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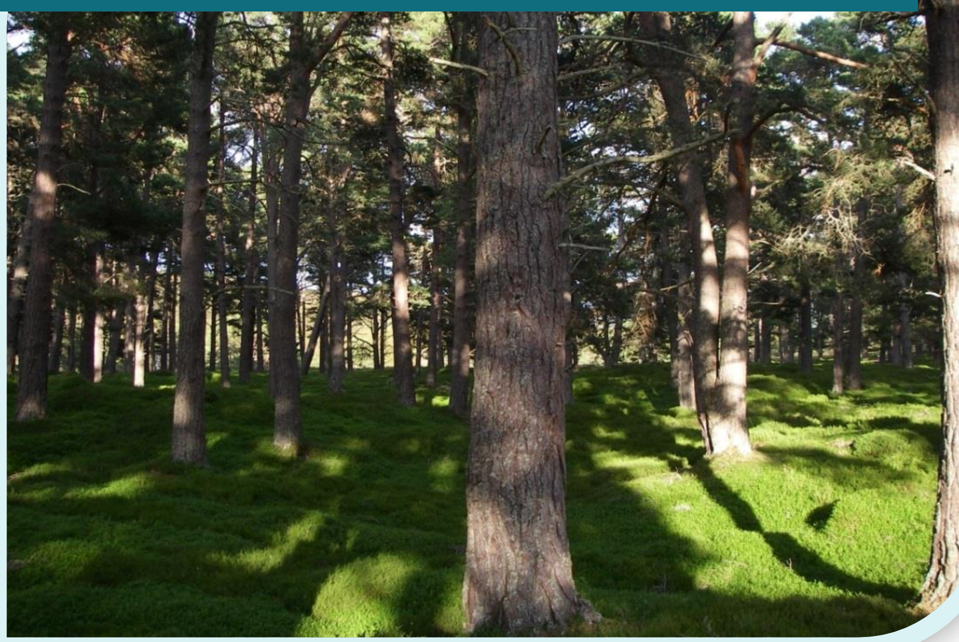
Reducing pollution from forestry related activities in the Galloway and Eskdalemuir forests: A review of Best Management Practices to reduce diffuse pollution



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This document was produced by:

Rachel Helliwell, Lisa Avery and Anna Conniff
The James Hutton Institute
Countesswells Road
Craigiebuckler
Aberdeen, AB15 8QH
Scotland

David MacNay
SEPA
Dumfries and Galloway Team
Irongray Road
Dumfries
DG2 0JE

John Gorman
SEPA
Dumfries & Galloway Team
Minnigaff
Newton Stewart
DG8 6AA

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Contents

EXECUTIVE SUMMARY

This report provides the scientific evidence to support a handbook/user guide that foresters and catchment specialists can use to identify measures to mitigate specific diffuse pollutants. It provides a list of control practices (measures), descriptions of their applications and estimates of their effectiveness. Commitment by companies to sustainable forest management objectives requires that solutions to water quality impacts associated with normal forest management and management in sensitive sites be developed. This report provides a guide to those control and mitigation practices.

A systematic search for peer reviewed papers, reports and grey literature (where scientific information was lacking or unavailable) was completed using Google Scholar, Web of Knowledge and Science Direct. Contact was made with authors of key reports from North America and Scandinavia to ensure that the most relevant and up-to-date material was incorporated in this review.

Measures described here vary in nutrient capture which reflects the difficulty in achieving greater than 75% nutrient removal efficiency, particularly for nitrogen. It is worth noting that there is often a trade-off between P or sediment removal and N removal, as different conditions are often required for removal of each. The measures reviewed provide a good cross section of effectiveness. Measures were assessed individually, however it should be recognised that in some circumstances, a combination of measures are used to control diffuse pollution to optimise performance.

The primary role of mitigation measures for forestry is to intercept run-off and drainage pathways. These measures comprise of individual or multiple structures that replicate natural processes. They are designed to attenuate water flow by collecting, storing and improving the quality of run-off within rural catchments. They will reduce localised flooding; recharge groundwater and provide valuable wetland habitats. They are best used as a component of the solution alongside other land use measures rather than a last attempt to control run-off and sedimentation.

The means of reducing diffuse pollution in order of preference is to:

1) control the source and reduce mobilization;
2) intercept the pathway; and
3) protect the receptor as a final option.

Background

SEPA is undertaking a project "Reducing Pollution from Forestry Related Activities in the Galloway and Eskdalemuir forests". The purpose of this is to a) determine the extent of the problem relating to pollution from forestry activities; b) to promote awareness and understanding of the problem through training of the forestry sector and SEPA staff and c) develop best practice through engagement with the forestry sector. Before these goals can be met, the effectiveness of diffuse pollution measures must be quantified through an assessment of scientific literature, drawing on national and international experiences of forestry managers and scientists.

Objectives of research

The aim of this report is to collate existing information on forest management practices from national and international case studies and to review the effectiveness of these measures to help reduce non-point sources of pollution entering water courses.

Specific objectives are to:

- create an inventory of control and mitigation options for specific management activities that are appropriate for mitigating diffuse pollution in areas of managed forestry;
- review the evidence base to enable the Scottish Environment Protection Agency and the forestry industry to provide more effective and targeted advice to forest managers and contractors to avoid, minimise, or mitigate water quality concerns during routine forestry operations;
- evaluate the effectiveness of measures based on evidence from national and international studies; and
- provide material for a guidance document for forest managers that is effective and beneficial to protecting and, where possible, improving the environment.

Key Findings

Qualitative summary of best management practices to mitigate the effects of diffuse pollution from forestry operations (E= performance based on expert opinion)

Table 1 Assessment category definitions

High	Well designed and sited systems regularly reported to remove greater than 75% of pressure during design condition events.
Medium	Well designed and sited systems regularly reported to remove between 25-75% of pressure during design condition events
Low	Well designed and sited systems regularly reported to remove less than 25% of pressure during design condition events

Note: Control measure split between 2 categories relate to a range of effectiveness reported in the literature.

Control measure	Performance				
	Suspended solids	Total Phosphorus	Total Nitrogen	Pesticides	Acidification
In-ditch options					
Sediment trap	E	E	E		
Swales					
Engineered and natural barriers	E	E			
Buffer strips					
Riparian dry buffer strips					
Riparian wet buffer strips				E	
Riparian forest buffer strips					
Ponds and Lagoons					
Detention ponds					
Retention pond					
Lagoon		E	E		
Erosion Control Blankets					
Sediment nets/matting/mulching					
Filter fences					
Liming (Acidification only)					
Soil					
Water					

Key words

Forestry, diffuse pollution, mitigation, effectiveness

1. AIM

The aim of this report is to collate existing information on forest management practices from national and international case studies and to review the effectiveness of these measures to help reduce non-point sources of pollution entering water courses.

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• evaluate the effectiveness of measures based on evidence from national and international studies;

• provide material for a guidance document for forest managers that is effective and beneficial to protecting and, where possible, improving the environment.

2. INTRODUCTION

Over recent decades a strong body of environmental evidence has come to light in support of forest management activities such as road construction, harvesting, and restocking having a deleterious effect on water quality. Important impacts have been documented, in some cases, for undesirable changes in surface water concentrations of nitrate (NO_3), phosphorus (P), suspended sediment (SS) and pesticides. In the 1970s and 1980s, when acid deposition threatened the quality of surface waters, the effects were exacerbated in acid sensitive areas that were managed for forestry. Forestry is still viewed by some as a confounding factor to the recovery of acidified surface waters in these areas. Degradation of water quality from forestry operations is considered a nonpoint source of pollution (or diffuse pollution) which requires specialist management to avoid, minimise or mitigate water resource concerns and to comply with current legislative objectives and Forest and Water Guidelines. This report is designed to provide a list of control and mitigation measures and quantifies the effectiveness of the measures based on a review of literature from European and North America studies. The measures discussed here are an important component of Best Management Practices (BMP) which has been used to mitigate diffuse pollution in areas where the following management activities have taken place: road construction, timber harvesting, site preparation and restocking, and forest chemical and fertiliser management.

Section 4 provides a detailed summary of control and mitigation options, covering the following elements:

a) Summary of the measure (for a quick reference)
b) Description of the measure with design features
c) Performance of measures (based primarily on the RSuDS)
d) Evidence based solely on examples from research on managed forests
e) List of references

In addition, Tables 2-6 in the Technical Annex (Section 6) provide a summary of the effectiveness of measures for Rural Sustainable Drainage Systems (RSuDS) for a suite of water quality determinands. Measures relevant to forestry have been included in this report, although their performance is based primarily on non-forested systems.

