3D buffer strips: Designed to deliver more for the environment

Chief Scientist's Group report

October 2020

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Professor Doug Wilson
Chief Scientist

Executive summary

Aquatic ecosystems remain under considerable pressure from sediment, nutrients, pathogens and other contaminants lost from agricultural land. These pressures are predicted to increase with a growing population and a changing climate. To date there has been slow progress in reducing agricultural diffuse pollution despite a range of policies being in place to address the problem and the availability of many cost-effective solutions. A highly effective place in the agricultural landscape to target management actions is within the riparian area (zone), the interface between farmed land and a river or stream.

Riparian buffer zones are commonly used to improve water quality by creating a physical barrier that slows the flow of overland runoff and increases infiltration in to the soil, thereby trapping and retaining pollutants before they reach the watercourse. Well designed buffers can have wider environmental benefits including improved wildlife habitat, creation of wildlife corridors, and flood protection. Simple 1-2 m buffers are a condition of cross-compliance and wider buffers are a frequently advised voluntary agri-environment advice measure. To better protect watercourses, now and in the face of increasing pressures, opportunities to improve buffer performance need to be identified, focusing on the structural design elements. This report introduces the concept of a 3-dimensional (3D) buffer zone working above and below the ground to tackle pollution pathways, including surface run-off, subsurface flow and gaseous exchanges with the atmosphere. Design aspects include deep roots to encourage soil biogeochemical processing, re-sculptured ground to enhance run-off capture and above ground vertical planting to allow canopy interception. This report examines the benefits provided by a hierarchy of riparian buffer options using written evidence and expert assessment to evaluate five different buffer types: vegetated (grass filter strip), wooded, designer (herbaceous) vegetation, raised soil and engineered buffers. For all riparian buffers to function effectively it is important that there is also good soil and crop management in the upslope field to minimise the amount of water and pollutants transported to the buffer.

The most basic buffers comprise narrow grass filter strips. These are widely adopted in the landscape as they form part of cross-compliance and are well-studied. When applied in linear, fixed widths these are simple to plan and manage. Their effectiveness in reducing diffuse pollution is limited by being either too narrow or because they are by-passed by surface run-off or sub-subsurface drains. They also have little effect on pollutants entering the water from the air (aerial pollutant pathways) and are easily damaged by livestock accessing watercourses. Existing buffers are often designed as dry buffers to help field drainage, whereas natural riparian areas rely on raised water tables and slower flow pathways to remove pollutants.

The concept of 3D buffers (working below and above the ground) brings more and improved benefits to the ecosystem (as shown by the wooded and engineered buffers). The aim is that buffer design and management are improved by implementing the described features tailored to local conditions and desired outcomes. Buffer design should be based on the nature of the pollution pressure from the adjacent field (for example, type of pollutant and pathway of movement), status of the receiving water environment (chemical and biological quality) and specific ecological and other goals (for example, shade requirements for salmonid habitat, or desire for wildflower diversity for insects). The designs need to consider field, riparian and ditch/stream hydrology in space and time, including the contribution of groundwater. Buffer width is an important factor and needs to be tailored to local circumstances. A 6 metre buffer is likely to be the minimum width compatible with the higher scoring buffer designs. A buffer of 10 to 12 metres (or wider where possible) would be more effective in situations of greater upslope pollution pressures.

Planting trees to establish a wooded buffer improves most functions and has a substantial supporting body of evidence. Wooded buffers scored highest overall in terms of combined functions. Increasing the existing recommendation on planting width of 6 m to 10 m should improve uptake in future environmental land management schemes.

Problematic sites with high pollutant pressures need greater intervention such as more engineered buffer designs. Options could include: re-sculpturing the buffer surface and/or stream banks to temporarily retain surface run-off and to intercept and trap suspended pollutants; creating wetland areas to enhance denitrification; disrupting pollutant delivery via subsurface flows by modifying field drain outlets; or installing within-channel measures. The uptake of engineered buffers is limited by several factors including the lack of observed data, unfamiliarity in the farmed landscape (versus the urban landscape), and a lack of guidance on planning, design and management.

Better advice and guidance on buffer design options could improve their uptake and effectiveness at field and catchment scale. Guidance needs to include which features are most appropriate in a range of situations, the issues and risks in that are likely to be faced and will need to be managed to avoid failure. There are many examples from natural flood management (NFM) work where land managers have installed new features and have been surprised how well they slow the flow of water. Correct installation and long-term management and maintenance of riparian buffer areas is critical to how well buffers function and their long-term effectiveness.

Unfamiliarity with, and a lack of documented evidence on, more ‘engineered’ designs has contributed to negative attitudes expressed in farmer focus groups. The cost-effectiveness of raised and engineered buffer measures for mitigating pollution and supporting wider ecosystem services needs to be compared with other options.

Demonstration studies could increase awareness and potential uptake as part of a shared agenda with NFM networks and land management groups. As expected, as the design of buffers become more sophisticated than simple vegetated grass filter strips, the range and value of environmental benefits increases. Wooded buffers and buffers using natural engineering principles slow the flow of runoff, reduce pollutant loss and support greater biodiversity. The findings suggest there are opportunities to enhance the environmental benefits that new and existing riparian buffers provide by improving the advice and guidance available on design features. Buffers can form an important part of the pollutant ‘treatment train’ alongside other broader field, farm and catchment pollution and soil erosion control measures.

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1 Rationale for 3D riparian buffers

Across England, 86% of rivers failed to reach the Water Framework Directive's (WFD) good ecological status in 2016. Agriculture is one of many influences on water quality and water-dependent ecosystems, has an important role to play and is making a positive contribution to achieving WFD objectives. However, there remains a need for a combination of best practice national measures operational at a farm level, and more locally tailored measures targeted at a number of high risk farming activities in high risk and impacted areas. These need to be implemented through a variety of voluntary, incentivised and regulatory policy mechanisms to achieve the agricultural pollutant reductions required for WFD compliance. There is also a need to tackle the other sectors contributing to the WFD problem in a cost-effective and proportionate way.

A range of mitigation measures are available to tackle agricultural pollution by: (i) controlling pollutant sources; (ii) slowing pathways between sources and receptors; or (iii) protecting receptors. Measures are assessed for their impact on a range of environmental pressures, however, there is uncertainty in relation to the efficacy of many measures over larger scales and longer timeframes. Field margins against watercourses have long been a favoured measure to help reduce agricultural pollutant loss. They are usually the final line of defence where other measures to prevent erosion and run off - such as good soil management - have not solved the problem. Correctly designed, located and managed riparian buffers work to intercept and retain water and pollutants transferred from adjacent fields by surface and subsurface pathways, diversify terrestrial habitats and provide other services to benefit communities and wildlife. Riparian buffers function in 2 ways. Firstly, they set back agricultural activities (cultivation, spraying and livestock grazing) from the watercourse and secondly, they provide a physical barrier to intercept and retain upslope pollutant loads. To ensure the buffer can function correctly and provide adequate protection to a watercourse, there is a need to understand the design elements of a buffer and how these influence effectiveness.

Farmers often regard the riparian margin as the least productive part of the field, as it is often shaded by trees and hedges, sometime flooded and difficult to cultivate with machinery. Farmers receiving a Single Farm Payment under cross compliance must not cultivate, or applying fertilisers, dredgings, slurry, manures or pesticides within 2 metres of the centre of a hedgerow or watercourse or 1 metre from the top of a watercourse bank. Payments for wider riparian buffer strips are available under agri-environment schemes such as Countryside Stewardship (CS). Without compensation payment through CS, land managers can feel riparian buffers are 'land needlessly taken out of production' so buffers are given minimum space and only limited designs are used. Improving the design and effectiveness of buffers brings opportunities to align with agri-environment funding for wider public goods and services by incorporating improved structural elements into the existing basic grassed field margin space that has limited effectiveness.

This report explores several core concepts, namely that:

- improved design, particularly structural aspects related to functioning, and siting of riparian buffers enhances their role from the currently widely-adopted and reasonably well understood but of limited effectiveness and poorly-targeted measures to effective interventions for intercepting and retaining pollution moving from farmed land to watercourses;
- as well as reducing diffuse agricultural pollution, a better and more innovative use of these areas can lead to a wider range of environmental and social benefits that can be more cost-effective and, in turn, reinforce the rationale for buffers and lead to more space or effort in adopting them;
- improved buffer designs can fit into a farm business by incorporating opportunities for biomass or alternative harvest areas, providing access for communities, or simply by realising that hard to manage wet field corners provide the best places to widen buffers locally.

We recommend a tiered approach to improved buffer design. For example, building on from uniformly-structured linear grass buffers to considering targeted design features that can be incorporated into the available space to greatly improve benefits for the environment, farm business and other public goods. This range of options should include herbaceous and woody vegetation management, mini-wetlands intercepting drains, and raised buffer features temporarily storing and filtering run-off water. Designs incorporating targeted tree planting may especially meet a range of goals, including improving water quality, habitat and climate change resilience. These options consider the processes and pathways of pollutants entering watercourses, including water, soil and air. The three-dimensional (3D) concept adopts new and innovative thinking that considers all factors from vegetative canopy to root and drainage zones.

Specifically, the report considers:

- Current knowledge of the role, function and deign of riparian buffers (literature review).
- The baseline of watercourse margin management currently adopted in England and the case for wider uptake and better designs.
- An evaluation of options that can be incorporated into the watercourse margin space against the opportunities and constraints to highlight new riparian buffer designs and incorporate 3D features that improve benefits for the environment.

The methods used for this report combined a literature review including research and evidence from grey and published sources, supported by an expert knowledge workshop approach (Appendix A1-5) with leading academic and environmental experts on buffer management. The expertise covered: hydrology, hydrochemistry, woodland management, catchment system engineering, sustainable agriculture, and soil management in agricultural systems. We also acknowledge the contribution of these experts in helping to co-write this report.

2 The role, function and design of riparian field buffers – literature review

2.1 Tackling the agricultural diffuse pollution transfer continuum – the role of buffers

Agriculture is one of many influences on water quality and water-dependent ecosystems, and has a role to play in meeting WFD and related environmental objectives [1]. The main agricultural pollutants are nutrients (phosphates and nitrates), pesticides and other agrochemicals, faecal bacteria, and soil (sediment). The negative impacts these can sometimes cause include eutrophication (the adverse ecological effects of excess nutrients), increased water treatment costs, and damage to tourism and fisheries. The costs to society from excess nutrients in fresh and coastal waters have been estimated at €5 to €8 billion across nine OECD countries [2], with annual costs estimated at £8 million for regulating diffuse pollution in England alone [3]. Estimates of pollution source contributions averaged across all waterbodies for England and Wales show agriculture as the dominant source for sediment (72%) and nitrogen (81%) and responsible for on average 31% of phosphorus pollution (second to sewage treatment works at 47%)[4].

It is useful to consider the model for addressing diffuse pollution proposed by Haygarth and others [5] of a transfer continuum, comprising source – mobilisation – delivery (or transport) – impact. The primary focus remains on reducing the sources of agricultural pollution i.e. direct inputs that enter through the farm gate, such as fertilizers, pesticides, imported animal feed stuffs and livestock manures. Management measures such as improved soil management are then required to prevent the mobilization of pollutants from land to water. Once mobilised, measures are needed to prevent the tr*ansport or* delivery of pollutants via overland flow, subsurface drainage, or leaching to groundwater. Once the pollutants reach the water, the chemical or ecological impact is extremely difficult to address. Developments in best management practices for reducing agricultural pollution sources and mobilisation may be reaching a limit and, therefore, greater effort is needed to prevent the transport of pollutants to receiving waters [6] using runoff detention features in the landscape such as buffers.

Riparian buffers are a widely used management option as:

- actions at the land-water interface can potentially restore chemical, hydromorphological and ecological functions to better protect river habitats, important species and water supplies
- local factors such as naturally higher soil water tables make the riparian zone less favourable to farming, more vulnerable (for example, to trafficking, bank erosion) and, therefore, critical to protect

- there is great potential for multiple benefits across terrestrial and aquatic systems
- river corridors connect habitats, provide wildlife diversity to farmed landscapes, and give space for natural stream form

There is scope to use multiple buffers to interrupt pollutant pathways in the landscape, such as using in-field, cross-slope buffers. While these can enhance the overall ‘treatment train’, this section focuses on riparian and source protection buffers as potentially the most cost-effective measures for removing pollutants and providing the widest benefits. We consider the main factors influencing buffer design and placement below.

2.2 Rethinking watercourse margin management

Riparian buffers, ranging from very basic to more complex, already occupy considerable space in agricultural landscapes due to the link to farm payments. However, many buffers are either incorrectly targeted or are not designed to cope with the continuing pressures, meaning much of England’s stream network remains insufficiently protected. Figure 2.1 shows examples of the current problems in managing watercourse margins.

