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epa Research

Specific Management and Robust Targeting of Riparian Buffer Zones

Authors: Daire Ó hUallacháin, Per-Erik Mellander, Simon Parker, Nikki Baggaley, Mark E. Wilkinson, Allan Lilly and Marc Stutter

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Rialtas na hÉireann
Government of Ireland

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Lead organisations: Teagasc and James Hutton Institute

Identifying pressures

The pollution of surface waters and groundwaters is a key environmental challenge for agri-ecosystems. Globally, water quality has declined over the last five decades. In the European Union, over half of surface waters are of less than "good ecological status", the minimum threshold required under the EU Water Framework Directive.

In order to halt declining water quality and improve aquatic and riparian habitat conditions, numerous mitigation measures have been implemented in recent decades. These measures typically aim to address the source–mobilisation–delivery process, either by undertaking mitigation to reduce the source of the pollutant or by "breaking the pathway" between source and receptor (e.g. the river). Measures targeting the riparian land–water interface have the potential to break the pathway, delivering water quality benefits along with a wide range of ecosystem services.

Although widely implemented, riparian mitigation approaches have frequently been established without due regard to the "Right Measure, Right Place" concept. The aim of the Specific Management and Robust Targeting of Riparian Buffer Zones (SMARTER_BufferZ) project was to support optimal targeting and management of riparian margins, within an agricultural context, for the effective management of Irish rivers.

Informing policy

A key tenet of Ireland's River Basin Management Plan (2022–2027) is to apply the right measure in the right place to protect and improve Irish waters.

To support stakeholders in identifying the right measures for riparian management, the SMARTER_BufferZ project identified and evaluated alternative riparian mitigation measures appropriate for Irish conditions. A riparian measures database was published containing a summary of the measures, details on their wider ecosystem benefits and an assessment of their effectiveness.

The project built on the work of the DiffuseTools project to develop tools for identifying locations where mitigation measures would have maximum impact. By coupling insights on ideal locations with target actions and knowledge on the measures that could be used, the project developed tools to identify the appropriate mitigation measures for each location. These tools used landscape context to prioritise the 16 mitigation measures identified. Using the tool ensures a consistent framework for applying rules and informing decisions on appropriate or inappropriate measures based on user inputs.

The outputs from SMARTER_BufferZ can support policymakers and catchment managers to expand beyond traditional riparian mitigation approaches.

Developing solutions

The SMARTER_BufferZ project aimed to develop a framework for the optimal targeting and management of riparian margins, within an agricultural context, for the effective management of Irish rivers. To achieve water quality objectives set out in the Water Framework Directive, mitigation measures addressing both individual delivery points within a field and collective delivery from sub-catchment areas should be considered, along with management actions to reduce the source of a pollutant.

This project has highlighted the potential of implementing new measures that are more effective than traditional grass buffers. However, there is little in the way of demonstration of such measures in an Irish context. The use of "demonstration farms" to demonstrate each of the 16 measures from the SMARTER_BufferZ database would help showcase the concepts behind these measures.

Lessons learned from the SMARTER_BufferZ project will play a key role in achieving water quality objectives. Developments in identifying and assessing riparian measures, coupled with tools to support the targeting of measures, can help to inform future projects and achieve targets under policies such as the Common Agricultural Policy and the Water Framework Directive.

EPA RESEARCH PROGRAMME 2021–2030

Specific Management and Robust Targeting of Riparian Buffer Zones

(SMARTER_BufferZ Project)

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EPA Research Report

Prepared for the Environmental Protection Agency

by

Teagasc and James Hutton Institute

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This report is based on research carried out/data from April 2018 to December 2022. More recent data may have become available since the research was completed.

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

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Executive Summary

Riparian buffer zones are patches of land adjacent to rivers, streams and field drains, and are key locations for targeting mitigation measures that aim to improve water quality. Measures that target the riparian land–water interface have the potential to deliver a wide range of ecosystem services (beyond water quality benefits), including providing habitats for biodiversity, enhancing floodplain connectivity, managing flood threat, mitigating water temperature increases, promoting carbon sequestration and controlling greenhouse gas exchanges, and providing aesthetic and recreational services. However, while riparian margins have commonly been implemented under compulsory Good Agricultural and Environmental Condition requirements and optional agri-environment schemes, measures have frequently been implemented without due regard to the "Right Measure, Right Place" concept.

The aim of the SMARTER_BufferZ project was to develop a framework for the optimal targeting and management of riparian margins, within an agricultural context, for the effective management of Irish rivers. The project assessed literature on buffer zone effectiveness (targeting run-off, sediment, phosphorus (P), nitrogen (N), coliforms and pesticides). This literature review highlighted that buffer width impacted the reduction in sediment, total P and dissolved P loads (however, there was a large amount of scatter between studies). Inclusion of data on soil clay content reduced scatter and improved model prediction (for sediment and total P) relative to width alone. Reductions in coliforms and total N retention were not impacted by buffer width. The review demonstrated the role of site-specific factors in the effectiveness of reducing pollution mass.

The project identified the most frequently occurring riparian mitigation measures (appropriate for Irish conditions), resulting in a shortlist of 16 measures. A riparian measures database was published containing a summary of the 16 measures, including details on their functioning, the evidence base for their wider ecosystem benefits and an assessment of their effectiveness (determined through expert opinion).

The project built on the work of the DiffuseTools project to develop tools to identify locations where run-off predominantly arises in adjacent fields and is delivered to watercourse margins. Topographical features can be coupled with soil risk factors (related to source and transport) to identify critical "breakthrough" areas of converging flow, where sediment and nutrient-rich run-off are most likely to occur, and thus where mitigation measures could be targeted. Remote-sensing approaches, along with field observations and landowner engagement, can play an important role in identifying potential flow paths and delivery points, and in targeting mitigation measures to these locations.

Building on knowledge of the **right place**, coupled with information on potential measures, the project developed tools to help target the **right measure** to the right place. These tools used landscape context to prioritise the 16 mitigation measures previously identified. A key output was the measures selection tool (https://measure-selection-tool.hutton.ac.uk/), which ensures a consistent framework for applying rules to inform decisions on appropriate or inappropriate measures based on user inputs to landscape questions.

The project developed and demonstrated the use of a hierarchical framework for implementing the **right measure** in the **right place** within an agricultural context. A three-tiered system for measure placement was developed, comprising level 1 (fixed-width 2 m grass margin), level 2 (targeted 5 m vegetated buffer) and level 3 (bespoke soft-engineered measures at key locations in the catchment) measures. An assessment of this system highlighted that the level 1 measures (2 m margins) allowed > 80% of sediment and > 90% of total P to be lost from the fields. The localised increase in the width of the grass margin buffer zone from 2 to 5 m at delivery points led to a substantial increase in effectiveness; for localised extra land take, the cost-effectiveness generally improved, with costs per unit mass of pollutant retained at least halving. The level 3 measures brought considerable cost savings, relative to level 1 and level 2 measures, under certain scenarios.

Lessons learned from the SMARTER_BufferZ project will play a key role in addressing the challenge of achieving water quality objectives. Developments in identifying and assessing riparian measures (e.g. database of measures, reviews of effectiveness), coupled with the development of tools to support the targeting of measures (e.g. the measures selection tool, hillslope models, pollution impact potential maps), can help to inform new projects (e.g. Waters of LIFE; Water Quality European Innovation Partnership) and future projects and schemes (future iterations of the Common Agricultural Policy strategic plans; implementation of the Water Framework Directive).

1 Introduction

1.1 Context and Background

The pollution of surface waters and groundwaters represents one of the primary environmental challenges facing agri-ecosystems (Dudgeon *et al*., 2006). Globally, water quality has declined over the last five decades (IPBES, 2019). In the European Union for example, over half of surface waters are of less than “good ecological status” (EEA, 2022), the minimum threshold required under the EU Water Framework Directive (WFD) (2000/60/EC). In the context of declining ecosystem quality, freshwater ecosystems are experiencing some of the highest rates of decline (IPBES, 2019), and this challenge is compounded by system vulnerabilities to climate change (Mack *et al*., 2019). In an Irish context, results from the EPA (Trodd *et al*., 2022) indicate that 54% of surface waters are achieving good or high ecological status. Data indicate that water quality has deteriorated in Ireland over recent reporting periods, from a 1% decline in the ecological health of rivers to a 16% decline in the quality of estuaries (in the 2016–2021 period relative to the 2013–2018 period).

Nutrients (Smith and Schindler, 2009), coupled with excess sediment inputs (Walling and Collins, 2008), are the primary pollutants in most freshwater ecosystems in the world. The major pressures acting on European rivers include hydromorphological pressures, diffuse source pollution (from agriculture in particular) and atmospheric deposition (EEA, 2018). Anthropogenic activities, including land use and agriculture, are among the main sources of pollutants in freshwater systems (Heathwaite *et al*., 2005; Vorosmarty *et al*., 2010). The loss of nutrients (nitrogen (N) and phosphorus (P)) from agricultural systems to surface water and groundwater receptors has been highlighted as one of the main threats to water quality in the EU, with agriculture being a dominant source of sediment and nutrient run-off to freshwaters (Rickson, 2014). Similarly in Ireland, the EPA (Trodd *et al*., 2022) has identified excess nutrients (emanating from agriculture and wastewater treatment activities in particular) as key stressors of surface water.

Recognising the need to halt declining water quality, improve aquatic and riparian habitat condition and adapt to hydroclimatic extremes, numerous mitigation measures have been implemented over the last few decades, particularly under the Nitrates Directive (Council Directive 91/676/EEC) and more recently the WFD. These measures include compulsory measures incorporated under Pillar 1 (e.g. Good Agricultural and Environmental Conditions (GAECs)) of the Common Agricultural Policy (CAP) and optional agri-environment measures (under Pillar 2 of the CAP). These mitigation measures typically aim to address the source–mobilisation–delivery process (Granger *et al*., 2010) by either reducing the source or breaking the pathway between source and receptor.

1.2 The Riparian Interface

The riparian interface, between land and the aquatic environment, has been identified as a key location for targeting mitigation measures that aim to improve water quality. Riparian buffer zones (RBZs) are patches of land adjacent to fluvial (e.g. rivers, streams and drains) and non-fluvial (e.g. lakes, estuaries) systems that have been removed from intensive production and contain permanent vegetation. Mitigation measures targeted at riparian areas can help to break the pathway between source and receptor (Stutter *et al*., 2019a). From a water quality point of view, RBZs are typically designed so that vegetation in the RBZ increases surface roughness and infiltration (Dorioz *et al*., 2006), thus slowing flows and reducing sediment concentrations and mass loads, together with the loads and concentrations of particle-associated nutrients and pesticides, within surface waters. The changes in the microenvironment within the RBZ result in a greater resistance to surface flow (because of above-ground vegetation) and an increase in infiltration (as a result of the root system). Riparian buffers are characterised by biological, hydrological and geological factors (Hill, 1996; Hoffmann *et al*., 2009; Christen and Dalgaard, 2013), and these factors determine their functioning (Feld *et al*., 2018).

Coupled with their potential for delivering water quality benefits, it is increasingly recognised that measures targeted at the riparian interface have the potential to deliver a wide range of ecosystem services, including providing habitats for biodiversity, enhancing connectivity, alleviating flood threats, mitigating water temperature increases, controlling greenhouse gas exchanges and providing aesthetic and recreational services (Stutter *et al*., 2012; Gilvear *et al*., 2013; Cole *et al*., 2020).

1.3 Policy and Practice Needs: Internationally and Nationally

Riparian measures seeking to enhance the delivery of ecosystem services and the protection of water quality have been in existence nationally and internationally for a number of decades. Numerous international scientific studies have been published on the effectiveness of traditional linear riparian buffers (Mayer *et al*., 2007; Stutter *et al*., 2012; Hille *et al*., 2018); however, effectiveness outcomes have varied (see Stutter *et al*., 2021a; see also section 2.2). Empirical evidence from studies assessing the effects of planting or restoring riparian buffers is unclear because of the variety of biological, hydrological and geological factors (Hill, 1996; Hoffmann *et al*., 2009; Christen and Dalgaard, 2013) that characterise riparian buffers and determine their functioning (Feld *et al*., 2018).

The implementation of riparian margin management prescriptions features in Ireland’s Programme of Measures, in particular as part of the Nitrates Action Programme (NAP). The measures broadly fall within cross-compliance (Council Regulation (EC) No. 1782/2003), which requires that farmers in receipt of incentives under the Basic Payment Scheme (within Pillar 1 of the CAP) abide by statutory management requirements, i.e. GAEC requirements (Kristensen and Primdahl, 2006. From a riparian margin perspective, the primary prescriptions within the NAP include step-back distances (exclusion zones) for application of nutrients, pesticides and cultivation (Table A1.1). More recent NAP riparian prescriptions include the exclusion of bovine access within 1.5 m of watercourses for derogation farmers (i.e. farmers with a derogation to apply > 170 kg N/ha). Riparian margin prescriptions have also featured strongly in every Irish agri-environment scheme (AES) since the first scheme was introduced in 1994 (Table A1.2).

However, while riparian margins have commonly been implemented under compulsory GAEC requirements and optional AESs, few Irish studies have evaluated the effectiveness of riparian measures. Riparian measures have frequently been implemented without due regard to the “Right Measure, Right Place” concept. Effectiveness and uptake or on-farm integration can be improved by identifying optimal places (**right place**) for management prescriptions and targeting these places with the appropriate mitigation measures (**right measure**).

In recent years, significant efforts have been made to develop tools to support the targeting of riparian mitigation measures to the **right place**, culminating in the development of the EPA’s pollution impact potential (PIP) flow delivery paths and PIP flow delivery points (https://gis.epa.ie/EPAMaps/Water). The value of these developments has been recognised in the latest Irish AES (the Agri-Climate Rural Environment Scheme (ACRES)), which indicates that PIP maps should be used to support the targeting of mitigation measures, including riparian buffer measures. Considering the development of tools to help identify the right places, it is important that tools that help to identify the right measures are also developed. Such tools can help to identify optimum buffer design and management options for a given local set of biophysical and desired outcome factors.

ACRES has seen a greater variety of riparian prescriptions included and greater flexibility in the implementation of measures (i.e. in recognition of the need for greater targeting of mitigation measures), and thus tools supporting the “Right Measure, Right Place” approach are given heightened importance. While a greater variety of riparian prescriptions have been included in recent iterations of AESs, there are additional riparian mitigation measures that could be suitable for Irish conditions. Thus, from a riparian margin perspective, the identification of potential measures and the integration of measures, with developments to identify the **right place**, will play a significant role in addressing water quality objectives and delivering wider ecosystem services.

1.4 Aims and Objectives

The aim of the SMARTER_BufferZ project was to develop a framework for the optimal targeting and management of riparian margins for the effective management of Irish rivers. Key objectives of the study were to:

- evaluate the effectiveness of riparian management measures to maintain and enhance water quality in Irish rivers, by assessing scientific literature/ expert knowledge on the optimum buffer design and management options for a given local set of biological and physical factors;
- identify a suite of potential riparian management measures appropriate for Irish conditions and evaluate the effectiveness of these measures to deliver multiple ecosystem services;
- recognise that general effectiveness evidence has high levels of uncertainty and site specificity and work towards developing decision support tools (at a farm level) for advisor or land manager on-site guidance aimed at maximising outcomes and uptake;
- make recommendations for actions, from basic strategies that are widely implemented to more specific requirements according to site-specific circumstances;
- develop screening-level tools to generate rules for placement and show how targeting designs and locations is more effective than blanket use of linear, surface interception buffers;
- advise on approaches for implementing measures based on local knowledge and existing catchment advisory structures, and promote demonstration and knowledge-sharing activities.

2 Literature Reviews

2.1 Rationale

Riparian measures to enhance the delivery of ecosystem services (and the protection of water quality in particular) have been in existence nationally and internationally for several decades. These measures include those incorporated under compulsory GAEC requirements (e.g. the NAP), typically implemented through Pillar 1 of the CAP, and optional AESs, implemented through Pillar 2 of the CAP.

The objectives of the literature reviews were to evaluate and synthesise information on existing EU and Irish legislation and policies for the protection of water quality. The literature reviews also aimed to collate, evaluate and synthesise information and relevant guidelines and measures for land uses and policies that underpin the protection of riparian habitats (section 2.2). The final literature review (section 2.3) explores the role of data in supporting the targeting of riparian measures.

2.2 Managing Riparian Margins: An Irish Perspective

Riparian margin prescriptions have featured strongly in every Irish AES since the first scheme was introduced in 1994 (see Table A1.2) and in each NAP (i.e. since 2006) (see Table A1.1). Narrow riparian margins were initially implemented in Ireland under (optional) AESs (Rural Environment Protection Scheme (REPS)) in 1994. However, the Code of Good Farming Practice (implemented under NAP1 in 2006) required that elements of REPS prescriptions (i.e. no application of pesticide, herbicide or chemical fertiliser within 1.5 m of watercourses) extended beyond optional Pillar 2 prescriptions and into compulsory Pillar 1 obligations. From a water quality point of view, these measures are likely to have played a role in:

- reducing the source of nutrients directly adjacent to watercourses;
- reducing machine activity adjacent to watercourses (and supporting bank stability);
- reducing direct (accidental) application of pollutants to watercourses;
- reducing cultivation (and associated soil erosion) on riverbanks.

More recent iterations of Irish AESs have seen the narrow margin measure include the full exclusion of bovines (i.e. no cattle access points). Full exclusion of bovines is also now compulsory for all derogation farms (under NAP4).

Wider riparian margins have also been included in various AESs over the last 20 years or so; however, these measures have proven to be relatively unpopular with farmers participating in Irish AESs (Ó hUallacháin, 2014). Thus, narrow riparian margins, either with (i.e. NAP prescriptions) or without (i.e. an AES) cattle access to watercourses, have been a dominant riparian measure in Irish agri-policy. Ireland (along with other EU Member States) is required to monitor the effectiveness of the Programme of Measures and agri-environment measures to ensure their effectiveness. However, although riparian margins have commonly been implemented, few Irish studies have evaluated the effectiveness of specific measures. In the absence of empirical evidence with which to assess effectiveness, several studies have used expert consultation to infer the effectiveness of measures.

- Finn *et al*. (2007) concluded that the "causal effect" of REPS measure 3 (protection and maintenance of watercourses, waterbodies and wells, i.e. narrow, fenced riparian margins) was low (scoring 1 out of 5): "the measure would be expected to only make a minor contribution towards achieving a medium-level environmental objective. The management prescriptions are very limited in their ability to achieve the agri-environmental objective and possess several major deficiencies."
- Carlin *et al*. (2010) concluded that the causal effect of REPS supplementary measure 4 (riparian buffers, i.e. wider riparian margins) was high (scoring 4 out of 5); however, the participation score was only 1 out of 5 (i.e. uptake was too low to achieve the expected environmental effects).
- Ó hUallacháin *et al*. (2019) concluded that the "protection of watercourse" measure under the

Green, Low-Carbon Agri-Environment Scheme (GLAS) (i.e. narrow, fenced riparian margins) could help to improve the ecological quality of watercourses in the short and long terms. However, the effectiveness was due more to the removal of bovine access to the watercourse (and reducing the impact that cattle access to water and instream activity has on sediment, nutrient and microbial dynamics) than to the buffering effect of the 1.5 m margin.
- ADAS (2021) undertook a broader evaluation of GLAS; however, the effectiveness of measures (in relation to benefits for water quality) was evaluated based on a modelling study, and at the scheme scale, as opposed to the effectiveness of measures being evaluated individually. Thus, the effectiveness of riparian margin measures could not be determined.

These limited studies highlight the lack of empirical data (from an Irish perspective) on the effectiveness of riparian mitigation measures. It is important to note that a lack of empirical data does not equate to a lack of effectiveness, but rather that the collection of evidence of the environmental performance of the riparian measures implemented (under Irish conditions) to date has been insufficient.

The limited studies also highlight that, until the most recent Irish AES (ACRES), there has been a relatively modest selection of riparian mitigation measures available to landowners under AESs, with narrow, fenced, riparian margins being the dominant riparian measure in Irish agri-policy. ACRES has resulted in a greater variety of riparian prescriptions being included, greater flexibility in the implementation of measures and recognition of the need to target mitigation measures. The effectiveness of measures will be determined by ensuring the targeting of the **right measure** to the **right place**; this requires information on buffer zone effectiveness and place specificity (see section 2.3).

2.3 Buffer Zone Effectiveness and Place Specificity: An International Perspective

2.3.1 Rationale

Despite extensive research internationally on RBZs and other edge-of-field and within-field buffer designs (a rate of ~10 studies annually in 1990, rising to ~70 annually in 2010; Haddaway *et al*., 2018), the evidence base for understanding processes contributing to buffer mitigation of pollution transfer to watercourses remains inconsistent. There remains a need to look across data from individual sites and studies for collective evidence on the site-specific nature of pollution mitigation and river water quality. Differing results are strongly influenced by site-specific factors, pressures and resulting RBZ functions. This limits the ability to correctly incorporate relevant factors of a given site when seeking to guide or make decisions on placement, designs and maintenance at catchment-planning scale.

Thus, there was a need for synthesis across existing evidence to evaluate influential factors in buffer performance across multiple pollutants, and to improve the outcomes of modelling buffer effectiveness predictions and design recommendations. Our review aimed to build on the simple, width-based effectiveness of RBZs for multiple pollutants by integrating site-specific factors. This is timely for the following reasons:

- RBZs applied in practice (to meet more stringent water quality legislation) over past decades now provide a resource for longer study duration evidence (whereas earlier reviews include proportionally more experimental plot studies).
- Interdisciplinary studies have developed across RBZ aspects, leading to a more systems-level understanding of functions.
- A greater range of buffer designs are conceived and tested (e.g. Stutter *et al*., 2019a), tackling pathways such as artificial subsurface drainage.

We set out to evaluate whether (i) pragmatic generalised relationships could be derived from quantitative effectiveness studies incorporating simple covariates to develop site-specific model predictions and (ii) a wider literature review would show evidence coherence regarding key factors related to site-specific aspects (e.g. soil hydrology or chemistry), management (e.g. managing vegetation) and RBZ functions (e.g. achieving reduction/retention of both dissolved and particulate pollutants, or comparing surface versus deeper flow pathways). Our review is available in full in Stutter *et al*. (2021a). It focused on outcomes for dominant pollutants – sediment, N, P, pesticides and pathogens/faecal indicator organisms

(FIOs) – and is linked to two supporting published databases (Stutter *et al*., 2021b,c).

2.3.2 Methods: a review of vegetated buffer zone literature

We documented buffer zone evidence (targeting run-off, sediment, P, N, coliforms and pesticides) from primary studies, supported by a major review incorporating key site-specific factors (Figure 2.1). Full methods can be found in section A2.1 and are summarised here. Briefly, the literature search (1980–2019) focused on RBZs and processes and used the terms riparian buffer; watercourse buffer; vegetated filter strips (VFSs); vegetated grass filter; riparian management; and riparian diffuse pollution mitigation. Papers were then screened as "not relevant", "primary studies" or "review papers" (supporting discussion). Papers were limited to those discussing run-off and pollution by sediment, N, P, pathogens (or indicator organisms) and pesticides.

The review of primary studies had two stages, supporting each of the databases:

1. Quantitative retention effectiveness (associated database: "Riparian Buffer Zone Quantitative Effectiveness Review Database"; Stutter *et al*., 2021b) across given widths, with quantified covariates: this comprised 75 studies (with 474 data rows), for which pollution mass load reductions were available, along with parameters recorded on soil, hydrology and management (parameters described in Table A2.1).
2. Significance testing of factors of influence in the relationship between width and pollution reduction/retention efficiency (associated database: "Riparian Buffer Zone Site-specific Factors Significance Review Database"; Stutter *et al*., 2021c): this comprised 94 studies. To interpret statistically significant negative or positive outcomes of factors on pollutant retention, definitions of the direction of effect of

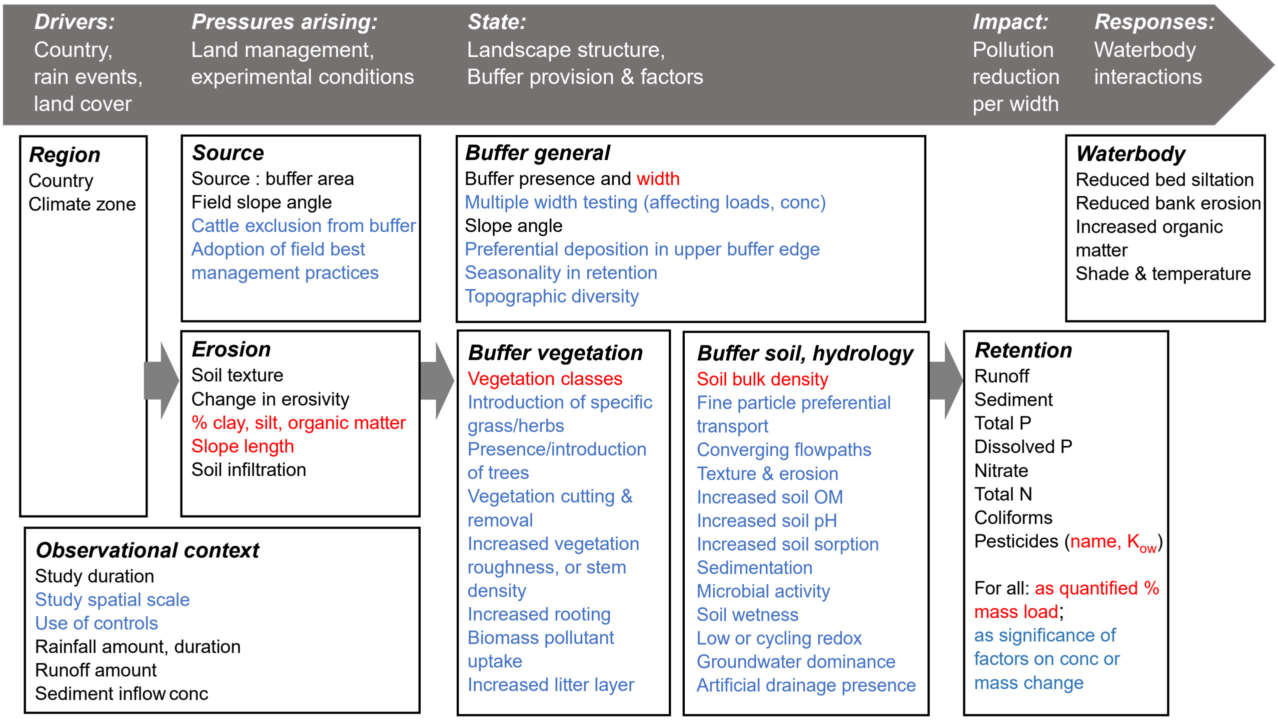

Figure 2.1. Summary of the parameter groups and factors assessed in primary literature during the SMARTER_BufferZ project, arranged using a drivers–pressures–state–impacts–response framework. Red font denotes factors that were documented in the quantitative review of percentage retention efficiencies. Blue denotes factors that were documented according to significance test results (with change direction) for their influence on pollutant retention efficiency. Black denotes factors common to both aspects of the review. Conc, concentration; OM, organic matter. Reproduced from Stutter *et al*. (2021a) with permission from Elsevier.

the factors are important (Table A2.2). A summary of metadata from studies used is given in Figure A2.1.

2.3.3 Results and discussion

Our quantitative assessment of pollution retention found considerable scatter in relationships for retention versus margin width (Figure 2.2), supporting the role of site-specific factors in influencing pollution mass reduction effectiveness. The data show the phenomenon of "negative pollution retention". For phosphate, it is known that RBZs may become saturated and convert incoming total (dominantly particulate) P to a soluble form (a form of pollution swapping), effectively becoming a source not a sink. However, it was also considered highly likely that studies, especially those on nitrate and other

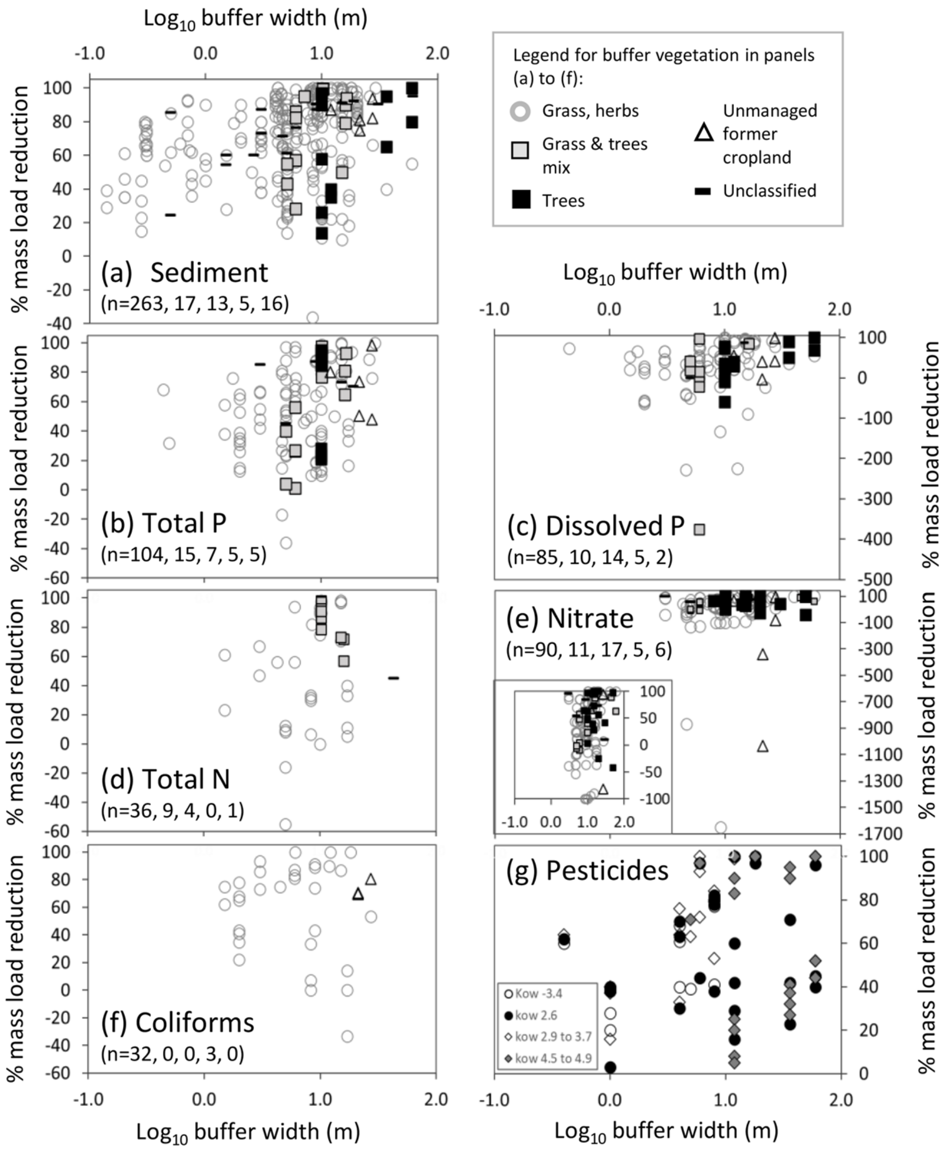

Figure 2.2. Pollutant mass retention (raw data, %) versus buffer width (log_{10}-transformed width (m); all common scales) for each pollutant. Negative retention indicates that the buffer was a net source of pollutant within the observation period. In panels (a) to (f), data are further categorised by vegetation type in the buffer (see legend at top right) and *n* values refer to numbers of data. Panel (e) (nitrate) has an inset showing a greater level of detail. Panel (g) (pesticides) is categorised by the octanol–water partition coefficient (K_{ow}) of different pesticides (–3.4, glyphosphate; 2.6, atrazine; 2.9–3.7, isoproturon, metolachlor, lindane; 4.5–4.9, fluazifop-P-butyl, chlorpyrifos, diflufenican). Reproduced from Stutter *et al.* (2021a) with permission from Elsevier.

soluble pollutants with subsurface pathways, under-represented inputs at the upper buffer edge, leading to the overestimation of outputs relative to inputs.