It is a goal of this report to provide a synthesis of information about the effectiveness of measures from a range of studies so that forest managers can make informed decisions with regard to forest management during all stage of forestry operations.

3. ASSESSMENT CATEGORY DEFINITIONS

The effectiveness of measures to reduce diffuse pollution prior, during and after forestry operations is spatially and temporally variable. This variability is dependent upon a number of factors outlined in the summary sheets included in Section 4. Summary tables of the performance of measures in forested areas were collated from a literature review covering studies from North America and Europe. To date there are very few studies that have investigated the effectiveness of measures to control diffuse pollution in forested regions, however evidence from forests is presented alongside findings from a much larger study which focused on Rural Sustainable Drainage Systems (RSuDS) to provide an assessment of their effectiveness at a broader level (Avery, 2012).

Qualitative categories from the RSuDS review (Avery, 2012) have been awarded based on the "performance" of the measure; these are not necessarily associated with forestry practices. The underpinning literature used to determine the performance categories can be found in Avery (2012). The "evidence" of effectiveness of measures is directly related to studies in actively managed forests in Section 4. As part of the RSuDS report a number of experts were invited to give their opinion on the performance of measures, and in these instances "E" is assigned to the measure in the assessment tables as a general guide.

Table 1 Assessment category definitions

High	Well designed and sited systems regularly reported to remove greater than 75% of pressure during design condition events.
Medium	Well designed and sited systems regularly reported to remove between 25-75% of pressure during design condition events
Low	Well designed and sited systems regularly reported to remove less than 25% of pressure during design condition events

Note: Text contained within the tables will refer to how effectiveness can vary, under different conditions, poor design and poor management. E = performance based on expert opinion

4. EFFECTIVENESS OF CONTROL AND MITIGATION MEASURES IN FORESTRY

a) In-ditch options

i. Sediment Traps

Measure	**Sediment traps**
Summary	A sediment trap is a containment area where sediment-laden runoff is temporarily detained under quiescent conditions, allowing sediment to settle out before the run-off is discharged [(1)].
Description	

Sediment traps can take a number of different forms. In fact, some of the measures described in this document essentially function as a type of sediment trap, particularly detention and retention ponds. However, many of the measures described benefit from additional sediment trapping before runoff enters them. This can vastly improve the longevity and functioning of other measures.

A simple sediment trap can comprise an excavation either with an inlet and outlet, such that it interrupts the flow path to allow particles to settle or collect drainage from a small surrounding catchment which is allowed to settle and passes out through the outflow. More complex designs may involve covered chambers with manhole access for removal of sediment build up, or straw bales to enhance the efficiency of sediment capture.

Sediment trap (Nelson, British Columbia)

From left: Sediment trap straw bales & log fall 1998; middle plate: Sediment trap in spring; right: Sediment trap in summer 2003

Photos courtesy of Tera Erosion Control http://www.terraerosion.com/projects/work/sediment-control/project1-buskcreek/sedimentcontrol-project1.htm

Design

Small temporary ponding area often formed by excavation and usually with a gravel outlet. Rocks and vegetation around outlet will protect against erosion[1]

Size depends on soil type, runoff volumes to be intercepted and desired removal efficiency. Generally the larger the basin, the greater the removal efficiency. This is often designed based on a 2 year storm volume. 50m^3 per acre has been suggested in USA although this is site/climate dependent[1]. Keep embankments to < 1.3m unless designed by a professional engineer.

Performance	Suspended solids	**High**[E,1] By default, suspended solids will be removed through settling
Evidence		

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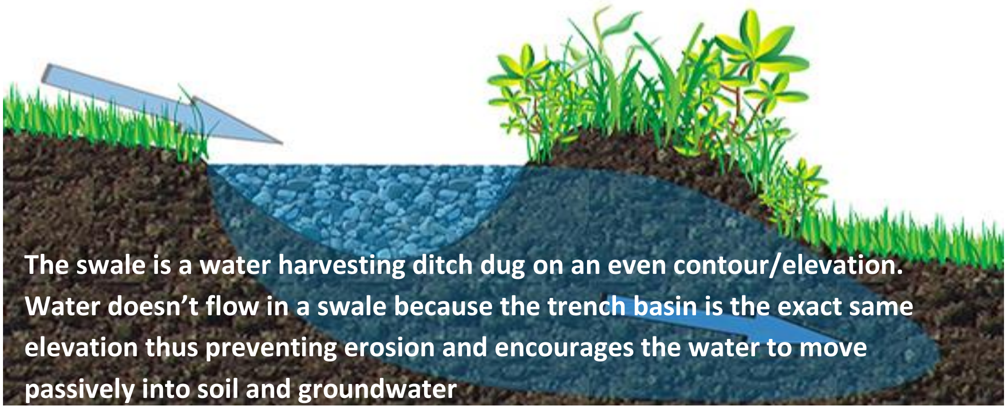
• Streamside Management Zone (SMZ) effectiveness for trapping sediment ranged from 71 to 99%[2] • 90% removal of sediment for sandy clay soil, 28% for fly ash. • Coarse particle efficiencies remained constant in ranges of 50 to 1000 mg/L suspended solids and fine particle efficiencies increased with load concentrations [3] • Sediment trap data collected within SMZs indicated that 97% of watershed erosion was trapped before reaching streams [4] • 90% of sediment flows from roads are trapped within 8 m of entering a buffer on nearly level ground. On 70° slope, sediment flows would require a 51 m buffer to ensure that sediment is trapped effectively [5] • NCASI (1986) found that for loess soil with up to 90% silt content, sediment traps could effectively capture sediment from ephemeral road runoff. Overall trapping efficiencies ranged from 52 to 96%[6]		
Performance	Total Phosphorus	**Medium**[E]: Particulate P will be retained with sediment
Performance	Nitrogen	**Low[E]:** Retention time assumed too short for N breakdown
Performance	Acidification	No information found
Performance	Pesticides	No information found
References	1. California stormwater BMP Handbook, January (2003). http://www.cabmphandbooks.com/Documents/Construction/SE-3.pdf. Accessed May 2009 2. Ward, J.M. and Jackson, C.R. 2007. Sediment trapping within forestry streamside Management Zones: Georgia, Piedmont, USA. Journal of the American Water Resources Association, 40, 1421-1431. http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2004.tb01596.x/pdf 3. Pandit, A. and Gopatakrishnan, G. (1996). Physical modeling of a stormwater sediment removal box. Final report to Brevard County, Florida, and the National Estuary Program, June 1996. http://www.stormwaterauthority.org/assets/37modelling.pdf Accessed February 2009. 4. Lakel, W.A., Aust, W.M., Bolding, M.C., Dolloff, C.A., Keyser, P. Feldt, R. 2010. Sediment trapping by Streamside Management Zones of various widths after forest harvest and site preparation. Forest Science 56, 6, 541-551. 5. Trimble, G.R., and Sartz, R.S. 1957. How far from a stream should a logging road be located? Journal of Forestry 55:339-41. 6. National Council for Air and Stream Improvement, Inc. (NCASI). 1986. A study of the effectiveness of sediment traps for collection of sediment from small forest plot studies. Technical Bulletin No. 483. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc. E. Avery, L. 2012. Rural Sustainable Drainage Systems (RSuDS). Environment Agency Report	

ii. Swales

Measure	Swale	
Summary	Swales are long, shallow depressions in the ground that are vegetated and, designed to convey or redirect runoff, reducing its volume and velocity and removing pollutants[1,2]. Swales are used to mimic the water-collecting and -holding abilities of thick forest mulch.	
Description		
Swales are broad and shallow channels covered by grass or other suitable vegetation. They are designed to convey runoff, reducing its volume and velocity and trapping particulate pollutants. They can act as conveyance structures to pass runoff between different stages of treatment or they can slow down the rate of runoff or provide temporary storage encouraging infiltration of runoff into the ground, depending on soil and groundwater conditions, and evaporation[1,2]. They treat runoff through filtering by the vegetation, through the subsoil and/or infiltration into the underlying soil.  Source: leafninjasmission.wordpress.com		
Performance	Suspended solids	**Medium:** Vegetation traps particulate pollution, temporary storage encourages sedimentation
Evidence		
• The grass filter strip between the forest and the cultivated field included a swale with a level lip spreader to disperse concentrated overland flow into the reforested area which functioned effectively to remove suspended sediments. A 35 m wide riparian buffer removed 43% of the suspended sediment concentration delivered from upslope[3]. • Approximately 50% of sediment breakthroughs occurred in areas of convergence (swales and gullies) and 25% where roads/skid trails were concentrated[4] • Contaminant removal is a function of the swale length. Removal efficiency was 70% from urban forestry[5].		
Performance	Total Phosphorus	**Medium:** Traps particulate pollution, probably little effect on dissolved pollutants
Evidence		
• Total Phosphorus (TP) was not removed by the buffer swale combination[3]. • Contaminant removal is a function of the swale length. Removal efficiency of Total P was 30% from urban forestry[5].		
Performance	Nitrogen	**Medium:** Minimal effect on dissolved pollutants, some plant uptake
Evidence		