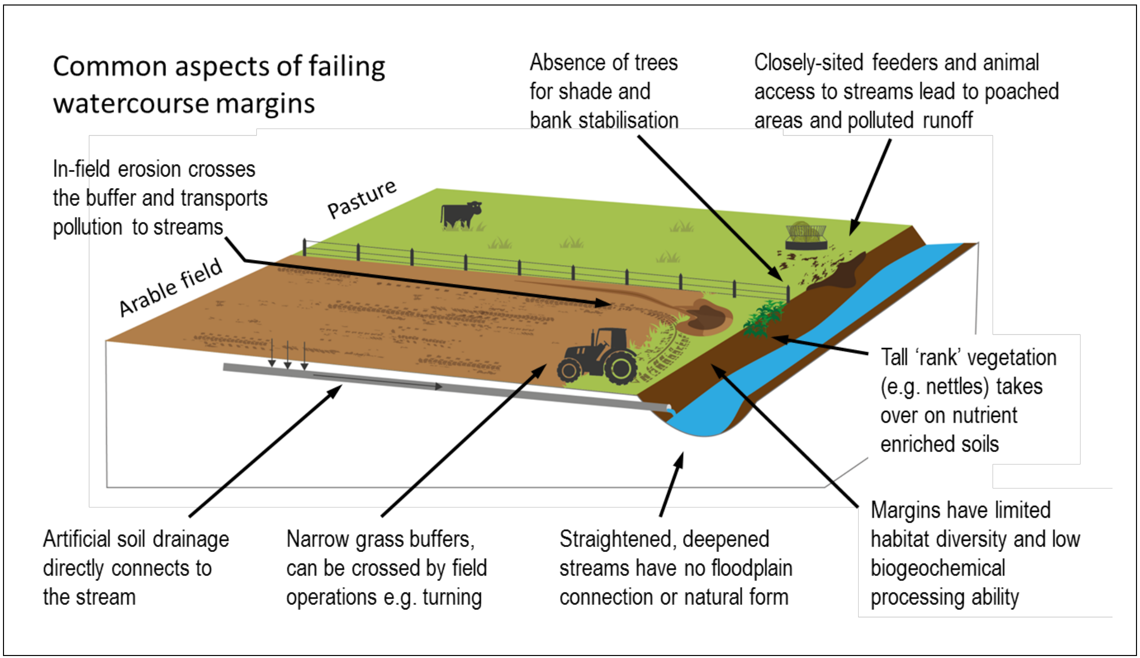


Figure 2.1. Aspects of current failings in watercourse margins for arable and pasture land

Currently, UK riparian buffers lack structural diversity to improve effectiveness. If the riparian space can host trees, deep rooting vegetation, ponds, swales and other structures designed to break pollutant pathways this could significantly reduce pollutant loads. A menu of riparian buffer measures could be developed, so that simple options could be selected for targeting sites with low pressures/at low risk, and a range of options for those more highly polluted, degraded watercourses.

2.3 Tiered approach to riparian buffer zones

A tiered approach to riparian buffer zones builds upon concepts [7] of progressing from moving the source, for example good soil management, to protecting the stream receptor progressively using zones of (i) no cultivation, excluding animals and agro-chemical use, (ii) altered vegetation, to (iii) altered vegetation and raised slope profiles. Table 2.1 summarises a progression of design aspects fitting the 3D buffer concepts in approximate order of intervention.

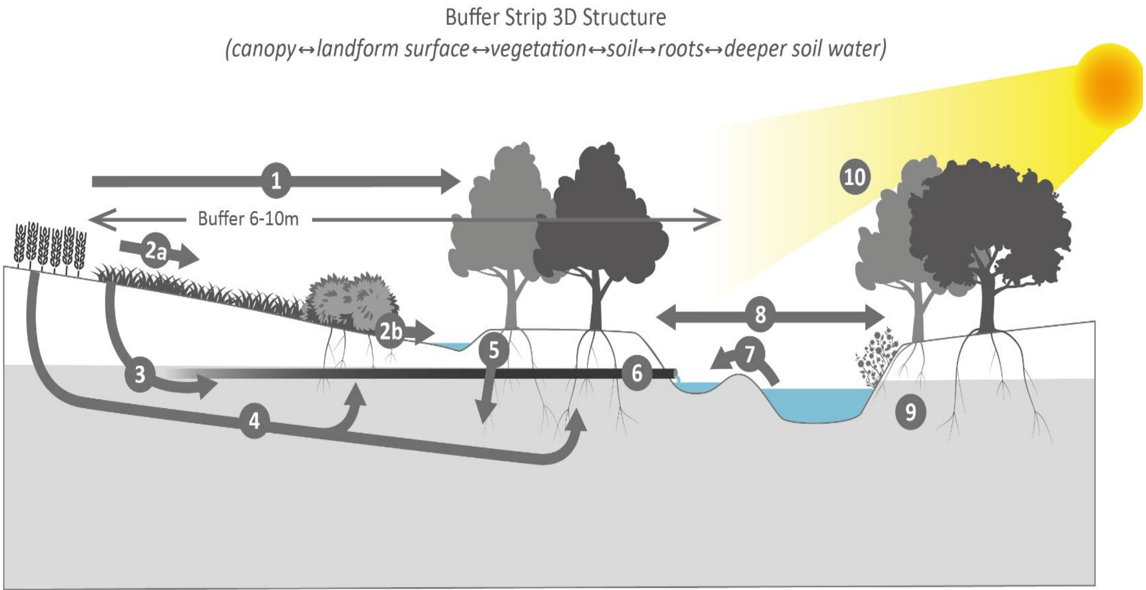
Table 2.1 Components of 3D buffer designs ordered in terms of increasing level of intervention/complexity/cost

Buffer component	Description
Basic cross compliance buffer strip	Green cover (usually grass) on land within 2 m of the centre of a watercourse or field ditch. Must not cultivate or apply fertilisers or pesticides to land within 2 m of the centre of a watercourse. Must not apply organic manure within 10 m of a surface water.
Extended grass filter zones. Buffer strips (Environment/ Countryside Stewardship)	Predominantly grass filter strips of more than 4 to 12 m width, where livestock, cultivation, fertilisers, manures and pesticides are excluded, and herbicide use limited.
Enhancement of grass buffer zones, mainly for biodiversity	An addition to the above is to plant flowers and herbs to improve habitat quality. This often needs managing to suppress competing vegetation. However, this may include new approaches of promoting nutrient 'mining' or deeper rooting plant species.
Livestock exclusion zones	Using fencing to exclude livestock to reduce faecal inputs and bank erosion.
Tree planting and management to enhance hydraulic roughness and pollutant retention	A range of practices of planting trees (including different buffer widths) and management to capture and remove pollutants as well as provide wider services, for example, harvesting for bioenergy.
Riparian landform alteration	Raised bank profiles to improve capture of local run-off and provide greater diversity in soil wetness. This includes measures to disrupt or manage subsurface field drainage such as swales and ponds.
Cross ditch or stream alterations	Amending channel form to delay run-off and improve siltation and in-stream processing of pollutants. Examples include constructing a series of in-line ponds or bunds, including leaky woody structures.

2.4 Main factors affecting buffer functioning

Buffer structure and complexity

The main pollutants of concern are sediments, nutrients, agro-chemicals (pesticides, animal veterinary products) and pathogens. There is significant potential to reduce the amount of these pollutants entering watercourses by moving the agricultural source/activity (tillage and chemicals) further away from the edge of the watercourse, and by creating a barrier to retain or remove them within the buffer zone. This can be done by several processes operating across the canopy - ground surface – soil – root zone, as explained in Box 1. The effectiveness of the barrier, filtering and processing functions of the buffer vegetation and soils depends on whether the pollutant travels in solution (for example, nitrate), is bound to soil particles, or via air (for example, pesticides can be transported by all three pathways). Furthermore, pollution transport via run-off interacts with local site conditions of soil type, slope and hydrology and in turn, often varying seasonally with climate and field management. An overview of the main factors controlling buffering efficiency for different pollutants is given in Table 2.2.



1	Interception by the tree canopy of airborne spray drift of agrochemicals	6	Stopping direct discharges from soil artificial drains allows time for processing of pollution in margins
2	Surface runoff is controlled by particle trapping by vegetation, water soaking in amongst roots and in extreme cases by hollows created by resculptured ground profiles.	7	Altered bank profiles can increase connection between the channel and a floodplain resulting in diverse soil wetness and sediment trapping
3	Slowing passing water and promoting infiltration allows time for natural processing of nutrients and contaminants by soil microbes and plants	8	Enhancing interactions between land and water ecosystems promotes healthier streams
4	Nutrients can be taken up and locked away in growing vegetation	9	Banks can be stabilised from erosion and collapse using tree roots
5	Increasing the content of soil organic matter aids natural attenuating processes in soils	10	Increased shading helps reduce thermal stress to aquatic life on hot sunny days

Box 1. Potential elements of a 3D buffer structure: main processes and functions

When using a riparian buffer to reduce the transfer of pollutants from the field to the watercourse it is important that appropriate steps are also taken to control pollutant sources. This is to avoid the functioning of the buffer being overwhelmed by pressures from the field. By doing this, the buffer becomes part of the 'treatment train' and not a panacea of ultimate edge of field protection [7, 8]. Feld and others [9] concluded that riparian buffers have their limits, and even when well-designed may only be able to mitigate 50% of the nutrient load, meaning that buffers must also be accompanied by broader catchment nutrient and erosion control measures.

Several important factors are considered for a riparian buffering scheme to most effectively reduce pollution. These can be summarised within two interrelated categories of:

- Pollution transfer to the buffer from in-field risk factors
- Functions within the buffer that determine effectiveness for reducing run-off and pollution. *Note: a table in Appendix A1 summarises how the main literature discussed here maps across the interactions of different buffer processes with diffuse pollution and wider benefits*.

Table 2.2 Interaction of the main buffer processes and their controlling factors with the main diffuse pollutants.

In (a) +, – and blank denote a positive, negative and no expected influence, respectively, on the pollutant by the process; in (b) the dominant controls are identified using shaded boxes.

	Physical trapping			Soil chemical and biological processing		Plant uptake and remobilisation		In-water-body processing
	Canopy interception	Deposition	Infiltration	Retention onto soil surfaces	Microbial processing	Plant uptake	Biological recycling	Water column and bed retention
(a)								
Sediments		+	+					-/+
Nitrogen forms	-/+		+		+	+		+
Phosphorus		+	+	+	-/+	+	-	+
Pesticides/ herbicides	+	+	+	+	+			
Pathogens		+	+	+	+			
(b)								
Field soil type		■						
Climate	■	■	■		■	■	■	
Buffer width		■	■	■		■		■
Buffer soil type		■	■	■	■	■	■	
Buffer flowpaths		■	■	■	■	■		■
Buffer vegetation	■	■	■		■	■	■	■
Buffer management		■	■			■	■	■
Channel form		■						■

In-field risk factors

Risks within the field such as slope, topography, crop and nature of cultivation and drainage influence the location, timing, pathway, load and rate of the incoming pollution into the buffer. The risk is determined by the combination of the pollution source and the likelihood of transport from the field into the buffer.

Two factors of field risk are fundamental to the effectiveness of edge of field measures. These are:

- buffer siting and design recognises areas of greater and lesser pressures coming from the field slope
- best management practices are applied in the field to limit pollutant sources and transport aspects

Taken together these factors drive the main carrier phases of pollution into buffers, for example run-off volume and sediment mass [10].

Because of the extensive existing literature on mitigation measures in general, we discuss in-field risk factors below only briefly.

- Land management controls source, mobilisation and delivery factors and interacts with the other measures of landform, soil and climate. The main aspects for arable land include soil erosion, compaction and nutrient management. Grassland risks comprise erosion associated with heavy grazing via poaching, excess grazing leaving bare ground, bank erosion [13], or microbial contamination from cattle access into watercourses.
- Slope is a risk factor for run-off volume and energy generation, with soil on steeper slopes more vulnerable to detachment and transport downslope
- Soil type is a well-established factor in processes of soil degradation, contributing to diffuse pollution transfers, such as erosion, compaction, organic matter change and loss of soil biota [14].
- Rainfall is an important factor in mobilising and transporting pollution from field sources. Rainfall splash energy can control mobilisation and run-off amount, while frequency and seasonality govern run-off volumes, pathways and energy.

Factors influencing buffer effectiveness

These factors relate to the ability of the buffer to form an effective barrier that either partially or completely traps and retains pollutants or slows the passage of run-off to allow the pollutant to break down in the soil. It is important to consider all contaminants and their pathways and processes when considering design and location[15].

(i) Buffer width

Buffer width interacts with all factors stated above to become an important control on pollutant retention. These can be physical, geochemical, biological, and in some cases, aerial interception affecting pollutants. The literature shows considerable variation both between-site and between-pollutants in terms of retention effectiveness under different situations.

Despite this the evidence can be generalised to establish overall guidelines for widths against main place-dependent risk factors, but also understood in terms of risk factors so that weaker combinations of buffer width, properties and pathways for specific pollutants can be identified and remedied. There will be competition between riparian space for environmental gain and agricultural production, therefore, it helps to identify an effective, optimal width.

This section examines the evidence for width-based effectiveness across a range of pollutants, and considers explanatory factors limited to leading review studies and some primary evidence summarised in Table 2.3.

Sediment trapping: Generally, the studies that looked at width and retention efficiency, suggest that in low intensity rainfall events, coarser sediment can be trapped in a relatively short distance at the upper buffer edge, while fine particles and dissolved constituents require greater widths in which to be trapped (Table 2.3).

Particle tracer experiments conducted across riparian grass buffer zones in the three UK Demonstration Test Catchments [16] showed that of the 29% of sediment mass trapped overall in 6 m buffers, the majority was in the upslope first 2 m, where often the presence of a plough strike-out furrow (step up to the buffer surface) provided this ‘leading edge’ effect. The small overall sediment retention values indicated poor trapping at sites subject to farm trafficking routes and turning circles entering buffers.

Several review studies [17, 18] have shown a logarithmic relationship between sediment trapping and buffer width, whereby steep increases in trapping efficiencies occur up to approximately 6 m, with little additional benefit after 10 m. This was supported by Collins and others [19] who suggested that for sediment, doubling buffer width from 7.5 m to 15 m did not significantly improve sediment trapping. However, these authors [19] questioned whether experimental sites contributing data to reviews are biased towards higher trapping efficiencies since studies are generally short-term, involving new and well-managed buffers, and often fail to incorporate complex terrain with compaction or concentrated flowpaths that lead in reality to reduced trapping. The importance of such additional factors was shown by Xu, Mang and Zhang[17] who observed that width accounted for only 29% of the variation in sediment trapping. Other proposed factors were soil, buffer slope, buffer, field area ratio, flow type across the buffer, rainfall intensity and vegetation.

Since particles help to transport pollutants bound to them, the texture and composition of eroded soil material affects the pollutant loading to the buffer. This is through a positive relationship between surface area and contaminant carrying-capacity [25].

Syversen and Borch[26] examined how buffer widths (5 m to 15 m) affected sediment and phosphate trapping across different particle sizes. The study found that trapping efficiency was greater for coarse than for fine particles, and that total P and clay contents were related in eroded material, where clay content was a negative factor in P trapping. Another study found that the clay content of eroded sediment entering a grass buffer was a negative factor in pesticide retention [27].

