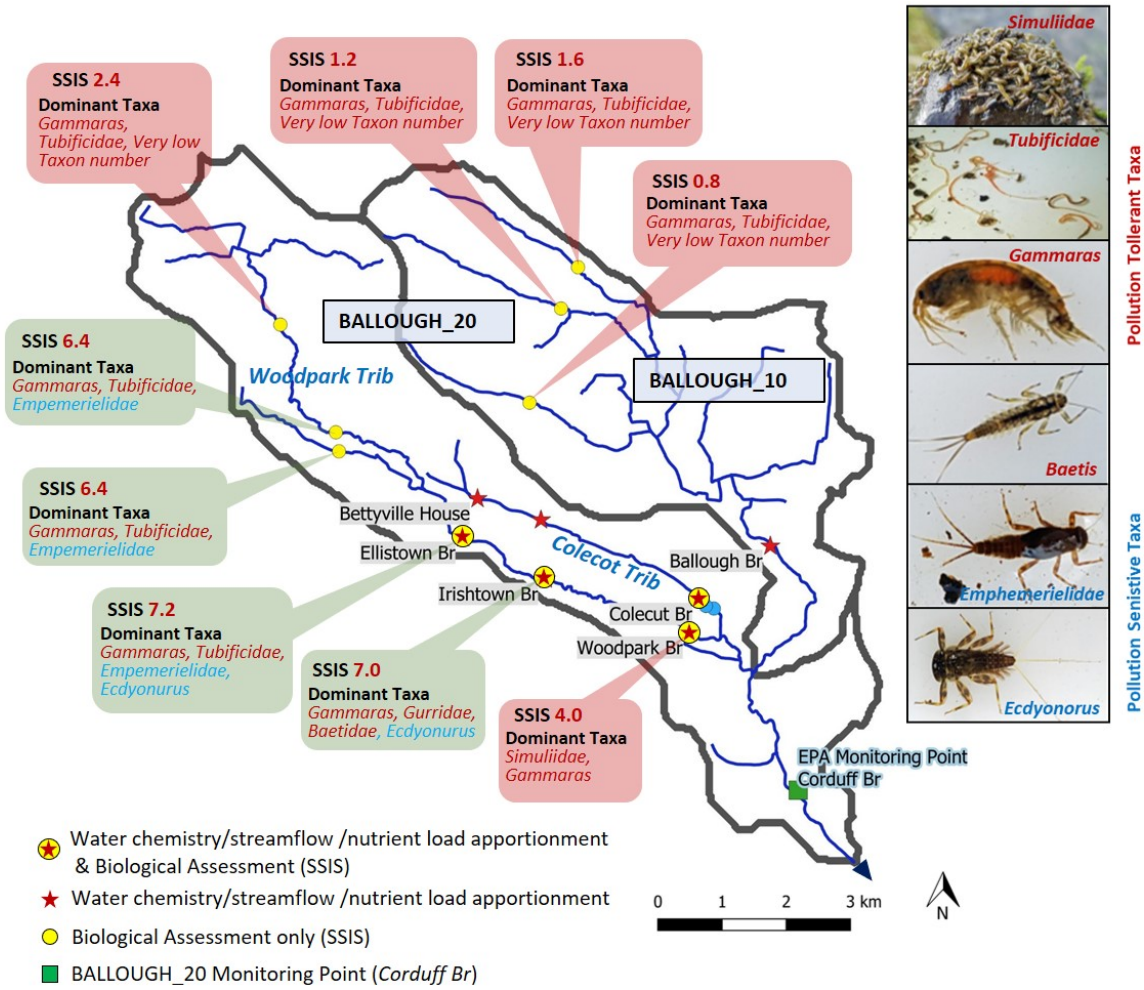

Figure 4. LCA locations along the Ballough river (BALLOUGH10 AND ballough_20 waterbodies). The analysis carried out at each location is described as are the results of the biological assessment.

To take a practical example, the three tributary branches in the headwaters of the BALLOUGH_10 were all highly impacted with SSIS scores of 0.8, 1.2 and 1.6, respectively (Figure 4). All sensitive stonefly and mayfly taxa were absent from the samples. As the stream has some of the highest phosphate concentrations in the country, evidence of stream eutrophication could have been expected. In contrast, no excessive plant or macroalgal growth was noted at the three locations. Nutrient tolerant mayfly such as *Baetidae* were absent from the sample. Numbers of taxa which thrive in organic rich streams (e.g. filter feeding *Simullidade*) were conspicuously low. Filter feeding Caddisfly species such as *Hydropsychidae* were also absent from the sample. Sediment deposition on the streambed itself was relatively low. Taken in isolation, the above series of findings is confusing, but when taken in context of the receptor analysis and conceptual understanding, a story emerges.

- Although phosphate concentrations were elevated, each of the stream reaches had considerable shading from tree cover: limited light availability precluded eutrophication.
- The three stream reaches are in Pathway Zones 1 & 2: the sloped topography of the zones resulted in high velocity streamflow, preventing excessive sediment deposition.

– High suspended sediment loads have a particular effect on filter feeding organisms (*Simullidade & Hydropsychidae)*, even if little sediment is evident on the streambed.

❖ Comparing the conceptual understanding with stream biology confirmed that a significant volume of fine sediment is carried from the headwaters of the Ballough river downstream towards the EPA monitoring point (*Corduff Br*) where sediment is a significant issue.

STREAM PHOSPHATE LOAD APPORTIONMENT

Stream phosphate loads were calculated at nine locations throughout the Ballough river (Figure 4), with fieldwork designed to complement a supplementary water chemistry dataset (2009-2018) collected and maintained by Fingal County Council. Phosphate enrichment has been discussed in detail throughout this paper as a significant issue impacting ecological status. In the opening paragraphs, a three year baseline concentration of 0.21mgP/L was described at the WFD monitoring point (*Corduff Br*). The first step in the load analysis was to assign a phosphate load reduction target. Based upon a measured average streamflow of 99 l/sec at the *Corduff Br* monitoring point and a target stream phosphate concentration of 0.030 mgP/L, it is estimated that a **550 KgP/Yr** reduction in the amount of phosphate lost to the stream is required to achieve Good stream phosphate conditions. Baseline stream phosphate concentrations and the phosphate load contribution from each of Ballough tributaries and supplementary monitoring points is shown in Figure 5.

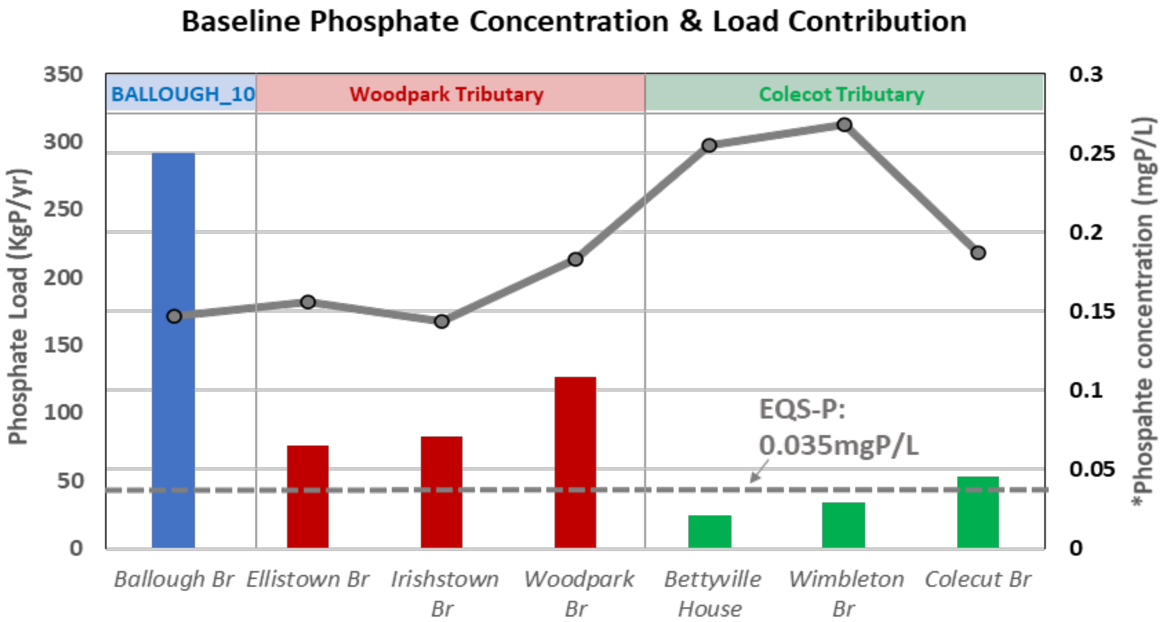

Figure 5. *Baseline phosphate (P) concentrations (3-year mean: 2016-2018) and stream phosphate load at each tributary.

The highest stream phosphate concentrations in the Ballough river were consistently measured on the Colecot tributary (Figure 5). In addition, it was demonstrated during the biological assessment that the entirety of the tributary had highly impacted macroinvertebrate communities. Given the above information, it is perhaps counter-intuitive to state that in the context of improving the WFD status of the Ballough river, the Colecot tributary is the least relevant river section. The ecological status of the river is measured at the *Corduff Br* monitoring point; in the context of improving WFD status, the ecological priority of the WFD monitoring point outweighs the priority of the tributary.

As demonstrated, a 550 KgP/Yr reduction in the amount of phosphate lost to the stream is required to achieve Good stream phosphate conditions at *Corduff Br*. The proportion phosphate load contribution from each river section to that target figure are:

- BALLOUGH_10: **55%**
- Woodpark Tributary: **24%**
- Woodpark Tributary: **10%**

Resources targeted at reducing the phosphate loss from the BALLOUGH_10 and Woodpark tributary are likely to have the greatest bearing on the ecological status of the Ballough river, as measured at the *Corduff Br* monitoring point. Improvements are also sought on the Colecot tributary, but the highest impact stretches are targeted first.

STREAMWALK & REFERRAL

The results from rainfall event winter fieldwork in the headwaters of the BALLOUGH_10 waterbody (Figure 6) and a subsequent referral to the Agricultural Sustainability Support and Advice Programme (ASSAP) is used as an example of the end product of the LCA approach. The following is one of multiple referrals made throughout the Ballough river.

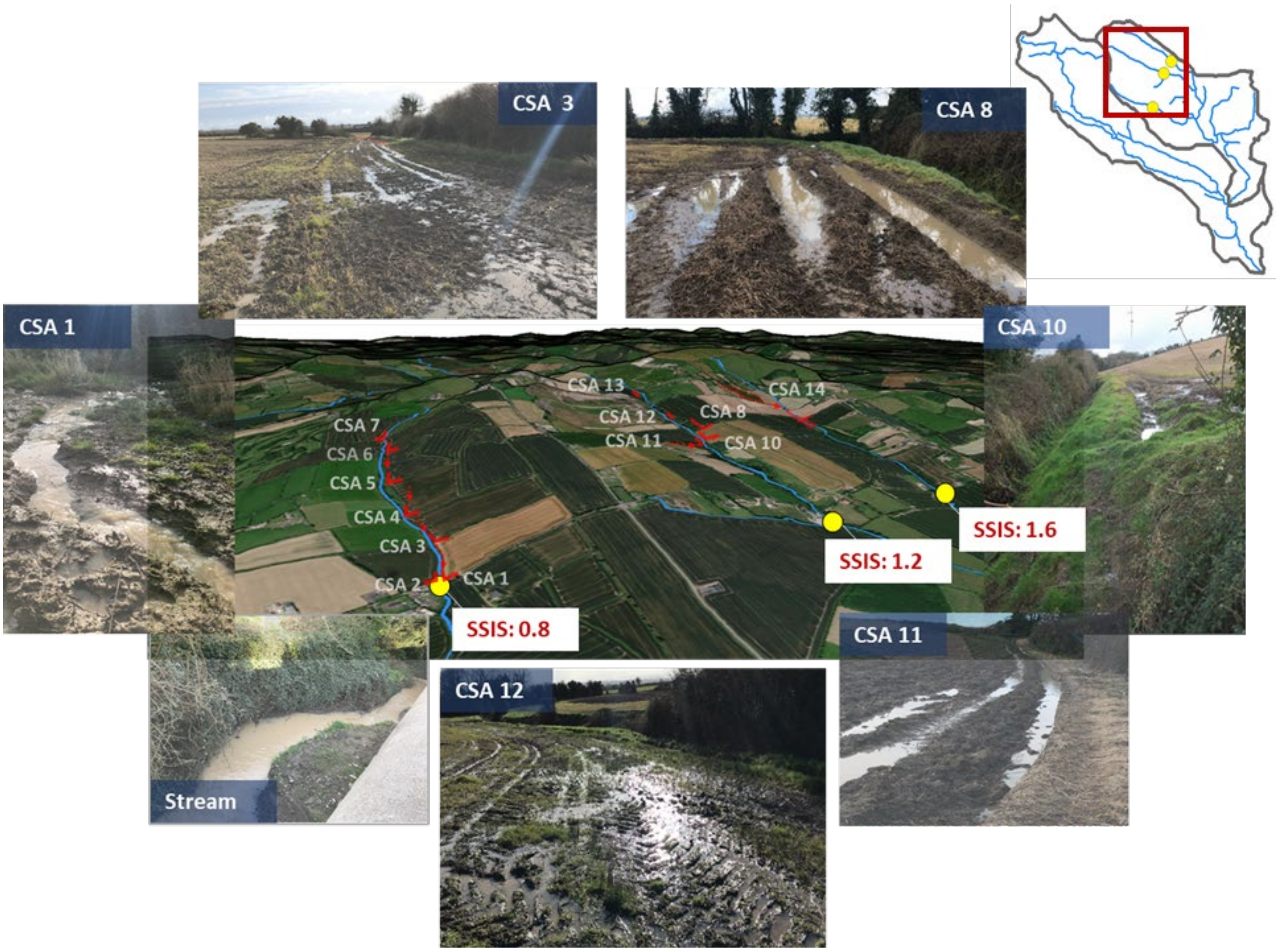

Figure 6. Rainfall event winter fieldwork results from the headwaters of the BALLOUGH_10 waterbody.

The focused streamwalk and detailed referral to an implementing body is the final part of the LCA jigsaw. The term "focused" is important as the choice of where/when to carry out the walk and what pressures to look for was derived from each deskstudy and LCA step. The BALLOUGH_10 headwater referral area includes the three tributary branches at the top of the Ballough river, totalling almost six km's of stream channel (Figure 6).

The following desktop, conceptual and LCA information determined the targeting of fieldwork in the area:

- 2015-2018 average phosphate concentrations measured at the nearest downstream EPA monitoring point (0.15mg/L) were over four times the EQS.

- In order to achieve Good status concentrations, a stream phosphate (P) load reduction of approximately 550kgP/yr is required in the river.
- Approx. 55% of the P load reduction target is lost from the BALLOUGH_10 sub-basin.
- The headwaters of the BALLOUGH_10 are in conceptual Pathway Zones 1 and 2, which are characterised by sloped topography, low permeability subsoil and tillage enterprise.
- Macroinvertebrate communities were highly impacted on each of the three tributaries with SSIS scores of 0.8, 1.2 and 1.6, respectively.
- A lack of filtering feeding taxa suggested a significant loss of fine sediment from the area.

Based upon the above, the streamwalk was targeted to identify near surface overland pathways for sediment and phosphate loss on sloped tillage land. The timing of the walk was designed to capture the highest risk period for fine sediment loss to the stream: during a substantial rainfall event coincident with bare soil conditions. In total fourteen critical source areas (CSAs) for sediment and phosphate loss were identified, mapped and photographed (Figure 6). Focusing of sediment through CSAs into tramlines was evident throughout the referral area. The CSAs were referred to ASSAP along with recommendations on mitigation measures; these included the provision of riparian buffers to intercept CSA runoff, early crop sowing to establish winter cover, contour ploughing, minimum tillage cultivation the alleviation of compacted field areas and a consideration of heavy machinery use during high risk times. ASSAP continue to work with the farmers in the area to put measures in place.

CONCLUSION

The term freshwater detective is one we often use as a public engagement tool, designed to stimulate the imagination of the public, particularly younger generations. While perhaps a little cringeworthy as a job description, it is an apt description of catchment science, nonetheless. Each investigative method which has been described herein, treated on its own merit could not provide a defensible conclusion. Taken together however, the stepwise analysis of background ecology, hydro-morphology, water chemistry and conceptual pathways understanding coupled with the interplay between macroinvertebrate dynamics with pressure and pathway observed in the field, forms a sophisticated *"Story of the Catchment"*.

Communicating this story to the stakeholder, whether that is the environmentalist, the farmer, the agricultural advisor or the institution is the key to implementing the *Right Measure in the Right Place* and achieving improvements in ecological status.

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CATCHMENTCARE: COMMUNITY ACTIONS FOR RESILIENT ECOSYSTEMS

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ABSTRACT

CatchmentCARE is an INTERREG VA-funded project that aims to improve freshwater quality within the North Western and Neagh Bann international river basins. The project is focussed on three cross-border catchments, the Arney, Blackwater and Finn but also includes other locations in representative catchments in the borders region. There are eight partners working on different aspects of catchment characterisation and water improvement measures. The Groundwater team are establishing long-term groundwater monitoring stations in the region, comprising 50 boreholes, as well as springs. This paper will focus on one of these catchments - the Arney - and give a flavour of water quality improvement works, community incentive schemes, education programmes, groundwater investigations at springs and boreholes and how they all link together.

INTRODUCTION

CatchmentCARE is an EU-funded project that aims to improve freshwater quality within the North Western and Neagh Bann international river basins. The project is focussed across three cross-border catchments, the Arney, Blackwater and Finn. The project aim of improving water quality in the three catchments is being achieved through a combination of policy actions, catchment actions and community actions. The work is ensuring the following criteria remain in focus throughout:

- Measurable impact on water quality;
- Transferable beyond the three catchments;
- Contribute to a project legacy.

The project overall is grounded in the Water Framework Directive (WFD). The WFD takes an integrated approach to the protection, improvement and sustainable management of the water environment. It revolves around a River Basin Management Planning process of action and review to improve water quality and achieve 'good' status in water bodies (rivers, lakes, estuaries and coastal waters, and groundwaters) by 2027.

CatchmentCARE supports an Integrated Catchment Management (ICM) approach, whereby policy, research and community action are brought together at local levels to develop a real, shared understanding of the challenges facing individual catchments in order to then agree specific actions for improvement, and to implement them.

The five year project started in November 2017 and is due to finish in October 2022. It is funded under the Environment measure of the EU Interreg VA programme, with a budget of €13,792,432, including match funding of €2,068,865.37 provided by Government departments from Northern Ireland and Ireland: The Department of Agriculture, Environment and Rural Affairs and The

Department of Housing, Planning and Local Government. A no-cost extension of 6 months has been sought from the Special EU Programmes Body (SEUPB) to ameliorate the impacts of COVID-19 on the project.

Eight partners from both sides of the border are working collaboratively to ensure the delivery of the CatchmentCARE Project: Donegal County Council (Lead Partner); Agri-Food and Bioscience Institute (AFBI); Armagh City, Banbridge & Craigavon Borough Council (ABC); British Geological Survey (BGS) and Geological Survey Ireland (GSI); Inland Fisheries Ireland (IFI) and Loughs Agency; Ulster University (UU). The partners each have key expertise in aspects of water quality improvements such as Hydromorphology, Water Quality, Catchment Management, Stakeholder Engagement and Groundwater, but are working together and are involved in multiple work packages with linkages and collaboration between the partners and work packages.

This paper gives an overview of the project but will focus on one of the project catchments - the Arney - and give a flavour of water quality improvement works, community incentive schemes, education programmes, groundwater investigations and how they all link together.

INTRODUCTION TO THE CATCHMENTS

The project is focused in three cross-border river catchments: the Finn (Donegal, Tyrone), the Blackwater (Armagh, Tyrone, Monaghan) and the Arney (Fermanagh, Leitrim, Cavan) (**Figure 1**). However, other geographical areas have been incorporated on their own merits by one or more partners. For example, the Derg catchment (Donegal, Tyrone) has been instrumented by the Groundwater team because it links in with the INTERREG SourceToTap project's investigations into MCPA in surface waters.

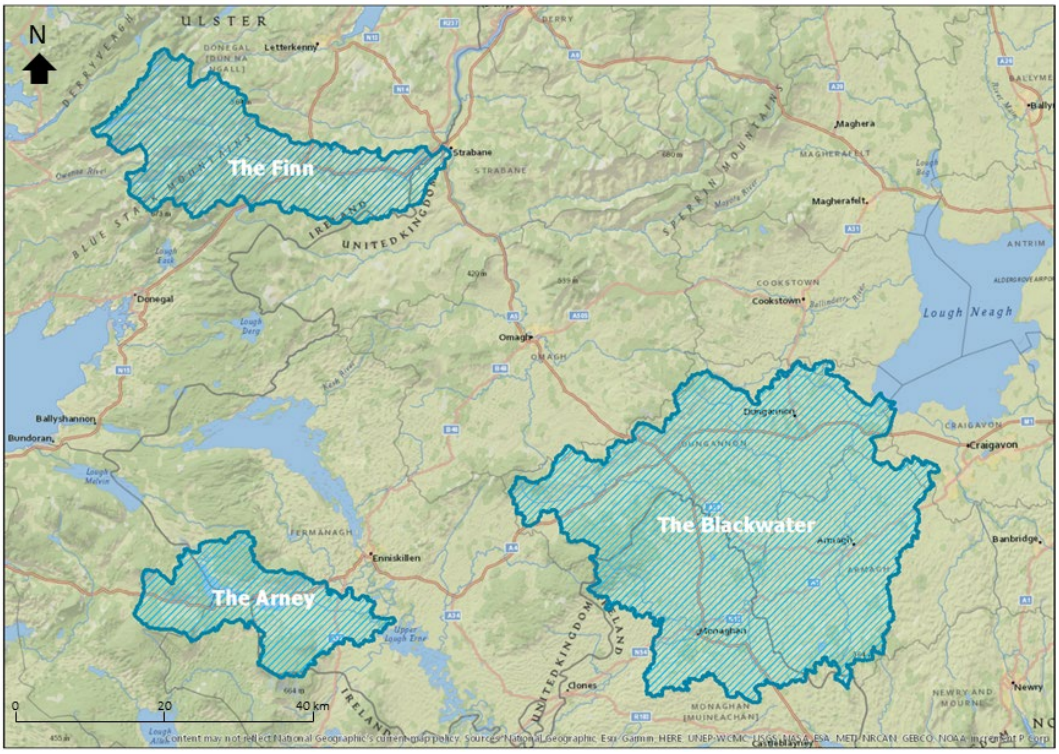

Figure 1: *The three CatchmentCARE catchments, which are the focus of the water quality improvement works and groundwater monitoring. The Groundwater team are also monitoring groundwater in the Derg catchment, adjacent to the Finn, and at other locations in the border area.*

The project catchments were selected due to specific waterbodies failing to achieve good ecological status (GES) under Water Framework Directive (WFD), and are the focus of the water quality improvement projects and installation of 50 groundwater monitoring boreholes across the region. Project actions in the catchments are addressing water quality issues related to hydromorphology, point and diffuse sources of pollution, farm nutrient management practices as well as characterisation and monitoring of groundwater quality, and lag times in response to the implementation of measures.

So far over 30 km of riparian and in-stream works have been carried out or are underway across the three catchments (**Figure 2**). This work includes fencing, drinkers, planting, wetland installation, meander complexes, pool creation, gravel regrading as well as soil and water quality sampling and freshwater invertebrate sampling. As part of AFBI's Farm Nutrient Management work, four hundred fields in the Blackwater catchment were soil sampled in early 2019. Seventeen farmers in the CatchmentCARE Project received tailored nutrient management advice for their farm, along with slurry and grass silage analysis. One Short Rotation Coppice (SRC) Willow plantation has been established to mitigate the effects of waste water treatment plant effluent. One more site is currently underway and a further one planned. These plantations can manage large volumes of dirty water and can remove significant quantities of nutrients and heavy metals, as well as many other benefits such as increasing biodiversity, flood prevention, biomass fuel usage.

Figure 2: *Riparian and instream works*

This partner work is done alongside community incentive scheme (CIS) projects and educational and outreach programmes. Examples of CIS projects include creation of river trails, educational programmes, interpretive panels, training events, community days. Outreach and educational programmes include fact sheets and infographics, educational videos and educational series for the school curriculum, such as the series on The River.

To date, 32 Groundwater monitoring points have been established at 23 Groundwater Monitoring Stations (GMSs). These monitoring stations include 17 boreholes and 15 springs (**Figures 3 and 4**). Three geophysical surveys and seven preliminary pump tests have been completed so far, with more planned in the near future, as well as down-hole geophysics and full pumping tests where warranted. Thirty data loggers have been installed, 15 in groundwater monitoring boreholes and 15 in springs. In addition, the first round of the groundwater hydrochemistry sampling has been undertaken at 17 boreholes, with samples taken at different depths (usually shallow and deep), and nine springs.

Figure 3: *Groundwater monitoring borehole drilling*

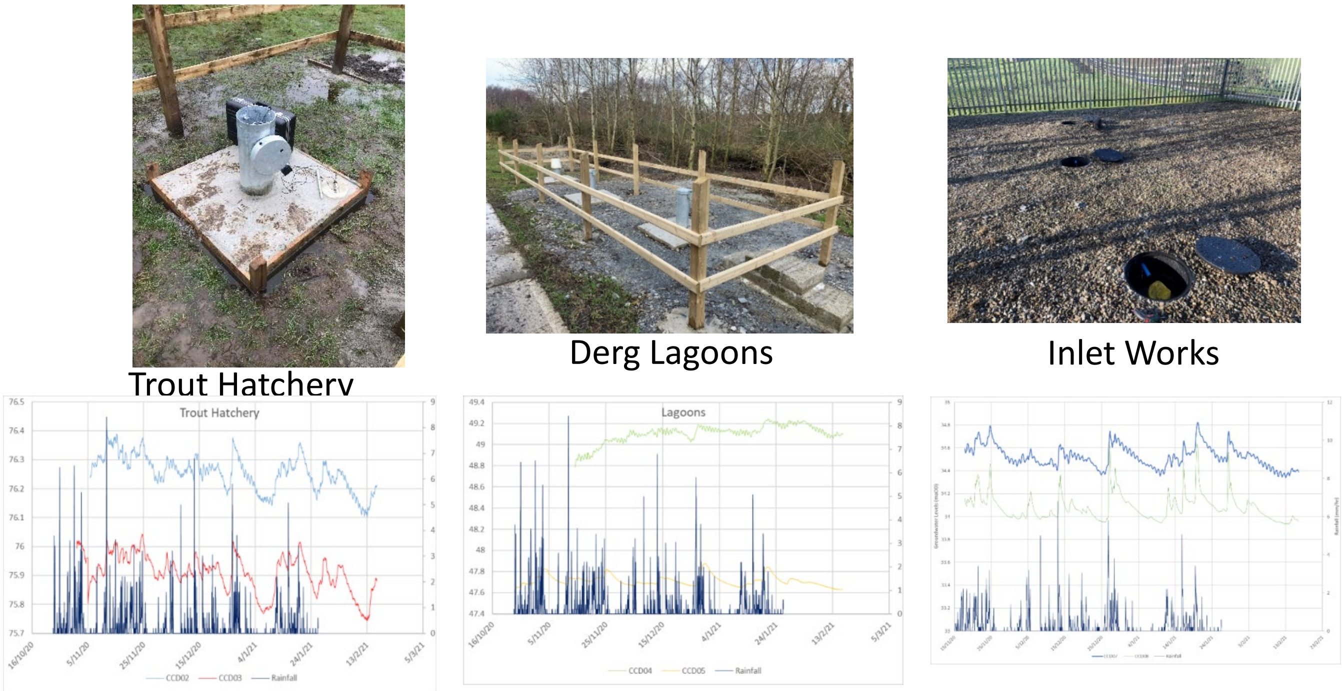

Figure 4: *Some examples of finished groundwater monitoring stations and some preliminary water level data from the boreholes.*

THE RIVER ARNEY CATCHMENT

CATCHMENT OVERVIEW

The Arney catchment lies in the North Western International River Basin District and is part of the larger River Erne catchment. It covers an area of 304 km^2, of which two-thirds is located in Northern Ireland and one-third is located in the Republic (ROI), and it includes parts of Counties Fermanagh, Cavan and Leitrim.

The catchment is dominated by two major lakes, Lough Macnean Upper (approximately 990 ha) and Lough Macnean Lower (approximately 457 ha), both at an altitude of just over 50 m (**Figure 5**). The Arney River flows from west to east, from Lough Macnean Lower to the River Erne, 15 km away. The Arney River and lakes sit in a wide, flat glacial trough between the uplands of Fermanagh, Belmore and the Cuilcagh Mountains. In fact, the lakes and river are surrounded by uplands on all sides, except the east.