• A grass filter strip included a swale with a level lip spreader to disperse concentrated overland flow and removed 26% of the subsurface nitrate flux[3]. • Contaminant removal is a function of the swale length. Removal efficiency of Total N was 25% from urban forestry[5]		
Performance	Acidification	No information found
Performance	Pesticides	No information found
References		

1. CIRIA (2004) Sustainable drainage systems: hydraulic, structural and water quality advice. CIRIA C609
2. Scottish Environment Protection Agency. Agricultural Best Management Practices: http://apps.sepa.org.uk/bmp. Accessed 13-02-09
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iii. Engineered and natural barriers

Measure	**Engineered and natural barriers** (Brush Barriers and Slash Windrow) within ditches and swales or open slopes
Summary	Barriers cause ditch water to pond inducing sedimentation and increased filtration. Sometimes the measure includes material which encourages further removal of pollutant from the water e.g. ochre traps[1]
Description	

Barriers and traps within ditches retain ditch water causing water to slow inducing sedimentation and increased filtration[1]. Under low-flow conditions, water ponds behind the structure and then seeps slowly through the barrier, infiltrates or evaporates. In high flow situations water flows over and/or through the structure[2].
Barriers/dams can be made from concrete, plastic, stone and earth[1,3] or constructed of straw bales or slash (brash and branches left from harvesting). Large logs are anchored against stumps, rocks, or trees at the foot of the slope and slash is placed to form a neatly compacted windrow. Filter windrows are also used at outlets of culverts, diversion ditches, water bars and dips[4]

Left: Filter Windrow of Slash at Horse Creek, Idaho, to Trap Sediment[5]
Right: Photograph of a sediment barrier © Newcastle University[1]

To enhance the water quality benefits, barriers can include sediment traps with filter material which aids pollution removal e.g. ochre traps made of small absorbent pebbles of Iron Hydroxide. These are capable of absorbing dissolved P and trapping fine sediment and the associated particulate P. The ochre can be recycled to land as slow release P fertilizer[1].

Performance	Suspended solids	**Medium**[E]: No data identified by RSuDS for basic barriers, assumed medium effectiveness due to flow retention encouraging sedimentation.
Evidence		

- The effectiveness of barriers was measured as the trapping efficiency which ranged from ~15 to ~90%[(6)] and ~18% and ~80%[4]
- Use of beryllium-7 to study the effectiveness of woody trash barriers in reducing sediment delivery to streams after forest clearcutting. Beryllium-7 was used to quantify soil redistribution on two sites using woody trash barriers along contours. Site one had barriers at 15 and 30m spacing, site two at 10, 15 and 30m spacing. For site one, the observed net soil loss was −0.4 ± 0.1 and −0.75 ± 0.08 kg m^{-2} and the sediment delivery ratio 34 and 92%. For site two, −1.0 ± 0.1, −0.7 ± 0.1 and −1.8 ± 0.1 kg m^{-2} net soil loss, with associated sediment delivery ratios of ~60, 55 and 88%. These results suggest that the shorter barrier spacings (~15 m) are more effective in reducing soil loss[7].

Performance	Total Phosphorus	**Medium**[E]: No data identified by RSuDS for basic barriers, high effectiveness for both dissolved and particulate where ochre traps and sediment traps included[1]
Evidence		No information found
Performance	Nitrogen	**Low**: Limited data identified indicated no impact on annual

		nitrogen loads.
Evidence		No information found
Performance	Acidification	No information found
Performance	Pesticides	No information found

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3. Cahil Associates Inc (2005) Pennsylvania Stormwater Management Manual http://www.webdesignpros.net/consult/pdffiles/veggieSwale.pdf
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b) Buffer strip options

i. Riparian dry buffer strips

Measure	**Riparian dry buffer strips**	
Summary	Medium width, dry, bands of natural or naturalized vegetation situated between areas of forestry and a watercourse [1]. Effective where sheet/overland run-off containing suspended solids is a problem. The buffer strip slows the run-off speed and allows sedimentation in the riparian area.	
Description	1-50 m wide bands, normally 5-15 m wide, of natural or naturalized vegetation situated alongside water bodies. The width depends on the slope, soil type and vegetation management. They ensure activities such as machinery operations are kept away from water bodies reducing the risk of direct pollution[1,2]. They also encourage sedimentation by slowing flow velocities and trapping suspended solids further reducing water pollution[1]. They are most effective when flow is kept slow and shallow. Careful cultivation is needed at the buffer edge since a plough feering (furrow) left at the edge of a buffer zone can act as a ditch, channelling water and exacerbating erosion. Often used as pre-treatment before other RSuDS techniques to reduce the risk of silting[1,3]. Because they use sheet flow and not channelised flow they are more effective than swales at removing suspended solids from runoff[3]. 	
Performance	Suspended solids	**Medium:** Filtration, CIRIA design values 50-85%[1] **High**: Encourage sedimentation and trap particles
Evidence		

- Riparian buffers were effective in preventing significant impacts on stream water quality. There was no significant difference in total suspended solid concentrations or yields due to the harvesting activities [4]. See Table below.

Watershed	*Calibration Period*	*n*	*Treatment Period*	*n*
Control	140.60 mg/l	100	62.93 mg/l	114
Treatment	241.22 mg/l	100	121.77 mg/l	114

- Compared 3 riparian buffer widths: 0m, 10m and 30m. Stream water chemistry, temperature and total suspended sediment measured weekly. TSS increased in areas without a buffer strip. 10m wide buffers provided effective protection with respect to stream water TSS.
- Water quality functions of a 15 year old riparian forest buffer system. A 35 m wide 3 zone riparian buffer removed 43% of the suspended sediment concentration delivered from upslope[5].
- The construction and use of permanent roads resulted in increased turbidity levels, but these increases only persisted in the catchment containing a number of stream crossings. This result suggested that road–stream connectivity was the most important factor in sediment delivery in catchments with roads. Harvesting in the absence of roads generally reduced turbidity levels[15].
- A review of the impacts of forest management practices in the USA indicated that TSS has been a major problem and Best Management Practices (BMPs) have been effective at reducing sediment loads in rivers. Numerous studies with effectiveness reported[16]

Performance	Total Phosphorus	**Medium:** CIRIA design values 10-20%[1] **High:** Encourage sedimentation and trap particles and plant uptake of dissolved nutrients. Potential to become a source of dissolved phosphorus if nutrients build up.

Evidence

- P reduction dependent on vegetation and binding capacity of the soil[6]
- Water quality functions of a 15 year old riparian forest buffer system. TP was not removed by a 35 m wide 3 zone riparian buffer[7]
- A 50 m wide buffer was effective at reducing total phosphorus concentrations in drainage waters from $10 mgl^{-1}$ to $<1 mgl^{-1}$, as long as flow rates were not high[8]
- A review of the impacts of forest management practices indicated that phosphorous concentrations were not degraded following forest management. Numerous studies with effectiveness reported [16]
- Evaluation of the potential of 20 constructed overland flow areas to function as riparian buffers 2-10m wide over land flow areas. Water quality above and below buffer strips did not differ significantly. Plugged outlet ditches and associated narrowed over land flow areas do not function as proper buffers in peatland areas. Area subjected to recent renovations/fertilization had elevated TP and PO_4. Overall water quality above and below the buffer strip did not alter significantly[17]

Performance	Total Nitrogen	**Low:** CIRIA design values 10-20%[1] **Medium:**

Evidence

- Compared 3 riparian buffer widths: 0m, 10m and 30m. Stream $[NO_3\text{-}N]$ decreased twofold with a buffer. 10m wide buffers may provide effective protection with respect to $[NO_3]$ [5].
- Water quality functions of a 15 year old riparian forest buffer system. A 35 m wide 3 zone riparian buffer removed 26% of the subsurface nitrate flux[7].
- A 30m riparian buffer removed nitrate to less than detection levels in shallow ground water flowing through a riparian forest in France[11]
- A 7m forested buffer was effective at removing nitrate through plant uptake and denitrification[12]
- Soil nitrate concentrations declined from 764 mg N kg^{-1} soil to 0.5 mg N kg^{-1} soil within the first 10m of the buffer area[13]
- 99% of the nitrate in waters draining from arable fields across a poplar floodplain in England was retained within first 5m of the buffer area[14]
- A review of the impacts of forest management practices in the USA indicated that forestry increased NO_3 concentrations but drinking water standards were not exceeded (except Hubbard Brook). Numerous studies with effectiveness reported[16]
- A large body of work has shown that riparian forests can remove most of the N inputs from uplands in both forested and mixed agricultural-forested watersheds on the coastal plains of eastern and south-eastern United States. Nitrate loads as high as 120 kg NO_3 $ha^{-1}yr^{-1}$ are retained in riparian forest buffers in Rhode Island[18]
- In a forest that received N fertilization, stream N concentrations reduced by 95% with buffers compared to streams without buffers[19]