Table 2.3 Summary of literature on buffer trapping efficiencies versus margin width (where blank values indicate pollutants not part of those studies and positive and negative values indicate pollution net retention and net loss, respectively)

Data description	Width	Sediment	Total P	Dissolved P	Dissolved nitrate	FIOs	Pesticides	Main covariates	Reference
Demonstration test catchment grass buffers (UK)	6 m	29%						Management (ploughing, trafficking)	[16]
Grass and tree buffers (Norway)	5 m-10 m	81-91%	60-89%		37-81%			Flow, season, site (slope)	[20]
Literature review on grass filter strips	Overall 1 m-3 m 6 m	30-100% 30-90% 58-95%	30-95% 30-85% 80%	 -83 to+95%	 -25 to +95%	53-100%	30-100%	Soil compaction, concentrated flows, study conditions	[19]
Literature review data on vegetated filter strips	<3 m 4 m-6 m >6 m	60% 72% 88%						Buffer slope, little difference with included trees in grass filter strips	[18]
Grass filter strips (US)	2 m 15 m		31% 89%					Flow, vegetation	[21]
Forested buffers (US)	10 m			78%	97%			Vegetation	[22]
Grass buffers (2-year-old grass)	7.5 m 15 m	89% 87%	57% 71%	29% 30%				Vegetation, climate-biological P cycling	[23]
Literature review data on grass filter strips	Overall	76%					61-76%	Pesticide sorption to particles	[10]
Grass and tree mix buffers (Italy)	6 m	95%	80%	Negligible effect	Increased			Run-off reduction dominated change	[24]
Buffers (US): Giant cane Forested buffer	 10 m 10 m			 100% 78%	 100% 97%			 Infiltration	[22]

Phosphorus trapping: Trapping of phosphorus follows similar processes to sediment. The width-effectiveness is the same as phosphorus is often bound to sediment. However, retention and processing of dissolved P is affected by a much wider set of within-soil processes contributing to the wide-ranging effectiveness, including negative values where the buffer has switched from a phosphorus sink to a source due to the soil adsorption sites being overwhelmed (Table 2.3).

Dorioz and others [23] summarised the greatest uncertainties as the abilities of buffers to store P over longer periods. Dissolved P remained high at the watercourse edge and a 6 m buffer width was ineffective without additional interventions to reduce P transfers. In understanding the P remobilisation issues in buffers, the favoured measure is promoting P offtake by harvesting vegetation [28] [29], with strategies and trade-offs for infrequent and frequent cutting in wooded and herbaceous buffers, respectively.

Nitrogen trapping: Total N transfers can involve particulate and dissolved N forms. In a Norwegian study, mixed grass and tree buffers of 5 m and 10 m width were observed with 60% and 80% efficiency in total N trapping, respectively, in winter. In the summer, efficiency increased to 80% for both widths [20].

Studies reviewed by Collins and others [19] found highly variable buffer nitrate retention, from approximately 25% to near-complete (95%) retention for 6 m buffer widths. In systems where nitrate is transferred to streams via deeper groundwater, gains in efficiency require larger buffer widths for greater root uptake.

Sweeney and Newbold [31] reviewed literature on forested buffers and found median reported subsurface nitrate removal was enhanced from 55% at <40 m width to 89% at >40 m widths. Dissolved ammonium efficiency is expected to be like that of nitrate. However, in areas of high ammonia-N deposition, buffer vegetation, most effectively trees, will scavenge atmospheric gaseous ammonia and provide a barrier [32]. However, this may be at the expense of local leaching in buffer soils unless soil biogeochemical mitigation is put in place.

Other pollutants: Pesticide retention was related to the association between the chemical and soil surfaces. Strongly sorbing pesticides followed trapping behaviour of sediments and retention declined with weaker sorbing pesticides which tend to travel in dissolved forms [10]. Pesticides may be effectively mitigated using tree shelterbelt barriers within buffers. A combination of studies suggested that 60% to 90% effectiveness is attainable.

Few studies have examined trapping of pathogens or faecal indicator organisms (FIOs) in run-off. A range of 53% to 100% removal across varying buffer widths has been reported [19], but there are strong interactions with concentrated flow occurrence and management factors like fencing. Success seems most likely where livestock are excluded from the buffer and where slope, soil and vegetation promote infiltration of run-off within-field.

(ii) Buffer soil profile in relation to dominant hydrological pathways and biogeochemical processing

Different hydrological pathways for water and co-transported particles and pollutants greatly affects buffer function. Both natural soil structure and structural change imparted from current and previous management (for example, degree of compaction) affect localised flowpaths. Four conceptual flowpaths for buffers have been considered [33], namely:

- above and below ground flows through the buffer
- overland flow generated on the field coming across the buffer
- artificial drain flow
- periodic inundation by river water

Pollutant retention in the buffer starts with physical trapping amongst vegetation and in hollows. Infiltration helps to reduce water velocity and volume, particle carrying-capacity and enables dissolved components to enter the soil matrix. This provides the opportunity for physico-chemical and biological processing of contaminants within the buffer's soil profile.

Sheet types of overland flow allow infiltration over larger buffer areas. Concentrated flowpaths are problematic for buffers as they can readily exceed buffer infiltration rates, quickly pass across the buffer or cause sediment dams increasing concentrated flows. Field surveys in the US [34] estimated that 83% to 100% of surface run-off leaving agricultural fields was as concentrated flow. In addition, there are preferential flowpaths of fast travelling water within soils between soil layers, through animal burrows and wetting-drying cracks that can limit pollutant processing and breakdown as the water by-passes the opportunity for adsorption [35]. Where by-pass flow occurs and where the pollution burden is large, additional measures include using deep rooting plants to intercept flows and uptake nutrients (for example, trying to remove P into vegetation) or using reactive barriers (for example, woodchip denitrification trenches) across flow lines.

Natural riparian zones are often defined by high water tables and associated soil processes and vegetation. Kuglerova L and others [36] advocate siting buffers along the line of these raised water tables and promote wider buffers to protect shallow groundwater from pollution. A potential conflict exists between maintaining drier soils to promote infiltration and eroded soil and P trapping [37] versus higher water tables that promote beneficial processes such as denitrification.

While N accumulation in the buffer may be offset by N lost from anaerobic soils the opposite may occur for P. Under low redox conditions (and exacerbated by higher soil organic matter) the chemistry of soil surfaces that bind P become altered so that the P becomes more soluble and potentially can leach [6, 37].

Managing water tables is an important factor in restoring riparian functions and specific issues where risks for N and P must be considered together. In general, favouring undulating ground (as in a natural riparian zone) to diversify buffer soil water conditions may be a best compromise for nutrient processes and habitat diversity. For specific problem-situations like high nitrate transfers saturated buffers favouring denitrification become more appropriate targeted designs.

Underground land drainage or tile drainage is an important component of pollution transfers from agricultural land to streams, which can undermine the action of buffers since designs generally focus on pollutant trapping for surface run-off pathways [7]. In their review, Feld and others [9] are surprised that tile drainage and its effects on riparian buffer performance did not feature more in the literature. A limited number of studies are examining ways to reconnect tile drain waters with the riparian soils (examined further in section 4).

Jaynes and Isenhart[38] investigated a system of raising soil drain water to the surface with a control box, then irrigating it out across the surface of wetted buffer soils to promote denitrification. A mini-wetland treatment system design for tile drainage is described by Lenhart and others [39] who showed that 0.1 ha wetlands at field edges were effective for removing approximately 70% of nitrate and phosphate from drain waters within 3 years.

Other methods have included using woodchip bioreactors as end of pipe methods to enhance denitrification of subsurface drainage and controlled drainage, where the latter seasonally closes a valve on the drain outlet to wet-up the field-slope and encourage denitrification and limit water passage [40]. Woodland buffers would naturally disrupt drain systems through rooting, with implications for local soil wetness, pollution pathways and fate.

(iii) Buffer vegetation and management

Riparian buffers may be left as uncultivated, unfertilised strips that become naturally recolonised by a mixture of plants spreading from the watercourse bank and by persistent field crop and weed species. However, naturally-recolonised grass buffers can fail to achieve biodiversity goals [41]. The resulting thick growth of nutrient-loving species, suppressing lower flowering species and the decomposing plant litter in winter can contribute to phosphorus remobilization from soils [28]. Therefore, continuing management of vegetation is often prescribed in riparian schemes and this is discussed in the section below.

Vegetation can affect diffuse pollution via several processes. The hydraulic roughness of ground vegetation, tree stems, deadwood, and surface rooting slows and/or temporarily stores surface run-off, reducing carrying capacities of particles and associated pollutants. Rooting, especially by trees, creates larger soil pores, increasing infiltration capacity and the retention of dissolved nutrients at depth. Growth of biomass increases nutrient uptake and removal. Leaves, dead wood and decaying roots increase soil organic matter, driving microbial assimilation or breakdown of chemicals. The physical barrier created by tall vegetation reduces pesticide spray drift and helps remove pollutant gases such as ammonia.

Including trees as part of the buffer is beneficial with the control of diffuse pollution, although much depends on woodland design and management. For example, Feld et al [9] noted that trees and shrubs can be less effective than grass for sediment trapping where heavy shading suppresses ground cover vegetation. Conversely, the review of Yuan, Bingner [18] showed no difference in sediment trapping for grass and appropriately designed forested buffers. It is clear that tree rooting can also promote riverbank stability [42], which is important as bank erosion can be a dominant source of sediments (22% on average across waterbodies in England and Wales[4]).

The optimum width of a woodland buffer is similar to grass and depends on a wide range of factors, including pollutant type and loading, soil type and condition, slope, topography, buffer design and management, as well as other desired functions. For woodland creation and replanting, the UKFS Guidelines recommend 10 m to 20 m minimum woodland buffer widths (according to channel width) of open-canopy (approximately 50%) planting, although this guidance was designed for mitigating impacts of adjacent forest management (as opposed to agricultural) activities on watercourses.

Woodland shelterbelts and riparian buffers can form a highly effective barrier for reducing pesticide spray drift to waters, achieving reductions of between 60% to 90%[43, 44]. Effectiveness can be complicated by local airflow patterns[43], which are influenced by tree species, tree height and leaf stage. Walklate [45] reported typical drift reduction efficiencies of 86% to 91% for a 7 m high windbreak of alder trees.

It is good practice to consider different zones between watercourse and crop when designing buffer width, especially where the buffer needs to reduce larger pollutant loads. Nearest the stream a narrow zone with permanent native trees provides shade, litter inputs and bank stability. A mid-zone has native trees (optimal for habitat, but these may be harvested) extending across the area of elevated water table for treating nitrate. The upslope zone, nearest the crop, provides a grassed filter strip for sedimentation.

Vegetation management is very important to sustain uptake and removal of nutrients and other contaminants accumulated in biomass, both for herbaceous vegetation [46] and trees [47]. This is particularly the case for some nutrients such as phosphorus where no gaseous loss pathways exist, unlike for N removal via denitrification. Without regular removal soils may become P saturated and switch to being a nutrient source rather than sink [28]. The question is often tackled in prescriptions for managing herbaceous buffer vegetation [29] for purposes of establishing flowering plants, encouraging vegetation offtake of nutrients, or improving the stem density for erosion trapping. At present in the UK, cutting vegetation by hand, light machinery or restricted grazing are deemed appropriate, although there are compromises with biodiversity. Canadian research [48] found no effect between differing mowing treatments of grassed buffers for removing N, P and faecal bacteria in run-off. Associated benefits of managing vegetation can include using vegetation harvested from buffers as a green manure to return trapped nutrients to adjacent cropped fields as partial replacement for fertiliser [49].

Trees must also be actively managed to maintain nutrient uptake. However, thinning or harvesting trees can potentially damage the soil and will temporarily reduce pollutant trapping until trees regrow. Impacts can be minimised by good management practices and appropriate design (UKFS Guidelines), such as by phasing or zoning harvesting work to always retain some standing trees. This becomes more difficult as the width of buffer reduces. Establishing an unmanaged or lightly managed buffer of native wet woodland can partly overcome these issues, but it will be less effective at sustaining nutrient removal.

Planting fast growing tree species such as poplar, willow or eucalyptus, or other river bank trees such as alder, and managing these for bioenergy as short rotation coppice (SRC) or short rotation forestry (SRF) can offer ways of maximising nutrient offtakes, where practicalities and economics of harvesting can be met. Although buffer strips are not fertilised, high biomass production can be sustained over the long term due to elevated nutrient supply from interception of run-off from adjacent fields.

Christen and Dalgaard[47] showed SRF yields ranging from 5 to 8 tonnes/ha/year (with optimal 12 to 20 year rotations, but possible shorter harvest cycles of 4 to 10 years, for example, for alder), compared to up to 14 to 16 tonnes/ha/year for SRC (willow and poplar at one to 5 year harvest cycles). Biomass yields of 55 to 194 tonnes dry matter, 25 to 91 tonnes C, 277 to 782 kg N and 20 to 105 kg P have been shown over 9 years for hybrid poplar bioenergy buffer plots on 4 sites of former cropland in the US. [30].

The bioenergy and water quality benefits can differ between woody and herbaceous biomass buffers, but benefits versus effort of multiple annual harvests for herbaceous vegetation must be considered against a single long harvest period for trees. A review [50] found that woody biomass was better for N uptake and removal, while herbaceous buffers were better at the combined actions of trapping sediment and P removal.

Other aspects of buffer management

Excluding farmed animals from the buffer using fencing is an important factor in buffer condition in pasture or rotation systems. Comparisons of pasture management in the US show that, compared to high run-off and sediment loads from conventional grazing, rotational grazing with a fenced riparian buffer controlled run-off and sediment delivery to the watercourse to levels similar to fields used for a hay-crop [13]. In comparison, rotational grazing with an unfenced buffer doubled sediment yields.

Specific management can be required for features incorporated into riparian buffer areas. Periodic management of bunds and small wetland areas by removing accumulated sediment will be needed to reinstate its function [25]. Other features such as controlled drainage may require frequent optimisation of water tables [40].

Regular access for managing buffer vegetation and other features, or inadvertent trafficking within buffers while managing adjacent field crops can act as a major pressure on buffer functioning. Buffer soils can be particularly prone to compaction and erosion, reducing their capacity to retain and remove pollutants. They are also prone to pollutant remobilisation due to their proximity to the watercourse. Excluding trafficking through fencing or planting trees can address this problem.

