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A Strategic Look at Natural Water Retention Measures: The SloWaters Project

Authors: Mary Bourke, Darragh Murphy, Paul Quinn, Mark E. Wilkinson, Simon Harrison, John Weatherill and Caspar Hewett

Lead organisation: Trinity College Dublin

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Government of Ireland

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5. Office of Communications and Corporate Services

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What did the research aim to address?

The SloWaters project addressed the pressing environmental challenges of flooding and declining water quality in Ireland, which are being exacerbated by climate change and intensive agricultural practices. It fills a critical knowledge gap: the lack of empirical evidence regarding the effectiveness of nature-based solutions (NbS) in Irish rural landscapes.

This research is crucial for policymakers, farmers and local communities, and provides a sustainable, low-cost framework for protecting infrastructure and restoring ecosystems. The approach is innovative, as it is the first project in Ireland to construct rural demonstration sites (in Wexford and Cork) specifically designed to test NbS measures, such as offline storage areas and leaky dams.

By integrating these field experiments with advanced numerical modelling (including the Pond Forensic Model and the Catchment Runoff Attenuation Flux Tool), the project provides a multifaceted evidence base to attenuate surface runoff and floodplain inundation. This research underscores the potential for NbS to complement traditional engineering in achieving climate-resilient catchment management.

What did the research find?

This work advances the state of the art by moving beyond theoretical modelling to real-world construction and instrumentation in Ireland. The research demonstrates that NbS are highly effective in Irish agricultural catchments. The findings address the primary evidence gap by providing the first Irish empirical data on rural NbS performance, including offline temporary storage areas and inundated woodland swales, which significantly reduced nitrate concentrations.

There is ample space in the farmed landscape for temporary floodwater storage (for 6–12 hours). Increasing floodwater storage capacity in the farmed landscape will have a big impact on larger flood events.

Societal and policy relevance is underscored by extensive stakeholder engagement, with over 200 visitors, including farmers, politicians and media, visiting the demonstration sites. Beyond experimental data, outputs include an online literature search tool and an interactive story map of natural water retention measures to assist practitioners.

While evidence for the efficacy of NbS at larger catchment scales (> 100 km^2) and more extreme events is beginning to emerge, the evidence base remains limited to frequent, low-magnitude floods in small catchments. Case studies in Ireland are needed at the catchment scale. In addition, the finding that a measure at one site occasionally acted as a phosphorus source needs further testing and suggests that designs must be carefully tailored to local conditions.

How can the research findings be used?

The findings provide a framework for mainstreaming NbS into Irish flood risk management. A critical next step is the explicit integration of NbS into national policy alongside traditional engineering, moving beyond recognition to mandatory feasibility in all flood relief schemes.

Future implementation requires establishing a dedicated, long-term funding stream to encourage uptake by private landowners for the provision of these ecosystem services. Farmers must be centred in any discussions of NbS governance, implementation and payment schemes.

The project's modelling tools and demonstration sites can be used to design "treatment train" networks of NbS features alongside bespoke training for land managers and advisors.

Future research should focus on the performance of NbS during extreme events, and the social and liability concerns of private landowners. It should also address unfavourable phosphorus dynamics where they occur. One possible approach would be to design water quality features and flood storage features differently, but to co-locate them in complementary parts of a farm plan.

Strategic monitoring of existing sites (e.g. floodplain ponds) will strengthen the empirical database, facilitating the transition from a "no NbS until quantified" approach to an adaptive "learn by doing" approach for climate-resilient catchment management.

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

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Contents

List of Figures

List of Tables

Executive Summary

Floods and declining water quality are pressing issues in Ireland, exacerbated by climate change and intensive agricultural practices. Nature-based solutions (NbS) offer a sustainable, lower cost and complementary approach to flood mitigation and water quality improvement, by working with natural processes to enhance the retention capacity of ecosystems. This research, conducted as part of the SloWaters project, examines the efficacy of various NbS measures in Irish agricultural landscapes, focusing on flood mitigation, water quality improvements and policy recommendations for wider NbS adoption. The SloWaters project, the first of its kind in Ireland, constructed rural flood mitigation demonstration sites and assessed the impact of NbS on stream hydrology and water quality.

To examine the efficacy of NbS for flood mitigation and water quality improvement in Irish agricultural landscapes, the SloWaters project employed a multifaceted methodology encompassing the following:

- **Field experiments:** two demonstration sites were established to monitor the performance of different NbS measures. At Site 1, in County Wexford, offline storage areas (OSAs) and leaky dams were installed to assess their impact on flood peak reduction. At Site 2, in County Cork, a wider range of measures were tested, including OSAs, leaky dams, a woodland swale and low-head boulder weirs, to investigate their effects on both flood mitigation and water quality.
- **Numerical modelling:** hydraulic models, including the Pond Forensic Model, Aggregate Pond Model and the Hydrologic Engineering Center (of the US Army Corps of Engineers) River Analysis System (HEC-RAS 2D) model, were utilised to simulate the performance of different NbS configurations and explore the scaling up of scenarios for larger catchments. A multi-scale rainfall runoff model (CRAFT) that includes NbS impacts was run against data from our field sites and from Teagasc Agricultural Catchment Programme (ACP) sites.
- **Water quality monitoring:** water samples were collected and analysed to assess the impacts of OSAs, woodland swales and low-head boulder weirs on key water quality parameters, including nitrate, phosphorus and dissolved oxygen. The CRAFT model was tested against nitrate and phosphorus data at the Teagasc ACP sites.
- **Vegetation and soil sampling:** to evaluate the potential ecological impacts of temporary inundation, vegetation and soil samples were collected and analysed from the OSAs, focusing on factors such as grass productivity, plant diversity and soil chemistry.
- **Policy and practice review:** a comprehensive review of existing policies, funding mechanisms and governance structures was conducted to identify barriers to and levers for wider NbS implementation in Ireland.

Project Outputs

Demonstration sites: the two demonstration sites serve as practical examples of NbS implementation and provide valuable insights into their construction, operation and effectiveness. These sites also served as platforms for knowledge transfer and community engagement, hosting over 200 visitors, including farmers, students, politicians, media and government agency representatives.

Literature search tool: an online literature search tool was developed to provide easy access to relevant research and guidance documents on NbS for flood risk and diffuse pollution management.

Reviews of runoff attenuation features and OSAs: two comprehensive reviews were conducted to summarise existing knowledge and evidence on the effectiveness of these specific NbS measures for managing flood risks.

Story map of natural water retention measures (NWRMs) in Ireland: an interactive story map was created to provide an overview of existing NWRM case studies in Ireland, showcasing their locations, objectives and key findings.

Policy recommendations: the project formulated a set of policy recommendations aimed at overcoming barriers and promoting wider NbS adoption in Ireland.

These recommendations encompass mainstreaming NbS into flood risk management plans, addressing funding gaps, enhancing knowledge and capacity, and strengthening stakeholder collaboration.

Project Findings

Flood mitigation:

- **OSAs are effective for mitigating localised flood peaks, particularly for frequent, low-magnitude flood events.** Field experiments demonstrated that OSAs can reduce flood peaks by up to 38% and increase the duration of lower flood peaks by 2.5 times. Modelling suggests that OSAs can effectively reduce peak flows in catchments of up to 12 km^2 if a target storage volume of 2000–3000 m^3/km^2 is achieved.
- **Leaky dams (LDs) can influence flood peaks, but their effectiveness is contingent on storage volume.** LDs reduced the time to peak for flow events with a return period of ≥ 3 years (i.e. an annual exceedance probability of ≤ 33%) at a test site. Modelling studies indicate that the volume of water stored by LDs is a more significant factor in peak discharge attenuation than the number or configuration of dams.
- **The evidence base for the effectiveness of NbS for flood mitigation is growing but remains limited, particularly for larger catchments (> 100 km^2) and higher magnitude floods.** Further research is needed to assess the scalability and performance of NbS under different hydrological conditions and climate change scenarios.

Water quality:

- **Enhancing farm drain morphology can improve water quality.** A woodland swale installed at a demonstration site increased dissolved oxygen concentrations and significantly reduced nitrate concentrations along its length. However, dissolved phosphorus, organic matter and ammonium were released during critical periods, suggesting that nutrient uptake was temporary, and further research is warranted.
- **Bunds may have mixed impact on water quality.**
  - Data demonstrated the bund's ability to trap sediment and facilitate nitrate removal processes. There was a statistically significant reduction in suspended solids and nitrate concentrations across all sampled floods.
  - However, significant increases in soluble reactive phosphorus and total phosphorus concentrations were observed. This suggests that the bund may act as a source of phosphorus. However, this occurrence should be infrequent for extreme events only.
  - In addition, dissolved oxygen concentrations were significantly reduced during temporary flood water storage, but, in our experiments, they remained in a healthy water range (above 9 mg/L^3).
  - Water quality changes varied significantly between flood events, within flood events and at different locations within the OSA. This variability underscores the complex interplay of factors influencing water quality dynamics in temporary storage ponds.
  - Further research is needed to fully understand the factors driving these contrasting effects and optimise bund design and management for enhanced water quality outcomes.
- **Targeting specific water quality pressures and employing a treatment train approach can enhance the effectiveness of NbS for water quality improvement.** Measures should be tailored to address the unique hydrological and biogeochemical characteristics of each catchment. Features for water quality should be designed differently to flood storage features, but features can be co-located and complementary.

Policy Recommendations

Mainstreaming NbS into flood risk management plans is crucial for wider adoption. This will involve moving beyond just recognising the value of NbS towards explicitly integrating them into relevant policies, fostering policy coherence across government departments, and systematically considering and prioritising NbS in flood risk management plans.

Addressing funding gaps is essential for scaling up NbS implementation. This requires dedicated, long-term funding mechanisms (e.g. 10 years) that align with the long-term benefits of NbS and alleviate the strain on local authorities with limited resources.

Building the evidence base for NbS effectiveness through robust monitoring and evaluation frameworks is key for informed decision-making. Assessments of large-scale catchments still rely almost entirely on numerical models, which often lack the real-world validation needed to convince flood risk managers. Trialling NbS in larger catchments will help quantify the benefits of NbS, demonstrate their return on investment, and refine design and implementation guidelines. As most studies are short term, they rarely capture the 1-in-50- or 1-in-100-year storms that define flood defence standards. This generates a false narrative where NbS appear highly effective for small floods, but their performance in larger-scale events remains unproven.

Fostering community engagement is crucial for successful NbS implementation, given the socio-economic implications for private landowners. This involves ensuring equitable benefit sharing, providing adequate compensation for land use changes and establishing clear governance structures that support landowner participation.

The SloWaters project represents a significant step towards advancing the understanding and implementation of NbS for flood mitigation and water quality improvement in Ireland. The project's outputs provide valuable resources for practitioners, policymakers and researchers, informing decision-making and promoting the adoption of sustainable and nature-based approaches to water management. This research underscores the potential of NbS for flood mitigation and water quality improvement in Irish agricultural landscapes. Overcoming policy and practice barriers and implementing recommendations will be crucial to realising the full benefits of NbS and promoting sustainable flood risk management in Ireland.

1 Introduction

1.1 Nature-based Solutions for Flooding

Nature-based solutions (NbS) are approaches to societal challenges that are inspired and supported by nature. NbS for the effective catchment management of water-related issues, also referred to as natural water retention measures (NWRMs), aim to enhance the retention capacity of aquifers, soil, and aquatic and water-dependent ecosystems with a view to improving their ecological status. They have the potential to be multifunctional measures that can protect water resources and address water-related challenges. This is achieved by restoring or maintaining ecosystems as well as natural features and characteristics of waterbodies using natural means and processes (Collentine and Futter, 2018). The term NbS encompasses approaches such as natural flood management. Recently, the European Commission has advocated using the term NbS (Nesshöver *et al*., 2017; Seddon, 2022) to capture other previously used terms. In Ireland, the national working group on NWRMs recommend the use of the term "nature-based solutions for catchment management" (OPW and EPA, 2020). Here, we use the term NbS to refer to measures installed for flood mitigation and water quality enhancement.

1.1.1 Flood management using nature-based approaches

The management of higher frequency floods globally has undergone a significant expansion, from solely working with structural (hard) defences to considering catchment-based "soft" engineering measures that attenuate flood runoff. The latter emulates natural processes to "slow the flow" through temporary water detention and to lengthen and roughen surface flow pathways. This growing field promotes NbS as a landscape design concept that will contribute to a lowering of flood peaks and, importantly, to delaying the time to peak.

A key characteristic of NbS for flood mitigation is the use of natural materials ("green infrastructure") rather than traditional hard-engineered materials such as concrete, steel or plastics (Ferreira *et al*., 2021). Catchment water retention may be increased through, for example, afforestation (Stratford *et al*., 2017; Xiao *et al*., 2021); restoration of alluvial wetlands (Thorslund *et al*., 2017; McInnes, 2018; Stratford, 2018) and mountain wetlands (using stone and/or wooden structures in peatland drains, e.g. Shuttleworth *et al*., 2019; Gatis *et al*., 2023); constructing ponds (using storage bunds on floodplains, e.g. Lockwood *et al*., 2022) or reintroducing beavers to river channels (Puttock *et al*., 2017; Puttock *et al*., 2021); and leaving large woody debris *in situ* or constructing wooden structures (leaky dams (LDs)) in low-order (headwater) channels (Barnes *et al*., 2023; van Leeuwen *et al*., 2024).

For valley floors, these measures can be categorised based on their location as "online", that is, in-channel, or "offline", meaning on the floodplain. Others view measures through an altered hydrological process lens as either changes to water flux (enhanced wet-canopy evaporation, enhanced soil infiltration) or changes to water surface storage (enhanced hillslope storage, enhanced in-channel storage, enhanced floodplain storage) (Chappell and Beven, 2024). Interventions that specifically target runoff flow pathways and build new temporary flow storage are known as runoff attenuation features (RAFs) (Quinn *et al*., 2022). These have the advantage of potentially tackling both water quantity and water quality issues.

1.1.2 Effectiveness of the nature-based solutions approach for floods

The evidence base for the effectiveness of NbS for flood mitigation has been growing over recent years (EA, 2025). This has allowed confidence levels for effectiveness to be assigned (see Table 1.1) to different measures. The columns highlighted in yellow in Table 1.1 include measures that are generally more applicable to the Irish agricultural landscape. The confidence levels reflect (a) the degree of agreement of scientific studies and (b) volume of information available.

Table 1.1. Summary of levels of confidence in the UK evidence base for the effectiveness of each NbS measure for flood risk management

Effect	Soil and land management	Runoff pathway management	Leaky barriers	Offline storage areas	Floodplain and floodplain wetland restoration	River restoration	Catchment woodland	Cross-slope woodland	Floodplain woodland	Riparian woodland	Headwater Peatland management
Effect on flood flows, peaks and storage	L–H	H	M	M	L–M	M	M–H	L	L–M	M	M
Effect on sedimentation and geomorphology	L–H	M	H	M	M	H	M	L	M–H	M–H	L
Effect at different catchment scales	H (s) M (m) L (l)	H (s) M (m) L (l)	L	M	L–M	M	H (s) M (m) L (l)	L	L–M	L–M	H (s) M (m) L (l)
Effect in different watercourse types	L–M	L	L	L	L	M	L–M	L	L–M	L–M	L
Design life and effectiveness	M–H	H	M	H	L	M	M	L	M–H	M–H	L–M
Maintenance requirements	M–H	M	L	M	M	L	H	H	M–H	M–H	L

The measures highlighted in yellow are explored in further detail in the SloWaters project.

Levels of confidence are indicated as follows: H, high; L, low; M, medium.

Catchment sizes are indicated as follows: (s), small catchment (~10 km²); (m), medium (~100 km²); (l), large (~1000 km²).

Low levels of agreement or low volumes of evidence result in a low overall confidence level. High levels of agreement and high volumes of evidence result in a high overall confidence level. A combination of medium and high levels of agreement and volumes of evidence results in a medium overall confidence level. Please see EA (2025) for information on the multiple benefits of NbS.

Source: EA, 2025.

The UK Environment Agency summary (EA, 2025) presented in Table 1.1 highlights that there is generally low- to medium-level confidence in several of these measure types, demonstrating the need for further research. Generally, there is a low level of confidence in measure effects in different watercourse types, suggesting that further transferable studies are required for different landscapes and climate regions.

Recent systematic reviews that have collectively analysed nearly 300 peer-reviewed papers and over 1200 case studies confirm that NbS are effective at mitigating fluvial floods. They note that their performance is highly dependent on scale, event intensity and the specific ecosystem type. Interventions are most effective in extra-small (< 1 km²) and small (1–99 km²) watersheds, where they can cover a larger proportion of the land. Performance is strongest for frequent (< 10-year) and intermediate (10- to 74-year) flood events. Effectiveness typically diminishes during extreme events (greater than 74-year return periods) (Bagheri-Gavkosh *et al.*, 2025; Howarth *et al.*, 2025).

1.2 Nuisance Floods

Current evidence suggests that NbS are suited to small-scale catchments (< 10 km²) and higher frequency floods (recurrence interval (RI) = 3 years) (Dadson *et al.*, 2017; EA, 2017). Until recently, the scale of flood events had not been broadly considered in flood management plans in Ireland or elsewhere. However, there is emerging evidence to suggest that more frequently occurring floods will have a significant impact on communities and that the extent of this impact will increase, especially under the most extreme climate change scenarios.

Just over a decade ago, the term “nuisance flood” was first used in the United States to describe occasional, minor coastal flooding experienced during high tide. These events were increasing in frequency and duration at the time, a trend that was expected to continue with climate change (Sweet *et al*., 2014). The impact of these events included overwhelmed stormwater drainage capacity, frequent road closures and the general deterioration and corrosion of infrastructure from salt water exposure. More recent work has refined the definition of nuisance flood to characterise it as water event inundation that is high enough to cause disruptions and damage (3–10 cm) but not high enough to warrant evacuations or cause structural failure (Moftakhari *et al*., 2017; Mei *et al*., 2021; Hsiao *et al*., 2024). The term is now used for fluvial and pluvial floods (Chang *et al*., 2010; Tanim *et al*., 2022; Singh *et al*., 2023), which occur across the complete spectrum of catchment sizes, affecting towns and cities as well as villages (Moftakhari *et al*., 2018).