Performance	Acidification	No information found
Performance	Pesticides	**Medium:** Effectively removes pesticides attached to sediment through filtration as water infiltrates into the underlying soil. Unsprayed buffer strips are used to minimize spray drift and environmental impacts to riparian and aquatic biota. Often, the width of the riparian buffer is the most argued point in debates about appropriate spray control programs. The effective buffer width is largely determined by the weather conditions, spray equipment, and application variables at the time of the spray.
Evidence		

- A literature review on pesticide use for southern forests in the USA concluded that buffer strips are effective in minimizing the impacts in streams. All the cases that had high (greater than 100 mgl^{-1}) concentrations in stream samples either had no buffer or the buffer was violated [20].
- Buffer widths from 10 to 250 m are reported in the literature to be effective in minimizing environmental impacts of pesticides[21, 22]. Many studies have demonstrated that pesticide deposits generally decrease rapidly away from the application area[23, 24, 25]

Pesticide	Application Method	Weather and Other Conditions	Buffer Width or Distance (m)	Toxic Effect Or Chemical Concentration	Test Organism	Source
endosulfan[a]	aerial	wind 1.6–2.4 $m s^{-1}$	10 50 200	50% mortality " " 90% mortality	water boatman caddisfly larvae threespine stickleback	Earnst et al. (1991)
imazapyr[b]	aerial		buffer no buffer	concentration = X concentration = 5X	N/A	Michael and Neary (1993)
permethrin[a]	back-pack spray	worst case scenario	20	<10% mortality <0.02% mortality	mosquito rainbow trout	Payne et al. (1988)
glyphosate[b]	aerial	worst case scenario	25	<10% mortality	fish and invertebrates	Payne et al. (1990)
permethrin[a]	aerial	ultra-low volume spray	25 100 250	75% mortality 10% mortality 0.01% mortality	mosquito toxicity levels compared to measured concentrations	Payne et al. (1991)
glyphosate[b]	aerial	large drop-size	10	no detect or trace level in stream water	N/A	Reynolds (1993)

[a] Insecticide
[b] Herbicide

Parent source[27]

- Ground applications require considerably smaller buffer widths to achieve 90% effectiveness. A ground application of the insecticide Permethrin had 90% effectiveness with a 20m buffer[23]
- Buffers have been effective under controlled conditions, in trapping highly adsorbed and moderately adsorbed pesticides. The table below summarises buffer studies showing trapping efficiency for specific pesticides and pesticide Koc values (sorption coefficient). Highly adsorbed pesticides were trapped at rates of from 62 to 100 %. Trapping of moderately adsorbed pesticides was more variable and ranged from 8 to 100 %. Buffers retained the lowest percentage of pesticide when buffer soil was saturated from previous rains. Many studies found pesticide trapping efficiencies of 50 % or more[9, 10]

K_{oc} values listed for each pesticide are from the NRCS Field Office Technical Guide, Section II Pesticide Property data base [9, 10.]

Highly adsorbed pesticides	K_{oc}	%
Chlorpyrifos	6,070	57–79
		62–99
Diflufenican	1,990	97
Lindane	1,100	72–100
Trifluralin	8,000	86–96

Moderately adsorbed pesticides		
Acetochlor	150	56–67
Alachlor	170	91
Atrazine	100	11–100
		52–69
		91
		30–57
		97
		35–60
		26–50

		44–100
Cyanazine	190	80–100
		30–47
2,4-D 20		70
		89–98
Dicamba	2	90–100
Fluormeturon	100	60
Isoproturon	120	99
Mecoprop	20	89–95
Metolachlor	200	16–100
		32–47
		55–74
		67–97
Metribuzin	60	50–76
		73–97
Norflurazon	600	65

Note: These figures represent a range of land uses draining to the buffer strip.

- No effectiveness of measures reported. Guidance on how to reduce the risk of contamination. Do not apply pesticides within 10 m of permanent watercourses, 20 m of lakes or reservoirs and 50 m of boreholes or wells. Only Asulam has full approval for aerial application. Requires 160m untreated buffer area and 50m for raindrop nozzle. Non-aerial methods have a much lower risk of pesticide drift and therefore require narrower buffer widths (1 and 6 m)[9]
- The 50 m buffer under the spraying restrictions as defined in the SEPA regulations provides adequate protection of sensitive species, e.g. aquatic plants, but resultant concentrations in water may not necessarily meet drinking water standards. No condition was identified whereby the buffer zone distance (50 m) should be reduced. On the contrary it should potentially be increased under wet antecedent conditions when adjacent saturated soils may increase rapid transport of Asulam to the watercourse[29]. This study does not relate specifically to forest practices.
- Recommendation: Do not apply pesticides within 10 m of permanent watercourses, 20 m of lakes or reservoirs and 50 m of boreholes or wells. Only asulam has full approval for aerial application. Requires 160m untreated buffer area and 50m for raindrop nozzle. Non-aerial methods have a much lower risk of pesticide drift and therefore require narrower buffer widths (1 and 6 m)[28]
- Different methods were tested to identify Cypermethrin in a suite of Welsh rivers. Semi Permeable Membrane Devices (SPMD) are the most sensitive method of monitoring for the presence of cypermethrin. Invertebrate monitoring and moss sampling did not return any evidence of impact or positive results for cypermethrin. Recommendation: Hylobius Management Support System or use of alternative pesticides such as "Gazelle" and maintenance of a buffer zone around watercourses and drains[10]

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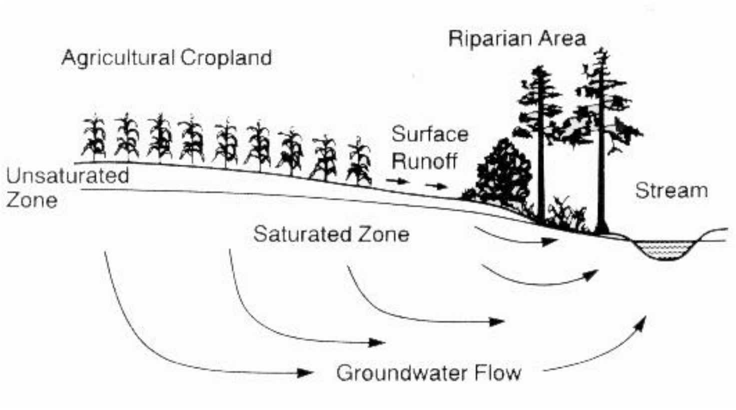
ii. **Riparian wet buffer strips**

<table>
<tr><td>Measure</td><td colspan="2">Riparian wet buffer strips</td></tr>
<tr><td>Summary</td><td colspan="2">A broad, strip of natural or naturalized wetland vegetation or wet woodland alongside a waterbody[1]</td></tr>
<tr><td>Description</td><td colspan="2">1-50m wide strips of natural or naturalized wetland vegetation or wet woodland situated alongside water bodies.