Buffer placement in relation to catchment risks and processes

Buffer placement and design must be considered locally according to field risks and local water quality outcomes. There are tools and data to help with this at different scales. Riparian buffers are often applied in a linear fashion with fixed widths according to baseline regulations or funding scheme stipulations.

There are compromises between the relative ease of using simple fixed-width approaches stipulated by regulation versus more site-specific buffers designed according to local needs and pressures [7]. Scientific tools are being developed to identify so-called 'critical source areas' by combining information on wet areas conveying flows to watercourses and the location of pollutant source areas. These can assist buffer siting and design decisions, [51, 52] but require more complex local risk mapping.

More simple frameworks include looking at the source to buffer area ratio, which has become a planning factor in buffer sizing according to source area management [10]. In addition, buffer efficiency 'modifiers' for soil texture, slope, field length and crop cover type have been incorporated in the US when sizing buffer widths [53].

In catchments, buffers need to be designed to mitigate higher energy parts of the network (for example, headwater erosion) and lower reaches where groundwater may be more of an issue. In so doing buffers will protect aquatic habitat that requires different styles of buffers between headwater ditches to wider reaches of the main river [8, 54]. A range of tools can be applied to help guide buffer design and placement depending on catchment location and desired outcome.

Qiu and Dosskey[55] compared the cost-effectiveness of placement strategies for riparian buffers to improve water quality, control run-off and erosion, and to benefit wildlife. They looked at:

- Fixed and variable width riparian buffers
- Soil-based approaches of predicted water and sediment trapping efficiency
- Topographic indices of water table height and soil water storage

The benefits were greater with targeting where the soil and topography was used as opposed to linear continuous riparian buffers. Buffers may be viewed as semi-permanent or temporary. For some land managers the latter may depend on funding, advice and local rules. Different vegetation options bring different levels of permanency of the buffers. Grass buffers may be more readily reinstated into the field, while wooded riparian buffers may be considered more permanent.

Buffer strips and land use change

Buffer strips are a form of targeted land use change that is generally considered to be more proportionate and effective at reducing pollutants than wider, non-targeted land use changes such as converting farmed land to woodland. Both types of land change remove pollution sources, for example, by reducing areas to which fertiliser is applied. Land use change to a lower intensity use removes agriculture from a larger area and so achieves a greater reduction in pollutant sources.

The riparian buffer zone involves a proportionately smaller area of land use change. Its position next to the watercourse means that change here can be much more effective at reducing diffuse pollutants entering water bodies, both in terms of removing the original pollutant source and by acting as a barrier for pollution crossing from upslope land. There is additional scope for riparian buffer strips to remove pollutants within watercourses, depending on the degree of interaction with surrounding riparian land, which is likely to be greatest at high flows. In all cases, the buffer zone should be correctly designed to cope with upslope inputs.

Targeted changes in land use in smaller critical zones is more likely to be cost-effective and acceptable to land owners than removing agricultural land from all but the most vulnerable catchments. A smaller land area in the riparian zone can reduce more pollutants and improve water quality.

An important constraint is making sure that the smaller area of the buffer is capable of intercepting and mitigating pollutant run-off from the larger upslope area and maintaining this into the longer-term. Crucial aspects of buffer design such as the ability to handle storms, intercept subsurface (artificial drainage) pathways and keep accumulating and locking-up nutrients such as P then become important. Here, a more innovative and engineered approach to buffer design can help. However, the challenge remains to co-ordinate and upscale the use of buffer strips to create a catchment network large enough to achieve water quality targets at the water body level.

2.5 Wider ecosystem and societal benefits

Aquatic habitat benefits

A riparian buffer can benefit aquatic habitat in both ditches and downstream river channels by influencing the shape of the channel [56]. This is particularly the case for bankside and riparian trees, whose rooting strengthens stream banks and provides shelter, and inputs of deadwood promote the formation of large woody debris (LWD) dams. The presence of partial or complete 'leaky' dams helps to create a pool and riffle structure, increasing structural diversity and benefiting aquatic life. Trees and LWD dams also deflect flows, forcing water out of bank, rewetting riparian habitat and driving the formation of multiple channels. There are several different options for LWD designs in meeting these objectives. Another important benefit is the input of leaf litter to watercourses, which can represent an important food source for invertebrate fauna [57]. In short-lived watercourses such as ditches, sediment traps associated with earth dams are used by birds for bathing, drinking and foraging in summer and autumn more than control sections of ditches without dams [58]. These features are also associated with a higher biomass of emergent insects, especially where there is minimal shading and a combination of open water and exposed mud in summer [58].

Riparian shade

An important benefit of riparian vegetation is providing shade to reduce water temperature extremes on hot sunny days and help to adapt to the impacts of climate warming. Water temperatures may be moderated to protect salmonids on hot, sunny days compared to open watercourses [59] and biological processes such as algal growth and algal blooms can be reduced. Tree cover provides the greatest level of shade, although this can become excessive in the case of conifers. Broadmeadow and Nisbet [59] recommended that around half of the overall length of a watercourse should be under dappled shade from trees and shrubs, although the optimum level will depend on local objectives and requirements of water users. For example, fisherman often require space to cast lines and some river margin species prefer patchy shade. Shading wetted ditches was noted to reduce emergent insect biomass [58].

Riparian habitats

It becomes especially important in intensively farmed landscapes that riparian buffers provide habitat connectivity [60], offering wildlife corridors or 'stepping stones' linking habitats, for example a woodland habitat network throughout a catchment or landscape. The riparian habitat often forms an important refuge for priority species such as otter and bank voles, as well as for bats and birds. For arable fields in southern England, certain pipistrelle bat species increased activity along margins sown with agri-environment scheme wildflower mixes. Other species decreased activity around grass-only margins but the number of bats and their Chironomid prey (species of mosquito like flies) increased along wooded shelterbelts [61].

Research in the UK Demonstration Test Catchments (DTCs) found that there was no difference in habitat for buffers adjacent to arable versus grassland. Both were found to have high richness of bumblebee food plants, indicative of promoting pollination services [16]. Conversely, there was low incidence of perennial flowering plants, limiting the value of buffer strips for other invertebrates, notably butterflies and beetles. It was noted that establishment by either natural regeneration or specific wildflower seed mixes improved biodiversity potential over a simple grass seed mixture.

Riparian habitat was restored via natural regeneration in French streams several years after cattle had been excluded from the area by fencing, although water quality did not improve concurrently due to additional catchment-wide pressures [62]. In Australia, 8 years after cattle exclusion from fenced riparian areas the vegetation had changed structurally but soil nutrient and organic matter properties did not change until influenced by a river flood [63]. A study of carabid beetles in Scottish riparian buffer zones created without additional management adjacent to intensive farmland showed that the sites did not create the habitat quality required for truly riparian species [64].

Biomass provisioning

It may be possible to harvest woody or non-woody biomass as a buffer crop and additionally to sustain and enhance the removal of nutrient pollutants [29, 49, 50]. Timber or the production of other wood products is also possible in woodland buffers if managed to minimise the temporary loss of woodland benefits and potential impacts on buffer soils. Using fast growth tree species can provide tree-associated services quicker (Fortier et al. 2015), but with the disadvantage of more frequent interruptions when harvesting occurs and potential negative effects due to trees using more water. A review [50] concluded that biomass 'bioenergy' buffers contribute in the longer-term to soil carbon sequestration, reduced groundwater nitrogen and nutrient run-off, soil erosion mitigation and improved soil health, and above ground biodiversity and biomass energy yield.

Flood management benefits

Buffer strips increase the hydraulic roughness of the landscape and reduce surface flow velocity, increasing travel time, soil infiltration and soil water storage capacity [65-67]. While these processes are well understood, there is a lack of observed data on how they scale-up to affect larger flood flows in large catchments [68]. Although buffer strips have been part of the agricultural system for decades, the scientific literature about them remains mainly biased towards diffuse pollution issues [7, 69], such as sediment trapping rather than any natural flood management benefits. Knowledge about related run-off influencing factors (soil permeability, soil organic matter or water storage capacity) is transferable but difficult to upscale. Modelling studies of the effects of planting 30 m wide buffer zones with riparian woodland suggest that these can bring about small (<10%) but nevertheless significant reductions in flood peaks, especially where combined with large woody debris dams [70].

2.6 Main messages from published literature sources

The main messages may be summarised under 3 headings:

- Correctly designed and sited riparian buffers will reduce pollutant loads, especially associated with certain types of particles.
- Field conditions, local buffer factors and the watercourse influence should guide buffer width and design.
- Riparian buffers can be either based on grass or include trees, but specific goals can be achieved seeding with wildflowers, while variation in soil water conditions diversifies habitat and nutrient processing options.

(i) ***Riparian buffers reduce pollutant loads:*** Interrupting transfers of diffuse pollutants into the water and so protecting water quality remain the main aims of buffer strips. The clearest water quality benefit buffers provide is avoiding soil disturbance and pollutant inputs by excluding agricultural activities within the buffer area itself. Furthermore, for maximum benefit, the margin must intercept and retain pollutant transport across it from the field to watercourse. To do this effectively, the buffer must slow, store and filter run-off, uptake and retain nutrients, degrade and breakdown other pollutants and intercept aerial pollutants in the canopy.

- Medium to coarse particles can be trapped in relatively short distances under moderate events to reduce overall pollution loads for sediments and bound phosphorus, plant and animal protection chemicals. Review studies report large sediment trapping efficiencies for buffers up to approximately 6m wide but further gains are limited beyond around 8m wide. Stopping transport of fine particles is considerably more problematic.
- A reduction in dissolved nutrients and pesticides is also possible but more difficult to achieve. For dissolved N and P effectiveness can range from negative (a source) to near-complete retention. Additional interventions can enhance performance.
- Airborne pollutants (gaseous ammonia and pesticide spray drift) can be effectively trapped in wooded buffers, but local effects on receiving soils must be considered.

Planning the location and extent of buffers is vital. This should include the water quality status of the local water body, the degree to which it is impacted by diffuse pollution from agriculture and which pollutants are involved, and the relative level of improvement required to achieve relevant objectives. It is also important to consider the nature of local pollutant sources and pathways in relation to the catchment context. Generally, diffuse pollution buffers should target a number of the main pollution hot spots in headwater catchments where collectively they can improve water quality. This includes focusing on critical source areas and protection zones based on understanding the main pollution delivery sources and pathways and helped by mapping elevated riparian groundwater tables for protecting habitat diversity and processing of nitrate in downstream reaches.

(ii) ***Field, local buffer factors and the watercourse influence buffer width and design:*** The commonly held view that buffers are good for pollutant removal hides common occurrences where concentrated run-off flowpaths readily exceed buffer soil infiltration or sediment trapping abilities and hence become overwhelmed, particularly during periods of heavy rainfall.

The main factors influencing the efficiency of buffers in reducing pollution are relatively well understood. These include

- the type of pollutant,
- pollutant load, such as areas of high chemical usage and run-off and its variation over time,
- transport factors such as slope, local topography, buffer vegetation, soil type and condition.

Sandy soils can result in the highest field erosion rates and sediment loading into buffers, but coarser particles are more effectively trapped by vegetation than fine particles such as clays, which also have large surface areas to help transfer sorbed contaminants. This highlights the need for appropriate soil management in-field to complement carefully targeted buffers.

Competition for space in intensively farmed landscapes leads to smaller watercourse margins being used. While a 6 m buffer width can provide a general level of protection, there will be locations of high pollutant source and run-off concentration that exceed buffer capabilities. Where it is not practical to increase buffer width, there is scope to improve effectiveness by using additional features within the buffer, such as constructing bunds, ponds and swales, or simple profile sculpturing to slow down and enhance temporary water retention.

Subsurface flows can be disrupted by blocking or controlling flows within field drains, or even using reactive barrier materials. These should work with natural landform variability. There is a lack of studies that quantify the effects of different buffer design and management factors, including how these interact with each other and with 'new' engineered building blocks. There is a need to examine how a targeted package of these measures would work at the catchment scale to meet water quality targets.

(iii) ***Margins can be based on a combination of grass, shrubs and woodland vegetation:*** Buffers of tall vegetation can be very effective at interrupting and reducing airborne pollutants such as pesticides and ammonia entering watercourses.

Planting trees offer some advantages over grass or herb vegetation in removing pollutants, as well as generating a source of income. However, woodland buffers also present challenges and some potential disadvantages for landowners, meaning they may be reluctant to plant them. These challenges include a long-term commitment to land use change (although this will secure pollution control), the perceived impact on land value, lack of experience in woodland management, potential impacts on adjacent crops and disruption to field drainage through tree rooting.

3 Current riparian buffer management practice in England and the case for improvement

3.1 The current baseline of riparian buffer zones in England

3.1.1 The potential scope of application of buffers to watercourse types

Every stretch of watercourse should be considered for one of three tiers of buffer protection to achieve a desired level of protection, namely progressively zones of (i) no cultivation, excluding animals and agro-chemical use, (ii) altered vegetation, to (iii) altered vegetation and raised slope profiles. These are set out in more detail in section 2.3. Watercourse lengths for England can be derived from the data presented by Brown [71], where lengths were stated separately for ditches, streams and rivers across the whole of Great Britain within landscape categories. In the case of agricultural land only (inclusive of rough grazing) the 9.3 million hectares of agricultural England has 346,000 km of ditches, 110,000 km of streams and 87,000 km of rivers.

A watercourse characterisation study in Oxfordshire (Table 3.1) [73] demonstrates the extent to which land in intensively-farmed regions of England is drained by ditch, stream and river lengths. Studies differentiating watercourse components are rare, but we use this to support the summary that:

- Artificial ditches have large cumulative lengths and are sediment- and ecologically-impacted. Ditches, therefore, become important locations for buffer and channel interventions to trap sediments and exploit processes that reduce P concentrations (for example, retention by natural iron compounds).
- It is necessary to protect streams by buffers higher up the channel network.