GEOLOGY

The bedrock geology of the Arney catchment is dominated by Carboniferous rocks (**Figure 6**). The majority of the catchment is composed of Dinantian-age rocks, although there are Namurian lithologies towards the west. The uplands surrounding the lakes are largely composed of sandstone. Descending from the high ground, the sandstone gives way to shale. The central third of the catchment is underlain by limestone of the Dartry Limestone Formation, which is karstic. This includes the north-facing flank of the Cuilcagh Mountain, which is home to the Marble Arch Cave system and many other caves and karst landforms. The lower half of Lough Macnean Lower is composed of shale which underlies most of the Arney lowland catchment. The rocks have undergone substantial deformation, with significant faults throughout, and folding in the west of the catchment

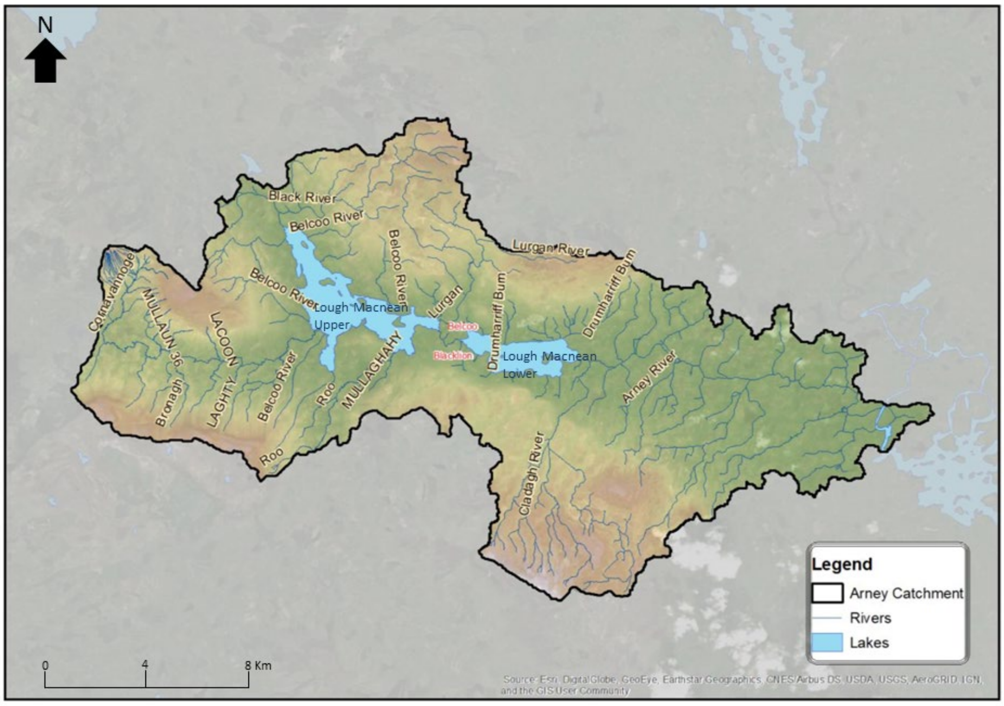

Figure 5: *Topography and surface water features in the Arney Catchment*

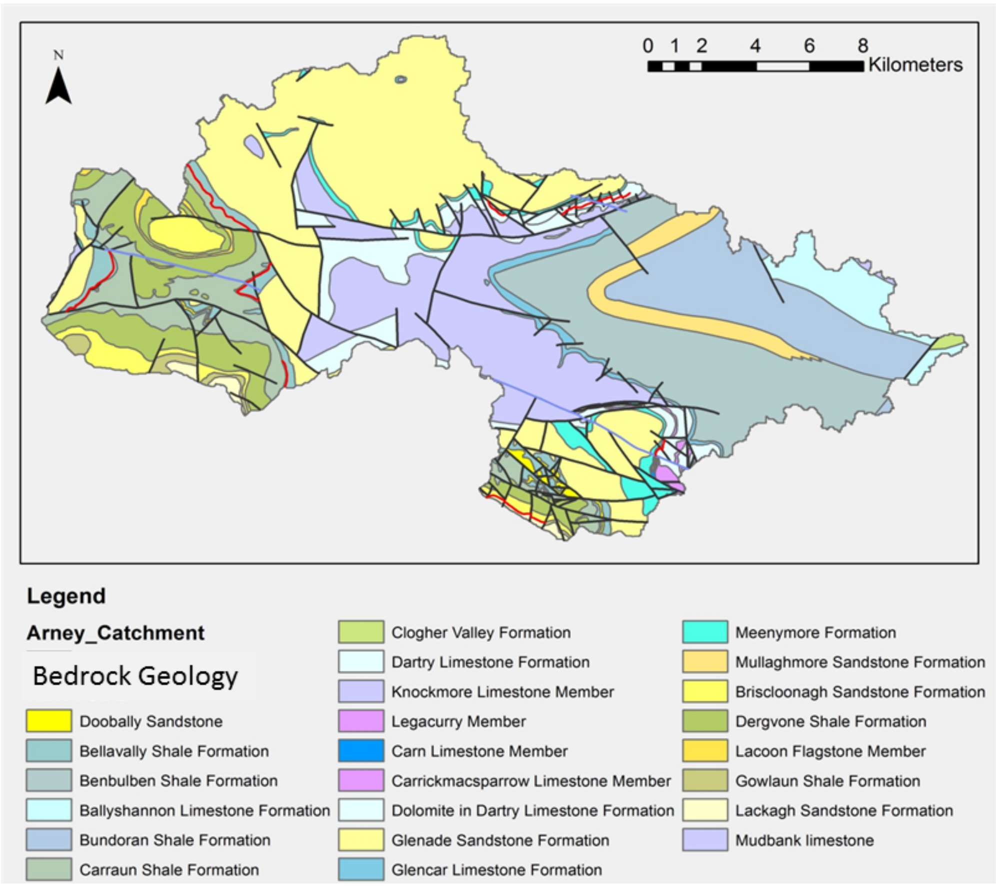

Figure 6: *Bedrock geology of the Arney Catchment*

The upland catchment areas are largely covered by blanket peat. Smaller areas of cut peat also occur in the Arney lowlands. There are some areas of exposed bedrock and karstified bedrock outcrop or subcrop such as at Corratirrim, south of Blacklion. However, the greater part of the catchment is covered by glacial tills ('boulder clay') derived from Namurian sandstones and shales, and from limestones.

HYDROGEOLOGY

The principal aquifers in the Arney Catchment are the Regionally Important Karst aquifers (Rkc) of the Dartry Limestone Formation (and its members). As these aquifers are highly karstified, rainwater recharges the aquifer via numerous stream sinks, enclosed depressions and caves, as well as diffusely. This groundwater emerges at springs towards the base of the limestone. Many of the streams that feed into the main Arney River (such as the Cladagh River), as well as the Upper and Lower Lough Macnean (such as the Roo), are fed by springs emerging from the limestone.

The shales and sandstones are generally poorer aquifers and most groundwater flow is likely to occur in the upper weathered section of the rock (Pl and Pu aquifers), with the exception of the well-fractured Glenade Sandstone Formation, which is a Locally Important Aquifer which is Generally Moderately Productive (Lm) and the Benbulben Shale Formation, which is classified as a Locally Important Aquifer - Bedrock which is Moderately Productive only in Local Zones (Ll).

WFD STATUS

The Arney catchment is divided into 11 river water bodies (RWBs) and two lake water bodies. It is associated with 11 groundwater bodies (GWBs). Of the 11 RWBs in the Arney catchment, one is at high status, five are at good status, and five are at moderate status. Lough Macnean Upper is classified at Poor status and Lough Macnean Lower is at bad status. Eight GWBs are at good status and not at risk. One GWB, the Marble Arch has improved from poor to good status. In NI the Belcoo Boho GWB and the Enniskillen GWBs have all been assigned poor status.

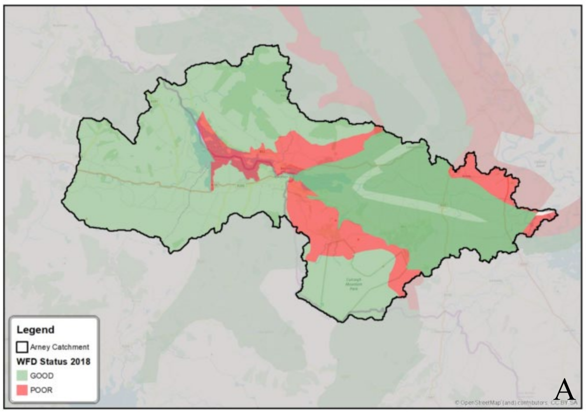

Figure 7A: *GWB status in the Arney Catchment*

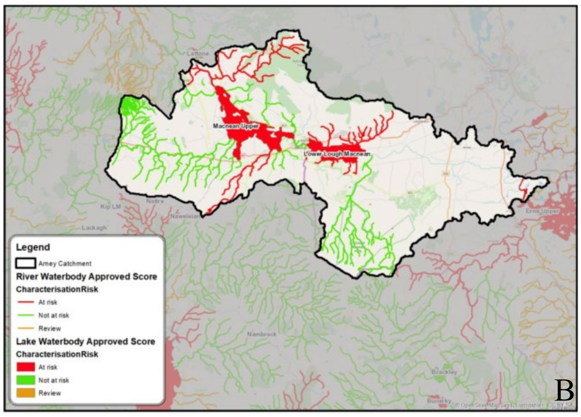

Figure 7B: *RWB status under WFD 3rd cycle*

Significant pressures impacting on water quality in the Arney catchment include agriculture and forestry, urban wastewater treatment effluent and domestic wastewater discharges. Forestry has been identified as a significant pressure in the Lough Macnean Upper catchment. The Roo valley has been specifically identified as an area with significant pressures from domestic wastewater systems.

The second cycle River Basin Management Plan for Ireland 2018 - 2021 identified 'Areas for Action' - waterbodies and their catchments where actions will be prioritised to achieve WFD objectives. The Roo River was selected by The Local Authority Waters Programme (LAWPRO) for Local Authority catchment assessment teams to assess and then drive the implementation of mitigation measures.

CATCHMENTCARE WATER QUALITY IMPROVEMENT WORK IN THE ARNEY

Riparian and in-stream works

The first phase in the surface water quality improvement work was assessing hydromorphology status and developing an evidence-base for prioritisation of in-stream and riparian works. IFI selected 36 sites in the Arney catchment, covering all waterbodies. All 36 sites were surveyed for fish and Ecological Quality Ratios (EQRs) were calculated, with the following results: High: 1 (3%), Good: 4 (11%), Moderate: 27 (75%) and Poor: 4 (11%). From those 36 sites, a total of 13 sites were surveyed for hydromorphological conditions (RHAT survey). RHAT surveys were also assessed in terms of EQRs for correspondence with fish survey results, showing the following results: High: 2 (17%), Good: 3 (25%), Moderate: 6 (50%) and Poor: 1 (8%). All potential barrier locations were visited for presence or absence of passage issues. Based on examination and use of the height and depth criteria, a total of 39 barriers were assessed in the Arney catchment.

The scoping showed that most water quality improvement works needed to be carried out in the Drumharriff Burn, the Roo, and the Arney River waterbodies, with most located in the Arney and its tributaries. The proposals by the IFI include improving 30 reaches of instream habitat, large woody debris pinning at 10 sites, 12 barrier modifications, 10 km of buffer strip creation, 500 pasture pumps / off line drinking solutions and 10 km of bank stabilisation. These works are currently underway in the catchment, with over 12 km of fencing and riparian buffer zones being put in place as well as 82 offline drinkers (consisting of solar and nose pumps and rainwater harvesting). Detailed pre and post monitoring of river habitat is also taking place (O'Leary, IFI. Pers comm 2021).

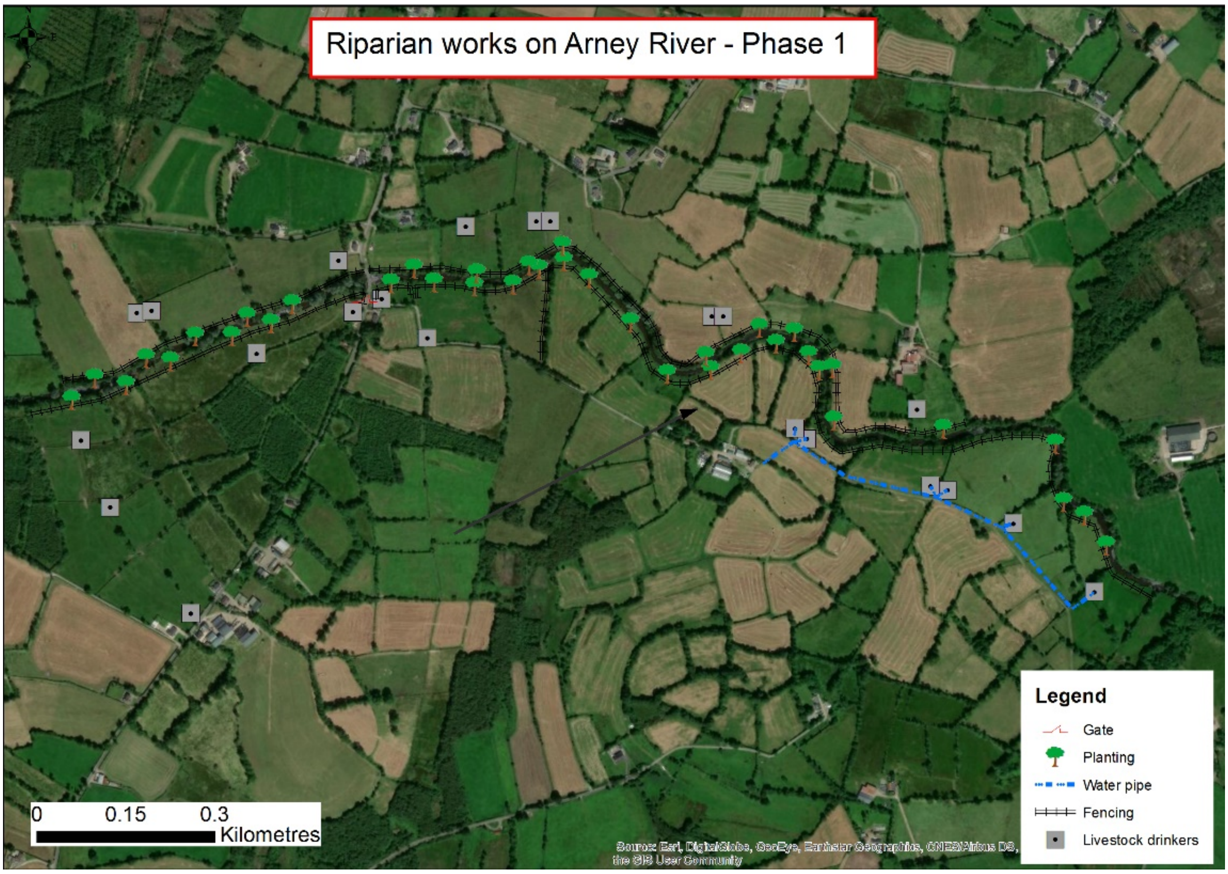

Figure 8: *A sample of the Riparian works underway for IFI as part of the CatchmentCARE project. Source: IFI*

Groundwater works
Due to the karstified nature of much of the Arney catchment, there is an abundance of karst springs in the catchment (e.g. **Figures 9 and 10**), transmitting large volumes of groundwater to the surface. Therefore, in the Arney Catchment most of the monitoring stations are established at springs (**Figure 11**). The majority of these are karst springs, with two located in non-karst rocks as a contrast (one in shale and one in sandstone). These springs range in size from tiny trickles (located in the non-karst rock) to overflow springs, that cease to flow in dry weather to large rivers such as the Cladagh Glen resurgence. There are also two pre-existing boreholes, located in the karst aquifer, which are being monitored.

Figure 9: *St. Patrick's Holy Well, Co. Fermanagh*

Figure 10: *Cascades Spring – a karst spring in the Arney Catchment that flows in to the Cladagh River*

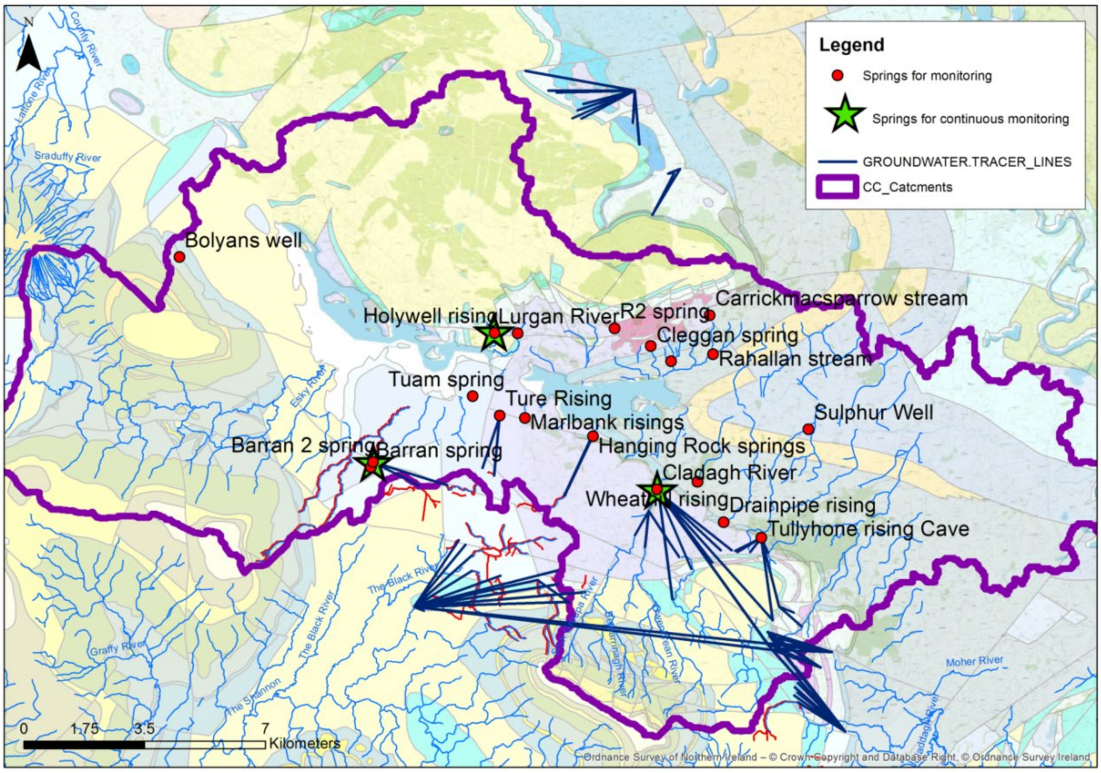

Figure 11: *The location of springs for monitoring (continuous data logger, hydrochemical spot sampling and continuous discharge monitoring) in the Arney Catchment, showing traced underground connections.*

Twenty sites were investigated for monitoring and a subset of 15 was chosen for installation of continuous data loggers. These loggers are monitoring water level, temperature and electrical conductivity, and were installed in February and March last year (2020). These springs were also sampled for a full suite of hydrochemical and heavy metal parameters. One round of hydrochemical monitoring has taken place, with a second round to commence once COVID-19 restrictions are lifted. Nine springs, one dug well and two boreholes were sampled in this round. This hydrochemical sampling will occur every three months, with scope for event-based sampling. These sites will be monitored for flow volume (discharge) every month. A further three sites have been chosen for continuous discharge measurements, which is critical to our understanding of the hydrogeological functioning of the karst aquifers.

Classically, due to their high degree of heterogeneity, the understanding of the hydrogeology of karst aquifers relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterise the karst as a whole entity. Discharge time series analysis, using several tools (spectral analysis, recession curve analysis) as well as additional hydrochemical parameters, such as temperature, electrical conductivity (EC), and others, provide information about the karst hydrodynamics and vulnerability and can be used classify karst aquifers.

The datasets are yielding some interesting preliminary results enabling classification of karst springs based on the hydrochemistry results, hydrographs and chemographs. This grouping enables an understanding of the type aquifer system supplying the spring. **Figure 12** clearly shows the two non-karst monitoring points having very different hydrochemical signatures from the cluster of karst springs, all plotting with a calcium bicarbonate signature.

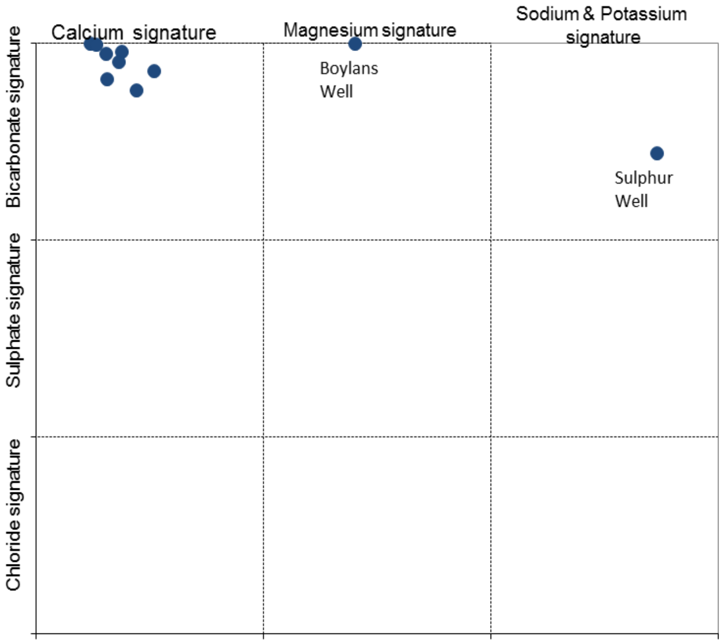

Figure 12: *Durov diagram showing the hydrochemical signature of groundwater sampled in the Arney*

Another example of the type of information that can be acquired is response times to rainfall events. This has implications for aquifer vulnerability as well as revealing information on the hydro-dynamical functioning of the system (or catchment) as a whole. **Figure 13** shows the response of the Cladagh River to an isolated rainfall event. The Cladagh River, which is fed by a combination of springs discharging from caves such as Marble Arch, is extremely flashy with little storage. The main spring emerging is fed from three sinking rivers: the Sruh Croppa, the Aghinrawn and the Owenbrean, all of which sink into limestone on the Cuilcagh Mountain and join up underground in the Marble Arch Cave system. In this event the system starts to respond within 10 hours, with the time from the peak rainfall to the lowest point in EC being 14 hours. The time for the system to recover from this rainfall event is estimated as five days. This contrasts some of the other springs, such as the dug well in the sandstone aquifer, which do not show any response to individual rainfall events.

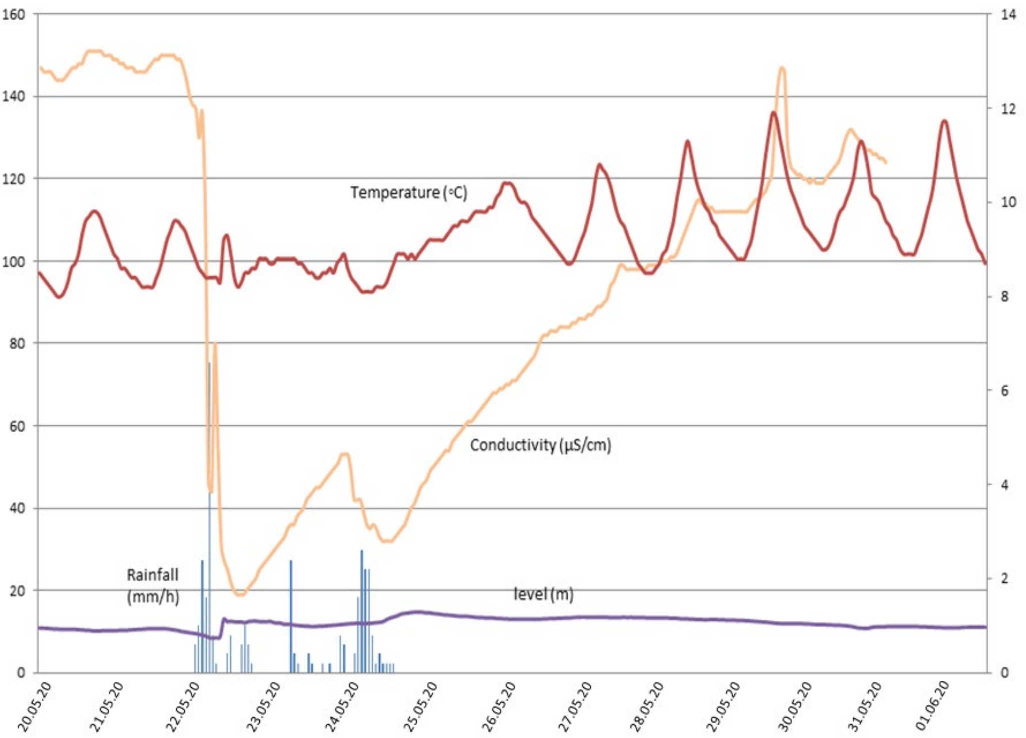

Figure 13: *Cladagh River hydrograph and chemograph showing a rapid response to hourly rainfall (hourly rainfall data provided by AFBI from their dedicated rainfall station established in the Arney Catchment).*

Linkages with other partners and examples of the catchment approach

The groundwater characterisation and data complement the characterisation and works being undertaken by IFI. There is now a baseline dataset of the hydrochemistry of many of the rivers and streams in the Arney. This dataset will capture the period during and, critically, after any water quality improvement works have taken place. The IFI are keen to use the continuous temperature data we are collecting, as this is an important factor in the ecology of the rivers and streams in the catchment. The hydrochemistry dataset is also critical to the project as a whole, as it fingerprints the water emerging from the ground at springs which, in the Arney, often form the headwaters of the rivers.

The initial desk study using the GSI and GSNI karst database showed that the groundwater boundary does not match the Arney catchment boundary, which was based on surface water (**Figure 11**). A large cave/ enclosed depression complex was traced to Barran Spring, which is the start of one of the larger tributaries of the Roo River. As previously mentioned this river is currently classified as being at risk of not achieving its WFD objectives and has also been selected as a Priority Action Area (PAA). It was, therefore, deemed critical to define the catchment to this river (both surface and groundwater).

The first round of Community Incentive Schemes was implemented in 2019, and included an application from Speleological Union of Ireland (SUI) to roll out a comprehensive dye tracing programme in the area. GSI and BGS are working closely with this project to ensure maximum benefit for the hydrogeological understanding of the area, and the CatchmentCARE project as a whole.

So far, two successful tracing experiments have been carried out which have increased our understanding of the route the water is travelling underground, and also the velocity of water flow.

There have been two new underground routes established and we now know that the water flows extremely quickly underground with groundwater velocities of 3.6 km/d (Brown and Kelly, 2021, pers comm). This has huge implications for water quality and land-use. One of these traces proves that the catchment to the Roo (and the Arney Catchment itself), is larger than we have already mapped. This again, has great significance for water quality and improvement works for the Roo, the lakes, and the Arney River.

The upcoming tracing work will focus on defining this boundary even further with a programme of karst landform mapping proposed to facilitate this. The other area of interest is to increase our understanding of the groundwater flow paths and catchment boundaries on the northern side of the lakes, at Belmore Mountain as there is little known about this area.

Communication and dissemination

Communication and dissemination is a critical aspect of this project. Communication and education is done through many different mediums such as websites, YouTube channels, training days, education days, education video series for the school curriculum, newsletters, community action days, information panels (**Figure 13**) and factsheets. This not only encourages community involvement and buy-in, but also increases the knowledge transfer and overall legacy of this project.

A range of interpretive panels are currently being installed at various locations throughout the CatchmentCARE region. The panels, in both English & Irish, contain a variety of information to help the public understand the local area, landscape, history, wildlife and water quality issues within the catchment. The Arney panels were coordinated through the Kiltyclogher Heritage Group and IFI. The panels represent a collaboration of knowledge from many project partners. **Figure 13** shows a panel in the Arney with considerable hydrogeological information.

It has long been recognised that communicating groundwater is difficult and complicated. In order to combat this, the groundwater team have embarked in large scale 'groundwater visualisation' project. This is being tackled through the use of virtual reality and immersive reality, allowing the user to actually enter different types of aquifers, groundwater boreholes, potholes and caves through the use of headsets computers and even mobile devices. There will also be detailed 'stories' that the user can embark on, such as how karst is formed, how different aquifers respond to pumping or rainfall and watching a water body recover after water quality improvement works.

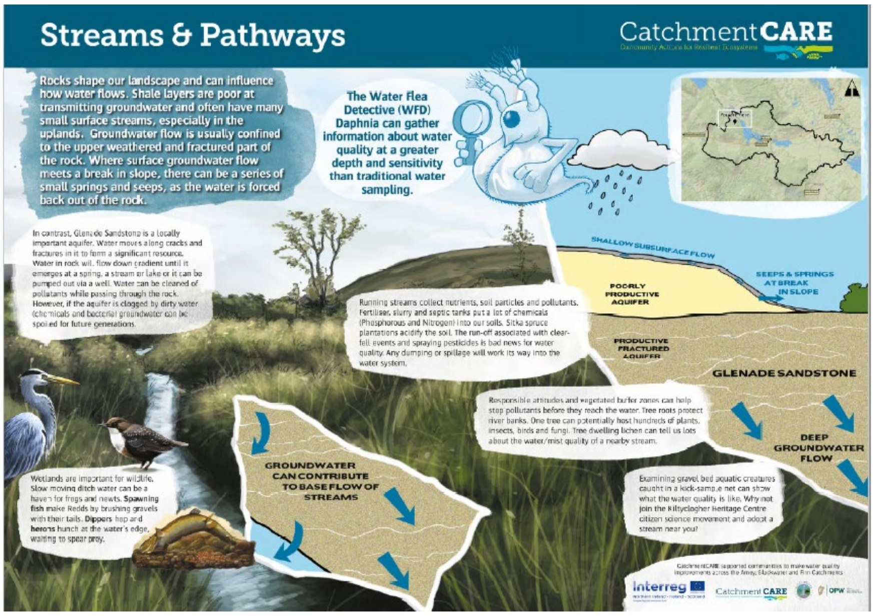

Figure 13: *An interpretative panel in the Arney Catchment showing groundwater pathways*

ACKNOWLEDGEMENTS

We would like to acknowledge the hard work and dedication of the whole CatchmentCARE team, and the landowners who are critical to the success of this project. We would especially like to thank Lisa Doyle, from IFI, for all her help with land access and fieldwork for the spring monitoring in the Arney. Thanks also to Dr Les Brown and John Kelly for their tracing work. This paper is written with the permission of the Director of Geological Survey Ireland, Koen Verbruggen.

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SESSION III

INVESTIGATING THE ROLE OF GROUNDWATER IN CATCHMENT FUNCTIONING IN THE EDDLESTON CATCHMENT, SCOTLAND

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ABSTRACT

BGS have been investigating the role of groundwater in catchment functioning for the past 10 years in the Eddleston Research Catchment – a tributary of the River Tweed, located in the Scottish Borders. The research is part of a wider initiative funded by the Scottish Government examining the evidence for the efficacy of natural flood management and river restoration measures. Here we give a brief summary of several of the experiments undertaken: (1) exploring the coupling of an upland floodplain aquifer with the river and hillslope; (2) examining soil permeability and infiltration in different land uses and superficial geology; (3) monitoring groundwater flow and soil moisture changes underneath a forest strip; and (4) using tracers to measure the partitioning between groundwater flow, soil water and event runoff during storm events. The research experiments reinforce the importance of subsurface conditions, and in particular geology in shaping the response of catchments to rainfall. Groundwater plays an important, but often unrecognised, role in mediating catchment flows, and variability in superficial geology often exerts a larger control on flooding than land use.

Key words: *groundwater, catchments, flooding, rivers, forests*

INTRODUCTION

Groundwater has long been recognised as an important part of hydrological functioning of catchments. Although early work on flood generation ignored the subsurface due to the specific environment being investigated (Horton 1933), research quickly evolved to include infiltrated water (Hursh and Brater, 1941; Dunne and Black, 1970). Much of this early focus on subsurface runoff mechanisms was on flow along the soil-bedrock interface and interflow through macropores. However, Sklash and Farvolden (1979), in their seminal paper "the role of groundwater in storm runoff", explained runoff generation processes in a completely different way. They used naturally occurring stable isotopes to show that most river water at high flows was actually 'subsurface water present in catchment soils and rocks before the rainfall event'. If the water being delivered to streams really was groundwater, the problem this raised was how such large volumes of groundwater become mobilised so rapidly. Research in the 1990s helped to address this issue further by proposing mechanisms in which soil layers near the soil-bedrock interface become saturated and then hydraulically connect during storm events of long enough duration. This process helps to mobilise old (pre-event) water towards the base of slopes through the development of a pressure head (McDonnell, 1990). This mechanism and a similar mechanism of 'transmissivity feedback' have helped explain the 'old water paradox' (Kirchner, 2006). At the scale of whole hillslopes, experiments have shown evidence for these mechanisms leading to threshold behaviour, in which whole hillsides are 'switched on' during events of particular rainfall intensities (McGlynn et al., 2003). This is sometimes called 'fill and spill' since it is not the surface topography that determines flow paths, but the subsurface topography and/or impermeable soil horizons and their role in controlling the development of saturated conditions. This significant body of research has led to a conceptual model of hillslope runoff mechanisms that includes overland flow due to infiltration excess, but emphasises flow processes within soils and bedrock.