Evans et al 1996 [2]
Most useful where field drain systems can be disrupted across the buffer and allowed to discharge onto the buffer creating continually wet conditions to encourage denitrification[1]
Denitrification occurs most in buffer strips containing stands of young stages of woodland succession because of high stem density. Coppicing and grass cutting (or restricted grazing) produces most efficient strips[1].</td></tr>
<tr><td>Performance</td><td>Suspended solids</td><td>Medium[1]: Some attenuation of flow encouraging sedimentation</td></tr>
<tr><td colspan="3">Evidence</td></tr>
<tr><td colspan="3">• Temporary bridge, Stabilization by seeding (slope greater than 10% and stream crossing sites were seeded, limed, fertilized, and mulched following harvesting), streamside forest buffer (Buffer width varied from 75 to 150 feet based on slope), Wetland area crossings (including drainage, laying of geotextiles covered with 6 inches of stone aggregate), Road and trail drainage (excavated drainage structures such as dips and water bars were constructed into roads and skid trails). Concentrations range from 1.3 mgl^{-1} to 1235.7 mgl^{-1} in the control watershed and 1.4 mgl^{-1} to 1971.2 mgl^{-1} in the treatment watershed. There were significant differences in mean TSS concentrations both between watersheds and between sampling periods[4]</td></tr>
<tr><td>Performance</td><td>Total Phosphorus</td><td>Medium[1]: Some attenuation of flow encouraging sedimentation</td></tr>
<tr><td>Evidence</td><td></td><td>No information found</td></tr>
<tr><td>Performance</td><td>Total Nitrogen</td><td>High[1,2,3]: Ideal conditions for denitrification.</td></tr>
<tr><td>Evidence</td><td></td><td>No information found</td></tr>
<tr><td>Performance</td><td>Pesticides</td><td>Low[E]: Minimal breakdown and uptake likely before reaches waterbody.</td></tr>
</table>

Evidence		No information found

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iii. Riparian forest buffer strips

Measure	**Riparian forest buffer strips**	
Summary	An area of trees, shrubs and other vegetation located in areas adjacent to and upslope from water bodies	
Description	The ability of a riparian forest buffer to remove pollutants is dependent on the width of the buffer, the type of vegetation, the manner in which runoff traverses the vegetated areas, the slope and the soil composition within the riparian area[1]. Effectiveness increases with increased detention time, and is reduced significantly in the absence of sheet flow. If the buffer is intended to function as a stormwater BMP, it should be used in conjunction with other BMPs, such as grass filter strips on the outer edge of the buffer to help diffuse runoff. This practice may achieve up to 75% sediment removal, 40% total nitrogen removal, and 50% total phosphorus [2]	
Performance	Suspended solids	
Evidence		No information found
Performance	Total Phosphorus	**Medium**[6,5,8]
Evidence		
• Riparian forests filter particulate P by sedimentation and filter dissolved P by infiltration into riparian soils. Phosphorus is readily attenuated in soils by adsorption and precipitation reactions[5]. • TP retained ranges from 30%[6] to 80%[5]. Orthophosphate-P retained ranges from 37%[8] to 73%[5]. Because of increased opportunities for infiltration and sedimentation, Riparian Management Areas (RMA) with abundant settling and infiltration opportunities, retain more P than narrow RMAs (local site conditions will greatly influence this function)[5]		
Performance	Nitrogen	**High**[4]
Evidence		
• Watersheds have predominantly subsurface flow in the south-eastern Coastal Plain. Most of the nitrate is removed after 7 to 12 m movement through a riparian forest[3]. Jordan, Correll, and Weller (1993)[4] measured 95% removal of NO_3-N within 25 to 35 m from the point where the upland contacted the floodplain. • A large body of work has shown that riparian forests can remove most of the N inputs from uplands in both forested and mixed agricultural-forested watersheds on the coastal plains of eastern and south-eastern United States. TN reductions range from 68%[6] to 89%[5]. Nitrate nitrogen is reduced 83%[6] to 99%[7], when conditions for denitrification are present. Other studies have reported nitrate removals in this range[8,4]. In a forest that received N fertilization, 95% reduction in N concentration for streams with buffers compared to streams without buffers[9] • Nitrate loads as high as 120 kg NO_3 ha^{-1} yr^{-1} are retained in riparian forest buffers in Rhode Island[10]. Removals up to 45 kg NO_3-N ha^{-1} yr^{-1} from subsurface flow and 14.53 kg TN ha^{-1} yr^{-1} from runoff[3]		
Performance	Acidification	No information found
Performance	Pesticides	No information found
References		

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c) Ponds/Lagoons

i. Detention pond

Measure	Detention ponds	
Summary	Normally dry basins designed to temporally store and slowly release runoff water. Often combined with other flood or water management systems[1,2]	
Description	Basins/depressions which are usually dry and are designed to temporally store and slowly release runoff water to meet flow and water quality criteria[5]. Water leaves the basin via a restricted outflow control leading to a longer detention time and improved particulate pollution sedimentation. Pollution removal improved by including features such as pre-treatment sediment traps, deeper areas at or near inlets and low flow channels[1,2.] If the detention time is increased to 24 hours or more, the basin would be referred to as an extended detention basin and increased treatment would result. These can also provide flood control by providing additional flood detention storage. It is possible to construct a permanent wetland around the outlet of the basin providing increased treatment opportunity and biodiversity	
Performance	Suspended solids	***High***: Encourages sedimentation and nutrient uptake by plants[1,2,6,7,8,9,11,12,13,14,15]
Evidence		
• Studies indicate that wet detention ponds can remove up to 50 to 90 % of suspended solids[4] The removal efficiencies for dry detention basins and hydrodynamic structures used in the Chesapeake Bay watershed model are currently 10% for sediment[5].		
Performance	Total Phosphorus	***Medium:*** Encourages sedimentation and nutrient uptake by plants[1,2,6,7,8,9,12,13,14]
Evidence		
• Effectiveness = 30 to 90 % of total phosphorous removed[4.] • The removal efficiencies for dry detention basins and hydrodynamic structures used in the Chesapeake Bay watershed model are currently 10%, phosphorus (P)[5].		
Performance	Nitrogen	***Medium:*** Encourages sedimentation and nutrient uptake by plants[1,2,6,8,9,12,15]
Evidence		
• Dry extended detention ponds remove 20% of nitrogen[3] • Effectiveness= 40 to 80 % of soluble nutrients removed[4] • The removal efficiencies for dry detention basins and hydrodynamic structures used in the Chesapeake Bay watershed model are currently 5% for nitrogen (N)[5].		
Performance	Acidification	
Performance	Pesticides	***Medium***[E,15]
References		

Detention basin
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ii. Retention Ponds:

No information specifically for forestry practices (Summarised from Avery 2012)

Measure	**Retention ponds**	
Summary	Wet ponds, designed to permanently retain some water at all times and provide temporary storage above it, through an allowance for large variations in level during storms[1,2].	
Description	Basins with a permanent pool of water (or at least throughout the wet season) with temporary storage provided above this level. They primarily differ from constructed wetlands through having a greater average depth of water[1,2].   Photographs © Fabrice Gouriveau Pollution removal occurs through the settling out of solids and biological activity in the ponds which removes nutrients[1,2].	
Performance	Suspended solids	***High***[1,3,4,5,6,7,8,9,10,11,12,13,14,15,16]**:** Removal of sediment and associated pollutants inc. P, FIOs, pesticides[15]
Evidence		No information for forestry
Performance	Total Phosphorus	***Medium***[1,3,4,6,7,8,9,10,11,12,14,15,16]**:** Removal of sediment and associated pollutants inc. P, FIOs, pesticides[2]
Evidence		No information available for forestry
Performance	Nitrogen	***Medium***[1,3,4,6,7,8,11,12,14,15,16]
Evidence		No information available for forestry
Performance	Acidification	No information available
Performance	Pesticides	***High***: No data identified, assumed high from high sediment removal

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2. Scottish Environment Protection Agency. Agricultural Best Management Practices: http://apps.sepa.org.uk/bmp. Accessed 13-02-09
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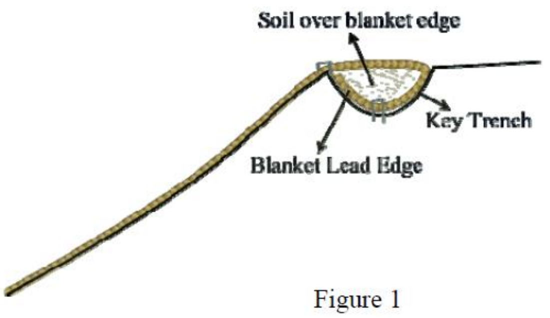
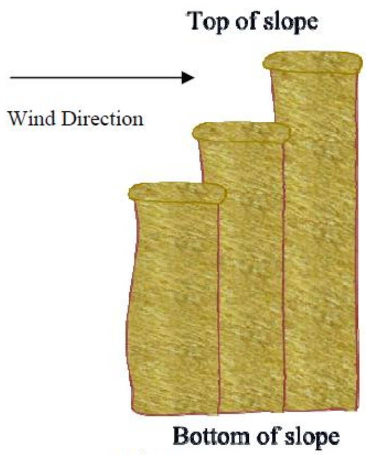
iii. Lagoons

Measure	**Lagoons**	
Summary	The lagoon is a small body of water enclosed by artificial banks and intercepts drainage water to remove influent pollutants.	
Performance	Suspended solids	No information found
Evidence		
Performance	Total Phosphorus	Medium[E,1]
Evidence		Rates of removal ranged from 9% to 55% for TP.
Performance	Nitrogen	Poor[E1]
Evidence		Rates of removal ranged from 0.9% to 8.7% for TN.
Performance	Acidification	No information found
Performance	Pesticides	No information found
References	1. Nakamura, K. 2009. Performance and design of artificial lagoons for controlling diffuse pollution in Lake Kasumigaura, Japan. Ecological Engineering, 35, 141–151.	