Table 3.1 Demonstrative watercourse lengths for a typical catchment in lowland England (River Cole catchment, 80 km^2; Oxfordshire) and water quality and biotic indicators (data taken from [73])

	Ditches	**Streams**	**Rivers**
Definition	*Man-made channels*	*Smaller waterbodies <8.25 m width?*	*Larger waterbodies >8.25 m width?*
Total lengths in River Cole	70 km	29 km	17 km
Nitrate (mgN/L)	5.6	8.1	5.8
Total phosphorus (mgP/L)	0.14	0.74	0.24
Suspended sediment (mg/L)	35	20	24
Mean invertebrate species	12.9	18.7	45.3
Mean wetland plant species	6.1	7.3	10.7

3.1.2 Current mandatory compliance buffer actions

Following a change in Jan 2017 to cross-compliance through the Good Agricultural and Ecological Conditioning rule (GAEC rule 1), there has been a requirement for a basic small grass buffer zone to protect adjacent watercourses from pollution [74]. This requires a zone without cultivation, fertiliser or pesticides and for which reasonable steps must be taken to maintain green cover. The zone should extend either 2m from the watercourse or ditch channel centre, or 1m from the top of the bank. Furthermore, organic manures, including human-derived and anaerobic digestate, have a no spread zone of 10m from a surface water (or 6m if injected), or 50m from a spring or borehole. There is also a requirement to map these features. The resulting baseline of good practice for basic riparian management is the 2m non-cultivated buffer with additional protection from organic manures. Rural Payments Agency data (2015 to 2017) suggests moderate compliance levels of 59% for mandatory GAEC1 buffer strips along watercourses, with breaches commonly associated with inadequate risk maps and applications of agro-chemicals or manures in the protection zone.

3.1.3 Funding and uptake of enhanced buffer measures

The current Countryside Stewardship scheme [75, 76] replaced the previous entry and higher level Environmental Stewardship scheme in England from January 2016. Appendix A2 shows that a considerable number of stewardship options are related to buffer management (providing the buffer space and livestock exclusion) or to managing specific features appropriate to place within buffers (areas of designed vegetation or banks around wetland features). The measures in Appendix A2 have been extracted to show current options related to protecting stream, ditch and pond features (riparian) rather than purely in-field measures.

The higher tier scheme contains provision to fund approaches for floodplain reconnection and bunded water retention measures elevating water tables, tree planting/woodland creation, wetland creation, in-channel woody barriers and more constructed permeable dams. Therefore, we can see that elements of the scheme already provide some building blocks for more effective buffers, with management and other guidance prescriptions well advanced. However, these are not currently being considered as part of ‘enhanced’ buffering packages.

Summary management requirements are noted in Appendix A2. Many of these give a sound basis to transfer existing knowledge into new measures for enhanced buffer designs, for example:

- 4 m to 6 m buffer strips on cultivated land (SW1) recommends cutting the upper slope 1 m to 3 m strip of the buffer annually, and for the 12 m to 24 m watercourse buffer on cultivated land option (SW4) cutting the upper slope 6m strip annually (after July). The 4 m to 6 m buffer strips on intensive grassland (SW2) recommends not cutting the entire strip. All requirements state that no fertiliser be used in the buffer, and that access by vehicles or stock is not allowed.

- Riparian management strip option (SW11) requires a 4m to 12m width buffer, excluding all livestock by fencing, controlling non-native invasive species and controlling shrub development. Plain wire fencing is recommended, as opposed to Rylock netting to alleviate debris capture during flooding.

- Flower-rich margins and plots (AB8) has recommended grass and flower seed mix species and sowing rate (20 kg/ha), time of establishment (March to May, or July to October) and annual timing (August to October) of removing vegetation by cutting or grazing (max 90%) to decrease grass suppression of flowers, while leaving 10% as refuge for species.

It should be noted that these mid-tier options do not include planting trees and, therefore, have no advice on buffer tree integration. There are also other measures for which elements of existing guidance are useful, but should be modified as we adapt them for new potential riparian buffer uses, for example:

- Constructed wetland (RP8) may be adapted to use in a riparian buffer space, for example to treat run-off from a large field drain. The management suggests establishing the pond, letting it heavily vegetate, restricting livestock and managing outlet water quality.

- Planting trees as part of a suite of measures for protecting water quality or preventing flooding has a minimum width limit of 10m (and even then, stating that minimum widths are only applicable where fully justified). If a wooded buffer or a grass buffer with a row of trees is to be used in a smaller (for example, 6 m width) buffer design, or integrated into future agro-forestry situations, then future guidance should consider changes in minimum widths for trees and additional guidance to use them as riparian buffers.

Across England, there were approximately 3,000 ha of buffer strips in Environmental Stewardship in 2017. In addition, a survey of around 5,000 lowland farms (>10 ha) from 2014 found that 44% of holdings surveyed carried out some form of unpaid environmental action from a list of 22 measures [77]. Grass buffer strips against watercourses or ponds had 17,000 ha in voluntary measures beyond the 2 m basic regulatory compliance (down 1% from 2013), and there were 7,387 km of voluntarily-fenced watercourses (increased by 605 km from 2013). A further 10,782 ha were under voluntary ‘field corner’ measures, and this could be explored for wet field corners in which water and sediment retention buffer features may be added to locally widened riparian margins (see Table 4.1 in this report).

Audit data from the Catchment Sensitive Farming (CSF) scheme from south-west England found 60% of farmers had riparian buffers and 55% had other (in-field) buffer strips [78]. Riparian buffer strips have been recommended to almost 4,000 farmers as part of CSF, and are considered one of the most effective measures in the CSF scheme [79].

3.2 Encouraging uptake of buffers

One of the arguments used in favour of buffer strips is that yield penalties around headlands, especially those where vehicle turning and shading take place, offset the impact of not cropping these areas [80]. The yield loss in field margins is due to a combination of additional compaction and competition for light, water and nutrients with persistent weeds [81].

A worked example in Appendix A3 considers the economic disadvantages of turning headlands into 3D buffers, assessing how much weight this argument should hold in considering new buffer strip arrangements such as 3D buffers, along with other arguments for habitat creation. We can do this by quantifying the area of land considered, the likely potential value of yield losses associated with headlands, and the costs of production lost by not cultivating. . These and a wide range of additional arguments (minimising pollution associated with run-off and lateral drainage, availability of pollinators and providing wider ecosystem services) need to be considered together when persuading and incentivising land managers to establish improved riparian buffer strips.

A survey of farmers’ attitudes to 86 measures within the demonstration test catchments (Hampshire Avon, Eden and Wensum) during 2012 showed a preference for buffers [82] (summarised in Appendix A4). Among cereal farmers, there was a high uptake of riparian grass buffer strips. However, there was only medium to low uptake of riparian buffers among dairy and mixed system farmers, although they were positive about including them in the future.

Across all farming systems, there was currently a low uptake of biomass crops and artificial wetlands, and negative attitudes about including them in the future. Clearly, farmers did not prefer more engineered solutions in landscapes with current incentives. This has since been supported by recent evidence from farmer focus groups. Furthermore, a survey on English farmers' attitudes towards the environment by the Campaign for the Farmed Environment [77] showed greatest importance of 'efficient use of inputs' and protecting soils and water'.

Research in the Republic of Ireland by Buckley [83] analysed 247 farmers attitudes to riparian management across 12 catchments. They were asked for their response to a proposal to install 10 m fenced riparian grass buffer zones on the same land as current mandatory 10 m no spread zones for fertilisers, with the option to a) participate, b) participate only if they were paid, or c) not to participate. 53% of respondents weren't willing to participate. The reasons they gave included that the buffer zones would interfere with farming, they would lead to a loss of production and income, and that the proposed buffer was too large. The remaining 47% were willing to participate at different payment levels. Their responses were influenced positively both by being involved previously in environmental schemes and through personal motivation towards environmental issues. Negative responses focused on the gross margin on the land that would be taken into a buffer. The study concluded that the farming community did not support this type of blanket scheme across the catchments, and that targeted schemes (that have a good uptake in the US) based on targeting highly erodible cropland or other environmental objectives would be favoured.

Kenwick [84] surveyed landowners and planners using a photo-questionnaire of buffer preferences. Respondents most preferred trees at the riparian edge, also expressing a preference for meandering, rather than straightened channel forms. The top influencing factors in terms of the styles of vegetation favoured were aesthetics, controls on pollution or flooding, and habitat provision. We were unable to find studies of preferences between different buffer widths in the international literature.

3.3 Main messages from current practice

A surprising number of elements for potentially enhancing buffers are already options within existing funding schemes. These and the supporting guidance on management practices could easily be put together into a menu of options for an enhanced buffer package. Elements of the package could be available for catchment-specific targeting to encourage greater and more effective uptake. A major constraint, however, concerns the current exclusion of tree planting within mid-tier buffer options and the minimum width of 10m set for woodland creation under higher tier options. We have considered here that 6 m may be a suitable minimum space for integrating several types of vegetation, ground structure and management elements of future buffers.

Farming and catchment advisors need to become familiar with possible options for combining buffer measures according to site-specific needs to improve advice and potential uptake. Indicators of farmer preferences currently suggest that incorporating further elements into buffers will meet with mixed opinions depending on the options chosen. While farmers generally seem to favour planting trees, constructed features such as bunded water retention measures, small wetlands, cross channel features and other solutions to slow and infiltrate sub-surface drainage are considered to be too engineered. Lack of familiarity with designs and/or benefits will limit uptake even though very similar measures exist within the present Countryside Stewardship scheme, but not specifically targeting riparian applications.

Farmers are clearly positive about including trees as buffers as they can aesthetically improve farmed landscapes. However, we need to better understand the reasons for their negative opinions of more ‘engineered’ components of buffer designs, such as lack of familiarity and guidance or perceptions on how the buffers may affect income, to see if we can easily address these.

4 Hierarchy of buffer types to increase ecosystem service function - proposed designs and assessment

Buffers can be tailored to address a range of functions by identifying design features that can enhance buffer performance. A long list of buffer types was initially considered in this section. By consulting with experts at a workshop, the list was reduced to five buffers with increasing complexity of design features to increase the number of ecosystem services provided.

4.1 Buffer types, designs and their functioning

There are a number of measures to be considered in a buffer zone within different English landscape settings. The first task was to identify all the measures that the authors and the workshop participants were aware of. The measures identified were:

Table 4.1 Full list of buffer types and improved features, adaptations or measures that could be placed within a buffer strip

1. Vegetated buffer (cross slope)
2. Vegetated buffer (watercourse)
3. Wooded buffer (cross slope)
4. Wooded buffer (watercourse)
5. Raised buffer (cross slope)
6. Raised buffer (watercourse)
7. Magic margin
8. Integrated buffer zones
9. Sediment traps
10. Swales
11. Wetlands
12. Controlled drainage
13. Cut back field drains

In the following section, information on each of the buffers identified in Table 4.1 are described, and assessed in terms of their limitations and potential for modification.

Name	1 – Vegetated buffer (cross slope)	2- Vegetated buffer (watercourse)	3 – Wooded buffer (cross slope, fenced)	4 – Wooded buffer (watercourse)
Image/ schematic				
Main aspects	• Placed along the contour of the land • Placed in valley bottoms or upper areas perpendicular to flow pathways • Suited to all types of arable system, particularly those on sloping land • Can reduce P/sediments by attenuating surface run-off • Funded via ELS and HLS • Usually permanent • Can be enhanced for biodiversity • Width can vary depending on setting	• Protecting watercourses from agricultural activity • Intercept overland flow • As with cross slope buffers, these features reduce run-off and pollutants into the stream from upslope • Restrict direct transfer of pollutants, for example livestock access and agricultural machinery such as sprayers, manure spreading • Can stabilise banks and roughen the riparian zone • Width can vary depending on setting	• Placed along the contour and can be designed as a series upslope • Potential to vary the width related to adjacent pollutant pressure and presence of convergent flows • Can be conifer, broadleaved or mixed woodland, depending on pollutant pressure and objectives (for example, conifers can maximise nutrient uptake) • Can increase surface roughness and soil infiltration, reducing pollutant run-off by uptake and/or soil retention • Can reduce aerial dispersion of pollutants such as pesticides and	• Primarily native broadleaved trees placed along watercourses • Potential to vary the width depending on pollutant pressure and convergent flows • Potential to vary management system to maximise pollutant uptake and removal, for example short rotation coppice • Can increase surface roughness and potentially soil infiltration, depending on soil wetness to reduce pollutant run-off • Can reduce aerial dispersion and deposition of pollutants to watercourse such as

			ammonia, as well as provide shelter, depending on prevailing wind direction • Semi-permanent tree cover, requiring periodic thinning and harvesting to maximise some water quality benefits • Structure can be graded to enhance pollutant removal • Can link up isolated woodlands, creating a woodland habitat network and wildlife corridor	pesticides and ammonia, as well as provide shelter • Semi-permanent tree cover may benefit from periodic thinning and harvesting to maximise water quality benefits • Source of woody debris that can promote the formation of leaky dams and the formation of riffle and pool structures • Provides shade and shelter, cooling water temperatures for the benefit of salmonid fish • Improves watercourse hydromorphology • Helps to slow the flow and reduce downstream flood risk • Can link up isolated woodland, creating a woodland habitat network and wildlife corridor
Appraisal and relevant literature	• Defra – MOPS1 (Field testing of mitigation options) • The Diffuse Pollution Measures User Guide report [85]	• Muscutt and others paper [86] • The Diffuse Pollution Measures User Guide report [85]	• Pont Bren catchment evidence in general • Nisbet and others paper [32] • Environment Agency report [70]	• Broadmeadow and Nisbet paper [56] • Nisbet and others paper [32] • Environment Agency report [70] or specific flood

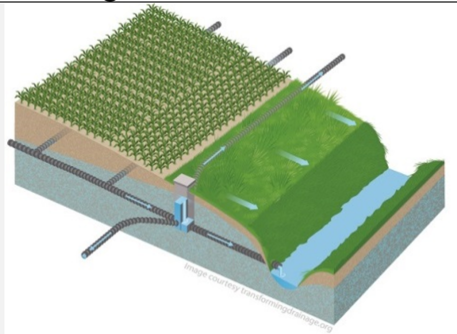
	• Muscutt and others paper [86]			references such as Odoni and others [87] • Opportunity mapping report(s)
Challenges and limitations	• Need time to establish • Reduce size of field • Vehicle compaction can make buffers less effective • Less likely to occur in-field on a mid-slope contour • Control of weeds may be needed	• Need time to establish • If placed in a livestock field these features need to be fenced • Reduce size of field • Flow can often bypass • Vehicle compaction can make buffers less effective	• Need time to establish, although some benefits can be realised quickly (for example, soil infiltration (1-2 years) • If placed in a livestock field, these features need to be fenced • Reduces size of productive field and can impact crop yield due to shading, depending on aspect • Flows can be bypassed at depth, although this can be reduced by tree rooting • Needs access for management such as thinning and eventual harvesting • Potentially vulnerable to wind blow •	• Need time to establish, with some benefits such as inputs of deadwood being slow to be realised • If placed in a livestock field, these features need to be fenced • Reduces size of productive field and can impact crop yield due to shading, depending on aspect • Flows can be bypassed at depth, although this can be reduced by tree rooting • Potentially needs access for management such as thinning and eventual harvesting • Potentially vulnerable to wind blow • Can increase local flood risk by backing up flood waters and the washout of dead wood

				• Limits access to watercourses for maintaining flood embankments, water supply and crossings • Potential for excessive shade, requiring management • Potential to deflect watercourse flows, increasing wetness and loss of local land
Potential for modifying	• Grazed buffers offer a form of land management	• Grazed buffers offer a form of land management	• Much scope to vary and tailor design/structure in line with nature of pollutant, loading and transport pathways	• Much scope to vary and tailor design/structure in line with nature of pollutant, loading, transport pathways and local sensitivities
Name	**5 – Raised buffer (cross slope)**	**6 - Raised buffer (watercourse)**	**7 – Magic margin**	**8 – Integrated buffer zones**

Image/ schematic				
Main aspects	• A bund (usually constructed of soil) placed across an overland flow pathway disconnects the pathway and temporarily stores surface run-off • Has a drainage outlet pipe and spillway • Can be placed on existing vegetated buffer • These features can trap a large amount of sediment (and valuable topsoil) • They can provide a dry access route for farm machinery • They do not affect farming productivity as much as more permanent wetlands	• These are simple low earthen banks constructed on floodplains to temporarily store floodwater during flood events. These storage areas then drain back out into the watercourses after the main flood peak has passed downstream • Has a drainage outlet pipe and spillway • Placed to target suitable areas where floodwaters can be directed towards topographic depressions on the floodplain • The storage areas and bunds are designed to permit the normal agricultural management of lower intensity grassland/meadow	• Creates many small ponded infiltration areas • Placed in an area where an existing vegetated buffer would be • Created using a tied ridger (potato farming) to create mini-dams • Cuts off run-off pathways creating new convergent pathways • Intercepts run-off and erosion pathways in a similar way to previous measures • Placed at bottom of slopes at field edge • Can improve ecological focus area	• Tackles field drain pathways, something previous measures fail to address. Land drains are broken and forced to enter temporary storage areas • Biomass crop placed downslope of temporary storage areas • Uses tree root-zone to promote N, P retention/processing • Used in a riparian context • Parallel ditch dug by natural stream • Tree section placed between (willows, alders) • Increases residence time of waters from drains • Sediment trap effect • Fine P sediments infiltrated on filter bed

	as they drain shortly after a storm • For management purposes should generally be no more than about one metre in height	• In many lowland examples, these ponds can be created within wide vegetated buffer strips beside streams		
Appraisal and relevant literature	• Belford, Northumberland: Wilkinson and others[88] indicated a 500 m^3 overland flow barrier was effective at storing run-off from a 1 in 5-year convective storm event • Measures installed to prevent muddy floods in the Belgian loam belt region have been investigated by Evrard and others[89]	• Belford, Northumberland: Wilkinson and others [90] and https://research.ncl.ac.uk/proactive/belford/ • From Source to Sea project – Holnicote, UK. https://www.nationaltrust.org.uk/holnicote-estate/documents/from-source-to-sea---natural-flood-management.pdf • Measures discussed in the SEPA NFM handbook	• Not much information for reducing diffuse pollution • An innovation technique developed at The James Hutton Institute research farms • Has been tried on other local farms • See https://ww2.rspb.org.uk/community/ourwork/b/scotland/archive/2017/05/10/magic-margins.aspx	• BufferTech project is central evidence point: www.buffertech.dk • Assessment covers biodiversity, biomass, water storage, nutrient retention/balances • Sites in Scotland (1), Denmark (3), Sweden (1) • Science paper (Zak and others JEQ)
Challenges and limitations	• Sediment accumulations need to be managed	• Needs a fair bit of space • Space required, bund width is usually around 6 m to 8 m	• If the infiltration is poor or the troughs not vegetated could create erosive convergent	• Ditch installation set-up and maintenance • Harvesting biomass and beneficial uses

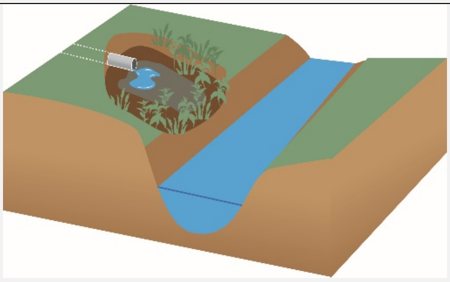
	• Space required, bund width is usually around 6 m to 8 m • Bund will require ongoing inspections, especially after storm events	• Bund will require ongoing inspections, especially after storm events	flowpaths that could connect to stream in a low corner	• Ditch dredging if a highly erosive site • Limited access to manage vegetated buffer • Potential for parallel ditch to become active channel during flood events
Potential for modifying	• Can be vegetated with a mix of grasses for extra stability to the bund • Usually fenced off in a livestock field to ensure livestock do not damage bund	• Can be vegetated with a mix of grasses. This provides extra stability to the bund. • Usually fenced off in a livestock field to ensure livestock do not damage bund	• Could be used on temporary grassland/leys	• Could be used on temporary grassland/leys • Due to initial set-up would target higher risk scenarios (for N, P, sediment and low biodiversity/tree cover)

Name	9 – Sediment traps	10 - Swales	11 – Wetlands	12 – Controlled and irrigated drainage
Image/ schematic				
Main aspects	• A point-based measure placed in an existing buffer zone, or alternatively in an agricultural ditch • Engineered feature, designed to hold back run-off/stream flow allowing time for suspended sediments to settle. Usually an outlet pipe or controlled spillway spills excess flow • It is usually better to have large surface areas as this allows	• A linear feature that is designed to collect and transfer surface run-off in a controlled way • Augmentation of a buffer rather than an actual buffer measure • Usually dry most of the time • Less expensive than a piped system • Attenuates run-off, swale is vegetated and this roughness slows the flow	• A point-based measure that is placed in an existing buffer zone or alternatively placed in an agricultural ditch • Can promote ecological diversity • Permanently wet and can have varying depths • Treats farm or field run-off by slowing the flow • Can be constructed or more natural in design • Requires some regulation to ensure	• Field drains are important rapid pathway for N to streams • Field drain direct discharges to watercourses are managed and the soil is used to promote denitrification of drain waters • Controlled drainage utilises a control valve in the riparian zone to wet the upslope field area during periods of minimum required access Control opened manually

	more time for sediment to settle • Usually placed upslope of an existing measure to provide a managed point for extracting captured sediment • Good for extreme erosion situations such as steep slopes, or exposed soil	• Sediments can therefore settle out within the swale • Allows infiltration to take place (assuming sandy or loamy soil) • Can direct flow to another measure, for example wetland	correct water depth is maintained • Should be fenced off if in livestock area	in spring before trafficking on field • Irrigated drainage uses a small weir control box to raise the water that is then irrigated onto the surface of a wet grass buffer in the margin. Control structures in riparian zone but uses either upslope area (controlled drainage) or riparian area (irrigated buffers)
Appraisal and relevant literature	• CREW Rural SuDs guidance document http://www.crew.ac.uk/publication/rural-sustainable-drainage-systems-practical-design-and-build-guide-scotlands-farmers • Netherton, Northumberland - https://research.ncl.ac.uk/proactive/netherton/	• CREW Rural SuDs guidance document - http://www.crew.ac.uk/publication/rural-sustainable-drainage-systems-practical-design-and-build-guide-scotlands-farmers • Netherton, Northumberland - https://research.ncl.ac.uk/proactive/netherton/natur	• CREW Rural SuDs guidance document - http://www.crew.ac.uk/publication/rural-sustainable-drainage-systems-practical-design-and-build-guide-scotlands-farmers • SEPA NFM Handbook	• Sweden, Denmark and Finland assessment on controlled drainage (www.balticdeal.eu/measure) • Apparently flat fields with permeable upper profile are suitable. Swedish trials report 70-90% reductions of water and NO3 and 60-90% reductions in soluble P

	naturalrunoffmanagementscheme/ • Defra MOPS2 project http://randd.defra.gov.uk/Document.aspx?Document=14063_WQ0127_MOPS2_Appendix5.1_Wetlands_Leaflet.pdf	alrunoffmanagementscheme/		• Trials in the U.S. on irrigated drainage (www.transformingdrainage.org). Best with sloping field and riparian buffer. Shown effective for nitrate and extreme water flows
Challenges and limitations	• Needs active management. This measure is designed to collect sediment and as a result this sediment will need to be removed • Best with larger surface area, however, this takes in a greater area of land	• Augmentation of a buffer rather than an actual buffer measure • Requires maintenance • Can require a lot of land	• Point-based measure placed within existing buffer zone • Requires some land to be taken • Requires an upstream/upslope sediment trap if placed next to intensive land management	• A degree of engineering and management required. Flat slopes require manual operations. Site suitability guidance support online • Limited knowledge in the context of UK
Potential for modifying	• Potential for managing subsurface land drains	• Stone (or another material) check dams can	• Soil bund placed around wetland can provide	• Could be used on temporary grassland/leys

		further attenuate the flow of water	extra storage (natural flood management)	

Name	13 – Cut back field drains
Image/ schematic	
Main aspects	• Field drains are fast pathways for N and dissolved P to enter streams • Therefore, identify artificial drains and cut back from stream so discharge enters a small constructed wetland area • Drain is cut back 10 m from stream bank • Wetland area dug to make a sump at new drain outlet • Wetlands can include reactive barrier materials (woodchip, ground shell)
Appraisal and relevant literature	• Evaluation ongoing in Denmark (http://watec.au.dk/research/constructed-wetland-treatment-technologies/mini-wetland-for-nutrient-removal/) • Not believed to have been tried in the UK under experimental conditions, but N and P retention and turnover rates can be estimated from existing constructed wetlands on a source: treatment area basis
Challenges and limitations	• Requires careful control to ensure that erosion does not occur, and surface run-off is not worsened • Could potentially encourage pollution swapping, for example, NO_3 to GHG • Point-based measure • Would need to be included in fenced area of cattle exclusion from the riparian space if used against pasture
Potential for modifying	• Could be used on temporary grasslands/leys • Can work in combination with another measure, for example sediment trap/wetland

4.2 Selecting and assessing a subset of riparian buffer types

4.2.1 Selected riparian buffers assessment

From the long list of buffer types in Table 4.1, five were taken forward for detailed scoring. The buffers selected, as shown in Table 4.2 were:

- **vegetated** buffer (watercourse) (measure 1)
- **wooded** buffer (watercourse) (measure 4)
- **designer** vegetation *(built on a vegetated buffer)* (building on measure 1)
- **raised** field margin (near watercourse) (measures 5-6)
- **engineered** buffer *(combining aspects of measures 6, 8, 11, 13 and including instream leaky barriers)*

Vegetated and wooded buffers were selected as these are the most common forms of buffer used. The next three measures were selected to assess how a buffer could be developed to provide more ecosystem services (building on measures 1 and 2 from Table 4.1). To keep the scoring simple, we applied a set width of 6 m to all shortlisted measures. As previously mentioned in section 2, width is an important factor in buffer effectiveness. Therefore, we chose one of the most common widths (6 m) to score as it was felt to be a width used by many farmers but it wasn't too narrow to severely limit the effectiveness of the scoring.

Table 4.2 shows a cross sectional schematic of the five selected riparian buffers, provides a definition, and describes the benefits and problems associated with the measure. The table progressively introduces more structural elements (top to bottom) enhancing or providing additional functions depending on site-specific needs. The engineered buffer system comprises a package of bespoke options where the greatest intervention level is required. It is recognised that there are trade-offs which increase down the list between effectiveness for increasing pollution pressures and required levels of planning and design for implementation.

Table 4.3 shows the scoring for each of the five buffer types against their effectiveness to address different functions (e.g. retain sediment) and the confidence in the evidence. A buffer, such as an engineered buffer, may score low in confidence because of limited studies specific to a function (e.g. pesticide capture), even though the knowledge behind the fundamental principles/processes might be well known. All scorings in Table 4.3 assume the land owner is following currently understood best management practices. While these buffers are appropriate at various watercourse scales from farm ditch to main river channels, the scoring and illustrative diagrams assume they are used in a small stream.

Effectiveness is depicted numerically as 5 (very good) to 1 (very limited) and level of confidence (number of formal studies) as three-points of shading (darker being higher confidence). The total row beneath each function group highlights the two best scoring buffer types (in bold). '+' denotes potential to achieve higher value in this function with extra effort in establishing diverse ground conditions maximising potential habitat mosaics. **Table 4.4** contains notes that support the scoring criteria behind Table 4.1.

Figure 4.1 shows scores against four criteria. The score ranged from 1 to 10, where 1 was the lowest and 10 the highest. The criteria were:

- Environmental quality improvement potential (how likely this measure is to improve the local environment).
- Fit with the farm business goals (is it likely to impact on the farm business in a positive or negative way, considering the role of environmental payments to offset loss of land).
- Likelihood of uptake (would the farmer implement this measure, note this is an estimate and would need to be assessed by the farming community).
- Lifespan relative to management effort (how long it will last for).

Table 4.1 Schematic, definition, and advantages and disadvantages of five selected riparian buffer types

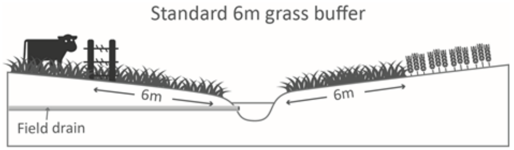
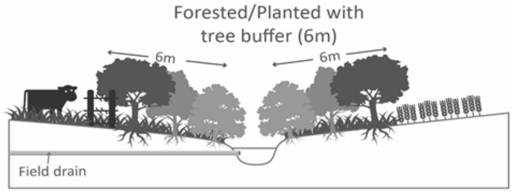
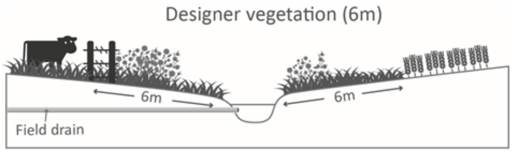
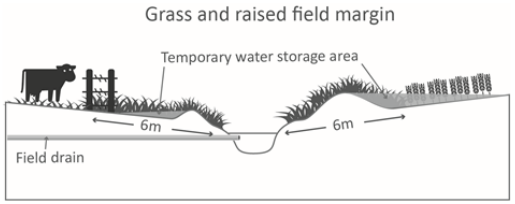
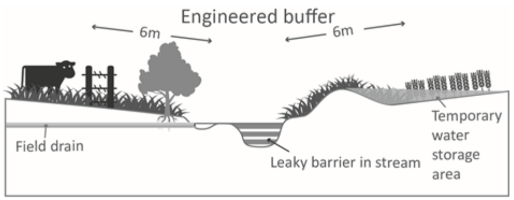
<table>
<tr><th></th><th>Schematic</th><th>Definition</th><th>Benefits (+) vs Issues (-)</th></tr>
<tr><td>Vegetated Buffer</td><td>
</td><td>A grass filter strip that slows and filters surface runoff, sets-back cultivation and agro-chemicals from the stream and excludes cattle.</td><td>+ Most common measure selected by farmers
+ Good knowledge on functioning
+ Other measures can be integrated onto this measure
- Limited enhancement of terrestrial – aquatic connectivity
- Pollutant trapping limited by fine sediments or converging flows
- Little intervention for subsurface flows</td></tr>
<tr><td>Wooded Buffer</td><td>
</td><td>Woodland planting (for example 3 rows of trees, approximating ~50% shade) with grass understory to set-back agricultural activities and excluding cattle, slow and filter runoff with rooting tapping into deeper nutrient flows and with canopy interception benefits.</td><td>+ Good knowledge on functions from roots to canopy processes
+ Increased pollution, biodiversity, amenity and carbon benefits
+ Can produce biomass with trade-offs with habitat
+ Enhances aquatic ecosystems by shading and woody debris
- Rooting may disrupt drains
- Buffers <10 m do not fit current woodland creation schemes</td></tr>
<tr><td>Designer vegetation</td><td>
</td><td>Enhancement of herbaceous vegetation (without introducing trees) for specific purposes e.g. wild flower mixes for biodiversity and pollinators, uses the natural variation in soil water conditions, sets-back agricultural activities and excludes cattle.</td><td>+ Popular with farmers and minimum maintenance
+ Existing basis for guidance in agri-environment schemes
+ Simple measure to enhance biodiversity (e.g. pollinators)
- Limited enhancement of terrestrial – aquatic connectivity
- Pollutant trapping limited by fine sediments or converging flows
- Little intervention for subsurface flows</td></tr>
<tr><td>Raised field margin</td><td>
</td><td>Enhanced runoff and erosion trapping of surface runoff through altering ground profiles to provide temporary water storage areas that increase diversity of soil water conditions (without introducing trees), sets-back agricultural activities and excludes cattle.</td><td>+ Improves attenuation and storage of surface runoff, sediment and pollutants where runoff is more extreme
+ Temporary runoff storage limits impacts on field practices
+ Habitat diversity associated with variation in wet ground
- Increased effort in planning, design and maintenance
- Limited enhancement of terrestrial – aquatic connectivity
- Little intervention for subsurface flows</td></tr>
<tr><td>Engineered buffer</td><td>
</td><td>A bespoke package of elements designed for site-specific issues that may include grass filter strips, raised ground features or sediment traps (including potentially across the channel), interception of field drain pathways, introduction of a small woodland areas (or biomass production) and mini-wetlands, sets-back from agricultural activities and excludes cattle.</td><td>+ Maximises attenuation and storage of surface runoff, sediment and pollutants where runoff is more extreme
+ Interventions may be included for field artificial drains
+ Features keep buffer soils wet longer for denitrification
+ Floodplain connectivity and some trees enhance aquatic ecosystems
- Maximises effort required in planning and design
- Technically possible but with considerable barriers to adoption
- Little precedent in UK farmed landscapes currently</td></tr>
</table>

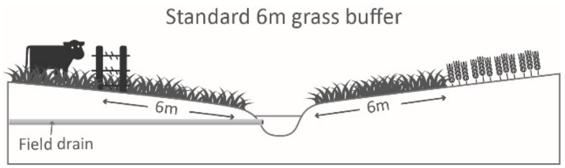
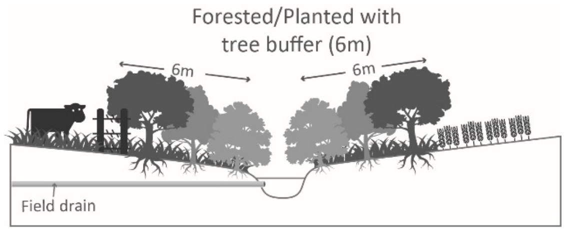
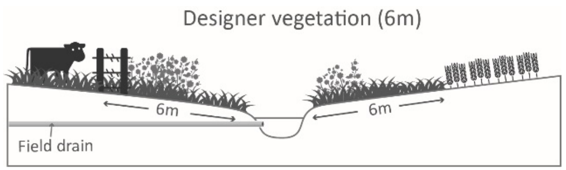
Table 4.3 Combined effectiveness and confidence matrix for the five riparian buffer types. *Effectiveness is depicted numerically as 5 (very good) to 1 (very limited) and confidence (number of formal studies) as three-points of shading (darker being better confidence).*

Functions		Vegetated buffer	Wooded buffer	Designer buffer	Raised buffer	Engineered buffer
Diffuse pollution	Soil loss control & sediment retention	2	3	2	3	4
	Phosphorus capture & retention	1	3	1	3	4
	Nitrogen capture, uptake, loss	1	3	1	2	4
	Pesticide/herbicide capture & breakdown	1	4	1	2	3
	FIO barrier/retention	3	3	3	3	3
	DIFFUSE POLLUTION TOTAL	*8*	***16***	*8*	*13*	***18***
Ecosystem	Aquatic processes: shading, leaf litter	1	5	3	1	3
	Terrestrial habitat diversity	2	4	4+	3+	4+
	System C retention: biomass, soils	1	3	1	1	2
	Hydro- / Geo- morphic improvement	1	4	1	3	4
	ECOSYSTEM TOTAL	*5*	***16***	*9*	*8*	***13***
Flood	Flood water retention / slowed flows	1	4	1	3	4
	FLOOD TOTAL	*1*	***4***	*1*	***3***	***4***
Infrastructure	Field processes: pollinators, pests	2	3	4	3	4
	Biomass: food/fuel/green manure production	1	2	2	1	1
	Required access: vehicles / cattle crossing	1	1	1	1	1
	INFRASTRUCTURE TOTAL	*4*	***6***	***7***	*5*	***6***
Amenity	Visual landscape enhancement	2	4	3	2	2
	Public access & recreation	3	3	3	2	2
	AMENITY TOTAL	*5*	***7***	***6***	*4*	*4*

Legend

Effectiveness	Very good	Good	Moderate	limited	Very limited
	5	4	3	2	1
Confidence	High	Medium	Low		

Table 4.4 Notes and assumptions on five riparian buffer types in relation to the scoring process (Table 4.3)

Schematic	Scoring notes and assumptions introduced during assessment
	1) The functionality for faecal indicator organisms (FIO) retention in grassland requires a fenced buffer and this brings management issues for providing off-stream animal watering. 2) Scoring on terrestrial habitat functions is low although increasing roughness with tussocky grassland could improve habitat for voles and associated bird predators. 3) Biomass harvesting was considered ineffective since this reduced hydraulic roughness and worsened run-off control, although it was recognised biomass harvesting can remove P. 4) Occasional access by animals was considered appropriate but use for vehicular access was likely to be negative.
	1) The model for planting considered is broad-leaved trees at 1,600 stems/ha. 2) The functionality for FIO retention in grassland requires a fenced buffer and this brings management issues for providing off-stream animal watering. 3) Shading functions were considered dependent on the ratio of tree height to watercourse width, but typically 50% shade is desirable. 4) Benefits for pests and pollinators were considered to depend on tree and understory vegetation types and could be lower than a grass buffer. 5) It was recognised that carefully-controlled stock access can benefit mosaic habitat creation among understory vegetation. 6) Biomass functions scored low due to a general desire not to regularly harvest trees to maintain other functions, but they could be appropriate and desired in some locations to help with nutrient offtake.
	1) The functionality for FIO retention in grassland requires a fenced buffer and this brings management issues for providing off-stream animal watering. 2) This option may require additional guidance to be developed for vegetation establishment and ongoing management if diverse or mosaic vegetation on different soil moisture regimes is to be established, or trees and herbaceous mixtures. For example, in existing 6 m grass margins for stewardship schemes there is already a recommended grass/wildflower sowing mix. This component may be already in the basic grass margin and not part of our ‘designer’ next level up. 3) Taking designer vegetation further, we consider that this involves rough-/stiff- stemmed grasses (as promoted in filter strips in US) or even nutrient phyto-remediating plants and plant offtakes for green manure.

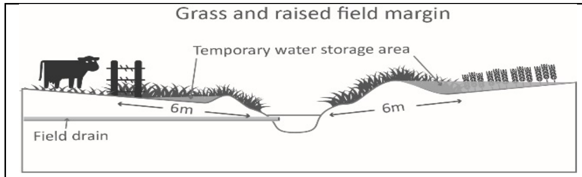
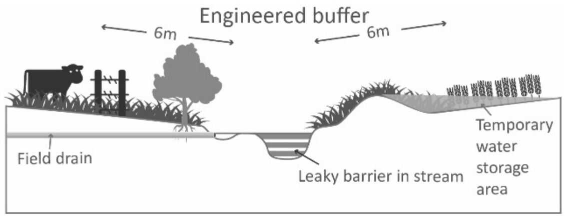
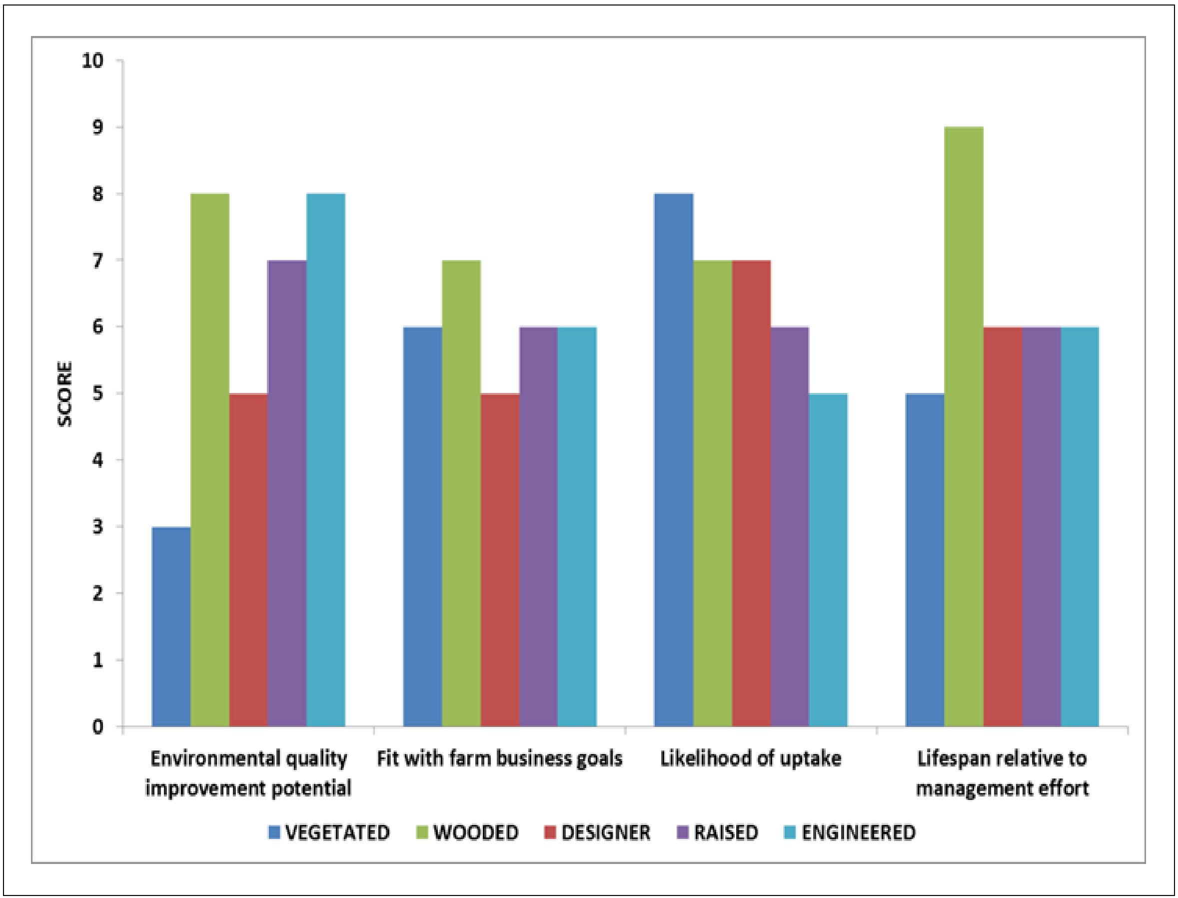
	1) In addition to a grass buffer, a range of options of bunded features for temporary water retention were considered available for placement on slopes within the buffer. 2) The functionality for FIO retention in grassland requires a fenced buffer and this brings management issues for providing off-stream animal watering. 3). Like engineered buffers, there is a potential to create a complex habitat mosaic from wetter and drier ground that elevates the terrestrial habitat potential and other field services such as pollinators, but this depends on design and management.
	1) Various designs comprised options including bunded features for temporary water retention, designs to intercept and slow artificial drain water and utilising both the buffer slopes and across the channel itself. A raised leaky barrier would likely elevate water levels higher than with raised buffers to better reconnect floodplain processes with the channel. 2) The scores given comprise an upper cap dependent on the designs chosen for a given place and reflect adopting current best management. 3) It was considered that measures that used the channel of a stream or ditch would be subject to a certain stream size above which consent to alter channel form would be prohibited. 4) The functionality for FIO retention in grassland requires a fenced buffer and this brings management issues for providing off-stream animal watering. 5) Benefits for recreation were dependent on designs and satisfactory health and safety concerning areas of wet or ponded ground. 6). There is considerable potential for complex habitat mosaics within such buffers, giving highest benefits scoring for terrestrial habitat and associated field services.