How these conceptualisations of groundwater in catchments actually work out in practice in the temperate, post glacial environment of Northern Europe is still poorly resolved. This is due in part to the challenges of undertaking research that can identify the different flow pathways through a catchment. Consequently, groundwater flow paths are still often neglected when examining or modelling flow in a catchment. This has implications for designing and implementing catchment measures which rely on increasing infiltration and catchment storage, such as flood alleviation measures, Natural Flood Management or re-afforestation. In this study we discuss recent and ongoing research in the Eddleston Research Catchment, a tributary of the River Tweed in the Scottish Borders, where we have developed several experiments to examine the role that groundwater plays in catchment functioning.

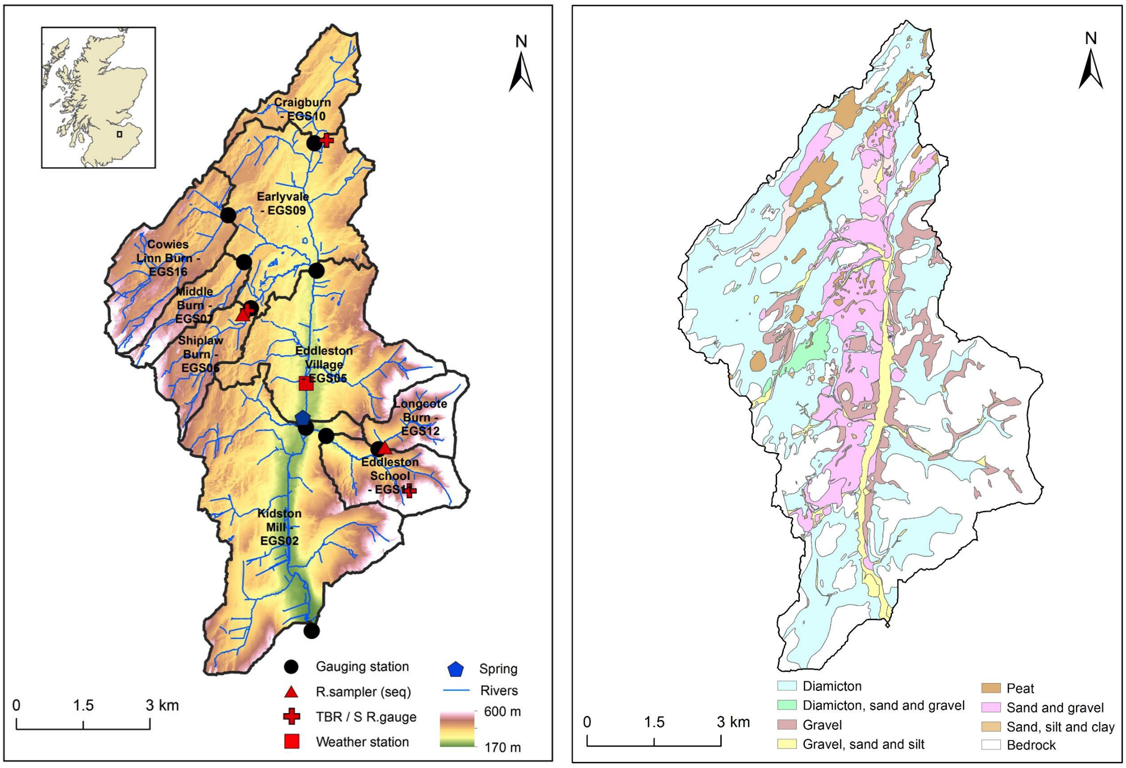

Figure 1: *The Eddleston catchment: (left) location of monitored sub-catchments, gauging stations and rainfall recorders (Peskett 2020a); and (right) superficial geology (Auton, 2011). BGS © UKRI*

THE EDDLESTON CATCHMENT

The Eddleston Water catchment (69 km^2) is a tributary of the River Tweed in the Scottish Borders, UK. The Eddleston Water flows due south and is fed by several distinct sub-catchments (Figure 1). The catchment is host to the Scottish Government's long-term study on the effectiveness of NFM measures to reduce flood risk to downstream communities and improve habitats for wildlife. The project is a partnership initiative led by Tweed Forum (a local non-governmental organisation), with the Scottish Government, the Scottish Environment Protection Agency (SEPA), the University of Dundee, the British Geological Survey and Scottish Borders Council (Black et al. 2021).

Catchment characteristics are typical of much of the UK uplands. Topography is in the range of 180-600 m (Figure 1), mean annual precipitation is ~900 mm, falling mainly as rainfall, and monthly mean temperatures range from 3 to 13 °C. Land cover is mainly improved or semi-improved grassland on the lower slopes, rough heathland at higher elevations and marshy ground in the hollows. Extensive coniferous plantations were established in the 1960s and 1970s in some of the western sub-catchments, with up to 90% forest cover. Forest cover in other parts of the catchment is typically mixed coniferous and deciduous woodland, concentrated along field boundaries. Soils on steeper hillsides are typically freely draining brown earth soils overlying silty glacial till, rock head or weathered head deposits. Towards the base of the hillslopes the ground is typically wetter and soils comprise sequences of gleyed clays and peats on sub-angular head deposits, or alluvial deposits closer to the river (Soil Survey of Scotland Staff, 1970).

Bedrock throughout most of the catchment is comprised of Silurian-age, poorly permeable, well-cemented, poorly sorted sandstone greywackes (Auton, 2011). Extensive glaciation during the last glacial maximum has affected the superficial geology and soil types (Ó Dochartaigh et al., 2019). The western part of the catchment has extensive, thick and poorly permeable glacial tills (often >5 m thick) (Aitken et al., 1984) but with some highly permeable glacio-lacustrine sands and gravels in isolated areas (Figure 1). The centre of the catchment has extensive alluvial and head sand and gravel deposits (up to 20 m thick) overlying bedrock or glacial till.

EXPERIMENT 1: INFILTRATION

The first groundwater experiment undertaken in the catchment was to investigate the influence that land use, and in particular forestry, has on soil permeability and infiltration (Archer et al. 2013). Figure 2 shows the experimental set up and some of the results, which are represented as runoff. The results show the importance of broadleaf woodland in increasing soil permeability, and therefore infiltration, when compared to neighbouring grassland. There was also a relationship with the age of woodland, with infiltration greatest in oldest forests, most likely due to the deeper organic layer and presence of coarse roots. However, there was no statistical difference in soil permeability between 40 year old plantation and neighbouring grassland. When examining only the grassland sites, superficial geology was the main control on soil permeability, and therefore infiltration to groundwater.

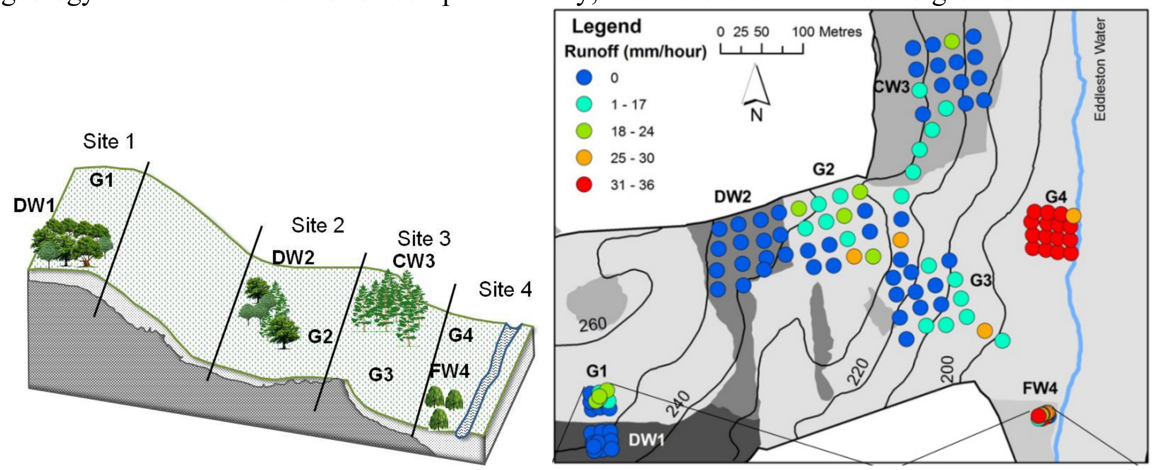

Figure 2: *Estimated runoff for grasslands and different types of forestry at the Darnhall observatory in Eddleston. G1-4 sites are improved grassland, DW1 is 500-year-old broadleaf woodland, DW2 is 180-year-old broadleaf woodland, CW3 is 45-year-old conifer plantation, and FW4 is floodplain woodland (Archer et al, 2013). Reprinted from Journal of Hydrology, 497, 208–222 © 2013, with permission from Elsevier* https://www.sciencedirect.com/journal/journal-of-hydrology

EXPERIMENT 2: FLOODPLAIN AQUIFERS

A second investigation was undertaken in the Darnhall floodplain, just north of Eddleston Village (Figure 1) to examine how groundwater in small upland floodplains interacted with the river and adjacent hillslopes (Ó Dochartaigh et al., 2019). Detailed geophysical surveys using a variety of electrical methods, and trial pits and site investigation boreholes, were constructed to develop a 3D geological model. Ten piezometers were then carefully sited, tested and monitored to characterise the 3D groundwater behaviour within the floodplain. Nine years of monitoring of groundwater, rainfall and river flow shows how the geological structure of the floodplain affects groundwater within the floodplain and mediates the interaction between the hillslope and river flow (Figure 3). Groundwater levels respond strongly to river stage for approximately 100 m distance from the river. However in the floodplain hillslope interface groundwater levels respond more slowly and continue to rise for several days after rainfall maintaining high (artesian) water levels for weeks – sustained by subsurface flow from the hillslope. Permeable solifluction deposits facilitate this sub surface coupling (Figure 3).

Adjacent to the river channel, the river generally loses water to the aquifer, and re-emerges just south of the study area in a wetland. During high river flows, the water levels rise rapidly in the floodplain, and then groundwater discharges back to the river in the following days as the river stage falls and the groundwater gradient changes.

The chemistry of the groundwater is impacted by the geological structure, with pockets of reducing groundwater associated with higher base metals, increased dissolved carbon and evidence of nitrate reduction, associated with the presence of silts and peat.

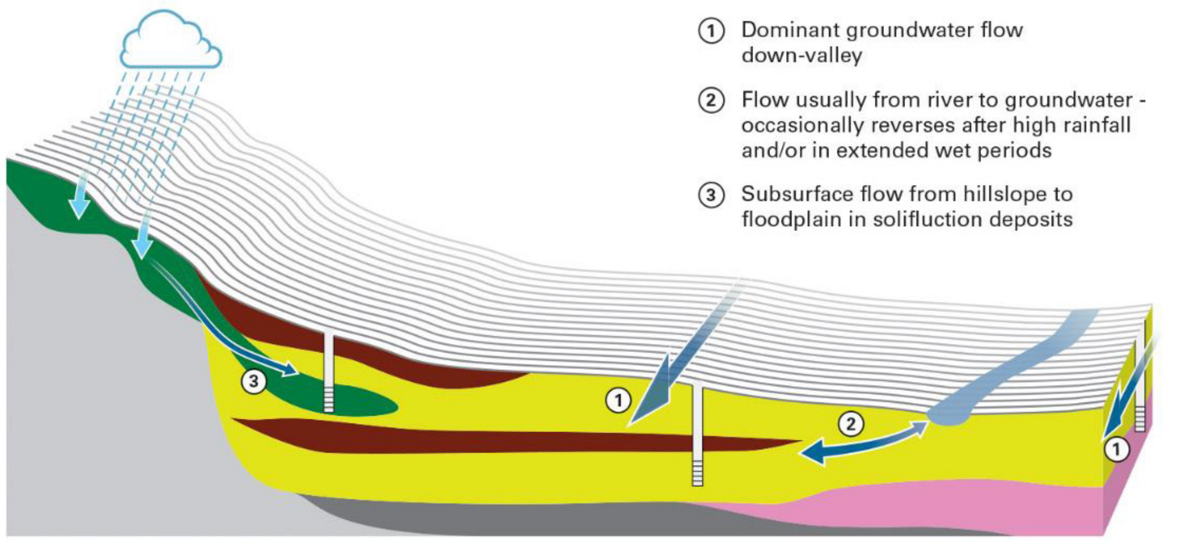

Figure 3: *Conceptual model of the groundwater flow at the Darnhall observatory in Eddleston (Ó Dochartaigh et al. 2019). Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/)*

EXPERIMENT 3: GROUNDWATER UNDER A FOREST STRIP

The impact of forest strips on infiltration and groundwater flow through hillslopes was examined on a hillslope on the main stem of the Eddleston Water 3 km south of Eddleston Village (Figure 1). Two 60 m long transects were instrumented with shallow piezometers (2.5 m deep) and soil moisture probes (0.15 and 0.6 m depth), one through a 27 year old forest strip and the other on improved grassland (Peskett et al. 2020b). Repeat ERT surveys were also undertaken along the surveys approximately every 6 weeks. In the parallel transects, soil and groundwater dynamics were recorded up slope, midslope (which encompassed the forest strip in the forested transect) and downslope

(Figure 4). The monitoring identified significant differences in sub-surface moisture dynamics underneath the forest strip: drying of the forest soils was greater, and extended deeper and for longer into the autumn compared to the adjacent grassland soils. However downslope of the forest, soil moisture dynamics was similar in the forest and grassland transects, and no significant effect was recorded 15 m downslope of the forest. Groundwater levels in the forest strip were persistently deeper than the grassland and this effect was observed downslope of the forest strip. However, during the wettest conditions, the monitoring indicated upslope-downslope water table connectivity beneath the forest (Figure 4) with response times similar for the grassland and the forest transect. This research suggests that fragmented forest strips may have little impact on groundwater connectivity within a catchment during wet periods, although further research in a variety of different geological environments is needed.

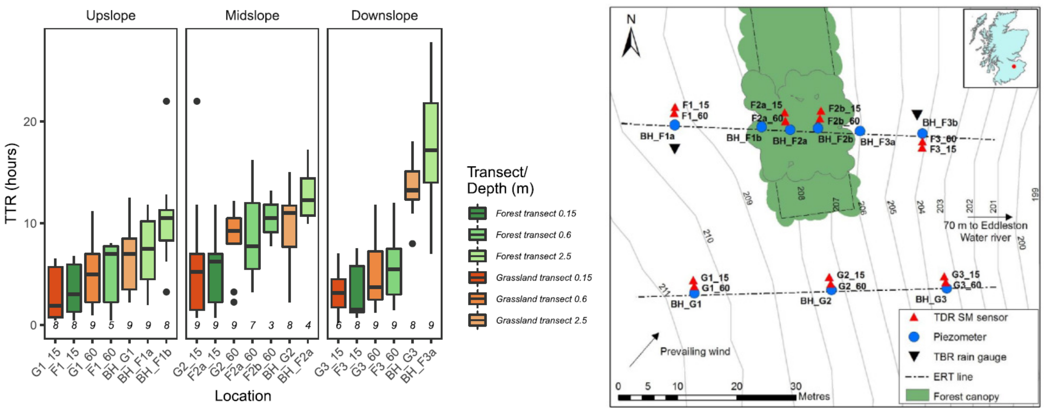

Figure 4: *Time to response from the start of rainfall (TTR) for uplsope, midslope and downslope for the forest strip and grassland transects for the 9 wettest events where the monitoring network responded to rainfall. G refers to grassland strip, F for forest, BH is piezometer and 15 and 60 refer to soil mositure at 15 cm and 60 cm respectively. In each domain shallower sensors respond quickest to rainfall. Groundwater response time increases with distance down slope, but with no statistical difference between the grassland and forest strip (Peskett et al. 2020b). Reprinted from Journal of Hydrology, 581, 124427 © 2020, with permission from Elsevier* [*https://www.sciencedirect.com/journal/journal-of-hydrology*](https://www.sciencedirect.com/journal/journal-of-hydrology)

EXPERIMENT 4: GROUNDWATER FLOW DURING STORM EVENTS

Detailed monitoring was undertaken over a two year period, 2015-2017, of three sub-catchments, Middle Burn, Shiplaw and Longcote (Figure 1) to determine the proportion of surface rainfall runoff, soil water and groundwater in streamflow during a storm event. Detailed fieldwork was undertaken during storm events to monitor temporal variability in stable isotopes ^{2}H and ^{18}O in rainfall and streamflow, and Acid Neutralising Capacity (ANC) in streamflow (Peskett et al., 2020a). These data, along with weekly baseline monitoring over the 2 year period, were used to separate hydrographs into three component parts: event runoff, soil water and groundwater. The three sub-catchments had different characteristics, Middle Burn and Shiplaw had similar geology, but Middle Burn had a much higher proportion of plantation (spruce) forestry (94% Middle Burn compared to 41% in Shiplaw). The geology for Longcote was different – with little superficial geology cover and mostly fractured Silurian bedrock close to surface – and had negligible forest cover. An example of the results for one of the storms is shown in Figure 5.

The results of this survey are soon to be published (Peskett et al., 2021) and indicate that pre-event water stored in soil and groundwater is an important component of stream discharge during storms for these small catchments (<10 km^2). Geology and soil type appeared to exert a stronger control on the fraction of event water compared to the extent of plantation forest cover – demonstrating the importance of the hydrogeological environments in flood generation.

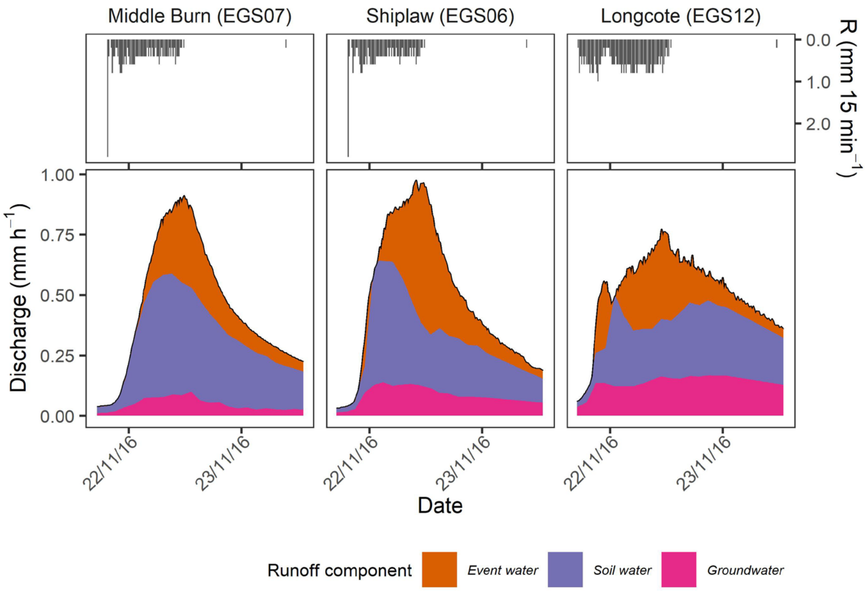

Figure 5: *Three-component hydrograph separation based on stable isotopes in streamflow and rainfall and ANC in streamflow relative to baseflow conditions. Much of the streamflow comprises pre-event water stored in the catchment, with the greatest proportion soil water (Peskett et al. 2020a). The Longcote catchment with limited glacial till, and more bedrock exposed, shows a slower response during storm events and a greater proportion of groundwater within streamflow.*

CONCLUSIONS

Ten years of research in the Eddleston Research Catchment has highlighted the importance of groundwater in catchments. Monitoring groundwater in poorly permeable upland catchments is challenging and a range of techniques are required, from detailed site characterisation and monitoring to integrating methods using tracers. Below are some of our findings.

- Soil type and superficial geology exert a strong control on infiltration to groundwater, with broadleaf forests increasing infiltration and also deepening groundwater levels. Coniferous plantations had a less demonstrable impact on infiltration to groundwater.
- Shallow groundwater flow through hillslopes is significant during wetter periods, and responds more slowly than soil water (hours - days) to heavy rainfall, but can persist longer (days – weeks) when activated. Groundwater connectivity appears not to be disrupted by fragmented forest strips. However, more research is required to observe how this changes with antecedent conditions.
- Pre-event water stored in soil and groundwater comprises a significant component of stream flow during storms, and for the headwaters monitored was >50%. The hydrogeological conditions of the catchment appear to exert strong control on this proportion, with a higher groundwater proportion, and longer delays in fractured bedrock compared to sub-catchments with low permeability superficial deposits.
- Groundwater in small floodplains helps to mediate the coupling between hillslope and river, providing a buffer to the connectivity. Higher river levels during flood events are propagated through the floodplain, reversing river/groundwater gradients after river levels recede. Elevated groundwater levels at the floodplain edge due to hillslope flow have been observed in the Eddleston and elsewhere (MacDonald et al. 2014).

Building on the long term monitoring and multidisciplinary study at the Eddleston has helped uncover some groundwater behaviour, with much more still to discover. The investment in characterising and monitoring the catchment makes it an ideal location for future research.

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Soil Survey of Scotland Staff, 1970. Soil maps of Scotland (partial coverage) at a scale of 1:25 000.

BLANKET BOGS AND STREAMFLOW – THE UNDER-APPRECIATED ROLE OF GROUNDWATER.

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ABSTRACT

Despite covering approximately 13% of Ireland, the hydrology and hydrogeology of blanket bogs remain poorly understood. Existing conceptual models provide paradoxical views of their influence on catchment hydrology, ranging from them as acting as sponges, which dampen flooding, to promoting flashy runoff regimes. Much of the data supporting these views derives from areas where blanket peat displays evidence of significant human disturbance, while conditions in relatively intact areas remain poorly characterised. Understanding hydrological processes in less disturbed areas proves necessary to provide realistic restoration targets, aimed at developing / preserving natural capital and improving ecosystem services. A four year EPA-funded study investigated hydrological processes operating in three relatively intact blanket peat-covered catchments, and adjacent, more degraded areas. This paper presents some of the main findings. Runoff monitoring revealed that although flow derived from peat could explain higher discharges, rates observed during prolonged dry periods required additional sources of water. Similarly, while water quality sampled during storm events resembled that collected from piezometers in peat in all catchments, base flow quality varied significantly between sites. Combining chemical and physical hydrological data suggest that sustained groundwater inputs from units underlying peat, mixing with variable amounts of bog water, explained the runoff quality observed. More limited evidence suggests that degraded peat results in more variable stream flow and water quality, as the contribution from bog groundwater is reduced, while deeper groundwater discharge remains unchanged. This in turn points to more stressful conditions in aquatic ecosystems draining more degraded blanket bog, which may influence WFD status.

Key words: *Blanket Bog, Baseflow, Water Quality, Aquatic Ecology.*

INTRODUCTION

Blanket bogs are a familiar feature in the Irish landscape, where peat overlies diverse geological units, ranging from low permeability clays to karstified limestone. Their occurrence in Ireland closely aligns to with areas experiencing high (>1200mm) and frequent (>160 rain days) rainfall throughout the year (Mitchel and Ryan, 1997). These conditions can allow them to develop on slopes of up to 30 degrees. Despite their coverage, and the importance of water in their development, the hydrology of blanket bogs remains poorly understood, with the peat having diverse processes attributed to it (Bacon et al., 2017). This knowledge gap arises in part because of the water logged conditions and low fertility encountered in blanket bogs, which has resulted in them being negatively perceived and receiving limited attention from the hydrological / hydrogeological community.

More recent recognition of the wider economic importance of peatlands has led to a reappraisal of more traditional perspectives on their value. This has included an improved appreciation of the importance of blanket bogs as sources of water, with the UK and Ireland using over 80% of all water derived from peatlands worldwide (Xu et al., 2018). The large volumes of high quality water, derived from them, coupled with their dominance in hosting high status water bodies in Ireland constitute important ecosystem services and an important basis for preserving blanket bogs as valuable elements of national natural capital (Bonn et al., 2016). This contrasts with possible ecosystem disservices, experienced when bogs have degraded, including diminished raw water quality and heightened flood risk. Despite these claims, underpinning evidence for many services and disservices remain scare and contentious. This includes the capacity of blanket bog to buffer against flooding. Some authors have claimed blanket bogs act as sponges, soaking up rainfall and limiting the impact of intense precipitation, while making an argument for the restoration of damaged areas to reduce levels of downstream flood intensity (Pearsall, 1950). However, little to no information exists concerning hydrological processes in blanket bogs undamaged by human activity. This in turn limits the establishment of realistic targets against which the success of restoration measures can be assessed. Similar arguments can be made concerning water quality, and aquatic ecosystem condition more generally.

CATCHMENT INVESTIGATIONS

Given the knowledge gaps concerning blanket bog hydrology, a four year EPA-funded research programme “Toward the quantification of blanket bog ecosystem services to water (QUBBES)” aimed to better characterise their hydrological & hydrogeological processes and the ecosystem services that they support. Application of multiple criterion analyses (MCA) to 1403 Irish blanket peat-covered catchments, allowed three of the most intact areas to be selected for detailed site-specific field investigations. (No catchment greater than $1km^2$ proved free of physical damage due to human activity). Although MCA aimed primarily to identify suitable sites based on the condition of blanket bog cover, climatic and substrate geological conditions also assisted in the final catchment selection process. Figure 1 presents the location of the selected catchments, while Table 1 summarises physical conditions at each.

Instrumentation of these areas, and adjacent more degraded catchments with hydrological, hydrogeological and water quality monitoring infrastructure permitted comparison of hydrological conditions between catchments. Clusters of piezometers, sited at representative locations, selected using the peatland hydrological model of Mackin et al. (2017), allowed water table and deeper peat (base of the peat) groundwater level monitoring, while also permitting hydraulic conductivity testing and collection of samples for water quality analyses. Simultaneous monitoring of evapotranspiration (at two sites), rainfall and stream stage at the outlets of both intact and degraded catchments provided runoff data needed to facilitate integrated physical hydrological / hydrogeological characterisation. Complementary water temperature and electrical conductance (EC) loggers allowed continuous measurement of runoff water quality, while lab analyses of grab samples enabled correlation of EC data with concentrations of specific analytes.

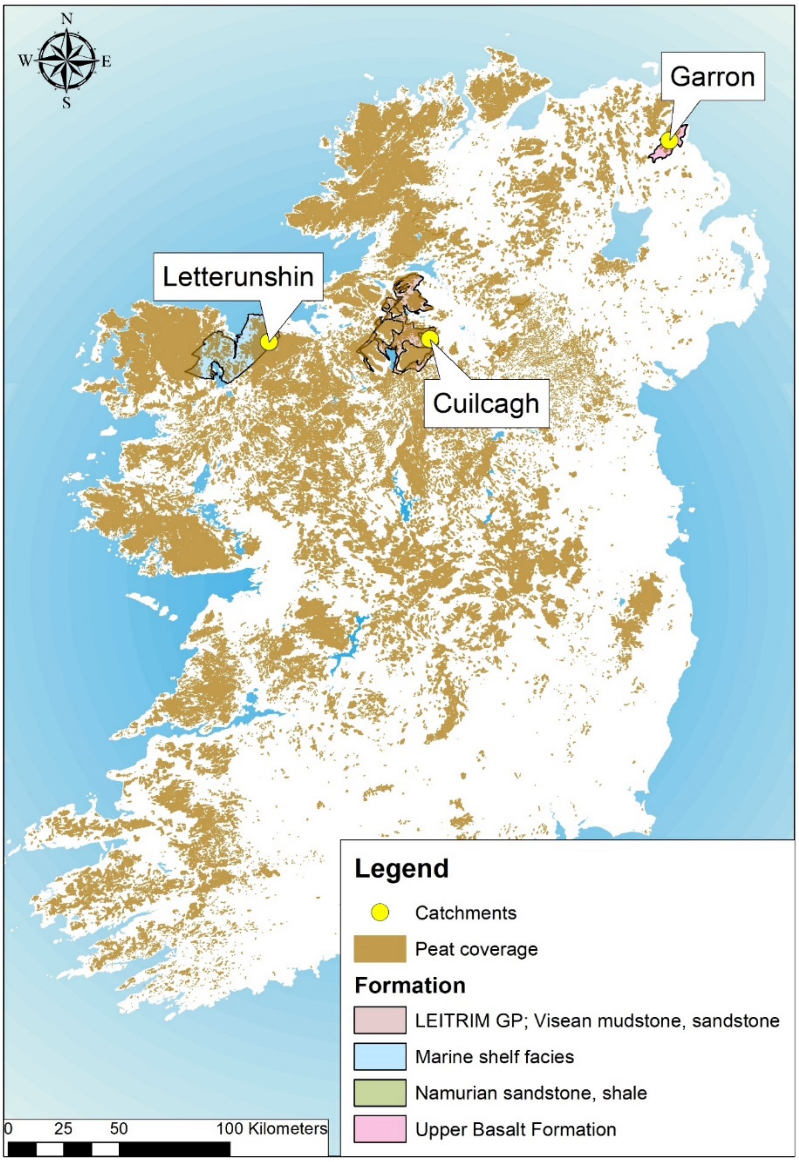

Figure 1: Location of (intact & Degraded) QUBBES test catchments selected for hydrological investigations. (Geological boundaries courtesy of the GSI)

FINDINGS

Water level monitoring at all locations in all three relatively intact (Intact) catchments revealed winter water tables in the peat remained consistently within 20cm of the ground surface. This compared to the hydrogeological regime in summer, when levels remained within 20cm of the ground surface for more than 80% of the time. However, logger data from all three catchments revealed that water levels can fall as low as 55-60cm below ground during prolonged drier periods (corresponding approximately to the rooting depth of heather (*Calluna vulgaris*)).

The decline in water table in the peat corresponds with a decrease in runoff rates and a change in stream water chemistry. Figure 2 summarises typical conditions, observed at Garron, Co. Antrim, during the summer of 2018. Although both groundwater levels and runoff during this time displayed significant sensitivity to rainfall, this relationship proved less responsive during the prolonged dry period between mid-June and mid-July. More specifically, periods of light rain during this period, although prompting rises in groundwater level, failed to generate corresponding increases in runoff rate, with discharge effectively remaining constant.