d) Erosion Control Blankets

i. Sediment nets/matting/mulching

Measure	Sediment nets/matting/mulching (Erosion control blankets)
Summary	Erosion control blanket is a general term for any cover that protects soil from erosion. The effectiveness of each cover type increases as the percentage of groundcover increases i.e. 96% ground cover of "straw alone" is needed to reduce erosion by 80% compared to no mulch control[1,2]
Description	Erosion control blankets are usually woven from a chosen material and are meant to slow down the speed at which water moves across the surface. The material chosen is usually something with ridges and obstructions to reduce water flow/speed. There are different types of erosion control blankets, some synthetic and some natural. There are even a few that are both synthetic and natural. These blankets can be made out of straw, coconut fibre, aspen fibre, jute, and polypropylene (plastic)[2].  Figure 1  Figure 2 Straw double jute net  (i) Made from ordinary straw, this is held together by a double layer of jute netting. Fibre rolls are the other type of erosion control device. These are usually made of the same materials used in erosion control blankets but are rolled into large diameter "logs." These logs can be made to just about any diameter and are usually encased in some kind of netting sewing into the desired shape. The purpose of these logs is to pool up and slow down water long enough for any sediment that is in the water to settle out. The three major materials used in fibre rolls are coconut fibre, rice wattle and wheat wattle. The concept behind the fibre roll is the same regardless of the material[2].

These rolls made of wheat will slow down water movement long enough for sediment to be deposited.
Source: University of Washington http://depts.washington.edu/propplnt/Chapters/erosioncontrolchapter%5B1%5D.pdf[2]

Sedimats™ are used in waterways during in-stream construction activities (such as pipe laying or dredging) to trap disturbed sediment that may pollute aquatic habitats downstream. They are a simple, yet effective, biodegradable matting, which are fixed to the stream bed, and do not impede water flow[7]

GrassMat™ Supreme is a new biodegradable textile, pre-sown with seed and fertilizer, which provides an easy method for effective vegetation restoration and erosion control on a wide variety of landscapes from lawns to steep slopes. It is a natural product made purely from cellulose fibre, which biodegrades over 4 to 5 months. It is fast to lay down (two people can lay $500m^2$ in around 40 minutes on a slope with a 35° to 40° inclination, while on plane surfaces the same operation takes just 20 minutes[8]

CoirLog and CoirPallet biodegradable, coconut fibre bio-roll and mattress substrates work in harmony with nature, to protect and support banks, and shorelines, while promoting restoration of wetland environments[9].

Performance	Suspended solids	High

Evidence

9 Mg straw ha^{-1} covered with a jute mat was the most effective mulch treatment in reducing erosion but in another treatment, 6.7 Mg straw (without jut mat) ha^{-1} was the most cost-effective. Wood chips performed poorly in that study on slopes above 60%[3].

Brush mulch at seeding reduces sediment yield from road-stream crossings compared to un-mulched seedings[4]. The brush mulch consists of logging debris (2 to 15 cm diameter) which is applied by hand on the ground parallel to the contour and then compacted with a tractor. Placing slash on skid trails that have had the topsoil removed reduced erosion by 98.5% on steep slopes. Leaving a remnant litter layer on trails with volcanic ash topsoil reduced first-year erosion by 72% on 15% slopes[5]

Goss, Blanchard, and Melton (1970) assigned numerical ratings to show the relative effectiveness of various erosion control treatments for the different types of erosion. *Notes these measures are used* *to control erosion from Highways (Note: The use of asphalt as a measure)*[6]

Erosion type	Jute Net	Excelsior Mat	Straw	Straw and Asphalt[b]	Asphalt	Wood Fibre (Hydromulch[c]	Sod
Sheet	9	10	8	10	6	3	10
Rill	6	10	8	10	6	3	10
Slump	9	8	6	7	3	3	8

Erosion Control Effectiveness of various Treatments on 1:1 Slopes (Adapted from Goss, Blanchard and Melton 1970) Effectiveness rating[a]

[a] 10 = most effective; 1 = not effective

[b] Application rate for asphalt is 968 gal/acre for asphalt alone and 400 gal/acre when applied with straw

[c] Application rate of 1,200 lb/acre

SedMat[7]- Before construction, the average percentage of sediment fines in the streambed just downstream of the work site was 12.2%. After construction, it rose slightly to 14.7%. In contrast, there were locations at six test streams that were subject to the disturbance but which were not protected by the mats. These were primarily areas between the edge of the trench and the upstream edge of the mats, or off to a side where mats were purposely not laid. After construction, the average percentage of sediment fines at these unprotected sites rose from 11.5% to 24%[7]
Note data taken from marketing website

GrassMat™ Supreme provides very good results even on slopes as steep as 85° *Note data taken from marketing website*[8]

CoirLog and CoirPallet- No information given on their effectiveness to reduce diffuse pollution[9]

Performance	Total Phosphorus	No information found
Performance	Nitrogen	No information found
Performance	Acidification	No information found
Performance	Pesticides	No information found

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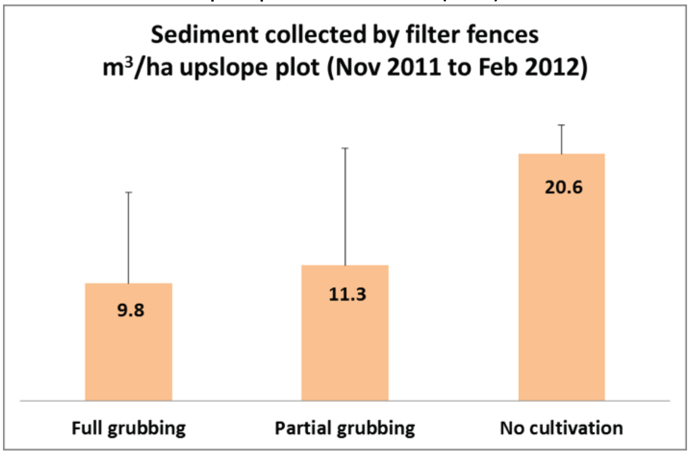
9. Hy-Tex UK http://www.hy-tex.co.uk/index.php/products/biodegradables/coirlog-and-coirpallet

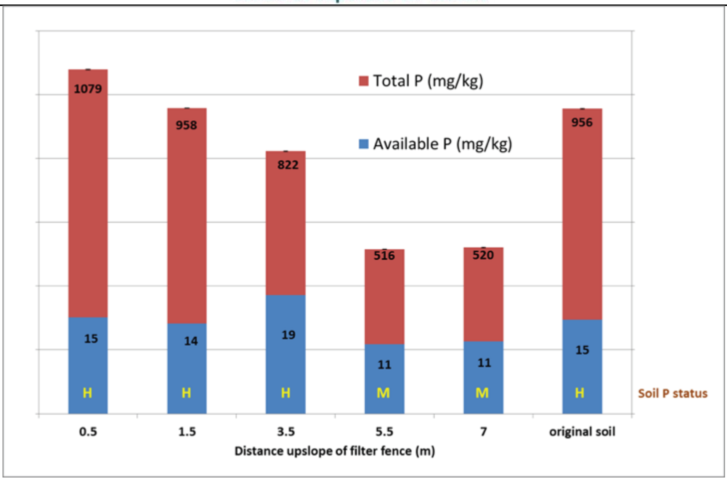
ii. Filter Fences

<table>
<tr><td>Measure</td><td colspan="2">Filter fences</td></tr>
<tr><td>Summary</td><td colspan="2">Specialised fence made from UV stabilised polythyene net, used as an entrenched interceptor fence to control pollution caused by sediment laden surface runoff.</td></tr>
<tr><td>Description</td><td colspan="2">Recent research at James Hutton Institute in association with SRUC has investigated the potential of filter fences - a technology used in the building trade to prevent sediment loss from building sites.

The material used was a close knit, UV stabilised polyethylene net with mesh aperture of 1.2mm, dug in and pinned to a 146m line of fence posts installed along the field contour at the foot of a field with average slope of 10-11%. Sediment accumulation was measured with a graduated cane. Deposited sediment was sampled for bulk density and P content (total P, available P and water soluble P).