Across the 75 studies, few site-specific parameters were consistently recorded and only soil texture class ($n=402$), buffer slope ($n=403$) and buffer vegetation ($n=454$) were carried forward into statistical testing. Vegetation class was not a significant factor in the retention of any of the pollutants studied. Statistically significant multiple regression models (not shown; see Stutter *et al*., 2021a) were developed for sediment, total P and dissolved P against width and percentage soil clay content; this especially improved the prediction of sediment and total P retention relative to width alone. Conversely, prediction was weak for N retention and not improved by including additional covariates.

As a demonstration of incorporating covariates into the prediction models, we were able to generate a set of retention-versus-width curves across nine clay-defined soil texture classes (Figure A2.2) that contrasted outcomes for sediment, total P and dissolved P. For more coarsely textured soils, at a given width, a curve order from lesser to greater retention was seen for dissolved P, particulate P and sediment, respectively (e.g. see the order of curves 1, 4 and 7, and 2, 5 and 8 in Figure A2.2). However, varying the content of clay included in the models showed that soil texture has complex and varying effects on the retention of the various pollutants. Increasing the clay content had a stronger effect on reducing the retention of total P than on reducing the retention of the other pollutants, leading to a switch in the order of the total and dissolved P curves for the clay-rich soil (note that elements from this analysis are included in section 5.3.4).

With limitations in the number of quantitative studies, our second approach examined the significance (formal testing versus inferred; $n=94$ studies) of the following factors on pollution effectiveness: source pressure, transport/physical, vegetation and soil biogeochemistry. We found the following:

- Sediment, nitrate, dissolved P and total P were well studied (≥ 35 studies each); total N and run-off volume were moderately well studied (≥ 19 studies each); pesticides, ammonium and coliforms were poorly studied (<19 studies each); and only one study dealt with colloidal P.
- The primary factor incorporated into formal statistical testing was the action of the presence of an RBZ on pollution retention (211 studies across all pollutants). Second, ~80 studies considered the effects of multiple buffer widths on either concentrations or loads.
- Additional formally tested factors were (i) site vegetation, i.e. tree planting/presence ($n=60$), management of herbs ($n=26$) and stand/stem density ($n=22$); (ii) rainfall, i.e. intensity ($n=41$) and amount ($n=14$); (iii) buffer site, i.e. preferential deposition at the upslope buffer edge ($n=32$) and seasonality in biogeochemistry ($n=19$); (iv) buffer soil, i.e. infiltration ($n=27$) and prevalence of groundwater versus surface flows ($n=13$); and (v) source area management, i.e. cattle exclusion ($n=9$).
- There was no formal testing of source area field erosion or slope, buffer topography, or vegetation rooting, interactions of bank erosion, stream organic matter inputs or light and temperature with pollutant retention.

The RBZ evidence showed considerable disagreement between studies (Figure A2.3). Additionally, there was a bias to shorter term studies (which is problematic considering that buffer processes operate over longer time periods). Screening for stronger evidence by study number and agreement left 15 factors informing on at least one pollutant, whereas only rainfall intensity, preferential deposition, tree planting and soil infiltration remained addressing three or more pollutants (Tables 2.1, 2.2). This gave some clarity of messaging; for example, all evidence together showed contradictions for the effects of managing vegetation on differing pollutants (Figure A2.3). However, the screened evidence (Table 2.2) suggests positive outcomes prevail and gives clearer messages across multiple pollutants in terms of the effects of management of grasses/herbs, cutting/removal and tree planting.

2.4 Review of Data Requirements

2.4.1 Rationale

To define and characterise riparian zones (Figure 2.3), there is a requirement for data to represent riparian hydrological regimes, covering the interactions between (i) surface waters and groundwaters;

Table 2.1. Summary of major mechanisms affecting retention across multiple pollutants with identified conflicts within mechanisms

Generalised retention mechanisms	Pollutant							Identified conflicts across pollutants within mechanisms
	Sediment	Total P	Diss P	Total N	Nitrate	Ammonium	Pesticides	
Infiltration into a dry buffer to reduce surface run-off erosion energy	++	+	–	+	–		++ (high K_{ow})	Limitations in nitrate, soluble P and low K_{ow} pesticide effectiveness, P saturation and leaching without sorption/uptake
Infiltration into a dry buffer to increase pollutant contact with reactive subsoils		+	++		–	+	++ (low K_{ow})	Soil surface-reactive solutes retained, not nitrate (worsened by leaching)
Slowing of flow to increase residence time to aid biotic processing and uptake		+	+	+	+	+	+	Limited conflicts
Saturated buffers to improve residence time and contact with organic matter-rich soils	––	––	–	+	++		–	Wet denitrifying buffers reduce particle retention, low redox solubilised P

++, +, – and –– symbols denote a strong positive, moderate positive, moderate negative and strong negative effect on that pollutant's retention in the RBZ, respectively (blank cells indicate uncertain effects). Diss, dissolved.

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Table 2.2. Summary of strong evidence factors from the factor significance review, with an evaluation of whether conflicts are supported by the strong evidence

Strong evidence parameters	Pollutant							Are conflicts supported by evidence?
	Sediment	Total P	Diss P	Total N	Nitrate	Ammonium	Pesticides	
Increased rainfall intensity	C1	B2 (–)	B2 (–)		C2			
Reduced source: buffer area							B3 (+)	
More preferential particle deposition	A2 (+)	B2 (+)	B2 (+)	A3 (+)	B3 (+)			No -ve effects on localised N, P saturation
Seasonal biogeochemistry				B3 (+)	B3 (+)			
Active vegetation management of herbs	A3 (+)	B3 (+)						
Active vegetation removal			B2 (+)					
Active tree planting management	B2 (+)	B2 (+)	B1 (+)	B2 (+)	C1	B2 (+)	B3 (+)	Consistent outcomes
Increased vegetation stem or stand density	A2 (+)	A3 (+)						

The evidence has been filtered to the strongest evidence, coded according to (i) outcome agreement (A, unanimous agreement of outcomes across studies; B, either positive or negative outcomes (not both), with some non-significant outcomes; C, positive and negative outcomes) and (ii) weight of evidence (1, very strong (n > 10); 2, strong (n = 5–10); 3, moderately strong (n = < 5)). Cells representing the highest outcome agreements (A or B) are marked with (+) or (–) to denote positive and negative outcomes on effectiveness, respectively, while those without a directional sign (C), indicating a mixture of positive and negative outcomes, can be considered to represent outcomes most dictated by site and experimental design factors. Blank cells indicate uncertain effects. Diss, dissolved.

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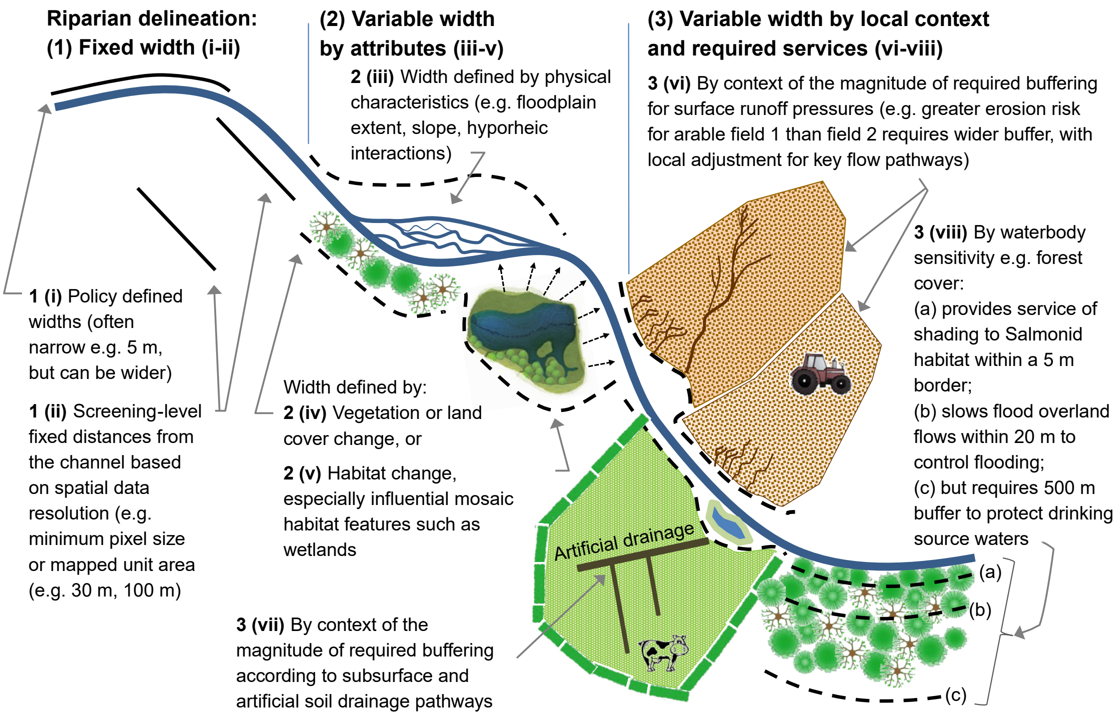


Figure 2.3. Different riparian scenarios illustrating the three main classes of riparian delineation considered here – fixed width, variable width by attributes and variable width by local context and required outcomes – together with eight submodels. Reproduced from Stutter *et al*. (2021d) with permission from Elsevier.

(ii) water and terrestrial habitats; (iii) dissolved nutrient delivery and processing; (iv) flow pathways, energy and erosion; and (v) *in situ* contaminant degradation and attenuation.

2.4.2 Key findings from review of data requirements

- Tools incorporating layers of data on hydrology, vegetation, landscape, geomorphology and hydromorphology could inform setting constraints on zoned activities across the riparian transition (ranging from allowing "natural conditions" only in the highest risk zones to permissible activities such as seasonal grazing or vehicle access in lower risk zones). Examples of "toolbox" approaches (packaged, multiple tools) being developed for research community usage are not commonly reported, and the translation of such tools to study sites relies on unity of core datasets that are likely to be country specific.
- Terrain and vegetation data have often been used as proxies for hydrological flow pathways and soil wetness. Kuglerová *et al*. (2014) cite several topographic (digital terrain model (DTM)-associated), data-derived tools for representing riparian hydrological regimes, from nearest neighbour cell flow routing to more complex algorithms and derived secondary data (topographic wetness index, cartographic depth to water, topographic position index, downslope gradient index and probability of depression index).
- Soil properties (such as hydraulic conductivity, texture) and profile characteristics (such as the depth to a slowly permeable layer or presence of groundwater) represent important properties that are not necessarily identified when using terrain or vegetation as a proxy (Lilly *et al*., 2002; Baggaley *et al*., 2009). For soil data to become more widely incorporated into riparian assessments, they need to be translated for non-soil specialists and available at a resolution that is appropriate for the application. An example of using translated soil data comes in the application of rules to estimate run-off, soil erosion, compaction and leaching risk using high-resolution spatial data (Baggaley *et al*., 2019). Predictive soil mapping has been used to

provide soil data at suitable resolutions for riparian applications when soil data are not available (Gagkas and Lilly, 2019).

- The identification of convergent flow pathways provides a basis for moving away from fixed-width approaches for riparian buffer management towards more location-specific understanding and management. The availability of high-resolution terrain data (< 2 m resolution) has been shown to improve this (Thomas *et al*., 2021). Holmes and Goebel (2011) warn that ground surveys should be used to support model assessment before restorative actions proceed (see section 4.2); however, the review found a very limited number of studies where this had occurred.

2.5 Key Messages from Literature Reviews

- Sediment, total P, dissolved P and nitrate dynamics on created management buffers are well documented. Limited studies exist on RBZ effectiveness for pesticides and microbial pollution. Phosphate and nitrate studies cover surface and subsoil or groundwater dynamics.
- While Irish studies on riparian buffers are limited, many international studies have been conducted in temperate zones, and hence the findings are transferable to Ireland.
- Studies utilising full before and after control interactions are near absent. There is a bias towards small-plot-scale studies compared with catchment-scale buffer effectiveness studies for total P.
- There were weaknesses in study durations, for example where study durations were shorter than the effect times of the intended treatments (e.g. studies of the effects of planting trees in buffers).
- Data complexities require careful interpretation. This includes so-called negative effectiveness associated with internal recycling and/or errors in constraining mass inputs for dissolved pollutant and subsurface transport.
- Empirical relationships could be developed across pooled studies for the percentage reduction in loads of sediment, total P and dissolved P against buffer width, with a large amount of scatter (as identified in previous reviews) being reduced by the inclusion of clay size fraction content and buffer slope. Reductions in coliform and total N retention appeared to be independent of buffer width (predicted by only slope and clay fraction-content, respectively).
- Designing and maintaining buffer structure to trap fine particles is important for particle pollution retention in fine-textured soils. Accumulated sediment in buffers led to a reduction in trapping efficiencies for sediment and total N, but increased the ability to trap dissolved P, presumably because deposited sediment surfaces have net P sorption, suggesting that research is needed to guide recommendations on ongoing sediment management in buffers.
- RBZs are considerably less efficient at retaining soluble pollution than particulate pollution. General evidence here suggests that coarser textured RBZ soils favour the retention of sediment, total P and total N, but worsen the retention of soluble N and P; increasing the stand or stem density of trees, grasses or herbs favours particle trapping at the expense of the retention of dissolved pollutants; and the soil biogeochemical cycling of nutrients in the buffers leads to polluting losses of dissolved nutrients to waters.
- Ongoing management (e.g. vegetation cutting) affects pollutants with particulate and dissolved phases differently; this must be understood to limit the pollution-swapping potential of RBZs.
- For siting the **right measure** in the **right place**, interpreting soil data, so that the key hydrological flow pathways are identified, is key. Terrain and vegetation proxies alone may be insufficient to represent the riparian hillslope context correctly.
- High-resolution terrain data can help to identify convergent flow pathways.
- Model assessment is an effective screening tool but on-site surveys should take place before restorative actions take place.

3 Towards a Consolidated Set of Measures for the Riparian Space

3.1 Rationale

Given the wide range of riparian mitigation measures, the variability of biological, hydrological and geological factors, and the range of ecosystem services delivered, determining the effectiveness of riparian mitigation measures can be challenging. Where there is variability in the reported effectiveness of environmental measures (as highlighted in section 2.3), the use of an expert group has been demonstrated to be a quick, cost-effective and efficient method of estimating the effectiveness of measures (Carey *et al*. 2005; Finn *et al*. 2007; Micha *et al*., 2018). Expert judgements draw on an extensive range of experience, potentially providing policymakers with the best available information on possible consequences, uncertainties and trade-offs in relation to the variables of interest.

The aim of this study was to evaluate the effectiveness of a selection of riparian management measures in delivering multiple ecosystem services, based on expert opinion. The key objectives of the study were to:

- identify potential riparian measures appropriate for Irish conditions;
- assess the relative effectiveness of specific riparian measures in delivering individual and grouped ecosystem services;
- identify the highest and lowest performing riparian mitigation measures for each ecosystem service;
- determine the effectiveness of the mitigation measures across ecosystem services.

3.2 Methods

3.2.1 Step 1: identification of riparian measures and impact on delivery of ecosystem services

The SMARTER_BufferZ project aimed to identify potential riparian measures, appropriate for Irish conditions, through a number of integrated approaches. The foundation for identifying riparian measures for inclusion in this study drew on the extensive knowledge and research experience (i.e. literature and field knowledge) of the project team, including from previous studies on riparian margins (Stutter *et al*., 2012, 2019a); natural flood management (Wilkinson *et al*., 2014; riparian functioning (Stutter *et al*., 2021a); the habitat value of margins (Ó hUallacháin, 2014; Madden *et al*., 2019); and riparian management (Ó hUallacháin *et al*., 2019). This knowledge and experience was coupled with a broad review of literature by the project team. Step 1 incorporated information derived from a study within the SMARTER_BufferZ project (see Stutter *et al*., 2021a; section 2.2) that undertook a wide review of literature on riparian mitigation measures relevant to humid northern latitude countries.

Sixteen measures database

The measures listed in section 3.1 were reduced by the authors to a list of 16 of the most frequently referenced measures deemed appropriate for Irish conditions. A descriptive summary of the 16 measures is presented in Table 3.1. Further details on the measures, in relation to their functioning and evidence-based ecosystem benefits, are described in Stutter *et al*. (2021a), and the database can be found at https://data.mendeley.com/datasets/ggc3pz78w4 (Stutter *et al*., 2021b). Note that these measures were used in the development of decision support tools and scenario testing described in Chapters 4 and 5 of this report.

The effectiveness of each mitigation measure was assessed in relation to the delivery of multiple ecosystem services. Fourteen individual ecosystem services (covering provisioning, regulating, supporting and cultural services) were selected for inclusion and were grouped into four broad categories:

1. **Water quality.** Ecosystem services within this category were soil loss control and sediment retention; P capture and retention; N capture, uptake and transformation; pesticide/herbicide

Table 3.1. Summary of 16 riparian measures identified by the SMARTER_BufferZ project

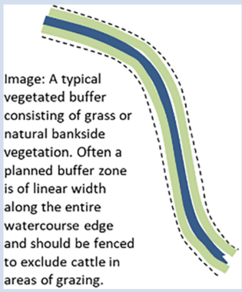
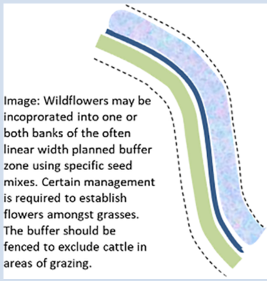
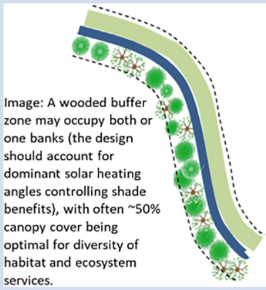
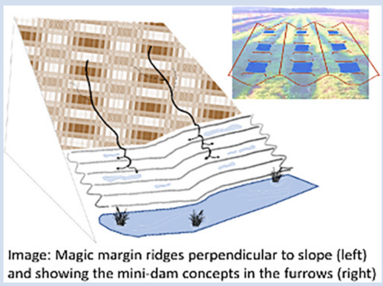
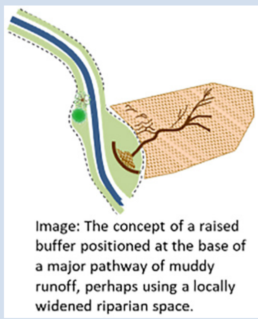
<table>
<tr><th>Measure</th><th>Photograph</th><th>Schematic of how it functions</th><th>Brief description</th></tr>
<tr><td colspan="4">Baseline margin space options</td></tr>
<tr><td>Grass buffer</td><td></td><td>
</td><td>Popular AES measure provides a physical barrier to agricultural activities, limited surface run-off trapping and bank stabilisation. Best if fenced for cattle exclusion</td></tr>
<tr><td>Wildflower buffer</td><td></td><td>
</td><td>Enhancement of the grass buffer. Uses wildflower seed mixes for biodiversity, or even to promote nutrient uptake or achieve biomass goals</td></tr>
<tr><td>Wooded buffer</td><td></td><td>
</td><td>Inclusion of trees improves airborne pollution interception, deep rooting and nutrient uptake into biomass, habitat, hydromorphology and aquatic protection</td></tr>
<tr><td colspan="4">Surface run-off and sediment options</td></tr>
<tr><td>Magic margins</td><td></td><td>
</td><td>A practical addition to grass buffers for soil erosion control, using a tied ridger and potato drill plough to create mini dams (sown with wildflowers to stabilise) that encourage water and sediment retention</td></tr>
<tr><td>Raised buffer: field run-off</td><td>
</td><td>
</td><td>A bund (soil, stone or wood) is placed across an overland flow pathway to interrupt the path, temporarily retain water and trap sediment. Spillways and exit pipes can be engineered to suit</td></tr>
</table>

Table 3.1. Continued

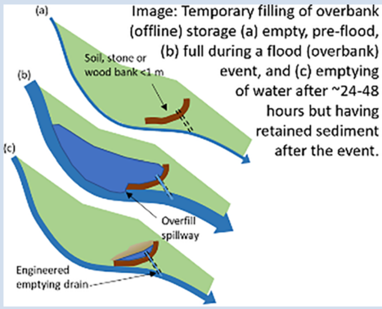
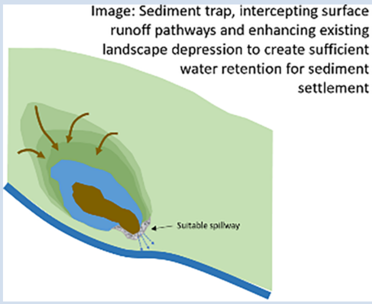
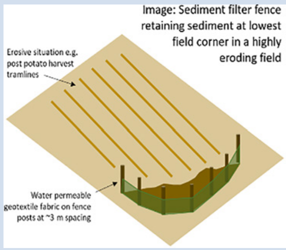
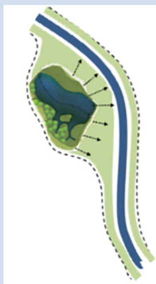
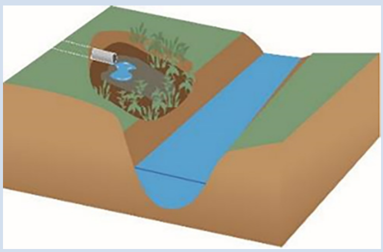
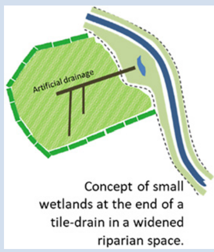
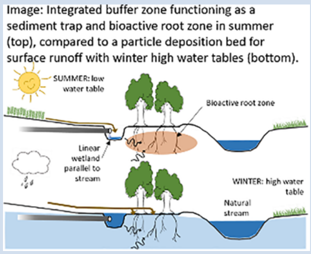
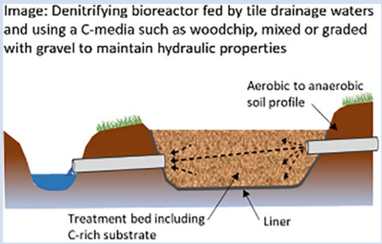
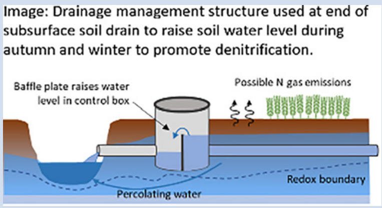
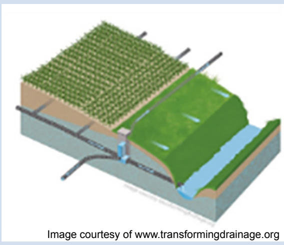
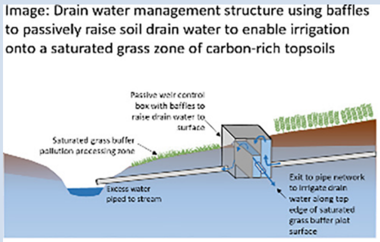
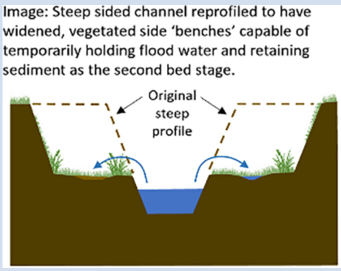
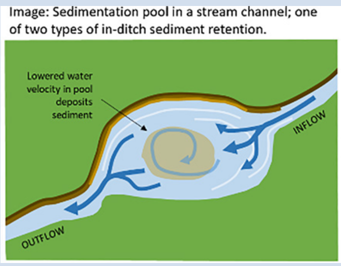
Measure	Photograph	Schematic of how it functions	Brief description
Raised buffer: overbank storage			A bund (soil, stone or wood) placed onto floodplains temporarily stores overbank floodwater and traps sediment. Engineered to drain back to the watercourse in <48 hours
Sediment trap			Enhancement of natural landscape depressions to trap water and sediment temporarily. Large surface areas benefit sedimentation. Outlets can be engineered
Sediment filter fences			A barrier (e.g. geotextile) for sediment retention. Used especially if erosion risk is high from surface run-off on steeper slopes or after (often temporary in a rotation) high-risk cropping
Subsurface pathway options			
Surface water, groundwater wetlands			Permanently wet, vegetated wetlands created by enhancing natural ones or constructing new ones. Fed by upwelling groundwater and surface water. Requires adequate retention time for treatment
Tile drain-fed wetlands			Preventing a main arterial field drain from exiting directly to water, instead directing it into a small wetland zone (with permanent vegetation and higher C soils for treatment)

Table 3.1. Continued

Measure	Photograph	Schematic of how it functions	Brief description
Integrated buffer zones			A zoned buffer approach comprising a linear wetland and tree zone for interrupting pathways of surface erosion and field drains, with subsurface treatment among tree roots and particle deposition onto seasonally waterlogged soils
Denitrifying bioreactors			Engineered solutions for channelling high-nitrate-load pathways into a bioreactor fed with enriched organic C. Engineered in terms of flow rates, bed particle size and infiltration, and C dosing
Controlled drainage			Field tile drain discharges with high nitrate loads are seasonally shut off at a control valve so that the field slope becomes a saturated wedge to encourage natural denitrification
Tile drain irrigation onto saturated soils			Field tile drain discharges with high nitrate loads are raised to surface levels by a control structure to enable water distribution onto topsoils of suitable organic C content for natural denitrification
In-channel options			
Two-stage channels			Artificial, steep-sided, open-drainage ditches are reprofiled to contain mini floodplains that retain sediments during high flows, become vegetated and treat nutrients and stabilise banks
In-ditch sediment trap, or filter			In-channel sediment traps comprising widened basins to insert (contained) filter materials (e.g. woodchip)

capture and breakdown; and FIO barrier and retention.

2. **Habitats.** Ecosystem services within this category were benefits to aquatic processes (shade, leaf litter); terrestrial habitat diversity; system carbon (C) retention (biomass, soil); and hydromorphic and geomorphic improvement.
3. **Water quantity.** Ecosystem services within this category were reduction in run-off velocity through attenuation, including flooding management.
4. **Wider ecosystem services.** Ecosystem services within this category were benefits to agronomic field processes (pollinators, pests); production of biomass (food, fuel, green manure); visual landscape enhancement; and integration with access and recreation.

3.2.2 Step 2: scoring effectiveness

The study followed a revised Delphi approach (Dalkey and Helmer, 1963). The approach retained core elements common to many traditional Delphi approaches, including anonymity of experts, iterative rounds of scoring (incorporating a questionnaire and a workshop) and structured feedback on analysis.

Step 2 focused on scoring the potential effectiveness of each of the 16 measures and determining confidence (based on current pool of evidence) in data availability. A pool of potential national and international experts (> 100) with knowledge and experience of riparian mitigation measures, with different backgrounds and competencies, was identified by the project team. Potential experts included researchers, advisors (including catchment officers and representatives from wider extension services) and practitioners. Experts were invited to complete a bespoke online questionnaire, assessing the effectiveness (Stage 1 scoring) of each of the 16 mitigation measures (Figure A2.4). An explanatory guidance video (explaining the approach) was created and shared with the experts (https://www.youtube.com/watch?v=oMbmACes2mo).

All experts who completed the questionnaires in step 2 were invited to join an online workshop to discuss the effectiveness scores. A total of 15 experts agreed to join the workshop, covering a range of expertise (research, advice, practice) and nationalities ($n = 9$). Following brief discussions, experts were given the opportunity to again score the effectiveness of each measure (Stage 2 scoring). Scoring options ranged once again from 1 to 5.

3.3 Results and Discussion

3.3.1 Summarising the effectiveness of the mitigation measures

Figure 3.1 shows the weighted group mean (WGM) effectiveness scores for the 16 mitigation measures for the 14 individual ecosystem services. This figure is based on Stage 1 scoring only, and thus it incorporates the views of a greater number of experts than Stage 2 scoring (where scoring is assessed following group elicitation). Across all ecosystem services (Table A3.1), **wooded buffers** were the highest rated mitigation measure and were the top-performing mitigation measure for 7 of the 14 individual ecosystem services (i.e. FIO barrier and retention, benefits to aquatic processes, terrestrial habitat diversity, system carbon retention, production of biomass, landscape enhancement, and integration with access and recreation). **Integrated buffers** were the second highest ranked mitigation measure across all ecosystem services and were the top-performing mitigation measure for P capture and retention. **Wetlands** were the third highest ranked mitigation measure across all ecosystem services, scoring highest for N capture, uptake and transformation. **Sediment fences** were the lowest ranked mitigation measure across all ecosystem services and were the lowest scoring mitigation measure for 5 of the 14 individual ecosystem services. **Grass buffers** were the second lowest ranked mitigation measure and ranked lowest for 2 of the 14 individual ecosystem services (P capture and retention, and N capture, uptake and transformation).

3.3.2 Key findings from expert opinion on the effectiveness of riparian mitigation measures

Grass buffers had consistently low scores for their effectiveness at delivering a range of ecosystem services

Linear grass buffer strips are an integral part of the CAP, and have commonly been implemented under compulsory GAEC requirements (Pillar 1) and optional AESs (Pillar 2) in Ireland and throughout

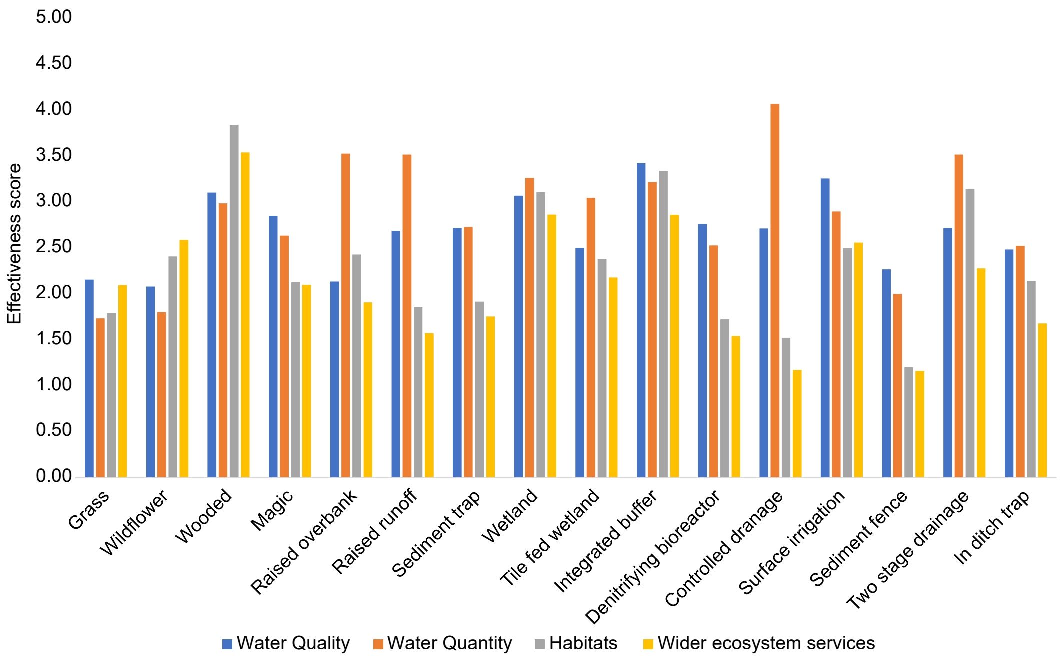


Figure 3.1. Effectiveness score for 16 riparian mitigation measures, grouped by ecosystem service category.

the EU (see section 2.2). However, this study found that linear grass buffer strips were consistently rated among the lowest of the evaluated mitigation measures, across the range of ecosystem services. Grass buffers were the third lowest ranked mitigation measure (the second lowest ranked measure after Stage 1 scoring) and ranked lowest for water quantity services (Figure 3.1) and three of the individual ecosystem services (P capture and retention, run-off velocity attenuation, and N capture, uptake and transformation). Grass buffers had a high response rate (23 of the 24 experts scored the measure) and were consistently rated among the top three measures with respect to confidence in scoring. Thus, when experts were determining that grass buffers have low levels of effectiveness for various ecosystem services, they were confident that there were studies to support this assessment. Of note is that grass buffers are frequently implemented as a tool to address water quality challenges; however, experts in this study ranked grass buffers lowest for the water quality ecosystem service parameters P capture and retention, and N capture, uptake and transformation.

Wooded buffers were effective at delivering a range of ecosystem services

Wooded buffers were the highest rated mitigation measure across all ecosystem services (grouped), and the top-performing mitigation measure for two of the four groups of ecosystem services (i.e. habitat services and wider ecosystem services) (Table A3.1). Wooded buffers were the most effective measure for 7 of the 14 individual ecosystem services (i.e. hydromorphic improvement, benefits to aquatic processes, C retention, landscape enhancement, terrestrial habitats diversity, biomass production and integration with access and recreation). For most of these individual services, wooded buffers also had the highest confidence score; thus, experts were confident that there were studies to support their assessment.

Riparian mitigation measures are consistently less effective at delivering certain ecosystem services (e.g. pesticides, FIO, nitrogen capture) than they are for other ecosystem services

Pesticide capture and breakdown was the ecosystem service with the lowest effectiveness score, i.e. the most effective measure for delivering this ecosystem service, integrated buffers, scored only 3.00, significantly lower than the most effective measure for delivering most other ecosystem services. This highlights the need for additional research on new and bespoke riparian prescriptions that target specific stressors or ecosystem services.

Multifunctional measures should not always be the goal

Being effective at addressing the challenge at hand may be more important than delivering a suite of ecosystem services. Specific stressors may require specific mitigation measures (e.g. sediment fences perform well at addressing extreme sediment erosion; however, they do not have multifunctionality). Aiming for multifunctionality might result in diminished ability to deliver the primary function. The effective management of riparian zones requires consideration of the wide range of ecosystem services and being cognisant of synergies and trade-offs between different policy objectives (Cole *et al*., 2020). There can be trade-offs between economic and environmental benefits as well as the trade-offs between contrasting environmental goals (Sonesson *et al*., 2021).

Caveat

It should be noted that expert scores were based on generalised effectiveness in relation to various pollutants. The scores reflect what each expert understood the form of nutrient (e.g. chemical and soluble/particulate forms of N and P) being lost from farmland and the mitigation effectiveness of each measure to be.

4 Siting Riparian Management in the Right Place

4.1 Rationale

It is increasingly recognised that “diffuse” can mean a myriad of smaller “hot-spot” locations in rural landscapes (e.g. dominant erosion pathways, main drains), requiring targeted actions. By integrating the multiple functions of buffer zones, within the framework of flow paths, appropriate riparian buffer mitigation measures (e.g. the suite of 16 measures (Table 3.1) identified in section 3.2) can be targeted to those locations where the run-off is focused. Identifying optimal places for establishing/managing buffers improves the effectiveness and uptake of on-farm mitigation measures. In addition, targeting riparian mitigation measures to key locations may be more cost-effective than universal installation. Chapter 4 discusses the development of tools and support measures related to placing riparian management in the correct place. The value of such an approach has been recognised by ACRES, which indicates that maps should be used to support the targeting of mitigation measures, including riparian buffer measures. Chapter 5 builds on this approach by demonstrating how measures can be identified and targeted in field/catchment scenarios.

4.2 Identifying Potential Run-off Delivery Points to Watercourses

There are various approaches that can be used to help identify those locations where run-off is focused. Remote-sensing technology (e.g. light detection and ranging (LiDAR)) can be used to create digital elevation models (DEMs) or their derivatives (e.g. a “wetness index”). Such approaches can identify morphological features such as slope, aspect, flow, length, contributing areas, drainage divides and channel networks. The use of DEMs can be coupled with soil risk factors (related to source and transport), to identify critical “breakthrough” areas of converging flow, where sediment and nutrient-rich run-off delivery points are most likely to occur. In addition, field observations and farmer engagement can also play an important role in identifying potential flow paths and delivery points.

4.2.1 Spatial evidence of delivery points

The DiffuseTools model (Thomas *et al*., 2021) is a national-scale hydrological model that identifies surface run-off critical points, where interventions to mitigate pollution could be located. The model is targeted towards mitigating the impact of P and sediment on watercourses (as P is typically a surface water issue).

The DiffuseTools model output is based partly on identifying those locations in the landscape most likely to generate run-off. The Diffuse Tools model has helped to inform the development of the EPA’s PIP flow delivery path and PIP flow delivery point maps (https://gis.epa.ie/EPAMaps/Water). The outputs from these maps can be displayed to show distinct delivery points or flow paths (Figure 4.1).

Full details of the methodologies and outputs from the DiffuseTools project can be found in Thomas *et al*. (2021). Spatial evidence can be thought of as one tool in the toolbox for identifying potential delivery points. Field observations, along with active engagement with landowners, can provide valuable information for the identification of delivery points.

4.2.2 Visual evidence of delivery points

Coupled with outputs from the PIP flow delivery maps, field observations can play an important role in helping to identify potential run-off delivery points to watercourses. Some indicators can be observed in the field to help locate the entry locations of run-off from the field into an adjacent watercourse. Although it is easier to identify such locations when there is substantial rainfall (see, for example, Figure 4.2), for a number of reasons (including opportunity, practicality and consistency), field assessments of delivery points will frequently be undertaken in the absence of rain (or without active overland flow). This leads to the need to establish visual indicators of delivery points under dry conditions.

Key features (in the field) for identifying potential flow delivery points and paths (see Figure 4.2) include:

- **Topography.** Natural channels (in-field) can indicate focused flow paths. They may be wide

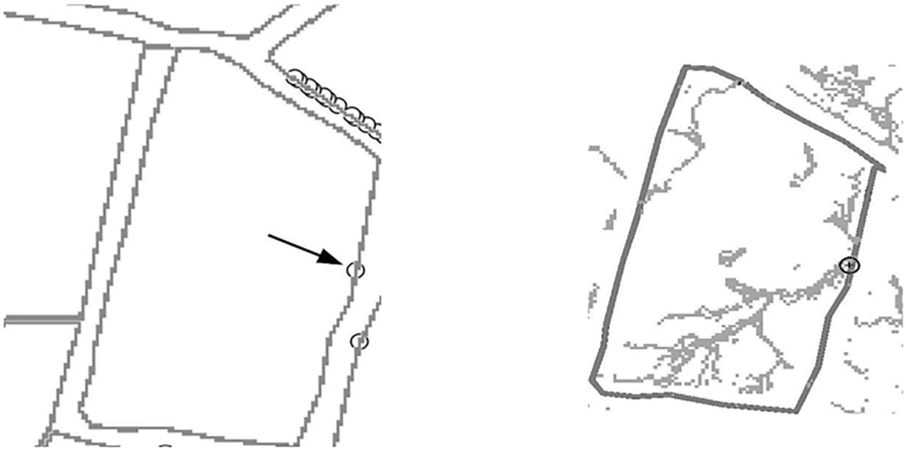


Figure 4.1. Left: single delivery point in field (PIP flow delivery point); right: delivery point in field with flow paths added (PIP flow delivery path).

Figure 4.2. Flow delivery point (left) and flow delivery path (right).

and shallow, or narrow and (relatively) deep. Drainage characteristics also play an important role. In a well-drained field or in a groundwater-dominated catchment, surface run-off along an in-field channel is potentially considerably less likely than it would be in a catchment dominated by poorly draining, slowly permeable soils.

- **Breaks in banks.** Breaks (or perturbations) in the bank may indicate flow paths and delivery points. They typically fall into one of two categories. The larger ones typically have an irregular, chaotic outline, whereas the smaller ones (rills) are frequently rectangular. In the absence of active run-off, they can be particularly difficult to see, as the sides may be vegetated and hide the incision.
- **Sediment.** Deposition or discolouration is a potential indicator of a focused flow path. Examples include evidence of erosion, evidence of sediment deposition, evidence of bare earth and evidence of dead vegetation.
- **Vegetation.** The type of vegetation or difference in vegetation compared with the main field is another potential indicator of a focused flow path. Specific plant species (e.g. soft rush (*Juncus effusus*), horsetail (*Equisetum arvense*), willow) can be associated more with wet areas because of flow paths.

4.3 Describing Management Contexts Using a Set of Hillslope–Riparian Flow Models

4.3.1 Rationale

The representation of varying dominant pollution transport pathways across differing landscapes is fundamental to being able to match the **right measure** to the **right place**. Broadly, this covers pollution pathways between surface run-off and subsurface flows, as topography and infiltration vary in space, but also includes artificial modifications of the inherent flow paths in soils. Since landscape variation in these aspects is continuous and complex, there was a requirement to simplify landscape types by grouping them into categories that related to factors contributing to dominant pollution issues in regions and could be related to the modes of action of different riparian mitigation measures. This led to the following research aims:

- to develop the concept of a set of flow path models to represent dominant pollution pathways using schematics of cross-sections of hillslopes to riparian zones;
- to develop a way of relating the model categories of landscape type to a given location of interest by understanding the underpinning factors through mapped data supported by questions;
- to validate the models with Irish stakeholders and use the models as a communication tool to build an understanding of the link between landscape attributes and the modes of operation of in-field pollution mitigation measures that target the watercourse edge.

4.3.2 *Methods: development stages*

First, literature was evaluated to establish how riparian processes have been represented diagrammatically and by what factors. We drew on factors represented by Hill (2000), Groffman *et al*. (2003), Weaver and Summers (2014), Exner-Kittridge *et al*. (2016) and Orozco-López *et al*. (2018). The initial list of attributes is shown in Table 4.1, together with the actions taken.

The initial set of models (Figure A4.1) developed adapted concepts from Groffman *et al*. (2003) in terms of including representative soil profiles down the hillslope transect, highlighting soil organic matter and redox processes associated with wetness, and also from Exner-Kittridge *et al*. (2016), by including aquifers and modification by artificial subsurface soil drains. These models represented well the hillslope flow and drainage processes and anthropogenic modifications. They were presented at the Catchment Science 2019 conference in Wexford (Stutter *et al*., 2019b,c,d) using a series of interactive displays progressively

Table 4.1. Attributes initially considered for inclusion in the hillslope–riparian flow models and resulting decisions on inclusion

Attribute	Decision
Slope form – hillslope	Included
Slope form – riparian zone	Latterly included
Microtopography – riparian zone	Outside scope
Soils – wetness and flow pathways	Included
Soil organic matter	Partly included
Soil water flow modifications	Included
Floodplain form	Latterly included
Channel form and stability	Outside scope
Vegetation – trees, wetland	Outside scope
Infrastructure – walls, hedges, tracks	Outside scope
Connection to typical pollution issues	Included

introducing the models. This allowed stakeholders to select appropriate riparian mitigation measures reliant on specific flow paths for their effectiveness and to locate where they thought the model landscape types occurred in Ireland.

Feedback from the conference and from consultation with staff at the EPA Catchments Unit was as follows:

- Importantly, such pollution pathway conceptual models provide a framework for the consideration of mitigation options and need to (i) comprise the main landscape settings present in Ireland and (ii) use widely understood terms for effective communication.
- The models need to include the main hydropedological and hydrogeological scenarios for water and pollutant movement in the vicinity of rivers, while remaining relatively simple.
- Landscape models need to take account of the main significant pollution issues, caused by P (PO_4 and total P), sediment, NO_3 and NH_4, in broad categories that keep communication of processes simple.
- An important landscape scenario is where there is a ditch/small watercourse collecting run-off from a sloping, poorly draining critical source area (CSA), which then bypasses the floodplain. This requires specific understanding and management.
- Anthropogenic land drainage is an issue, and this needs to be represented to enable understanding and better management.

The models were refined during 2020 following engagement between the project team and the EPA Catchments Unit. This involved discussions around hand-drawn sketches enhancing concepts; the initial graphic production of images by the EPA; revisions by the project team for the inclusion of artificial drainage, the inclusion of additional models for rarely occuring but specific landscape situations, and adjustments of flow arrows and the order of submodels; and further discussion and agreement on terminology to finalise the models.

4.3.3 Results and discussion: final models and their usage

The final hillslope–riparian flow models representing dominant pollution pathways are described in Table 4.2, and examples are given in Figure 4.3. The full set of five main models, including submodels, is presented in Figure A4.2.

Some simple accompanying guidance was produced to allow the translation of a field or landscape situation into the flow models. The resulting question-based

Table 4.2. Attributes of the hillslope–riparian flow models

Major scenarios			Submodels			
Scenario	**Inherent drainage**	**Artificial drainage**	**Submodel**	**Floodplain and type**	**Direct CSA ditch connection**	**Main pollution issues**
1[a]	Poorly draining soil with low-permeability subsoil	Absent	A	Yes, mineral, poorly draining floodplain	No	PO_4, total P and sediment
		A ditch	B		Yes	
		Absent	C	Absent	No	
2[b]	Poorly draining soil with low-permeability subsoil	Absent	A	Yes, peat floodplain	No	NH_4, sediment and potentially PO_4
		A ditch	B		Yes	
3	Freely draining soil, moderate permeability subsoil and permeable bedrock	Absent	A	Yes, mineral, free-draining floodplain	No	NO_3
		Absent	B	Yes, mineral, poorly draining floodplain	No	
		Absent	C	Absent	No	
4	Inherently poor-draining soil and low-permeability subsoil modified by artificial drainage	Present	A	Yes, mineral soil, drained floodplain	No	PO_4, NO_3, total P and sediment
		Present	B	Yes, peaty soil, drained floodplain	No	
		Present	C	Absent	No	
5[c]	Permeable soils affected by fluctuating groundwater and modified by artificial drainage	Present on hillslope and floodplain	A	Present	No	PO_4
		Local to floodplain only	B	Extensive floodplain present and artificially drained	No	

[a]Describes the situation where a soil develops a saturated zone at or near the surface due to the presence of a slowly permeable layer that impedes the downwards movement of water but can remain unsaturated in the zone immediately below the zone of saturation.

[b]Variable depths of peat may be encountered on the floodplain with essentially the same water flow paths and common issues.

[c]These additional classes for groundwater gleys may occur locally throughout Ireland. Phosphate is the dominant issue. Nitrate delivery may occur sometimes, although generally it is expected that denitrification and N gas emissions from wet soils would limit the amount of nitrate that could leach into groundwater.

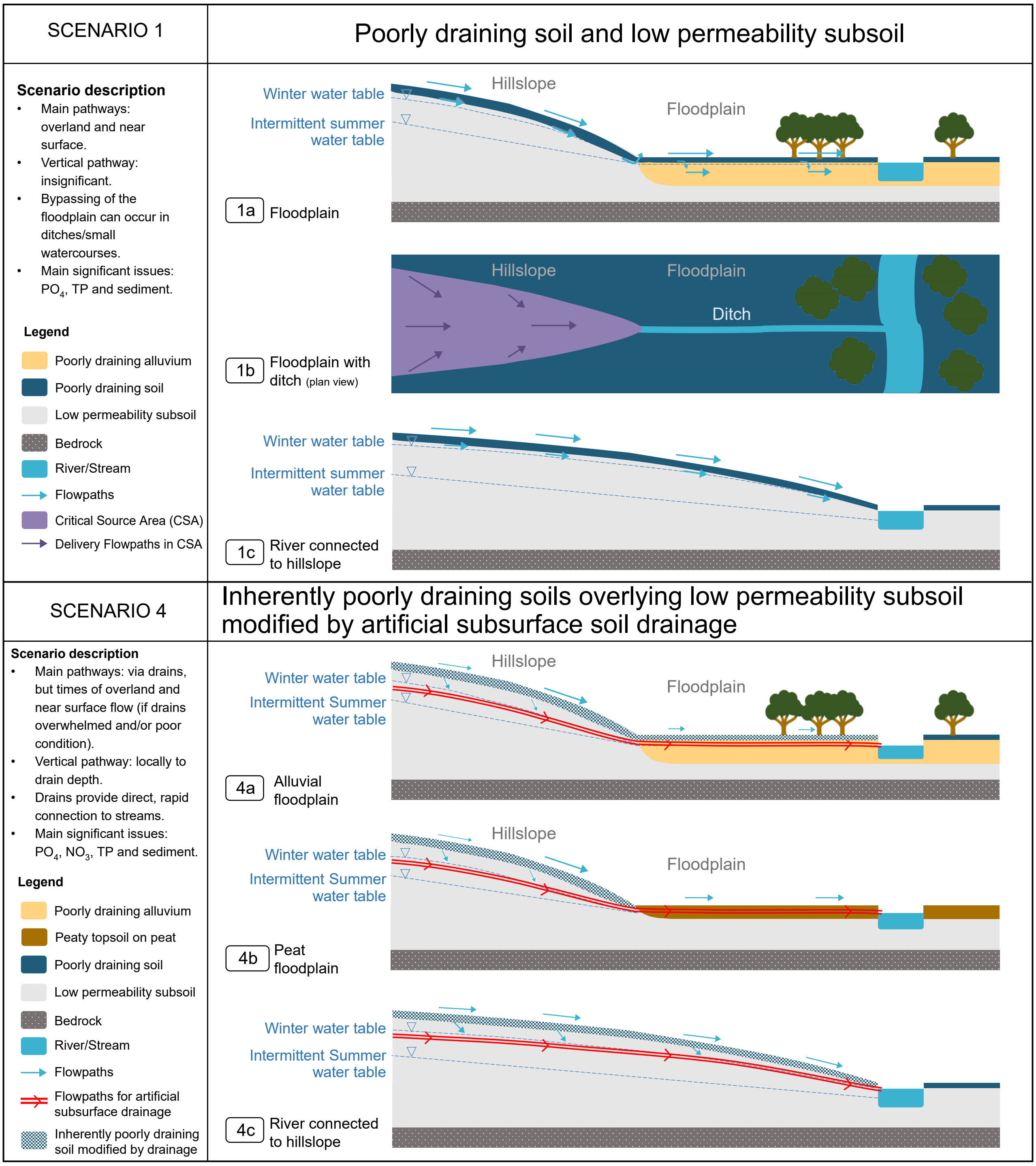


Figure 4.3. Examples of the hillslope–riparian flow models using scenarios 2 and 4, where an inherently poorly draining landscape is unmodified (top) or modified by artificial subsurface drainage such that the pollution pathways are significantly modified (bottom) (compare scenario 1a with scenario 4a and scenario 1c with scenario 4c).

flowchart (Figure 4.4) was used to accompany the models on the project web pages (see http://www.smarterbufferz.ie/BC-Blog-19022021.html). This formed the basis of the preliminary development stages of the riparian mitigation measures selection tool (section 4.4).

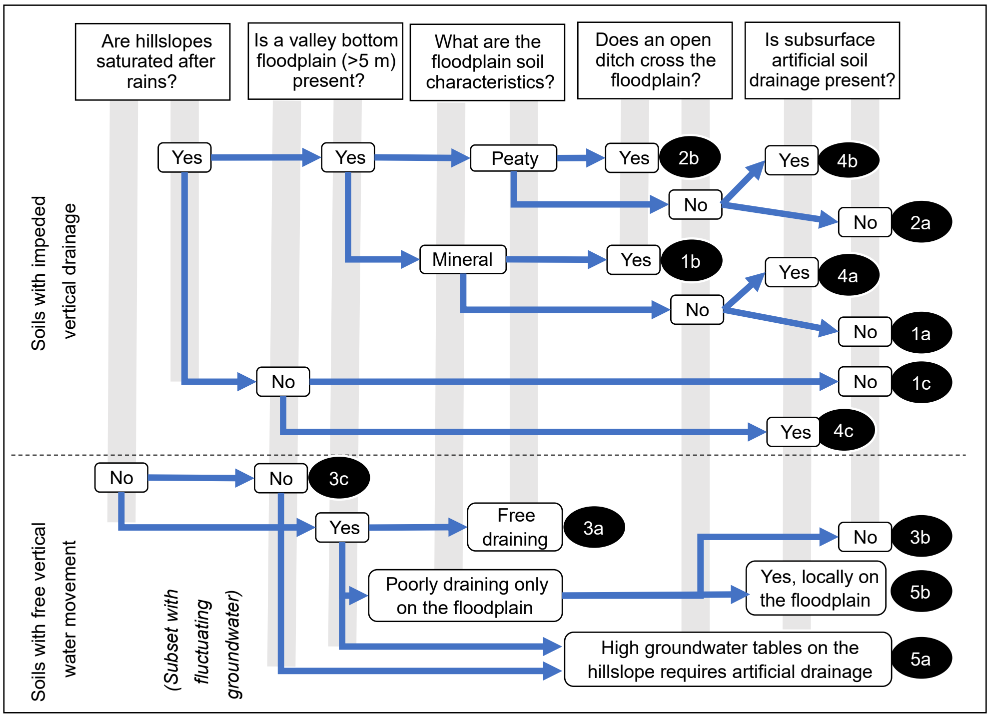


Figure 4.4. Flow chart decision tree developed to assist in relating an area of interest to the hillslope–riparian flow models using a set of questions.

4.4 Development of Decision Support Tool for Identifying the Right Measure and the Right Place

4.4.1 Rationale

An early project group exercise was to evaluate the suitability of each of the 16 mitigation measures against the hillslope–riparian flow models, then discuss and identify literature and wider evidence on how the measures functioned against the landscape attributes encompassed in the hillslope–riparian flow models, for integration into the riparian mitigation measures tool. This led to the development of the rules in Table A4.1.

Based on the results of the review, the riparian mitigation measures tool (hereafter referred to as “the tool”) was developed. The tool aimed to:

- use a landscape context to prioritise a long list of mitigation measures suitable for the riparian space;
- give a consistent framework within which to apply rules to inform decisions on appropriate or inappropriate measures based on user inputs to landscape questions;
- introduce a wider set of riparian measures than may typically be considered and provide information on their modes of operation, and hence suitability against landscape factors;
- raise awareness of how measures shown to be suitable within landscape constraints (field scale, as defined by user questions) may have varying potential effectiveness for different pollution reduction goals on the catchment scale (defined by expert judgement outside the tool development process).

4.4.2 Methods

The tool uses a question-based approach that seeks to elucidate attributes of the landscape from the user as opposed to using only the flow model schematics (building on Figure 4.4). The questions are designed to help ensure that specific measures are sited in the **right place**. These include questions aimed at identifying:

- field-specific pressures, deriving these from a rule-based inherent erosion risk model (Lilly *et al.*, 2002), where run-off potential, slope and soil texture are combined with land cover to provide a risk of sediment and P delivery to the riparian zone (Cloy *et al.*, 2021);

- the nature of surface of flow pathways, and whether they are parallel or convergent, to inform decisions on whether targeted buffers rather than linear strips along watercourses are appropriate;
- the presence of artificial subsurface drainage channels that often bypass riparian surface mitigation methods (Cloy *et al*., 2021);
- freely draining landscapes at risk from nitrate leaching;
- hillslope types that determine the connectivity of the hillslope to the river channel and the presence of a riparian zone, thus moving away from solely terrain-based conceptual models.

The development of the tool (Figure 4.5), based on comments from the expert group, led to an understanding that users may wish to use a decision support tool that can be used to screen fields based on landscape attributes (e.g. pollution pathways, slope and floodplain form) to match to mitigation measures and evaluate the effectiveness of measures for specific pollutants.

The final version of the tool uses the minimum number of clear questions to address the most relevant risks and landscape factors to identify the place-specific attributes necessary for understanding the functioning of different measures in that location. The component 15 questions (Figure 4.6) are arranged into five sections in the tool (each developed under tabs to be answered sequentially), namely:

1. field-specific pressures;
2. the nature of delivery paths;
3. the nature of the riparian zone;
4. the nature of the watercourse;
5. additional considerations.

Further details on the specific questions can be found in Appendix A4.1.

Development of methods for satisfying tool inputs

Information for input to the tool can be derived from field inspections, or from national spatial datasets, to make an initial assessment prior to a field visit, or a hybrid approach can be taken. For example, the inherent erosion risk (providing data on soil texture, soil permeability, soil drainage class) can be evaluated using mapped data before a field visit, then may be subsequently refined in the field with farmers, advisors and catchment officers.

The following describes how these different approaches may operate individually or in

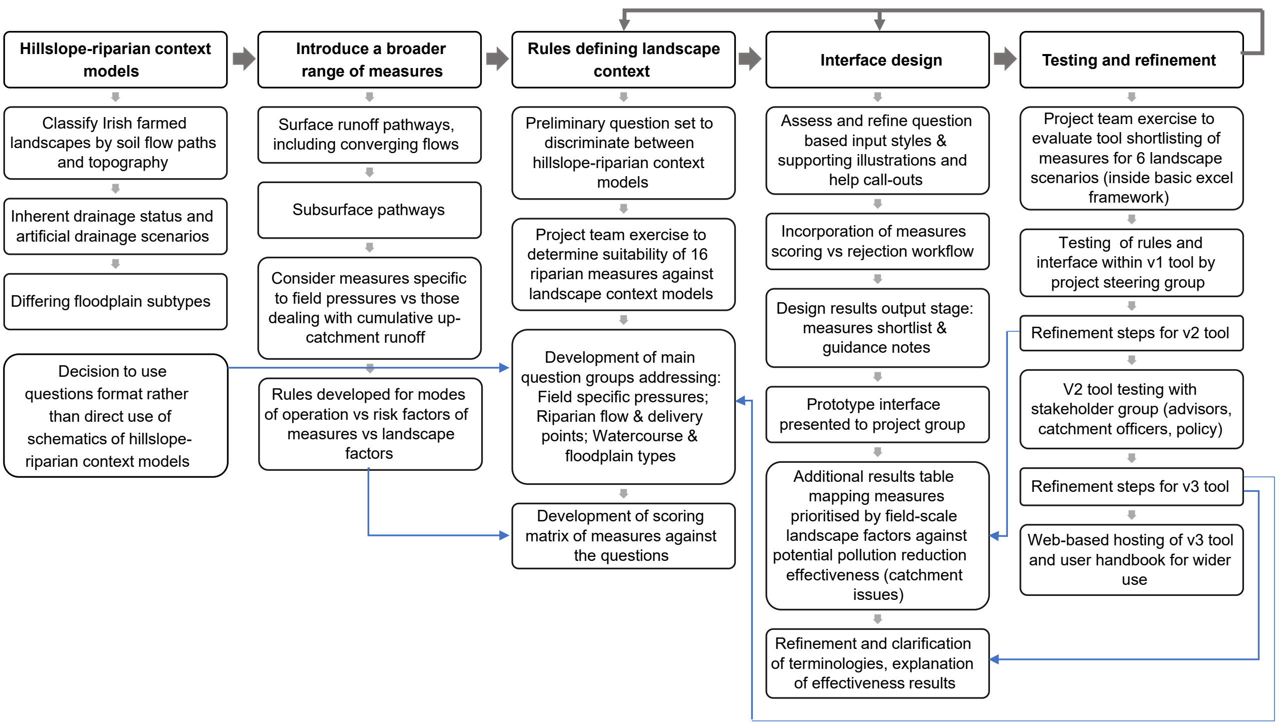


Figure 4.5. Process for the development of the riparian mitigation measure selection tool.

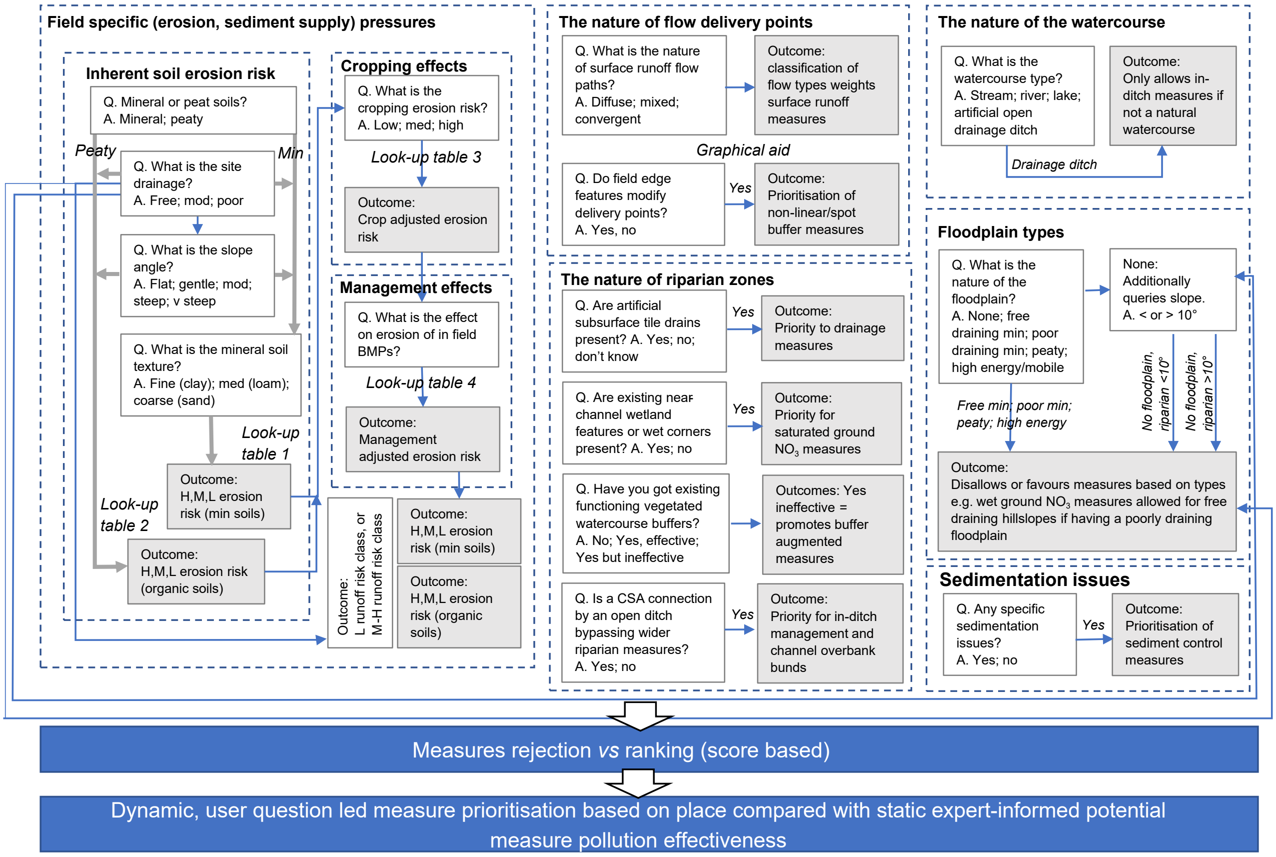


Figure 4.6. Question structure, order and interactions in the final version of the tool.

combination, with headings corresponding with those in Figure 4.6:

- **Inherent soil erosion risk.** The soil components of the inherent erosion risk (Figure 4.6; Lilly *et al*., 2002) were matched to existing nationally available Irish soil datasets. The run-off component (as depicted in the hillslope–riparian models) can be assessed by combining the Irish soils map (Fealy *et al*., 2009) and a map of slowly permeable subsoils (Meehan, 2017) to achieve three soil run-off categories (low, moderate and high) and establish whether soils are mineral, peat or peaty. For mineral-textured soils, the texture can be assessed using the texture of the dominant soil series in the Irish Soil Information System national soil map (Creamer *et al*., 2014), and the slope can be obtained from the 5 m resolution national DTM. Where field-specific soils information is available, this can be updated in the tool, as can the slope assessment.
- **Cropping and management effects.** Land cover and cropping information can be obtained from field observations and farm records, or from land cover maps and agricultural census data. These data indicate how intensively the land is being managed and allow for adapting the inherent erosion risk, for example lowering the risk for extensive grassland and enhancing it relative to the inherent risk for crops such as root crops. The dominant cropping over previous years, particularly if fields are in rotation, can then be updated in the field with the farmer or land manager, considering farm records and management-specific issues that may exacerbate or mitigate the risk of run-off and sediment delivery to watercourses rather than relying solely on current land use.
- **The nature of flow delivery points.** Along with survey and field observations, an indication of flow pathways can also be obtained from flow direction and routing algorithms applied to the national-scale 5 m resolution DTM (see Figure 4.7). Field walkovers are important for confirming the nature of the flow paths derived from digital data and obtaining knowledge from land managers of where water flows within fields. Where higher resolution LiDAR data are available, these can also be

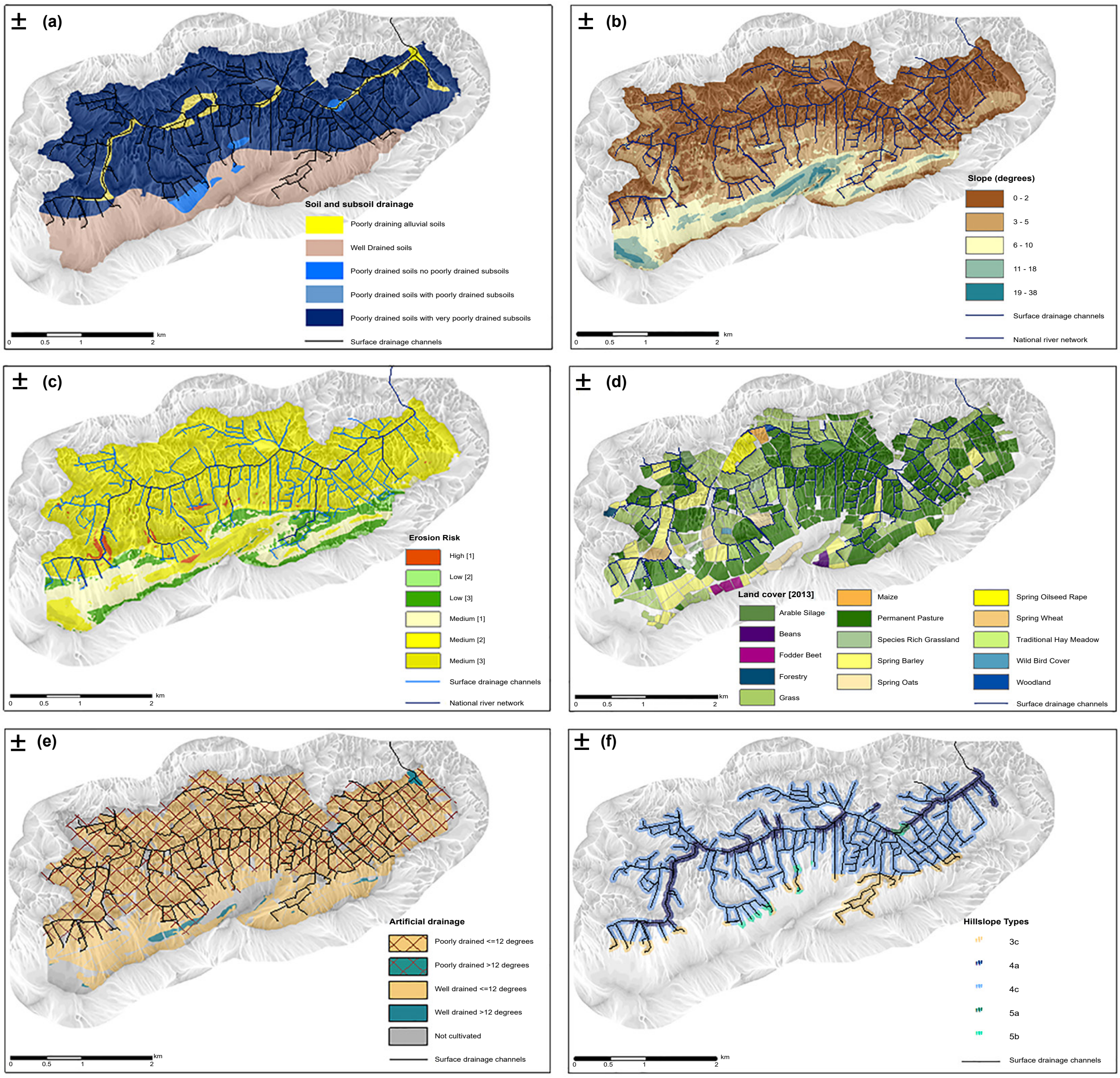


Figure 4.7. Catchment maps for Ballycanew, Co. Wexford: (a) combined soil and subsoil drainage; (b) slope; (c) inherent soil erosion risk; (d) land cover for use in modifying the inherent erosion risk; (e) potential for soil artificial drainage; and (f) hillslope model types. Source: EPA.

used to assess the potential for convergent flow. Additional field management observations that may modify delivery points can be added to the tool, for example information on whether there are vehicle tracks, plough steps, gateways or hedges.

- **Nature of the watercourse.** In Ireland, the major river network is mapped at a national level, allowing the assessment of buffer zones for natural watercourses. However, artificial open drains could also benefit from buffers to protect natural surface waters (as highlighted in ACRES). In Ireland, the presence of ditches is not mapped at a national level (see Figure 4.7e for an example of the density of a ditch network on a catchment scale) and thus field assessment is required, either by a walkover or using aerial photographs.
- **The nature of riparian zones.** The presence of subsurface drains is used to determine whether buffers are required to deal with the flow pathway. Drainage records in Ireland are not regularly registered and held by farmers. The assumption of soil drainage being present on poorly drained cultivated mineral soils below 12° slope and 200 m elevation is made following Mockler *et al.*

(2013). However, field walkovers are required to determine if this assessment is correct, and to assess the nature and functioning of drains. Field walkovers are also required to determine the presence of wetlands, the functioning of current of RBZs and the presence of management-derived CSAs.

- **Floodplain types.** Defining the hillslope models requires a combination of data on the presence and nature of alluvial soils, the nature of the soils in the hillslope and the presence of artificial subsurface drains. The presence of alluvial soils provides an indication that soil hydrological flow paths are disconnected from the hillslope. If this is not the case, it can be assumed that there is a connection between the hillslope soils and the drainage channel or river watercourse (section 4.3). The nature of the floodplain, based on these concepts, can be assessed by site survey and information entered into the tool directly, or it can be assessed using a combination of the information contained in the soil maps (Figure 4.7), refined by site surveys. The national soil map identifies both alluvial soils and the soil drainage characteristics needed to identify the soil water flow pathways. The slope of the narrow riparian zone is difficult to assess using the nationally available 5 m resolution DTM; either field walkover or LiDAR data are required to assess this.
- **Sedimentation issues.** At a national level, there are no datasets that contain specific data on in-stream sedimentation issues within watercourses, which may need to be prioritised in the selection of measures; this is therefore something that would need to be obtained in conversation with land managers or catchment officers.

4.4.3 Results and discussion

As an example of how existing spatial datasets can be used (and to highlight potential pitfalls), the hillslope models and inherent erosion risk were mapped for the Agricultural Catchments Programme (ACP) Dunleer (Co. Louth) catchment using both the national-level soils data (Figure 4.8) and higher resolution, catchment-specific soil series mapping (Figure 4.9), and the results compared.

The area mapped as having low run-off potential and low erosion risk in the north-east of the catchment (Figure 4.8) using the national soils data (Fealy *et al*., 2009; Meehan, 2017) is shown as having moderate erosion risk with high run-off potential in the more detailed soil maps (Figure 4.9). On further investigation, these soils are mapped as freely drained with poorly draining subsoils in the national data interpretation, whereas in the soil series data they are classified as poorly draining soils with slowly permeable subsoils with high run-off potential. Further investigation of the national soil map (Fealy *et al*., 2009) shows that around 8% or approximately 2000 km^2 of freely draining soils are mapped as having poorly or very poorly drained subsoils (Meehan *et al*., 2017). If the classification of erosion risk and hillslope type was to be extended to the whole of Ireland, further investigation of the links between the Irish soil map, subsoil drainage classes, soil series data from the Irish Soil Information System and the contexts of the soil associations and Geological Survey Ireland aquifer maps could be explored to improve the mapping of soil hydrological classes.

While there is uncertainty in the spatial data and the rules that have been applied, spatial data and the rules do allow a first appraisal of the data inputs to the tool. Additional field-specific management information and confirmation of drainage characteristics and flow paths are needed for a final assessment. Hence, the measures selection tool may be populated with some of the data available, but has flexibility to allow the factors in the “question fields” to be refined based on land manager or advisor knowledge.

Tool layout and rule base

- **User question inputs for landscape context.** The rules within the tool are implemented by a multicriteria master table (shown in Figure A4.7) and further lookup tables for the erosion risk assessments (not shown here). When a question is answered, the program checks the rule table for an indication of a criteria score (1–3) to build into the ranking for a given measure against others, or a zero. Where a zero occurs in any question outcome for a given measure, that measure is disallowed (“one out, all out” rule).

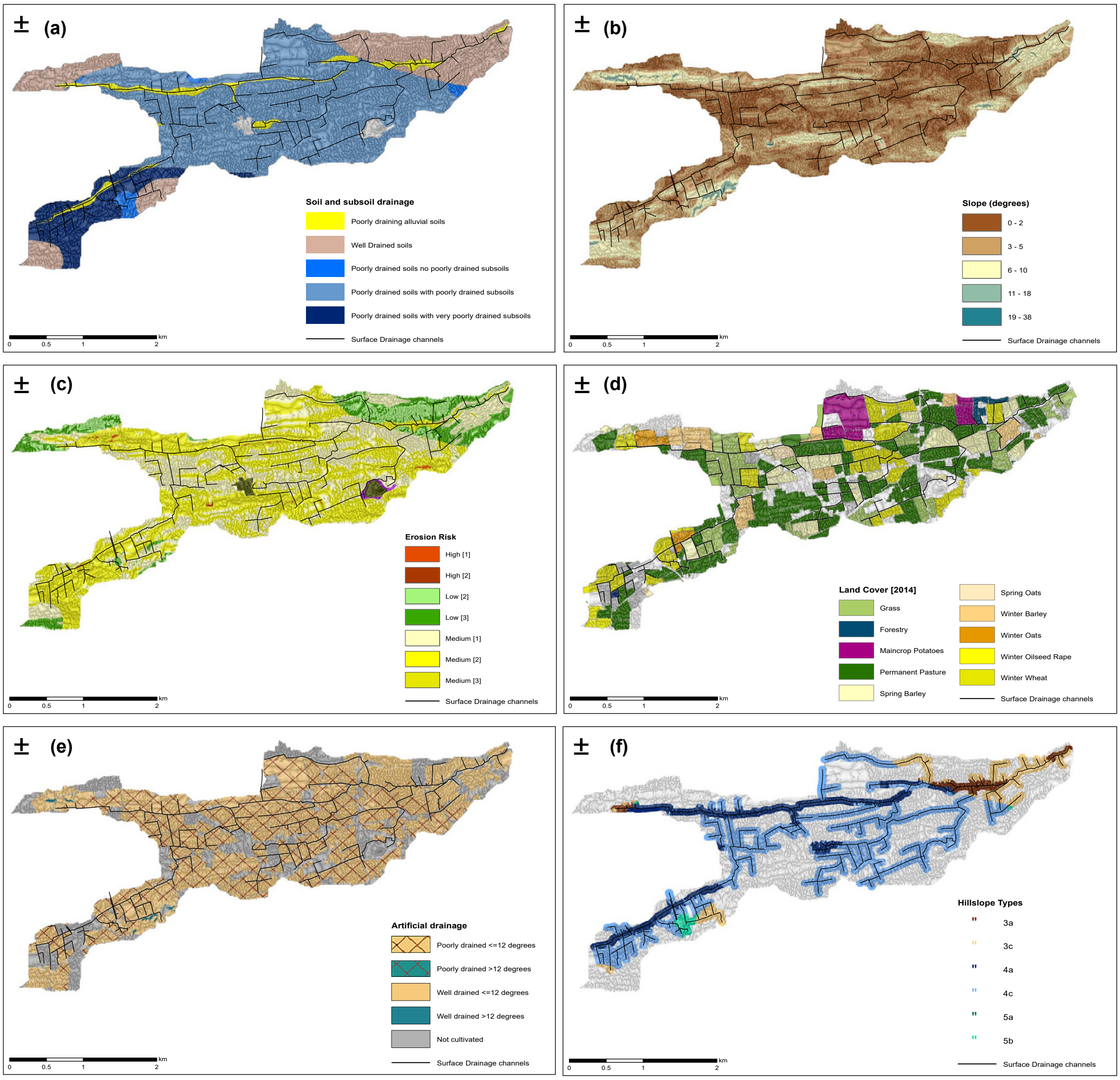


Figure 4.8. Catchment maps for Dunleer, Co. Louth: (a) combined soil and subsoil drainage; (b) slope; (c) inherent soil erosion risk; (d) land cover for use in modifying the inherent erosion risk; (e) potential for soil artificial drainage; and (f) hillslope model types. Source: EPA.

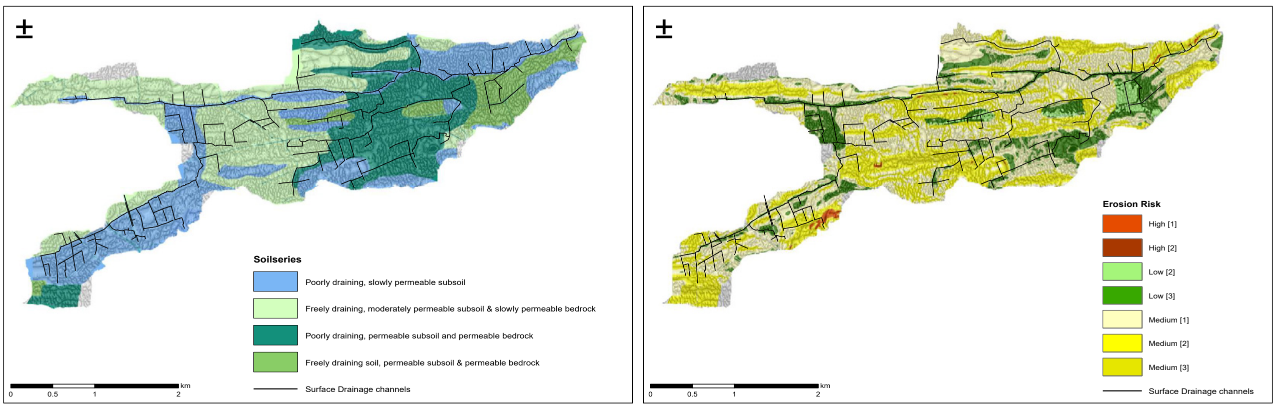


Figure 4.9. Catchment maps for Dunleer: a map of the dominant soil hydrological flow pathways based on the soil series mapping (left) and the revised erosion risk map (right). Source: EPA.

- **Encapsulating effectiveness for specific pollutants.** The ability to select measures of varying effectiveness for specific pollutants based on prior knowledge of significant issues for a catchment of interest was incorporated by including a table of potential effectiveness against the key pollutants stated in the results page against the ranked measures according to the landscape attributes. The effectiveness data were taken from the expert process described in Chapter 3, and a modified high, medium and low scoring system was used (Table A4.2). The tool

(a)

Intro | Field Specific Pressures ✓ | The Nature of Delivery Points ✓ | The Nature of the Riparian Zone ✓ | The Nature of the Watercourse ✓ | Additional Considerations | Results (upper) | Original layout | Enlarge upper | Reset

Measure prioritisation (rows: *dynamic*, based on user inputs) vs potential for pollution effectiveness (columns: *static*, based on pre-determined expert assessment of the upper ceiling for well-designed and maintained measures).

More information on the measures can be found by clicking on each of the buttons on the lower half of the web page.

The table below shows the non-excluded measures ranked from highly (green), moderately (blue) and potentially suitable (yellow) for the field situation as defined by the answers to questions. Excluded measures are red. Colours here match those used on the measure tabs.

In addition to their suitability for the field situation it is recognised that further prioritisation will likely be based on tackling known catchment water quality issues. The table therefore also indicates the potential effectiveness of the measures for improving water quality for a range of pollutants as High (H), Medium (M) and Low (L) as determined by a panel of experts.

Order of priority based on fit to field-landscape factors	Ability to address specific water quality issues				
	Sediment	Total phosphorus	Nitrogen	Pesticides	Microbial contaminants (FIOs)
Moderately suitable: Wooded buffer strip	H	M	L	M	M
Moderately suitable: Raised buffer: overbank storage	M	L	L	L	L
Moderately suitable: Surface-, ground- water wetlands	M	M	H	L	M
Weakly suitable: Grass buffer strip	M	L	L	L	M
Weakly suitable: Wildflower buffer	L	L	L	L	L
Weakly suitable: Magic margins	H	M	L	M	M

The High (H), Medium (M) and Low (L) refer to the scores of 1-2, 3 and 4-5, respectively, from the expert effectiveness assessment as indicated in the measure tabs.

Moderately suitable **10**: Wooded buffer strip

Inputs & results log | Enlarge upper | Grass buffer strip | Wildflower buffer | Wooded buffer | Magic margins | Raised buffer: field runoff | Raised buffer: overbank storage | Sediment trap | Sediment filter fences

Surface-, ground- water wetlands | Tile drain-fed wetlands | Integrated buffer zones | Denitrifying bioreactors | Controlled drainage | Tile drain irrigation onto saturated soils | Two stage channels | In ditch sediment trap, or filter

(b)

Intro | Field Specific Pressures ✓ | The Nature of Delivery Points ✓ | The Nature of the Riparian Zone ✓ | The Nature of the Watercourse ✓ | Additional Considerations | Results (upper) | Original layout | Shrink upper | Reset

Measure prioritisation (rows: *dynamic*, based on user inputs) vs potential for pollution effectiveness (columns: *static*, based on pre-determined expert assessment of the upper ceiling for well-designed and maintained measures).

More information on the measures can be found by clicking on each of the buttons on the lower half of the web page.

The table below shows the non-excluded measures ranked from highly (green), moderately (blue) and potentially suitable (yellow) for the field situation as defined by the answers to questions. Excluded measures are red. Colours here match those used on the measure tabs.

In addition to their suitability for the field situation it is recognised that further prioritisation will likely be based on tackling known catchment water quality issues. The table therefore also indicates the potential effectiveness of the measures for improving water quality for a range of pollutants as High (H), Medium (M) and Low (L) as determined by a panel of experts.

Order of priority based on fit to field-landscape factors	Ability to address specific water quality issues				
	Sediment	Total phosphorus	Nitrogen	Pesticides	Microbial contaminants (FIOs)
Moderately suitable: Raised buffer: field runoff	H	M	L	L	M
Moderately suitable: Raised buffer: overbank storage	M	L	L	L	L
Moderately suitable: Sediment trap	H	H	L	L	L
Moderately suitable: Integrated buffer zones	H	H	M	M	M
Weakly suitable: Grass buffer strip	M	L	L	L	M
Weakly suitable: Wildflower buffer	L	L	L	L	L
Weakly suitable: Wooded buffer strip	H	M	L	M	M
Weakly suitable: Magic margins	H	M	L	M	M
Weakly suitable: Surface-, ground- water wetlands	M	M	H	L	M
Weakly suitable: Tile drain-fed wetlands	L	M	L	L	M
Weakly suitable: Denitrifying bioreactors	M	L	H	L	L
Weakly suitable: Controlled drainage	M	M	M	M	L
Weakly suitable: Tile drain irrigation onto saturated soils	H	M	H	M	L
Weakly suitable: In ditch sediment trap or filter	H	M	L	L	L

Inputs & results log | Expand lower | Grass buffer strip | Wildflower buffer | Wooded buffer | Magic margins | Raised buffer: field runoff | Raised buffer: overbank storage | Sediment trap | Sediment filter fences | Surface-, ground- water wetlands

Tile drain-fed wetlands | Integrated buffer zones | Denitrifying bioreactors | Controlled drainage | Tile drain irrigation onto saturated soils | Two stage channels | In ditch sediment trap, or filter

Figure 4.10. Example results output table showing mitigation ranking and the expert-informed effectiveness of the measures for different pollutants. (a) Example output table for a free-draining arable field with nitrogen loss risks. (b) Example output table for an inherently poorly draining grassland field with artificial subsurface drainage (tool inputs and outputs derived from https://measure-selection-tool.hutton.ac.uk/).

is not designed to take the place of professional or policy advice but to act as a screening and engagement tool leading to bespoke site surveys that inform final decisions.

Tool results reporting

The tool output recognises the need to understand the landscape context on the field scale when selecting mitigation measures with differing modes of action, but also that there will be a need to address known pollution issues with improvement goals on the larger farm and catchment scales. Hence, the tool output is twofold:

1. It prioritises the 16 mitigation measures through measures disallowed (red) and those placed in a ranking: weakly suited (yellow), moderately suited (blue) and well suited and targeted (green). This prioritisation is informed by the rules shown in Figure A4.7 and responds dynamically to the user questions.
2. It provides a simple tabulation of the potential achievable effectiveness of well-placed, well-designed and well-maintained measures for a range of pollutants as informed by the expert assessment process, reported here as static results, i.e. the effectiveness does not vary with the question inputs (see Table A4.2 for scores).

Examples of results output tables are given for a free-draining arable field with N loss risks (Figure 4.10a) and an inherently poorly draining grassland field with artificial subsurface drainage (Figure 4.10b). The link to the stored inputs and outputs of the tool is also given.

Final tool testing

The testing of the final version of the tool was conducted at a workshop attended by 13 stakeholders representing advisory, regulatory and policy sectors, held in Wexford in November 2022. The process at this workshop involved a presentation on the tool and the 16 measures; an introduction to three testing scenarios (Figures 4.11 and A4.8); the opportunity in three small groups to explore the tool and enter questions relating to the three testing scenarios, before wider exploration; and the completion of an individual feedback form (Figure A4.9) and a group discussion.

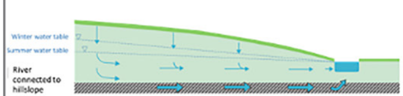
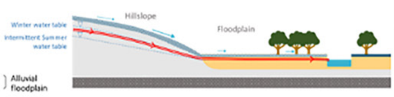
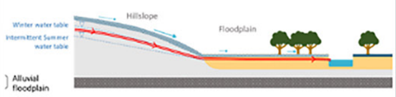
1. Intensive grassland (moderate drainage)	**2. Intensive grassland (subsurface soil drainage)**	**3. Arable (high erosion)**
e.g. Timoleague	e.g. Ballycanew North	e.g. Ballycanew South
		
		
Main water quality issues: Nitrogen leaching to groundwater and surface water	*Main water quality issues:* Phosphorus in overland flow and drain flow	*Main water quality issues:* Sediment and phosphorus erosion

Figure 4.11. Three testing scenarios used in the stakeholder workshop together with a set of suggested starting-point input parameters (see Figure A4.8) to explore the functionality, tool question–entry interface and results presentation.

The results of this stakeholder process informed a set of final edits to the tool being actioned, although some suggested edits were considered outside the scope of the tool. This led to the final version of the tool (v4) being produced. A further recommendation taken forward from the stakeholder testing was the provision of a “user handbook” documenting the measures, rules within the tool, aspects of terminology, definitions, functionality and the way outputs are presented.

The tool and this accompanying handbook can be accessed via the following web page: https://measure-selection-tool.hutton.ac.uk/

5 Integrated Catchment Demonstration: A Case-based Approach

5.1 Rationale

The literature review in Chapter 2 highlighted the need to move away from considering solely fixed-width linear riparian mitigation measures. Chapter 3 identified a suite of potential riparian measures, with varying levels of effectiveness in delivering multiple ecosystem services. Chapter 4 highlighted conceptual approaches to selecting the **right measure** and the **right place** with regard to riparian-based interventions.

Building on these lessons learned, a hierarchical approach is needed to consider and place measures in a catchment. The overall aim of this chapter was to develop a framework for implementing the right measures in the right places, and to demonstrate the application of the framework in an intensively managed landscape. The framework was applied and tested in the Ballycanew catchment, County Wexford. The specific objectives were to:

- develop a hierarchical framework for measure placement that considers measures ranging from traditional fixed-width measures to more bespoke, targeted approaches;
- apply this framework in the Ballycanew catchment to give a spatial overview of measures, including example measure designs;
- discuss and assess the framework with stakeholders to consider the benefits of, barriers to, challenges for and costs of the uptake of interventions;
- summarise the wider benefits of measures and undertake a simple evaluation of cost versus effectiveness across three progressive levels of implementation for a subset of fields.

5.2 Methods

5.2.1 Developing a hierarchical framework

Here we build on the lessons learned in Chapters 3 and 4 and propose a three-tiered system (Table A5.1) for measure placement.

Level 1 measures comprise traditional fixed-width grass margins. These act as exclusion areas for the watercourse, for example an exclusion boundary for spraying chemical herbicides and/or pesticides and fertilisers or to stop livestock from entering the watercourse. We use 2 m grass margins for level 1 measures in this study. However, widths can vary and in practice can be as narrow as 1.5 m in some cases for fencing (in line with AESs/NAP).

Level 2 measures comprise more targeted, vegetated (e.g. grass, wildflower, magic or wooded) buffers. These buffers are not long, narrow, fixed-width buffers but instead are wider, shorter and targeted to smaller convergent flow paths. In essence, they are pocket buffers tailored to dealing with high volumes of run-off at certain points.

Level 3 measures are more bespoke, soft-engineered measures (i.e. the measures in the SMARTER_BufferZ 16 measures database that are not level 1 or 2 measures), targeted at key points in the catchment. These measures can deal with the target pressure and are generally more effective. The design of these measures is based on the “Right Measure, Right Place” philosophy.

The level of each of the measures in the 16 measures database is shown in Figure 5.1.

The system uses a tiered approach. Therefore, level 2 and 3 measures are always applied in addition to level 1 measures (although for simplicity in the cost-effectiveness sections (sections 5.2.5 and 5.3.4) level 3 measures are considered by themselves). Level 1 measures should be seen as the basic-level intervention for the field, and then opportunities should be found for applying level 2 then level 3 measures where necessary. In a small number of cases, applying only level 1 and 3 measures could be possible. This would occur, for example, if a convergent flow pathway had a large contributing area and was the dominant flow path in the field. It is acknowledged that a level 2 measure may not be able to cope with such flows and that a level 3 measure would be required.

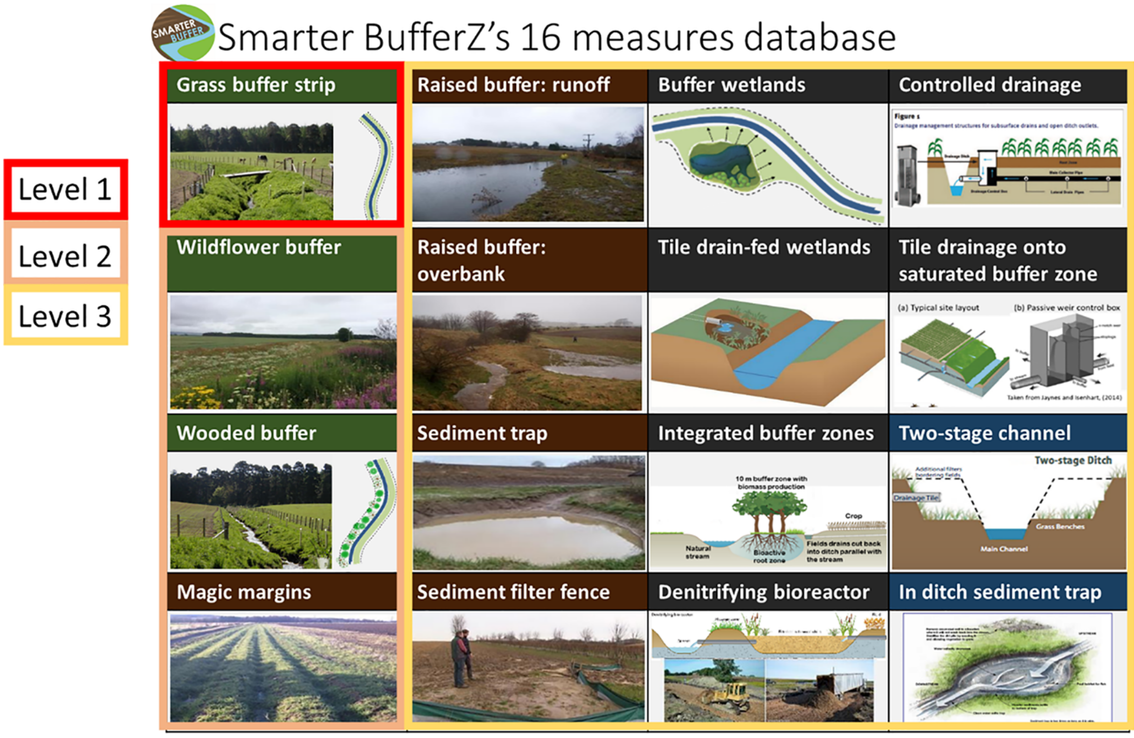


Figure 5.1. Applying level 1, 2 and 3 measures to the SMARTER_BufferZ 16 measures database.

Another example would be if a field was very flat or had a small area of diffuse flow pathways leading to an open ditch. In this case, level 2 measures may not be relevant (and level 1 measures may be adequate), but in-ditch sediment traps (a level 3 measure) may be required to deal with sediment-rich channel flows.

5.2.2 *Study catchment – Ballycanew, County Wexford*

The framework was applied and tested in the Ballycanew catchment, County Wexford (see section A5.1 for further details on the catchment characteristics). The catchment (which lies within one of the EPA's selected priority areas) has been monitored within the ACP since 2009 with ongoing collaboration with the catchment farmers. Long-term and high-frequency data are available and a conceptual understanding has been documented.

P is the main nutrient at risk of being lost from this site through overland and near-surface flow. The catchment has an elevated 10-year median total reactive phosphorus (TRP) concentration of 0.064 mg/l, which is well above the environmental quality standard (EQS) of 0.035 mg/l. The probability of exceeding the EQS was 93.7% (Mellander *et al*., 2022). The quickflow components of run-off have been identified as the most important pathway to manage in terms of moderating P transfers (Mellander *et al*., 2015). Shore *et al*. (2017) found that 87% of TRP was delivered by stormflow and only 1% by baseflow, highlighting the importance of quick stormflow in the catchment. The catchment was further characterised as being risky in terms of "mobilisation" and "delivery" of P (Mellander *et al*., 2022). Most of the sediment losses in the catchment were found to come from stream bank/bed erosion and road losses. The soil permeability had a large influence on the sediment loss (Sheriff *et al*., 2018). Ditches and drains in the catchment enhance the hydrological connectivity; an understanding of their physical characteristics, spatial distribution and effect on fine sediment retention/transfer can be used to develop management strategies for reducing downstream P transfers (Shore *et al*., 2015).

5.2.3 *Data analysis techniques*

A desk-based approach (building on lessons learned in Chapter 4) was used initially to determine measure placement using the hierarchical approach developed in section 5.2.1. A core reason for selecting Ballycanew was to take advantage of its rich and diverse spatial datasets (see Table A5.2) and field scientific knowledge of the area. All of these datasets were used by the project team to perform a desk-based assessment for measure placement. Results were then validated with a brief field visit and the outputs further refined (building on the lessons learned in section 2.2).

5.2.4 Field walkovers and measure designs

A field walkover was carried out to verify the findings from the desk-based assessment. The field assessment was carried out to determine whether measures would be suited to certain locations. Generally, all level 1 and 2 measures were applicable to the landscape, as these measures aim to create riparian exclusion zones (adjacent to the channels). However, the field walkovers allowed us to scope out in more detail the applicability of level 3 measures. This field information, e.g. photography and rough estimations of channel depth, allowed us to produce some conceptual designs of level 3 measures.

Level 3 measure designs were created for three fields, hereafter referred to as Field G, Field 7 and Field 8. Those fields were selected as they facilitated the exploration of several different measure options (as highlighted in the 16 measures database). The highest resolution DTM (25 cm resolution) was used to calculate the spatial characteristics of the level 3 measure designs. It also was used to correctly position the measures. Annotated photography was used to communicate how the measures would look. This pro forma methodology is similar to that presented in Wilkinson *et al*. (2014).

5.2.5 Cost-effectiveness of the hierarchical approach to measure placement

The effectiveness of riparian pollution mitigation is a fundamental factor in the protection of water quality and is often taken as the ability of a mitigation measure to retain pollutants as a fraction of their load reduction. In this study, we simplified the concentrated flow path (CFP) concept and determined "buffer loading" and "retention estimates" for each CFP on a field scale.

"Buffer loading" was based on the attributes of a given field, coupled with a field pollution loss coefficient. Flow path characterisation and delivery points along field margins were derived from DTM data. Each major flow area associated with a delivery point to a watercourse margin was derived by assigning a run-off contribution area (informed by the terrain analysis). The area was multiplied by the field-specific sediment or total P mass, to get the load associated with each CFP. Multiple CFPs flowing into one margin were dealt with separately then latterly summed. The flow and pollution load to each delivery point were always apportioned pro rata.

Pollutant "retention estimates" were based on models developed by Dosskey *et al*. (2008) (see Figure A2.2). The model uses erosion risk factors of slope, soil type and crop management to define suitability to a set of curves that predict the percentage load reduction for sediment, sediment-bound or dissolved pollutant and changes in soil texture, slope or cropping assigned via a lookup table. Once the appropriate curve has been identified, the regression line is used to calculate the ratio of effective buffer area to contributing flow area, which is then used as input for the model, and, from this, the percentage load reduction is calculated.

The approach highlighted here enables a direct comparison of the effectiveness of various watercourse margin management types, based on pollution load reduction. Information on pollution retention effectiveness was then coupled with simple annualised metrics of costs (associated with land area taken from the field, fixed expenses of installation and maintenance). The resulting effectiveness versus cost estimations present a powerful way to identify and compare the most suitable levels of interventions.

5.3 Results and Discussion

5.3.1 Applying the hierarchical measure system to Ballycanew using spatial datasets

In total, 34 fields were analysed during the desk-based assessment. Three fields were found to have no open drains or watercourses along the field margin and therefore were excluded from analysis. A level 1 measure was applied to the remaining 31 fields (i.e. 2 m grass buffer/exclusion from channel). Level 2 measures were applied to 23 of the fields, to manage convergent flow pathways with a small contributing area (e.g. field scale) – see Figure 5.2.

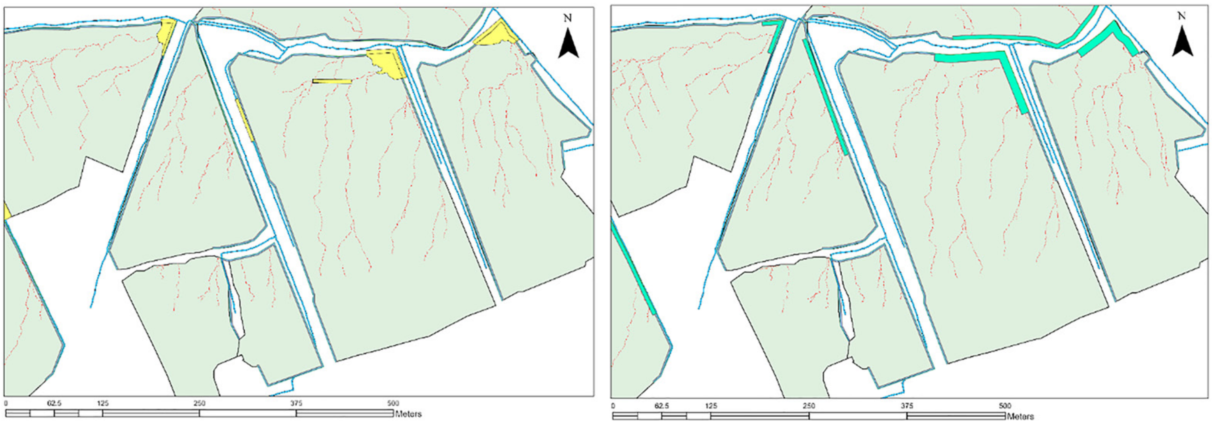


Figure 5.2. Left: level 1 (thin blue lines between field boundary and open drain network (light blue)) and level 2 (thicker green lines strategically placed to disconnect overland flow pathway (red lines)) measures positioned in the south-west corner of Ballycanew catchment. Right: level 3 measures (yellow) were strategically targeted to the open-ditch network and key overland flow pathways in same area.

Level 3 measures were applied to 14 fields, in each case to deal with a specific challenge, for example to disconnect a larger convergent flow pathway (with a raised buffer) or manage flow within an open ditch with either a sediment trap or a denitrifying bioreactor. More than one level 3 measure (e.g. a treatment train approach) was applied in two fields. Table 5.1 presents a summary of applicable level 3 measures in the Ballycanew assessment areas (Figure 5.1). Here, only five measures were applied to the assessment areas. These were found to be the most applicable measures for dealing with run-off pathways. However, it should be noted that this number could change in a detailed field assessment. For example, it is likely that there are more opportunities for in-ditch sediment traps, but a detailed survey of the ditch is required to confirm this (as no dataset indicated ditch dimensions). There were three occasions when only a level 1 and a level 3 measure were applied in a field. On these occasions, a level 2 measure was not considered, as the convergent flow pathway area was deemed to be too large to be managed by a level 2 measure.

The land take (i.e. the land required by an intervention that can no longer be farmed) was calculated for each field using ArcGIS Pro software (by calculating the area of the intervention in each field based on the rules in Table A5.1). For level 3 raised buffer measures, two land take areas are presented: the “dry” and “wet” areas. The “dry” area represents the area of land that contains the physical bunded intervention, which in many cases is the bund. The “wet” area represents the area of land that would be temporarily inundated with flood water. However, this would occur infrequently (perhaps several times a year), and the measure is designed to drain the area from full to empty within 1–2 days. Therefore, this area could still be farmed for most of the year. In-channel measures such as in-ditch sediment traps were assumed to be associated with no land take. It was found that 2.2% of the total land area was required for the level 1 interventions. This

Table 5.1. Summary of level 3 options for Ballycanew

Level 3 measure type	Number	Assumptions on land take
Raised buffer (run-off)	6	Both dry (i.e. bund) and wet (i.e. temporarily flooded) area calculated
Raised buffer (overbank)	1	Both dry (i.e. bund) and wet (i.e. temporarily flooded) area calculated
Sediment trap	1	Assumes no land take, as measure contained within channel
In-ditch sediment trap	6	Assumes no land take, as measure contained within channel
Denitrifying bioreactor	1	Assumes no land take, as measure contained within channel

Table 5.2. Land take for level 1, 2 and 3 measures in Ballycanew study areas

Parameter	Whole field area	Area of land take by measure level			
		Level 1	Level 2	Level 3	
				Dry	Wet
Absolute area (ha)	191.2	4.2	2.2	0.3	1.2
Percentage area (%)	100	2.2	1.2	0.1	0.5

dropped to 1.2% for level 2 and to only 0.1% (0.5% wet) for level 3 interventions (Table 5.2).

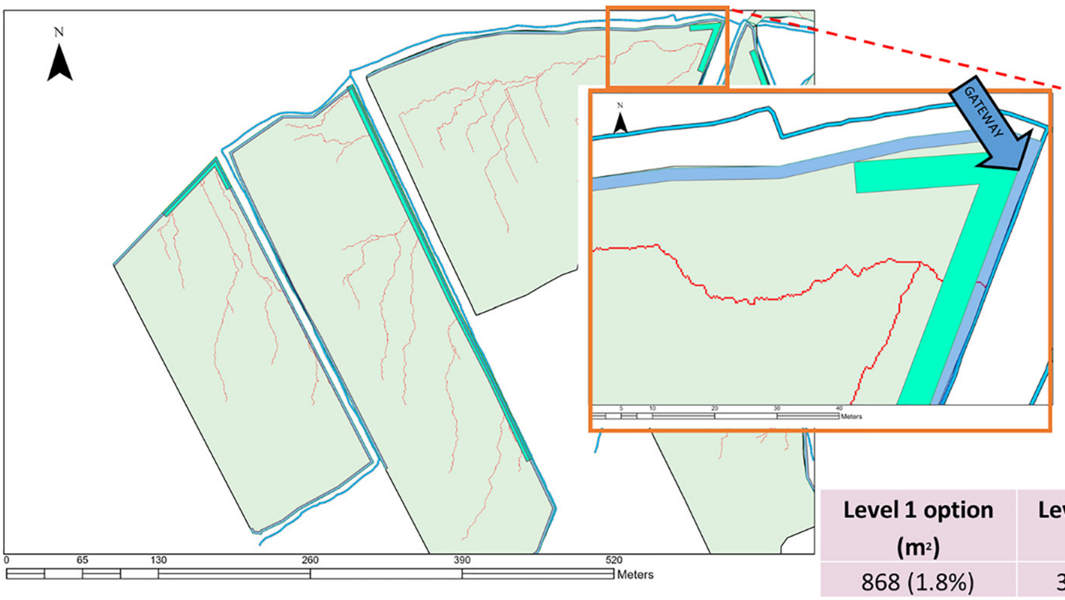
5.3.2 Scenarios

Scenario 1: an example of a level 1 and level 2 measure approach

Three fields were selected in the south-west corner of Ballycanew to demonstrate the principles of an approach using level 1 and level 2 measures. Figure 5.3 highlights the field areas used for level 1 measures as blue buffer zones parallel to the open-ditch network (light blue lines). The left and centre fields in Figure 5.3 have a series of diffuse run-off pathways leading to the open drain. Here, we propose implementing level 2 measures (5 m wooded buffer) following the line of overland flow pathways. For the field on the far left, the level 2 measure is targeted to the northern part of the field. The level 2 measure is targeted to the eastern ditch in the centre field (as a series of run-off pathways lead to the ditch). The field on the right has one convergent pathway that leads to the north-east corner of the field. Here, an L-shaped level 2 measure is applied to the corner of the field (along with the level 1 measure). However, this may not be enough to deal with the flows of such a large convergent pathway, so an approach using level 3 measures could also be considered (a bund of a similar shape). A field gateway presents a possible barrier to implementing a level 2 or 3 measure approach in the corner of this field. For this scenario, the land take area of the level 2 measure approach is roughly half the land take area of the level 1 measure approach.

Scenario 2: an example of a level 3 measure approach utilising a sediment trap and raised buffer (overbank)

An opportune site was identified for a raised buffer (overbank) measure during our desk-based assessment (and validated during a field visit). This site lies in the north of the Ballycanew catchment in the phase 1 study area. All DTM models identified this feature as lying on a major channel pathway.



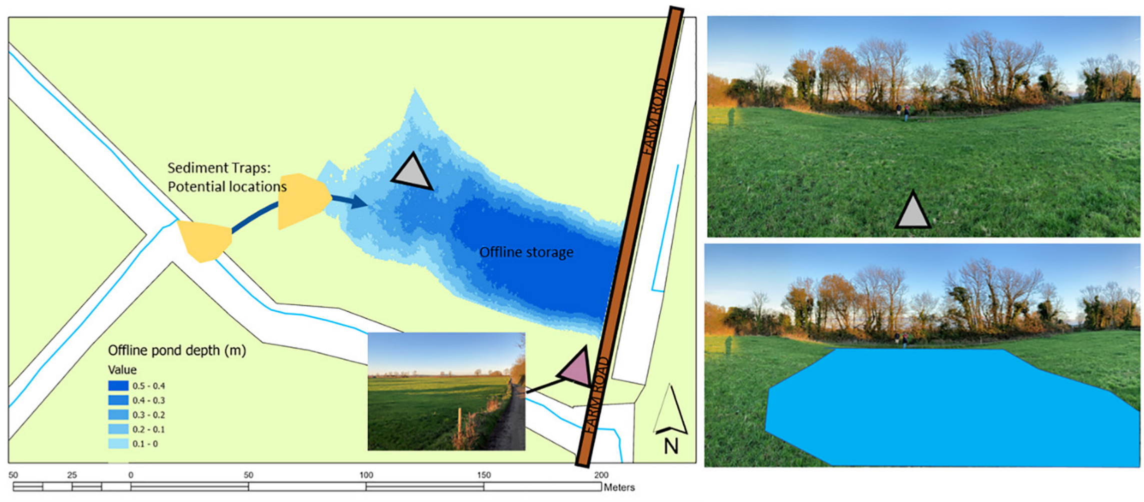
Level 1 option (m²)	Level 2 option (m²)
868 (1.8%)	327 (0.7%)

Figure 5.3. Level 1 (thin blue line) and 2 (thicker green line) measures in the south-west corner of Ballycanew (including field area associated with each level).

However, the field walkover and open-drain network dataset identified this not as the main channel but as a historical fluvial feature, and the current drain has been diverted around the side of the field. It is possible that this field already floods during high-flow events (but this would need to be validated by the landowner). Therefore, this level 3 measure approach would look to gently engineer the channel so that it would spill during certain high-flow events across the floodplain and the water would be stored temporarily due to a bund (blue area in Figure 5.4). This could simply involve raising the farm road (up to 50 cm at the deepest point), and it therefore acting as a bund (allowing the landowners to drive over the bund). Less soil would be needed for the bund in this instance compared with other scenarios, as the track is already currently slightly raised above the ground. Further investigations are needed to identify an efficient means of draining the impacted area after a flood peak has passed. This could be via a subsurface drain. It is possible that this bund could capture large amounts of sediment, as it would capture channel flow and field run-off from a catchment area of 30 ha. Therefore, installing a sediment trap at the inlet is proposed to manage sediment at a controlled point. No land would be lost for the “dry” area of this level 3 intervention, as the track would act as a bund. The wet area would be roughly 2500 m^2; however, the measure would be designed to drain within 1 or 2 days of the flood peak (and therefore this area could be farmed most of the year). Figure 5.4 shows that there is the potential for this feature to hold 1013 m^3 of water temporarily during a flood event. The stream level at which the pond fills from stream overbank flow could be set by creating either a swale or a woody feature (see Quinn *et al*., 2022); to calculate this level, further surveying is required. However, if the level was set so that the pond fills during the rising limb of a flood event, managing the flood peak correctly, this approach could have the potential to manage flooding locally (Quinn *et al*., 2022). Therefore, this feature could provide wider benefits in addition to improving water quality. The potential of this flood management effect is being investigated further by the EPA-funded SloWaters project.

Scenario 3: an example of a level 3 measure treatment train approach utilising in-ditch sediment traps and a raised buffer (run-off and overbank)

A field was identified in the south-west corner of Ballycanew for a level 3 measure option consisting of a series of in-ditch sediment traps and a raised buffer bund. Dr Paul Quinn (EPA SloWaters) identified this site as having large amounts of sediment deposited in the western ditch. It is likely that this field (and ditch) is collecting large amounts of surface run-off from upslope arable fields (verified by field visit). Therefore, to manage these high-sediment loads, installing a



Bund (track) Height (m)	Bund length (m)	Approx. bund area (m2)	Temporary storage area (m2)	Temporary storage volume (m3)
0.5m	35	160	2465	1013

Level 1 option (m2)	Level 2 option (m2)	This option (m2) [dry]
2953 (2.3%)	630 (0.5%)	0 (0%)

Figure 5.4. A level 3 measure scenario proposed for a field in the north part of Ballycanew. This level 3 intervention consists of a raised buffer (overbank flow) and sediment traps. The farm track would act as a bund.

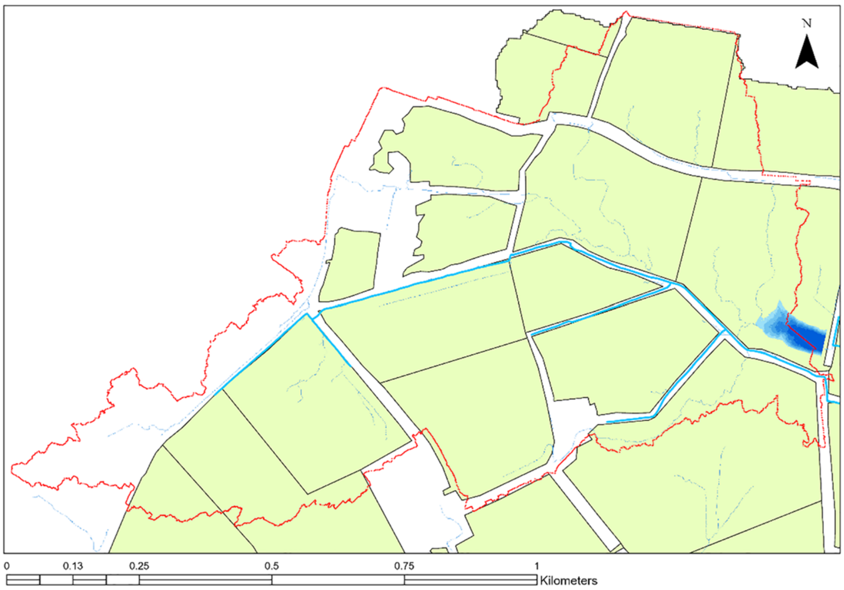


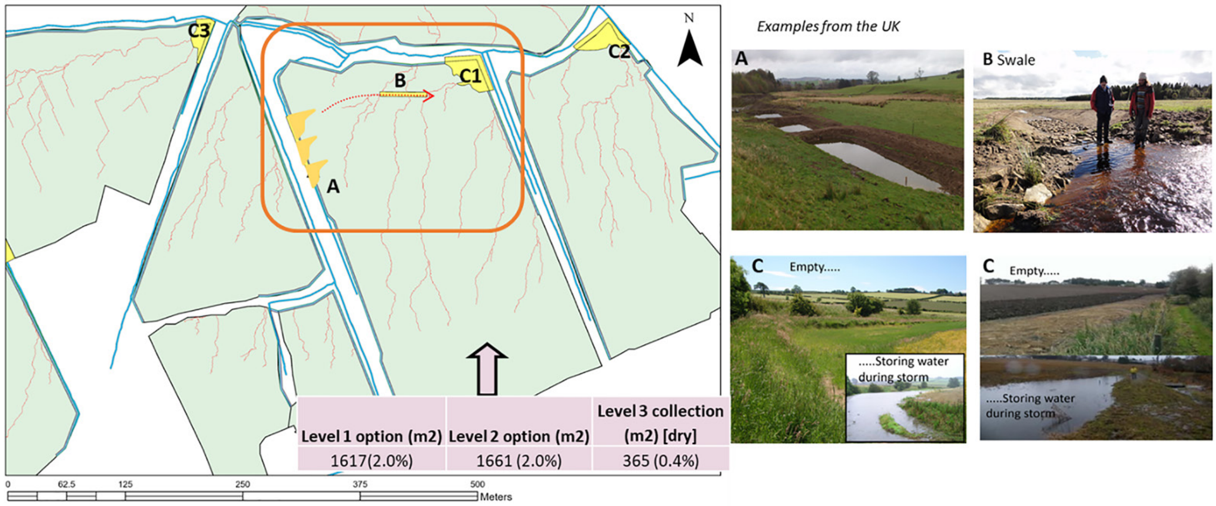
Figure 5.5. Catchment area (red line) above the level 3 intervention proposed in Figure 5.4. This measure would predominantly capture overbank flow from the open-ditch channel. However, a small amount of field run-off would be captured in the feature (blue lines leading away from blue shaded area). The feature would therefore manage high-flow in-channel run-off from at least 12 upstream fields. Note that some uncertainties are associated with calculating catchment areas in flat landscapes such as Ballycanew, so it is likely that the catchment area could be up to 10% larger or smaller.

series of in-ditch sediment traps in the western ditch of the field was proposed. These sediment traps would capture sediment in controlled locations. However, during high-flow events, it is likely that these sediment traps would become inundated with run-off. If this were to occur, flow could be diverted across the field and connected to a raised buffer bund in the north-east corner of the field. A shallow swale could be dug to help connect the western ditch and the bund, thus creating a treatment train approach. The bund would therefore manage field run-off and high flow from the sediment traps. The principles of the bund are similar to those in scenario 2; however, here, the bund would need to be 1 m high, to store approximately 600 m^3 of water. Figure 5.6 presents the principles of this treatment train approach along with some images of similar measures used in the UK. As with scenario 2, this treatment train approach will provide wider benefits such as flood risk management.

5.3.3 *Stakeholder workshop*

In the previous sections, we describe the development of a hierarchical framework approach to measure placement. This approach was tested and validated in the Ballycanew catchment. In most cases, level 1 measures are likely to be the most familiar to farmers, advisors and landowners (i.e. regulatory fencing and grass margins alongside watercourses). Level 2 options are less well known and have less funding (e.g. wooded margins), while many of the level 3 options presented are new in the Irish context. Therefore, there is a need to discuss the approaches with stakeholders, in particular agricultural advisors, catchment planners and those tasked with the delivery of measures. We presented scenarios 1, 2 and 3 from Ballycanew (section 5.3.2) to a group of 14 catchment advisors and environmental experts. The purpose of the exercise was to assess the opportunities, challenges, costs and barriers associated with such approaches using the measure designs from the catchment planning exercise outlined in this chapter. Our expert assessment exercise on measure effectiveness (Chapter 3) has already identified that level 3 measures were generally more effective than level 1 measures. However, there is a need to assess the acceptability of these types of measures to help mainstream such approaches in the future.

The first session of the workshop posed five questions to the stakeholders on each measure scenario.



Location	Bund Height (m)	Bund length (m)	Approx. bund area (m2)	Temporary storage area (m2)	Temporary storage volume (m3)	Catchment area est. to bund (ha)
C1	1m	70 (L shape)	365	875	595	20
C2	1m	80 (L shape)	374	689	473	12
C3	1m	60 (L shape)	250	844	307	6

Figure 5.6. Left: the level 3 measure treatment train approach presented in scenario 3. Here, the in-ditch sediment trap is connected to the raised buffer bund (C1). C2 and C3 represent other raised buffer run-off disconnection level 3 measure approaches. Right: images from other examples used in the UK (see 16 measures database, Figure 5.1).

Level 3 measures were perceived by the attendees to be most effective (especially as a treatment train approach – scoring between 4 and 5 out of 5). All scenarios were deemed to be a better fit to the farm business when associated with an appropriate payment scheme. Level 1 and 2 measures were perceived to be a better fit for the farm business than individual level 3 measures. However, when level 3 measures were combined in a treatment train approach, it was perceived that uptake would be stronger than for approaches using level 1 or level 2 measures alone. Level 3 interventions were reported to have acceptably long lifespans.

In the second part of the session, the attendees were asked to discuss opportunities, challenges and costs associated with the three scenarios. They then summarised the key opportunities and key barriers (see Table 5.3). Loss of land was a key barrier to the level 1 and 2 measure approaches. A theme associated with the two level 3 measure scenarios was a lack of evidence and funding to support such approaches, which could act as a barrier to these measures. Those questioned saw the advantages of such targeted approaches and most felt that there was a need for key demonstration sites, to convey the principles of such measures and collect further evidence on their functioning.

5.3.4 Cost-effectiveness considerations

The method applied is concerned with an improved representation of the action of two types of grass buffer zones (level 1 and 2 measures) versus point sediment and total P retention measures (level 3 measures) in the common situation of convergent flow paths of surface run-off from sloping fields. This method is based on the fact that the retention efficiency of the incoming pollution load for a grass margin is dependent not only on the margin width but, more critically, on the ratio of the effective margin segment area at the specific delivery point to the area of the contributing flow from the field. The method seems appropriate for addressing this issue and has possibilities for further use, in either a spreadsheet format as used here or a formalised system.

Three case study fields (Fields G, K and 3; Table 5.4) were assessed in relation to cost-effectiveness of mitigation levels. We found low ratios of 0.001–0.013 for level 1 measures, increasing to ratios of

Table 5.3. Short feedback points from group discussions on opportunities, challenges, barriers and costs for all three scenarios

Discussion point	Scenario 1	Scenario 2	Scenario 3
Opportunities	1.5 m required on most farms already Level 2 could bring extra revenue	Temporary storage has an impact on farms for only short periods throughout the year Low impact on farm Could be highly effective	Reuse topsoil Water quality improvements perceived as strong Good demonstration site potential
Challenges	Maintenance might not be effective Moving gateways	Will it become a wet area in time? Needs a shift in the thinking of farmers and advisors	Issues about animals in the feature and animal diseases Fencing perhaps needed Lack of evidence (and funding) on approach (but can see it could be very effective)
Costs	Access for level 2	To build, 2–5 digger-days would be needed, but need to consider maintenance, advice and materials costs	3–5 days with digger Need to consider an annual payment, e.g. for maintenance
Key challenges	Loss of land Cost of fencing drains, which is not mandatory	Who advises on such a novel measure? Funding source Evidence required for advisors/farmers Sediment management costs	Access, animal diseases and lack of evidence (to answer, “Why build this?” “Will it work?”)
Key opportunities	Fit with existing schemes Wider benefits	Macro-scale opportunity to manage water quality, likely to lead to improvements (e.g. keeping sediment out of channel) Shows catchment-level thinking Brings wider benefits Low maintenance	Can see how it will improve water quality (even with lack of evidence) and is therefore a good demonstration site to collect evidence Reuse topsoil

0.002–0.033 for level 2 measures. The resulting predicted retention of sediment and total P was low for all but the CFPs with small contributing areas; this is useful for highlighting the limitations of grass margins of relatively narrow widths for pollutant mass load retention for larger CFPs. Where these are known to occur, locally widened grass margins or level 3 measures are recommended. The situation of Field 3 gave a very large CFP (the whole field drained to one delivery point); this overwhelmed the margins, leading to near negligible edge-of-field retention, which was coupled to a very high expected P loss risk associated with high soil test P levels.

The total net field surface mass losses for Fields G, K and 3 were 7.9, 18.7 and 7.4 tonnes sediment/year, respectively, and for total P were 3.2, 0.9 and 14.7 kg P/year. In comparison, the retention values in Table 5.4 show that the level 1 grass buffers were predicted to retain 16%, 22% and 2% of the sediment and 6%, 9% and 1% of the total P only.

The level 2 grass buffers (basic plus targeted grass margins) were predicted to retain 51%, 52% and 6% of the sediment and 20%, 22% and 3% of the total P. This highlighted that the buffer width of 2 m (a representative regulatory minimum width scenario) allowed > 80% of sediment and > 90% of total P to be lost from the fields. The localised increase in the buffer zone grass margin width from 2 m to 5 m at delivery points led to a substantial increase in effectiveness for only localised extra land take and a general improvement in cost-effectiveness, with costs per unit mass of pollutant retained being at least halved.

The level 3 measure scenarios presented are illustrative but are based on data extrapolated from other relevant studies coupled with desk-based data, backed up by walkover surveys in planning their designs and locations. The level 3 measures in Fields K and 3 were predicted to retain 34% and 49% of the sediment and 23% and 33% of the total field losses. The assumed retention values of 49%

Table 5.4. Cost-effectiveness results for the level 1, 2 and 3 mitigation measures

	Field								
	G			K			3		
	Mitigation measure level								
Parameter	1	2	3	1	2	3	1	2	3
Effectiveness									
Total sediment retained (tonnes/year)	1.25	4.01	7.94	4.09	9.72	6.34	0.13	0.45	3.60
Total P retained (kg/year)	0.19	0.63	2.14	0.08	0.20	0.21	0.11	0.40	4.85
Costs									
Total field land take area (ha)	0.12	0.18	0.00	0.16	0.20	0.00	0.09	0.11	0.03
Total annual cost (euros)	317	408	556	420	489	252	228	392	524
Cost-effectiveness									
Euro/tonne sediment	254	102	50	103	20	50	1761	873	145
Euro/kg P	1709	650	187	5114	2434	1498	2010	991	108

Level 2 values are inclusive of the load reduction value already achieved by level 1 measures. Level 3 values are for the point measure only and do not include the effects of retention under level 1 or 2 measure scenarios.

and 33% for sediment were based on an appropriate level of annual maintenance that was costed into the scenarios. In the case of Field 3, these retention values were substantially better than the maximum 6% sediment and 3% P field load reductions attained with level 1 grass buffers. Hence, in the case of Field 3, with one main delivery point channelling all the field area run-off, grass margins alone seemed to produce an unacceptable level of performance, and enhanced measures built into the margins are required. In the case of Field G, the effectiveness of the level 3 measure scenarios was additionally enhanced by an accompanying adaptation of the ditch, allowing water to spill from outside the field area towards the raised buffer bund for part of the duration of annual flow.

6 Conclusions and Recommendations

Mitigation measures aimed at improving water quality typically address the source–mobilisation–delivery process (Granger *et al*., 2010) by either reducing the source or breaking the pathway between source and receptor. While the focus of the SMARTER_BufferZ project is on "breaking the pathway" measures, it is important that an integrated approach that breaks the pathway and reduces the source is taken where possible.

6.1 Conclusions

- Pollutant pathways in the farmed landscape are varied. Surface run-off is a major issue and is often delivered to discrete points on the stream network, determined by topography. Pathways for dissolved pollutants are a matrix of preferential subsurface flows (e.g. artificial soil drains) beneath buffered margins.
- Narrow grass buffers, although widely implemented, have limited resilience to surface and subsurface flows and loadings, and thus are weak interventions for improving water quality and have limited wider ecosystem benefits (e.g. habitat, flood, C storage benefits). Some benefits (resulting from fencing to restrict animal access, or stopping direct adjacent cultivation) can be attained over small distances. However, for subsurface flows and aggressive surface run-off, widened buffers are needed, and these can be targeted to maximise effectiveness per unit of land take.
- Each field brings its own challenges and site-specific characteristics (e.g. soils, landform, management, topography, regional climate, socio-economic drivers, policies), and extrapolation of the effectiveness of riparian measures such as narrow grass strips is highly uncertain.
- Understanding of a wider range of riparian interventions is growing, meaning that presenting a set of options is possible (e.g. our 16 mitigation options), providing riparian management space and offering specific point interventions within that space for intercepting pollution pathways. Evidence on the benefits of the different options varies, but all options are at a stage where implementation and demonstration will lead to a rapid trajectory of environmental gains. Farmers, advisors and local environmental engineers already have many of the skills to implement such options and could be supported through additional knowledge transfer and training.
- Putting an RBZ into a landscape context is critical to making decisions in line with the "Right Measure, Right Place" approach.
- Irish soils data can be used as an effective screening tool, but on-site surveys should take place before restorative actions. Contemporary spatial data and field walkovers (coupled with landowner knowledge) should be combined to offer bespoke advice, as has been illustrated in our scenarios.
- It is possible to combine the elements of measure selection and measure siting (https://measure-selection-tool.hutton.ac.uk/) within a decision support framework that can use field and mapped knowledge for screening mitigation measures based on how they function against risks and key landscape elements. Use of this, alongside demonstration sites and the sharing of technical and anecdotal evidence across the regulatory and farm business sectors, will increase confidence among stakeholders (e.g. advisors, catchment managers, farmers) to move more quickly towards improving the specificity of measures in the riparian space and greatly improve environmental outcomes for water quality and deliver wider ecosystem benefits.

6.2 Recommendations

- Spatial data tools allow powerful screening of risks that can be linked to the mechanisms of riparian measures. Higher quality spatial datasets have the potential to help with better measure placement. Improved resolution of spatial data (e.g. improved LiDAR coverage for Ireland, national habitat map), coupled with the development of water and drainage maps on the farm to catchment scales, is vital.

- Further work on creating and integrating the available soils data where the key hydrological flow pathways are identified is key to targeting RBZs. This should include information from the Irish soil map (Fealy *et al*., 2009), subsoil drainage class map (Meehan, 2017), soil series data from the Irish Soil Information System (Creamer *et al*., 2014) and the contexts of the soil associations and Geological Survey Ireland aquifer maps.
- Resolving issues at the catchment scale should be an end goal, but the problems often arise at the field scale and require tracing issues back to the origins of sources and delivery to the channels. Once this information is known, management actions to reduce the source of a pollutant should be explored. Coupled with this, mitigation measures addressing both individual delivery points within a field and collective delivery from sub-catchment areas can be integrated into a riparian intervention plan (e.g. within-ditch and watercourse overbank spill measures effectively treat pollution from upstream areas within an appropriate field space).
- The tools developed in this project can help to indicate how effective measures are likely to be and indicate a relative scale of effectiveness. This helps the user to develop an understanding of effectiveness, e.g. that one measure performs relatively better or worse than another under conditions of "good" design and placement). The effectiveness is apparent only after the criteria of the landscape have been considered, to help reach that point of the measures being targeted to a suitable location. How short-listed measures should subsequently be prioritised should be informed by additional factors, including catchment objectives under the River Basin Management Plan (areas for restoration, areas for protection).
- We have shown the potential of implementing new types of measures and that these measures are more effective than traditional grass buffers. However, there is little in the way of demonstration of such measures in an Irish context. The tool can be used to engage farmers about potential diffuse pollution issues on their farms and measures that can be used to mitigate them; however, the use of demonstration farms and sub-catchments, demonstrating measures from the 16 measures database, would help to better communicate the concept behind these measures. If measures were implemented and effectiveness monitored, or if measures were located in monitored catchments, this would improve our evidence database (providing empirical evidence rather than relying on only expert scoring).
- It should be noted that the application of a suite of measures in some ACP catchments has been proposed. This will serve the purpose of both monitoring and demonstrating the efficacy of these measures.
- Facilitating maintenance (not only one-off capital payments) should be a fundamental consideration in future funding and resourcing of riparian measures to ensure that they remain functional and to increase additional benefits.
- All measures in the 16 measures database deliver wider benefits beyond diffuse pollution mitigation. Therefore, there is a need to collaborate with other partners, e.g. in the fields of flood risk, C mitigation and biodiversity, to work collectively to finance and deliver measures in catchments. This can help to ensure greater integration across environmental policies.

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Abbreviations

ACP	Agricultural Catchments Programme
ACRES	Agri-Climate Rural Environment Scheme
AES	Agri-environment scheme
CAP	Common Agricultural Policy
CFP	Concentrated flow path
CSA	Critical source area
DEM	Digital elevation model
DTM	Digital terrain model
EPA	Environmental Protection Agency
FIO	Faecal indicator organism
GAEC	Good Agricultural and Environmental Condition
GLAS	Green, Low-Carbon Agri-Environment Scheme
LiDAR	Light detection and ranging
NAP	Nitrates Action Programme
PIP	Pollution impact potential
RBZ	Riparian buffer zone
REPS	Rural Environment Protection Scheme
WFD	Water Framework Directive

Appendix 1 Evolution of Riparian Management/Exclusion Measures (for Grassland) under Agri-environment Policy in Ireland

Table A1.1. Evolution of riparian management/exclusion measures (for grassland) under the Nitrates Action Programme in Ireland

Measure	NAP1 2006	NAP2 2010	NAP3 2013	NAP4 2017	NAP5 2022
Chemical fertiliser	1.5 m	2 m	2 m	2 m	2 m
Organic fertiliser/ soiled water	5 m – watercourse 3 m – drain; 1 ha 10 m – > 10% incline	5 m – watercourse 3 m – drain; 1 ha 10 m – > 10% incline	5 m – watercourse 3 m – drain 10 m – > 10% incline 10 m – periodically	5 m – watercourse 3 m – drain 10 m – > 10% incline 10 m – periodically	5 m – watercourse 3 m – drain 10 m – > 10% incline 10 m – periodically
Cultivation	n/a	n/a	2 m	2 m	2 m
Cattle exclusion	n/a	n/a	n/a	1.5 m – derogation farms	1.5 m – derogation farms

Table A1.2. Evolution of riparian measures (for grassland) under AESs in Ireland: a synopsis

Scheme	Cattle exclusion from watercourses	Riparian margins
REPS (1994)	Bovine access to within 1.5 m of all watercourses on farm is prevented Cattle drinking points are permitted (Comp)	Within 1.5 m of watercourses, application of chemicals and fertilisers is prohibited (Comp) Withdrawal of agricultural production on margins 10–30 m wide along designated salmonid waters
REPS2 (2000)	As REPS (Comp)	As REPS
REPS3 (2004)	As REPS (Comp) Option 3a: increase margin to 2.5 m Option 3b: as REPS measure, but fully exclude bovine access (no drinking points permitted)	As REPS Tree planting on up to 50% of riparian zone recommended Option 3c: 5 m-wide planted (with suitable plant species) buffer zone
REPS4 (2007)	As Option 3b in REPS3 (Opt) Bovine access to within 1.5 m of watercourses is prevented Cattle drinking points are not permitted	As REPS3
AEOS (2010)	As Option 3b in REPS3 (Opt)	Fenced riparian margins: 3, 5.5, 10.5, 30.5 m wide Fixed-width margin per field Margin **may** be mulched/mown at least once per year No fertiliser/pesticides permitted
AEOS2	As Option 3b in REPS3 (Opt)	As AEOS
AEOS3	As Option 3b in REPS3 (Opt)	As AEOS
GLAS1	As Option 3b in REPS3 (Opt)	As AEOS, but margin width revised to 3, 6, 10, 30 m Margin **must** be mulched/mown at least once per year No fertiliser/pesticides permitted
GLAS2	As Option 3b in REPS3	As GLAS1
GLAS3	As Option 3b in REPS3	As GLAS1
ACRES[a]	As Option 3b in REPS3 (Opt)	Margin width of 1.5, 3, 6 m Variable width margins per field Zone > 10 m wide Margin **can** be mulched/mown at least once per year No fertiliser/pesticides permitted

While the AESs are optional, some measures within the various AESs were compulsory (Comp) for participants in the scheme and others were optional (Opt).

[a]ACRES also includes ACRES cooperation projects, incorporating greater variability and flexibility of riparian mitigation and management.

AEOS, Agri-Environment Options Scheme.

Appendix 2 Buffer Zone Effectiveness and Place Specificity

A2.1 Supplementary Methods for the Buffer Effectiveness Literature Reviews in Section 2.3 of this Report (reproduced from Stutter *et al.* (2021a) with permission from Elsevier)

The literature search focused on the Web of Science Core Collections (http://wok.mimas.ac.uk) and subsequently other search engines and ResearchGate (https://www.researchgate.net/home), and included citations within identified papers. Search terms used were riparian buffer*; watercourse buffer; vegetated filter strip; VFS; vegetated grass filter; riparian management; and riparian diffuse pollution mitigation. The date range was from 1980 to 2019. The initially large number of papers was then allocated into groups: (i) insufficient information and not usable, (ii) primary data papers that contributed to the databases and synthesis results here, and (iii) review papers that contributed to the discussion and introduction of our study. Since buffers adjacent to watercourses were the target, studies had to be specific to riparian landscape positions, hydrology, soils and vegetation. General plot studies of surface run-off were also included where their stated goal was to understand stream protection zones. Papers were limited to those discussing run-off and pollution by sediment, nitrogen, phosphorus, pathogens (or indicator organisms) and pesticides.

The two review stages, supporting respectively the two databases, comprised reviews of quantitative retention effectiveness across given widths with quantified co-variates (review 1) and significance testing of factors of influence in width (review 2).

Quantitative retention effectiveness: we carried out a review of studies documenting percentage efficiencies in pollutant retention, defined as the percentage reduction in pollutant mass load, calculated as the difference between output and input mass load (Out_m and In_m, respectively) as a percentage of input mass load:

$$\%\ reduction = 100 \times \left(\frac{(In_m - Out_m)}{In_m}\right) \qquad \text{(A2.1)}$$

Parameters were recorded on soil, hydrology and management (Appendix 2.2.2 in Stutter *et al.*, 2021a) according to a conceptual framework (Figure 2.2.1 in Stutter *et al.*, 2021a). Included studies were limited to those of primary data describing reductions in pollutant mass loads across buffers (i.e. excluding those reporting change only in terms of concentrations).

Factor significance: analysis of studies was undertaken examining site-specific factors for pollution retention effectiveness across spatial and temporal scales. This second approach completed review 1 because (i) many studies described buffer pollution only in general terms or concentration difference (not conforming to the mass balance requirements of review 1), (ii) we wished to evaluate co-variates that were formally statistically tested and also discussed as important (non-tested) interactions in buffer, and (iii) quantitative retention was seldom documented in reach- to catchment-scale studies. Review 2 evaluated key parameter groups in Fig. 1 (in Stutter *et al.*, 2021a). To interpret statistically significant negative versus positive outcomes of factors on pollutant retention, definitions of the direction of effect of the factors are important (Table A2.2 in Stutter *et al.*, 2021a).

Table A2.1. Full parameter descriptions as collated in the quantitative retention efficiency database (available in full at: https://data.mendeley.com/datasets/t64dbpv63x/3)

Parameter	Explanation
Location	
Study	Citation of the study detailing the primary data
Study ref. number	A unique number per study
Country	Country of field site
Source: rainfall and run-off	
Study duration	Duration of study period, or individual rain simulation events (*n*, events)
Rainfall (mm/h)	The average rate of natural or applied rainfall during the experiment
Total amount (mm)	The total amount of natural or applied rainfall during the experiment
Run-off (mm)	The run-off total during the experiment
Source: source area	
Watershed slope (°)	The slope of the field or source area
Area ratio (slope:buffer)	The ratio of the area of the slope to the area of buffer (generally equal to the ratio of length)
Slope length (m)	The slope length of the eroding field
Source: erosion parameters	
Soil texture	The stated topsoil texture
% clay	The percentage of clay sized particles in the topsoil if stated, or as an average for the texture class if not stated (size < 2 µm, USDA system)
% silt	The percentage of silt-sized particles in the topsoil if stated, or as an average for the texture class if not stated (size 2–50 µm, USDA system)
% OM	The percentage concentration of organic matter of the buffer topsoil
Source management	Stated management of the source area
Sediment inflow (mg/l)	Where given the concentration of sediment in run-off entering the plot
Buffer strip: width	
Width (m)	The buffer strip width, or subdivisions of a given width where sample collection allowed multiple observations across a buffer
Buffer strip: soil properties	
Filter slope (°)	The slope specific to the buffer zone
Soil bulk density (g/cm^3)	The topsoil dry bulk density of the buffer soil
Soil K_{sat} (cm/h)	The topsoil saturated hydraulic conductivity for the buffer soil
Infiltration (%)	The percentage of infiltration, either stated or calculated from rainfall and run-off
Buffer strip: vegetation	
Buffer vegetation	The stated description of the vegetation in the buffer
Grasses and herbs	A categorisation of the vegetation if near exclusively grass or wild flower species (either natural or planted)
Grass and tree/shrub mix	A categorisation of the vegetation if a mixture of trees with a substantial component of grass understorey
Trees and shrubs	A categorisation of the vegetation if a compartive plot of cropland is used
Unmanaged cropland	A categorisation of the vegetation if dominated by trees
Retention efficiencies (i.e. output–input budget as % reduction)	
Total P	Retention of the load of incoming pollution at the stated width, based on total (soluble + particulate) P
Dissolved P	Retention of the load of incoming pollution at the stated width, based on soluble P
Sediment	Retention of the load of incoming pollution at the stated width, based on sediment mass
Nitrate	Retention of the load of incoming pollution at the stated width, based on nitrate
Total N	Retention of the load of incoming pollution at the stated width, based on total (soluble + particulate) N, often Kjeldahl N unfiltered
Coliforms	Retention of the load of incoming pollution at the stated width, based on coliform or *E. coli* (MPN) analyses

Table A2.1. Continued

Parameter	Explanation
Herbicides/pesticides	Retention of the load of incoming pollution at the stated width, based on the analysis of the stated pesticide/herbicide
What pesticide	The named pesticide/herbicide
Pesticide LogK_{ow}	The octanol–water partition coefficient, whether stated or described by reference to PubChem online (https://pubchem.ncbi.nlm.nih.gov/)

MPN, most probable number; USDA, United States Department of Agriculture.

Table A2.2. Legend for parameters used in the site-specific factors significance database (available in full at: https://data.mendeley.com/datasets/t42s2fb2p8/4)

Parameter	Parameter direction of change
Buffer effectiveness	
Buffer presence	The buffer presence/riparian restoration effects reduced the pollutant concentrations or loads (if widths not specifically tested)
Buffer width: load effect	Where multiple widths were tested an increase to wider buffers resulted in greater pollutant load reductions
Buffer width: concentration effect	Where multiple widths were tested an increase to wider buffers resulted in greater pollutant concentration reductions
Rainfall and run-off	
Rainfall amount	Increasing rainfall/irrigation amounts
Rainfall intensity	Increasing rainfall event intensity or run-off flow rate into the buffer
Field slope soil risk parameters	
Source: buffer area	Reduction in the source area: buffer area
Field soil texture	Change in soil texture to be coarser
Field soil erosion	Increased soil erosivity
Source inflow conc.	Increased inflow concentration of pollutant in run-off
Source area slope	Increase in field slope steepness
Cattle exclusion	Cattle exclusion from the buffer (including where reduced grazing or rotational grazing was compared with continuous)
Best management practices	Improving crop or pasture management towards best management practices
Within-buffer processes: site	
Leading edge retention effect	The effect of preferential deposition of a pollutant at the upslope edge of the buffer (surface and below ground) meaning that buffer width became less important
Seasonality in retention	A seasonal effect for the summer period relative to the winter period
Buffer slope	Increased steepness of the slope of the buffer zone
Buffer topography	More diverse local topography, or intervention of sculptured ground profiles
Within-buffer processes: vegetation	
Vegetation management: herbs	Introduction or presence of specific grasses, herbaceous or rush vegetation
Vegetation removal	The cutting and removal of grass or other vegetation from the buffer
Tree planting	Presence or introduction of trees in the buffer
Stem or stand density	An increase in roughness and or stem/stand density associated with vegetation/forest
Vegetation rooting	Increased rooting of vegetation
Pollution biomass uptake	Uptake of a pollutant into vegetation biomass
Vegetation litter layer	An increased presence of vegetation litter on the buffer soil surface
Within-buffer processes: soil	
Soil infiltration	Increased infiltration
Fine particle transport	Preferential selection towards fine particle sizes crossing buffer
Converging flow paths	Increase in preferential/converging flow routing crossing the buffer
Soil–run-off interactions	More coarse buffer soil texture interacting more with erosive run-off entering the buffer
Soil organic matter	Increased availability of soil or dissolved organic matter
Soil pH	Increased soil pH
Soil sorption	Increased strength of soil sorption interactions
Sedimentation	Increased sedimentation over time acting on longer term efficiency
Microbial processing	Increased microbial activity and directly attributed effects (e.g. denitrification)
Soil wetness	Increased soil wetness or elevated water table
Soil redox	Increased effect of low redox or cycling between soil redox states

Table A2.2. Continued

Parameter	Parameter direction of change
Groundwater flows	A switch to deeper flow paths or more groundwater flow relative to surface flow paths
Artificial soil drainage	An increase in artificial soil drainage pathways
In-channel nutrient processing	
Benthic habitat	The effect of reduced bed siltation and greater benthic habitat diversity on reach/catchment pollutant retention
Bank erosion	The effect of reduced bank erosion on reach/catchment pollutant retention
Stream organic matter	The effect of increased terrestrial organic matter inputs to the channel on reach/catchment pollutant retention
Light/temperature effects	The effect of an altered light or temperature regime on reach/catchment pollutant retention

	Runoff vol	Sediment	Total P	Dissolved/filterable P	Specific colloid P	Total N	Nitrate	Ammonium	Coliforms/ E Coli	Pesticides
	12	40	29	32		17	29	8	6	9
Simulation	67	53	48	38	0	41	24	25	50	22
Created buffer	25	43	48	47	100	53	52	38	50	67
Natural riparian	8	8	3	19	0	12	24	38	0	22
Simulation	67	38	48	38	0	47	24	0	50	44
Natural	33	5	55	69	100	53	83	100	50	56
Event/simulation/single sample	58	35	34	38	0	29	21	13	50	56
<month	17	18	14	3	0	18	7	0	0	22
month-year	8	15	14	16	0	12	21	25	17	11
>year	25	30	38	47	100	41	55	63	33	11
Profile	8	5	3	3	0	0	0	0	0	0
Plot	92	73	69	59	100	76	59	75	50	78
<100m reach	0	8	14	6	0	12	10	13	17	11
Catchment	0	8	38	16	0	12	14	0	33	11
Multiple	8	8	10	13	0	0	10	13	0	0
No control	75	55	48	38	0	29	31	25	33	67
Pre - vs post-	0	3	7	9	0	6	0	0	0	0
Intervention vs control	25	48	45	47	100	65	69	75	67	33
BACI	0	0	3	3	0	0	0	0	0	0
Ssurface+shallow	100	80	90	66	100	88	52	75	33	67
Deeper flows+subsoil interactions	0	5	34	41	0	6	38	13	0	44

Figure A2.1. Summary of the metadata of all studies in the factor significance review. Top row numbers are the absolute numbers of studies for the different pollutants. The coloured rows show the percentage distributions of the studies between metadata attributes grouped by colours. Blue=experimental factors of the studied buffer; green=simulated vs natural rainfall; red=the experimental duration; orange=the spatial scale of the study; blue=the use of controls in the study; and pink=focus between overland and shallow surface pathways only vs subsurface or deep groundwater pathways.

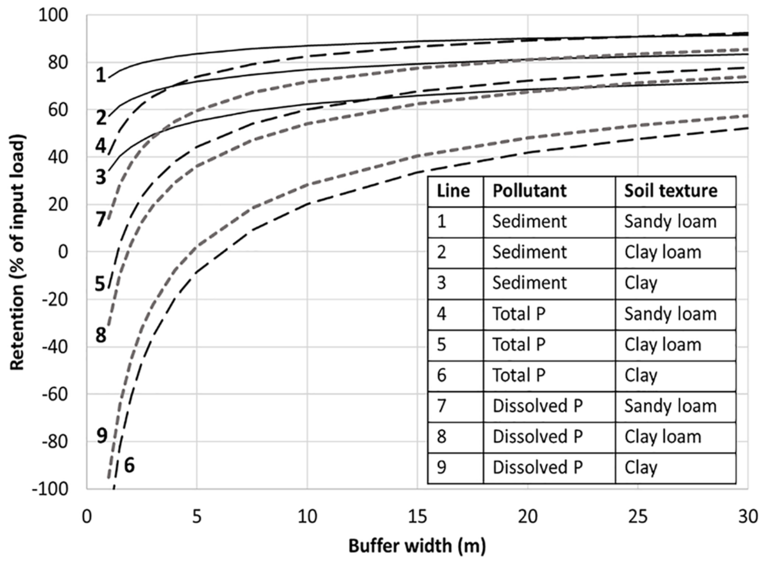


Figure A2.2. Graphical "design aid" in the style of Dosskey *et al*. (2008) for sizing buffer widths on three soil texture types according to required protection. The negative portion of the *y*-axis shows the predicted disbenefits of narrower buffers for P retention on clay-rich soils. Curve notation: solid line = sediment; long dash = total P; short dash = dissolved P. Reproduced from Stutter *et al*. (2021a) with permission from Elsevier.

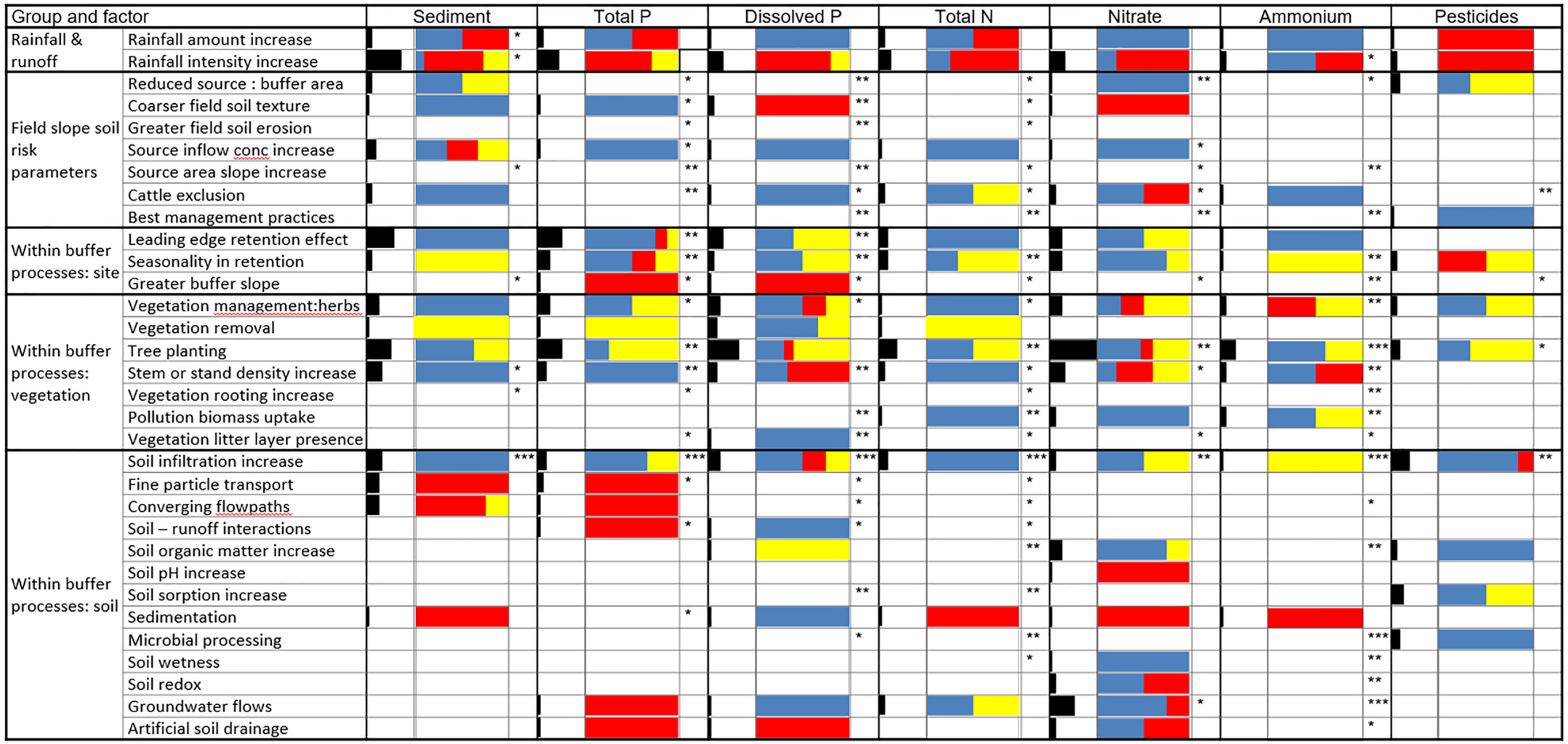
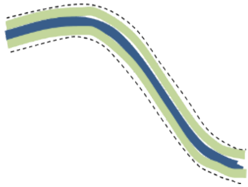


Figure A2.3. Summary of the influence of groups of factors (rows) determined by global studies into pollution functions of buffer zones. Pollutants (columns) are considered separately (note that studies addressing more than one pollutant can be counted here twice). For each pollutant, black bars denote the number of studies formally testing that factor (max. 15); blue, red, yellow segments denote the percentage distribution of those studies reporting that each factor had a positive, negative or non-significant influence, respectively, on increasing pollutant retention for a given width; and stars denote where studies implied (as opposed to formally tested) the importance of that factor (*1 study, **2–5 studies, ***6–10 studies). Reproduced from Stutter *et al*. (2021a) with permission from Elsevier.

Synopsis A typical vegetated buffer consisting of grass or natural bankside vegetation. Often a planned buffer zone is of linear width along the entire watercourse edge and should be fenced to exclude cattle in areas of grazing.



Grass Buffers

	Parameters for scoring	*Reference values for 6 m grass buffer strips*	Effectiveness (1 low-5 highest)	Confidence by weight of evidence (H, M, L)
Potential outcomes: Water quality	Soil loss control and sediment retention	2, H	**2**	**Medium**
	Phosphorus capture and retention	1, H	**1**	**Low**
	Nitrogen capture, uptake and transformations	1, H	**1**	**Low**
	Pesticide/herbicide capture and breakdown	1, H	**1**	**Low**
Potential outcomes: Habitat	FIO barrier and retention	3, H	**3**	**Low**
	Benefits to aquatic processes (shade, leaf litter)	1, H	**1**	**High**
	Terrestrial habitat diversity	2, H	**1**	**Medium**
	System C retention (biomass, soil)	1, H	**1**	**High**
	Hydromorphic and geomorphic improvement	1, H	**1**	**High**
Potential outcomes: Water quantity	Reduction in runoff response speed and volume including flooding management	1, M	**1**	**High**
Potential outcomes: Wider ecosystem services	Benefits to agronomic field processes: pollinators, pests	2, M	**1**	**Low**
	Production of biomass: food, fuel, green manure	1, M	**1**	**Medium**
	Visual landscape enhancement	2, L	**1**	**Medium**
	Integration with access and recreation	3, L	**2**	**Low**
			Additonal Notes:	

Figure A2.4. Example sheet from the SMARTER_BufferZ bespoke online questionnaire to assess expert opinion (and confidence) on effectiveness of riparian mitigation measures (n=16) across 14 key ecosystem services.

Appendix 3 Effectiveness Scores of 16 Mitigation Measures for Delivery of Ecosystem Services

Table A3.1. Weight group mean effectiveness score of 16 mitigation measures for 14 individual ecosystem services (Stage 1)

Measure	Sediment	Phosphorus	Nitrogen	Pesticide	FIO	Aquatic	Habitat	Carbon	Hydromor	Run-off	Agronomic	Biomass	Landscape	Recreation	All_es
Grass	2.71^{b}	2.12^{c}	1.16^{d}	2.00	2.80	1.39^{dc}	2.26^{a}	1.77^{b}	1.69^{b}	1.73^{c}	2.15^{bc}	1.51^{bc}	2.26^{cde}	2.78^{abc}	2.01^{cd}
Wildflowers	2.45^{b}	2.22^{bc}	1.53^{bcd}	1.73	2.49	1.98^{dc}	3.45^{abc}	1.84^{b}	1.75^{b}	1.80^{c}	3.63^{a}	1.63^{bc}	3.31^{abc}	2.57^{abcd}	2.31^{cd}
Wooded	3.62^{ab}	3.26^{ab}	2.41^{abc}	2.99	3.24	4.10^{a}	3.91^{a}	3.91^{a}	3.45^{a}	2.99^{abc}	2.94^{ab}	3.31^{a}	4.05^{a}	3.53^{a}	3.37^{a}
Magic	3.64^{ab}	2.77^{abc}	2.05^{abcd}	2.73	3.05	1.59	3.27^{abc}	2.05^{b}	1.37^{b}	2.64^{abc}	3.00^{ab}	1.50^{ba}	2.41^{cde}	1.55^{cd}	$2.41b^{cd}$
Raised run-off	4.07^{a}	3.06^{abc}	1.83^{abcd}	1.82	2.69	1.39^{dc}	1.90^{cd}	1.55^{b}	2.27^{ab}	3.52^{ab}	1.53^{bc}	1.24^{bc}	1.76^{de}	1.78^{dc}	2.19^{cd}
Raised overbank	2.88^{ab}	2.41^{abc}	1.74^{abcd}	1.45	2.23	1.84^{dc}	2.58^{abc}	1.74^{b}	2.87^{ab}	3.53^{a}	2.13^{bc}	1.45^{bc}	2.52^{cde}	1.71^{cd}	2.20^{cd}
Sediment trap	4.09^{a}	3.53^{a}	1.85^{abcd}	1.84	2.45	1.66^{dc}	2.28^{c}	1.96^{b}	1.77^{b}	2.73^{abc}	1.41^{c}	1.39^{bc}	2.27^{cde}	1.75^{cd}	2.20^{cd}
Wetland	3.47^{ab}	2.91^{abc}	3.56^{a}	2.49	2.89	2.96^{abc}	3.70^{ab}	2.94^{ab}	2.67^{ab}	3.26^{abc}	2.78^{ab}	1.50^{bc}	3.83^{ab}	3.23^{ab}	3.02^{abc}
Tile-fed wetland	2.24^{a}	2.62^{abc}	2.86^{abc}	2.29	2.52	2.19^{bcd}	2.90^{abc}	2.14^{b}	2.05^{ab}	3.05^{abc}	2.33^{abc}	1.43^{bc}	3.00^{abcd}	2.00^{bcd}	2.40^{bcd}
Integrated buffer	4.07^{a}	3.88^{a}	3.07^{ab}	2.98	3.12	3.46^{ab}	3.63^{ab}	2.98^{ab}	2.93^{ab}	3.22^{abc}	2.78^{ab}	2.51^{ab}	3.32^{abc}	2.73^{abc}	3.19^{ab}
Denitrifying bioreactor	3.24^{ab}	2.24^{abc}	3.71^{a}	2.35	2.29	1.76^{dc}	1.82^{cd}	1.88^{b}	1.59^{b}	2.53^{abc}	1.41^{bc}	1.18^{bc}	1.82^{cde}	1.41^{cd}	2.09^{cd}
Controlled drainage	2.71^{ab}	2.93^{abc}	3.29^{ab}	2.93	1.71	1.29^{dc}	1.43^{cd}	1.43^{b}	1.86^{ab}	4.07^{a}	1.00^{c}	1.21^{bc}	1.21^{de}	1.00^{d}	2.01^{cd}
Surface irrigation	3.80^{ab}	3.00^{abc}	3.80^{a}	3.30	2.40	2.00^{bcd}	3.60^{abc}	3.30^{ab}	1.90^{ab}	2.90^{abc}	2.60^{abc}	1.80^{abc}	2.70^{abcde}	2.40^{abcd}	2.82^{abcd}
Sediment fence	3.54^{ab}	2.88^{abc}	1.39^{cd}	1.49	2.05	1.10^{d}	1.00^{d}	1.51^{b}	1.51^{b}	2.00^{bc}	1.00^{c}	1.07^{a}	1.00^{e}	1.22^{d}	1.63^{d}
Two-stage drainage	3.60^{ab}	2.92^{abc}	2.60^{abc}	2.16	2.32	2.88^{abc}	2.84^{abc}	2.48^{ab}	3.72^{a}	3.52^{ab}	2.28^{bc}	1.68^{bc}	2.64^{bcde}	2.32^{abcd}	2.71^{abcd}
In-ditch trap	3.69^{ab}	3.12^{abc}	1.86^{abcd}	1.67	2.10	1.67^{dc}	2.45^{bc}	1.93^{b}	2.31^{ab}	2.52^{abc}	1.48^{bc}	1.10^{a}	2.19^{cde}	1.71^{cd}	2.13^{cd}

Pairwise comparisons between measures effectiveness (at delivering each ecosystem service) performed using LSMEANS in SAS. Significant difference ($p<0.05$) between measures are identified by different superscript letters.

All_es, all ecosystem services.

Appendix 4 Siting Riparian Management in the Right Place

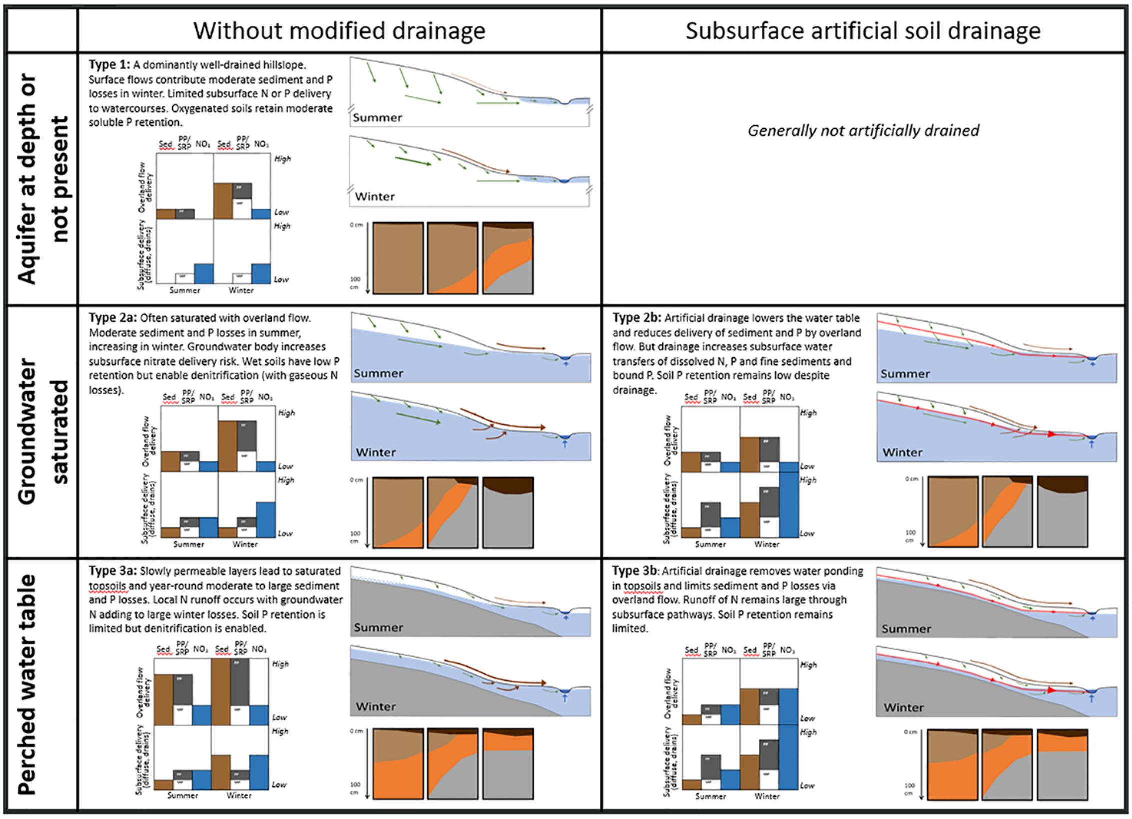


Figure A4.1. Initial set of developed conceptual landscape flow models.

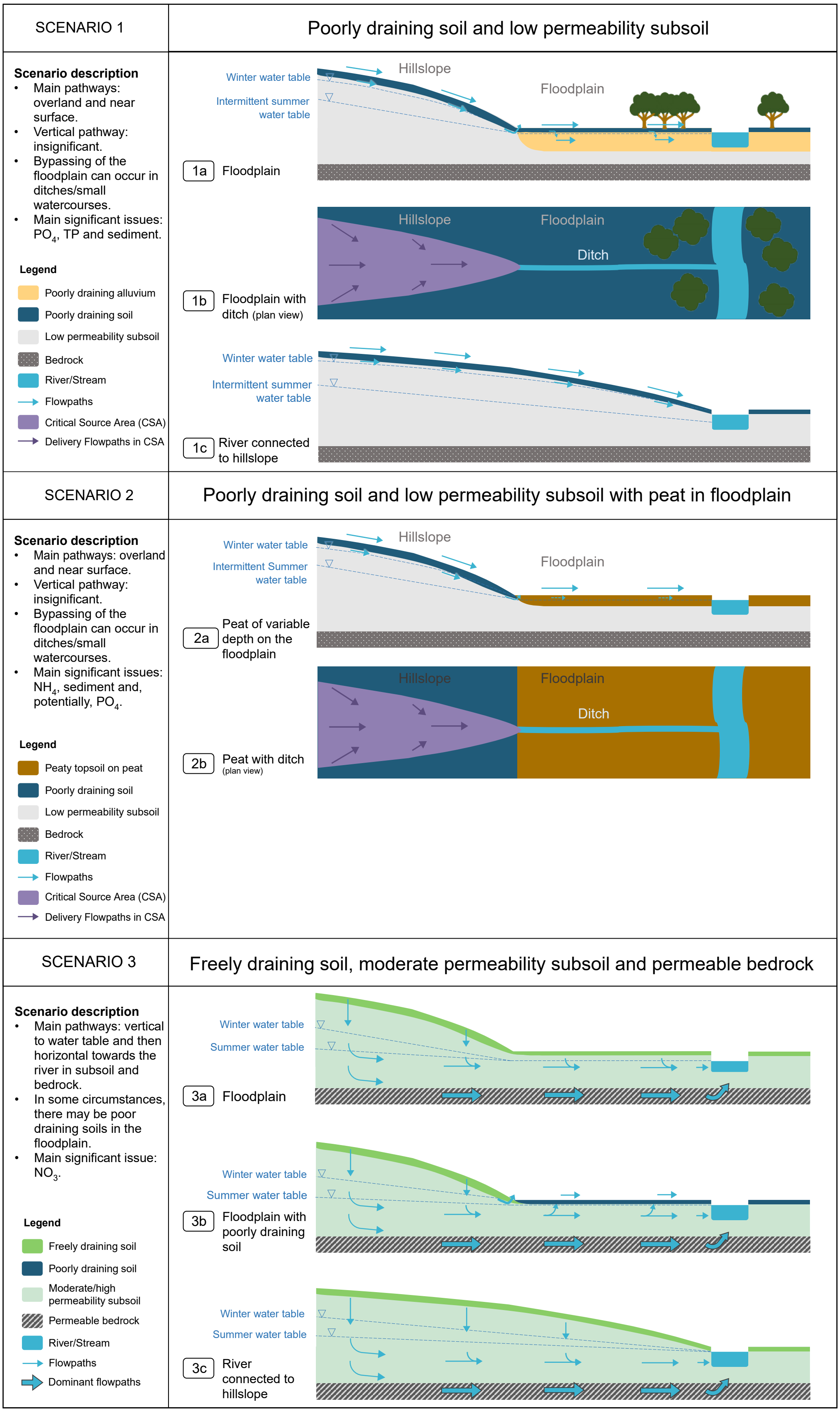


Figure A4.2. Final set of five major scenarios and subtypes of hillslope–riparian flow models developed to contrast pollution pathways from land to watercourses and increase understanding of needs for models of operation of riparian mitigation measures.

SCENARIO 4

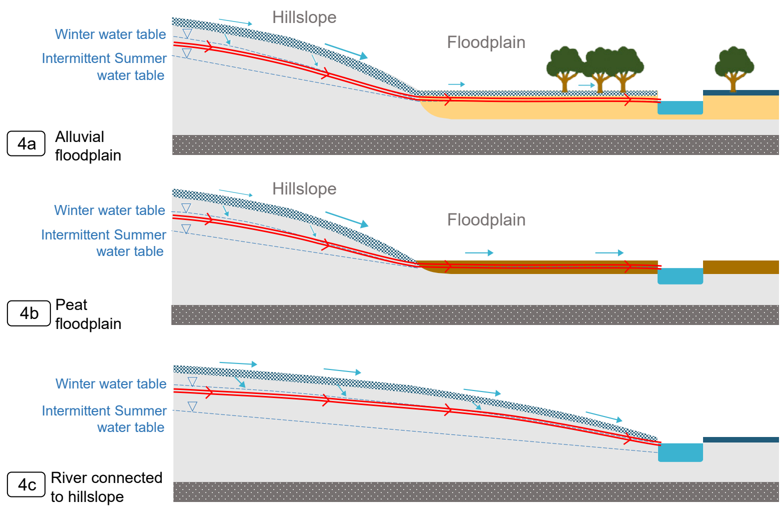
Inherently poorly draining soils overlying low permeability subsoil modified by artificial subsurface soil drainage

Scenario description

- Main pathways: via drains, but times of overland and near surface flow (if drains overwhelmed and/or poor condition).
- Vertical pathway: locally to drain depth.
- Drains provide direct, rapid connection to streams.
- Main significant issues: PO_4, NO_3, TP and sediment.

Legend

- Poorly draining alluvium
- Peaty topsoil on peat
- Poorly draining soil
- Low permeability subsoil
- Bedrock
- River/Stream
- Flowpaths
- Flowpaths for artificial subsurface drainage
- Inherently poorly draining soil modified by drainage



SCENARIO 5

Permeable soils affected by fluctuating groundwater and modified by artificial subsurface soil drainage

Scenario description

- Main pathways: upwelling groundwater with preferential drainage pathways.
- To assist cultivation wide floodplain areas with poor draining soils may be artificially drained.
- Main significant issue: PO_4.

Legend

- Freely draining soil
- Moderate/high permeability subsoil
- Groundwater gley modified by drainage
- Poorly draining soil
- Inherently poorly draining soil modified by drainage
- Permeable bedrock with groundwater
- River/Stream
- Flowpaths
- Flowpaths for artificial subsurface drainage

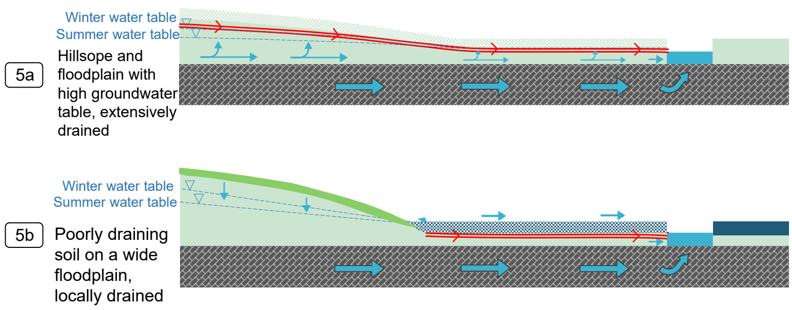


Figure A4.2. Continued.

Table A4.1. Rules for integrating the modes of operation of riparian pollution mitigation measures with the landscape attributes

Measure	Integration with dominant run-off pathways	Integration with hillslope or floodplain form and wetness	Other rules
Baseline margin space			
Grass buffer strip	Effective up to moderate surface run-off. Ineffective at subsurface matrix flows and artificial drainage.	A flatter floodplain receiving zone makes these more effective than steeper, convex slopes.	
Wildflower buffer	Effective up to moderate surface run-off. Ineffective at subsurface matrix flows and artificial drainage.	A flatter floodplain receiving zone makes these more effective than steeper, convex slopes.	
Wooded buffer	Moderate effectiveness at subsurface leaching interception on hillslope and floodplains due to deep roots. Ineffective at artificial drainage by itself.	Increased roughness increases surface run-off effectiveness on moderately steep ground.	Unsuitable for peat soils on floodplains or hillslopes due to potential for soil carbon loss due to evapotranspiration lowering the water table.
Surface run-off and sediment options			
Magic margins	Effective at surface run-off and sedimentation. Ineffective at subsurface flows.	Can be used at the slope base on steeper ground. Requires moderate drainage at the slope base for infiltration; cannot be waterlogged.	First-level augmentation of grass buffer, used in higher erosion risk situations of slope and cropping on soils that generate less run-off.
Raised buffer: field run-off	Effective at surface run-off and sedimentation. Ineffective at subsurface flows and for freely draining soils.	Suitable for a greater range of soil wetness due to being a raised feature and because outlet pipe can be engineered. May be built into moderately sloping banks.	Used in higher erosion risk situations of slope and cropping on soils that generate low–medium run-off. May be used in low erosion risk situations to manage flood risk. Combine with other drain options for artificially drained fields.
Raised buffer: overbank storage	Effective at water storage and sedimentation from rising streamflow.	Suitable for a greater range of soil wetness due to being a raised feature and because outlet pipe can be engineered.	Works in a catchment context to treat local and upstream run-off so may be suited to a location based on upstream, and not solely local, risk of run-off generation. Not suitable for steeply sloping banks as sited on floodplains.
Sediment trap	Effective at surface run-off and sedimentation. Ineffective at subsurface flows and for free-draining soils.	May be built into moderately sloping banks. Cannot be waterlogged or has no trapping capacity.	Mostly a measure for extreme erosion in other than poorly draining soils. Combine with other drain options for artificial drained fields.
Sediment filter fences	Effective at aggressive situations of surface run-off and sedimentation. Ineffective at subsurface flows and for free-draining soils.	Useful on steeper slopes where other measures are less suitable for aggressive erosion situations.	Considered a "measure of last resort" for sediment control.
Subsurface pathway options			
Surface water, groundwater wetlands	Good for retaining surface- and groundwater for treatment, including effective for denitrification.	Only suitable for floodplain, shallow slope situations. Higher water tables required so less effective on artificially drained landscapes.	Suitable for high water table soils, especially peaty, where it benefits C storage and C availability fuels denitrification. Appropriate on freely draining hillslopes where wet concave slope base or floodplain exists.
Tile drain-fed wetlands	Intercepts tile drainage for wetland treatment, e.g. denitrification. May intercept some groundwater if capacity designed well.	Only suitable for floodplain, shallow slope situations.	May be overwhelmed if receiving a lot of surface run-off.

Table A4.1. Continued

Measure	Integration with dominant run-off pathways	Integration with hillslope or floodplain form and wetness	Other rules
Integrated buffer zones	Multiple elements: (i) tile drain interception, (ii) soil matrix flow interception in bioactive tree root treatment zone, (iii) linear pond system capable of receiving surface run-off if managed.	Only suitable for floodplain, shallow slope situations. Designed for seasonally high water tables but may usefully intercept artificial drainage on a drier floodplain situation.	Tree planting should be excluded from peat soils due to soil C loss risks with lowered water table.
Denitrifying bioreactors	Intercepts artificial drainage pathways to load bioreactor with N for treatment.	Only suitable for floodplain, shallow slope situations. Requires anaerobic wet conditions and high C but both can be engineered into a wider set of situations.	May be suitable for local tile drainage on floodplains if intercepts hillslope water to ensure sufficient loading.
Controlled drainage	Intercepts artificial drainage pathways and holds water in an artificially wetted hillslope for certain seasons.	Requires correct gentle slope and riparian profiles to maintain saturated topsoils on a limited cropland area for winter seasons.	Requires large artificial subsurface drainage catchments extending up hillslopes. Farmer must be prepared for non-cultivation periods of low trafficking during time the drain valve is shut and soils wetted to avoid soil damage.
Tile drain irrigation onto saturated soils	Irrigates tile drain water onto saturated surface soils for nitrogen treatment.	Only suitable for floodplain, shallow slope situations. Requires anaerobic wet conditions and moderate soil C levels.	
In-channel options			
Two-stage channels	Has multiple aspects of (i) sedimentation and (ii) N processing in wet, secondary (side-benches) channel profile zones.	Requires fluctuation of river level from high to baseflow. Cannot work with high water table floodplains where stream height is maintained.	Works in a catchment context to treat local and upstream run-off so may be suited to a location based on upstream and not solely local pollution risks. Undrained wet floodplain situations are excluded. Can work with no floodplain if water table allows low stream flow.
In-ditch sediment trap or filter	Functions for moderate- to high-risk erosion areas by providing sediment trapping in the channel.	Can work with a variety of slope forms and floodplain presence or not, or water tables adjacent to the channel suing different designs or trap or filter.	Works in a catchment context to treat local and upstream run-off so may be suited to a location based on upstream, and not solely local, erosion risks. Most suitable for high surface run-off areas. Unlikely sufficient sediment source area in freely drained landscapes.

A4.1 Explanation of Questions within the Tool

Field-specific pressures: this section (see example in Figure A4.3) has a top line question “**Are the soils mineral or peaty?**”, which subsequently sets out five or four questions for mineral or peaty soils, respectively. For mineral soils, questions on texture and drainage are included. The difference for peaty soils is that drainage and texture questions are omitted. Instead, the question is whether the soils are **drained, lowland peat and peaty soils; undrained, lowland peat; or upland blanket peat**. This sets the context of soil drainage and erosion risk. This question set identifies inherent soil erosion risk classes, comprising nine classes for mineral soils (three subclasses within each of high, medium and low), seven classes for lowland peats (low to moderate subdivisions) and one class (high) for upland blanket peat. The erosion risk class is based on work done in Scotland, UK, by Lilly *et al*. (2002) using erosive energy (run-off and slope) and erodibility (based on texture for mineral soils and peat type for organic and peaty soils). The next stage adjusts up/down the subdivisions of these inherent risk classes for the effects of cropping and land management, with guidance notes provided. A further stage acts to lower the erosion risk by one or two subdivisions if one or more in-field mitigation measures are present.

The nature of delivery points: the next set of questions (see example in Figure A4.4) aims to define the extent to which diffuse flow occurs across large parts of the soil surface (or immediately beneath the surface) when it rains (such that linear general buffer zones are more appropriate) or often as convergent pathways of overland flow (where point sediment retention measures are more appropriate). A second question concerns modification of the flow paths by linear features on the field, and guidance for both questions is provided in the form of a schematic.

The nature of the riparian zone: two questions in this section address important pathways known to bypass surface buffer zone management, such as grass strips along the watercourse edge. First, a question about the occurrence of the key subsurface bypass pathway of artificial soil drainage is asked. This acts to prioritise the group of subsurface drain measures. Second, a very specific question addresses the occurrence of an open drainage ditch section that connects a high-pollution source area of the field (a CSA, e.g. an area of high soil nutrient content, an area poached by cattle or another source area with high transport over/through soils) to the watercourse. Guidance on CSAs is given by schematics. Other questions here address existing field-edge grass margins and wet areas of margin space. The latter favours saturated ground features that have denitrification functions.

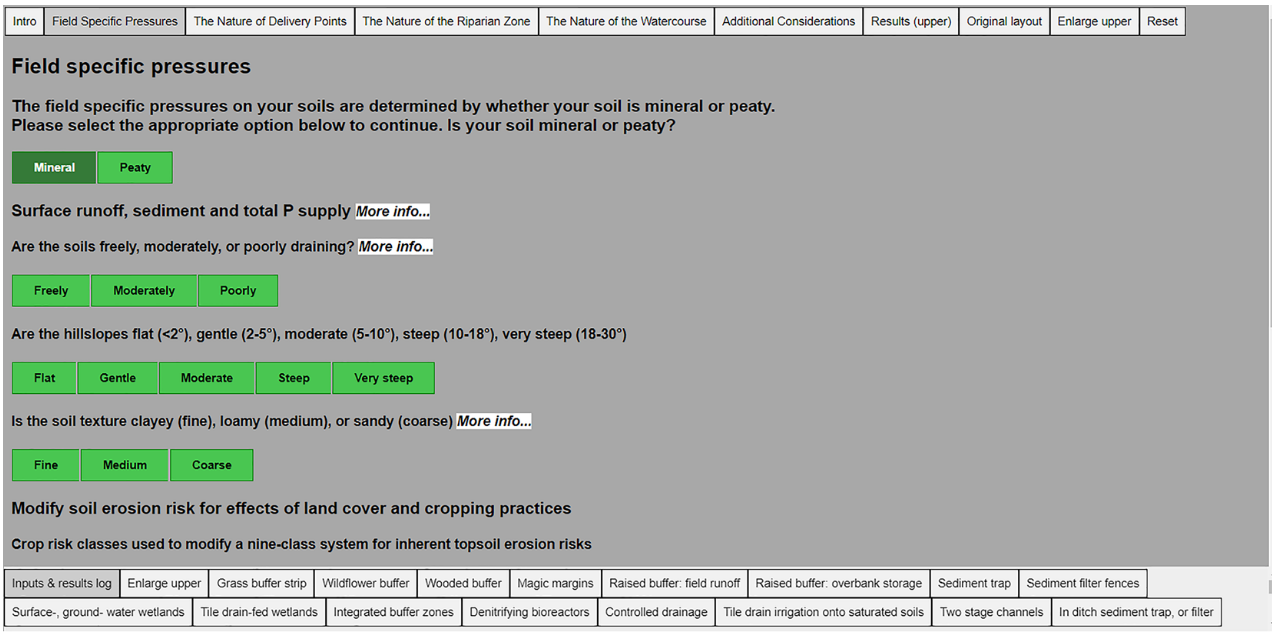


Figure A4.3. A section of the question input tab “Field-specific pressures”.

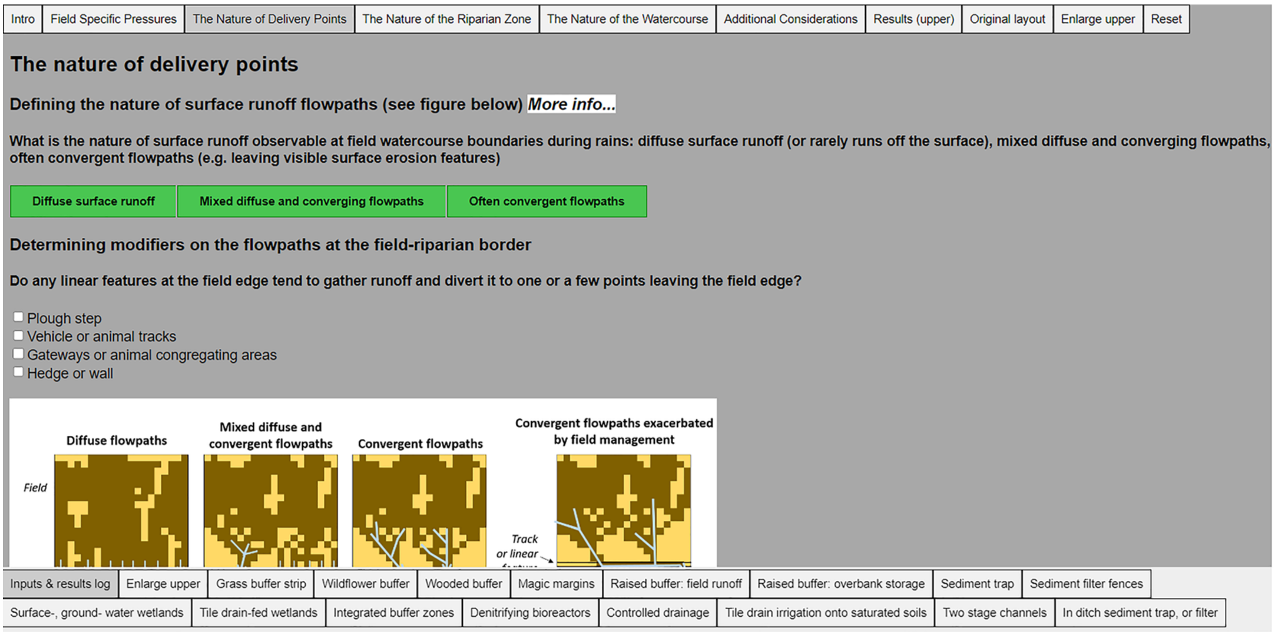


Figure A4.4. A section of the question input tab "The nature of delivery points".

The nature of the watercourse: the first question (see example Figure A4.6) on the watercourse type either allows in-ditch mitigation measures or disallows them for a natural watercourse (see Figure A4.6). Mitigation is considered similar for a lake and a natural stream. The floodplain context is addressed here in a further question that allows differing combinations of drainage on the hillslope and floodplain. For example, freely draining soils on both hillslope and floodplain disallow saturated ground denitrification measures and leave only measures that have low to moderate effectiveness for nitrate pollution. However, freely draining hillslopes where nitrate may leach, if coupled with wet riparian zones and poor draining floodplains, allow surface water and groundwater wetlands and saturated ground measures, which increase nitrate mitigation effectiveness, to be implemented. A final question on specific watercourse issues related to sedimentation increases the weighting for sediment and total P retention measures.

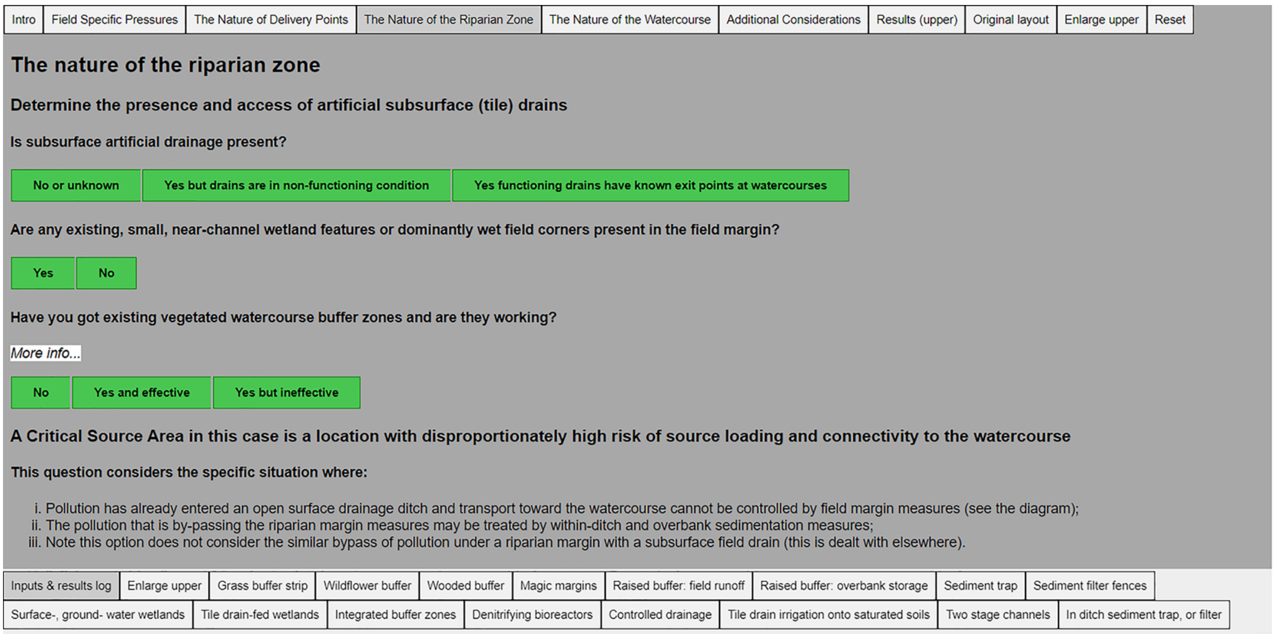


Figure A4.5. A section of the question input tab "The nature of the riparian zone".

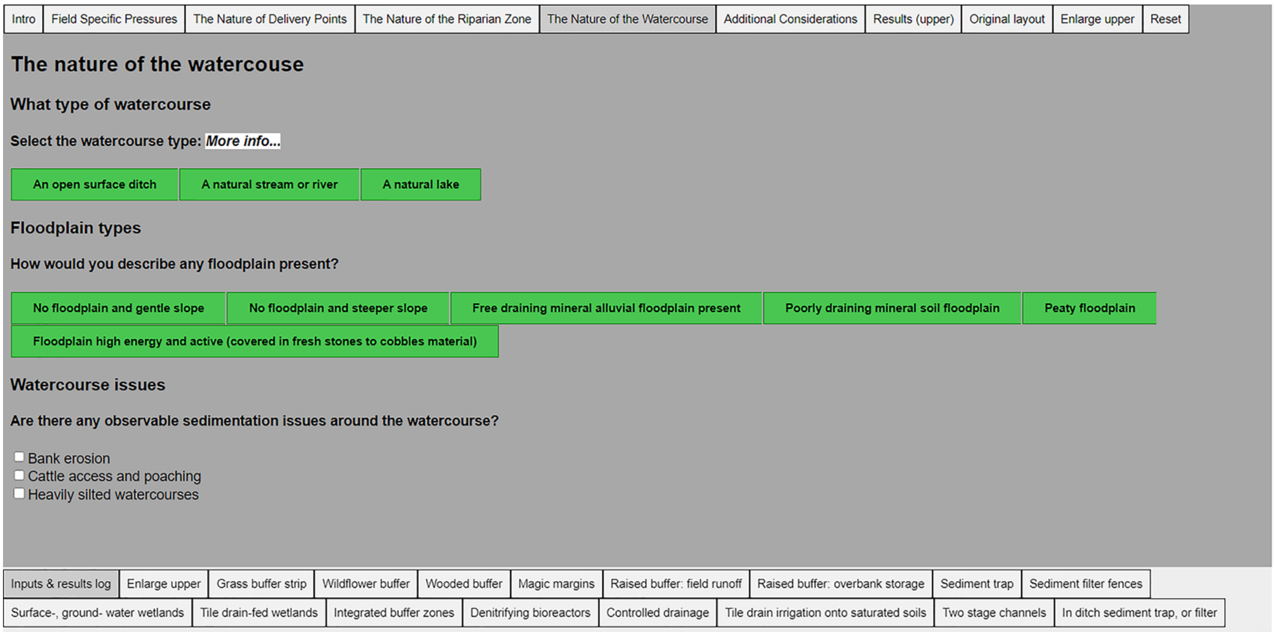


Figure A4.6. A section of the question input tab "The nature of the watercourse".

Additional considerations: this tab does not affect the outcomes of the scoring. It uses pop-outs to give guidance on three key aspects of habitat when considering components of riparian mitigation, their installation and their management. The advice is generic, without citing policy or regulation, so that the tool is transferable between regions and is not date limited.

		Question group outcomes	Grass buffer strip	Wildflower buffer	Wooded buffer	Magic margins	Raised buffer: field runoff	Raised buffers: overbank storage	Sediment traps	Buffer surface and ground water wetlands	Tile drain fed wetlands	Integrated buffer zones	Denitrifying bioreactor	Controlled drainage	Tile drain irrigation onto saturated soils	Sediment filter fence	Two-stage channels	In-ditch sediment trap or filter
Field specific pressures	Question group: Q. Is the soil mineral or peaty?; Q. Are the soil freely, moderately, or poorly draining; Q. Are hillslopes flat, gentle, moderate, steep or very steep slopes?; Q. Is soil texture clay, loamy, sandy?; Q (peats only), Is the peaty soil lowland drained, lowland undrained or blanket upland peat?; Q, Crop classes that modify inherent topsoil erosion risks?; Q, In field mitigation measures that modify the erosion risk class?	L erosion risk, low runoff	3	3	2	1	1	1	1	2	0	1	2	0	0	0	1	1
		M erosion risk, low runoff	1	1	2	2	2	2	2	2	0	1	2	0	0	0	2	1
		H erosion risk, low runoff	0	0	1	2	2	2	2	2	0	1	2	0	0	2	2	2
		L erosion risk, mod-high runoff	1	1	1	1	1	1	1	2	2	1	1	2	2	0	1	1
		M erosion risk, mod-high runoff	2	2	2	1	1	1	1	2	2	2	1	2	2	0	1	1
		H1 erosion risk, mod-high runoff	0	0	2	1	2	2	2	2	2	2	0	1	2	1	1	2
		H2-3 erosion risk, mod-high runoff	0	0	1	2	2	2	2	2	2	1	0	1	2	2	1	2
		L erosion risk, peaty soils	1	1	0	0	1	1	0	1	2	1	0	1	1	0	1	0
		M erosion risk, peaty soils	2	2	0	0	2	2	0	2	2	1	0	1	1	1	1	1
Nature of delivery points	Q, What is the nature of surface runoff?	Diffuse surface runoff	2	2	2	1	0	1	0	2	2	2	2	2	2	0	1	1
		Mixed diffuse and convergent flowpaths	1	2	2	1	1	1	1	1	1	2	1	1	1	1	1	2
		Often convergent flowpaths	0	0	1	0	2	2	2	1	1	2	1	1	1	2	1	2
	Q, Do any linear features at the field edge modify flow?	Selection of any of the listed modifiers	1	1	1	2	2	2	2	1	1	1	1	1	1	2	1	1
Subsoil drains	Q, Is artificial subsurface drainage present?	Not present/unknown	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
		Yes present (any of the 2 yes options)	1	1	1	1	1	1	1	1	3	3	3	3	3	1	1	1
Wet areas	Q, Any existing near-channel wetland features or dominantly wet field corners in the margin?	Yes	1	1	1	1	1	1	1	2	2	2	1	1	2	1	1	1
Existing Veg strips	Q, Any existing grass buffer zone features and are they working?	Yes and effective	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
		Yes but ineffective	1	1	1	2	2	1	2	2	2	2	2	2	2	1	1	1
CSA bypass	Q, Is an open drainage ditch bypassing buffer zones?	Yes	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	3
Watercourse type	Q, Select the watercourse type	Yes to natural stream, river or lake	1	1	2	1	1	2	1	2	1	1	1	1	1	1	1	0
Floodplain types	Q, How would you describe any floodplain present?	No floodplain, sloping directly to banks (a) look at slope Q = slope <10°	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
		No floodplain, sloping directly to banks (b) look at slope Q = slope >10°	1	1	1	1	1	0	1	0	0	0	0	0	0	1	0	1
		Freely draining mineral alluvial floodplain	1	1	2	2	2	2	2	0	0	1	1	1	1	1	2	1
		Poorly draining mineral soil floodplain	1	1	2	1	2	2	2	3	3	3	1	1	2	1	0	1
		Peat-dominated floodplain	1	1	0	0	1	1	1	3	2	0	0	0	1	0	0	0
		High energy floodplain	1	1	1	0	0	0	1	1	1	0	1	1	1	0	0	0
Watercourse sedimentation	Q, Any observed sedimentation issues around watercourses?	Yes to any	1	1	2	2	3	3	3	1	1	2	1	1	1	1	2	3

Figure A4.7. Finalised criteria scoring table for weighting and excluding the measures against questions. Numerical values per row denote measure exclusion (zero) or a positive score that is incorporated into the summed overall score. Questions result in one outcome row per group (field-specific pressures only) or individual question (all others).

Table A4.2. Scores for potential (upper ceiling for well-designed, sited and maintained measures) pollutant effectiveness used in the reporting table of the tool against the dynamic (i.e. user question-derived) tool ranking of measures according to landscape suitability: (a) original 1 (low) to 5 (high) effectiveness scores from the first level of scoring by 24 international experts (response rate 32% to a questionnaire) and (b) a simplification of the results used in the tool report table using a low (L), medium (M) and high (H) classification

(a)

Measure	Sediment	P	N	Pesticide	FIO
Grass buffer strip	3	2	1	2	3
Wildflower buffer strip	2	2	2	2	2
Wooded buffer strip	4	3	2	3	3
Magic margin	4	3	2	3	3
Raised buffer: field run-off	4	3	2	2	3
Raised buffer: overbank storage	3	2	2	1	2
Sediment trap	4	4	2	2	2
Sediment filter fence	4	3	1	1	2
Surface water, groundwater wetland	3	3	4	2	3
Tile drain-fed wetland	2	3	3	2	3
Integrated buffer zone	4	4	3	3	3
Denitrifying bioreactor	3	2	4	2	2
Controlled drainage	3	3	3	3	2
Tile drain irrigation onto saturated soil	4	3	4	3	2
Two-stage channels	4	3	3	2	2
In-ditch sediment trap, or filter	4	3	2	2	2

See Chapter 3 for method details.

(b)

Measure	Sediment	P	N	Pesticide	FIO
Grass buffer strip	M	L	L	L	M
Wildflower buffer strip	L	L	L	L	L
Wooded buffer strip	H	M	L	M	M
Magic margin	H	M	L	M	M
Raised buffer: field run-off	H	M	L	L	M
Raised buffer: overbank storage	M	L	L	L	L
Sediment trap	H	H	L	L	L
Sediment filter fence	H	M	L	L	L
Surface water, groundwater wetland	M	M	H	L	M
Tile drain-fed wetland	L	M	M	L	M
Integrated buffer zone	H	H	M	M	M
Denitrifying bioreactor	M	L	H	L	L
Controlled drainage	M	M	M	M	L
Tile drain irrigation onto saturated soil	H	M	H	M	L
Two-stage channels	H	M	M	L	L
In-ditch sediment trap, or filter	H	M	L	L	L

See Chapter 3 for method details.

		Scenarios		
Tool input tab	Tool question	1. Intensive grassland	2. Intensive grassland (subsurface soil drainage)	3. Arable (high erosion)
Field specific pressures	Soil type	Mineral	Mineral	Mineral
	Soil drainage	Free	Poorly	Moderately
	Slopes	Moderate	Gentle	Moderate
	Soil texture	Medium	Fine	Medium
	Crop classes	Low	Low	Medium
	In field mitigation	Rotational grazing	Rotational grazing	None
Nature of delivery points	Surface flowpaths	Diffuse	Mixed diffuse and converging	Converging
	Flow modifiers	Animal tracks	Animal tracks	Plough step
Nature of riparian zone	Subsurface drainage	No	Yes, functioning drains	Yes, functioning drains
	Distance crop to watercourse	2-5m	<2m	2-5m
	Wet field corners	No	Yes	No
	Cattle access restrictions	Yes, fenced	No, direct access	Yes, a fence
	Direct Critical Source Area connection	No	No	No
Nature of the watercourse	Watercourse type	Natural stream	Open surface ditch	Natural stream
	Floodplains	No floodplain and gentle slope	Poorly draining mineral floodplain	Poorly draining mineral floodplain
	Watercourse issues	None visible	Cattle access, poaching	Heavily silted watercourses

Figure A4.8. Tool-suggested inputs given to the stakeholder testing group of November 2022.

Questions	Respondents							
Score out of 10 for:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1. Clarity of concepts	10	7	8	7	7	4	9	9
2. Display of measures selected	10	8	7	6	5	8	8	9
3. Understanding of factors	10	5	7	7	6	6	8	8
4. How may help your role as: (i) stand-alone tool (e.g. online)	8		9	8	8	8	8	7
(ii) as an advisor-practitioner discussion prompt	10		9	8	8	10	10	10
A limited amount of explanation of input factors is provided in the tool by use of 'more info' functions and diagrams. Are there examples where more of this is required, relative to a balance of decluttering the tool and making it's usage more slick?	Options to link to biodiversity outcomes by e.g. differing woodland type buffers	Assume a non-expert user: have a go-to manual for relative weighting of parameters and rational of the decision rules	Depends on user knowledge and term familiarity	No, slick and fairly informative as is	In cases the factors could be less subjective	Instead of info pop-outs consider separate tabs with guidance or a user manual with schematics and tables	Good. Initial advisor training would help.	Needs to define open drains vs stream.
We could have explained more in the tool the logic rules for why inputs lead to measures rankings. But there is a balance of that with slick operability and changing inputs is a way to explore change in outcomes. What do you think of this balance?	Good balance	Include a user guide that user can consult	Fine, but could have a user manual	The balance works well	Balance is okay	User dependant: good now for an expert (or expert-stakeholder discussion), more needed for non-expert	Balance is good but depends on user knowledge	Good for advisor farm visits.
Included with the ranking of the measures is an output table of measure effectiveness for major pollutant groups. How useful is this and why?	Useful reminder of range of measure effectiveness	Useful to an extent: explain why cannot manipulate the measure effectiveness through the questions	Uswful visual aid but should be improved	Works as you get the options that best fit the catchment and allowing then to pick against the most effective measures. Could though be improved.	Useful, but the ranking is misleading as could encourage the selection of less effective measures for the key issue	Very useful to relate to catchment pressures but need to clarify ranking prioritisation vs effectiveness.	Useful in informing chats advisor, to farmer	Useful as shows best landscape fit but allows choice of that against effectiveness
How should we use the principal of a CSA connecting through a field margin or field edge via an open drain to a natural watercourse?	Should also recommend to break this pathway by physical separation.		This does occur and is correct to deal with separately to the buffer margin		Use a video of a CSA connecting during a flood		Good concept in using open ditches as a mitigation tool	Need to explain CSA concept better (e.g. to farmers). Where do we need to intervene with these measures?
Any factors of the design of the tool that you feel could be improved?		Could incorporate better the varying receptor aspects of significant issues (like estuaries vs rivers, tool suits best the latter)	It is well designed overall but clunky due to the job complexity	Good overall design and of use to an advisor on farm.	On the final output table could also have a ranking of the likely issues affecting water quality	Lower panel could benfit from being down-sized when filling upper tab info. Explain the expert process in the effectiveness. Clarify the scales of the tool use e.g. field to (sub)catchment	Good to have available online. Good photos/schematics of the measures.	Could consider cost-effectiveness. How will soil texture be assessed (from national databases)? Has huge potential for advisors and catchment officers.

Figure A4.9. Results of the stakeholder tool testing carried out in November 2022 and the proposed actions for the tool revisions compared with suggestions considered outside the scope of this tool version. No shading indicates general comments, while green, orange and red shading indicates comments were incorporated into tool revisions, incorporated in part or considered outside the tool remit, respectively.

Questions						
Score out of 10 for:	9	10	11	12	13	Average score (range)
1. Clarity of concepts	8	8	7	8	8	8 (4 to 10)
2. Display of measures selected	9	7	10	9	8	8 (5 to 10)
3. Understanding of factors	7	5	10	8	6	7 (5 to 10)
4. How may help your role as: (i) stand-alone tool (e.g. online)	6	10	10	8	10	8 (6 to 10)
(ii) as an advisor-practitioner discussion prompt	6	10	10	10	8	9 (6 to 10)
						How aspects will be incorporated in revisions
A limited amount of explanation of input factors is provided in the tool by use of 'more info' functions and diagrams. Are there examples where more of this is required, relative to a balance of decluttering the tool and making it's usage more slick?	Ok, more worked examples needed	Could use 'open in a new page' and 'return to page' options	More diagrams beneficial to user and for farmer communication	The current amount of 'more info' is good	Currently good	Include more guidance pop ups e.g. for soil texture; Improve overall terminology and give efinitions.
We could have explained more in the tool the logic rules for why inputs lead to measures rankings. But there is a balance of that with slick operability and changing inputs is a way to explore change in outcomes. What do you think of this balance?	Keep it simple and visual	Good for those that want more info. "I love this tool"	Better to say how the tool inputs relate to changing the ranking of measures	Current balance okay, but more info on the rules would aid explanations to the farmer	Should be summarised to develop understanding of the tool	Include in an accompanying user handbook a summary of the rules behind the weightings leading to the measure ranking.
Included with the ranking of the measures is an output table of measure effectiveness for major pollutant groups. How useful is this and why?	Good but conflicts with few N measures being effective	I'd prefer a numerical ranking than H, M, L	Very useful but shows conflicts between phyical placement possibilities and effectiveness	Useful for interpreting results against effectiveness	Very useful for matching rankings to main pollutant of concern	Show up front that this is an education and guidance tool, aiming to show coherence and conflicts between landscape fit of measures (field scale) and pollutant issues at (sub)catchment scales; Fix the blanket rejection of surface-/ground-water wetaldns in free-draining hillslopes (N risky landscapes) so that these are ranked well in appropriate situations of wet riparian zones; Explain the H, M, L as the static results (ie not varying with altered inputs to user questions in the tool) from expert effectiveness assessment representing the upper ceiling of effectiveness for optimum designed and maintained measures; Remove confusing question elements around cattle access as this is already prescribed management of a measure.
How should we use the principal of a CSA connecting through a field margin or field edge via an open drain to a natural watercourse?	Explain why it is a CSA in this aspect	Drains need to be mapped, are they connected to fields or farm yards?	Could use a sedimentation pond here or a planted riparian zone	Good to highlight the CSA concept	Didn't understand this	Keep the concept in for the direct connection of a Critical Scource Area bypassing riparian management via an open surface drainage ditch, but improve the wording and include a diagram.
Any factors of the design of the tool that you feel could be improved?	More on how you would link these features together	Consider a final cartoon map with placement of the measures typified.	Use further diagrams /images. Explain why the inputs are changing the rankings	Colour sceme for ranking could be improved (e.g. WFD colour scheme for quality). Design is good but could be visually 'modernised'	Switch yellow-orange in ranking order; some Qs are unclear (e.g. cattle access); Include maize as a high risk crop; a stand-alone 2-page paper checklist on this would also be useful	Include a button for shrink/enlarge lower panel; Change colours, swap yellow and orange order so adheres to traffic light; Crop management – add maize into high risk group in the guidance; Temporal element - for field specific tab page change question text to 'surface runoff sed and total P supply' (answer for non-extreme rainfall events and the combination of questions derives likelihood of runoff, the measures selection include some safety margin for risk) and add to handbook/video/guidance.

Figure A4.9. Continued.

Appendix 5 Integrated Catchment Demonstration: A Case-based Approach

A5.1 Case Study Catchment – Ballycanew

The Ballycanew catchment is located north of the village of Ballycanew, County Wexford, in the south-east of Ireland. The catchment is 11.9 km^2, has an altitudinal range of 25–230 m a.s.l. and is drained by a second-order stream flowing into the River Brackan sub-basin of the River Owenavoragh (36 km^2). Just over a third of the catchment has slopes with gradients of greater than 5%.

Most of the land (97%) within the catchment is used for agriculture: grassland accounts for 77% and tillage for 20%. The remaining 3% of catchment land is used for woodland and other uses. The main grassland-based farm enterprises are beef production and dairying, with some sheep production. Spring barley is the main tillage crop, with small areas used for other cereals. While tillage in the catchment is limited to the southern upland area with well-drained soils, dairying is expanding with drainage and nutrient management of the heavier soils. The average organic P source based on stocking rate was 12.5 kg organic P/ha for 2010–2018. During that time, agronomic intensification took place, with the amount of land under derogation increasing from 13% to 30%.

Two-thirds of the catchment has poorly drained soils due to its location on the edge of the Macamore soil association (fine loamy over clayey calcareous Irish Sea till). The Macamore soils (surface water gleys) are found across the lowlands of the catchment. These consist of thick, gravelly clay deposits and some lenses of more sandy or gravelly material closer to the surface. In that area, the drainage has been improved over time by the owners through tile and mole drainage. Well-drained Clonroche soils (non-calcareous brown earths) are found in the uplands, in the south-west of the catchment. Where the two soils meet, in the break of the slope, there is a spring line.

The mean annual total rainfall monitored within the Ballycanew catchment is 1037 mm, of which 46% contributes to the river discharge and only a small fraction goes to deeper storage. In some years, there is negative storage. The mean annual river discharge is 506 mm, with a relatively low proportion of baseflow (baseflow index = 0.63). The river flow is "flashy" (Q5/Q95 = 126), indicating large surface run-off contributions with a relatively short transit time of water from the landscape to the stream (Mellander *et al*., 2022).

Table A5.1. Measure hierarchical framework

Measure level	Details
Level 1 – fixed linear 2 m width, basic measure	A default 2 m-wide buffer (where appropriate fenced cattle exclusion) following a watercourse or ditch. Retention of existing wooded features is required.
Level 2 – variable width at flow delivery points with enhanced wooded features	Additional measures to level 1, including: • increases in width where flow delivery requires it; • enhancement of wooded features if justified by run-off trapping or absence of such features for habitats on a natural stream reach.
Level 3 – bespoke measures considering many aspects and upstream areas	Additional measures to level 1 often instead of level 2 option. Includes a wide range of measures bespoke to the field situation including 16 measures in the riparian space and in the ditch. Level 3 measures particularly consider the wider functioning of the catchment in terms of collective flow from areas through the channel network as well as wider aspects of infrastructure development/improvement.

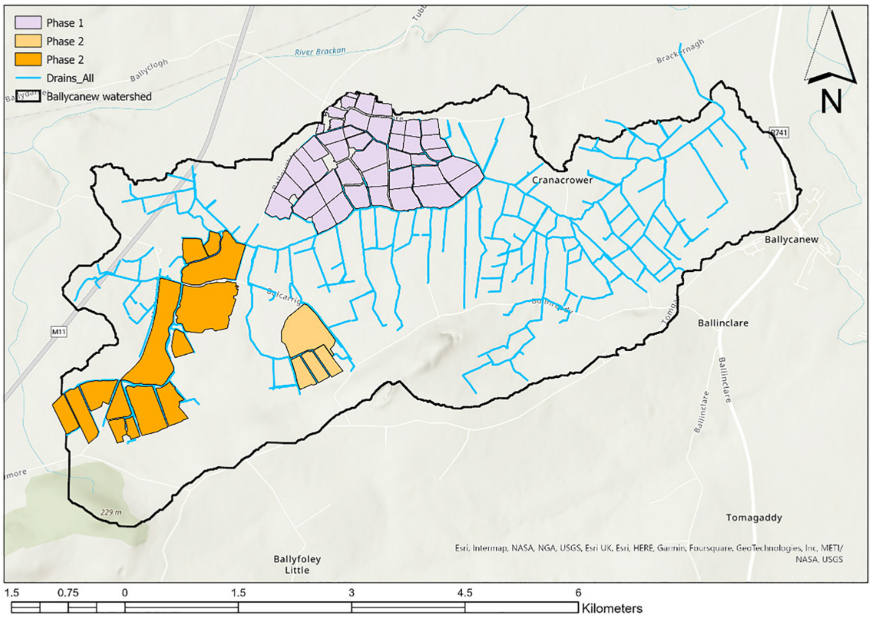


Figure A5.1. Ballycanew catchment, Co. Wexford, with field analysis (phases 1 and 2) areas highlighted. The two assessment areas equate to roughly 20% of the total catchment area.

Table A5.2. Summary of datasets used in desk-based assessment

Spatial dataset	Resolution	Source/acknowledgement
DEM (inc. hydrologically corrected dataset)	0.25 cm to 5 m	Teagasc Agricultural Catchments Programme
P-Maps Outputs	5 m	EPA
Soil maps	Unknown	Unknown
Field boundary dataset	N/A – shapefile	Teagasc Agricultural Catchments Programme
Watercourse and open drain network	N/A – shapefile	Teagasc Agricultural Catchments Programme
Aerial imagery	N/A	Google Earth © 2022 Maxar Technologies
Google street view	N/A	© 2022 Google
OPW flood maps	N/A	https://www.floodinfo.ie – provided by the Office of Public Works

A5.2 Stakeholder Workshop

A 1-day workshop was held in Wexford on 9 November 2022. During an afternoon session, delegates at the workshop were asked their views on the level 1, 2 and 3 measures from selected areas in the Ballycanew catchment. First, the delegates were split into three groups, with four to six people per group. One group looked at the level 1 and 2 measures in the south-west of Ballycanew (Figure 5.3), another looked at the sediment trap and raised buffer (overbank) in Field G (Figure 5.4) and the last group looked at the treatment train of measures in Field 7 (Figure 5.6). The groups were first asked questions on the topics listed in Table A5.3 and were asked to come to a consensus. In some cases, the groups ran short of time, so only the overall measure score was presented or only the individual measure score was presented and not the overall package.

The groups were then asked to discuss the opportunities and challenges presented by each measure scenario. This led to a discussion about costs, where we presented some indicative timescales needed to construct the measure. Only capital costs were considered. Finally, the groups were asked to put forward up to three barriers and opportunities for each measure scenario.

Table A5.3. Question topics covered by workshop delegates

Question topic	Score method
Environmental quality improvement potential	An effectiveness score between 1 and 5 should be given for a measure's **potential** effectiveness. Think of 1 as a standard minimum regulatory width buffer
Fits with farm business and goals (no payment)	A score of between 1 and 5 should be given 1 = works against farm business; 3 = no impact either way; 5 = boost to business in some way
Fits with farm business and goals (part of scheme)	A score of between 1 and 5 should be given 1 = works against farm business; 3 = no impact either way; 5 = boost business in some way
Likelihood of uptake	A score of between 1 and 5 should be given 1 = certainly would not consider this; 3 = would potentially consider with further advice/discussion; 5 = no issues, build away
Lifespan relative to management effort	A score of between 1 and 5 should be given 1 = cannot see it lasting long; 3 = will last a good while; 5 = will last a generation and beyond

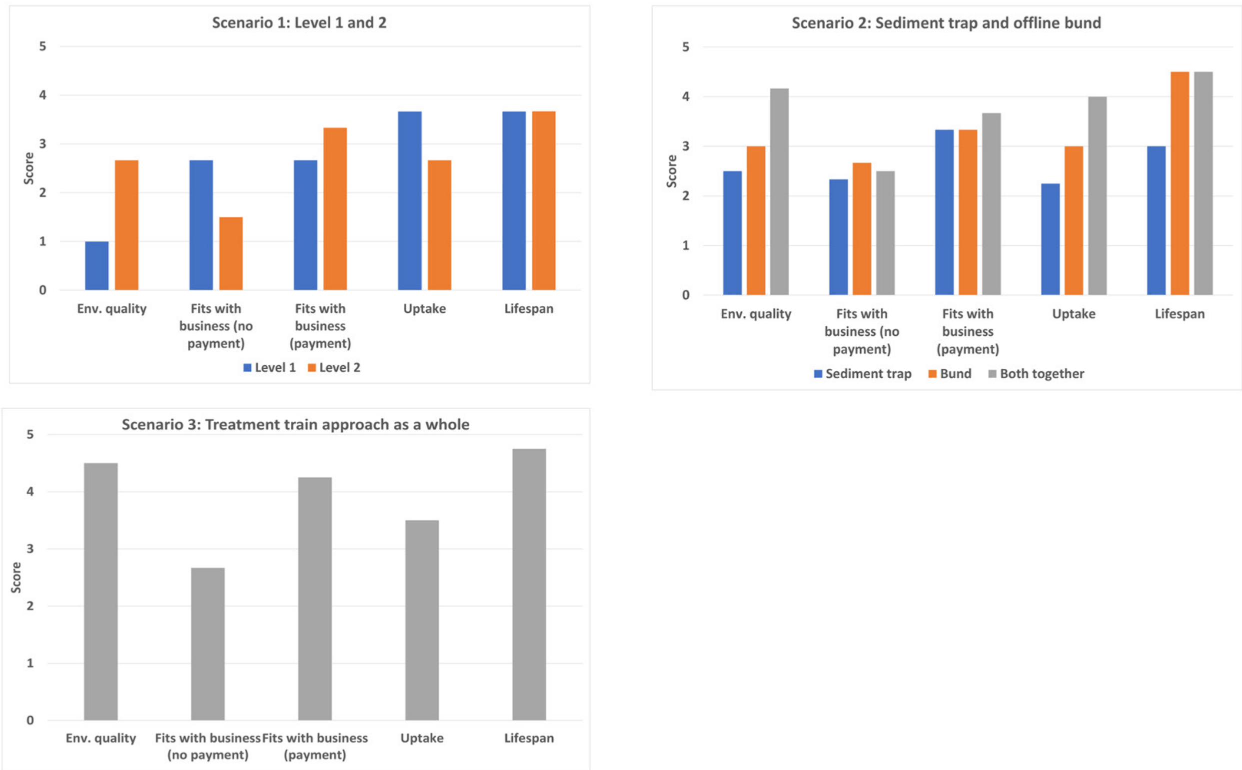


Figure A5.2. Scenario effectiveness scoring from stakeholder workshop.

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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