Figure 4.1 Scoring of five riparian buffer types against 4 criteria (based on a 1 to 10 scale with 1 being low/unlikely and 10 being high/very likely).



4.2.2 Management: capital outlay and maintenance

Management, including capital outlay and maintenance varies among the five shortlisted buffers. The management of the buffer, both in terms of installing and continuing to maintain the features, will influence the quality of the results they provide and how long they last.

The nature of wooded buffers (planting density, ground flora) and exact features within engineered buffer packages are examples of where early installation needs to be well managed.

Resourcing future maintenance should also be considered when assessing the options and choices of buffer types. Buffers where maintenance is important as part of their continued operation include sediment traps and bunds which may require repairs after larger storm events and sediment removing occasionally. Wooded buffers may also need managing in the longer term through thinning or harvesting. **Table 4.5** gives a brief overview of the management requirements for each type of measure.

Table 4.5 Capital and management requirements for the five selected riparian buffers

Buffer	Capital and management requirements
Vegetated	This measure requires the least amount of investment out of the 5 shortlisted measures. However, it still requires a certain level of effort to establish the buffer, for example to establish a grass sward. Once established, the level of maintenance required is potentially low. However, cutting and removing vegetation improves the nutrient retention capabilities and may guard against P leaching. There can be issues such as weed control and compaction that need to be addressed. If the buffer is located within a livestock field, then fencing will be required.
Wooded	Planting and initial maintenance costs are significant and increase with the extent of fencing and other infrastructure required. Getting rid of grass and competing weeds at tree bases is recommended until canopy closure to help trees become established. Once trees are established costs are relatively low, depending on the management system adopted. Standard capital costs are available, and up to 80% are met by grant payments under the Countryside Stewardship Scheme. However, area and width limits for funding apply (present 10 m width limit prevents funding for tree planting on 6 m buffers). For qualifying planting schemes, annual payments may also be available to cover maintenance costs for the first 10 years. Harvesting wood will provide biomass but requires effort. It must be done with care not to destroy soil structure or leave preferential run-off paths and may give marginal returns on small areas relative to effort.
Designer	Many of the points of management are similar to a vegetated buffer. However, there may be greater costs in establishing a broader range of vegetation and maintaining this. Specialist wildflower seed mixes are available off-the-shelf for different climatic regions and goals. Often competing vegetation must be mechanically removed to allow flowering plants to establish.
Raised	The capital costs for a raised buffer are higher than vegetated or designer measures. There is a cost in establishing a bund that acts to temporarily retain surface run-off, and aspects of design and advice become necessary in many cases. If soil is sourced on the farm, the main capital costs are the time to construct the bund, install an outlet pipe and create a rock spillway. Much of this can be done with machinery available on-farm. Maintenance will be required to inspect bunds from time to time, especially after a flood event, and to repair breaches and remove excess sediment. Information on building bunds can be found in this video - https://vimeo.com/217366315
Engineered	Out of the 5 measures, this is the most expensive to build and maintain and requires the most design and advice, especially considering there are numerous potential aspects included in this category from bunds to in-ditch measures, integrated buffers, wetlands and aspects of intercepting artificial soil drainage. Capital construction costs vary depending on the site-specific context but may be reduced by using on-

	farm machinery. Maintenance points noted above also apply to this buffer type, but the site pressures of pollution and run-off may be greater where these are installed, which will increase maintenance. Maintenance will be required to inspect bunds from time to time, especially after a flood event, and to repair breaches and remove excess sediment. Periods of construction and maintenance of features (both may need regulatory consents) pose a risk of pollutant washout and disturbance to watercourses that must be managed.

4.2.3 Recommendations for buffer design to maximise ecosystem service functions

The workshop-based expert assessment process found that:

- It is apparent that the buffers that provide the widest range of ecosystem services are the wooded, raised and engineered examples that enhance the structural aspects of the buffers associated with a range of functions (Table 4.3). Trees were highlighted as an important feature within buffers to provide many ecosystem services. Engineered features also have considerable potential to improve the ecosystem, but these had been much less tested than trees.
- A limited body of evidence meant that confidence was low in the pollution reduction functions of raised and engineered buffers, whereas high confidence in many aspects of vegetated grass buffers and wooded buffers showed the bias of studies towards these more simple designs. Nevertheless, the components of engineered buffers are known to be technically feasible (for example, sediment traps) or are recently improving in evidence (for example, artificial drainage interception) and, therefore, they are seen to have the potential to be more effective than a vegetated or bunded buffer.
- The overall scoring on potential for improving environmental quality increased as the design of the buffer became more complex (vegetated had lowest scoring and engineered and wooded scored highest). However, the increasing complexity of the design, especially for raised and engineered buffers, brings a need for greater advice and planning based on emerging design and maintenance guidance. Therefore, currently, the complexity of these buffers is associated with low uptake and lack of demonstration examples.
- Wooded buffers help to enhance terrestrial habitat but especially protect and enhance nearby aquatic processes in the channel. The diversity of wet-dry ground in raised and engineered buffers was considered to bring complex terrestrial habitat mosaics that enhanced biodiversity.
- For diffuse pollution, carbon retention, geomorphic and flood management benefits vegetated grass filter strips and designer vegetation buffers were least effective, whereas wooded buffers and the more complex raised and engineered systems were more effective.

- Amenity and biomass were somewhat reduced for the raised and engineered buffers relative to other systems due to the complexity of sculpted terrain for access.
- The concept of 3D buffers (working below and above the ground) provides more and improved ecosystem service benefits (as shown by the wooded and engineered buffer measures) through a qualitative assessment. More research is needed to assess the quantitative benefits of 3D buffer structure aspects across ecosystem services as confidence in their effectiveness is lower in many functions.
- All measures had a similar moderate scoring for integration with farm business and for lifespan except for a wooded buffer that gained a high scoring of 9 (Figure 4.1)

5 Conclusions

Reducing agricultural diffuse pollution and attaining WFD water quality targets has been challenging. This emphasises the need for enhanced protection of watercourses by containing the source of pollution through good practice and interrupting pollutant pathways for both surface and subsurface routes. Improving the effectiveness of riparian buffers from the current designs, that generally comprise only grass or wildflower margins, is essential in achieving better water quality and many other objectives of government's 25 Year Environment Plan.

The main objective of riparian buffers is to reduce pollutant loads leaving the field and entering the adjacent water. Having a range of designs and options for a riparian buffer will help address different landscape pressures and potentially address a wide range of ecosystem services. Currently, riparian buffers are not widely adopted even where they are mandatory. This issue needs to be addressed through better advice and guidance, regulatory enforcement and incentivisation.

This report concludes that:

- many of the recommended options are available in existing agri-environment schemes - supporting/encouraging uptake is a win-win
- Many buffers are not constructed or managed to maximise their benefits - technical guidance on making small changes to existing buffers could increase the wider environmental benefits
- A hierarchy of designs are available and these need to be targeted to the most effective locations/settings – existing guidance needs updating to include more complex buffer designs
- Tools and models to help target buffer types effectively to the critical source areas in fields and catchments are mostly in the research domain

Along with a review of published evidence this report includes an expert assessment of the likely benefits of enhanced buffer designs based on pollutant control effectiveness, cost, acceptability etc. We conclude that establishing wooded buffers scores highly for improving many functions and has a substantial supporting body of evidence. Increasing implementation by farmers will require encouragement but should only require limited technical guidance.

Aspects of the designs highlighted in the report have significant potential for controlling pollution but also for improving habitat, managing flooding, amenity and wider aspects that increase cost-effectiveness across a range of public benefits. These include new designs not previously considered as part of stream-side buffer management. Existing buffers are often designed as dry buffers to aid infiltration, but many functions of natural riparian areas exist due to the raised water tables in that zone (wetter habitats and services such as denitrification or nutrient uptake through roots).

There are new approaches in landscaping the stream-side zone (for example, resculpturing of the ground profile and wetting margin areas using waters from artificial drainage to encourage nutrient processing in soils). These features can enhance buffer performance and where appropriate influence the watercourse margin's wetness.

The diversity of nutrient retention, biogeochemical processing and complex mosaic habitat quality provided by areas of wetter and drier soils within more integrated buffer designs will help the positive functions of the buffer such as nutrient capture.

New designs have been put forward that can be considered in a hierarchical approach. The five buffers identified can be applied to riparian margins with widths between 2 to 10 m depending on local conditions and desired outcomes. Wooded and engineered buffers require more space for trees and other structures related to functions and we have compared them here based on a model 6 m width.

The most basic buffers comprise vegetated (grass) filter strips and these are commonly accepted, widely adopted and well-studied. When applied in linear, fixed widths these are simple to plan and management guidance exists (for example, periodic vegetation cutting). However, these buffers are often compromised in effectiveness for surface run-off pollution by convergent flows and/or delivery of fine soil particles and are ineffective for subsurface pathways. Designer vegetation introduces specific habitat into these buffers but with little additional pollution control benefits.

The scientific review of evidence and expert panel assessment drawn together here conclude that improving the buffer functions of nutrient capture and retention, habitat protection of aquatic ecosystem services and space for natural channel form and roughness can best be implemented with riparian trees in wooded buffers and/or using combinations of interventions locally, comprising raised ground, sediment traps, artificial drainage solutions, wetlands and channel dams according to local pressures.

Establishing wooded buffers scores high for improving many functions and has a substantial supporting body of evidence. Increasing implementation by farmers will require encouragement but is likely to only require limited guidance.

We recognise that certain water-dependent protected sites require the highest levels of interventions. For these sites, it may be necessary to incorporate options including:

- Re-sculpturing the buffer surface and/or stream banks to trap extreme sediment delivery and temporarily store water;
- Enhancing denitrification with wetlands;
- Treating large field drains and installing across ditch measures.

We recognise that the greater range and efficacy of ecosystem functions gained from engineered buffers is offset by challenges to implementing them for farmers due to their unfamiliarity, need for demonstration, guidance, planning and a developing evidence base. While the engineered buffer is perceived as the most complex to implement, the various options can be progressively increased in complexity by starting with a vegetated buffer, then applying wooded areas, then water-holding features at recommended designs and densities.

Where and how to use the options

The choice of the options for any given location depends on the pollution pressure, status of the water environment and specific ecological goals (for example, shade requirements for salmonid habitat or desire for wildflower diversity for insects). The designs need to consider field, riparian and ditch/stream hydrology in space and time, including groundwater. A set of guidance tools going from coarser screening to fine (field) scales could comprise:

- Water quality and ecological condition as reported under River Basin Management Plans to identify waterbodies currently failing or in trajectories of decline (for higher protection), especially those failing or at risk of failing due to agricultural diffuse pollution. Objectives at this level need to recognise catchment connectivity and downstream areas with special ecological requirements.
- Risk modelling and mapping of pollutant sources and pathways such as soil vulnerability to erosion, compaction and nutrient leaching. These are all available and being further developed to aid coarse to medium-scale targeting of measures within catchments of failing water bodies. At this scale, differences between pollution delivery and styles of necessary buffering between steeper, erosive headwaters and lowland soils with groundwater connectivity or soil drainage become more apparent. This is achieved by scientific developments, regulatory authorities and catchment advisory bodies.

In terms of guidance on the design, installation and ongoing maintenance requirements there is already technical guidance available to build on. Further guidance should be developed to make buffer design options clear as to where and when they are appropriate and how processes can be compromised by risk factors or improper management. At the highest tier of protection, the more complex bundled sets of measures may require advisors to provide support in terms of design.

Future requirements

Including trees in riparian buffers is novel to land managers and is not currently being implemented widely enough and where it is required. Support for future environmental stewardship schemes should consider an ability to promote wooded buffer creation in narrower (6 to 10 m) wide margins that are smaller than current forestry minimum planting widths.

Unfamiliarity and a lack of documented evidence for buffer designs considered to be more ‘engineered’ contribute to current negative attitudes in farmer focus groups. Evidence must be developed to show the potential environmental outcomes versus the cost of raised and engineered buffers for pollution mitigation and their additional habitat potential compared with other options. Demonstration systems should aim to increase awareness and uptake as part of a shared agenda with NFM communities.

To persuade the farming community to adopt wider, more complex buffer designs there is a need for clear advice, funding and ongoing maintenance commitments. There is also a need to demonstrate the benefits of new and unfamiliar designs and promote confidence in the work of buffer zones. Other aspects likely to persuade farm businesses include cash cropping of bioenergy margins or improving numbers of pollinating insects.

Decisions are needed on when and how additional schemes for variable width targeting ought to be and can be used, as opposed to the regulatory simplicity of prescribed, fixed widths. The trade-offs of effectiveness versus space with much wider (>10 m) but simpler margins (grass and/or trees) should be compared with smaller margins (around 6 m) with a density of engineered features. Variable options increase the potential for local interventions but require scientific tools and local advice and knowledge for tailored planning. We consider that methods of buffer targeting are improving and provide a basis for implementing complex riparian buffers in prioritised catchments. This will be achieved through discussions between advisors and farmers.

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