Terrastop™ Premium is a special, high quality, permeable, technical filter fabric that can be installed as an entrenched vertical entrapment fence, and is designed to intercept and detain run-off, trapping harmful silt through settlement and filtration before it leaves the site[2]</td></tr>
<tr><td>Performance</td><td>Suspended solids</td><td>High: Based on land uses other than forestry</td></tr>
<tr><td>Evidence</td><td></td><td>Estimated volume of sediment deposited in front of the filter fences as a function of upslope cultivations (n=3)[1]

</td></tr>
<tr><td>Performance</td><td>Total Phosphorus</td><td>High: Based on land uses other than forestry</td></tr>
<tr><td>Evidence</td><td></td><td></td></tr>
<tr><td colspan="3">Despite post-harvest contour grubbing an estimated 80 tonnes of soil containing 60-70 kg P was trapped from a 17ha field after potatoes. A further trial was undertaken in 2011/12 on the adjacent field with post-harvest cultivation treatments comprising. This methods is suitable for forested sites[1]

Soil P status of sediment collected by filter fences, compared with the original soil.[1]</td></tr>
</table>



Silt fences have been used extensively in other countries for many years, and their proven performance (intercepting up to 86% of suspended solids) has made them a standard Best Management Practice on a diverse range land management projects[2]

Average removal efficiency for five storms in March of 1993. Plot is on the 34% slope of a landfill. Soil is clay cap mixed with topsoil. Plot of bare soil is 32' by 9'. Trapping efficiency of TSS 36%[3]

Efficiency determined by calculating sediment in a silty soil that will not settle after 25 minutes. Trapping efficiency of TSS 76%[4]
Construction site stockpile with a 24% slope. Gravelly sandy loam soil. Thirteen storms recorded over two winters on a 36' by 9' test plot. Trapping efficiency of TSS 86%[5]

Performance	Nitrogen	No information found
Evidence		
Performance	Acidification	
Performance	Pesticides	

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e) Liming (acidification only)

i) Soils

Measure	**Liming (Soils)**	
Summary	Addition of calcium carbonate material directly to surface waters to reduce acidity	
Description		
Performance	Suspended solids	No information found
Evidence		
Performance	Total Phosphorus	No information found
Evidence		
Performance	Nitrogen	No information found
Evidence		
Performance	Acidification	**Medium/High** Effectiveness is dependent upon the length of time since liming treatment
Evidence		Treatment: Coarse grained dolomite powder. The transport of inorganic Al to watercourses was reduced, and a more stable water quality (pH and Al) achieved throughout the year. Increased base saturation in the forest soil and increased pH of the runoff after liming may decrease the preferential ion exchange with H^+ and Al in acid soils and transport of these ions during and Al in acid soils and transport of these ions during sea salt episodes [1] The application of a low dose of lime (3 tonnes ha^{-1}) to a forest soil did not result in significant changes in surface water chemistry in the study catchments and changes in soil chemistry were mainly restricted to the humus layer during the 16 years following treatment[2.] Water quality at Loch Fleet prior to liming was incompatible with a trout fishery. Liming about 40% of the catchment in 1986 and 1987 raised the pH and calcium levels, and reduced toxic aluminium concentrations. The improved conditions have been maintained up to 1994, but water in the loch, and its principal inflow stream, is now falling close to the desired threshold of quality. Liming may have led to a short-term increase in nutrients, with some evidence of increased productivity[3]. Following single lime applications, acid-base chemistry in treated streams changed significantly. High mean pH (> 6), increased calcium (> 2.5 mg l^{-1}) and low aluminium (< 0.1 mg l^{-1}) persisted throughout the 10 years following liming[4]. Episodes of low pH continued to affect acid-sensitive taxa even after liming.
Performance	Pesticides	

References

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ii) Surface waters

Measure	**Liming (Surface waters)**	
Summary	Addition of calcium carbonate material directly to surface waters to reduce acidity	
Description	Liming surface waters is one of the most widespread mitigation techniques to protect lakes and fish stocks in acid sensitive areas. Adding calcium carbonate to surface waters in order to raise the pH is commonly termed liming. Liming of lakes has occurred for centuries in order to support aquaculture and control the pH for aquaculture production. Liming has also been used to increase the productivity of lakes. In addition, in more recent years, liming has been used to control eutrophication [4] Liming to mitigate acidification of waters has been implemented in North America and many European countries but the largest liming programs are in Norway and Sweden. Sweden has invested 3.8 billion SEK (approximately €0.4 billion) on liming between 1983 and 2006 (Bostedt et al 2010)[5].	
Performance	Suspended solids	No information found
Evidence		
Performance	Total Phosphorus	No information found
Evidence		
Performance	Nitrogen	No information found
Evidence		
Performance	Acidification	**High**[1,2,3,4] Effectiveness is dependent upon the length of time since liming treatment
Evidence		From 1987 to 1989, the river was limed only during the spring snow melt, and pH varied in the range between 5.5 and 7.0. In 1990 to 1993, the river was limed to pH 6.2 from 15 February to 1 June and to pH 5.7 during the rest of the year. Since 1994, the pH during late winter and spring was maintained above 6.5. Liming treatment reduced labile Al but the treatment had no significant effect on salmon stocks.[1] On average, liming increased the abundance and richness of acid-sensitive invertebrates and increased overall fish abundance, but benefits were variable and not guaranteed in all rivers. This systematic review indicates that liming has the potential to mitigate the symptoms of acidification in some instances, but effects are mixed[2] After the last liming, pH decreased steadily in both reacidifying lakes until annual mean values stabilised around 5.5–6.0 and 6.2–6.5 respectively. ANC and concentrations of non-marine Ca+Mg decreased after the termination of liming. The decreasing pH resulted in increasing trends of inorganic Al (Ali), which during recent years exceeded the lowest known effect level for fish on several occasions[3.] The search found 143 relevant articles. The available evidence suggests that on average liming increases the diversity of fish, zooplankton and phytoplankton, whereas the diversity of benthic organisms is not increased. The diversity of zooplankton and

		phytoplankton is estimated to decrease in some lakes but only in a small minority. The meta-analysis on the abundance of zooplankton, phytoplankton, and benthic invertebrates indicates they do not increase with liming. The impact of liming on fish abundance is less clear cut. The largest fish study suggests fish may increase in abundance with liming. However, there is a lack of studies with both baseline and control sites, making it hard to be certain whether the changes observed were due to liming. Liming has also been used to restore fish abundances by providing conditions for survival of stocked fish. The liming appears to have enabled the restocking of fish in some instances. However, many studies did not actually test if fish would have survived before liming or stock fish in control sites[4]. *Excellent review but ecological response only*.
Performance	Pesticides	No information found

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5. SUMMARY AND CONCLUSIONS

This report provides the scientific evidence to support a handbook/user guide that foresters and catchment specialists can use to identify measures to mitigate specific diffuse pollutants. It provides a list of control practices (measures), descriptions of their applications and estimates of their effectiveness (Table 7). Long-term commitment by companies to sustainable forest management objectives requires that solutions to water quality impacts associated with normal forest management and management in sensitive sites be developed. This report provides a guide to those control and mitigation practices.

A systematic search for published papers, report and grey literature (where scientific information was lacking or unavailable) was completed using Google Scholar, the Web of Knowledge and Science Direct. Contact was also made with authors of key reports from North America and Scandinavia to ensure that the most relevant and up-to-date material was incorporated in this review.

Measures described here vary in nutrient capture, reflecting the difficulty in achieving greater than 75% nutrient removal efficiency particularly for nitrogen. It is worth noting that there is often a trade-off between P or sediment removal and N removal, as different conditions are often required for removal of each. The measures reviewed provide a good cross section of effectiveness. Measures were assessed individually, however it should be recognised that in some circumstances, a combination of measures are used to control diffuse pollution to optimise performance.

The primary role of mitigation measures for forestry is to intercept run-off and drainage pathways. These measures comprise of individual or multiple structures that replicate natural processes. They are designed to attenuate water flow by collecting, storing and improving the quality of run-off within rural catchments. They will reduce localised flooding; recharge groundwater and provide valuable wetland habitats. They are best used as a component of the solution alongside other land use measures rather than as a last attempt to control run-off and sedimentation.

The means of reducing diffuse pollution in order of preference, is to:

1) control the source and reduce mobilization;

2) Intercept the pathway;

3) protect the receptor as a final option.