Although the immediate impacts of an individual nuisance flood may be relatively small, the cumulative effects of these events, especially as sea levels continue to rise, are considered substantial (Li *et al*., 2021). The negative impacts of coastal, pluvial and fluvial nuisance floods include the following: (a) public inconvenience, in particular disruption of transport networks (Moftakhari *et al*., 2017; Jacobs *et al*., 2018); (b) business interruption, particularly in the tourism sector (Moftakhari *et al*., 2017; Moftakhari *et al*., 2018; Hsiao *et al*., 2024); (c) infrastructure damage, particularly to subsurface sewer and drainage infrastructure (Moftakhari *et al*., 2015; Vandenberg-Rodes *et al*., 2016; Moftakhari *et al*., 2017; Hsiao *et al*., 2024); (d) property damage, as nuisance flooding can lead to the deterioration of buildings (Jacobs *et al*., 2018); and (e) public health risks, such as the spread of waterborne diseases (Moftakhari *et al*., 2015; Vandenberg-Rodes *et al*., 2016; Moftakhari *et al*., 2017; Hsiao *et al*., 2024). Evidence is emerging to suggest that cumulative costs associated with coastal nuisance floods, in some locations, are similar to those for more extreme floods and, with time, may exceed the costs of extreme floods (Moftakhari *et al*., 2017; Hino *et al*., 2019; Fant *et al*., 2021). One study found that businesses in Annapolis, Maryland, experienced a 3% reduction in revenue during nuisance flooding days (Li *et al*., 2021). It is reasonable to expect that other investigations into the costs of pluvial and fluvial nuisance floods will find that they carry a comparable economic impact.

Studies on the efficacy of NbS for reducing the risks of nuisance fluvial and pluvial floods are few in number, but emerging data suggest that they play an important role. Ferguson and Fenner (2020) examined the effect of upstream NbS (hillslope tree planting and in-channel large woody debris) on the performance of an underground culvert during floods. Local housing estate residents had reported surcharging and nuisance floods in a 2012 flood event. The modelling study found that the NbS were effective, as they delayed the runoff by 45 minutes, which reduced flood volume by 65%, and recommended their use to mitigate the worst effects of nuisance flooding.

1.3 Larger Catchments, Larger Floods

As catchment scale increases, so does the level of uncertainty in the effectiveness of NbS measures (assuming that flood mitigation measures are in place in only a small part of a large-scale catchment), and, generally, the level of confidence in approaches at larger scales is low (see Table 1.1) (Dadson *et al*., 2017; EA, 2025). However, a recent review of more than 450 NbS studies found no strong empirical evidence (from both field data and modelling) to support the assertion that increased catchment scale and increased rainfall intensity diminish the effectiveness of natural flood management in the UK (Zhu *et al*., 2025).

Research is progressing on estimating the impact of NbS on larger flow magnitudes and at larger catchment scales (Bourke *et al*., 2022), and the knowledge base on the efficacy of NbS for flood mitigation is advancing internationally (e.g. Howarth *et al*., 2025). There exists a large pool of international literature, reports and case studies on NbS in catchment headwaters. Although most reviews capture modelling studies, there is also a growing body of empirical studies. For example, there have been several detailed systematic reviews on woodlands (Stratford *et al*., 2017; Cooper *et al*., 2021) and wetlands (including peatland restoration) in recent years (Acreman and Holden, 2013; Allott *et al*., 2019; Hare *et al*., 2022). A recent study used modelling to upscale small catchment (< 3 km^2) data to large catchments (70 and 280 km^2) (Hankin *et al*., 2021). It found that, for certain floodplain geomorphology types in the UK (these floodplains are also found in Ireland), the potential for expandable storage reduced peak flow[1] by 6–10% across all flow magnitudes modelled (from RI = 5 years to RI = 1000 years). While the reduction in peak discharge may be considered small, the cumulative cost saving of this reduction in average annual damages over a 30-year time frame is estimated to amount to €0.7 million (Hankin *et al*., 2021).

In a review of over 100 case studies, Howarth *et al*. (2025) found that, while NbS are effective across all catchment sizes, they are currently most "proven" in smaller catchments where their footprint is large enough to dominate the local hydrology. They report consistent reductions in peak discharge from 40% to 80% in extra-small (< 1 km^2) and small (1–99 km^2) catchments. In large catchments (> 1000 km^2), flood reductions tend to be relatively small (often under 20% and averaging only about 10% across different types of flood events). They suggest that taking a systems perspective is key to effectively scaling up flood mitigation in large river catchments. This is where strategically combining different types of NbS (e.g. forests, wetlands and ponds) across various sub-catchments allows the heterogeneity and complexity of larger catchments to be addressed.

The implementation of significant temporary storage on farmland has not been fully studied. Roberts *et al*. (2023) highlighted evidence from seven UK case studies that focus on offline storage (temporary ponds). They found that, as the amount of new storage (per km^2) increases, so too does the impact on reducing flood peaks. However, as most studies are based on modelling, more empirical evidence is required to confirm this trend. Our data on the hydrological functioning of small individual features can, therefore, guide and inform any modelling studies seeking to predict the impact of NbS on larger flood peaks. In addition, if NbS are considered as part of a suite of measures in a catchment (e.g. measures that also include traditional grey infrastructure), then the combined effect of all approaches may aid in mitigating large-scale/extreme events.

1.4 Floods, Land Use and Water Quality in a Changing Climate

1.4.1 Floods

Climate projections indicate that a change in precipitation magnitude intensity and frequency will likely impact catchment runoff regimes in Ireland (Nolan and Flanagan, 2020). Extreme events, such as floods and droughts, are expected to increase in frequency and intensity relative to their historical occurrence (Noone *et al*., 2017; Blöschl *et al*., 2019). An analysis of mean catchment flows already shows increasing trends in frequency, particularly for winter in the west of Ireland (O'Connor *et al*., 2023). Indeed, large increases in precipitation (25% and 20% per degree of warming at some locations) and rainfall intensity (detected for 30% of locations examined) will increase flood risk (Murphy *et al*., 2023a). This is for both fluvial and groundwater flooding and in both rural and urban locations in Ireland. Extreme events, such as the 2023 Midleton flood, have now been attributed to climate change (Clarke *et al*., 2024), linking Ireland to the global trend in attribution studies. Critical infrastructure corridors that track major rivers (roads, rail, power, communications and water services) face compounding outage risks, with national-level economic consequences, because upstream and floodplain management is not being redesigned at the same scale as the hazard is increasing due to climate change.

1.4.2 Land use change

Along with climate change, there is strong evidence to suggest that modern land use management practices have enhanced surface runoff generation at the local scale (O'Connell *et al*., 2007; Wilkinson *et al*., 2013), increasing flood frequency and magnitude. Wilkinson *et al*. (2013) suggested that improving soil water storage and disconnecting fast overland flow pathways are key to reducing storm runoff on agricultural fields. Good soil health has been shown to reduce flood risk (Hallett *et al*., 2016; Burgess-Gamble *et al*., 2017), as this improves soil infiltration rates. However, in extreme events, and when the soil becomes saturated,

1 Peak flow refers to the maximum instantaneous flow (Q) passing a given cross-section, often read from the crest of the event hydrograph and expressed in m^3/s.

runoff generation can occur (which is exacerbated further in compacted soil) (Pattison and Lane, 2012).

Agricultural land covers 71.6% of Ireland (80% of which is permanent grassland). Agricultural productivity is contingent on landowners managing how water and nutrients move through or are stored within the land. Agricultural catchments are typified by highly modified channel morphology and high fluxes of nutrients from source areas such as field surfaces, trackways and compact soils (Rogger *et al*., 2017; Fenton *et al*., 2022; Zhang *et al*., 2024). Management has substantial effects on flood peaks and the flux of nutrients to lower parts of the catchment during flood events and during periods when water tables are high (Jordan *et al*., 2005; Shore *et al*., 2016).

1.4.3 Water quality

The EU Water Framework Directive aims to improve the quality of waterbodies across Europe. It is in the interests of and an obligation for Member States to manage rivers and catchments in a way that supports high ecological status (at the chemical, biological and hydromorphological levels). The funding of the intensification of agricultural production from livestock farming over the past few decades has been driven by government policy. The most recent report from the EPA states that the biggest issue impacting water quality is nutrient pollution from agriculture and wastewater (EPA, 2024).

Alongside climate-forced changes in fluvial floods, climate change is also likely to impact water quality, resource availability and riverine ecosystems. A higher flux of water during rainfall events brings with it a greater flux of water quality pressures such as sediment, particulate and dissolved organic matter, and nitrogen and phosphorus in various forms, as they are washed from the surfaces of fields and farm trackways and areas of contaminated hard standing, such as farmyards, and as they are eroded from channel banks and streambeds (Doody *et al*., 2016; Shore *et al*., 2016; Harrison *et al*., 2019; Fenton *et al*., 2022; Rice *et al*., 2022).

Agricultural catchments may also have great potential for hosting NbS to mitigate issues of flood risk and improve water quality (Dadson *et al*., 2017; Wilkinson *et al*., 2019). NbS have been advocated by numerous authors as viable and cost-effective approaches to tackling hydrological and water quality problems in rivers (Krause *et al*., 2014; Grabowski *et al*., 2019; Lewandowski *et al*., 2019; Collier and Bourke, 2020).

The measures that are put into place in agricultural catchments should be designed and implemented to address the specific water quality and hydrological pressures derived from the relevant agricultural practices, while minimising the risk to the livelihoods of landowners and stakeholders (Deasy *et al*., 2009; Collentine and Futter, 2018). Indeed, it has been advocated that investment into best management practices and NbS to mitigate and manage water quality and flood issues in agricultural areas may be an effective means of reducing the cost and severity of post-flood repairs in afflicted urban areas (Parrott *et al*., 2009; Cooper *et al*., 2021).

To be effective, these measures must be designed with an understanding of the relevant pressures and of the pathways by which they can be delivered to at-risk waterbodies (Fenton *et al*., 2021). Depending on the water quality pressure in question, certain microbial and geophysical conditions will be required to achieve a desirable level of attenuation from polluted waters before they reach higher order streams, where mitigation tends to be much more difficult and costly. Numerous authors have further broken down NbS for water quality management into broad forms of intervention such as riparian zones (Stutter *et al*., 2019), constructed wetlands (Vymazal, 2007; Babatunde *et al*., 2008; Vymazal and Kröpfelová, 2009; Saeed and Sun, 2012; Ockenden *et al*., 2014; Peter *et al*., 2019) and instream measures (Haralambous *et al*., 1992; Hester and Doyle, 2008; Hodaj *et al*., 2017; Peter *et al*., 2019). Other reviews have been published that assess the effectiveness of various NbS for catchment management in the attenuation of specific water quality pressures in agricultural catchments (McDowell and Nash, 2012; Carstensen *et al*., 2020). New publications exist, however, that consider the nature of the source areas, the specific water quality pressures and the biological, chemical and hydrological contexts of water quality pressure attenuation in agricultural catchments (e.g. Harrison *et al*., 2019).

The policy landscape in Ireland, including clear policy conflicts, requires that the high-level national and international policy ambitions on NbS be translated into sectoral policies and action plans to ensure effective and coordinated implementation of NbS (Molloy *et al*., 2024).

As high numbers of scientific reviews and technical reports (including plain English guides) have been produced in recent years, we will not repeat the available material here. Rather, we will direct the reader to the project outputs where this information is further discussed.

Output 1: The SloWaters Literature Search Tool

This online tool allows users to easily locate online documents of interest (Wilkinson *et al*., 2023a). For this, we reviewed and distilled documents, identifying those related to NbS for flood risk and diffuse pollution management. The measures focused on related to woodlands, river and floodplain management, soil, runoff management and wetland/peatland restoration. The database includes literature from up to and including 2023. This tool uses a gravity form structure, where users can use filters to find the most relevant literature.

Output 2: Review of runoff attenuation features

In Quinn *et al*. (2022), we included a literature review of RAFs that highlights the effectiveness of nature-based approaches for managing flood risks. We emphasised the importance of factors such as sustainable flood retention basins, grassed waterways and earthen dams (bunds). Our review shows the efficacy of grassed waterways and bunds for effectively controlling muddy floods in tillage catchments. We emphasised the importance of a dense network of RAFs for accurate simulation and management of flood risks, particularly in small catchments. We used the Belford (UK) site to outline how these RAF networks can effectively manage flash flooding caused by intense storms, with a focus on managing flood intensity rather than volume. We found that nature-based flood management measures tend to work better in small catchments and for small return interval events.

Output 3: Review of offline temporary storage areas

In Roberts *et al*. (2023), we completed a review of temporary storage area measures. Using seven UK case studies, we showed that, as the flood storage volume per unit catchment area increases, so too does the flood attenuation effect. We also highlighted a conceptual model on how such interventions function.

Output 4: PhD thesis including a thorough review of nature-based solutions and water quality

This PhD thesis quantified the impact on hydrology and water quality of a range of experimental NbS (offline storage areas (OSAs), LDs, modified drainage channels and instream low-head boulder weirs at a field demonstration site in County Cork (Murphy, 2024).

Output 5: Findings of a holistic study on the effects of a rural flood detention basin

In this paper, we included a review of NbS for water quality and highlighted the dearth of quantitative data on the wider benefits of NbS for floods (Murphy *et al*., 2025). The work indicates that, while NbS are capable of reducing peak flows, the operation of NbS features is complex, as shown by the results on water quality and pasture health, and that multifunctionality is not always a facet of NbS.

Output 6: Investigating the barriers to natural water retention measures on Irish farms

In this MSc thesis, research on the perceived barriers to implementing NbS for flood mitigation in agricultural landscapes is presented (Alverado, 2021). The research adopted a mixed-methods approach, conducting surveys and interviews with institutional stakeholders and farmers. The findings highlight the complex interplay of EU policies related to flooding and flood risk management; identify the synergies and contradictions that exist in policy; and suggest that the oversaturation of water management bodies can lead to conflicting agendas and diluted responsibility.

The work also highlights an open-minded perspective from interviews with farmers ($n = 30$) regarding NbS adoption. Common barriers to NbS implementation identified reflect those already known in the literature, including a lack of financial incentives, a low level of technical expertise in the field, an absence of clear leadership and an overall ineffective communication space.

Output 7: Findings of study on nature-based approaches for peatland restoration in Ireland

This desktop study, undertaken as part of the fulfilment of an MSc, examined the critical role of peatland restoration in Ireland using NWRMs (Borklund, 2022). The author argued that restoring these degraded ecosystems offers multiple benefits, including improved water quality, flood adaptation, carbon sequestration and biodiversity habitat renewal. All these benefits align with several EU directives and international climate goals. However, the study highlights significant challenges to widespread implementation. These include policy inconsistencies, a lack of cohesive inter-agency strategies and public distrust stemming from top-down management approaches. To overcome these barriers and ensure the long-term success of peatland restoration efforts in Ireland, a more integrated and community-engaged approach is advised, drawing lessons from successful ecosystem-based restoration programmes in the UK and elsewhere. A summary of this research is available in Bourke (2025a).

Output 8: Findings of a study on the implementation of natural water retention measures within Irish forestry

This desktop study, undertaken as part of the fulfilment of an MSc, focused on the implementation of NWRMs within Irish forestry to combat climate change and mitigate flood risks (Leronomahos, 2022). It highlights Ireland's historical and current afforestation efforts, noting the nation's low forest cover compared with other EU Member States and the increasing role of the private sector. The critical review examined the benefits and efficiency of NWRMs across various landscapes, such as catchment, cross-slope, floodplain and riparian woodlands, citing studies that demonstrate their positive impact on water retention and flood reduction. It also critiqued existing Irish forestry policies and grant schemes, arguing that current stringent regulations, particularly the perpetual replanting obligation and licensing complexities, deter private landowner participation. Finally, the review proposed modifications to policy and practices to encourage greater engagement in afforestation, integrate NWRMs more effectively and help Ireland to achieve its ambitious climate action goals. A summary of this research is available in Bourke (2025b).

1.5 A Survey of Nature-based Solutions in Ireland

Early in the project, we undertook a review of catchment-based NbS case studies in peatlands, forests and agricultural areas that have been or are being implemented in Ireland. Case studies range from small-scale projects (e.g. farm-level measures or river reach restoration) to full catchment restoration (e.g. large-scale tree planting or peatland restoration). We used both a survey approach (with surveys distributed via our website and steering group) and a literature/website search to get information on any case studies that stakeholders may have implemented or may be implementing. We were interested in understanding the primary purpose(s) (goals) of the studies, for example whether for flood risk management purposes or to improve water quality and ecological habitat (e.g. to meet Water Framework Directive targets). Through this literature review and online survey with practitioners in Ireland, we were able to identify 22 studies or initiatives and ~85 sites (either in progress or completed as at 2022).

Only a few case studies were identified that were built for flood mitigation, and hardly any included monitoring to support the outcomes. Most of the other case studies focused on other primary drivers, such as water quality and carbon sequestration. Our findings suggest that the amount of empirical evidence related to rural-based NbS case studies in Ireland that have a primary aim to mitigate flood risk is limited (and that such case studies are usually confined to urban areas). Of the rural case studies we identified, many were in progress and some had recently been completed (e.g. Inishowen Rivers Trust, 2022). Therefore, the knowledge base on how measures work to mitigate flood risk from an Irish perspective is limited. However, the number of case studies is starting to grow (i.e. some new studies are at the scoping stage, e.g. the Farming for Water European Innovation Partnership). This limited evidence base is currently being strengthened through the SloWaters demonstration sites. The results of our scoping study are presented online as an ArcGIS story map (Wilkinson *et al*., 2023b).

2 Nature-based Solutions for Flood Mitigation on Agricultural Land

2.1 Study Sites

2.1.1 Site 1: Ballygow, County Wexford

This site is located on the Battle stream near Ballygow, County Wexford (52°12'57.43"N, 6°52'3.37"W). The small, 3 km², catchment drains the Booley Bay Formation (grey-to-black mudstones with siltstones). It is overlain by a predominantly shale drift and the resultant soils are poorly drained. It terminates in the Special Area of Conservation Bannow Bay, a further 3 km downstream. The land use in the catchment is predominantly improved grassland, with some Sitka spruce plantations. The study site (Figure 2.1) is located on a mixed-use farm of 70 ha that changed from a nitrogen derogation beef farm to an organic farm during the project. The weather of the South

Figure 2.1. Site 1: Ballygow, Co. Wexford. Panel (a) shows the demonstration site and its features; panel (b) shows the floodplain reconnection swale and location of trunk elevation; panel (c) shows logs (to raise intake threshold); panel (d) shows the bund (75 m in length); panel (e) shows the sediment pond; and panel (f) shows the spillway. For a detailed description, see www.slowaters.eu.

Wexford area differs from national averages. It has lower annual rainfall (800–1000 mm/year), with fewer rain days (< 150/year), is milder (mean temperature 10–11°C/year) and has maximum sunlight receipts (> 1550 hours/year).

2.1.2 Site 2: Leades, County Cork

This study site is located within the upper Lee Valley in County Cork (51°56'09"N, 8°52"59"W) (Figure 2.2). It lies approximately 150 m above sea level on a tributary of the Glashagarriff River, a sub-catchment of the River Lee. The stream rises approximately 2 km north of the study site in the Boggeragh Mountains, dominated by peat and coniferous forest. The catchment drains fine loamy soil over Devonian Old Red Sandstone bedrock. Land use in the catchment is primarily agricultural grassland (80%), with the remaining land being dominated by heathland and conifer plantations, with some broadleaf plantations within the farm itself. The area receives an average annual rainfall of 1305 mm.

2.2 Offline Measures

2.2.1 Demonstration measures

OSAs temporarily (for < 24 hours) store water derived or diverted from stream channels during peak flow. We designed and installed OSAs at each of our demonstration sites (Figures 2.1 and 2.2). Our aim was to study the impact of such features on the hydrology of downstream stretches, specifically during flood events.

There are four morphological components of offline storage:

1. The intake. The essential design principle is to optimise the inlet spills. If inlet spills are too low, inlet flow can cause damage. If they are too high, inlet flow can reduce the potential floodwater storage. An inlet can be a simple excavation of an embankment or the lowering of the riverbank (e.g. Site 1). Some may require armouring to prevent further erosion, and some inlets have a weir structure and adjustable gate (e.g. Site 2).

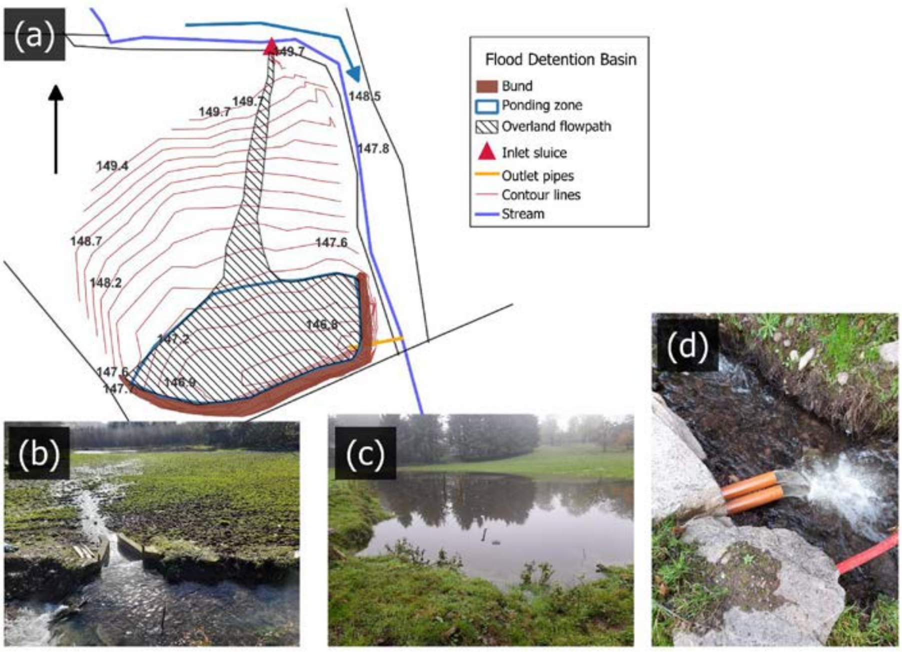


Figure 2.2. Site 2: Leades, Co. Cork. Panel (a) shows the Leades stream (blue arrow) flowing from north to south along the northern and eastern side of the field and the NbS that were constructed. The red contour lines denote elevation above sea level. Panels (b), (c) and (d) show features functioning during an inundation event: (b) shows the intake, high flows being partially directed from channel through the sluice of inlet; (c) shows the temporary pond; and (d) shows outlet pipes draining pond waters back to the stream channel.

This is a suitable approach for locations that require some control of (a) the season of flood ingress (e.g. due to summer tillage crops and/or stock use) or (b) the volume of water ingress (e.g. higher flows to recharge during drought periods). Online structures can be constructed to enhance the diversion of channel flow onto the floodplain. These can be leaky wooden structures (a leaky board; see Site 1) that extend onto the floodplain. This may also be an in-channel stone check dam (e.g. see Site 2).

2. The flow path. This is the area of inundation from the inlet to the storage pond. Longer flow paths may require riparian structures (e.g. the 100 m levee installed at Site 1) to contain the flow offline.
3. The bund. This is a low (< 1 m) soil ridge behind which a pond forms during flood flows.
4. The outlet. This can be in the form of PVC pipes (30–50 cm diameter) installed in the bund for slow drainage back to the channel. In some locations, an armoured spillway can be installed (as at Site 1).

The essential design principle for effective temporary offline storage is to optimise the inlet spill and outlet heights, as outlets that are too large can reduce potential storage and flow peaks.

2.3 Storage Performance: Empirical Data

Several flows spilled onto the OSA during the project. At Site 1, the OSA capacity was 850 m^3. Six storms observed during 2021 demonstrated that the pond fills quickly and empties slowly (usually in less than 24 hours), as required for impact (Figure 2.3). Water disappears from the larger floodplain, which

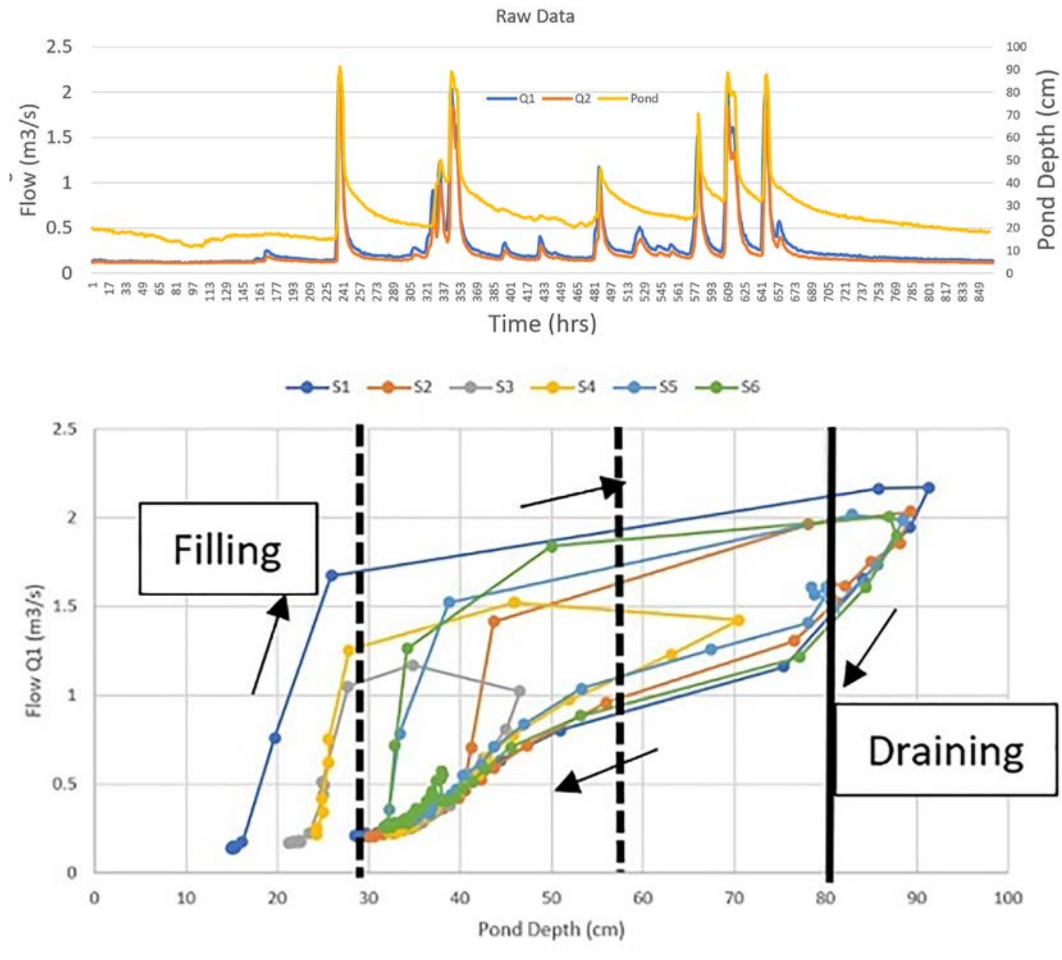


Figure 2.3. The top panel shows flow data from a series of storms in 2021 at Site 1. Q1 and Q2 show data from water-level sensors located upstream and downstream of the intake, respectively. The bottom panel charts six distinct storms filling and emptying. The dotted line represents the pipe position (30 cm in diameter) and the solid line shows the maximum height of the bund (80 cm).

quickly becomes suitable for agriculture activity, and some water and sediment are retained in the sediment pond (Figure 2.1). We note that a single bund at Site 1 is subject to flows from a 3 km^2 catchment, and the data show that the bund is overtopped during most large flows (Figure 2.3). This led to bund erosion and required redesign of the inlet thresholds and outlet flow rate.

The performance of the OSA at Site 2 was assessed by using the volumetric differences measured upstream and downstream of the OSA during 15 inundation events (March 2021 to January 2023). The estimated storage capacity was 245 m^3. The OSA attenuated flows across a range of peak-flow events, which ranged in RI from 1 month to 2.7 years (Murphy, 2024; Murphy *et al*., 2025). Analysis of water volumes in the OSA found a mean of 820 m^3 of water storage from the stream during storms. This equated to attenuating 33.48% of peak-flow discharge (Murphy, 2024). This was greater than the volume calculated to have been stored at the surface of the OSA, and additional attenuation volume may be attributed to soil infiltration, water being retained on the soil surface upslope of the ponding zone and loss of water to tile drainage. The OSA extended flow duration (with lower flood peaks) to 2.5 times the mean flood peak duration (i.e. 21 hours 50 minutes) (Figure 2.4).

The bund was overtopped at least once (October 2022) following wet antecedent conditions. The intake sluice was adjustable, and this allowed us to raise the intake level to reduce the volume of water entering the bund and prevent further overtopping. We note that the potential for flow peak attenuation may have been more influenced by rainfall volume over an extended period and antecedent stream and soil storage conditions than by the scale of individual flood peak discharges.

Result:

- Both OSAs showed a pattern of rapid filling and slower drainage, leading to attenuation of downstream flows.

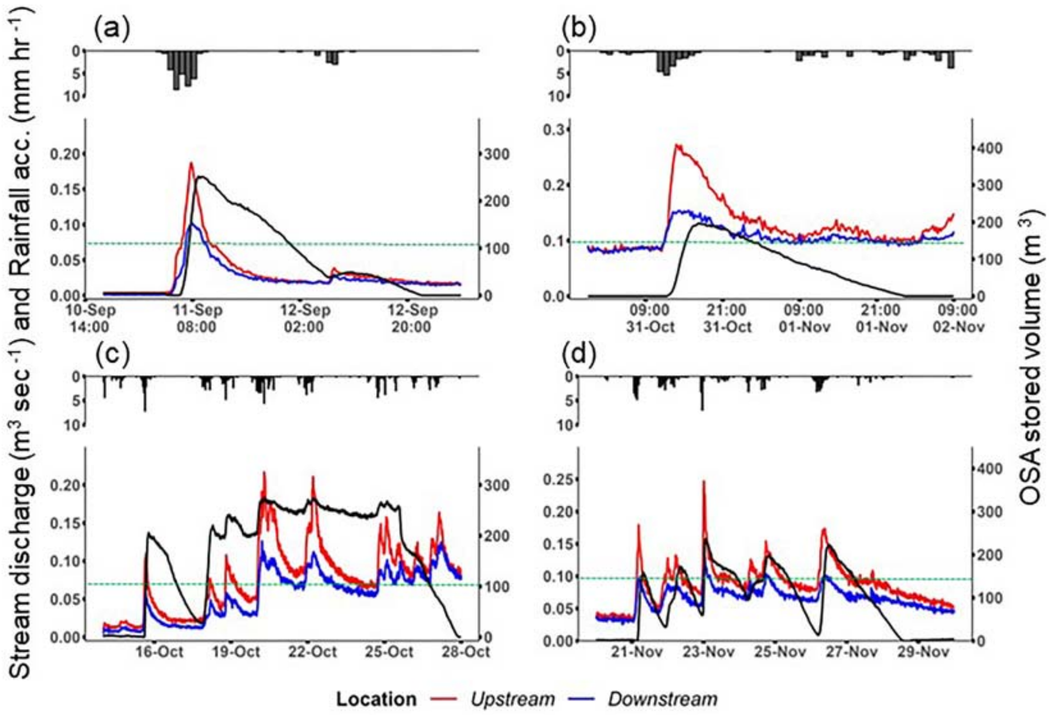


Figure 2.4. Selected OSA inundation events in 2022. Events on (a) 11 September 2022 and (b) 31 October 2022 were single-peak events; events between (c) 16 and 28 October 2022 and (d) 21 and 29 November 2022 were multi-peak events. Red lines indicate discharge at 15-minute intervals upstream of the OSA; blue lines show downstream discharge; bars show hourly rainfall at the study site; the black line denotes estimated volume stored in the OSA; and the green dashed line shows the take-off discharge at the sluice, which increased from 0.075 m^3/second to 0.1 m^3/second on 27 October 2022 due to the bund overtopping. Acc., accumulated.

- The OSA installed at Site 2 reduced peak flows immediately downstream by up to 38%.
- Both sites needed modifying post construction (Site 1 via adjustment of the intake height and increase of temporary water storage area; Site 2 via the construction of armoured intake and outtake) to prevent overtopping of the bund.
- The OSA demonstrated significant storage capacity during peak flow (>800 m^3).

2.4 Storage Performance: Numerical Modelling

We used a Pond Forensic Model (PFM) (Nicholson *et al.*, 2020; Quinn *et al.*, 2022) to identify the optimal design of a single pond in the 3 km^2 catchment at Site 1. Following several optimisations for a large event derived from the measured flow data (peak flow of 1.5 m^3/second), we found that, as shown in Figure 2.5, an improved pond function required:

- more storage (increase capacity from 1000 to 1500 m^3);
- increased inlet threshold volume (from 0.4 to 0.7 m^3/second);
- increased outflow rate (pipe diameter from 30 cm to 50 cm).

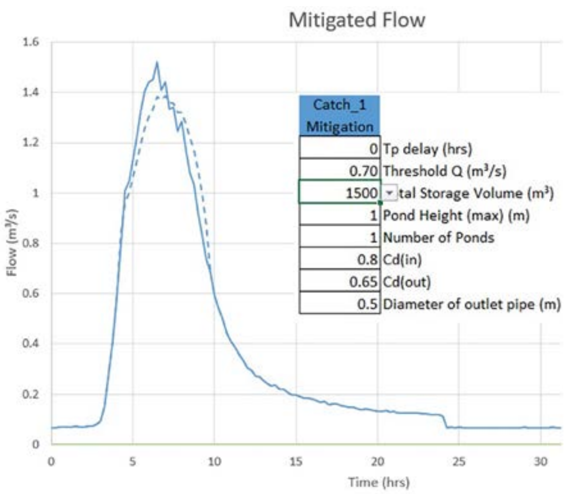


Figure 2.5. Optimised design for a pond. The dashed line illustrates the mitigated flow. Peak discharge was reduced by 8% and there was a slight increase in peak flow duration. Cd(in), drag coefficient for incoming flow; Cd(out), drag coefficient for return flow; Q, m^3/sec; Tp, time to peak.

It was not possible to add new storage during the project. Thus, we implemented a new inlet threshold at 80 cm above the average flow level (Figure 2.1c). We also set the outlet flow rate to at least 1 m^3/second (Figure 2.1f). This redesign significantly improved performance.

Result:

- The combined use of recorded water levels and the PFM is an effective method to assess physical modification of the measures for optimum results.

2.5 Online Measures

2.5.1 *Demonstration measures*

Online hydraulic storage measures, for example LDs, have been advocated for increasing roughness in channels so as to attenuate peak flows (Black *et al.*, 2021). However, the evidence supporting LD efficacy is limited and evaluations are mixed (Burgess-Gamble *et al.*, 2017). The emerging data suggest that reach-scale efficacy for 1-year floods is 10% peak flow reduction (van Leeuwen *et al.*, 2024). At larger catchment scales, how LDs affect lag time for events of different magnitudes is not clear (Roberts *et al.*, 2023). However, they can be effective for causing spillage onto the floodplain at high flows (e.g. the leaky board at Site 1).

In May 2022, we installed four LDs along a 120-m-long reach (with spacing of 25 ± 5 m) at Site 2 (Figure 2.6). The 2.5-m-wide low-gradient (1.7%) Leades channel has been artificially deepened to the extent that peak flows are rarely above bank-full height. The LDs were designed to interact with moderate peak flows only (>0.75 m^3/second) and water was forced to back up until it flowed over each of the LDs. Low flows passed beneath the LDs. The channel was instrumented with water-level sensors in July 2021 upstream and downstream of the experimental reach before measure installation so that the change in reach flow conditions with and without the measures could be assessed.

2.5.2 *Measure performance: empirical data*

We tested the overall efficacy of the installed LDs at reach scale by comparing seven flow events prior to LD installation with seven events following the installation. To assess the impact of LD reach

Figure 2.6. LDs at Site 2. The left panel shows the LDs' location and the basic design. The right panel shows the view from the upstream side of the first LD, showing woody debris build-up following the first high-flow event following installation (June 2022).

installation at attenuating peak flows, we used the difference between the water-level sensors installed upstream and downstream of the LD array. We used three widely used metrics: (a) peak discharge attenuation; (b) peak discharge velocity reduction; and (c) "peakiness" (i.e. the effect of LDs on the shape of flood peaks) (van Leeuwen *et al.*, 2024).

Result: the flow characteristics of the channel reach differed following LD installation (Figure 2.7):

- Peak discharge was reduced.
  - Pre-LD installation, peak discharges increased along the channel reach.
  - Post LD installation, the percentage difference between upstream and downstream peak discharge reduced significantly (27%).

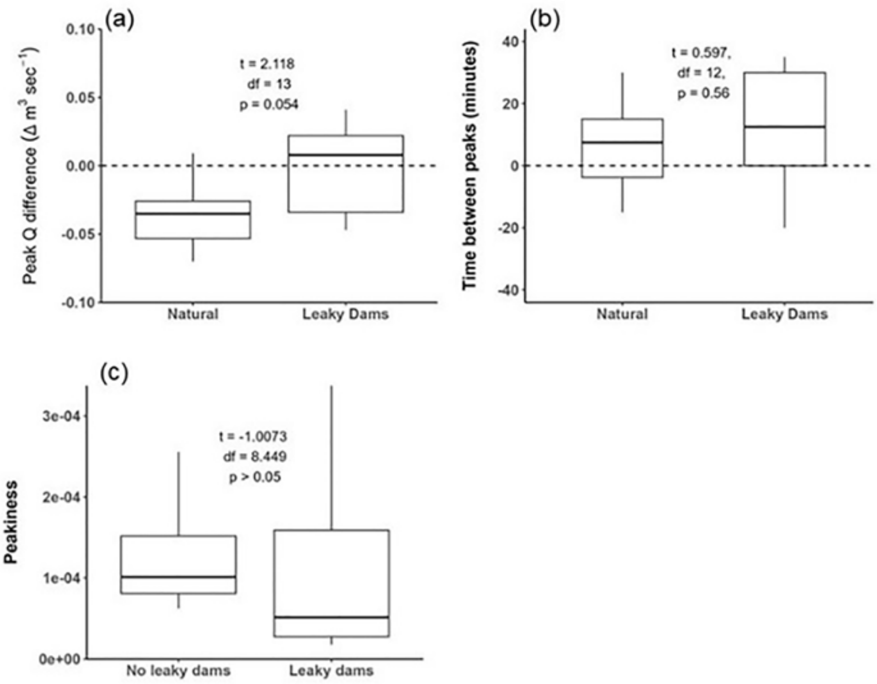


Figure 2.7. Box plots and linear model summary statistics on attenuation parameters. Source: Murphy, 2024.

- No difference was found in peak flow velocity attenuation during peak discharge.
- No difference was found in flood peak peakiness.

The observation that peak discharges were attenuated by LDs is promising, but examination of hydrographs indicates that high-flow events are not affected, as the LDs are submerged. The LDs functioned by locally restricting the flow of water down the channel. This increased the local erosional forces at each of the LDs, causing increased lateral erosion of the banksides either side of each LD and (more gradually) erosion of the streambed underneath the LD. This bed erosion most likely reduced the flood attenuation potential of the LDs over time by increasing the area of the flow pathway of water through the LD during spates. Two of the LD structures were dislodged during the investigation due to the erosional forces on banksides and the channel bed, but the "sled" construction design ensured that the structures were moved only 1–5 m downstream and did not disintegrate.

2.5.3 Measure performance: numerical modelling

We modelled woody LD efficacy under a range of scenarios using the two-dimensional HEC-RAS hydraulic model. Two flow domain discrete element methods (DEMs) (1 m resolution) were synthesised to allow flow routing and LDs to be represented. We used two design storm flows (RI = 2 years and RI = 50 years), which were input at the top of the domain assuming the upstream catchment was ~1 km^2. The size, number and placement of LDs for each scenario were tailored to maximise storage depending on the terrain geometry while avoiding any backwater effects that extended beyond the inflow boundary or another structure (Figure 2.8). The LDs were represented as weir structures, with a leakage factor represented by a custom outlet rating curve.

The models were run to provide a hypothetical assessment of changes in peak discharge (ΔQp) and peak discharge travel time (ΔQpt). A comparison of upstream and downstream flows shows the efficacy for each scenario (Figure 2.8).

Result:

- Hydraulic simulations suggest that LD water storage volume has more impact than flow routing, irrespective of the number or configuration of the dams. A significant impact was detected for Scenario 2 (one LD with storage capacity of 1869 m^3; RI = 2 years) and with the peak discharge (ΔQp) being reduced by 29% (0.08 m^3/second).
- The time delay to peak (ΔQpt) was 210 minutes. The hydrograph shape showed a broadened peak and slower rising and falling limbs.
- All other model outputs showed a generally small effect on ΔQp (< 5%) and ΔQpt (15 minutes). The number of dams or the use of the 6 m floodplain makes little difference if there is little total storage.
- Changes in overall hydrograph shape were small.
- The LDs have negligible impact on the peak discharge magnitude for a storm with an RI of 50 years.
- These findings align with several of the empirical findings at Site 2, but we note that the empirical data show a 27% reduction in peak discharge for the four LDs, a result not returned in the model data. Further empirical data and testing are required.

The use of LDs to help redirect flow to floodplains, as shown at Site 1, is a promising approach.

2.6 Scaling Up to 5 km^2: Nature-based Solutions for Flood Mitigation

In addition to the PFM and the HEC-RAS model, we used the Aggregate Pond Model (APM) (Nicholson *et al*., 2020; Quinn *et al*., 2022) and the Catchment Runoff Attenuation Flux Tool (CRAFT) (Adams *et al*., 2015; Adams *et al*., 2016; Barber and Quinn, 2012). When used together, these models support each other in determining effective scaling-up approaches. We assume that this work is best applied at the field scale and at catchment scales of 1–5 km^2.

We ran three model scenarios that examined the effect that increasing offline storage would have on peak discharge and flood duration. Scenario 1 was applied to Site 1 in County Wexford. We investigated what effect the addition of storage (×3) had on peak discharge events of 1.5 m^3/second. Scenario 2 was also applied at Site 1. Here we increased the storage substantially (×7.5) but ran the model for a larger flood event (modelled at 2 m^3/second). Finally, in Scenario 3, we tested the potential for scaling up to a larger catchment (Ballycanew, 11.5 km^2).

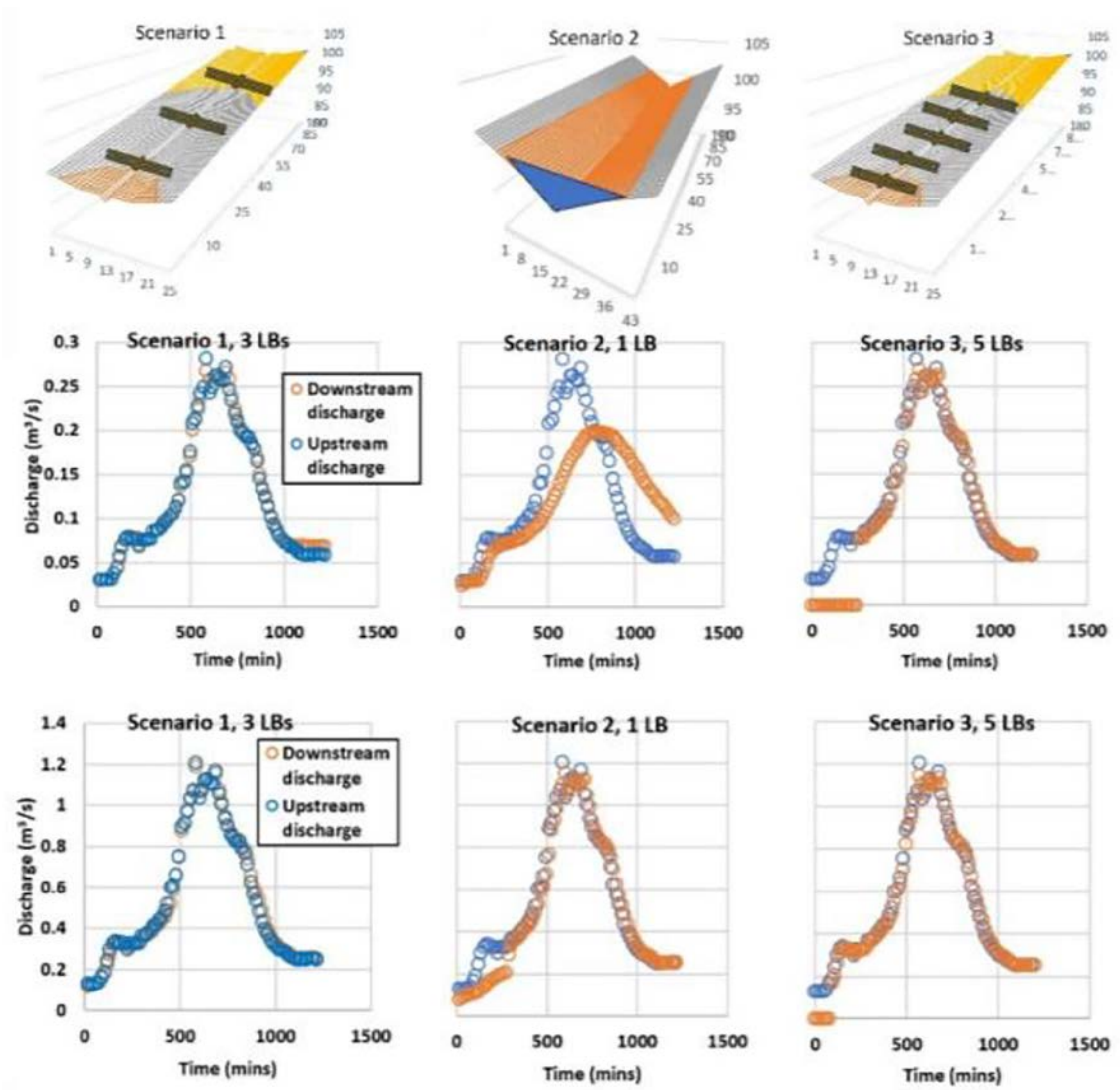


Figure 2.8. Top panel: HEC-RAS-2 model output for two different channel types. Middle panel: RI = 2 years. Bottom panel: RI = 50 years. Scenario 1: three LDs, yielding a maximum storage of 238 m^3. Scenario 2: one LD, yielding a maximum storage of 1869 m^3. Scenario 3: five LDs, yielding a maximum storage of 855 m^3.

2.6.1 The Aggregate Pond Model

Using the spatial tool package, validated by field visits, we identified additional opportunities for bund construction at Site 1 (Figure 2.9). We used these data to increase catchment storage using our APM.

Scenario 1: increase catchment storage (assuming three offline storage areas) at Site 1

We assumed we could include two additional OSAs, each with a volume of 1000 m^3 (Figure 2.9). We also assumed that the flow was shared equally between the ponds, with the same inlet threshold, and that they would fill and empty at the same time.

Result:

- We saw significant impact on the flood hydrograph.
- The addition of two additional pond storage areas to the existing one resulted in a 34% reduction in peak flow.
- Flood duration was not significantly affected (i.e. it did not change by more than 1 hour) because of the model assumption of synchronous filling and draining.

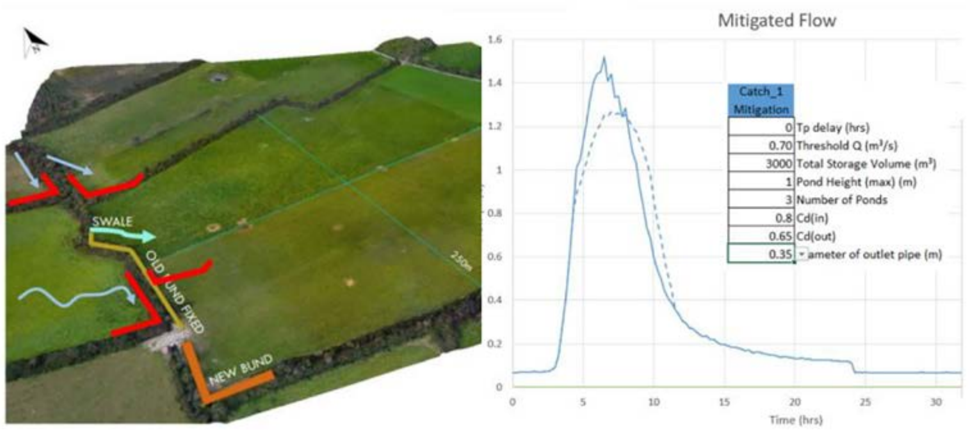


Figure 2.9. The left panel shows opportunities for installing additional bunds (and ponds) identified upstream of the built measure. Three of these (idealised bunds) were modelled in the APM. The right panel shows the Scenario 1 output from the APM. The modelling assumed three identical ponds with 1000 m³ storage each and the same drainage rate. Cd(in), drag coefficient for incoming flow; Cd(out), drag coefficient for return flow; Q, m³/sec; Tp, time to peak.

Scenario 2: larger storm event at Site 1

In this model run, we increased storage further and targeted the peak discharge using a set of 10 ponds with a combined total volume of 7500 m³ (i.e. each pond has 700–1000 m³ capacity) (Figure 2.10). The optimum pond drainage rate is notably lower than that obtained for a single pond due to the large number of ponds (pipe diameter has been reduced to 25 cm). The inlet threshold for flow into each pond remained at 0.7 m³/second. Figure 2.9 shows a large observed event in Ballygow. Given many years of flood modelling, and using evidence from similar catchments such as at Ballycanew, it was determined that the event RI was between 50 and 100 years for this location. In Figure 2.10, the peak flow of the storm modelled in Figure 2.9 was increased to 2 m³/second (RI = 200 years). It is worth noting that the drainage rate of the pond must be optimised to a low value for the network of ponds to work at the optimum level. There is a bespoke trade-off between total storage and pond drainage rate.

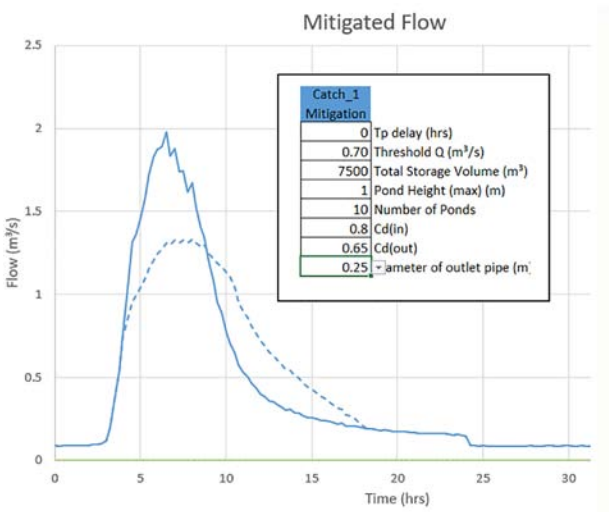


Figure 2.10. Scenario 2: the APM output for a higher magnitude storm. The impact on peak discharge for 10 ponds with 7500 m³ of storage in a catchment of 3 km² (Site 1). Cd(in), drag coefficient for incoming flow; Cd(out), drag coefficient for return flow; Q, m³/sec; Tp, time to peak.

Result:

- The model output demonstrates a significant impact on peak flow.
- The data show a reduction of 32% in peak flow. This is accompanied by an increase in flood duration by 3 hours.

Scenario 3: upscale to 12 km² (Site 3)

We applied this modelling task to the high-resolution topographic data available for the Ballycanew Teagasc Agricultural Catchments Programme catchment (we refer to this location as Site 3). The work was undertaken with the Specific Management and Robust Targeting of Riparian Buffer Zones project using field visits and geographic information system tools. Below (Step 1), we show one example site for a small sub-area of the larger catchment. We then increased the search to a broader catchment to locate additional sites where these designs could be situated (Step 2).

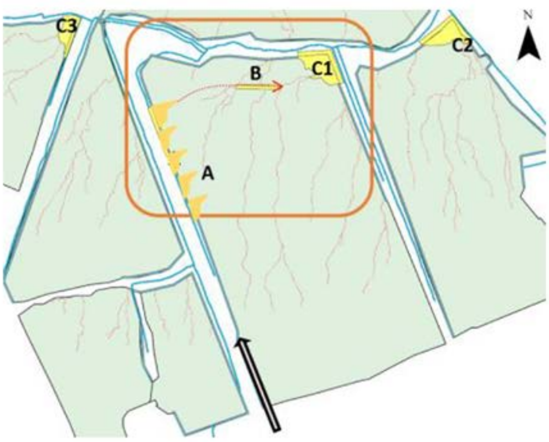
Step 1. We used the 5 m DEM data and the 1 m DEM combined with flow accumulation to site temporary storage ponds and assess capacity data. We used the spatial data tools and a bespoke system to allow farm infrastructure to be better represented (Compagnucci *et al*., 2019). This is similar to the EPA critical source area mapping tools but determines the optimal placement for measures that disconnect overland flow (thereby managing flood runoff and sediment erosion). Using the Arc Hydro Tools available in ArcGIS, three potential sites for storage ponds were located (Figure 2.11). A design was drawn up for flood mitigation. This required the identification of optimal locations and the design of three temporary ponds (C1–3 in Figure 2.11). For this site, we also designed a series of sediment traps (Figure 2.11, right panel).

Result: Together, ponds C1, C2 and C3 can provide over 1000 m^3 of temporary storage in this small area (Table 2.1).

Step 2. We repeated this approach with similar pond designs (volume 500–1000 m^3) over the larger catchment. The total amount of potential storage capacity was determined using a 1 m DEM for the larger areas, identified as Phase 1 and Phase 2 in Figure 2.12. Table 2.2 shows the final estimate of the potential flood storage.

Result:

- There is ample space/opportunity in the farmed landscape for flood storage. These sites are often located downstream on the farm (between 0.5 km^2 and 1 km^2) and are often small natural hollows of small floodplains.



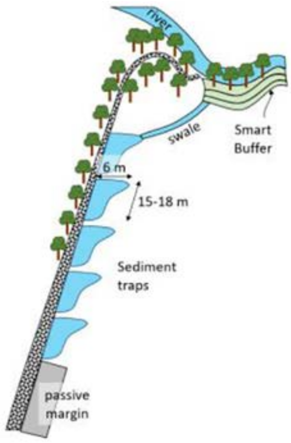


Figure 2.11. Design implementation for Scenario 3 at Site 3. In the left panel, blue lines indicate the local natural and anthropogenic (surface drain) drainage network; orange lines indicate the additional surface flow pathways identified. A indicates the interconnected sediment traps and B indicates the swale connecting runoff from the sediment traps to a temporary storage pond. C1, C2 and C3 are the temporary storage ponds, with an opportunity to design one (C1) as a smart buffer for further treatment of the sediment pond outflow. The large arrow shows the artificial subsurface drain that supplies this field with a large amount of flow and pollution from the adjacent fields. The right panel shows a network of sediment traps (location A) used to address the water quality issue. A simple draw-off structure and swale (location B) then push floodwater into the C1 pond for storage. Source: Based on Figure 5.6 in Ó hUallacháin *et al*., 2025.

Table 2.1. Details of the construction and capacity of the three ponds at Site 3

Location	Bund height (m)	Bund length (m)	Pond storage area (m^2)	Temporary OSA (m^2)	Temporary OSA volume (m^3)	Upstream catchment area (km^2)
C1	1	70	365	875	595	0.2
C2	1	80	374	689	473	0.12
C3	1	60	844	844	307	0.06

The location of bunds and storage areas (C1–3) are shown in Figure 2.12.

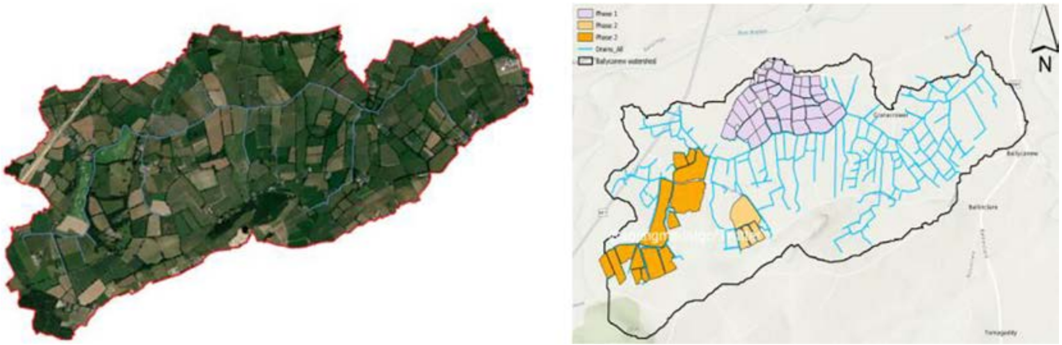


Figure 2.12. The left panel shows an aerial view of Site 3, Ballycanew Agricultural Catchments Programme research site. In the right panel, shaded areas refer to Phases 1 and 2 of OSA site identification (see also Table 2.3). Source: Based on Figure 4.7 in Ó hUallacháin *et al.*, 2025.

Table 2.2. The potential storage of flood flow in the Phase 1 and 2 study zones

Phase	Total field area (ha)	Level 3 field area – dry (%)	Level 3 field area – wet (%)	Volume (m^3)	Catchment upslope
Phase 1	93.8	0.05	0.4	1451	35 > 37 ha
Phase 2	97.4	0.2	0.6	3456	58 > 60 ha
Total	191.2	0.1	0.5	4907	2500 m^3/km^2

- Constructing ponds would be relatively easy and low cost.
- Our key finding here is that 2500 m^3/km^2 of land is available. Most landscapes studied afforded a number of potential pond sites with typical sizes of 500–1000 m^3; therefore, locating three to four ponds is required.

2.7 Quantification of Online and Offline Nature-based Solution Measures Using the Catchment Runoff Attenuation Flux Tool

The CRAFT model represents the functions of farmed landscapes. Ideally, it runs on hourly data and at a scale of 1–3 km^2. When a simple flow routing function is added (Adams and Quinn, 2023), CRAFT can be used at large scales. The model focusses on the roles of three dominant flow pathways: near-surface fast flow (including overland flow) (QSR), subsurface flow in the soil and groundwater flow.

CRAFT can represent the impact of slowing the flow velocity for smaller features in the landscape (LDs, boulder berms, riparian buffers, sediment ponds). Sediment trap and wetland impacts are estimated using a retention store function for small field areas with drains. The slowing effects of buffer strips and riparian woodlands can be simulated using the storage/discharge function for the three flow pathways (this is usually an exponential function). However, as assessing the impact of new offline features was not part of the model, we added this capability to the model as part of the SloWaters project.

The model emulates the function of the APM (Section 3.1) in that it includes a draw-off level, the drainage rate of the pond (assumed to be exponential) and the aggregate storage volume. We note that the shape of the pond is not important within CRAFT, as storage capacity is expressed in mm per unit area. The model sets all dimensions as rainfall depth equivalent in mm and flows as mm/hour. For example, if a catchment has 2000 m^3/km^2 of storage volume this would be equivalent to 2 mm per unit area of storage. In this way, the model can be used for any size of catchment. The converted data for Site 3 and Site 1 are shown in Figure 2.13.

We ran the new enhanced model for larger catchments and focused on the impact of measures on larger storms. We aimed to determine the catchment-scale target metrics required to achieve a significant reduction in peak discharge. Such models allow specific design storage targets and networks of OSA ponds to be set a priori or to reflect a network of NbS already built.

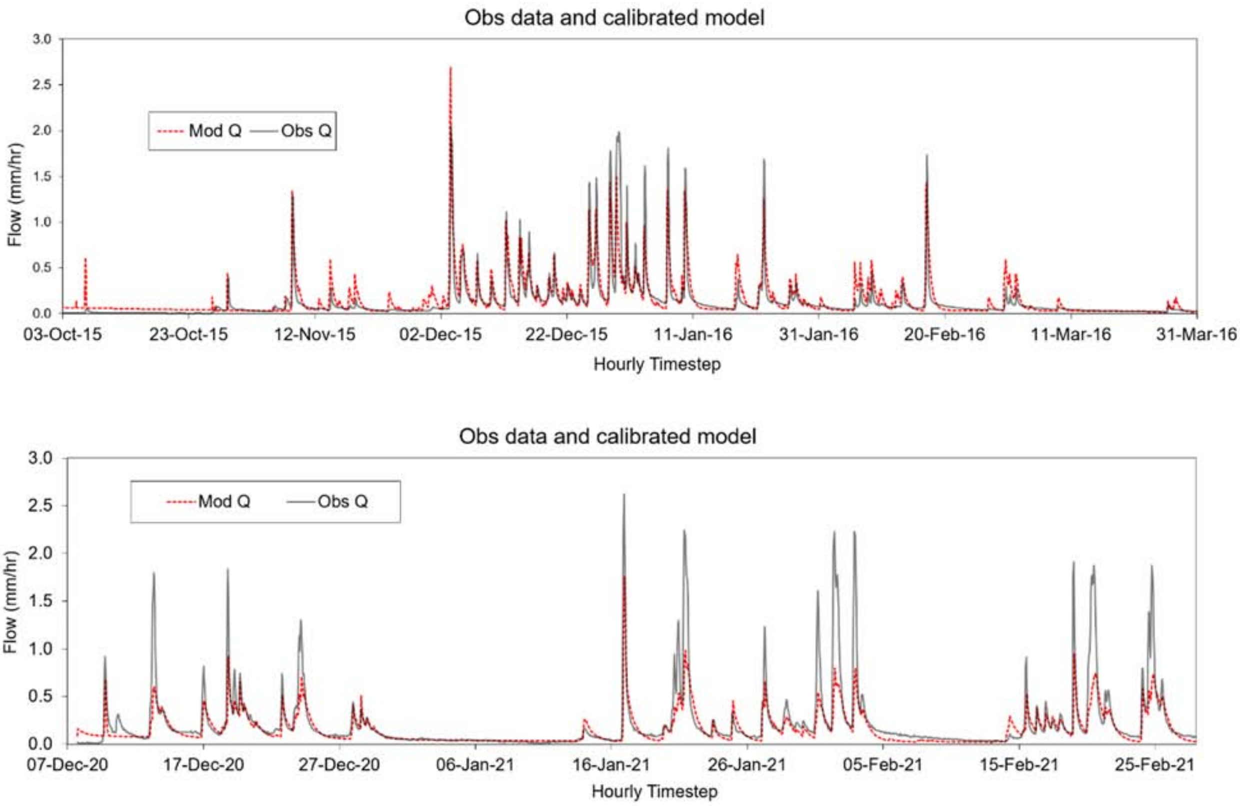


Figure 2.13. The CRAFT model calibrated to the observed hourly data. The conversion is to mm/hour. We note that the model underpredicts the flows slightly, but we assume the rating curve is overgenerous at high flows. The top panel shows Site 3 and the bottom panel shows Site 1. The black boxes outline the focus time frames. For Site 3, this is December 2015 (Storm Desmond). For Site 1, this is January 2021 (Storms Isha and Jocelyn). These time frames were chosen because they include a major flood event and several smaller events. Mod Q, modelled discharge; Obs Q, observed discharge.

2.7.1 Scaling up for storm magnitude: Storm Desmond, 2015, Site 3

Ireland had a series of large storms in December 2015 (Storms Desmond, Eve and Frank). We used the time series data from Site 3 for this period to run the CRAFT model (Figure 2.14).

Result:

- The catchment had a significant peak discharge reduction.
- Storms below 1.5 mm were not affected.
- Around 2–3 mm per unit area storage is needed (2000–3000 m^3/km^2).
- Only peak flow should be targeted – the rate needs to be over 50% of the peak discharge value (e.g. 2 mm/hour requires a draw-off level of ≥1 mm/hour). Please note that the optimum value is dependent on the size of the storm event targeted.
- Only after a storm (or an RI design storm) has been chosen for mitigation can the pond filling and emptying be optimised using the drainage flow rate.

2.7.2 Scaling up for storm magnitude: Storm Isha, 2021, Site 1

We assumed that we had identified offline ponds and added a dense network of smaller NbS features (e.g. buffer strips and sediment traps). We modelled a catchment-scale “runoff treatment train of features”. The model output is shown in Figure 2.15.

Result:

- Both smaller and larger storms were impacted.
- We conclude that offline ponds are effective for flooding.
- Online ponds are less effective at the catchment scale but have other environmental benefits.

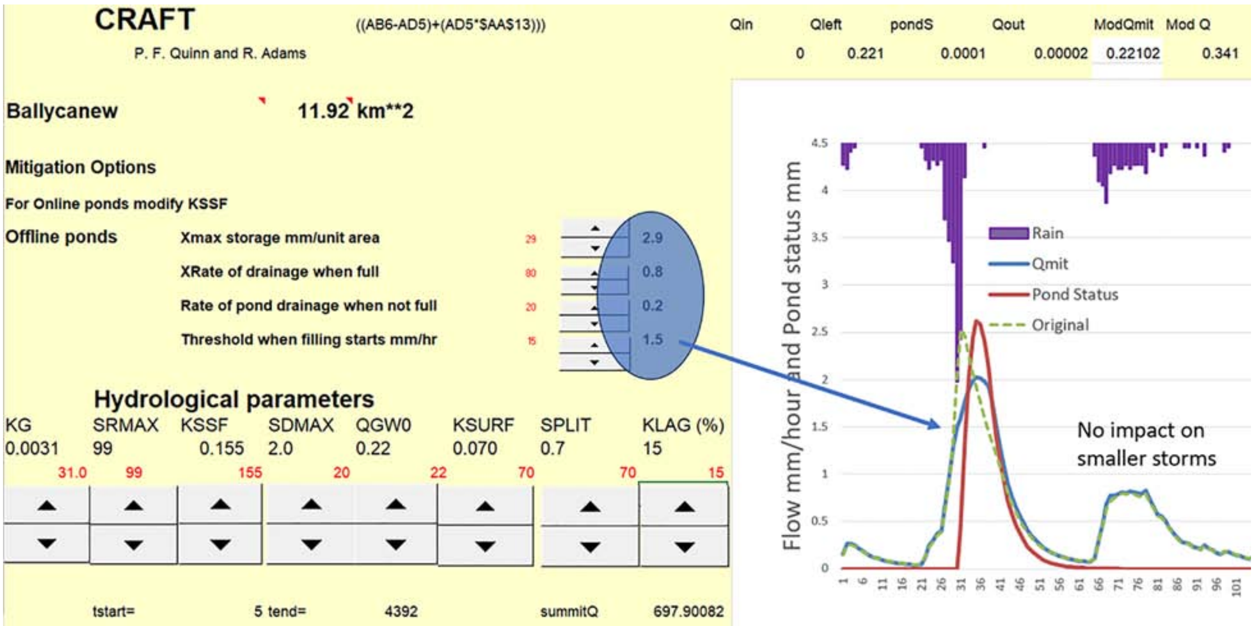


Figure 2.14. Site 3 model output. We used a storage potential of 2.9 mm per unit area (or 2900 m^3/km^2); the draw-off inflow rate was set for 1.5 mm/hour; and a drainage rate of 0.2 (or 20% rate of emptying per hour) was used. The pond fills exactly to its maximum capacity during the event. KLAG, delay coefficient for surface runoff in attenuation store; KSSF, delay coefficient for fast subsurface runoff; KSURF, delay coefficient for surface runoff draining from surface storage; Mod Q, modelled runoff (mm/hour); ModQmit, modelled runoff downstream of mitigation feature (Qleft + Qout) (mm/hour); Qin, inflow into pond (mm/hour); Qleft, runoff remaining that is not diverted into the pond (mm/hour); Qout, runoff leaving the pond (mm/hour); pondS, pond storage (mm); pond status, filling/emptying; SDMAX, maximum soil moisture storage (mm); SPLIT, coefficient partitioning excess drainage from soil moisture storage to either fast subsurface runoff or slow groundwater; SRMAX, maximum surface storage (mm).

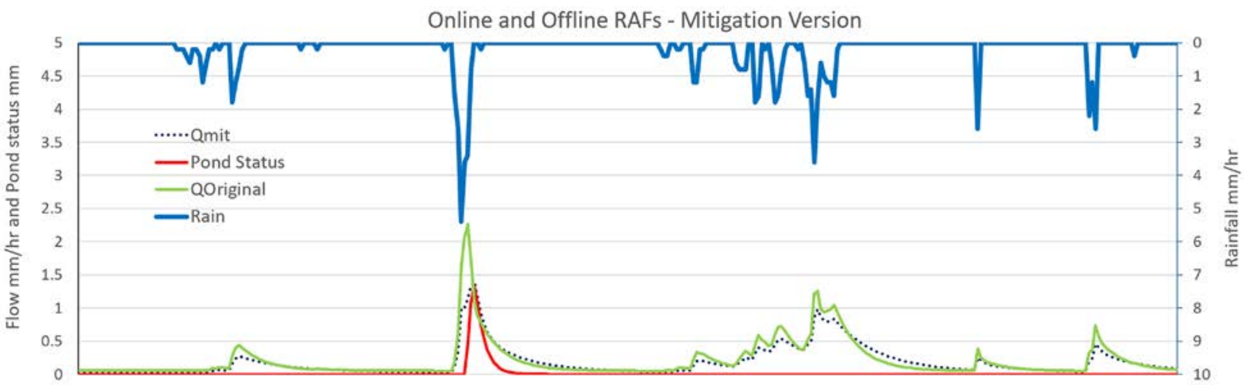


Figure 2.15. The impact of adding online and offline NbS at Site 1 (blue line) for Storm Isha. The storage is set at 2.5 mm per unit area, the threshold for draw-off is set at 1.0 mm/hour.

3 Nature-based Solutions for Improving Water Quality on Agricultural Land

Streams in agricultural catchments typically lack much of the biological and morphological complexity that promotes nutrient uptake and metabolism by micro-organisms at the surface of and within streambeds (Gooseff *et al*., 2007). At Site 2, two measures were installed to investigate their potential impact on organic and inorganic nutrients in streams and drainage ditches (woodland swale (WS) and low-head boulder weirs). In addition, the detention basin installed for flood attenuation was investigated for its potential effect on downstream water quality.

3.1 Offline Demonstration Measures

3.1.1 Woodland swale

Organic matter inputs in agricultural streams induce high biochemical oxygen demand and, consequently, low-oxygen conditions, which are harmful to aquatic life. Agricultural drains conveying high organic matter loadings to downstream waterways are typically linear and have a narrow and deep cross-sectional profile. This design offers a low degree of contact between benthic microbial communities and the water column. Shallow swales are advocated as a simpler alternative to traditional constructed wetlands as a means of attenuating high nutrient and organic matter loadings in feeder streams and drainage ditches. Through maximising contact areas between benthic surfaces and aerobic and ultraviolet-based attenuation processes, swale structures have displayed high removal efficiencies for nitrate and complex organic molecules (Lightbody *et al*., 2008; Jasper *et al*., 2014a,b). We modified an existing narrow open drain flowing through a deciduous woodland plantation at Leades House to create a series of shallow and wide "cells" comprising a WS in order to investigate its potential role in nutrient processing and water quality over a 20 m length (Figure 3.1). The drain flowing into the swale became intermittently contaminated with nutrient-rich organic matter from runoff from adjacent fields and trackways, which supported a herd of *c*.50 beef cattle.

Surface water from the cells of the WS was sampled at the downstream end of each cell and analysed for concentrations of ammonium (NH_4^+-N; mg N/L), nitrate (NO_3^--N; mg N/L), soluble reactive

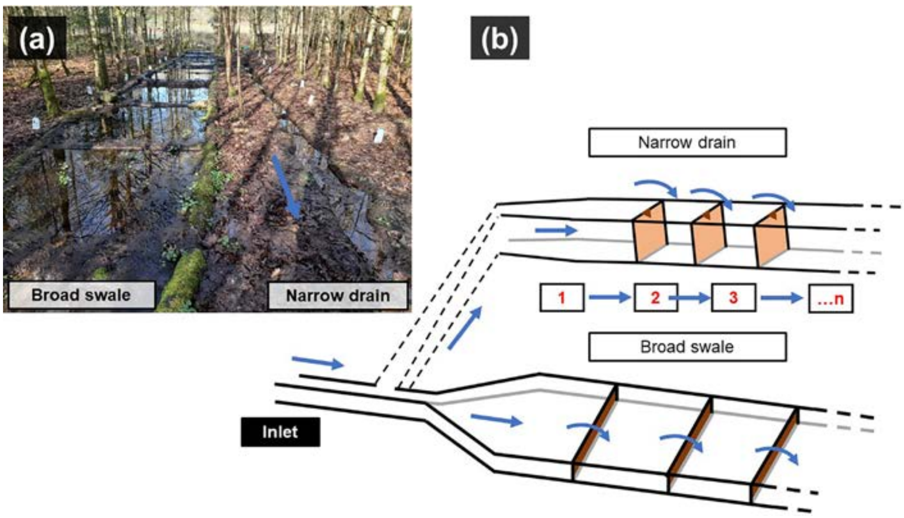


Figure 3.1. Open water wetland installed at Site 2 in 2021. (a) On the left is the broad swale and on the right is the narrow drain. (b) A conceptual diagram of the experimental design. A detailed description of the installation is found in Murphy (2024). The two drains were monitored so that the effect of the WS on water quality could be compared with a more traditional surface drain morphology.

phosphorus (SRP; mg P/L) and chloride (mg/L). *In situ* readings were also made on dissolved oxygen (DO) concentrations (mg/L), DO saturation (%) and electrical conductivity (mS/cm). Changes in concentrations along the WS were analysed in mixed-effect linear models, accounting for sample date as a random factor. When samples were collected from both the broad cells of the WS and the narrow cells of the traditional drain, concentration changes were compared between the two treatments.

Results

Our experiment shows that simple modifications to typical agricultural drain morphology can dramatically improve DO concentrations and promote greater infiltration and may improve rates of mineralisation of organic matter to ammonium, SRP and dissolved organic carbon (DOC), which are readily available to soil microbes. The narrow and broad cells were equal in terms of volume, but effects on oxygen recovery were markedly different. Changes in solute concentration along the WS revealed the significant recovery of oxygen along its 20 m length. Oxygen recovery in the WS broad cells was significantly greater than in the narrow drain. DOC and SRP concentrations increased significantly along the broad cells. Ammonium and nitrate concentrations did not change significantly. Nitrate concentrations increased more along the narrow cells than the broad cells. We found that the discharge and initial concentrations at the top of the drain affected changes in wetlands. An increase in hydraulic residence time may promote the breakdown of organic matter and soil infiltration. Although nitrate in drain water was reduced slightly by the WS, the impact on phosphorus, organic matter and ammonium was more complex. There was evidence that the WS intercepted and stored these substances, but also that they were released during critical periods, indicating that any uptake was only temporary. Further research is needed to elucidate the functioning of this feature in terms of nutrient processing.

3.1.2 Offline storage area

The role of the bund is to intercept polluted hydrological flow pathways. There is evidence that temporary ponding can facilitate the nutrient uptake, transformation and attenuation processes of natural floodplains. This is achieved by providing surface area and extended hydraulic retention time at the interface between the floodwater and the soil within the pond. The dissolved nutrients are geochemically or biologically retained and attenuated on land. In addition, attenuation can promote the deposition and retention of particulate organic matter and sediment, reducing the efflux of particulates from adjacent channels during rainfall or peak-flow events (Fiener *et al*., 2005; Robotham *et al*., 2023). However, there is also evidence that the transient diversion and/or detention of water on floodplains may be a net source of nutrients and sediment, particularly in low-order streams with legacy soil nutrients from past agricultural practice (Jones *et al*., 2015). As a result, the previous decades of agricultural land use in Ireland may have reduced the potential for temporary storage ponds to both attenuate flood peaks and re-establish the geochemical and biological functions of natural floodplains and wetlands. Work on restored floodplain connectivity sites, which have shown an overall improvement in water quality, found only moderate success at increasing the trapping of phosphorus, nitrogen and sediment, with relatively little phosphate release (Noe *et al*., 2019).

The bund at Site 2 (Figure 2.2) was sampled during inundation events for water quality. Samples were analysed for nitrate, ammonium, SRP, total phosphorus (TP), DOC and chloride. *In situ* readings of DO were taken from the OSA during inundation events (Table 3.1). Attenuation was estimated for each inundation event as percentage removal efficiency (Carstensen *et al*., 2020). Changes in water quality parameter concentrations over all sampled events were estimated using mixed-effect linear models, which included the sample date as a random effect using a significance level of $p < 0.05$ for rejection of the null hypothesis that the OSA would not contribute to changes in water quality parameter concentrations.

Results

- Attenuation of suspended solids and nitrate was statistically significant across all events.
- Concentrations of SRP and TP increased significantly.
- Concentrations of DO were shown to be significantly reduced by storage of floodwaters, but did not drop below 9 mg/L.
- Concentrations of other sampled water quality parameters (ammonium, DOC, chloride) did not change significantly.

Table 3.1. Water quality data from the OSA during 11 sampled inundation events (March 2022 to December 2022)

Water quality parameter	Sample size, *n*	Mean inlet concentration, mg/L (SD)	Mean outlet concentration, mg/L (SD)	Mean change in concentration, mg/L (2.5% CI, 97.5% CI)	Mean RE, %
Ammonium	70	0.09 (0.08)	0.09 (0.09)	0.004 (–0.01, 0.03)	9.62
Chloride	70	19.98 (5.69)	19.96 (5.56)	–0.016 (–1.2, 0.69)	0.22
DOC	70	7.88 (3.9)	8.51 (3.9)	0.627 (–2.06, 0.44)	13.12
Nitrate*	70	4.14 (1.8)	3.57 (1.64)	–0.567 (0.24, 0.95)	–13.37
SRP*	70	0.04 (0.02)	0.07 (0.03)	0.030 (–0.04, –0.02)	94.13
Suspended solids*	70	19.55 (24.21)	11.72 (10.81)	–7.835 (–0.52, 22.6)	–5.35
TP (mg P/L)*	70	0.12 (0.14)	0.19 (0.21)	0.071 (–0.15, 0.01)	83.03
DO (mg/L)*	44	9.85 (0.87)	9.06 (0.87)	–0.788	–7.50

Results from analysis of water quality sampling from inlets and outlets over 11 sampling events between 2 March 2021 and 23 November 2022. Mean concentration data were calculated directly from water quality concentrations for all sampling events and were used to calculate removal efficiency, based on change in mean concentration, and percentage removal efficiency ("Mean RE"). Results from mixed-effect models use comparisons of inlet and outlet concentrations, accounting for variance between sampling events. CI, confidence interval; SD, standard deviation.

***Water quality parameters whose concentrations changed significantly ($p < 0.05$) between the inlet and outlet.**

- Water quality changes varied between flood events, within flood events and at different locations within the OSA.

3.2 Online Demonstration Measures

3.2.1 In-channel low-head stone weirs

Channels in agricultural catchments are often denuded of gravel beds and morphological complexity (meanders, pools, riffles, boulders). This serves to impair the flow of nutrient-rich water over microbial biofilms in streambed gravels (the hyporheic zone). Low-head boulder weirs may promote hyporheic exchange and nutrient uptake by increasing head pressure at the upstream side. This increase in hyporheic exchange and transient storage of waters within the streambed is suggested to reduce surface flow velocities and induce greater loss of stream water to subsurface aquifers. We installed four low-head boulder weirs in the channel at Site 2 (Figure 3.2).

Changes in hyporheic exchange and transient storage were quantified through examination of electrical conductivity breakthrough curves from conservative and biologically available tracer (bio-tracer) pulses (for further details, see Murphy, 2024).

Results

- The deposition of fine sediment upstream of each of the weirs is likely to have reduced the infiltration of water into the streambed, and biological processing, at a reach scale, was reduced by the weirs.
- Weirs led to a reduction in solute storage and nutrient uptake by the streambed at low flows.
- At higher flows, weirs helped to reduce flow velocities.
- There was substantial upstream deposition of sediment and downstream scour.

Poor performance may be related to the presence of elevated levels of dissolved organic and inorganic nutrients and suspended solids, which can block streambed interstices. In addition, the construction of the boulder weirs may have diminished the potential for epilithic transient storage without contributing to improvement in hyporheic transient storage in the absence of a viable gravel bed.

3.3 Scaling Up for Water Quality

The CRAFT model can estimate the likely changes in water quality if networks of NbS are applied at the catchment scale. It can simulate flow and

Figure 3.2. Instream weirs during (a) low and (b) medium flows. Blue arrows indicate direction of flow. Panel (a) shows the downstream side of a low-head boulder weir (foreground) and the next most upstream weir (photo taken on 26 May 2022). Panel (b) shows the view looking down at a boulder weir and streambed (photo taken on 4 April 2022). Sediment accumulation and slow-moving water are visible at the upstream side, and a clear streambed and high flow are visible on the downstream side.

diffuse pollution well using only three flow pathways. We applied the model at Site 3 using hourly data (nitrogen, TP and SRP). Using expert knowledge or other pollution models, the suitable concentrations of pollutants such as phosphorus and nitrate can be added to the flow paths. Thus, the model can simulate the impact of pollution concentration and flow pathway management on the final flux seen in the catchment at the outfall. The model is calibrated to the time period in the black box (Figure 3.3); the ability to simulate nitrogen and phosphorus flux with this accuracy using only three flow pathways is the key deliverable.

Figure 3.3 shows the accuracy of the flow prediction, nitrate, TP and total reactive phosphorus (or dissolved P). The model works well for most of the period, apart from the dry early summer. After the calibration period in the early new year, the model overpredicts the nitrogen and phosphorus losses, as, in reality, the available nitrogen and phosphorus in the soil is being adapted. Other versions of the CRAFT model allow for this depletion effect (Adams and Quinn, 2023).

Essentially, KLAG (the delay coefficient for surface runoff in the attenuation store) is the residence time for QSR, and as sediment and TP are linked with QSR they can be removed. Thus, introducing a KLAG and a sediment removal rate term into the model can demonstrate the potential to significantly reduce peak TP concentrations (Figure 3.4).

Results

- The impact of adding a network of well-designed sediment traps to the catchment is an increase in the residence time for QSR (and sediment) in the trap.
- The effects of the measures studied were variable, as the forces that mediate effectiveness are complex.
- Measures should target specific issues, guided by scientific principles.
- Measures must be simple, safe and unintrusive with regard to farming practices.
- The interventions shown at the demonstration sites, for example those demonstrated in Site 2 and those proposed for Site 3, should be targeted at key processes (operating at lower flow rates).
- NWRMs can be built at low cost and have pronounced effects on hydrology and water quality.
- Therefore, we propose a runoff management treatment train approach to catchment management on farmland.

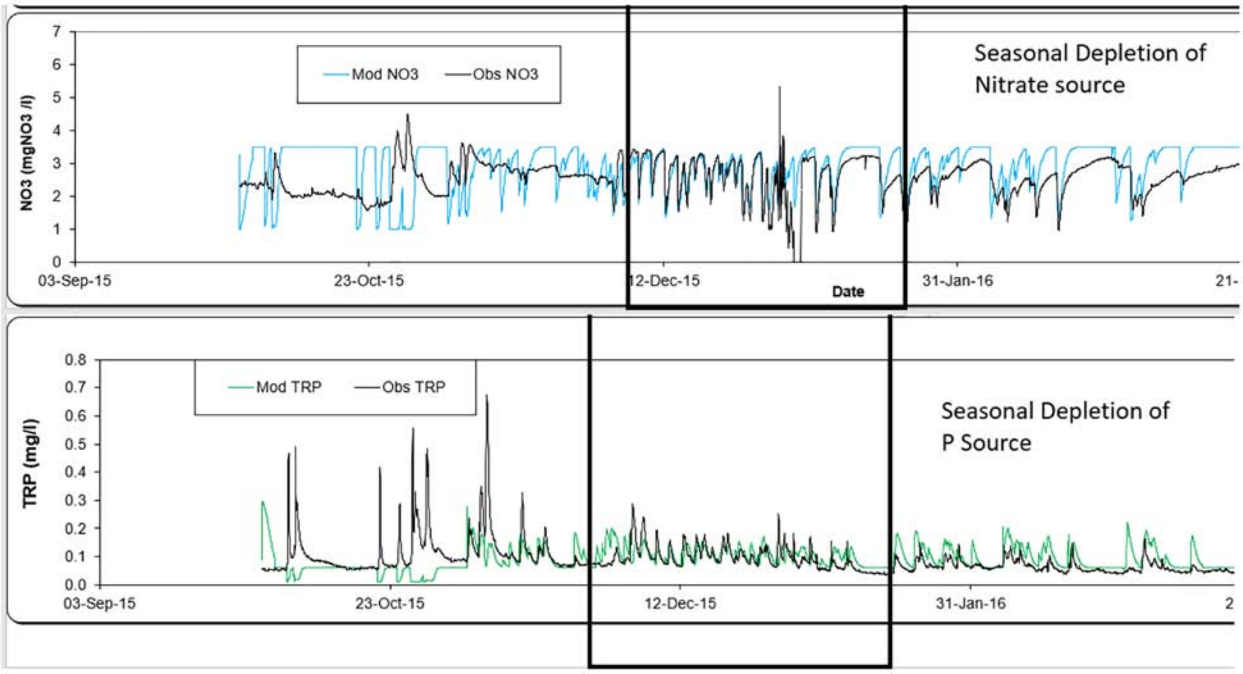


Figure 3.3. CRAFT model calibration to hourly data for Site 3. The top panel shows hourly flow and nitrates. The bottom panel shows hourly TP and total reactive phosphorus simulation. The black box is the calibration period. Mod, modelled; Obs, observed; TRP, total reactive phosphorus.

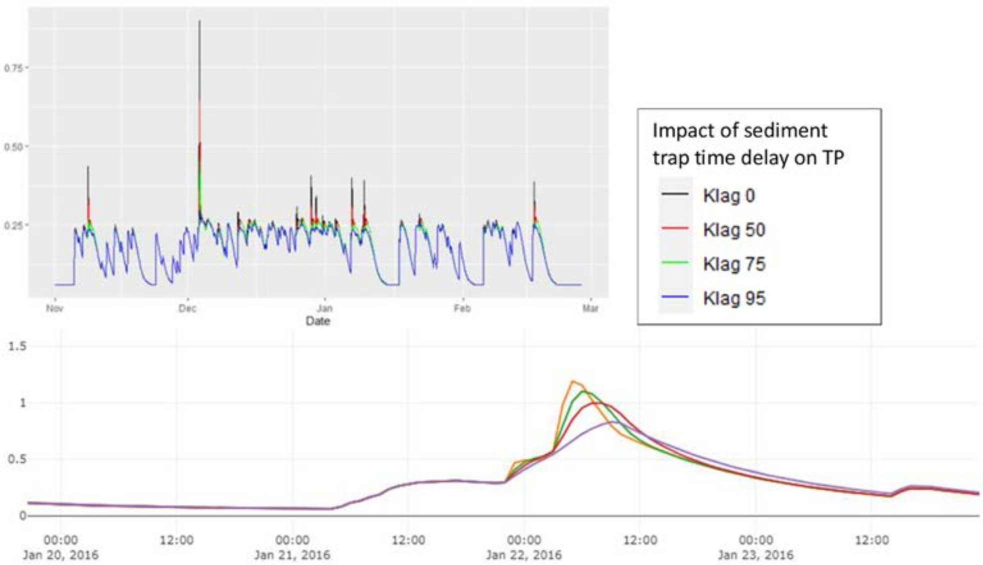


Figure 3.4. CRAFT model output for January 2016. KLAG is the residence time for QSR in the trap. Top panel: the *y*-axis shows flow in mm/hour. This shows changes for KLAG values of 0, 50, 75 and 95, demonstrating the impact of adding sediment traps (the more KLAG increases, the more peak flow is delayed). Bottom panel: the *y*-axis shows TP mg/L. TP is linked only to QSR; therefore, the KLAG and the sediment removal rate can significantly reduce peak TP concentrations.

4 Wider Benefits of Flood-related Nature-based Solutions

Emerging data suggest that there are biodiversity benefits, in addition to those for climate change adaptation, of the installation of NbS measures (Key *et al*., 2022).

4.1 Grass Productivity

We explored whether inundating a pasture field for flood peak mitigation affected biomass production and sward health over a 13-month period. Sward health (biomass and chlorophyll content) within six livestock-proof enclosures in the ponding zone ($n = 3$) and in the non-ponding zone ($n = 3$) of the OSA was measured monthly between July 2022 and July 2023 (Figure 4.1). Sward diversity measurements within the enclosures were made on sampling occasions between April 2023 and July 2023 to assess the effect of inundation on plant diversity and abundance. Soil core samples from the OSA were taken in the summers of 2021 and 2022 to assess impacts of inundation on soil chemistry.

Over the study period (June 2022 to July 2023), the OSA was inundated for a total of 42 days. Of these, 30 days were during peak-flow events that led to temporary inundation (*c*.12 hours) up to a depth of 0.85 m, and the remaining 12 days were during minor overland flow events when the OSA was partially inundated to a maximum depth of 0.3 m.

Result:

- During the growing season (April to October), the ponding zone had 2052.82 mg more fresh biomass than the dry zone per 0.1 m^2 plot (12.8%) per month.
- During the winter, the ponding zone had lower mass (791.3 mg less per 0.1 m^2 plot) than the dry zone.
- The ponding zone had 11.32% less total chlorophyll than the non-ponding zone (Figure 2.2). The difference was most pronounced during the period between November 2022 and March 2023, indicating that inundation combined with seasonal winter senescence impaired the production of total chlorophyll in ponding-zone plants. During the growing season, the ponding zone produced more total chlorophyll than the dry zone due to greater biomass density (Figure 2.2).
- Sward diversity and the abundance of grassland species were not affected by inundation, nor was any effect of flooding detected on soil chemistry in the field.

4.1.1 Hydromorphology

The installation of measures on farmland and in the adjacent channels can change their hydromorphology. Below is a summary of our observations.

Figure 4.1. Livestock-proof sward enclosures at the OSA. Vegetation samples were harvested monthly from four subplots, each being 0.1 m^2 in area, within each enclosure 5 cm from the ground to prevent damage to the meristem.

Leaky dams

- Woody debris (sticks and branches) can accumulate upstream of the measure. Such woody debris has the potential to reduce the leakiness of LDs during spate periods, increasing the hydraulic and erosional forces on LDs and banksides.
- Localised stream bank erosion occurred at LDs. During very large flows (e.g. Storm Babet, 9 October 2023), one dam was undermined and dislodged some 5 m downstream. The strong "sled" construction of the LD structure prevented it from disintegrating and moving further downstream. Stream bank erosion may need to be mitigated in future designs by suitably constructed armoured bank protection (Scottish Environment Protection Agency, 2020).
- All LDs induced streambed erosion downstream and underneath LD structures.

Low-head channel weirs

- Prior to construction, the streambed was largely homogeneous such that the depth of water was similar along the entire reach during most flows. The channel bed was a mix of gravels and stones and there was an absence of pools or riffles.
- Following the installation of the weirs, scour pools developed downstream of each weir and a layer of sediment accumulated at the upstream side. There were larger water depths of slow-moving water upstream and swiftly flowing water downstream for 1–2 m. This merged into a section of shallow water. During the driest periods (summer 2022), the scour pools retained water in an otherwise dry channel.
- The area upstream of each weir accumulated sediment up to 10 cm deep and was seen to accommodate chironomid larvae, which presumably grazed on accumulated organic material. This material, which is more loosely packed than the channel bed, continues to accumulate.

Bund spillway

- Overflow from the spillway at Site 1 drops 1 m into the adjacent open drain. High energy flows have formed a new pool (2 m × 1.4 m × 80 cm). The pool floor contains gravel and is adjacent to a downstream gravel bar composed of pool-sourced gravels. Like at Site 2, the pool has not been observed to not dry during summer and the gravel has chironomid larvae.

Floodplains

- The Site 1 inlet shows fresh accumulation of sediment (fine gravel).
- There is no evidence of erosion along the flow pathway at either demonstration site.
- No sediment was observed on the long grass blades following inundation.
- The sediment pond accumulated fine-grained soil deposits.

5 Policy and Practice Barriers to and Levers for Nature-based Solutions

The implementation of measures to improve environmental quality in catchments is not a new idea. For decades, humans have been trying to intervene to reverse environmental damage. Policy frameworks have evolved in recent decades that advocate NbS approaches (United Nations, 2022; European Commission, 2024), and, certainly, the implementation of NbS at scale could make a significant contribution to meeting several of the United Nations Sustainable Development Goals (e.g. Sustainable Development Goal 13: climate change and its impact). Achieving a climate-resilient Ireland will require multiple approaches to adaptation. Nature-based approaches are recognised as an increasingly important part of a portfolio of adaptation actions (Murphy *et al.*, 2023b). Several barriers to and levers for implementation have been identified and will be discussed.

A state-sponsored arterial drainage programme was systematically implemented after 1945 (Arterial Drainage Act). The catchment-scale schemes straightened, diverted, embanked, widened and deepened over 11,000 km of Irish rivers and riparian zones. The central aims were to lower water levels for flood prevention, reduce waterlogging and support drainage during the spring to autumn growing season. In essence, the aim was to improve hydraulic conveyance efficiency (Lynn, 1981; Bruton and Convery, 1982; Bhattarai and O’Connor, 2004; de Smeth *et al.*, 2024). The Office of Public Works (OPW) is required to maintain arterial drainage works and flood relief schemes in proper repair and effective condition (section 37 of the Arterial Drainage Act). The impact on flood hydrographs was, essentially, a change from well-rounded low flood peaks with sluggish recession to higher and narrower peaks and rapid recessions. Some research found that the unit hydrograph for the post-drainage case was twice as great as that of the pre-drainage case (Bhattarai and O’Connor, 2004; de Smeth and Murphy, 2024). The effects on the aquatic environment include impacts such as the destruction of salmon- and trout-spawning rivers (Kelly and Bracken, 1998). Several of the current maintenance practices (dredging, removal of riparian vegetation and large woody debris (OPW, 2019) are in direct conflict with the objectives of European directives. There are growing calls to address issues with the management of the arterial drainage network (Lacchia, 2022).

EU policy now clearly promotes NbS for water and flood management, through the EU Adaptation Strategy (2021), Water Framework Directive, Floods Directive, Nature Restoration Law and guidance on natural water retention measures. The Floods Directive (European Union, 2007) introduced legislation to better manage flood risk in catchments. Notably, the directive requires a holistic approach that integrates combinations of “hard” and “soft” (non-structural) measures to enable prevention, protection, preparedness, emergency response and recovery. Some EU Member States implemented an integrated catchment management approach for managing flood risk (e.g. Scotland’s Flood Risk Management Act 2009), while others did not.

Under the auspices of the OPW, communities in Ireland facing significant flood risks (i.e. Areas of Potentially Significant Flood Risk, as defined by the EU Floods Directive) were identified. As is common elsewhere in Europe, the target Standard of Protection (SoP) for structural flood risk management measures in Ireland is the 1% annual exceedance probability (AEP) event for fluvial risk. Each flood relief scheme under Ireland’s National Development Plan requires the development of a climate change adaptation plan, which could include NbS (Collier and Bourke, 2020). However, NbS have, to date, been rejected as a “preferred option” because they have not been shown to work in large catchments or for larger floods (AEP: 1%). This has led to the implementation of a preferred option that favours a hard-engineering approach (Adamson, 2018). As part of the National Development Plan (2021–2030), there are currently 150 completed and ongoing flood relief schemes (OPW, 2024a), with an additional 54 anticipated across Ireland in towns and cities. Several hundred structural measures for smaller villages and rural areas are funded through the

Minor Flood Mitigation Works and Coastal Protection Scheme (OPW, 2024b).

Nevertheless, NbS have continued to be advocated by the Irish Government in several national policies (e.g. Buckley *et al*., 2021; GOI, 2021a,b, 2023). More recently, commitments have been made in the National Biodiversity Action Plan to "promote more catchment-wide and non-structural flood risk management measures" (GOI, 2024a). Target 8 states that "Nature-based Solutions (NBS) will be promoted in national, regional and local programmes, including flood relief schemes" (GOI, 2024a). A national strategy and guidance documents on urban surface water management have been released for urban areas. These include many sustainable urban drainage measures (GOI, 2021b, 2024b) that can be applied to rural Ireland and have been adapted for managing farmyard rainfall runoff management plans for landowners participating in the Farming for Water European Innovation Partnership (F. Igoe, personal communication).

There are significant additional potential benefits delivered by NbS implementation (improved water quality, increased biodiversity, ecosystem health, carbon sequestration, etc.). However, we observed a negative impact of the detention basin at the Leades House site (Site 2) on downstream soluble and dissolved phosphorus concentrations, although there was a slight positive impact on nitrate and suspended sediment concentrations.

It is vital that we do not consider these NbS approaches as being only for flood risk management but that we also acknowledge that they deliver wider ecosystem services and that we value these extra services (Hartmann *et al*., 2018). The 2024 National Adaptation Framework recognises this and suggests that "nature-based solutions in flood risk management should be explored further and expanded in partnership with other sectors, noting the benefits such measures can have across a range of sectors" (GOI, 2024c).

Recent high-level reviews on ecosystem restoration and NbS for climate action also identify policy and finance barriers and opportunities that are relevant for flood mitigation. Readers are directed to these sources (McGuinness and Bullock, 2020; Molloy *et al*., 2024; Ní Dhúill *et al*., 2024).

5.1 Four Types of Policy Action

The policy actions that emerge from these reviews can be summarised under four headings, as set out below.

5.1.1 Mainstreaming nature-based approaches to floods

There is a need to move beyond recognising the value of NbS to explicitly integrating them into relevant policies and plans. Enhanced policy coherence across government departments would foster a shared understanding of NbS and their multifaceted value. Flood risk management plans developed under the EU Floods Directive should systematically consider and prioritise NbS. Spatial planning policies should mandate the incorporation of NbS into urban development and infrastructure projects. The National Adaptation Framework, while acknowledging the importance of green infrastructure, lacks specific guidance on NbS implementation. A revised framework should provide concrete examples and standards for integrating NbS into climate resilience measures (Molloy *et al*., 2024).

5.1.2 Strengthening governance and coordination

The lack of clear policy frameworks and incentives specifically targeting NbS could hinder their uptake. Integrating NbS into existing policies and regulations, such as building codes and land use planning guidelines, is crucial for creating an enabling environment. Alongside this is the need for clearer roles and responsibilities for NbS implementation across government departments and agencies. This will enhance coordination and avoid overlap (Ní Dhúill *et al*., 2024). This could be achieved by doing the following:

- A lead agency or coordinating body could be established to oversee the implementation of a national NbS strategy for flood hazard mitigation. It would be responsible for coordinating actions across different sectors, ensuring policy coherence and monitoring progress (Ní Dhúill *et al*., 2024).
- Communication and collaboration could be improved among stakeholders, including government agencies, local authorities, communities and the private sector. Implementing

NbS often requires coordination and collaboration across different sectors (e.g. agriculture, forestry, water management and urban planning). Silos between government agencies and a lack of integrated planning can create barriers to effective implementation (Murphy *et al.*, 2023b). Improving collaboration could involve establishing platforms for knowledge sharing, capacity building and joint planning (Molloy *et al.*, 2024).

5.1.3 Enhancing knowledge and capacity

A knowledge transfer gap exists between research and practical application. A dearth of technical expertise and practical guidance is a significant barrier to NbS adoption in Ireland. Building capacity among farmers, local authorities and environmental non-governmental organisations is essential for the successful design, implementation and long-term management of NbS.

Policy recommendations include the following:

- Invest in research and development to enhance the understanding of NbS effectiveness for flood hazard mitigation in different contexts. Decision-makers often lack readily available data on NbS effectiveness, implementation methods and economic benefits, slowing wider adoption and the development of best practice guidelines for their implementation.
- Implement robust monitoring and evaluation frameworks using methods like natural capital accounting or the self-assessment tool (IUCN, 2023) to demonstrate the potential effectiveness of NbS, quantify their benefits, and inform adaptive management and future policy decisions (Molloy *et al.*, 2024; Ní Dhúill *et al.*, 2024).
- The absence of reliable historical data on flood events and impacts makes it challenging to establish baselines and track the outcomes of NbS interventions. This hampers efforts to assess their long-term effectiveness and refine their design (Murphy *et al.*, 2023b).
- Develop capacity-building programmes for professionals in relevant sectors, such as engineering, planning and agriculture, to equip them with the knowledge and skills necessary to design, implement and manage NbS projects (Murphy *et al.*, 2023b; Molloy *et al.*, 2024).
- Create a centralised knowledge hub to disseminate information and resources on NbS (e.g. the Natural Flood Management Network Scotland (https://www.nfm.scot/).
  - This will make it easier for practitioners and stakeholders to access relevant guidance and best practices (Molloy *et al.*, 2024).
  - This would include developing a national mapping framework where soil type, topography and land use patterns are identified in contexts where NbS would be most effective. This would then permit site-specific assessments and the development of tailored designs.

Undertaking meaningful community engagement with local communities is crucial for the successful implementation of NbS (O'Donnell *et al.*, 2025). Neglecting place-based values and failing to incorporate local knowledge, particularly in rural communities, can lead to resistance and potentially result in maladaptation. Sensitive and participatory approaches are crucial for addressing these concerns and building community support (Murphy *et al.*, 2023b):

- A key challenge is the difficulty in measuring and demonstrating the effectiveness of NbS in reducing flood risk. While their potential benefits are widely acknowledged, robust evidence and standardised methodologies for quantifying their impact are often lacking (Murphy *et al.*, 2023b). The direction of travel internationally is towards adaptive portfolios where NbS are deployed at meaningful scale, monitored and improved over time, that is, a "learn by doing approach".
- Raising awareness through education, outreach and knowledge-sharing initiatives is crucial for promoting NbS uptake. Public perceptions of risk and preferences for familiar solutions can influence adaptation choices. Hard-engineering solutions may be perceived as more effective or reliable, even when NbS offer comparable or superior benefits in the long term (Murphy *et al.*, 2023b).

5.1.4 Addressing funding gaps

While existing funding streams (e.g. the OPW's Minor Works programme or local authority climate adaptation funding) have been identified, there is no funded national programme for retrofitting catchments upstream of at-risk towns with distributed storage, rewetting and reconnection, even though these measures are now standard recommendations in EU guidance on climate-resilient flood management. There is a need for dedicated and long-term funding for NbS aimed at addressing flooding. The current short-term funding focus clashes with the long-term benefits that NbS offer, and puts a strain on local authorities with limited resources.

5.2 Key Considerations for Funding Nature-based Solutions for Flood Mitigation

- Need for long-term funding. NbS projects for flood hazard mitigation often require ongoing maintenance and management to ensure project continuity and efficacy. Securing long-term funding mechanisms is crucial.
- Integration of funding sources. Combining public and private funding sources can create more sustainable and impactful projects. Public funding can provide initial investment and support, while private investment can contribute to long-term sustainability and innovation.
- Demonstration of value. Clearly demonstrating the potential (quantitative) hydrological, water quality, biodiversity, economic and social benefits of NbS for flood hazard mitigation is essential for attracting funding from both public and private sources. Natural capital accounting can help to quantify and communicate the value of these projects, particularly their long-term value and co-benefits, which are currently difficult to quantify and incorporate into cost–benefit analyses.

The following policy actions have been proposed for biodiversity and nature restoration funding (McGuinness and Bullock, 2020; Ní Dhúill *et al.*, 2024), but are also options for NbS for flooding.

5.3 Policy Actions

- Integrate NbS into existing climate-related funding schemes (Molloy *et al.*, 2024; Ní Dhúill *et al.*, 2024). This would require explicitly stating that NbS for flood mitigation are eligible activities. For example, the potential for a strategic allocation within the Infrastructure, Climate and Nature Fund (a significant financial allocation of €3.15 billion from 2026 to 2030) offers a critical opportunity. The Infrastructure, Climate and Nature Fund's focus is on capital works. This limits its applicability to ongoing maintenance and management, which are crucial for the long-term effectiveness of NbS. In addition, the absence of a dedicated allocation to nature restoration is a concern (Ní Dhúill *et al.*, 2024). Another source is the carbon tax (McGuinness and Bullock, 2020). This has raised €5.3 billion (2010–2023) and is allocated for green initiatives and climate-related policies (e.g. home retrofitting, agriculture sustainability). A portion of that revenue stream could be ring-fenced to fund NbS for flood hazard mitigation, as these NbS projects could contribute to both carbon sequestration and flood risk reduction.
- Use existing EU funding streams. These streams are crucial for supporting nature-based approaches in Ireland and support a range of activities, from research and innovation to on-the-ground implementation. The European Agricultural Fund for Rural Development is a significant source of funding for agri-environmental schemes (McGuinness and Bullock, 2020). These could be instrumental in funding NbS for flood hazard mitigation. The Common Agricultural Policy and national initiatives like the Agri-Climate Rural Environment Scheme provide opportunities to encourage farmers to adopt land management practices that benefit flood mitigation and biodiversity. These schemes can provide financial incentives for farmers to implement NbS and adopt climate-smart agriculture practices (Murphy *et al.*, 2023b). Current supported practices, such as the maintenance of low-input permanent pasture, protection of watercourses from cattle and traditional hay meadows, enhance water retention and reduce runoff. Future schemes could be further tailored to incentivise the implementation of NbS specifically designed to reduce flood risk. Many of these were highlighted by the National Working Group on Natural Water Retention Measures, which reviewed opportunities for NWRM in Ireland (OPW and EPA, 2020). This working group found that significant benefits for flood mitigation could be found by implementing the following: engineered basins and ponds, floodplain restoration and management,

re-meandering, and wetland creation and restoration.

- Attract private sector investment. Tapping into private sector funding is crucial for scaling up NbS implementation. Several mechanisms, such as green bonds and payments for ecosystem services, can attract private investment in NbS, broadening the funding base and leveraging private sector resources. A portion of the Irish Sovereign Green Bond funds are allocated to "climate change adaptation" (McGuinness and Bullock, 2020). Flood mitigation is specifically mentioned. Funds could also be directed towards NbS projects for flood hazard mitigation. These and additional options are discussed further in Ní Dhúill *et al*. (2024).

The OPW's Climate Change Sectoral Adaptation Plan for Flood Risk Management (CCSAP FRM) in Ireland (OPW, 2025) reflects a maturing policy environment and outlines a strategic shift in Irish flood management. The OPW now mandates that NbS be considered in all new flood relief schemes, viewing them overall as being complementary to existing hard flood-defence infrastructure. Such a "hybrid" approach positions NbS for managing frequent runoff and improving catchment health, while engineered defences are in place to handle the extreme 100-year events. This ensures that opportunities for NbS are not overlooked, even if they only partially reduce overall flood peaks. However, it is mandatory to conduct only a **feasibility study** not to deploy NbS. The OPW views flood resilience as being aligned with broader ecological and climate objectives.

The OPW is progressing a specific NbS pilot scheme in partnership with the Local Authorities Water Programme and Tipperary County Council. This scheme is aimed at providing flood reduction and water quality co-benefits. However, these partners have identified an implementation gap, as NbS projects have not yet been widely implemented through existing frameworks such as the Minor Works Scheme. They note that to implement NbS "at scale" collaboration is required across multiple sectors (agriculture, forestry, etc.) that may have competing land use priorities. Nevertheless, the recent establishment of the National Environmental Research Coordination Group and the existence of the Interdepartmental Flood Policy Coordination Group provide government frameworks for facilitating the cross-sectoral collaboration needed to support the integrated catchment management required for NbS.

The OPW is undertaking a nationwide catchment assessment to identify and map areas most suitable for implementing NbS for flood mitigation. While this is welcomed, the OPW also identifies the inherent uncertainty of NbS. Not knowing the precise hydrological responses to NbS in different Irish catchment types can complicate certain design and investment decisions.

Internationally, many countries have moved away from a "no NbS until adequately quantified" approach towards adaptive portfolios where NbS are deployed at meaningful scale, and monitored and improved over time. For example, Germany deploys natural water retention measures as part of a cost-efficient portfolio, using catalogue-type guidance and cases. Similarly, the UK Environment Agency has built an evidence directory (EA, 2025) that summarises the effectiveness of natural measures using ranges and confidence levels. It also funded catchment-scale pilots with embedded monitoring instead of holding back until the evidence was complete. In the Netherlands, the "Room for the River" and "Adaptive Delta Management" approaches are explicitly about experimenting, learning and adjusting measures over time, using system-scale portfolios (floodplain lowering, use of side channels, relocation of dykes) rather than waiting for perfect performance numbers for each measure.

Although the OPW plan broadly aligns with mainstream EU thinking on NbS for flooding, it is comparatively cautious and infrastructure-centric, with less explicit mainstreaming and spatial targeting and not so much scaling commitment. Compared with the approaches of the Netherlands and Germany, Ireland's 2025–2030 CCSAP FRM is more incremental. It creates an enabling framework and signals openness to NbS, but is less prescriptive on land use change, quantitative restoration goals and the large-scale, spatially explicit roll out of NbS for flood risk. Ultimately, the extent of implementation will depend heavily on how the OPW translates the CCSAP FRM into scheme-level design standards, funding criteria and partnerships with agriculture, forestry and peatland programmes. There remains a reliance on using hard structural measures for flood relief schemes as the primary means of flood protection.

Devising funding schemes that move beyond the farm scale to the catchment scale will enable a more connected ecosystem and enhance the effectiveness of flood mitigation measures. This would include designing biodiversity corridors, strategically incorporating renewable energy infrastructure and planting diverse tree species in woodlands and forests (Murphy *et al*., 2023b). Equally important is providing farmers and rural communities with access to climate services, including data, forecasts and decision-support tools. This would empower them to make informed decisions about land management and adapt to climate change. It would also help optimise agricultural practices and forestry for flood mitigation and improve resilience to extreme weather events (Murphy *et al*., 2023b).

Moving forward, the OPW could provide clear guidelines and criteria for the selection, design and implementation of NWRMs in different catchment areas, and a pathway for the funding of those measures. In addition, it could fund research and scaled-up projects to quantify the flood reduction benefits of various NWRM types and configurations. The OPW could also be instrumental in developing a national inventory of existing and potential NWRM sites to identify implementation opportunities and monitor effectiveness. Finally, it could identify and address potential barriers, such as land ownership issues, funding limitations and lack of public awareness, to facilitate the wider uptake of NWRMs. Incorporating NWRMs into spatial planning policies and development regulations would encourage their adoption in new development projects and promote a more integrated approach to flood risk management in Ireland.

6 Summary and Recommendations

6.1 Summary

This report presents research on NbS for flood mitigation and water quality improvement in Irish agricultural landscapes. The study examines the effectiveness of several NbS measures, including OSAs and LDs, through both field experiments and modelling. Results indicate that OSAs are particularly effective at reducing flood peaks in smaller catchments. The research also explores the wider benefits of NbS, such as improved grass productivity and hydromorphology, and identifies policy and practical barriers to wider implementation. Finally, the document offers recommendations for future research and policy actions to promote the adoption of NbS in Ireland.

- The SloWaters project, the first of its kind in Ireland, constructed rural flood mitigation demonstration sites to assess the impact of NbS on stream hydrology and water quality.
- OSAs can significantly reduce localised flood peaks for flow events with an AEP of 33% or more. OSAs at Site 2 reduced flood peaks by up to 38% and increased the duration of lower flood peaks by 2.5 times. Modelling suggests that OSAs can effectively reduce peak flows in catchments of $3\,km^2$ or less, and potentially in larger catchments (up to $10\,km^2$) if a cumulative target storage volume of $200–3000\,m^3/km^2$ can be achieved.
- Scaling up using our modelling approach suggests that investment in a larger scale research demonstration is warranted, specifically the installation and instrumentation of three or more OSAs in sequence in a catchment.
- OSAs require small land take and could remain productive for pasture if designed appropriately.
- LDs can impact flood peaks, but the effect depends on storage volume. At Site 2, LDs reduced the time to peak for flow events with an AEP of 33% or more occurring. Modelling suggests that the volume of water stored by LDs has a more significant impact on peak discharge attenuation than LD number or configuration.
- Simple enhancements to farm drain morphology can improve water quality. At Site 2, a WS increased DO concentrations and significantly reduced nitrate concentrations along its length. However, there was evidence of dissolved phosphorus, organic matter and ammonium release during critical periods, suggesting that nutrient uptake was temporary and further research is needed.
- Temporary inundation from OSAs had minimal negative impact on grassland productivity. In summer, grass growth and productivity were higher in the OSA ponding zone, while, in winter, flooding negatively impacted growth.
- The research also identified several policy and practice barriers to and levers for wider NbS implementation, including the need to mainstream NbS into flood risk management plans, address funding gaps, build the evidence base for NbS effectiveness and consider the socio-economic implications for landowners.

There is a requirement for the maintenance of specific features over time. In addition, certain NbS (e.g. wooden constructions) will degrade naturally and require replacement (over 5- to 10-year time frames and perhaps following large floods). Management protocol for follow-up inspections and maintenance works of individual measures will be required. Of equal importance, but beyond the scope of this study, are the socio-economic barriers and levers that may exist for private landowners. In addition, the financing, design and post-installation monitoring of measures will all require careful consideration.

Therefore, our recommendations are based on the physical attributes of the landscapes and performance of the measures installed in this project. We do not assume that our recommendations will be undertaken without appropriate governance and expert support for communities and landowners.

6.2 Recommendations

6.2.1 Nature-based solutions for low-magnitude floods in small catchments

Our empirical data show a reduction in flood peaks by more than 30%. Model data support this and suggest that OSAs may have the most immediate, low-cost and significant impact on floods of any NbS measures tested in this research. Given the known efficacy of NbS in smaller catchments, alongside the more recent findings of Howarth *et al*. (2025), we suggest that an NbS-based approach be designed and implemented for communities at risk of frequent flooding (RI = 50 years and perhaps longer) and in catchments smaller than 100 km^2.

Recommendation 1: install OSAs for flood flow mitigation in multiple rural sub-catchments of larger river catchments.

Leaky dams

The LDs at Site 2 did reduce the time to peak for flow events occurring once every 3 years or more frequently but were not effective for less frequent, larger discharges.

The leaky board installed at Site 1 was effective. Our design positioned the measure above the channel bankfull height, was only engaged during the lower probability floods and extended over one of the channel banks to preferentially direct the floodwaters. This ensured the diversion of larger discharges across the floodplain to the temporary offline storage, while bankfull flows continued uninterrupted downstream.

Recommendation 2: LD installation should be focused on the diversion of peak flows to OSAs. This will increase the likelihood that offline storage on floodplains is engaged only during flood peaks and will ensure maximum downstream flood mitigation.

Offline intake design

The weir structure and adjustable gate (e.g. Site 2) was very effective for the control of flow into the offline area. This is a suitable approach for locations that require some control of the season of flood ingress (e.g. due to summer tillage crops and/or stock use) and the volume of water ingress (e.g. higher flows to recharge during drought periods).

Recommendation 3: the sluice gate design is useful for restricting offline storage to specific seasons. For example, it can restrict inundation to the winter season when tillage and grazing are not active.

Soil bund

Bund capacity should be designed for large floods so as to future-proof for climate change, antecedence moisture and multiple flood peaks. Our demonstration sites show that single offline field storage measures are effective in small (< 3 km^2) catchments and have the capacity to store up to 800 m^3 of floodwater. This capacity could be significantly increased by increasing the bund elevation. However, the drainage rate of the ponds in a network must be altered to offset the increase in total storage, as there is a clear storage drainage relationship.

Recommendation 4: OSAs should be designed for maximum potential storage in co-designed and agreed locations. Outlet storage design should be suitable for the largest floods (e.g. spillways in addition to drainpipes).

Field drainage

Subsurface field drainage contributes to stream flashiness (Zhou and Margenot, 2024). Recent work has found that the arterial drainage schemes in Ireland have led to an increase in the annual maximum flow and hydrograph flashiness (de Smeth, 2024). At Site 1, we captured part of the flow from the subsurface drainage to build a pond feature in the OSA. This capture most likely delayed the subsurface drainage contribution before, during and following the flood peak. The pond feature did not affect the efficacy of the subsurface drainage system upslope of the pond.

Recommendation 5: where pond installation is desired by the private landowner, subsurface PVC drain capture should be used to reduce the contribution of subsurface drains to the channel.

Woodland swales

We found that simple enhancements to drain morphology in woodlands can improve water quality and reduce the risk of runoff reaching waterbodies. WSs show potential to address significant water quality issues. Swales can be easily constructed by modifying open drains within agricultural holdings.

Recommendation 6: a temporary storage element for flood mitigation could be added to wetlands.

Demonstration sites

We had over 400 visitors at our two demonstration sites (farmers, students, politicians, media, government agencies) and continue to support visits. These proved to be highly effective for knowledge transfer. A wider geographical spread of demonstration sites would benefit the understanding and potential uptake of NbS.

Recommendation 7: install measures for demonstration and public viewing at additional sites across Ireland.

6.2.2 Training and expertise

Training is essential for the wider effective and safe implementation of measures. Bespoke training should be offered to those who advise communities on land management (e.g. Agricultural Sustainability Support and Advisory Programme advisers, rivers trusts, the Local Authority Waters Programme and local authorities). This training should pay specific attention to the installation, monitoring and evaluation of NbS for flood reduction.

Recommendation 8: provide training on NbS for flood mitigation to land managers and advisers.

Measure design

Designing measures is difficult in ungauged catchments. Although the PFM informed optimal design, adjustments and repairs may still be required. For example, the sluice take-off point may need to be armoured and a robust draw-off structure may need to be installed.

Recommendation 9: a dynamic approach by managers will be required, as will a willingness to repair and maintain structures, particularly in the initial stages in ungauged catchments.

Approach to construction

To minimise the risk of measure failure (see LDs at Site 2 and the bund at Site 1), we suggest a careful approach to construction. Any NbS scheme for flood reduction that carries significant risk for downstream communities in the event of structural failure needs to be monitored on a systematic basis.

Recommendation 10: ensure that construction design and implementation are overseen and coordinated by a competent authority.

6.2.3 Funding and investment

Private landowners need to be compensated for the disruption and build costs and for the ecosystem services they provide. In the agriculture sector, this could be aligned with existing payment schemes such as the Agri-Climate Rural Environment Scheme.

Recommendation 11: a bespoke fund should be made available for the implementation of NbS at catchment scale.

Response to extreme events

The response of NbS measures to extreme events is understudied. Valuable data can be collected immediately following an event but prior to repair or additional floods happening. International research programmes (e.g. National Science Foundation Rapid Response Research and Natural Environment Research Council Urgency Funding) make funds available to support quick-response research on transient and unexpected scientific opportunities such as extreme events. A similar programme in Ireland would benefit NbS implementation.

Recommendation 12: provide funding to support the rapid deployment of research teams to monitor NbS during extreme events.

6.2.4 Building the evidence base

Current barriers to the implementation of NbS in Ireland include a lack of evidence and published data on NbS effectiveness (Molloy *et al*., 2024). There is a need for more monitoring of the effectiveness of NbS at reducing flood peaks (Black *et al*., 2021; Connelly *et al*., 2023; Mulligan *et al*., 2023). Monitoring and evaluating the effectiveness of NbS is essential for determining if they have a positive impact. There are two ways of doing this.

First, legacy projects could be used. We have provided the first empirical data set on the effectiveness of NbS for flood mitigation in Ireland, but monitoring needs to be continued and extended. The sites and monitoring equipment have been established and there is the potential to continue monitoring. The retention of field experimental sites beyond the initial project period will maximise the initial investment and longitudinal data, capturing long-term variability in non-stochastic flows. This will enrich the research outcomes and offer deeper insights.

Second, a scoping study could be undertaken of NbS that have been installed elsewhere in Ireland and are not currently monitored for flood mitigation. A strategic assessment of suitability for flood monitoring may yield additional important sites that could be monitored in the future. Existing NbS databases may be a useful starting point (e.g. Clarke and O'Donoghue-Hynes, 2020; Wilkinson *et al*., 2023b; Molloy *et al*., 2024).

Recommendation 13: strategically monitor existing NbS to increase the empirical database.

6.2.5 Recommendations for further research

Specific measure performance

The scaling up of networks of OSAs within a catchment must be coordinated and managed to ensure optimum flood risk management. There is a need to better understand the importance of preventing the synchronisation of flood peaks from different contributing areas when OSAs begin to discharge water stored within them during the filling phase.

The finding of an increase in phosphorous downstream of the OSA at Site 2 requires further investigation to see if it is a local effect or a widespread phenomenon. Although we note that this has not been found at other sites, the finding warrants further study. However, a well-designed flood storage pond should only operate infrequently in extreme events.

The analysis of flow records for flood relief schemes shows the non-stationarity of floods, particularly under climate change scenarios (mid- and high-end scenarios). Current recommendations for hard engineering propose an "uplift" of 20–30% for peak flows (O'Neill and Quigley, 2023). In addition, the SoP (1% AEP) for hard-engineering structures will deteriorate over their design life (50 years) to an AEP of approximately 10–20% SoP by 2075 (O'Neill and Quigley, 2023).

Adding new temporary storage to upstream catchments could be a long-term goal, with new measures being added each year, slowly building more storage at the catchment level and addressing larger floods and creeping climate change. Our modelling suggests that if locations for larger OSA features are found they may provide substantive additional catchment storage. This suggests that larger scale flood events could be better managed.

Recommendation 14: research the role that the installation of NbS may have to play in the support of hard-engineering structures under uncertainty in climate change scenarios and the decline in the target SoP of hard-engineering structures.

Nuisance floods

Compared with extreme flooding and disasters, the occurrence and impacts of nuisance floods are poorly understood (Moftakhari *et al*., 2017). Systematic monitoring combined with a review of existing data on the cost of nuisance floods will permit policy development and strategic management of the hazard.

Recommendation 15: undertake an assessment of nuisance floods in Ireland.

Resilience of nature-based solutions

As measures are constructed of natural materials (soil, wood), they require monitoring, as performance may decline over a 5- to 10-year time frame. For example, their elevation may decrease (soil will settle in bunds), they may collect debris and soil (LDs and sediment ponds), or they may dislodge or erode (LD, channel banks, beds or bunds). Such monitoring will allow timely intervention for repair and a more robust evaluation of maintenance costs (both financial and time).

Geomorphic change. We have reported change observed on channel beds and banks because of measure installation. The permanency of the NbS is unknown, as channel reaction time and recovery are not well understood (Addy and Wilkinson, 2019). Continuous monitoring of streambed topography, particularly around measures, will inform us on whether the geomorphic feedback is positive or negative. Field visits (annually and following extreme events) will permit the evaluation of maintenance needs.

Biodiversity impacts. Little empirical data exist on the impact of NbS on natural capital. Studies indicate an improvement in ecosystems (van Rees *et al*., 2023), but more quantified studies are needed.

Recommendation 16: monitor change of/to NbS measures and sites.

Governance, funding and responsibility for nature-based solutions

A significant barrier to the implementation of NbS for floods is the absence of a clear governance structure, a bespoke financial plan and a maintenance programme. The following is an outline of some issues that will require further research and planning to permit widespread measure uptake. Any future scheme should be voluntary. Despite this, there may be impediments to deployment. For example, the identification of suitable sites for flood storage within a catchment may not coincide with landowners' willingness to install such features on their land. Where landowners are willing to install measures, the permanency of such features on individual land holdings cannot be guaranteed. This may occur as land use priorities change over time, through both intra-annual land management (e.g. re-seeding of grassland lays, silage cutting) and inter-annual changes to land use (e.g. conversion of grassland to arable cropland).

The design, construction and implementation of small-scale voluntary NbS will depend to a great extent on the willingness and technical ability of landowners to construct and manage such NbS. Landowners will need to be fully indemnified against failure of features, which could result in potential damage to downstream individuals, landowners and infrastructure. However, with small-scale individual features this may represent a small risk of downstream damage. Land asset values are an important aspect of agriculture in Ireland. Installation of NbS features on agricultural land may impact these values.

Recommendation 17: further research is needed on the social, political, economic and liability issues regarding NbS for private landowners in rural areas.

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Abbreviations

AEP	Annual exceedance probability
APM	Aggregate Pond Model
CCSAP FRM	Climate Change Sectoral Adaptation Plan for Flood Risk Management
CRAFT	Catchment Runoff Attenuation Flux Tool
DEM	Discrete element method
DO	Dissolved oxygen
DOC	Dissolved organic carbon
KLAG	Delay coefficient for surface runoff in the attenuation store
LD	Leaky dam
NbS	Nature-based solutions
NWRM	Natural water retention measure
OPW	Office of Public Works
OSA	Offline storage area
PFM	Pond Forensic Model
QSR	Near-surface fast flow
RAF	Runoff attenuation feature
RI	Recurrence interval
SoP	Standard of Protection
SRP	Soluble reactive phosphorus
TP	Total phosphorus
WS	Woodland swale
ΔQp	Assessment of changes in peak discharge
ΔQpt	Peak discharge travel time

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

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

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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