Catchment	**Letterunshin[1]**	**Garron[2]**	**Cuilcagh[1]**
Area "Intact" (ha) Area Degraded (ha)	160.3 214.5 (incl 160.3)	140.8 183 (incl 140.8)	239.1 138.2
Bedrock	Dinantian Upper Ballina Limestone Formation	Palaeogene (Tertiary) Upper Basalt Formation	Dinantian Orthoquartzitic Sandstone, with mixed sandstone and shale units
Aquifer Classification	Regionally Important Karst (Rk)	Moderately Productive Fissured (Bmf)	Locally Important, Moderately Productive (Lm)
Peat substrate subsoil	Till derived from Metamorphic rocks (TMp). No outcrop visible.	Till (Diamicton)	Till derived from Namurian Sandstones and Shales TNSSs
Permeability	Moderate	Low	Low
Effective Rainfall (mm/yr)	1105	n/a	1381
Recharge (mm/yr)	44	n/a	55
<u>Maximum elevation (mAMSL)</u> "Intact" Degraded	 150<x<140 150<x<140	 431.5 334	 660 <370<x<380
<u>Min Elevation (mAMSL)</u> "Intact" Degraded	 <110<x<120 <100<x<110	 298 278.5	 300<x<310 220<x<230
Nearest Surface Water Hydrometric Monitoring Point	Easkey_030 RS35E010020	n/a	Swanlinbar River RS36S010100
WFD Surface Water Status	Good	n/a	High
<u>Causes of Degradation</u> Intact Degraded	 Grazing Grazing or forestry, burning	 Drainage, Grazing Drainage, Heavier Grazing	 Burning, Grazing Grazing, peat cutting, drainage
Stocking Density (L.U./ha)	0.44	0.075	0.57
Nearest Weather Station	Cloonacoo, Co. Sligo (No. 3135)	Ballypatrick Forest, Co. Antrim	Cuilcagh Mountains, Co. Cavan (No. 2037)
Weather Station Elevation (mAMSL)	204	156	290
30 year Average Precipitation	1598	1313	1999
30 year Average Evapotranspiration	493	n/a	614
30 year Average Rain Days (>0.2mm/day)	259	n/a	238
30 year Average Wet Days (>1mm/day)	218	n/a	198
Other Hydrological Comments.	Widespread piping at headwaters	Piping feeding stream	Localised calcareous springs

Table 1: Summary of physical conditions encountered at the QUBBES research catchments. (Hydrogeological data from GSI and GSNI)

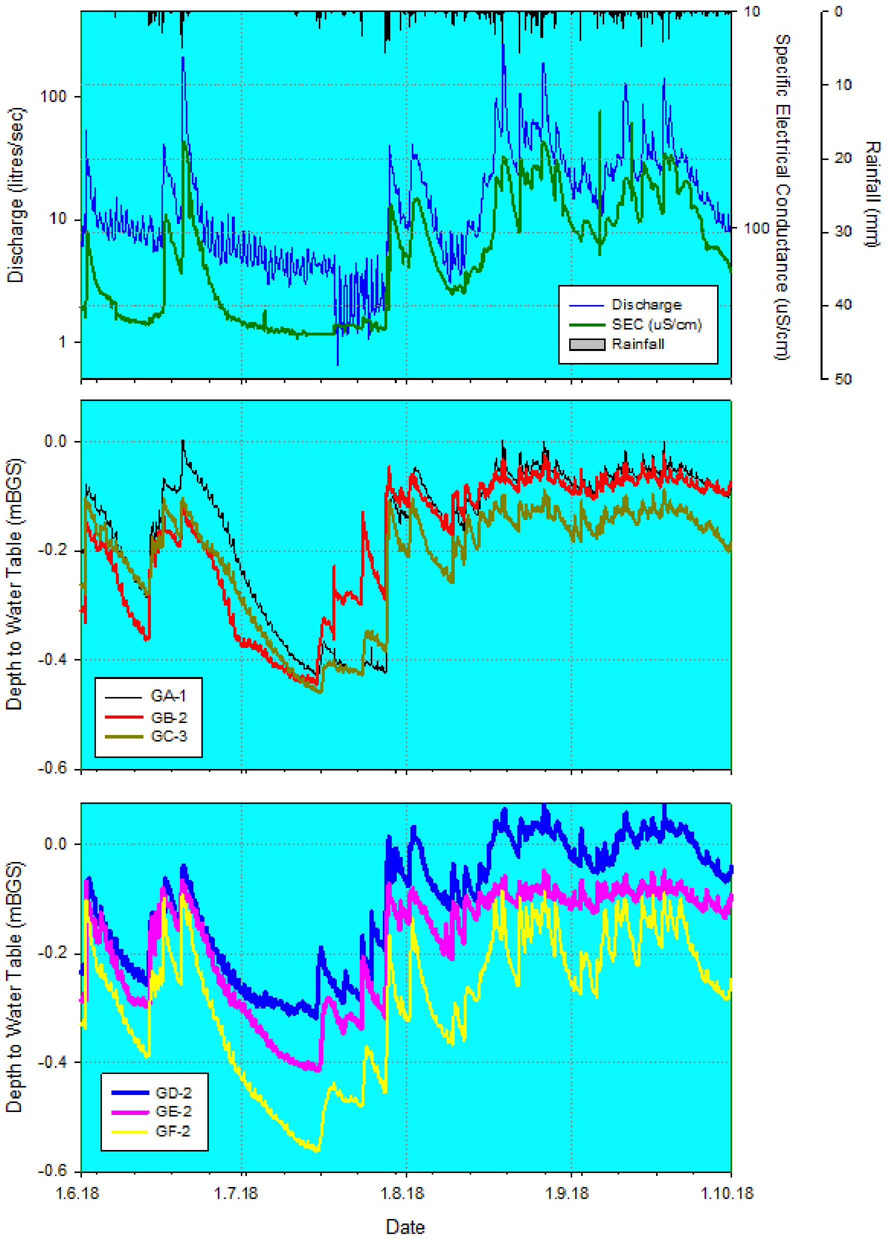

Figure 2: Above: rainfall runoff response for the stream draining the Garron Intact Catchment. Centre and Below: Groundwater hydrographs for peat piezometers.

Electrical conductivity data (at Garron), reflecting the ionic content of the water displayed a similar response, with water at the end of the prolonged dry period proving significantly more conductive than that during the mid-June flood peak, which closely resembled bog water. Monitoring data from the other catchments revealed comparable trends of bog water becoming more mineralised with decreasing flow to be consistent across all (intact and degraded) catchments studied. On the other hand, conductivity levels varied significantly between catchments for equivalent dry periods.

Incorporation of ionic data sheds further light on this trend and revealed that water chemistry, although comparable during peak flow, becomes progressively more distinct with declining discharge (Figure 3). Crucially, base flow chemistry differs between catchments, and reflects interactions between recharge flowing through peat and the units underlying it. Findings from Letterunshin prove particularly informative, as base flow is calcium rich, while neither the peat nor the inorganic subsoils immediately underlying it have significant levels of Ca, thus demonstrating that much of the baseflow derives from deeper more calcareous units, such as the limestone bedrock.

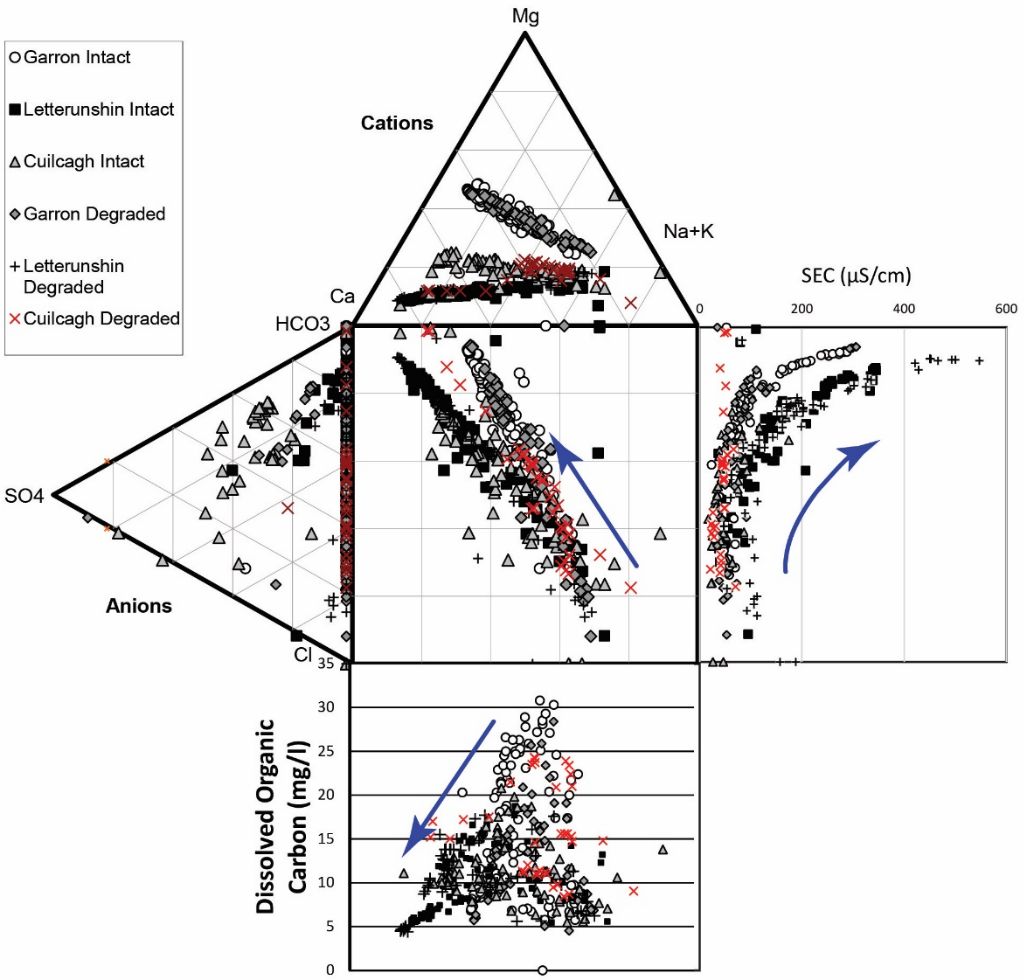

Figure 3: Expanded Durov plot summarising the change in water chemistry in QUBBES blanket bog research sites with declining flow rates (indicated by bold arrows).

Examination of stream flow rates and persistently high water tables in the peat indicate that the driving hydraulic gradient for stream baseflow is essentially invariant and that the contribution made by ground water to stream flow is constant. By contrast, mixing models using SEC and dissolved organic carbon (DOC), derived from peat groundwater, can account for the variation in stream water quality observed.

Pairwise comparison of water quality sampled at degraded catchment outlets, with that sampled from the outlet of intact sites reveals that the runoff affected by forestry displays higher degrees of mineralisation, while DOC levels display no significant differences, despite higher concentrations encountered in shallow groundwater under forestry. Investigations on the ground reveal this to be a consequence of sustained upwelling of deeper groundwater, which makes up a greater relative proportion of stream flow. On the other hand, while the degraded bog water has a higher DOC water content, discharge from the peat is reduced due to lower peat hydraulic conductivity, compacted due to drainage. Consequently, forestry has reduced the diluting effect of bog water, leading to more mineralised runoff. This mineralisation is further reflected by increased levels of iron precipitation on the stream bed, which can lead to a lower number of sensitive invertebrate taxa.

CONCEPTUAL MODEL

Compiling the results of the physical and chemical hydrological data, collected for all three research catchments, has allowed the conceptual model, presented in Figure 4, to be developed. Contributions to stream flow from the inorganic materials underlying the peat provide a constant base flow throughout the year. This is supplemented by variable contributions of bog water, derived principally from the upper layers of peat, as indicated by slug testing. This results in a more stable water chemistry and is suspected to give rise to less variable stream flow.

This situation contrasts with sites that have experienced drainage, which has altered peat properties. Despite the damage caused, groundwater heads in the peat remain high, continuing to drive discharge of more mineralised deep groundwater. By contrast, discharge from the peat proves more variable, with significantly lower contributions to stream during prolonged dry periods, giving rise to more mineralised water. This compares to storm water fluxes, which are suspected to be higher. Overall, these changes lead to more variable, and ecologically more stressful conditions in areas where peatland has been degraded.

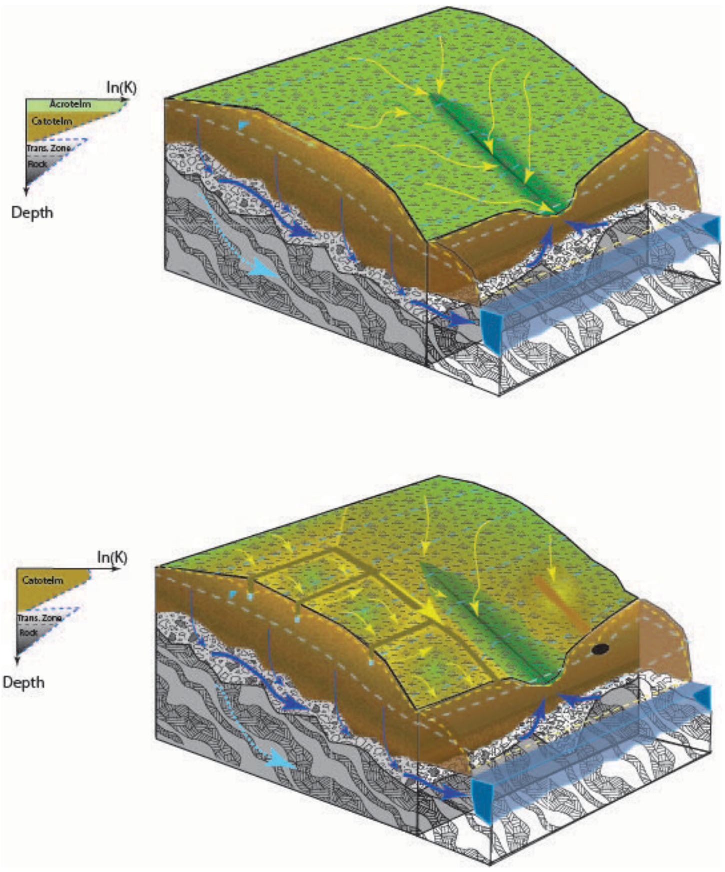

Figure 4: Conceptual model of blanket bog hydrology. (Above) Intact peat (Below) Degraded Bog, affected by drainage.

IMPLICATIONS

The findings of the QUBBES research have implications for a number of ecosystem services

1. Biodiversity: The information collected in the QUBBES study has demonstrated that blanket bog drainage has the capacity to not only affect terrestrial biodiversity, with the loss of hydrologically sensitive moss species, but also to impact the status of aquatic ecosystems. The on-going degradation of Irish high status sites, the majority of which are located in

catchments containing blanket bog, can at least, in part, be explained by bog degradation. Water bodies which have experienced degradation require a programme of measures to restore them. Identification of appropriate abiotic supporting conditions will prove necessary to establish realistic restoration targets.

2. Water Quality: Many Irish drinking water supplies derive their raw water from areas containing blanket bog. These include not only those areas in the north and west of the country, but also larger cities (e.g. Dublin, which draws water from the Wicklow Mountains). Blanket bog degradation gives rise to increases in DOC levels in raw water, which needs to be removed at considerable expense, along with carcinogenic disinfection by-products, such as trihalomethanes (THMs). On the other hand, reducing DOC levels at source, through maintenance of healthy blanket bog can keep DOC levels lower, leading to more sustainable water management.
3. Stream Flow / flood risk: Evidence collected from all sites suggested that more degraded catchments displayed flashier flow regimes. However, quantifying these differences has been complicated by contrasting topographic conditions and the need to develop coherent integrated hydrological/hydrogeological models to simulate blanket bog stream flow. More work is needed on this topic.

Overall, the findings of this study have helped further highlight the importance of groundwater in maintaining hydrological processes in areas lacking significant aquifers. More work is needed to more confidently quantify many of the relationships observed in data collected from the study catchments. Most notably, this includes investigations into quantifying the impact of developments on peatland and how these affect hydrological processes. Ultimately, the findings of such research will feed into catchment models aimed at more integrated and sustainable management of the one eighth of Ireland underlain by blanket peat.

ACKNOWLEDGEMENTS

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CHARACTERISATION OF FLOWS IN A WESTERN KARST TERRAIN, USING HYDROLOGICAL AND HYDROGEOLOGICAL METHODS

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ABSTRACT

Catchment management in karst settings poses a particular set of challenges, resulting from the inherent heterogeneity of the hydrogeological and hydrological setting. This results in significant variability in groundwater and surface water responses to rainfall, potentially over small distances. This occurs at flood locations at Ballyfree and Carrowroe townlands in Sligo, which are 1km apart, but which have contrasting flow and flooding mechanisms, requiring different management responses. Design of effective catchment management responses is informed by characterisation of the setting, derived at a scale appropriate to the required management and including data collected about the specific flow conditions to be managed.

Key words: *karst, conceptual model, quantitative data analysis*

INTRODUCTION

Flooding at the southern outskirts of Sligo town in December 2015 caused damage to commercial and domestic properties, at a scale which had not previously occurred, in areas removed from mapped risk of fluvial flooding. Extreme rainfall conditions occurred in Winter 2015–16 (Noone *et al*., 2016), resulting in the highest groundwater levels and the most widespread groundwater flooding which have been recorded (McCormack *et al*, 2018). Sligo Co. Co. and the Office of Public Works initiated projects to characterise and mitigate against flooding at the scale of the 2015 events, at two affected locations approximately 1 km apart, in the townlands of Carrowroe and Ballyfree.

SUMMARY OF METHODS

A regional conceptual model (CM) was developed to provide a framework and boundaries for more detailed works, from which it was iteratively updated. The evolution of the 2015 flood at each location was characterised. Field mapping and survey of hydrogeological and hydrological features, topography and hydrochemistry were carried out. These works informed the subsequent monitoring programme and detailed surveys. Monitoring of water levels, temperature and gauging was carried for a minimum period of six months, at two swallow hole inflow channels, three springs, a lake, a borehole and a sub-annual flooding topographic basin. Surface water channel and basin numerical flow modelling, level-volume modelling, time series analysis and event based water balance calculations were carried out.

CONCEPTUAL MODEL

BEDROCK AND SUBSOIL COMPOSITION AND GEOMETRY

Bedrock geology within the area of the regional conceptual model comprises a localised shallow dipping synclinal basin of Dinantian pure bedded limestones (Dartry Formation, comprising fine grained, cherty, pure bedded limestones) overlying Dinantian upper impure limestone (Glencar Formation, comprising dark fine limestone and calcareous shale). The basin occurs on the north western, down block side of the Ox Mountains-Pettigoe Fault and the Precambrian quartzites, gneisses and schists, which form a topographic ridge on the south side of the fault (MacDermot *et al*, 1996). Steeper bedrock dips in this area of the basin result from fault drag in this area. See **Figure 1** Regional Geology and Hydrology. The pure bedded limestone is therefore bounded below, to the north and to the west by the upper impure limestones and to the south by the very low permeability Precambrian rocks. They are karstified, and wedge out towards their boundary with the underlying upper impure limestones. A thick shale bed (3 m) is reported at 13 m b.g.l. in a GSI borehole c. 0.8 km south of Carrowroe, which may represent the transition to the underlying Glencar formation. This would indicate that the depth of pure bedded limestones in this area is limited and that the relatively lower permeability of the shale beds may act as a barrier to downward groundwater flow, resulting in concentration of groundwater flow within the overlying karstified limestones.

Subsoils in the study area result from several phases of glacial activity. Sub-glacial tills dominate the study area and form drumlins in the north east. Ice meltwater landforms comprise hummocky sands and gravels and esker ridges (Teagasc/EPA, 2014 and Geological Survey of Ireland databases). These meltwater landforms occur predominantly across the area between Tobernaveen and Carrowroe. Glacial action and patterns of deposition have resulted in enclosed basins in this area. Areas of exposed karst rock also occur.

GROUNDWATER AND SURFACE WATER INFLOWS AND OUTFLOWS

Two swallow holes have been identified at the flood location at Ballyfree, which have inflow rates indicative of connection to karst conduits. Enclosed topographic depressions, which will, where subsoils are thin or permeable, result in concentrated recharge, occur in other locations, including at and surrounding the flooding locations at Carrowroe. The relative paucity of point karst recharge features may indicate that recharge of any conduit karst flowpaths is primarily via connectivity with overlying epikarst. Diffuse recharge rates across the pure bedded limestone area vary from 60% up to 85% (Geological Survey of Ireland, groundwater databases).

Spring discharges fall into two broad categories. Numerous springs, such as at Tobernaveen, discharge where karst flow paths reach the edge of the pure bedded limestone (Dartry formation) at its contact with the likely extent of the upper impure limestone (Glencar Formation), in the north and west. Springs at Carrowgobodagh, in the south, discharge from the base of a pure bedded limestone escarpment and flows here are typical of fissured or conduit groundwater pathways. These springs are the sources of broadly permanent watercourses. Smaller, frequently ephemeral, springs and seepages occur where shallow groundwater discharges from subsoils and from bedrock, where and when the groundwater level intersects the topography in enclosed topographic depressions. These discharges contribute to wetlands and lakes, such as occur at Cloverhill Lough and Carrowmore lake and result in ephemeral waterbodies at Carrowroe and Cuilbeg townlands. Flows at springs at Carrowroe reflect a likely shallow epikarst pathway.

Regional groundwater gradients, in winter 2016 and derived by Higgins (1985) indicate that the dominant regional hydraulic control on groundwater flow direction is the coastal discharge boundary, towards which groundwater flows from the west and centre of the pure bedded limestones area. Tracing has identified karst flow pathways both north-westwards to Tobernaveen spring and southwards to Carrowgobodagh from Ballyfree in the centre of this area. Lough Gill, and its discharge via the Garavogue River, forms the eastern hydraulic boundary control. A regional groundwater divide must occur in a broadly north-south direction between Carns Hill and Slieve Dangan. Localised gradients will occur in shallow groundwater flows in response to topography. Surface watercourses occur downstream of discharges from major springs or as artificial drainage channels which intermittently convey water from topographically enclosed areas.

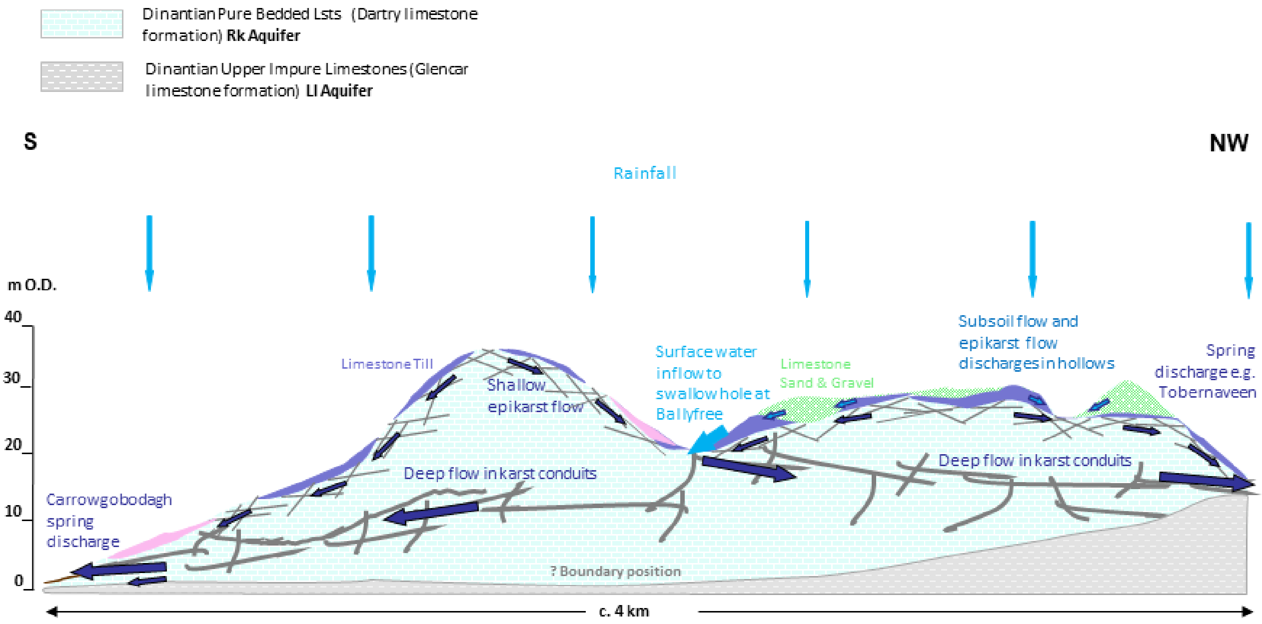


Diagram 1: *Conceptual Cross Section (See **Figure 1** for location)*

BALLYFREE FLOOD AREA

SETTING AND METHODS

The area around two swallow holes SH1 and SH2 at Ballyfree, flooded in 2015. They receive surface and groundwater from an artificially enlarged surface water catchment (2.2 km^2), comprising a series of enclosed topographic sub-catchments linked by a network of deep 19th century drainage channels. This results in flows from the Carrowmore Lough sub-catchment to SH1 and from the linked two Cloverhill Loughs sub-catchment to SH2. These flows include both spring discharges into the lakes and surface water run-off.

Water levels during the 2015 flood event were estimated primarily from photographic records, which are not continuous. Flood storage volumes and net inflows and outflows at Ballyfree were estimated from height-volume models and 2D numerical flood models (Flood Modeller 2D), derived from topographic data. Water levels in the two inflow channels to SH1 and SH2 at Ballyfree, in spring discharge channels at Tobernaveen and Carrowgobodagh east and west (with which tracing has shown connectivity) and at Carrowmore lake, were monitored continuously for two periods in 2018 – 2019. The water level-flow (stage-discharge) relationships were derived from short 1-D numerical channel models (Flood Modeller 1D), calibrated with gauged flows, with highest weight being given to high flow data. Flows were estimated from water level using regression models.

ANALYSIS AND CHARACTERISATION

The first and most rapid flood peak in 2015 occurred in the wake of rainfall between 4/12/2015 17.00 and 6/12/15 06.00 comprising 95.4 mm, falling on a saturated catchment. The resultant flood volume peak on 6/12/2015, which comprised 50,207 m^3, was approximately 27 hrs later, indicating a response time to rainfall of considerably less than 27 hours. This time to peak flow was approximately one day less than that of the Garavogue River at a gauge close to its discharge to Sligo Bay. Flow in the swallow hole inflow channels did not occur throughout the 2018-2019 monitoring period, ceasing in summer 2018. **Plot 1** illustrates that flows peak in response to rainfall events and recede rapidly. Response time from the start of the rainfall events varies, from 9 hours to 12 hours, depending on the magnitude of the rainfall event. Flow response is more dampened in Channel SH1 than SH2, likely because of available storage capacity in the two lakes in the Cloverhill Loughs sub-catchment and the presence of controls on surface water flows through the low gradient drainage system. Water temperature at SH1 in 2018 – 2019 is highly correlated with air temperature (range 5 to 15 ºC). These characteristics are typical of surface water dominated flows.

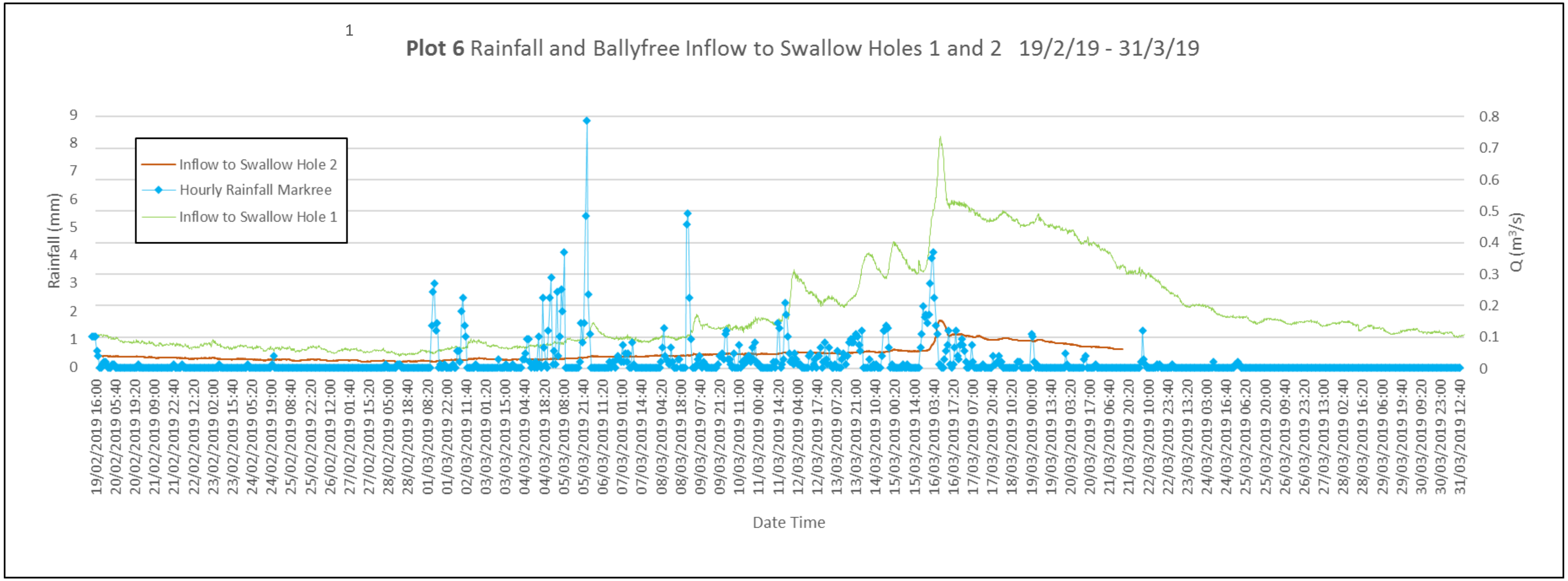
Maximum estimated inflow rate to the swallow holes in 2019 was 0.86 m^3/s. Averaged maximum net inflow rate during the 2015 flood, calculated from the increase in flood storage volume over time, was 0.5 m^3/s. Assuming a swallow hole outflow rate of 0.6 m^3/s (see below), an average rate of 1.1 m^3/s can be estimated for 2015. This is less than the 1.38 m^3/s average flow rate estimated from 85% of catchment ER during the first flood response. Flows of the order of the higher value are therefore used in mitigation proposals.

Channel SH1 has a calculated conveyance rate of up to 1.0 m^3/s. However, the characteristics of the maximum recorded 2019 flow event suggest that the flow peak of 0.71 m^3/s relates to the capacity of the swallow hole being exceeded, causing an instantaneous spike in water level, until the flow rate reduces back to 0.5-0.6 m^3/s and a more constant flow pattern. A catchment water balance was iterated for the critical 2015 flood peak event, using a range of swallow hole outflow capacities, in combination with the known event flood volume in storage. Assuming a swallow hole outflow rate of 0.6 m^3/s, the water balance indicates surface water run-off of 84% of effective rainfall from the catchment. This is a reasonable run-off rate, given the antecedent rainfall and soil moisture conditions (www.met.ie). This rate is approximately twice the average annual expected run-off rate, estimated as the compliment of groundwater recharge rate. Maximum net outflow rate estimated during 2015, is considered a significant underestimate at 0.05 m^3/s, due to uncertainty in data timing and continuing inflows during the period.

The fact that exceedance of the swallow hole capacity can occur briefly as in March 2019, which had below average antecedent rainfall conditions, indicates that the outflow capacity of SH1 (with SH2) is the dominant hydrological control on outflow from the Ballyfree flood storage area. Flood water will accumulate when it is exceeded. Groundwater levels downgradient at Carrowgobodagh are almost certainly not a significant controlling factor on inflow to the swallow holes. The likely minimum linear gradient between Ballyfree and Carrowgobodagh in 2015 was of the order of 0.007. This is also indicated by the timing of the downgradient flooding in 2015. The maximum flood peak and commencement of recession occurred on 9/12/2015 at Ballyfree, but peak flood occurred on 13/11/2015 in the downstream Carrowgobodagh wetland area. The Carrowgobodagh springs pattern of flow peak and recession in 2018 is closely aligned to that at Ballyfree (See **Plot 2).** Response of peak flows to rainfall lags behind Ballyfree SH1 peak inflows by just a number of hours, when flows are occurring at Ballyfree, indicative of fast flow pathways in conduit type karst. Flow rate at Tobernaveen spring is the least variable and significantly dampened relative to Ballyfree. It does however have a similar response time to the most significant monitored rainfall event at Carrowgobodagh, indicating at least intermittent karst conduit flow. Flows at all springs continue when inflow to the Ballyfree SH1 has ceased and cumulatively are greater than combined flows from Ballyfree, indicating additional recharge sources.

CATCHMENT MANAGEMENT RESPONSE

The measures to mitigate against flooding at the scale of the 2015 events comprise two elements. The source control proposal is to restrict outflow from the Carrowmore Lough sub-catchment and utilise additional storage available in this enclosed topographic basin. The proposed reduction in outflow allows the remaining flood volume to be stored in the Ballyfree area. Iterative 2-D modelling of the Ballyfree area indicates that a flood defence, with a top height at c. 21.5 m O.D., will protect adjacent properties from flooding.



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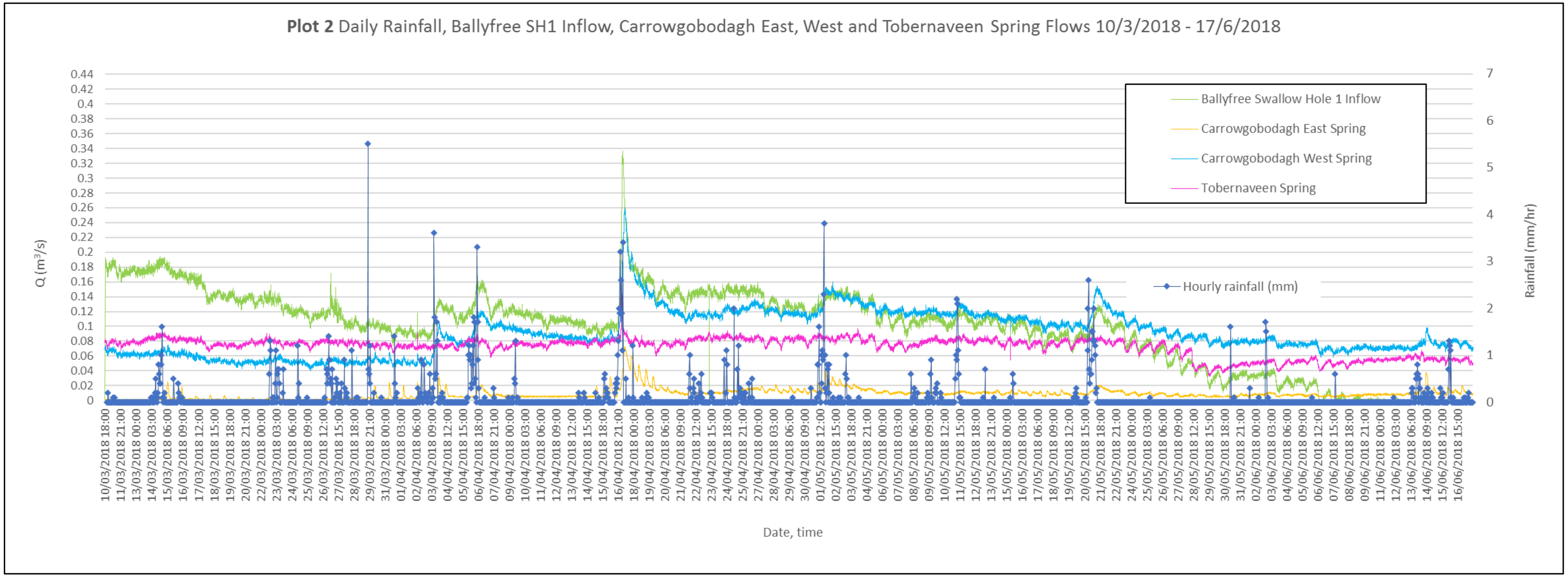
Plot 6 Rainfall and Ballyfree Inflow to Swallow Holes 1 and 2 19/2/19 - 31/3/19
Inflow to Swallow Hole 2
Hourly Rainfall Markree
Inflow to Swallow Hole 1
Rainfall (mm)
Q (m3/s)
Date Time



Plot 2 Daily Rainfall, Ballyfree SH1 Inflow, Carrowgobodagh East, West and Tobernaveen Spring Flows 10/3/2018 - 17/6/2018
Ballyfree Swallow Hole 1 Inflow
Carrowgobodagh East Spring
Carrowgobodagh West Spring
Tobernaveen Spring
Hourly rainfall (mm)
Q (m³/s)
Rainfall (mm/hr)
Date, time

CARROWROE FLOOD AREA

SETTING AND METHODS

The Carrowroe flood location comprises two shallow enclosed topographic basins, separated in part by the remains of an esker ridge. Filans Field (FF) is a natural depression in agricultural land which floods sub-annually within its boundaries. MRM is a yard area excavated into bedrock, 200 m west, which very rarely floods. Land westwards, in Carrickhenry townland, comprises agricultural land which had not flooded in living memory until 2015.

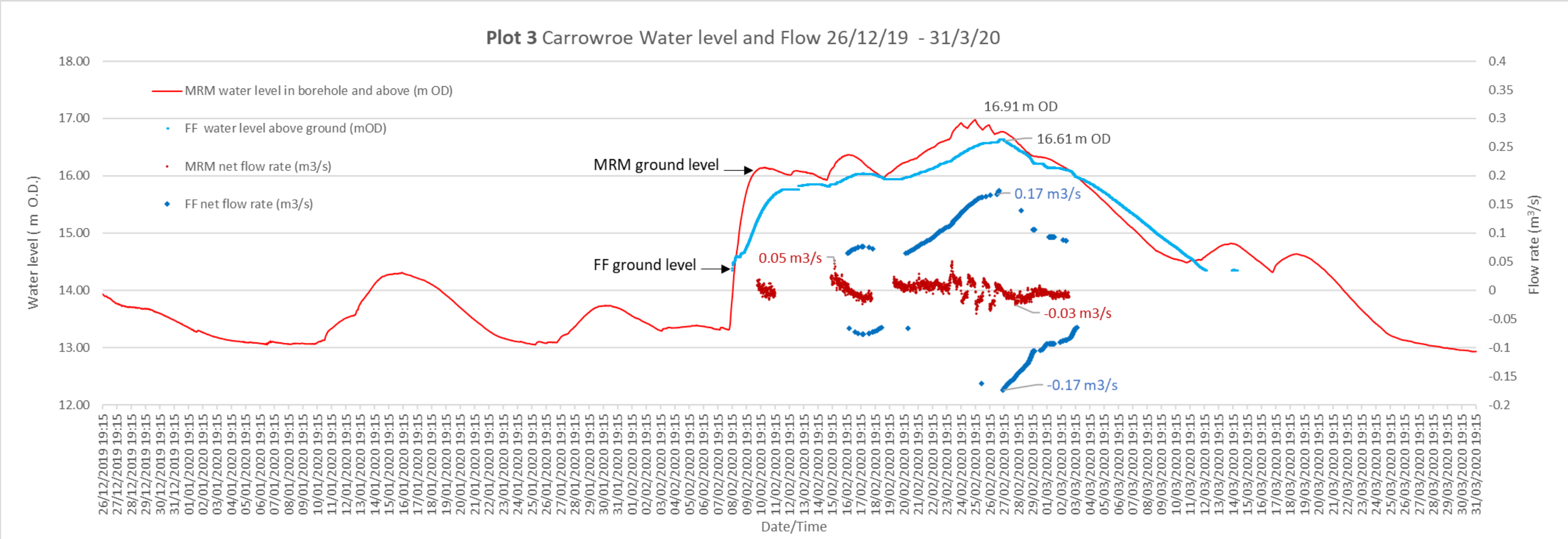
Water levels in 2015 were estimated from aerial photographs and photographic and measured records. They are not continuous and subject to uncertainty. Continuous water level monitoring was carried out during 2018 – 2020 above ground level at FF and during winter 2019-2020 at a pre-existing borehole to -15 m O.D. at MRM. Flood storage volumes and net flow rates were estimated from height-volume models derived from topographic data.

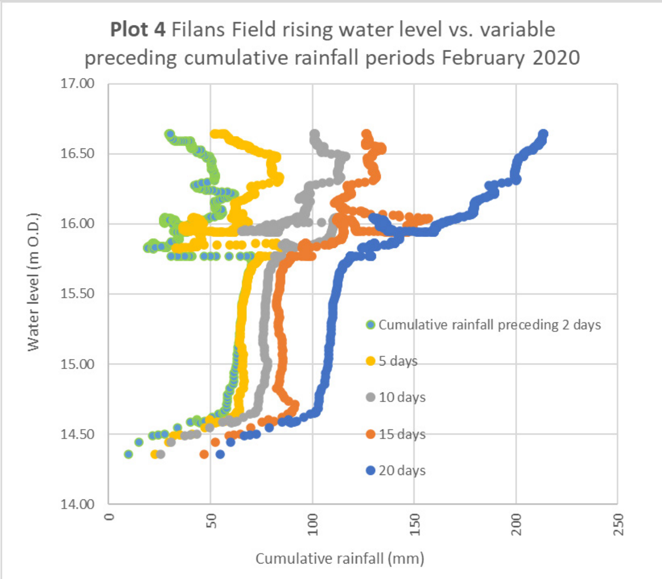
ANALYSIS AND CHARACTERISATION OF FLOWS

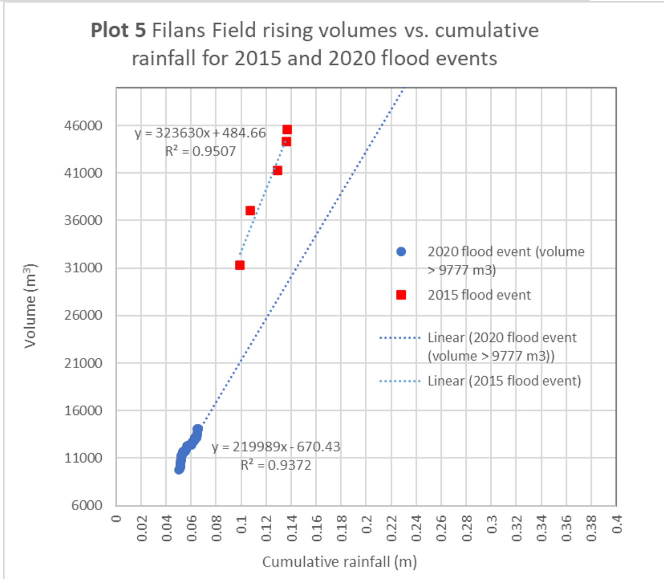
The 2015 rainfall event between 4/12/2015 17.00 hrs and 6/12/15 06.00 hrs, which fell on a saturated catchment, comprised 95 mm. This resulted in a rising water level at Filans Field (FF) resulting in a flood volume of approximately 41,000 m^3, and in the MRM excavation, resulting in a flood volume of approximately 7,000 m^3. A number of houses and the regional road adjacent to FF and the MRM yard flooded. A smaller rainfall event occurred on the 9th and water levels continued to rise smoothly peaking on 11 December at MRM and across 11-12 December at FF. Peak water level estimates at FF of 17.9 m O.D. (45,500 m^3) are 0.4 m higher than at MRM (8,800 m^3), though there is some uncertainty in this data. Disconnected pockets of agricultural land to the west and south were also flooded by the 11th. A single flood event occurred over the 2018-2020 monitoring period, in February 2020, illustrated in **Plot 3** and only within the bounds of FF and MRM**.** The two sites have the same pattern of response to rainfall, albeit that the rising flood limb at MRM reaches a given water level approximately 30 hours in advance of FF. The available 2015 data points to a similar lag. The maximum peak of 16.9 m O.D. which occurred in MRM, is approximately 0.3 m above FF. The peaks result in flood volumes of 5,700 m^3 and 14,000 m^3 at MRM and FF respectively. Soil moisture conditions were saturated during both flood events, at zero soil moisture deficit.

The relationship between rising water levels and cumulative rainfall over a range of preceding time periods was examined. The data indicates that water levels at FF and MRM above ground level are most highly correlated with cumulative effective rainfall from the preceding 20 days. **Plot 4** shows the series of distinct linear relationships which occur at FF, each segment with an r-squared value of >0.90. FF receives surface water drainage from a section of road and an adjacent row of houses and this is reflected in the high degree of correlation with all of the 2 to 20 days cumulative rainfall. Two distinct ephemeral springs occur at 15.75 m O.D. The significantly stronger correlation between 20 day cumulative rainfall and water level above this height, indicate that water levels at and above this level are dominated by groundwater inflows.

In addition to longer term cumulative rainfall, initial water level rises during both flood events were preceded by significant two-day rainfall amounts, 95 mm in 2015 and 59 mm over two days in 2020. Cumulative rainfall amounts in 2015 preceding the two-day rainfall event were 184% of average monthly cumulative amount, whereas cumulative rainfall in 2020 preceding the event, was at the expected average monthly amount. Response time to the two day event on 8-9 February was within 24 hours in the MRM borehole, with rapid water level rise commencing on 8 February, although this did not result in damaging flood levels. The peak flood was on 25 February and was not preceded by a single large, short duration event.


Plot 3 Carrowroe Water level and Flow 26/12/19 - 31/3/20
MRM water level in borehole and above (m OD)
FF water level above ground (mOD)
MRM net flow rate (m3/s)
FF net flow rate (m3/s)
16.91 m OD
16.61 m OD
MRM ground level
FF ground level
0.17 m3/s
0.05 m3/s
-0.03 m3/s
-0.17 m3/s
Water level (m O.D.)
Flow rate (m3/s)
Date/Time


Plot 4 Filans Field rising water level vs. variable preceding cumulative rainfall periods February 2020
Water level (m O.D.)
Cumulative rainfall (mm)
Cumulative rainfall preceding 2 days
5 days
10 days
15 days
20 days


Plot 5 Filans Field rising volumes vs. cumulative rainfall for 2015 and 2020 flood events
y = 323630x + 484.66
R² = 0.9507
y = 219989x - 670.43
R² = 0.9372
2020 flood event (volume > 9777 m3)
2015 flood event
Linear (2020 flood event (volume > 9777 m3))
Linear (2015 flood event)
Volume (m3)
Cumulative rainfall (m)

Cumulative rainfall from commencement of rising water level is strongly linearly correlated with flood storage volume (r-squared value of >0.90), see **Plot 5**. However, extrapolation of the regression, based on lower values in 2015, significantly underestimates the volumes which occurred in 2015, underlining the importance of extreme value data in characterisation.

Maximum net inflow rates above ground level calculated for the 2020 flood are 0.17 m^3/s at FF and 0.05 m^3/s at MRM. These are in excess of net values derived from the 2020 flood data of 0.1 m^3/s and 0.03 m^3/s. This may be due to averaging of discontinuous 2020 data or, less likely, due to different inflow rates at the higher range of water levels recorded in 2015. Net inflows of the order of the higher value are therefore used in mitigation proposals.

The 2020 data shows a smooth rise in inflow rate, with water level height at FF ranging from 0.6 to 0.17 m^3/s (rates below this have not been included in this analysis). In contrast, rates at MRM are constrained between 0 and 0.05 m^3/s. This is attributed to a greater increase in transmissivity at FF, due to its basin geometry. This geometry causes contributing upgradient width to increase with (water level) height. The MRM excavation has a constrained contributing upgradient width. This will result in a higher net accumulation rate and higher levels over time in FF, while inflow is greater than outflow. This is likely the cause of the higher 2015 peak water levels in FF.

This increase in transmissivity with height, coupled with the continuity in water level height and inflow pattern across disconnected basins in 2015 and 2020, is considered to indicate flows from an epikarst zone, rather than discrete fissure or conduit type flows. In addition, there is no tidal influence in the MRM borehole (to -10 m O.D.), indicating no connectivity with deep groundwater. Rapid increase in water levels on 8 February indicate low storage in the epikarst zone. Groundwater flow direction in the area is therefore presumed to be aligned with topographic gradient and from the north east.

Maximum net outflow rates above ground level calculated for the 2020 flood are -0.17 m^3/s at FF and -0.03 m^3/s at MRM. The pattern of decreasing rate is expected with decreasing hydraulic head. These rates are an order of magnitude in excess of net values derived from 2015 data, although there is significant uncertainty here due to data gaps. High water levels in the downgradient epikarst in 2015 are likely to have decreased groundwater gradient, impeding outflow during the available data period. Net outflows of the order of the lower values are therefore used in mitigation proposals.

CATCHMENT MANAGEMENT RESPONSE

The proposed flood mitigation proposals comprise a number of elements, based on the above characterisation. These are: Permanent diversion of piped road surface water drainage away from FF and a sump in the area, in order to maintain available flood storage volume; Monitoring in a borehole, to identify rapid rises in water level up to 16 m O.D. in response to rainfall events, and use of the time lag to initiate flood response; Trigger height levels in FF will be set for commencement of pumping into the public surface water drainage system downgradient and outside of the topographic basins; Trigger levels will be set relative to known maximum inflow rates and available storage; Demountable defences are likely to be provided to properties that flooded in 2020, to defend houses in situations where net inflow rates are in excess of pumping rates and available storage is exceeded.

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SESSION IV

THE RECAST OF THE DRINKING WATER DIRECTIVE – CHALLENGES AND OPPORTUNITIES FOR PROTECTING OUR SOURCES

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ABSTRACT

Irish Water abstract raw water from approximately 290 surface water and 960 groundwater catchments, that cover approximately 50% of the land area of Ireland. Source protection is the first line of defence in the multi-barrier approach to ensure safe and secure drinking water is provided to our customers. Irish Water has adopted the WHO Drinking Water Safety Plan (DWSP) approach to protect human health by identifying, assessing and managing risks to water quality and quantity; taking a holistic approach from source (catchment) to tap (consumer). Irish Water have developed evidence-based risk assessment methodologies for source hazardous events. Irish Water also has several source protection initiatives underway to manage risk within drinking water catchments, including implementing the Interim Pesticide Strategy and two pilot projects focused on reducing pesticide contamination at source.

The challenge still remains to develop a process to manage risks in all drinking water catchments on a prioritised basis. This can only be achieved with the support of stakeholders who have the ability and resources to take the actions required. The improved alignment between the revised DWD and the WFD should help to facilitate this collaboration between stakeholders and the pooling of resources and expertise. The new risk-based approach to monitoring should allow funding and resources to be targeted at higher risk hazards that are most relevant to the catchment risks. The data and information generated will be extremely valuable for helping to achieve the aim of a safe and secure water supply to protect human health.

Key words: *Drinking water, source protection, Recast Drinking Water Directive, risk assessment, DWSP, Drinking Water Strategy Plan, Pesticides*

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INTRODUCTION TO IRISH WATER'S APPROACH TO SOURCE PROTECTION

Every day Irish Water provides 1.7 billion litres of treated drinking water from 918 treatment plants to over 80% of Ireland's population. We abstract raw water from approximately 290 surface water and 960 groundwater catchments. When combined, these drinking water catchments cover approximately 50% of the land area of Ireland, as shown in Figure 1.

It is important that the quality of drinking water sources is protected and improved in order to safeguard human health and the aquatic environment. Source protection is the first line of defence in the multi-barrier approach to ensure safe and secure drinking water is provided to our customers. By focusing on solutions that tackle the source of the problem rather than dealing with the consequences, we will manage risk in a much more holistic and efficient manner that can achieve additional benefits. These additional benefits are widely recognised, and include improving the quality of our aquatic environment, the potential to improve local biodiversity, and limiting the carbon intensive energy requirements, which additional "end-of-pipe" treatment would require.

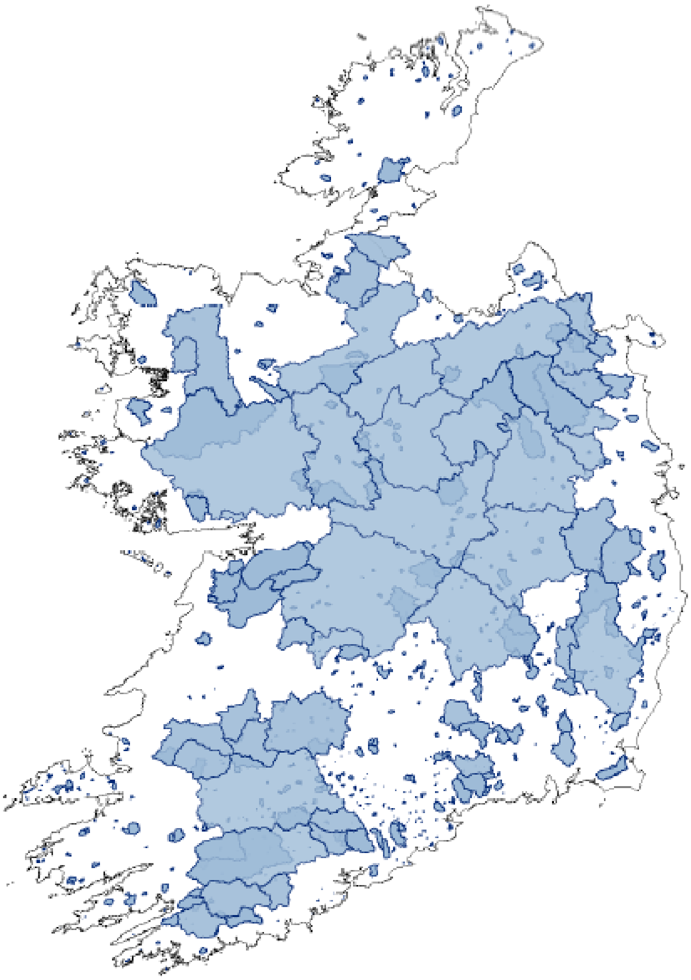

Figure 1: *Coverage of surface water and groundwater catchment areas for abstraction points for public water supplies (draft)*

In 2015, Irish Water published its Water Services Strategic Plan (WSSP), which sets out our strategic objectives for the delivery of water services up to 2040. Our WSSP strategic objectives and aims relevant to drinking water source protection are outlined below:

Ensure a Safe and Reliable Water Supply:

- Manage the sustainability and quality of drinking water **from source to tap** to protect human health.
- Prepare and implement **Drinking Water Safety Plans**

Protect and Enhance the Environment:

- Ensure that Irish Water services are delivered in a **sustainable manner,** which contributes to the protection of the environment.
- Work effectively with other stakeholders to support a **catchment-based approach.**

DRINKING WATER SAFETY PLAN APPROACH

Under the “Ensure a Safe and Reliable Water Supply” objective of the WSSP, Irish Water has adopted the Water Safety Plan approach. This approach is recommended by the World Health Organisation (WHO) in their Guidelines for Drinking Water Quality (2004) and Water Safety Plan Manual (2009). The approach, more commonly referred to as the Drinking Water Safety Plans (DWSPs), seeks to protect human health by identifying, assessing and managing risks to water quality and quantity; taking a holistic approach from source (catchment) to tap (consumer). Irish Water commenced the development of a new evidence-based approach to DWSPs for all water supply zones in 2018. The completion of DWSPs is also a key requirement of the revised Drinking Water Directive (DWD) (EC, 2020a) which is discussed further on in this paper.

Source Risk Assessment

The DWSP approach involves assessing a comprehensive range of hazardous events that could potentially occur in a drinking water supply from source to tap. DWSP hazards can be grouped into various categories e.g. biological, chemical, physical, radiological etc., all of which have the potential to impact the safety and/or security of a water supply. Where a hazardous event occurs, it can lead to the presence / manifestation of a hazard (e.g. the runoff of fertiliser to a river or leaking septic tank). The risk assessment of DWSP hazardous events involves determining the potential impact (i.e. severity) and likelihood (i.e. probability) of a hazardous event occurring and reaching drinking water.

The ‘source’ component of DWSPs is a key component, and understanding the catchment characteristics is important to support the identification, assessment and prioritisation of the risks (WHO Europe, 2017). Irish Water is developing scientifically robust semi-quantitative methodologies using GIS to risk assess drinking water sources and carry out site-specific Source and Sanitary Surveys (Figure 2). A greater emphasis is being placed on the source-pathway-receptor (SPR) concept for contaminant delivery. Historically the DWSP source risk assessments would have largely been subjective and relied on professional judgement. The SPR approach requires an understanding of the pathways that contaminants might travel. These pathways differ depending on whether surface water or groundwater are the receptor, and the characteristics of environmental components, such as soils, subsoils and geology. The impact on the receptor is also influenced by the level of dilution. Existing national scale catchment related datasets published by the Environmental Protection Agency (EPA) and Geological Survey Ireland (GSI) are being utilised, as well as the significant work to date undertaken by the GSI, EPA and local authorities to create Source Protection Zone (SPZ) reports.

Figure 2: *Irish Water’s approach to DWSP source risk assessment*

A Source and Sanitary Survey will be undertaken at every abstraction location to help ground truth and validate the GIS-based catchment level assessment. The process will help to determine if visible hazards exist immediately adjacent to the abstraction point. This information may provide indications of potential point source loads that could be underrepresented in the GIS-based catchment level assessment.

Source Risk Management

Irish Water’s multi-barrier approach to managing risk to drinking water takes a source to tap approach; by seeking to reduce the level of contamination entering water sources, applying robust multiple treatment barriers at the water treatment plants and having appropriate temporal and spatially distributed monitoring programmes to validate performance. A barrier is defined as any action, process, procedure, standard or asset put in place across the entire system, from source to tap, to help achieve water of sufficient quality and quantity.

When completed, the new DWSP source risk assessments will be used to inform the required interventions that will manage or mitigate the likelihood of the hazardous events from occurring. The evidence-based approach to risk assessment will enable more informed decision making and prioritisation of risks to target the implementation of “*the right measures in the right place*” (DHLGH, 2017). This data and information can be used to target higher risk areas of land, where catchment management measures would be most beneficial.

Irish Water is in the early stages of conceptualising drinking water catchment action plans for managing the identified source risks with the appropriate mitigation measures. These will include the identification of the main risks to source water quality, the actions required to address those risks and the relevant geographical areas where those actions should be focused. The plans will be developed in collaboration with the relevant stakeholders, who share the common goal of reducing the risk of contamination of our drinking water sources.

CURRENT SOURCE PROTECTION INITATIVES

Partnership working
Irish Water is committed to working with public bodies and other stakeholders towards a common goal of the protection of drinking water sources. As part of WSSP objectives, we are developing an Interim Pesticide Strategy for our drinking water sources (to be published in 2021). It will serve as an interim strategy whilst pilot projects are ongoing, and we develop our long-term approach for catchment management for drinking water source protection.

The strategy will cover our collaboration with stakeholders in order to assess and manage the risk of pesticides in the catchment, with the DWSP forming a central role. The Interim Pesticide Strategy risk management framework consists of three key pillars with collaboration with stakeholders occurring during all stages of the risk management process as shown in Figure 3.

Figure 3: *Three key pillars of the Interim Pesticide Strategy*

Since 2015, Irish Water has been an active member of the National Pesticides and Drinking Water Action Group (NPDWAG). The NPDWAG is chaired by the Department of Agriculture, Food and the Marine (DAFM) and was formed to provide a coordinated and collaborative approach to prevent the ongoing prevalence of pesticides in drinking water catchments. Members include the Department of Housing, Local Government and Heritage (DHLGH), Teagasc/ Agricultural Sustainability Support and Advisory Programme (ASSAP), Agricultural Consultants Association (ACA), EPA, Local Authority Water Programme (LAWPRO), the Irish Farmers Association of Ireland (IFA), Irish Creamery Milk Suppliers Association of Ireland (ICMSA), Animal and Plant Health Association (APHA), National Federation of Group Water Schemes (NFGWS) and local authorities, among others. The main objectives of the NPDWAG are to:

- Enhance collaboration between key stakeholders.
- Facilitate communications regarding pesticides exceedances in drinking water.
- Raise awareness at a national and regional level.
- Promote best practice of pesticide use.
- Support Catchment Focus Groups for priority catchments.
- Identify policy and implementation gaps.

When made aware of pesticide exceedances, all group participants engage with their own network of staff and stakeholders to raise awareness of the issue in the relevant catchment area. When a drinking water supply has more persistent exceedances of the pesticide standards, a sub-group of the NPDWAG is formed to try to tackle the issues locally. These are called NPDWAG Catchment Focus Groups. The local stakeholder groups are an important step to harness local knowledge, identify synergies and coordinate efforts between stakeholders. Information obtained from the industry funded catchment monitoring programme are efficiently disseminated through these groups, so that stakeholder resources can be targeted within the catchment.

Since 2018, we have also taken a proactive approach to raising awareness regarding responsible use of pesticides, by issuing press releases and coordinating media engagement undertaken by NPDWAG members and engaging with relevant stakeholders. An annual spring media campaign, specific to every county, targets the farming community and other users of pesticides.

Pilot source protection projects

Irish Water is actively involved in pilot source protection projects in Ireland to trial catchment scale interventions to reduce the risk of pesticides causing exceedances in water supplies. The two key projects are described below:

a) **Source to Tap Project:** is a cross-border partnership project that focuses on the River Erne and the River Derg catchments, which cross the border between Ireland and Northern Ireland. Irish Water is a project partner, which is funded by INTERREG and match-funding has been provided by the Department of Agriculture, Environment and Rural Affairs in Northern Ireland and the DHLGH in Ireland. The project began in 2017 and will continue until the end of 2021. It aims to develop sustainable, catchment-scale solutions for the protection of rivers and lakes, which are the main sources of our shared drinking water. Source to Tap also delivers a learning and outreach programme targeted at informing and empowering the public about their role in protecting our clean and healthy freshwater environment. An Agricultural Land Incentive Scheme is being delivered in the Derg catchment, focused on changing land management practices for the protection of our water.

b) **Pilot Drinking Water Source Protection Project:** as committed to under the River Basin Management Plan 2018-2021 (RBMP), Irish Water is coordinating a pilot drinking water source protection project to "*trial innovative monitoring and management strategies aimed at reducing the risk of pesticide contamination of drinking waters*". Catchment management interventions are to be undertaken as part of the project and will involve a combination of behavioural-change initiatives and promotion of the sustainable use of pesticides. Scoping, consultation and planning of the project began in 2019 and the project will launch in 2021 in the selected pilot catchment.

REVISED DRINKING WATER DIRECTIVE

GENERAL OVERVIEW: WHAT'S NEW COMPARED TO DIRECTIVE 98/83/EC

On the 16 December 2020, the European Parliament formally adopted the revised Directive of the European Parliament and of the Council on the quality of water intended for human consumption, more commonly referred to as the Drinking Water Directive (DWD) (2020/2184) (EC, 2020a). The revised DWD entered into force 20 days after publication in Official Journal on 12 January 2021. The revised DWD must be transposed into national law by 12 January 2023. The revised DWD is intended to modernise the 20-year-old DWD (98/83/EC). The overarching objective of the revised DWD is to ensure a high-level of quality and transparency to make drinking water safer across Europe [EC, 2020b].

Under this revised DWD the following are the key changes:

- The requirement for a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer, with the inclusion of the requirement for catchment or raw water monitoring.
- Updates to quality standards for water intended for human consumption, in line with latest recommendations of the WHO. Specifically, there are:
    - Revised limits for: Antimony, Boron, Chromium, Lead, Selenium; and
    - New parameters: Bisphenol A, Chlorate, Chlorite, Haloacetic acids (HAA5), Microcystin-LR, PFASs – total, Sum of PFASs, Uranium.

- The establishment of a watch-list mechanism to allow for the monitoring of substances or compounds of public or scientific concern to health, such as endocrine disruptors, pharmaceuticals and microplastics.
- Minimum hygiene requirements for materials in contact with drinking water (e.g. pipes, taps) are required.
- Greater transparency of water quality information for customers is required.

IMPLICATIONS FOR DRINKING WATER SOURCE PROTECTION

Risk assessment and risk management of catchment areas

The revised DWD introduces the risk-based approach for the catchment areas for abstraction points of water intended for human consumption under Article 8. The risk assessment and risk management of the catchment areas is required to be implemented for the first time by 12 July 2027 and updated thereafter at least every six years.

As previously highlighted, the risk-based approach is not new and has been at the core of the WHOs holistic and proactive approach to managing risks in drinking water from catchment to tap since 2004 (EC, 2016). However, the risk-based approach has been missing in the DWD up to now and this is the first time it will be required by legislation. Currently the DWD encourages drinking water to be controlled at the "end-of-pipe" (EC, 2019) and does not recognise the cost savings by reducing the use of chemicals such as pesticides at the source, which is only a fraction of the costs of installing additional treatment (EC, 2016). The EC have recognised that the missing link in the DWD to drinking water source protection is an important factor which makes it difficult to achieve the objectives of the DWD and that many drinking water quality issues relate to contamination in the catchment (e.g. pesticides, nitrate and ammonia) (EC, 2016). This missing link makes the application of the polluter-pays-principle difficult (EC, 2016) but the revised DWD puts the risk-based approach at its core and allows for further prevention and mitigation measures to protect drinking water sources (EC, 2019) and favours actions to reduce pollution at the source (EC, 2020c).

Given the number and scale of drinking water abstraction catchments (Figure 1), it is unlikely to be possible to address every risk at the source. A stepwise approach will be required, that addresses the higher risks first, with the resources available and with the support of stakeholders who have the ability and resources to take the actions (WHO, 2016).

A new approach to monitoring

Currently the DWD requires that monitoring is undertaken at regular intervals independent of the level of risk (EC, 2018). WHO Europe (2017) recognised that measuring long lists of chemical parameters, whether or not they were present, can divert funding and resources away from preventing and reducing hazards at customer taps, and that it's not as effective as monitoring parameters that are most relevant to the catchment. The revised DWD brings in the concept of risk-based monitoring. This risk-based monitoring will help to ensure that resources are focused on the key issues for the water supply and the catchment (WHO Europe, 2017).

Understanding the source water quality and its variations is essential to support the identification, assessment and prioritisation of the risks and in turn to develop mitigation to control the risk in the catchments (WHO Europe, 2017). Article 8(2c) of the revised DWD provides a new requirement for appropriate monitoring in surface water or groundwater, or both, either in the catchment areas, or in raw water, of relevant parameters including DWD microbiological and chemical parameters. Monitoring already undertaken in relation to other European directives may be utilised in order to avoid overlapping of monitoring requirements. It will be a challenge to design and manage a national monitoring programme for this purpose, and to ensure that it is complimentary to existing monitoring networks. Microbiological monitoring programmes, in particular, will need to be suitable for understanding and capturing short-term variations (WHO Europe, 2017). Investigative monitoring of source water alongside catchment appraisals will also need to play a role (WHO Europe, 2017). However, the value of the data obtained to the risk-based approach to source protection will be enormous and can be used to validate source risk assessments, potentially locate hotspots of pollution and target areas of catchments for risk management measures, as well as evaluating the effectiveness of these measures.

The first requirement for a watch-list mechanism for drinking water is included in the revised DWD. The drinking water watch-list is intended to make it possible to respond to emerging concerns in a more dynamic and flexible way. The commission will establish the first watch-list by 12 January 2022 and Beta-estradiol and Nonylphenol will be included due to their endocrine-disrupting properties and the risk they pose to human health. The watch-list will indicate guidance values for each parameter and method of analysis (that does not entail excessive costs). Member States are required to monitor substances on the watch-list in order to establish their presence or absence. Member States may take into account the information collected under Article 8 of the revised DWD, with regard to the source risk assessment and monitoring.

Linkages with the Water Framework Directive (WFD)
The Water Framework Directive (WFD) (2000/60/EC) post-dates the current DWD and whilst there are currently no discrepancies between DWD and WFD; it is the view of stakeholders at a European level that there are issues with the way the current DWD has been implemented (EC, 2016). Article 7 of WFD requires the protection of drinking water sources and a reduction of the level of purification treatment requirements and recognises the catchment as the first line of defence. However, Article 7 is considered to be poorly implemented by Member States (EC, 2016). For example, the WFD and its daughter directive on Environmental Quality set environmental quality standards for a range of chemical substances in the aquatic environment, which does increasingly contribute to produce sufficiently clean and safe water (EC, 2016). However, certain substances with exceedances of the DWD standards are not regulated in environmental waters e.g. pesticides such as MCPA, an active ingredient in a herbicide commonly used to treat rushes.

In addition, managing risks to drinking water is often perceived as the sole duty of the water supplier, however, there are many catchment stakeholders that have the ability to influence the quality of source waters (WHO Europe, 2017). Ongoing collaboration is required between Irish Water and catchment stakeholders, and engagement will be required at all scales from national and regional to local level.

Under the revised DWD there are provisions to address the missing link between the DWD and WFD and the protection of drinking water supplies, in order to try to overcome some of these issues. The provisions include the following:

- Article 7(3) of the revised DWD requires that Member States ensure that there is a clear and appropriate distribution of responsibilities between stakeholders for the implementation of the risk-based approach. The improved alignment of the two pieces of legislation may help to facilitate this collaboration between stakeholders and pooling of resources and expertise. There will be challenges for how this will work in practice and how to evaluate effectiveness and track progress of the implementation.
- Article 7(4) of the revised DWD creates a clear link with the WFD Article 7 and requires that the risk assessment and risk management should take into account the requirements of WFD Article 7.
- Other links between the two directives are made with regard to the specific elements of risk assessment and risk management, and also WFD safeguard zones and other relevant zones and catchment monitoring. This will help to create clearer synergies and opportunities to pool resources for the implementation of WFD and revised DWD.

CONCLUSION

Currently the DWD encourages drinking water to be controlled at the “end-of-pipe”. The revised DWD introduces the risk-based approach for the catchment areas for abstraction points, which provides the missing link for source protection and encourages actions to reduce pollution at source. Irish Water has already begun to implement the DWSP approach and our source risk assessment methodologies are significantly developed.

Irish Water has several source protection initiatives underway to manage risk within the drinking water catchments, including implementing the Interim Pesticide Strategy and two pilot projects focused on reducing pesticide contamination at source. The challenge still remains to develop a process to manage risks in all drinking water catchments on a prioritised basis. This can only be achieved with the support of stakeholders who have the ability and resources to take the actions required. The improved alignment between the revised DWD and the WFD should help to facilitate this collaboration between stakeholders and pooling of resources and expertise.

In addition, the new risk-based approach to monitoring will allow funding and resources to be targeted at higher risk hazards that are most relevant to the catchment risks. The data and information generated will be extremely valuable for helping to achieve the aim of a safe and secure water supply to protect human health.

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DETERMINING MITIGATION ACTIONS USING THE POLLUTANT TRANSFER CONTINUUM

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ABSTRACT

Where contaminant concentrations in drinking water sources are found to be above their associated screening value, mitigation action is needed. Diffuse sources identified as significant pressures are challenging to deal with, as the critical source areas (CSAs) for these sources are more difficult to locate in the landscape than point sources. The 'pollutant transfer continuum', is a landscape-based framework for considering diffuse (non-point) contamination. Mitigation actions aimed at reducing / eliminating contaminant loads may be targeted at source, along the contaminant pathway or at the receptor itself. In considering which point along the continuum that an action to protect or improve the source water quality would be most effective, account needs to be taken of the properties of the pollutant of concern as well as the landscape setting. Ensuring the 'right measure in the right place' is critical to achieving a desired water quality outcome, as well as optimum use of resources. Failure to achieve a water quality outcome from efforts undertaken can mean wasted time and money, disenchantment and reputational loss. Deciding on the right action or actions and achieving a desired outcome is challenging in the complex farming, land and landscape settings in Ireland. However, the likelihood of success is increased if a systematic approach is taken. In addition, by placing an emphasis on co-benefits, it encourages relevant disciplines and organisations to collaborate in the pursuit of mutually beneficial objectives.

INTRODUCTION

The group water scheme sector was largely constructed in the 1970s as a response to Ireland's entry to the then European Economic Community (E.E.C) and the increased emphasis on hygiene standards in food production, not least in the dairying sector. Farmers and local dairy co-operatives were the main drivers of the sector, while the goodwill of individual landowners in providing access and wayleaves for pipework and other infrastructure was a key factor in keeping costs down and ensuring the successful construction and establishment of schemes. Inevitably, the majority of GWS sources are therefore located in rural settings, with agriculture a principal activity in virtually all source catchment areas and zone of contributions (ZOCs) of wells and springs. In an effort to provide guidance to GWS managers and others involved in the development of drinking water source protection plans, the National Federation of Group Water Schemes (NFGWS) have produced 'A Handbook of Source Protection and Mitigation Actions for Farming' (NFGWS, 2020) to help identify appropriate actions to prevent or reduce nutrient (i.e. phosphorus, nitrogen), sediment, pesticides and microbial pathogen losses from agricultural pressures. While it is acknowledged that drinking water contamination can originate from a multitude of non – agricultural related sources, this paper for the most part provides examples on how mitigation actions can be implemented from an agricultural context.

Undertaking the required actions is generally time and resource intensive. Therefore, it is essential that thought and planning is undertaken to ensure that they are efficient and effective. To that end, there are a number of prerequisites that are needed before the design of any source protection action can be considered. Firstly, sufficient water quality data are essential to determine if the untreated source water is in a satisfactory condition and merits **'Protection'** or is unsatisfactory and necessitates an **'Improvement'**. Secondly and dependant on the source type, the contributing surface water catchment and/or groundwater zone of contribution (ZOC) must be established. A robust source catchment delineation is a key step towards identifying with confidence where contamination potentially derives from. Finally, through a sequential catchment characterisation process, such as that described in the NFGWS's Framework (NFGWS, 2019), critical source areas (CSAs) can be then identified. Critical sources areas are areas that deliver a disproportionally high quantity of pollutants from diffuse sources compared to other areas of a sub-catchment or ZOC, and represent the areas with the highest risk of impacting on water quality.

The ‘pollutant transfer continuum’, is a landscape-based framework for considering diffuse (non-point) contamination. It consists of four components (see Figure 1):

1. The presence of a pressure or source with an associated load of potential pollutants, such as organic and inorganic fertiliser applications, faeces and urine from grazing animals and high concentrations of P in poorly draining soils.
2. Mobilisation, whereby a potential pollutant – such as ammonia or MCPA – becomes soluble or attaches to soil particles and starts the journey from the soil to a receptor, such as a stream or borehole.
3. Delivery/transport along the pathways, underground or over ground to a drinking water source.
4. Impact in terms of pollutant concentrations in untreated water.

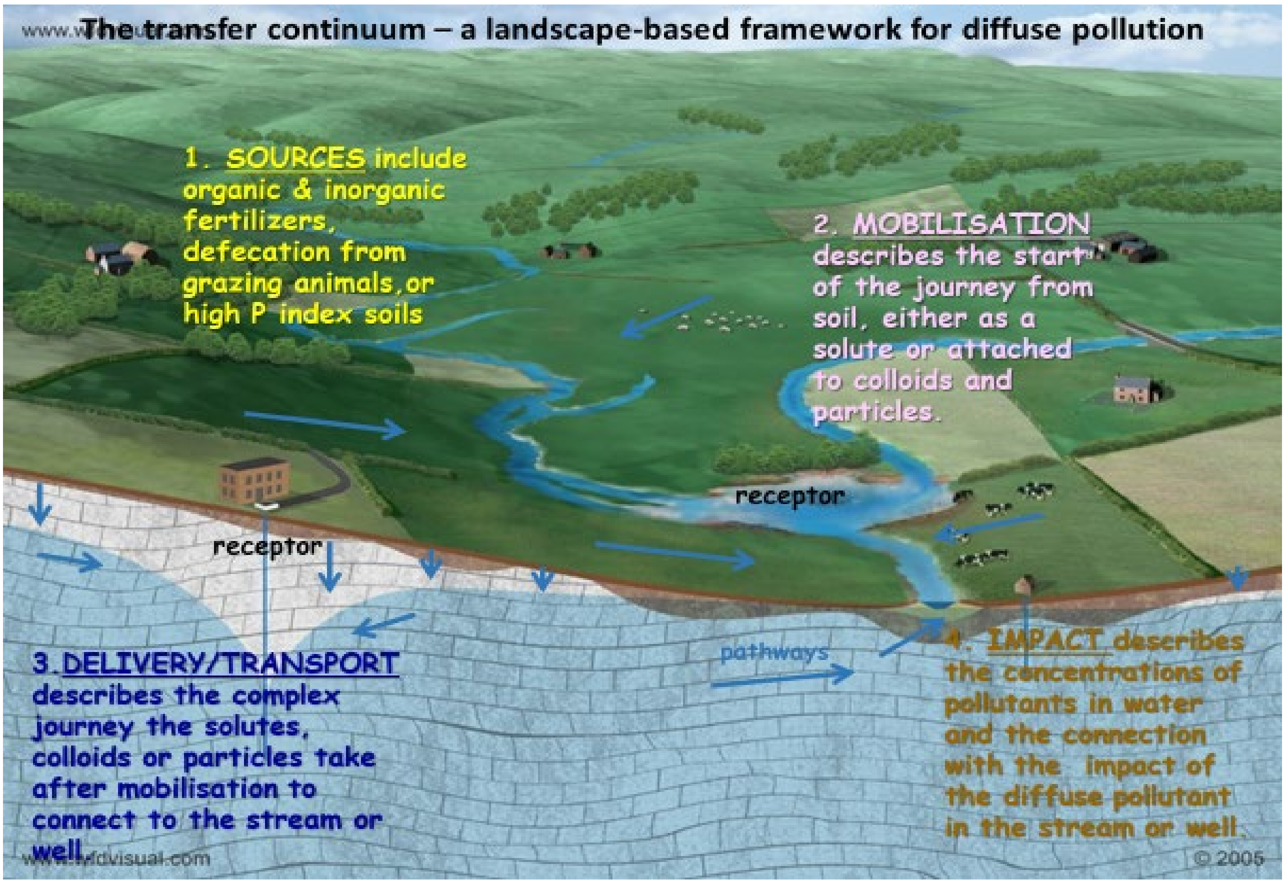

Figure 1: Representation of the pollutant transfer continuum (copied from NFGWS (2019)

Figure 2 shows the process being followed by the NFGWS in deciding on appropriate mitigation actions and highlights how they are considered according to the point in the source-pathway-receptor (SPR) continuum on which they take effect. This allows management strategies and mitigation measures/actions designed to deal with relevant pollutants to be ‘followed’ conceptually from application to impact, and provides clarity on what role a particular measure has. The recommended relevant points along the continuum for consideration of specific measures and actions are:

i) source reduction or elimination;
ii) mobilisation control;
iii) pathway interception;
iv) receptor/instream works; and

v) treatment (as part of the multi-barrier approach.

ACTIONS AIMED AT TACKLING THE POLLUTANT SOURCE

As previously alluded to, a decision on the appropriate actions required depends on a number of factors: i) the environmental stressor or pollutant; ii) the pressures in the catchment / ZOC; iii) the landscape setting, in particular whether it is a freely draining or poorly draining scenario; and iv) the input of and acceptability to the landowner. Whilst famer engagement and collaboration may be required for actions targeted at different points on the continuum, source reductions / eliminations certainly cannot be achieved without the farmer's agreement. Within the GWS sector, there are numerous examples of where GWSs have worked in conjunction with landowners to reduce source loadings as a direct response to water quality deterioration. A prime example of such is evident from an examination at the water quality results over the preceding 20 years for Kilcorran Lough, Co. Monaghan, the source of the Aughnashalvey GWS.

The Integrated Water Quality Report for Monaghan and Louth (EPA, 2013) identified that Kilcorran Lough was at a 'Moderate' physico-chemical and ecological status during this period. In the previous years, water quality data derived from both the GWS and Monaghan County Council's annual monitoring programme also highlighted periodic elevations in total phosphorus and chlorophyll a concentrations. In response to and acting on recommendations contained within '*A Preliminary Report on Source Protection'* completed by DkIT (2011) for the scheme, a series of source protection measures were implemented through the co-operation of the local farming community. A key action included group discussions with all landowners in the catchment in 2013 and a subsequent commitment to reduce organic and inorganic fertiliser application on lands bordering the lough. A marked improvement in the nutrient conditions of the lough has been observed since source reductions commenced, where the waterbody has now returned to a 'Good' water quality status. Furthermore, chlorophyll a conditions when considered in isolation would signify a 'High' water quality status. Whilst paleolimnological investigation of the sedimentary record for Kilcorran Lough would suggest that significant water deteriorations commenced c. the 1960's (i.e. in line with a period synonymous with agricultural intensification), there are several examples of water quality decline in more recent times. Agricultural diversification within the Inner Protection Area (SI) of the Ballybricken–Luddenmore borehole in Co. Limerick resulted in nitrate concentrations exceeding the Groundwater Threshold Value (GTV) in 2019 (Figure 3). Through consultation with the landowner in question, a reduction in nitrate usage within the SI zone was agreed, which has resulted in nitrate concentrations declining to below the GTV for the proceeding monitoring years.

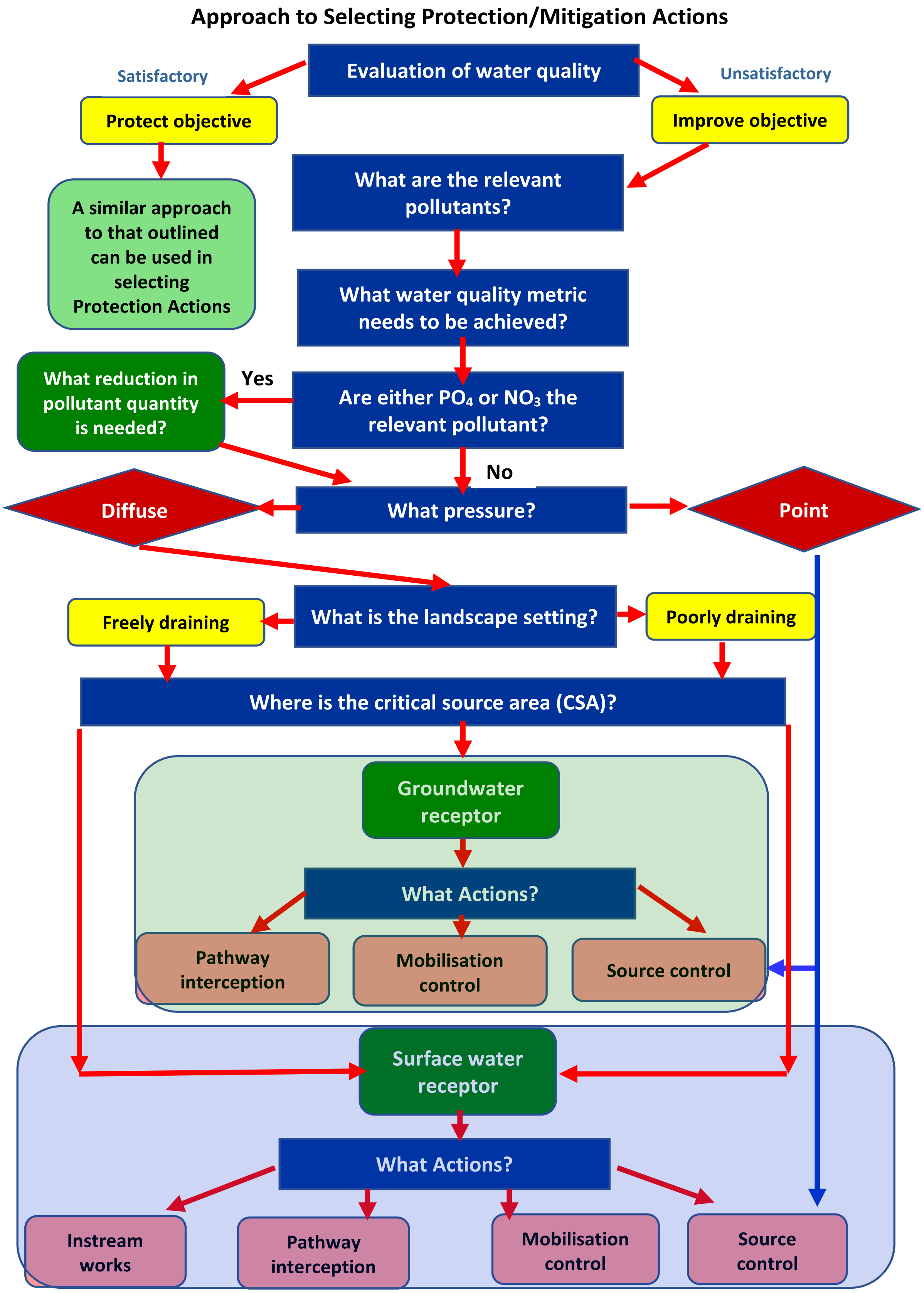

Figure 2. Process flowchart illustrating a recommended approach to deciding on appropriate mitigation Actions (Copied from NFGWS, 2020).

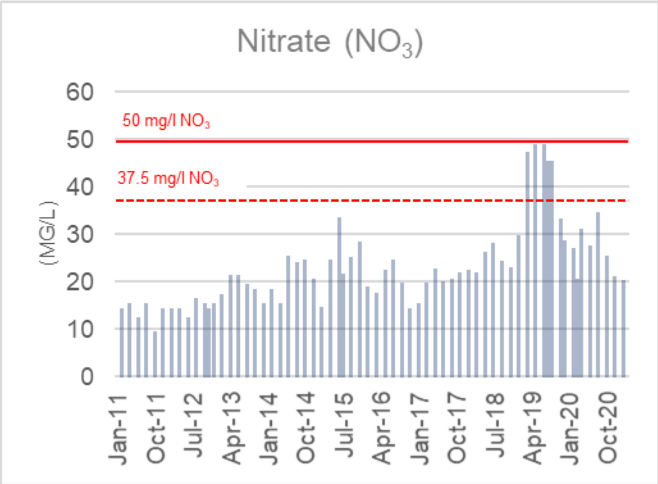

Figure 3. Nitrate concentrations recorded within the Ballybricken GWS - Luddenmore borehole from January 2011 – February 2021 (Data supplied by EPS Water). Concentrations ranging from 28 mg/l NO_3 to 49 mg/l NO_3 were recorded from January 2019 to December 2019, which coincides with a change in land management practices within the Inner Source Protection Area.

BREAKING THE PATHWAY (CASE STUDY)

In certain situations, it may not be feasible to reduce the contaminant load at source, sufficiently enough to achieve the desired objective. In these circumstances, measures aimed at intercepting the pathway are essential. Such actions may also be implemented in combination with a reduction in pollutant loading or mobilisation. In 2018, the Stranooden GWS, which abstracts circa 1,900m^3 of water per day from White Lough in County Monaghan, was selected to participate in the NFGWS's Phase II Source Protection Pilot Project, primarily due to the elevated concentrations of MCPA and TP within the lake (NFGWS, 2020).

Within the Derryvalley sub-catchment (a sub-catchment covering 33% of the overall White Lough catchment), over 75% of the lands are found to be highly susceptible to near surface phosphate runoff, as identified by the EPA's susceptibility mapping (Figure 4). Additionally, a substantial portion of the sub-catchment has been attributed a high Pollution Impact Potential (PIP) risk score (i.e. Rank 1 – 3) – this area therefore is the CSA for phosphate loss, and consequently is the area where mitigation actions were targeted. Conversely, the remainder of the overall catchment is recognised as having a higher proportion of freely draining soils with a predominance of PIP scores ranging from 5 – 8, thus explaining the lower P concentrations found within the associated watercourses. Whilst free draining, annual average concentrations of nitrate and ammonium where below their respective NFGWS source protection framework 'Guide Values'.

A load reduction assessment, using the approach outlined by Mockler et al. (2016), was undertaken for the Derryvalley subcatchment. The mean phosphate concentration was 0.067 mg/l and the mean flow available from the hydrometric station located on the outflow from this sub-catchment was estimated as 0.0532 m^3/s. Therefore, in order to reduce the concentration to below 0.035 mg/l, it was estimated that a phosphorus load reduction of approximately 540 kg/year was needed.

Eighteen farmers, who were identified within the critical source area (CSA) for phosphorus losses to watercourses by overland and near surface flows, agreed to implement a series of measures to break the diffuse pathway. For example, targeted, field specific buffer margins were established, meaning that extended buffers were specified at the perceived runoff discharge points, whilst reduced buffer distances were to be created outside of these zones. This approach, as an alternative to a generic buffer width, was met with a greater approval from the landowner, who recognised the compromise needed to meet the water quality objective. A number of landowners also opted for inclusion within the existing Native Woodland Establishment Scheme, whereby the woodlands are to be strategically planted within phosphorus CSAs.

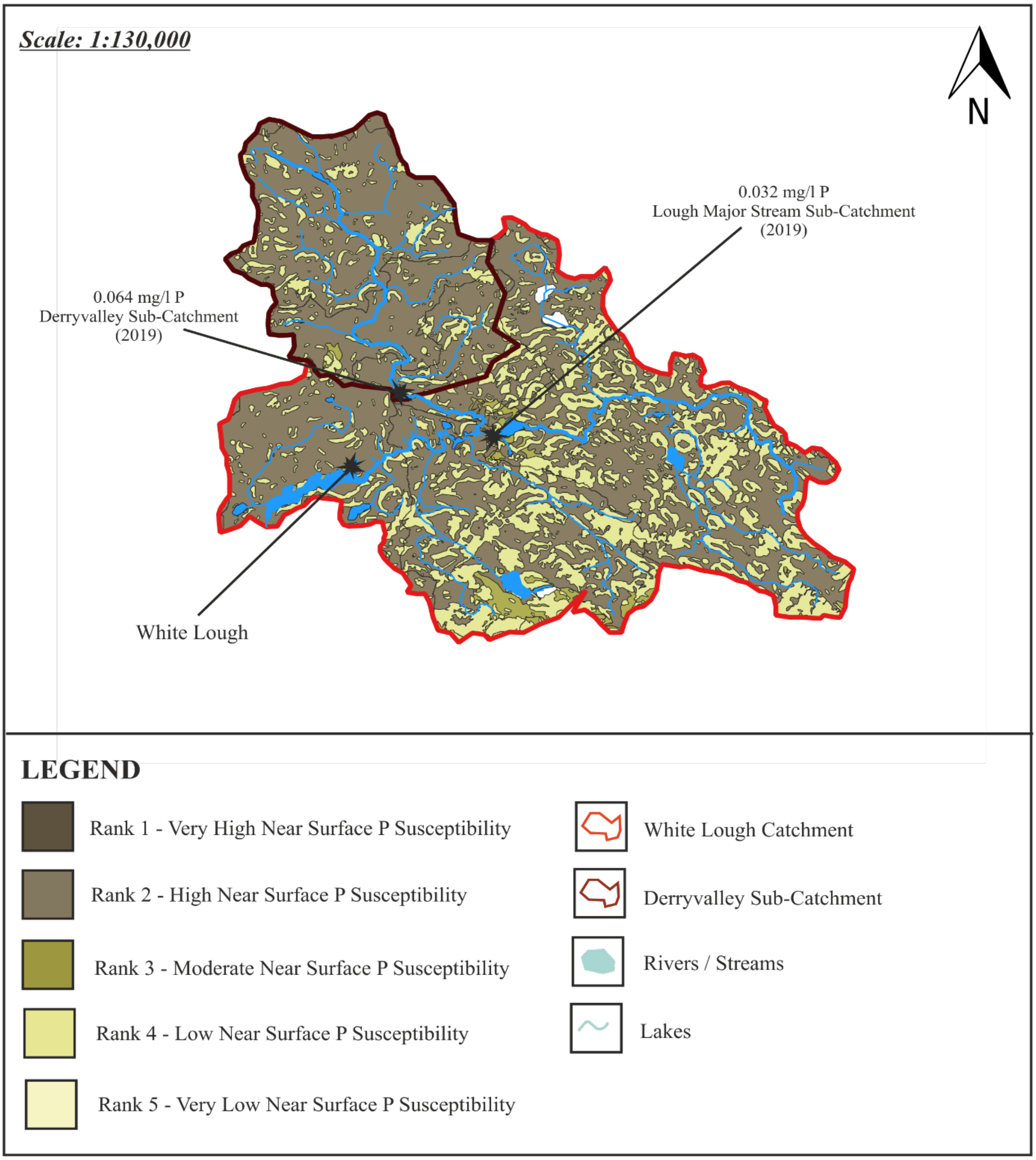

Figure 4. Near Phosphorus Susceptibility map for the White Lough Catchment, Co. Monaghan (Based on the susceptibility map provided by the EPA Catchments Unit).

RECEPTOR / INSTREAM WORKS

Due to the natural geochemical makeup of the environments in which certain sources are situated, water treatment will be an essential component of the multi barrier approach when trying to deliver safe drinking water. For example, elevated iron and manganese concentrations in the absence of other indicators of organic pollution at the Kildallan GWS source in County Cavan, is attributed to geological processes (GSI, 2015). In other instances, careful management of abstraction regimes may prevent the introduction of naturally occurring chemicals into drinking water supplies. For example, reduced groundwater levels during extended dry periods appeared to trigger an increase in fluoride concentrations in the Tydavnet GWS source during the 1995 – 2001 period (JOD, 2001). It was determined that the presence of elevated fluoride was linked to whether the aquifer was confined or unconfined as a result of the abstraction regime (GSI, 2019).

Conversely, physical works at both surface water and groundwater abstraction points may be appropriate when trying to mitigate against anthropogenic pressures. Sediment was found to be a significant pressure on the Dromore River system in Co. Monaghan which forms the principal inflow into White Lough. Bank erosion, as a consequence of livestock poaching, was identified to be a major contributor to the problem. Thus, as a means of alleviating the issue, riverbank rehabilitation will commence in 2021 at a number of sites on the river system. Where flow velocities are greatest, a deep bank revetment technique will be utilised, while willow spiling will be established on the lower order tributaries. At some groundwater supplies, improvements in well head construction have seen a reversal in rising coliform trends (see Figure 5a & 5b). Well head protection may also be a suitable action when trying to protect against natural processes. For example, fluvial flooding from the Templeport Lake Stream has historically contributed to increases in the turbidity levels of the Templeport GWS's borehole (GSI, 2016), once inundated with flood waters (see Figure 6). In this instance, raising the well head above the flood level, would break the hydrological connection and remove the potential for contamination from diffuse sources within the largely agricultural catchment draining into the stream.

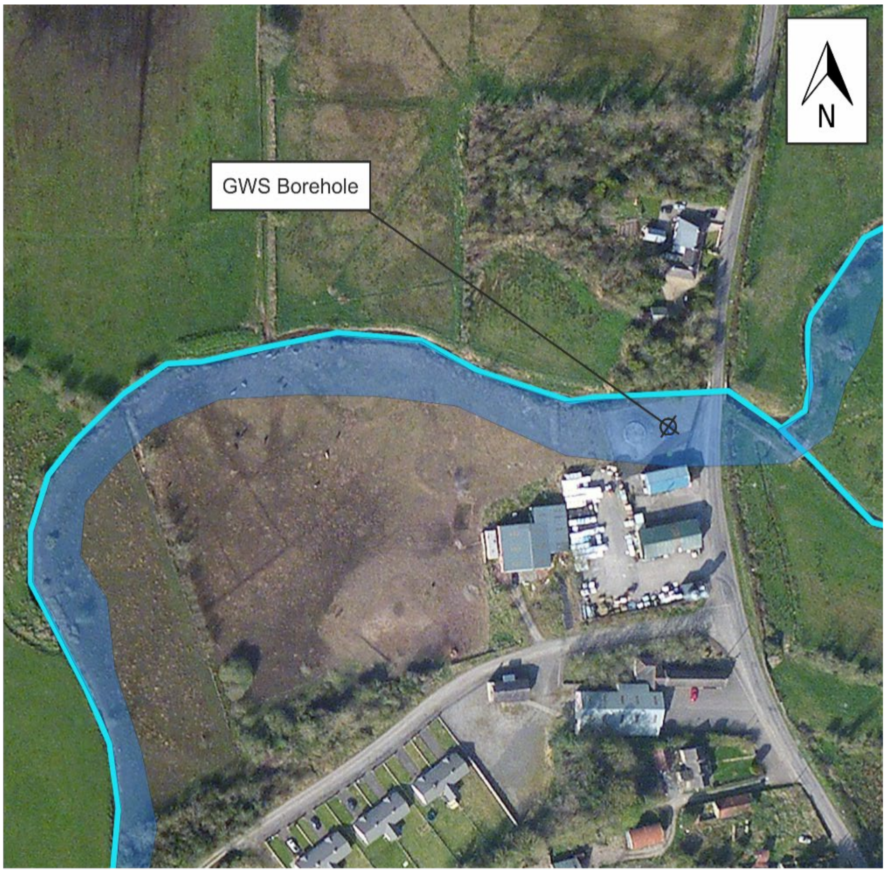

Figure 5a (Top Left). Borehole at Ballyallen GWS, Co. Carlow. Figure 5b (Bottom Left). Borehole at Ballyallen GWS, post well head improvement works.
Figure 6. (Right). Location of Templeport GWS's abstraction borehole within potential fluvial flood zone (i.e. blue hatch is indicative of the 1 in 100-year fluvial flood zone predicated during the Preliminary Flood Risk Assessment (2011)).

OPPORTUNITY FOR MULTIPLE BENEFITS

In addition to meeting water quality objectives, consideration of the additional benefits from the mitigation options for related environmental goals (e.g. biodiversity, carbon sequestration and flood mitigation) is recommended as a means of achieving optimal outcomes for the environment and, perhaps, public acceptance for the activities.

The NFGWS Source Protection Pilot Project Phase 2 in Roscommon is trialling initiatives aimed at improving water quality using a novel approach involving collaboration and awareness raising through biodiversity enhancement. As part of the characterisation process, elevated levels of MCPA and glyphosate were identified as significant pressures in a number of GWS catchments. The "Let it Bee" initiative, which is being trialled in the Corracreigh and Mid Roscommon GWSs, has given a selected number of farmers beehives, equipment, mentoring and training with a view to changing the mindsets and practices on pesticide usage on their farm, ultimately improving water quality through a biodiversity focus (NFGWS, 2020).

Similarly, a campaign called "I've planted a tree and my garden is pesticide free" has been developed as a national school project and is currently being rolled out across County Roscommon. Every child attending national school in Roscommon will receive a tree along with information about the damaging consequences of pesticide use and on how to go pesticide free in their garden. It is envisaged that projects like this will raise local consciousness about the importance of environmental appreciation and protection.

OTHER CONSIDERATIONS

Undoubtably, source protection actions, which aim to improve water quality conditions, is a positive objective. However, it is imperative that we don't become siloed in our thinking when designing such measures. Actions which have a positive impact on water quality need to be considered against any potential detrimental risk to other aspects of our environment. For instance, many of our GWS catchments / ZOCs are positioned within or partially overlap areas designated as Natura 2000 sites. Whilst actions aimed at improving water quality from a drinking water perspective may have a co-benefit to designated sites with water related conservation objectives, similar actions elsewhere may cause a disturbance. Fencing works for example in the portion of the Glaslough Tyholland GWS catchment that encroaches upon the Sliabh Beagh Special Protection Area (SPA), would need to be cognisant of the potential presence of grounding nest birds such the Hen Harrier (*Circus cyaneus*). Similarly, the aforementioned bank reprofiling works scheduled for the Dromore River will need to give due deference to any potential impact to White-clawed Crayfish (*Austropotamobius pallipes*) populations known to inhabit the waterbody.

CONCLUSIONS

The protection of drinking water sources is a cornerstone of the recently introduced recast Drinking Water Directive (DWD). Where drinking water suppliers formerly relied solely on treatment barriers to contamination, the battle now begins in the source catchment / ZOC. Improving or protecting source water quality and implementing effective measures to minimise risks at catchment level will provide reassurance to consumers that everything that can be done is being done to halt preventable contamination. This will, in turn, increase public confidence in the tap water supply. With that being said, careful analysis of the mitigation and protection options is essential if the effort undertaken is to be effective and justifiable. Furthermore, monitoring needs to be undertaken at appropriate intervals to track progress and to determine if the implemented actions are effective or if catchment / ZOC activities are changing. Finally, and where appropriate, prioritising mitigation actions with more than one environmental benefit should be considered. These additional benefits emphasise the connectedness of nature and are, therefore, a means of delivering genuine environmental and economic sustainability for communities.

ACKNOWLEDGEMENTS

The NFGWS would like to thank all stakeholders and personnel involved in the preparation of the *'A Handbook of Source Protection and Mitigation Actions for Farming'* and in particular to Donal Daly who was instrumental in its development. I would also like to thank my colleagues in the NFGWS for providing data, images and information used within this paper.

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NOVEL CATCHMENT MODELLING METHODS TO SUPPORT IRISH WATERS LEAD MITIGATION PROGRAMME

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ABSTRACT

As part of the National Lead Mitigation Plan Irish Water propose to treat drinking water supplies with orthophosphate. This is a proven method to mitigate the impact of elevated lead in water pipes throughout the entire water network. Arup/RyanHanley has completed catchment modelling to assess the potential impact of this additional orthophosphate load on the environment. The project has assessed over 100 water supply zones from small villages to towns and cities (Dublin and Galway). The first tier of assessment adopted a risk based approach based on the methods developed in the PATHWAYS research project. Further characterisation has been progressed for Dublin and Galway which includes the development of 3D Groundwater Flow and Transport Models and the installation of a network of nested groundwater monitoring boreholes to provide model calibration data, samples for soil sorption analysis and ultimately operational monitoring.

Key words: *Catchment Modelling, Orthophosphate, Modflow, MT3D, Sorption.*

INTRODUCTION

Legacy lead piping can be a major source of contamination in drinking water which has been associated with reduced cognitive development in young children[1,2] and an increased risk of coronary heart disease or stroke because of increased blood pressure[3]. Limits on lead content in drinking water only began to apply in 1998. The EU Drinking Water Directive, following World Health Organisation (WHO) advice, proposed a staged reduction in lead limits for drinking water from a previous standard of 50µg/l (parts per billion) to an interim level of 25 µg/l .This limit applied until 25th December 2013, when it was further reduced to 10 µg/l[4].

Public water utilities in the UK and parts of Europe and North America routinely treat drinking water supplies with phosphate to prevent pipe corrosion and the dissolution of lead. Inorganic phosphate (commonly phosphoric acid or monosodium phosphate) is used to treat drinking water supplies, leading to the formation of lead phosphate or calcium phosphate precipitates on the inside of service lines and household plumbing. These precipitates have lower solubility than lead corrosion products (primarily lead carbonates) that otherwise line the inside of drinking water supply pipes, thereby reducing the concentration of lead in solution alongside the concentration of other solutes derived from pipe corrosion products, including copper[5].

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[1] Edwards, M.; Triantafyllidou, S.; Best, D. Elevated blood lead in young children due to lead-containing drinking water. Environ. Sci. Technol. 2009, 43, 1618−1623.

[2] Edwards, M. Fetal death and reduced birth rates associated with exposure to lead-contaminated drinking water. Environ. Sci. Technol. 2014, 48, 739−746.

[3] World Health Organization (WHO). Booklet on Childhood Lead Poisoning; WHO: Geneva, Switzerland, 2010; ISBN: 978-924-150033-3

[4] https://www.water.ie/projects-plans/our-plans/lead-mitigation-plan/

5 Comber, S.; Cassé, F.; Brown, B.; Martin, J.; Hillis, P.; Gardner, M. Phosphate treatment to reduce plumbosolvency of drinking water also reduces discharges of copper into environmental surface waters. Water Environ. J. 2011, 25, 266−270.

Irish Water has completed the process of removing legacy lead mains on the public water supply mains, and water discharged into the network from Water Treatment Plants (WTP) is free from lead. However, there remains a significant quantity of legacy lead pipes on the private side of the network. Lead plumbing was widely used in houses built before the 1980's. It is estimated that 180,000 homes in Ireland together with public buildings, schools, medical centres and other buildings over 40 years old, may have lead plumbing[4].

The Government has a National Strategy to Reduce Exposure to Lead in Drinking Water and Irish Water has developed the Lead Mitigation Plan. The Consultation Report, Detailed Business Case, Strategic Environmental Assessment (SEA) Report and Appropriate Assessment for the plan are all freely available on the Irish Water Website[4]. The government had provided a grant scheme that can assist homeowners with the replacement of lead pipes, however the uptake from the public has been very limited.

As a result, until such time that the risk of lead contamination is removed from the system, part of the Irish Water Mitigation plan is to treat at risk water supply zones with orthophosphate. This paper sets out the catchment modelling undertaken to assess the potential impact of Mains Water Leakage of Phosphate (MWL-P) on the aquatic environment.

ENVIONMENTAL IMPACT ASSESSMENT METHODOLOGY

An Environmental Assessment Methodology (EAM) was developed in 2016. The EAM process followed the EPA PATHWAYS Project Catchment Characterisation Tool[6],[7],[8] which included the assessment of diffuse sources orthophosphate and its transport through groundwater and surface water pathways.

The existing literature on MWL-P, particularly from the UK[9],[10] focused on attempting to retrospectively discern how much phosphate in the environment was sourced from MWL-P as the treatment had commenced prior to the Water Framework Directive (WFD) and therefore the Initial Characterisation of the waterbodies already included this loading. A report was commissioned by Irish Water by Prof. Laurence Gill of TCD to advise on the potential phosphorus attenuation factors based on research completed on the transport of effluent from septic On-Site Wastewater Treatment Systems (OWWTS).

The EAM considers orthophosphate transport through the groundwater, surface water and the water supply, effluent and storm water networks. This paper provides a summary of the groundwater pathways. The conceptual model for the groundwater transport is presented in Figure 1. The model tracks the flow from the leaky water mains from the trench (Source), through a number of groundwater Pathways towards the ultimate Receptor which are the surface water bodies (rivers, lakes, transitional and coastal water bodies). For each pathway there is an associated attenuation factor which are based on the Gill**Error! Bookmark not defined.** report.

6 Mockler, E., Bruen, M. (2013) Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures (Catchment Tools Project) (2013-W-FS-14). EPA Research Report.
7 Mockler, E. et al (2017) Sources of nitrogen and phosphorus emissions to Irish rivers and coastal waters: Estimates from a nutrient load apportionment framework. Science of the Total Environment 601–602 (2017) 326–339.
8 Archbold, M. et al (2007) Contaminant Movement and attenuation along pathways from the land surface to aquatic receptors: The Pathways Project. (2007-WQ-CD-1-S1). EPA Research Report.
9 Gooddy, D et al (2017) Mains water leakage: Implications for phosphorus source apportionment and policy responses in catchments. Science of the Total Environment 579 (2017) 702–708
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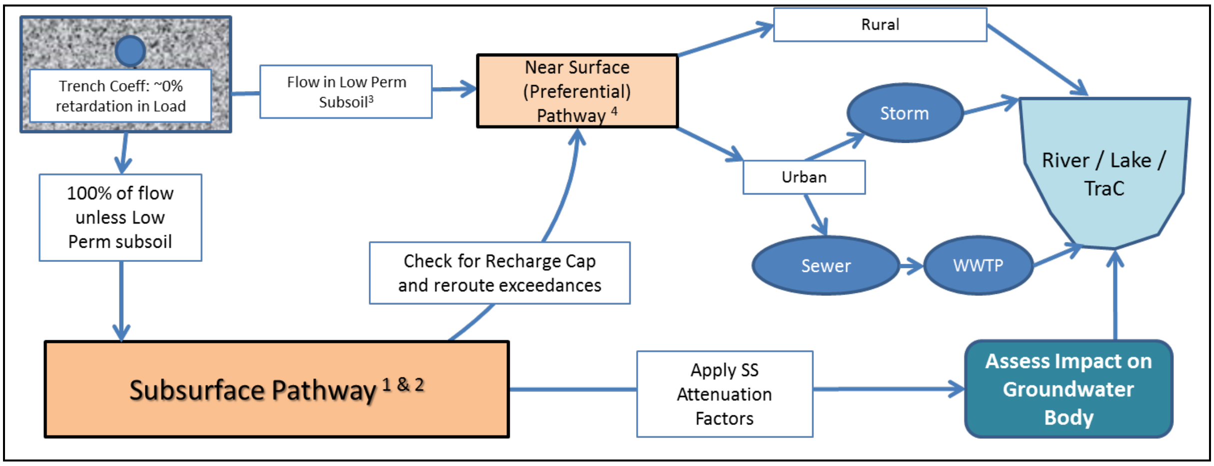

Figure 1: EAM Conceptual Model

The conceptual model is implemented in a GIS/Excel based model. The required attribute layers listed below for the model are combined and used to split the linear water mains layer and to populate each resulting stretch of water main with the relevant attribute information:

- Source:
  - Water mains (Polyline);
  - Domestic On-Site Wastewater Systems (Point), any house within the Water Supply Zone (WSZ) not contained within a Waste Water Treatment Plant (WWTP) agglomeration/catchment;
- Pathway:
  - Aquifer type;
  - Annual recharge & recharge cap;
  - Groundwater vulnerability;
  - Subsoil Type (presence of Peat, Made Ground);
  - Depth to bedrock;
  - Subsoil permeability category;
  - Distance to karst feature;
  - Discharge to surface water feature.
- Receptor
  - EPA Water Bodies mapping including rivers, groundwater, lakes, transitional, coastal
  - Natura 2000 Network water dependant sites.

The GIS layers are exported to excel where the relevant attenuation factors are applied based on the Pathway attributes and the resulting transported flux of orthophosphate from each length of water mains or house is summed within the river sub-basin. At that point the total load is converted to a concentration based on the average river flow and an assimilative capacity and WFD status assessment is completed to determine the potential increase in orthophosphate concentration and assess this in the context of the WFD water body status. The load from each river sub-basin is tracked downstream in a cumulative assessment to determine the impact on each river water body until it reaches the sea. The EAM results for each WSZ is then used as the basis for an Appropriate Assessment under the Habitats Directive.

This assessment has been completed at over 200 WSZs across the country. Cumulative assessments for the all WSZs were completed to track the load from upstream WSZ all the way through the catchment adding in the load from each downstream WSZ. The orthophosphate transport in the river was assumed to be conservative with no reduction in concentrations due to the uptake of orthophosphate by aquatic flora/fauna or sorption by stream sediments.

EAM RESULTS

The EAM has been completed on 106 Arup/RyanHanley assessed WSZs ranging in size from small town supplies to large urban centres like Dublin and Galway. The results show that the orthophosphate concentration increase in the vast majority of river water bodies is below 1µg/l and is expected to have an indiscernible impact on water quality.

Where the initial assessment indicated a potential risk to water body status this was further assessed and mitigated either through:

- Site specific monitoring to provide data for unassigned water bodies;
- Targeted treatment to reduce the proportion of the WSZ that is treated and thus reduce orthophosphate loads to the environment;
- Reduction of the orthophosphate treatment concentration;
- Improve WWTP to tertiary treatment (the EAM assumes no treatment of additional orthophosphate in Primary or Secondary WWTPs).

Following the application of these measures it was found that further characterisation was required for Dublin and Galway which is outlined in the following sections.

FURTHER CHARACTERISATION FOR DUBLIN AND GALWAY

The further characterisation of Dublin and Galway includes the following proposed approach:

1. Develop 3D numerical groundwater models in order to:
    a. Provide more realistic model of groundwater flow (Modflow) in the WSZs;
    b. Allow explicit modelling of orthophosphate sorption process with the transport model (MT3D).
2. Install a network of groundwater monitoring boreholes to:
    a. Provide groundwater level calibration data for the model;
    b. Collect samples of Made Ground and subsoil for chemical analysis to determine site specific orthophosphate sorption coefficients;
    c. Provide baseline data for orthophosphate prior to treatment;
    d. Allow for monitoring of orthophosphate following implementation.
3. Model recalibration with on site detailed monitoring information and site specific sorption coefficient.

A groundwater monitoring network was installed in Limerick city in 2016 prior to the commencement of treatment there in December 2016. Monitoring results have shown that there is no upwards trend discernible in the orthophosphate groundwater concentration. Isolated increases (spikes) in orthophosphate appear to be correlated with intense rainfall when leakage from Combines Storm Overflows (CSO) can lead to spikes in orthophosphate in conjunction with elevated E.Coli.

GROUNDWATER MODEL DEVELOPMENT

The groundwater models were developed using Groundwater Vistas with groundwater flow modelled with Modflow2005 and groundwater transport with MT3D. Figure 2 shows the model domain for Galway and Dublin which is 49km^2 and 492km^2 respectively. The domain largely follows natural topographic catchments with some truncation of large upstream catchments which does not include any WSZ areas subject to treatment.

Figure 2: *Groundwater Model Domains for Dublin and Galway*

The model grid cell size is 25m for Dublin and 20m for Galway. A conceptual section showing the representation of the boundary conditions in the Galway model is shown in Figure 3. The models represents four geological layers: Made Ground, Subsoil, Shallow Bedrock and Deep Bedrock. The model is run on an average annual time step as the EAM assessments are completed on average water quality over WFD monitoring cycles.

The boundary conditions are set up as follows:

- Upgradient topographic boundary – represented as no flow cells;
- Downgradient coastal boundary – represented as general head boundary at 0mOD;
- Water mains –represented as constant flux cells which inject water at the defined rate equal to the leakage rate and a concentration equal to the proposed orthophosphate treatment concentration. The water mains are defined as being within the first layer (Made Ground) as these are generally less than 1m below ground;
- Storm water drains – represented as drain cells in the model with the conductance of the drain being calibrated such that the leakage of groundwater into the drains reflects the infiltration rate from other studies such as the Greater Dublin Strategic Drainage Strategy[11]. The storm water drains are represented in the second layer, subsoil, as they are generally deeper than the water mains and this excludes the potential for having conflicting boundary conditions within the one cell;
- Rivers are represented as Drain cells which remove water from the model. The stage of the river is based on the ground elevation within the cell;

[11] http://www.greaterdublindrainage.com/wp-content/uploads/2011/11/GDSDS-Final-Strategy-Report-April-051.pdf

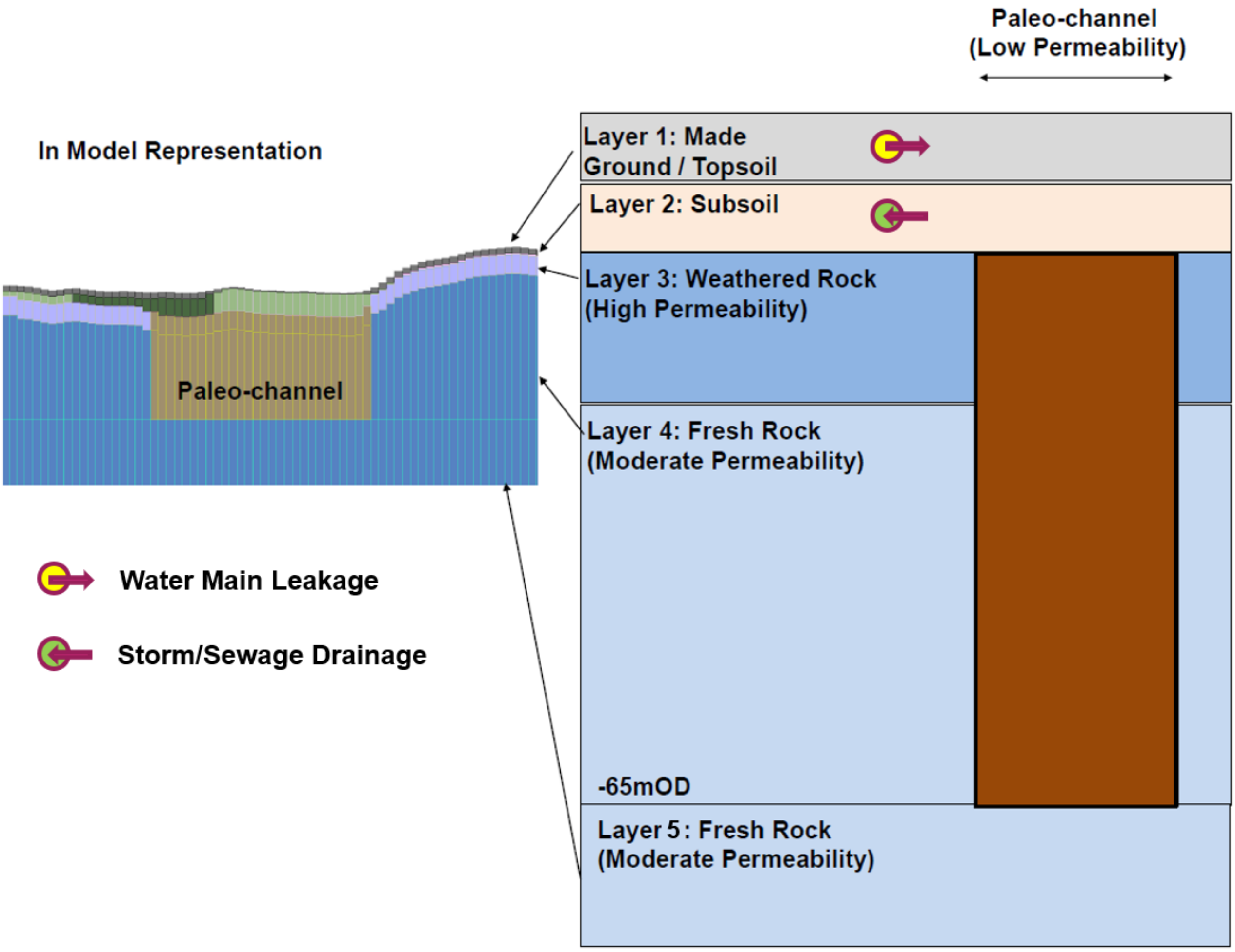

***Figure 3:** Galway Model Configuration*

The aquifer parameters in the initial model have been based on literature values[12]. A preliminary calibration process was completed in Dublin using groundwater level data from Arup projects within the city. As this data was from different time periods the calibration was used as a guide only in terms of overall model structure as opposed to detailed parameter inverse calibration. In Galway monitoring data from the N6 Ring Road Environmental Impact Assessment Report (EIAR) was used to provide initial calibration.

The N6 EIAR also highlighted the presence of infilled paleochannels in Galway which explain the presence of small streams (Terryland) which flow over parts of this highly karstified aquifer. This is reflected in the conceptual model shown in Figure 3. The drilling from the N6 demonstrated that these paleochannels can be over 60m deep and were incised into the limestone during previous glacial periods when the sea-level was significantly lower. These low permeability zones have been explicitly represented in the model.

In addition, it is clear from a detailed assessment of topography in the south east of the city that there are three parallel dry valleys in the karst aquifer flowing towards the coast. These have been represented in the models as zones of higher permeability than the surrounding karst bedrock as shown in Figure 4. The observed groundwater levels from the N6 project show that there is a deeper shallow groundwater-table in the karst aquifer whereas the water-table is shallow in the granite which is a poor (low permeability) aquifer with a higher drainage density (rivers) than on the limestone where the rivers only occur where the infilled paleochannels provide an impermeable base.

12 Kelly, C., Hunter Williams, T., Misstear, B.M., Motherway, K. 2015. Irish Aquifer Properties – A reference manual and guide. Prepared on behalf of the Geological Survey of Ireland and the Environmental Protection Agency.

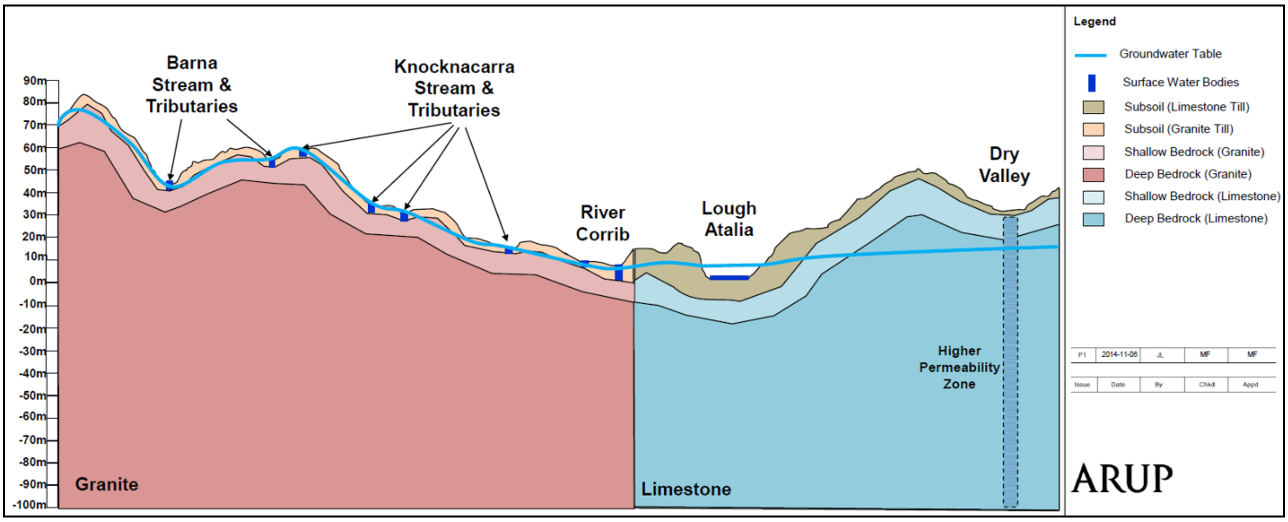

Figure 4: *Galway Conceptual Model*

The groundwater flow models provided an adequate calibration against the available data and therefore a preliminary set of predictive models was developed to represent the orthophosphate transport. The baseline concentration for orthophosphate in the model was set to zero as the key factor for the EAM model is the increase in orthophosphate above baseline in the down-gradient receptors.

The MT3D model was used to represent sorption of orthophosphate. Sorption was only permitted in the Made Ground and subsoil, no sorption is expected to occur in the bedrock as this is dominated by fracture flow. Sorption in MT3D is represented via different sorption isotherms which set the relationship between dissolve solute and sorted solute concentrations. The user can select the isotherm type Linear, power law (Freundlich), rate limited (Langmuir)[13]. The Gill 2016 report indicated that the Freundlich Isotherm provided the best representation of orthophosphate sorption in trench substrate. Research from Teagasc[14] suggests that the Langmuir isotherm provides a better representation, however this study assesses sorption properties of organic topsoil, whereas MWL-P discharge will occur below the topsoil. Site specific results from the borehole drilling samples will be used to inform the final sorption parameters and calibrate the models.

GROUNDWATER MODEL PRELIMINARY RESULTS

A range of sorption isotherm coefficient values were adopted to test the model sensitivity to the results however the results presented below are the values for the average sorption isotherm, which was quite close to that of the limestone clast material. These preliminary results were feedback into the overall EAM model and combined with the surface/utility pathways to assess the combined impact. In both Galway and Dublin it demonstrated there was sufficient sorption of orthophosphate to prevent a deterioration in status of the receiving water bodies. The preliminary results provided the justification to progress with the development of the monitoring network in Galway and Dublin.

DUBLIN AND GALWAY GROUNDWATER MONITORING NETWORK.

The proposed monitoring networks in Dublin and Galway comprise 12 monitoring locations in both cities. At each monitoring location there is a shallow and deep borehole as shown in Figure 5. The shallow borehole is screened in the subsoil and the deep borehole is screened in the top 10m of the bedrock aquifer. In Dublin there is a nested installation provided in the shallow borehole where the Made Ground is sufficiently deep (in places this can be over 4m thick in Dublin). Each subsoil and bedrock borehole will be installed with a logger recording hourly readings of water level, temperature and electrical conductivity.

13 Anderson, M., Woessner, W. & Hunt, R. 2015. Applied Groundwater Modelling. Elsevier.
14 Daly, K et. Al (2015) Phosphorus sorption, supply potential and availability in soils with contrasting parent material and soil chemical properties. European Journal of Soil Science, 2015

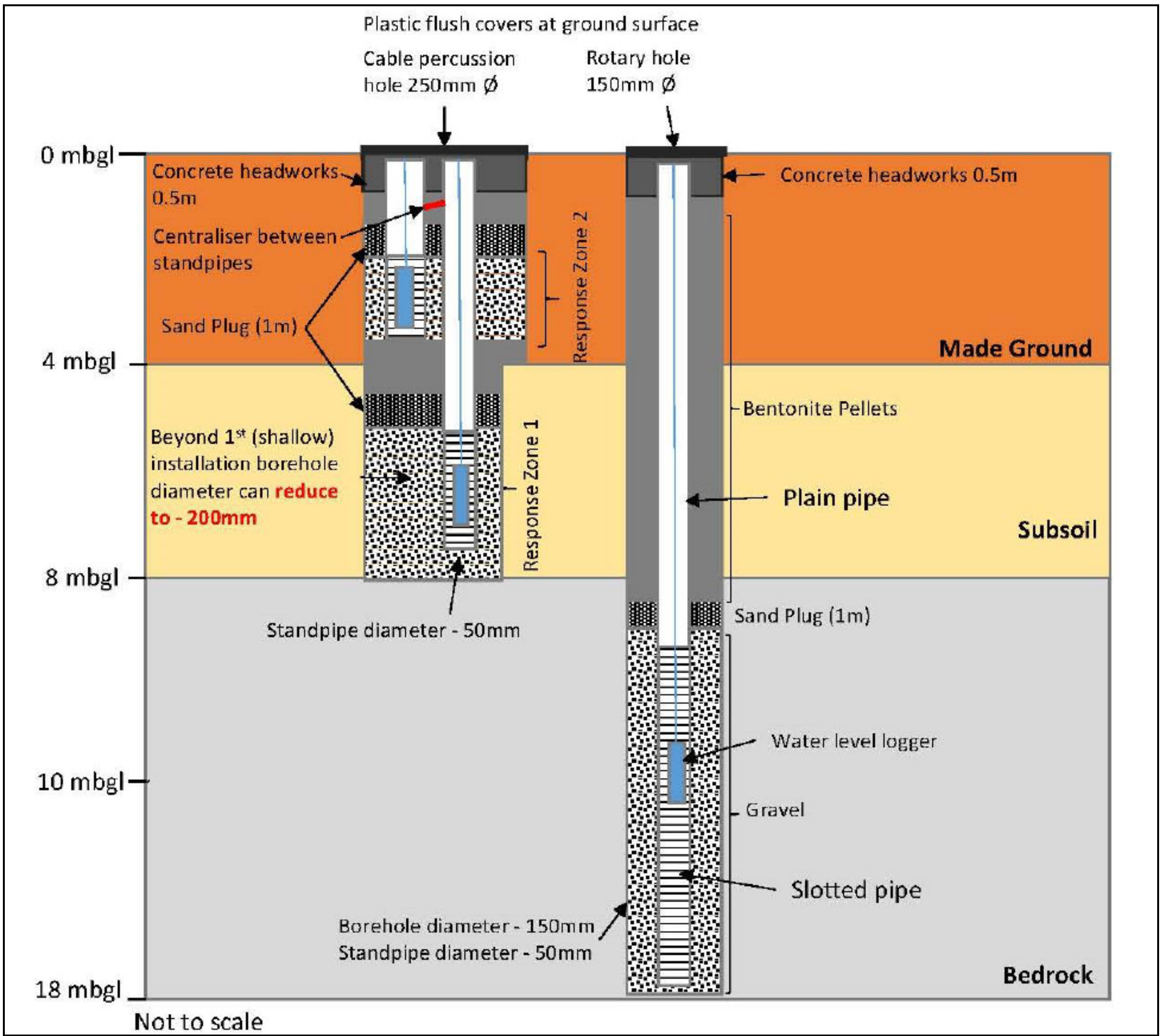

***Figure 5:** Dublin & Galway Groundwater Monitoring Borehole Design*

SUMMARY

Arup/RyanHanley has completed catchment modelling to determine the fate and transport of mains water leakage orthophosphate associated with proposed treatment of water supplies as part of the Irish Water Lead Mitigation Plan. The project has assessed over 100 water supply zones from small villages to towns and cities (Dublin and Galway). The first tier of assessment was carried out using an Environmental Assessment Methodology (EAM) which utilised methods developed in the PATHWAYS project. The EAM assessments have demonstrated that the resulting increase in orthophosphate concentrations in receiving water bodies would be indiscernible for the vast majority of Water Supply Zones. Further characterisation has been progressed for Dublin and Galway which includes the development of 3D Groundwater flow and transport models and the installation of networks of nested groundwater monitoring boreholes to provide model calibration data, samples for soil sorption analysis and ultimately operational monitoring.

The groundwater monitoring networks in Dublin, Galway and Limerick provide a unique opportunity to acquire high quality data on urban hydrogeology in Ireland. Irish Water have consulted with agencies such as the GSI and local authorities in developing the monitoring networks and selecting sites. The boreholes will be made available to stakeholders to support groundwater studies to address a broad range of issues such as rising groundwater levels with climate change, groundwater flooding of basements, impact assessments of construction dewatering, shallow geothermal potential due to urban heat island effect and urban impacts on groundwater quality.

CHALLENGES AND OPPORTUNITIES FOR CATCHMENT MANAGEMENT IN A KARST ENVIRONMENT - INSIGHTS FROM A WORK IN PROGRESS IN THE RATHCROGHAN UPLANDS, COUNTY ROSCOMMON.

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Donal Daly (Catchment Scientist)

ABSTRACT

This paper describes the role of hydrogeology in the development and implementation of a Source Protection Plan in a large karst groundwater catchment. Hydrogeologists have played an important role in the characterisation of the catchment, the assessment of significant threats and risks, the communication and collaboration with key stakeholders, and in putting together an ambitious, but achievable, plan that seeks to improve and protect groundwater sources through catchment management. The plan incorporates mitigation, biodiversity and engagement strategies. Implementation is ongoing through a dedicated resource which provides the necessary impetus and engagement with relevant stakeholders regarding the main goals of the Plan. Continued hydrogeological input is required to support the roll out of the Plan. This paper demonstrates the iterative nature of catchment science and management in a large karst area and seeks to highlight the challenges and opportunities with such catchments.

INTRODUCTION

The first iteration of the 'Rathcroghan Source Protection Plan' was published in 2020 as part of a pilot project set up by the National Federation of Group Water Schemes (NFGWS) and Geological Survey Ireland (GSI) (Kelly *et al.*, 2020). This project, outlined in detail by Deane (2020), included developing an integrated source protection plan for the numerous group schemes on the Rathcroghan Uplands in County Roscommon because it was representative of a challenging karst environment in terms of the size and hydrogeological complexity. There was good, relevant information readily available, but all of the challenges of a catchment approach to protecting group scheme drinking water sources in such an environment became apparent through time.

'Groundwater and Catchment Management' was the focus of the IAH annual conference in 2013, in which Daly *et al.* (2013) presented and proposed an Integrated Catchment Management (ICM) approach for '*achieving the sustainable use of our water and land resources*' with a vision of a '*healthy, resilient, productive and valued water resource, that supports vibrant communities*'. Progress, acceptance and adoption of this approach nationally were described by Daly *et al.* (2016). This integrated approach, together with Drinking Water Safety Plans (EPA, 2011) and Multiple Barrier Approaches (NFGWS, 2012 a, b), led to the development of the Drinking Water Source Protection Framework (NFGWS, 2019; Deane, 2020), upon which the Rathcroghan Source Protection Plan is founded. A summary flow chart of the approach in the framework is provided in **Figure 1**.

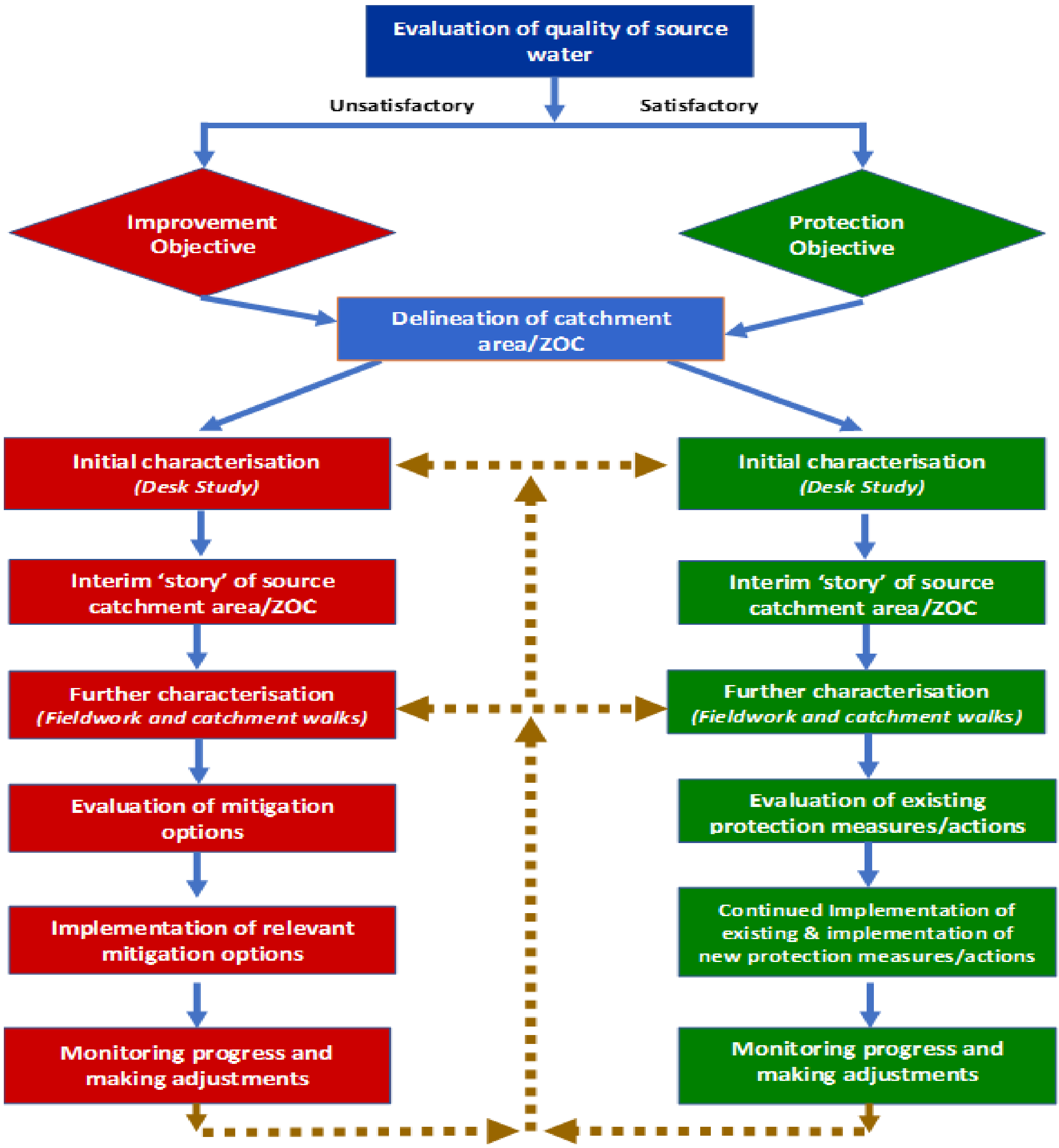

Figure 6: Source Protection Framework (NFGWS, 2019; Deane, 2020)

The framework provides an overarching structure and enables integration of groundwater and surface water protection approaches. It brings to play characterisation approaches that are used for implementation of the Water Framework Directive (WFD), and central to the framework is that the steps are easily communicated and understood by all parties involved, in particular the communities that live in the catchments. The framework provides a structured path to establish achievable and practicable targets, and maximise co-benefits in terms of improving and/or securing water quality, biodiversity, community awareness and engagement, and stakeholder communications and collaboration.

The Rathcroghan Source Protection Plan is being implemented through protection and improvement strategies. This includes simple measures such as fencing, improving and actively communicating about biodiversity with the introduction of bee hives, school demonstrations and promotion of the initiative through local media. The engagement and interest shown by local communities, and in particular by the farming community, is positive and encouraging.

ICM sits within a broader framework of policies, payments and grants. This is one of, if not *the key* fundamental drivers of landuse and in some areas has unintentionally been in conflict with some of the objectives of ICM. However, this has long been identified and is now also being addressed.

Rathcroghan group water scheme drinking water sources

There are five groundwater supplied Group Water Schemes (GWSs) in the Rathcroghan area, including Polecats, Corracreigh, Mid-Roscommon, Oran-Ballintubber, and Peak-Mantua GWSs that provide an approximate combined supply of 1,900 m^3/d (**Table 1**, **Figure 2**). The Oran-Ballintubber and Mid-Roscommon GWSs each utilise two separate sources. **Figure 2** shows the location of the group water schemes and their respective catchment areas. The catchment area is also shown for Castlerea Public Water Supply.

The GWSs are drawing water from karst springs and owing to the inherent nature of spring flows, as well as the regional geology, hydrogeology and landscape, all have large catchments. The individual GWSs are treated as a single group, mainly for hydrogeological reasons as they share a common physical setting with similar land uses, and risks, and are discharging comparable untreated water. Their catchments enclose the upland areas from Elphin in the north of Rathcroghan, through to Oran and Ballintubber in the south of the region, encompassing an area of approximately 180-200 km^2 (**Figure 2**).

Table 1 The GWSs in Rathcroghan

County	**Group Water Scheme**	**Number of Domestic Connections**	**Groundwater**	**Estimated daily abstraction (m^3/day)**
Roscommon	Peake Mantua	38	Groundwater	80
Roscommon	Corracreigh	354	Groundwater	265
Roscommon	Mid Roscommon	750	Groundwater	737
Roscommon	Oran Ballintubber	390	Groundwater	414
Roscommon	Polecats	395	Groundwater	426

Previously-completed work on the GWSs delineated potential spring catchment boundaries as an initial focus on group scheme management, but also recommended much more detailed mapping and analysis (Meehan *et al.*, 2015a, b; Kelly *et al.,* 2015a, b, c). In this work, no detailed, field-scale hydrogeological mapping, or associated dye tracing and analysis, had been completed.

Hydrogeological conceptual and pathways model

It was known from the dye tracing work completed on the Castlerea sources by GSI in collaboration with Roscommon County Council that groundwater pathways were complicated with fast travel times (Hickey, 2008; Lee *et al.*, 2003). Thus, in order to advance the management of the individual spring catchments, more detailed mapping was required to delineate with more certainty the catchment boundaries, and to formulate the initial stages of the management plan. Defining and delineating the currently-understood catchments to the springs was therefore primarily based on water tracing conducted by GSI, and others (Duncan *et al.*, 2017).

The current conceptual model is presented in the Source Protection Plan (Kelly, *et al.*, 2020) for the schemes, and published as a case study in the Karst of Ireland (Drew, 2018).

The 200 km^2 karst limestone plateau of the Rathcroghan Uplands is set at approximately 40–150 m above sea level. The plateau generally receives over a metre of rainfall per year and is characterised by sinking streams, swallow holes, turloughs, an absence of surface water courses, and relatively large springs dotted around its lower-lying perimeter. Contamination of these springs is relatively common, and severe pollution incidents have occurred historically.

Rainfall percolates down through soils, shallow subsoils and bedrock across the land surface in varying amounts, depending on the nature of the subsoil. There is also direct recharge to the bedrock through swallow holes, enclosed depressions and sinking streams. Once the infiltrating rainwater reaches the limestone bedrock aquifer, it rapidly flows as groundwater *via* karstic conduits and enlarged fissures towards the springs.

Dye tracing has provided sufficient information on the general groundwater flow directions to the main springs. The groundwater velocities were rapid, with dye appearing at the springs within days, including those that travelled significant distances – up to 10 km in some cases. The results highlight an intricate network of flow with some unexpected directions, and provided evidence for delineating a 'jigsaw puzzle' of abutting ZOCs across the entire plateau area (**Figure 2**). The results demonstrate that each of the springs is fed by groundwater originating beneath the uplands and also that each of the main springs is fed by a specific ZOC. The total area encompassed by the zones of contribution is approximately 190 km^2.

Whilst the tracing has been successful in establishing ZOCs, uncertainties still remain. Each boundary needs to be treated with an element of caution. The traces also indicate that surface water and groundwater divides are not coincident in all cases. There are no long-term flow records for the spring overflows and this presents difficulties in attempting a water balance. It is assumed that the ZOCs are reasonably accurate even though there are surface water courses exiting these catchments and it is likely that the springs are 'overflow' springs and that not all the groundwater emerges at the springs. There are further traces and hydrogeological work that could be carried out to improve information on the catchments. These are detailed in the Source Protection Plan as part of additional actions and recommendations.

The untreated water quality is generally poor in the springs and they are occasionally polluted, with shutdowns of the GWSs required. The *significant issues* are the persistent presence of microbial contamination with relatively high counts, allied with suspended solids, and turbid water in response to heavy rainfall events. This contamination is associated with occasionally elevated chloride, iron, manganese, aluminium, ammonium, nitrite, potassium, and the occasional presence of pesticides and herbicides, and suggests an anthropogenic impact, linked with direct recharge *via* karst features. The rapid response to rainfall events is evident from the corresponding rapid changes in turbidity and electrical conductivity. The water quality reflects a combination of the inherent susceptibility of the springs and the impacts from *significant pressures* such as septic tank systems, farmyards, cattle access to watercourses, slurry spreading, and the application of inorganic fertilisers, pesticides and herbicides (including in gardens) in the catchment areas to the sinking streams and swallow holes.

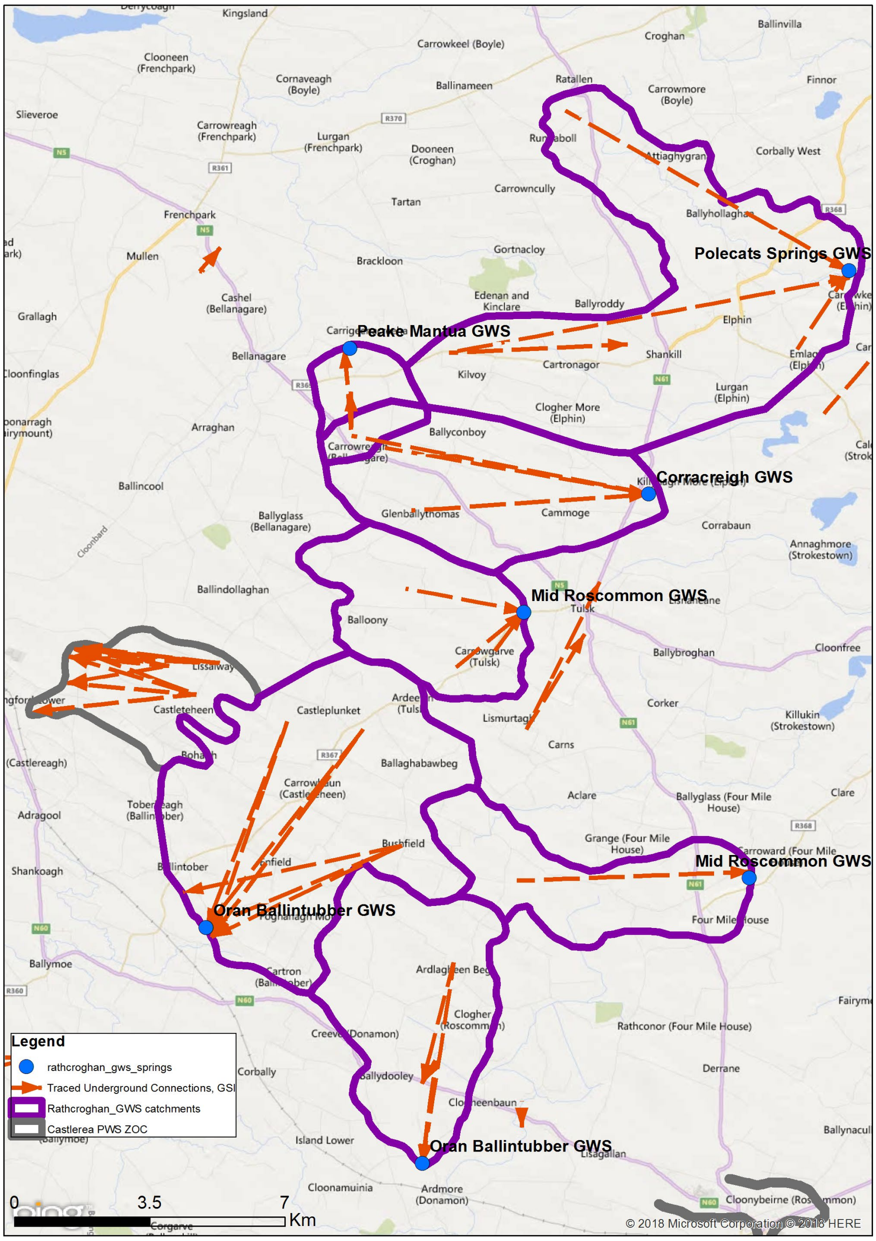

Figure 7: Location map showing Group Water Schemes, catchment areas, and dye tracer lines that enabled the catchments to be delineated

DEVELOPMENT OF THE SOURCE PROTECTION PLAN

Based on the above work, therefore, the Rathcroghan Source Protection Plan had a basis on which to be rolled out, *i.e.*, there were catchments and water quality data available, for a large karst setting. The development of the plan was based on the overarching framework summarised in **Figure 1**. In terms of the 'steps' in the framework, much was already known and several steps were already in place, namely, the catchment areas and the initial characterisation. The water quality evaluation was an important component in the process as it had to be decided whether the focus of the plan was 'improve' or 'protect'. As outlined in the section on the conceptual and pathways model, there are *significant issues* and *pressures*, causing the untreated water quality to exceed the guideline values in the Framework document. Therefore, it was decided that the objective for the group scheme sources was to achieve 'improvement' in the untreated source water. This enabled progression of the following elements:

- Further characterisation, involving fieldwork and catchment walks.
- Analysis and conclusions on the potential mitigation strategies and activities needed.
- Implementation of specific targeted and appropriate mitigation activities.
- Communication, awareness, education and outreach.

The further characterisation focussed on additional field mapping, water sampling, and, identifying and examining 'Critical Source Areas' (CSAs). The field mapping and walk overs enabled analysis and discussion on potential mitigation strategies in the CSAs (discussed below).

In parallel to further characterisation, establishing the plan involved several groups of stake holders. Site walkovers with agricultural advisers, department officials including forestry experts, caretakers and farmers, colleagues, catchment scientists were also conducted to discuss issues and solutions.

The Source Protection Plan incorporates:

- Mitigation actions in CSAs
- Inspections
- Communications, Awareness, Education and Outreach
- Land use management
- Water quality monitoring
- Improving definition of catchments and CSAs.

Having established a plan that consists of several strands and concurrent tasks, the NFGWS dedicated resources to implement the plan. This is discussed under Implementation and Progress. Key to the implementation is the location of the 'Critical Source Areas'.

Critical Source areas (CSAs)

'Critical Source Areas' are the areas that are likely to deliver a disproportionally high amount of pollutants compared to other areas in a source catchment or ZOC. In groundwater catchments, CSAs are located by combining the hydrogeologically susceptible areas for pollutant losses to water with the significant pressures that can contribute these pollutants, thereby posing a threat to the drinking water source.

As part of the pilot project, field work was undertaken to improve the information and examine CSAs. Given the size of the catchments in the Rathcroghan area (c.200 km^2) and the degree of hydrogeological complexity, it was not considered feasible to field map the entire area within the time frame of the pilot. Focussed field scale mapping was therefore carried out in appropriate sub-catchments. The field mapping provided detailed information on the physical setting and resulted in:

- Identified new, unrecognised areas of bedrock close to surface,
- Improved definition of mapped rock close areas/boundaries,
- New karst features (swallow holes, depressions, dry valleys, a sinking stream, and a turlough),
- Cattle access points to water courses/ditches, and,
- Observations on new drainage and landscaping work (timing and location of slurry spreading, new mole drains, re-seeding areas).

From existing knowledge and experience, the desk study and field mapping, there are numerous features across the landscape that offer opportunities for rainfall to enter and rapidly move through the groundwater system to the springs in a few hours or a few days. For instance, many newly-mapped swallow holes have been found and there are likely to be more unrecorded. From the further characterisation as part of the pilot plan, an additional 16 swallow holes and 120 dolines were mapped across approximately 5 km^2, which is approximately 2.5% of the entire 200 km^2. As the source protection plan evolves and further information is gathered from future characterisation, additional CSAs may be identified and included in the plan. Indeed from the ongoing implementation since the plan was adopted, additional swallow holes have been discovered. Site specific information relating to CSAs, land use, potential contamination sources, and water quality continues to be gathered. This highlights the interactive nature of further characterisation and the need for feedback and review of the plan.

As can be seen from the pathways model, the sinking streams and swallow holes are important CSAs. An example is shown in **Figure 3**. It was proposed in the initial plan to focus on the CSAs consisted of a sinking stream typified by poor draining soils, with a risk to quality from sediment, nutrients, pesticides and organic wastes.

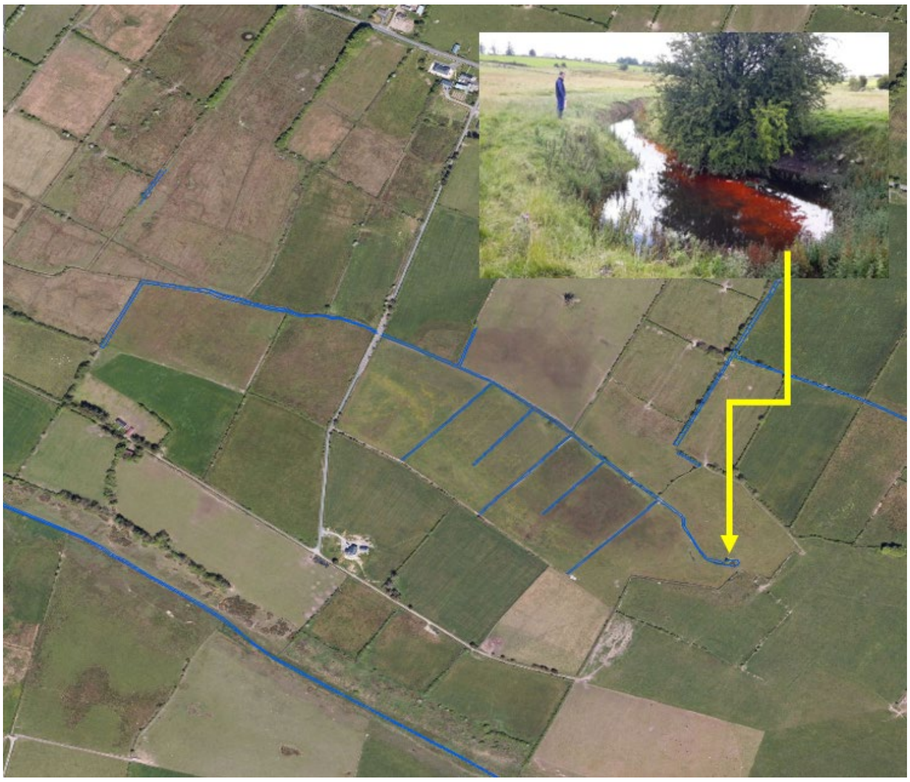

Figure 8: A Critical Source Area: sinking stream sub catchment

The CSAs are prone to the rapid delivery of sediments, nutrients and other contaminants to the springs. Mitigation could be achieved through a variety and combination of options/methods. These include fencing, pesticide/herbicide controls, sediment controls, riparian buffers, alternative water sources, septic tank inspections/remediation, and the introduction of appropriate cover of woodland in places. These are actions to break the 'pathway' in the 'hazard – pathway – receptor' model. This topic is being presented at this conference by the NFGWS (McCabe, 2021) and further actions are outlined in the recently published 'Handbook of Source Protection and Mitigation Actions for Farming' (NFGWS, 2020).

Implementation of Mitigation and Protection Strategies

The NFGWS and the GWSs have progressed a number of elements in the development and implementation of a Source Protection Plan. A dedicated catchment officer of the NFGWS is working with the schemes and the people in the community on a regular basis. The NFGWS approach to implementation is underscored by the following motivators:

- Protect the local water supply.
- Improve biodiversity.
- Provide a habitat and food for their bees.
- To help the local community.
- Climate change (co) benefits.

As such, implementation focuses on the physical aspects of mitigation, *e.g.*, fencing, and 'softer measures', but perhaps more importantly, talking to farmers and the wider community, enthusing people along the way about the natural beauty of the catchment, and introducing interested parties to biodiversity and bee-keeping.

The NFGWS, through working with the farmers and the wider community, have met some barriers. However, there is a great willingness to engage and a demand for knowledge and direction (**Table 2**).

Table 2 Some findings from listening to the community (NFGWS, 2021)

Barriers	Positives
Isolation	Keen to engage
Knowledge gap	Keen to learn
Loss of Farm payments	Keen to get involved
Delay to Farm payments	Want a clear direction

The work being carried out includes focussed farm visits to assess currently-unmapped CSAs through the use of the mitigations handbook. This has involved detailed field walkovers that examined specific portions of fields, ditches, slopes, and included in-depth detailed discussions on nutrient management with landowners, farm advisers and catchment scientists. Small sinking stream catchments have been selected to trial nutrient/sediment mitigation through a combination of fencing, buffers and native woodland. This is being trialled through the mechanism of the Department of Agricultures Native Woodland scheme and potentially the agri-forestry schemes. Further water quality testing is being undertaken, including selected sinking streams. The field work has additionally revealed 'new' karst features and further information on the character of the sinking streams. Implementation at one of the sinking streams is shown and summarised in **Figure 4**.

Figure 9: Selected sinking stream stretches and fields for mitigation (numbers represent the farmers that have got involved)

As testament to the enthusiasm and willingness to get involved several families, farmers and group schemes have taken on bees under a 'Let it Bee' campaign. This scheme has obtained a European Bee award under the category of land management practices.

Signage through contactless water fountains have been placed in strategic locations to promote awareness.

Through the listening and talking and engaging frequently with the community, the NFGWS have had 'spin-off' success, where through word of mouth other communities outside the Rathcroghan Uplands have sought to get involved. In parallel, there is a national schools project being rolled out: "*I've planted a tree and my garden is pesticide free*" for which there is great take up across the whole county.

The NFGWS have prepared nine short videos available on youtube, available on www.nfgws.ie specific to the Rathcroghan Uplands. Several of these feature a ‘champion’ farmer that discusses changes made on their respective farms around management generally, and specific actions, such as weed wiping and slurry spreading.

The NFGWS are continuing to seek ways to protect drinking water supplies and current research is examining the links to behavioural changes by promoting pollinator actions and intensive awareness and communication strategies (Corrigan, 2021).

SUMMARY AND CONCLUSIONS

It is technically challenging to establish a geoscientifically robust source protection plan in a karst area, particularly if it encompasses a large geographic karstic area like Rathcroghan. Establishing where and how big the catchment area is to a karst spring or borehole generally requires a considerable investment of labour and time. Deciding if the objective is to ‘improve’ or ‘protect’ the drinking water source depends on the available untreated and treated water quality data. Determining the CSAs within the catchment is dependent on the level of work done to characterise the catchment. The framework shown in **Figure 1** provides a structure to follow. The plan becomes a ‘living’ active iterative cycle. For areas where the information is limited, it may be daunting to consider and establish a plan, particularly, if dye tracing is required to prove catchment boundaries.

There will likely be sufficient information to form an initial view of the water quality and to start ‘initial characterisation’. There is a suite of well established datasets and layers available from a variety of sources, *e.g.* GSI and EPA, that enable a preliminary assessment of the catchment, the water quality, and the potential pressures and risks. Of particular use are the geology, groundwater vulnerability and the pollution impact potential maps, and the karst datasets. Establishing the catchment area to the source is potentially an iterative task that can start with a relatively simple model, and develop into a more detailed and evidence based conceptual/pathways model. Many drinking water sources have had catchment areas delineated so these may enable an initial characterisation. It is useful to re-iterate the developing nature of this and to outline the uncertainties. Continuous development of the conceptual/pathways model is part of the final step in the framework (**Figure 1**). The Rathcroghan Source Protection Plan includes further characterisation to improve the hydrogeological information, such as further tracing, water sampling and karst feature mapping. As specific mitigation and protection strategies are rolled out, additional CSAs will be identified and assessed.

It was a challenge to communicate with the stakeholders and the communities that live in the Rathcroghan Uplands as it covers a very large area. Several approaches were adopted and the more successful included: media engagement through local radio and newspaper; field visits and presentations to local agricultural advisers and consultants; and, school visits and demonstrations. These communications were steered through a committee that included the main farming groups, the local authority, Group Scheme management, NFGWS and GSI.

For catchment management in karst terrains, the role of groundwater scientists is important throughout the development of a source protection plan, and is crucial to the communication and linking of the different components: from the characterisation to the identification of CSAs; with respect to the communications between the various parties, particularly in formulating the mitigation and protection strategies; and the implementation and monitoring.

Starting small, with a few CSAs, and by listening and talking to local farmers, has realised a willingness and interest to learn amongst the farmers and wider community. This has yielded real action around nutrient, sediment and weed controls. It has fostered a positive relationship between the group schemes and the community. Parallel biodiversity and awareness initiatives with farmers, schools and the wider community has given traction and momentum to the Rathcroghan Source Protection Plan.

What has developed in the Rathcroghan Uplands demonstrates that a catchment approach can work. Every catchment can be characterised, and the basic foundation exists.

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