Table 7: Qualitative summary of best management practices to mitigate the effects of diffuse pollution from forestry operations (E= performance based on expert opinion)

Control measure	Performance				
	Suspended solids	Total Phosphorus	Total Nitrogen	Pesticides	Acidification
In-ditch options					
Sediment trap	E	E	E		
Swales					
Engineered and natural barriers	E	E			
Buffer strips					
Riparian dry buffer strips					
Riparian wet buffer strips				E	
Riparian forest buffer strips					
Ponds and Lagoons					
Detention ponds					
Retention pond					
Lagoon		E	E		
Erosion Control Blankets					
Sediment nets/matting/mulching					
Filter fences					
Liming (Acidification only)					
Soil					
Water					

6. TECHNICAL ANNEX (Avery, 2012)

Table 2: Performance- Sediment Traps

Removal efficiency (per cent, unless otherwise stated)	
	Pandit and Gopatakrishnan (1996)
Flow	
SS	90% removal of sediment for sandy clay soil, 28% for fly ash. Coarse particle efficiencies remained constant in ranges of 50 to 1000 mg/L suspended solids and fine particle efficiencies increased with load concentrations
TP	
Dissolved P	
Particulate P	
TN	
Dissolved N	
Particulate N	
Total pesticides	
Details of study	Physical modeling of a stormwater sediment removal box

References

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Table 3: Performance- Swales

	Removal efficiency (per cent, unless otherwise stated)						
	Briggs et al (1999)	Horner & Mar (1982)	Center for Watershed Protection, 2000	USEPA, 2002	Atlanta Regional Commission 2001	Barrett, 1998	Claytor and Schueler, 1996
Peak flow	47						
SS		80	60-83	81	80	70	80 wet/ 90 dry
TP			29-45	9	25 wet 50 dry		20 wet/ 65 dry
Nitrogen			Negative (nitrate)	38%	40 wet 50dry		40 wet/ 50 dry
Pesticides	Av 56%						
Study details	Compared to non grassed waterways	61m			Design manual		Design Mannual

	Removal efficiency (per cent, unless otherwise stated)						
	Wash et al, 1997	Highways Agency et al 1998	Macdonald & Jefferies, 2003	Luker & Montague, 1994	Winer, 2000	Schueler, 2000	CIRIA, 2004
SS	60-83	60-90	55-72		38	81	60-80 wet 70-90 dry
TP	30		7.7increase to 100 (ortho-P)	42-63	14	34	25-35 wet 30-80 dry
Nitrogen	25		45	41-51		84	30-40 wet 50-90 dry
Study details	Literature review						

	Removal efficiency (per cent, unless otherwise stated)						
	Hicks, 1995	Urbonas, 1994	EPA, 1999				
SS	50%	80%	30-65%				
Study details							

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Performance- No additional information for Engineered and natural barriers in Avery, 2012

Table 4: Performance- Riparian dry buffer strips

	Removal efficiency (per cent, unless otherwise stated)					
	Borin et al (2004)	Patty et al (1999)	Arora et al (2003)	Atwill et al (2002)	Hussein et al (2008)	Duchemin and Madjoub (2004)
SS	93%	87-100%	86-90%			90%
TP	80%					87%
Dissolved P	78%	22-89%				
Particulate P						5%
Nitrate/ nitrogen	72%	47-100%				85%
Pesticides	60-90% terbuthylazine, alachlor, nicosulfuron, pendimethalin, linuron	72-100% Lindane 44-100% Atrazine 99% isoproturon, 97% diflufenican	47-52% atrazine 48- 54% metolachlor 77-83% chlorpyrifos			
Study details	strip of grass (next to the field) and a row of old woodland vegetation (confining with the stream), for a total width of 6 m	Grass buffer strips 6-18m	Simulated runoff, 1.52m wide drainage area to buffer are ratio 15:1 and 30:1	slope of ≤20% and a length of ≥3 m		3m buffer, 5 years

	Removal efficiency (per cent, unless otherwise stated)							
	Cole et al (1997)	Doyle et al (1977)	Dillaha et al (1986)	Syversen (1995)	Schmitt et al (1999	Lowrance et al (1995)	Petterjohn & Correll (1984)	Schwer & Clausen (1989)
SS			91%	61-91%	63-93%	92%	89.7%	95%
TP				45-73%	48-79%	70%	73.7%	89%
Dissolved P	93%	62	58-69%	0-88%	19-50%		58.1%	92%
Particulate P								
Nitrate/ nitrogen				54-91%		74%	60.4%	92%
Study details	4m, rainfall events	4m, rainfall events	4.6-9.1m rainfall events	5-15m rainfall events	8-15m rainfall events	19m	19m	26m, 3 to 7 years

	Removal efficiency (per cent, unless otherwise stated)							
	Young et al (1980)	Lowrance et al (1995b)	Uusi-Kamppa et al (2000)	Wong & McCuen (1982)	Lim et al (1998)	Vinten (2006)	Magette et al (1989)	Schmitt et al 1999
SS	78%			90-95%				
TP		77-79%	-64% - 14%			30-40% (5m)		
Nitrate/ nitrogen							TN -15-35%	TN – 35-51%
Pathogens	70% (10m)				100%			
Study details	21.3m	23.6 – 28.2m	27-97m	30.5-61m			Grass buffer width 4.6-9.2,,	Grass buffer width 7.5-15, surface

							surface flow, sandy loam soil	flow, silty, clay loam soil

	Removal efficiency (per cent, unless otherwise stated)							
	Dillaha et al (1988)	Dillaha et al (1989)	Zirschky et al (1989)	Vidon & Hill (2004)	Martin et al (1999)	USEPA (2005)		
Total Nitrogen			38%					
Nitrate	-27- -15	27-57%		60-99%	80-100			
Nitrogen/nitrate						*Surface:* 33.3%,3m 50%,28m 75% 112m 90% *Subsurface* 89.6%, *Forest* 90% *Grass* 85% *Grass/forest* 80.5%		
Study details	Grass buffer width 4.6-9.1,, surface flow, silt loam soil	Grass buffer width 4.6-9.1,, surface flow, silt loam soil	91m grass buffer strip, surface water	Grass, grass forest, and forest buffer strip, 24-66m, various soil types	Grass and grass forest buffer strip, width 50-70m, subsurface	Review of 66 studies		

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Table 5: Performance – Riparian wet buffer strips

	Removal efficiency (per cent, unless otherwise stated)					
	Evans et al (1996)					
SS	85-90% in wooded transition area					
Nitrate/ nitrogen	85% annually					
Study details	Review					

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Table 6: Performance – Detention Ponds

	Removal efficiency (per cent, unless otherwise stated)							
	Urbanas 1994	EPA, 1999	North Carolina CES, unknown	Novotnv & Olem, 1994	CIRIA 2004	USEPA, 2002	Atlanta Regional Commission, 2001	D.Arcy 1998
SS	91	50-80	90	40-87	75-90	67 (20-99)	80	90
TP	0-79	30-65		40	30-50	48 (12-91)	50	50
Nitrogen	0-80	30-65		30	30-50	31 (-12-85)	30	
Study details							Design guidelines	

	Removal efficiency (per cent, unless otherwise stated)							
	Commings et al, 1998	Schueler 2000a	Schueler 2000b	Schueler 2000c	Jefferies, 2001	Winer , 2000	Mikkelsen et al 2001	Gouriveau et al, 2008,
SS	61-81	78	83-93	75-86	+0.3	61 +/- 32	70-84	72%
TP	19-46	49	50-55	56-67		20+/- 13	40-74	20%
Nitrogen		-12	52-87	-1-18		Total 31+/- 1 16	7-33	Nitrate 59% Ammonium 44%
Study details						Dry, extended detention basin		

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Table 7: Performance – Retention Ponds

	Removal efficiency (per cent, unless otherwise stated)							
	Urbanas 1994	EPA, 1999	North Carolina CES, unknown	Novotnv & Olem, 1994	CIRIA 2004	USEPA, 2002	Atlanta Regional Commission, 2001	D.Arcy 1998
SS	91	50-80	90	40-87	75-90	67 (20-99)	80	90
TP	0-79	30-65		40	30-50	48 (12-91)	50	50
Nitrogen	0-80	30-65		30	30-50	31 (-12-85)	30	
Study details							Design guidelines	

	Removal efficiency (per cent, unless otherwise stated)							
	Commings et al, 1998	Schueler 2000a	Schueler 2000b	Schueler 2000c	Jefferies, 2001	Winer , 2000	Mikkelsen et al 2001	Gouriveau et al, 2008,
SS	61-81	78	83-93	75-86	+0.3	61 +/- 32	70-84	72%
TP	19-46	49	50-55	56-67		20+/- 13	40-74	20%
Nitrogen		-12	52-87	-1-18		Total 31+/- 1 16	7-33	Nitrate 59% Ammonium 44%
Bacteria						78		
Pathogens								Feacal coliforms 93%
Study details						Dry, extended detention basin		

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CREW Facilitation Team

James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK
Tel: +44 (0) 844 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk