Attenuation of diffuse-source agricultural sediment and nutrients by riparian buffer zones

A review to support guideline development

Prepared for DairyNZ

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Contents

Tables

Figures

Executive summary

New Zealand currently faces declining aquatic biodiversity and water quality, in part as a result of the inputs of nutrients (nitrogen and phosphorus), sediment and faecal bacteria from agricultural lands. The government's Essential Freshwater package (October 2019) has proposed new requirements for riparian set-aside on lowland streams and rivers and protection of wetlands on private lands.

One component of the joint NIWA-DairyNZ "Accelerating uptake of wetlands and riparian buffers" project requires NIWA (in consultation with DairyNZ) to develop initial guidelines for various mitigation tools. These mitigation tools are intended to enable farmers to reduce the input of key contaminants to freshwater. Although a very extensive knowledge base exists with regard to the characteristics, design and performance of on-farm mitigation tools, much of the information available from the scientific literature is not readily applicable to New Zealand conditions, farming systems or practices. This report is the first phase of development of guidelines which reviews and summarises current knowledge regarding one class of mitigation tool – the riparian buffer. The review summarises the factors that determine performance (contaminant reduction or mitigation), key design features and anticipated performance. The review also contains the analysis used to develop the guidelines performance recommendations.

Riparian buffer zones (RBZs) are bands of vegetation – comprising grass, trees and shrubs - managed as buffers between productive lands and surface waters. Two processes considered in this review are:

- filtering of contaminants from surface runoff, and
- removal of nitrate-N and soluble forms of phosphorus from subsurface flow.

Riparian buffer zones reduce contaminant loads in surface runoff and subsurface flow through several processes, including physical retention, biological uptake and biogeochemical processing. These occur above ground, in the root zone of plants, and in the subsoil.

Quantifying the performance of riparian buffer zones is challenging. It requires estimation of contaminant removal as the difference between buffer inflow and outflow load/concentration, expressed as the proportion of inflow load/concentration (attenuation efficacy, %). Measurement of flow and concentrations of various contaminants across and through the RBZ is challenging, and has to some extent limited data availability.

The systematic review of published data and information identified several key performance characteristics that may be expressed in terms of contaminant and flowpath. These are summarised in Table i:

Table i: Key factors determining the efficacy of riparian buffers summarised from previous literature reviews.

Contaminant + delivery flowpath	RBZ impact on contaminants and optimal conditions for attenuation
sediment + surface runoff	*Attenuation:* variable, but >40 % in most cases *Optimal conditions:* dense groundcover, high infiltration, unsaturated soils
TP/TN + surface runoff	*Attenuation:* sink for particulate P/N, may be source of soluble P/N, source of particulates in floods. *Optimal conditions:* dense, young vegetation, high infiltration, unsaturated soils
nitrate + subsurface flow	*Attenuation:* consistently nitrate sinks (>70% attenuation). *Optimal conditions:* organic carbon, anaerobic conditions, saturated soils, high temperatures
DRP + subsurface flow	*Attenuation:* variable *Optimal conditions*: aerobic conditions, unsaturated soils

Guidelines (a companion report) were developed for RBZs primarily treating either surface or subsurface flows. For both flowpaths it is necessary to account for multiple factors, including contributing area characteristics (e.g., land use, slope, soil type and texture, hydrological flowpaths) and buffer characteristics (e.g., vegetation, width, soil texture).

We collated data from New Zealand and international studies that describe filtering of surface runoff during passage through the RBZ, and removal of nitrate-N from subsurface flow. These datasets were used to derive semi-quantitative guidelines. For filtering surface runoff, efficacy of the buffers in terms of key variables generally takes the form shown in Figure i. Performance efficacy varies widely - the large range occurs because some filters remove contaminants more effectively than similar-sized filters in landscapes where less favourable conditions exist.

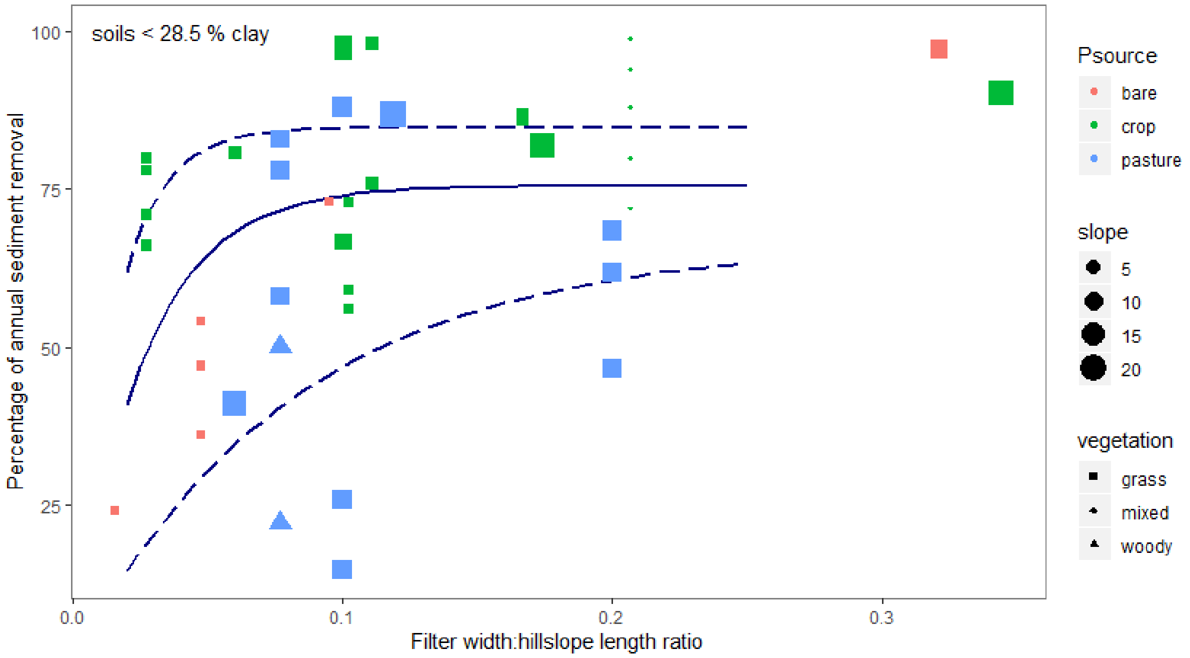


Figure i: Preliminary guidelines for sediment removal by riparian filter strips for soils with <28.5% clay on uniform flat to rolling slopes (curves) compared with published data. The fitted lines are a non-linear regression (solid line) and 95% confidence intervals (dashed lines). Data points are coloured by source, sized by hill slope (%) and shaped by filter vegetation. For example, the largest blue square (at 85%) is data for a grass filter strip receiving runoff from pasture, on a moderate (~20%) slope.

We found that it was necessary to separate data for surface runoff according to clay content; we defined two classes: soils with high clay (≥ 28.5%) and lower clay (<28.5%) content (Figure i). Assessment of these data following this classification provided the following key information:

- strong relationships exist between efficacy of sediment removal, and total phosphorus and total nitrogen removal in surface runoff
- consistently high (>40%) removal efficacy for nitrate-N from subsurface flow when the RBZ is underlain by a shallow impermeable layer, and
- higher removal of nitrate-N from subsurface flow in finer textured soils compared with sandy/gravelly soils.

Insufficient information is available to develop robust performance guidelines for nitrate-N removal from subsurface flow in all RBZs. This is partly due to the complexity of multiple inter-related processes that influence removal performance. Although natural seepage wetlands (characterised by permanently saturated organic soils and visible surface water) have been studied and guidelines included in Overseer®, there are few studies of RBZs with unsaturated surface soils but subsurface flow above an impermeable layer. The limited data indicates that nitrate-N removal is determined by depth of permeable soils, soil characteristics, slope, and timing and magnitude of nitrate flux. In general, nitrate removal is high where nitrate-laden water flows through fine textured soils underlain by an impermeable layer.

This review and guideline development process has highlighted a paucity of New Zealand data regarding processing of contaminants derived from agriculture by riparian zones. Additional studies of RBZ are required before a robust model and quantitative guidelines can be developed, and to quantify efficacy of RBZs excluded from our preliminary guidelines (e.g., removal of clay particles from surface runoff).

Guidelines (including those presented in the accompanying report) are often developed for single contaminant-flowpath pairings. In reality however, each RBZ simultaneously provides some level of efficacy for multiple contaminants and across a range of flowpath conditions. As this review of the literature has shown, the level of efficacy for all contaminants is dependent on multiple inter-related factors, including factors over which the farmer has no control (e.g., season, rainfall, slope, soil type and depth). To ensure that mitigation tools such as riparian buffer zones deliver the water quality outcomes anticipated by farmers, communities and government in a cost-effective manner, tools that address multiple contaminants and tradeoffs across scales are required. These should include appropriate models and associated decision support tools.

1 Introduction

New Zealand currently faces declining aquatic biodiversity and water quality, in part as a result of habitat destruction and rural and urban pollution.

The recently released Environment Aotearoa report (MfE & Stats NZ 2019) highlights serious degradation of freshwaters, and the government's Essential Freshwater package (MfE & MPI 2018; Office of the Minister for the Environment and Office of the Minister of Agriculture 2019) has proposed new requirements for riparian set-aside on lowland streams and rivers and protection of wetlands on private lands. National reporting has indicated that nutrients (nitrogen and phosphorus), sediment and faecal bacteria are the dominant contaminants arising from agricultural lands.

Edge-of-field mitigations including riparian buffers, natural and constructed wetlands, bioreactors and detention bunds are part of the solution, but must be matched to appropriate landscapes.

Many landowners are in the process of identifying and implementing mitigation strategies, tools and devices to reduce the entry of contaminants to waterbodies. These actions and activities (as well as others) are required to give effect to the regional limit-setting processes required by the National Policy Statement for Freshwater Management (NPS-FM). Riparian buffer zones (RBZs) are key edge-of-field mitigation options that farmers can use to reduce contaminant losses in many landscapes. DairyNZ and NIWA are collaborating on the INTERCEPTOR project which aims (in part) to prepare a set of design and performance guidelines for RBZs in New Zealand agricultural landscapes.

1.1 Project brief

The first step in the INTERCEPTOR project was to review and summarise current knowledge on riparian buffer performance for attenuation of three water contaminants (sediment, nitrogen (N) and phosphorus (P)) derived from diffuse sources in agricultural landscapes. The review focuses on the hillslope-scale performance of RBZs. Focusing on **intersystem variability** – how comparable RBZs perform, and the factors (such as landscape and design) that cause this variability at the hillslope-scale – enables us to make progress towards designing site-specific (i.e., variable width) RBZs. Optimising water quality outcomes requires design parameters that include paddock- or hillslope-scale topography, soils and flowpath factors.

Development of guidelines is a specific output from the INTERCEPTOR project. This strand of work is a component of the INTERCEPTOR project focused on delivering:

- sufficient guidance and certainty of expected contaminant reduction to enable accounting for riparian effects within farm nutrient management plans and regional planning responses to the NPS-FM,
- a set of provisional RB performance and design guidelines for immediate use by landowners and regional councils,
- criteria for on-farm location, design, construction, planting and maintenance, and expected performance,

- riparian buffer performance (viz., expected levels of contaminant reduction) for N, P, sediment and bacteria (with bacteria on hold by mutual agreement).[1]

The report contains five main sections:

(1) Introduction.

(2) Synthesis of information on filtering surface runoff and nutrient removal from subsurface flow derived from previous reviews.

(3) Systematic reviews of relevant quantitative field studies organised by:

- filtering of surface runoff, and
- nitrate removal from diffuse subsurface flow.

(4) Synthesis of existing guidelines and our guideline development process.

(5) Conclusions and recommendations for future research.

1.2 Definitions and key terminology

Care is needed regarding use of the term 'riparian buffer' because it potentially means different things to different people. In this report, we use the term **'riparian buffer zone'** (RBZ) to describe a band or strip of vegetated land (grass, trees or shrubs) established and managed as a buffer between land and water (Figure 1). RBZs may be managed for a range of functions or to achieve several values or outcomes, including water quality, terrestrial biodiversity, fish habitat, aesthetics, recreation benefits and cultural values (Quinn et al. 2001). This report focuses solely on water quality improvement - reducing contaminant loads delivered to waterways from pasture.

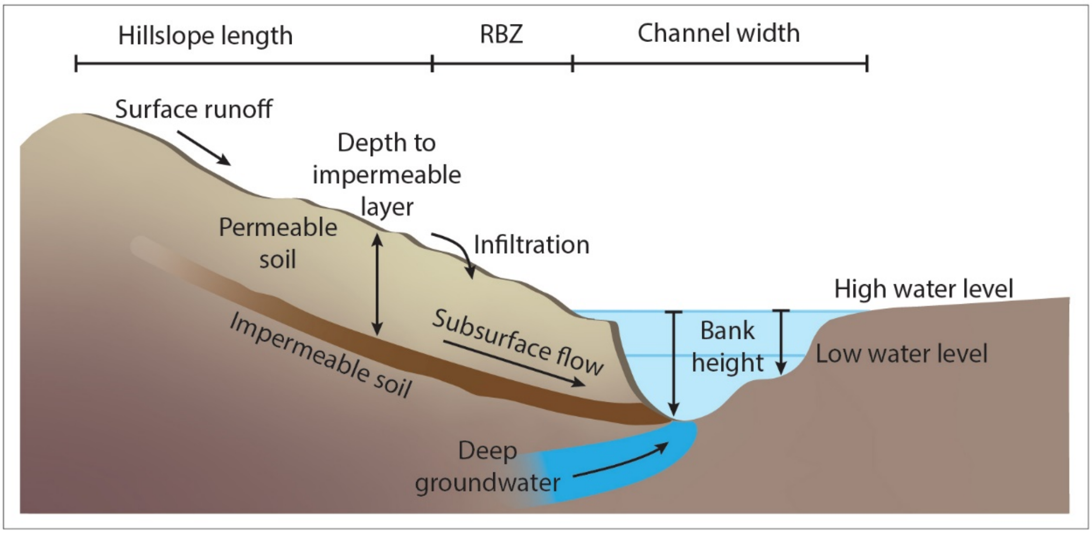


Figure 1: Riparian buffer zone definitions, features and water flowpaths.

[1] It was mutually agreed by DairyNZ and NIWA on [date] that insufficient data exists to extend development of the guidelines to include Faecal Indicator Bacteria such as *E. coli*.

Riparian buffer zones can improve water quality and reduce the adverse effects of agricultural activity (Figure 2) by:

1. filtering particulates out of surface runoff, and/or
2. removing solutes from subsurface flow.

RBZ design and management requirements vary according to the landscape, farming system and desired outcomes. Four basic RBZ forms are shown in Figure 2.

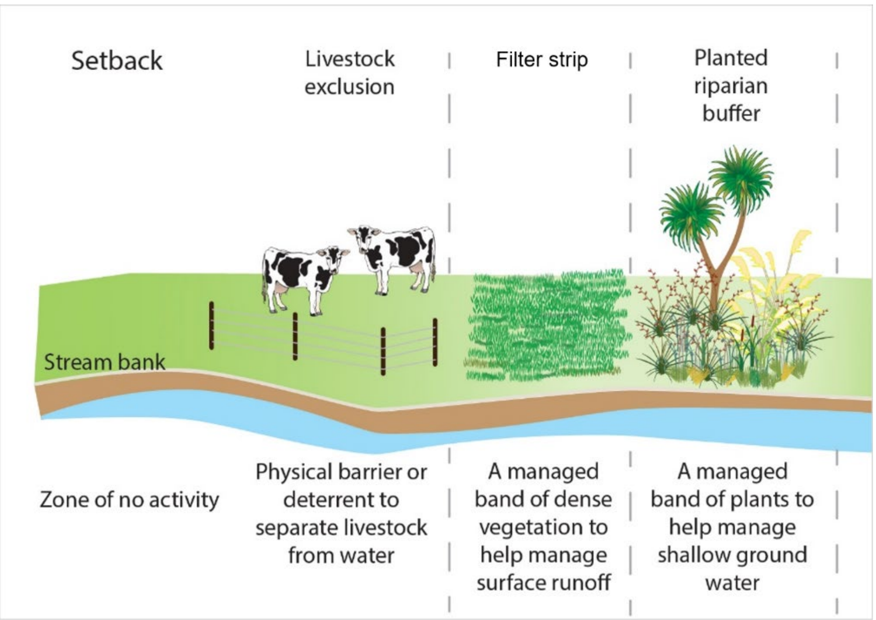


Figure 2: Schematic and definition of basic RBZ forms.

This report addresses two of the riparian buffer forms shown in Figure 2:

1. filter strips, and
2. planted riparian buffers.

Filter strips are primarily designed to intercept surface runoff. Planted riparian buffers may be designed to filter both surface and subsurface runoff, with the balance varying according to local landscape and design.

Types of RBZ <u>not included in this report</u> are (Figure 3):

1. **Setbacks** which are areas of "no activity" between contaminant sources and a waterway (Figure 3). They may be used to separate fertiliser and dairy effluent application from waterways. Setbacks are covered by existing policy and guidelines (e.g., Fertiliser Association of New Zealand 2013; DairyNZ 2015; Northland Regional Council 2016).
2. **Livestock exclusion**, which is practiced in New Zealand, is described in the Sustainable Dairying: Water Accord (Dairy Environment Leadership Group 2013) and is incorporated in the provisions of most regional plans. Livestock exclusion can be achieved using fencing or animal behaviour management techniques. There is consensus in the literature that cattle

exclusion can lessen the impacts of livestock on riparian vegetation and stream water quality (see O'Callaghan et al. 2019).

3. Novel engineered buffers including:

   a. **Grassed waterways** constructed to carry surface runoff at a non-erosive velocity along ephemeral waterways, and which improve runoff water quality by slowing water, strengthening soils, and filtering sediment.

   b. **Saturated buffers** which include flow control structures that disperse tile drain flow into riparian soils to allow similar attenuation processes to occur as those that occur in RBZ soils (Jaynes and Isenhart 2014).

4. **Seepage wetlands** with unconsolidated organic soils and standing water. Seepage wetlands can be major sinks for nitrate in the New Zealand agricultural landscape (see review by McKergow et al. 2016). Although seepage wetlands and RBZs share many biogeochemical processes, a clear disconnection between the biogeochemistry of the saturated soil zone and the near-surface unsaturated soil is often observed in RBZs (Vidon 2017).

Focus	Reducing contaminant loads from pasture							
	Riparian buffer (or set-aside) type							
Forms	set back	livestock exclusion	seepage wetlands	**filter strip**	**planted riparian buffer**	productive riparian buffer	grassed waterway	saturated buffer
Key flowpath(s)	surface runoff	surface runoff	subsurface flow	**surface runoff**	**subsurface flow & surface runoff**	subsurface flow & surface runoff	surface runoff	tile drainage
Level of planning & design required	Low → High							
Other resources	Fertiliser Industry; FDE guidelines	DairyNZ riparian planner	NIWA Client reports for DairyNZ	DOC guidelines		Productive Riparian Buffers SFF project		Iowa State University and USDA preliminary guidance

Figure 3: Riparian buffer forms and flowpaths. Bold RBZ forms are the focus of this review.

1.3 Riparian buffer zone processes and flowpaths

Riparian buffer zones can intercept, transform and/or remove contaminants from hillslope runoff. They also stabilise streambanks and reduce the impact of contaminant-generating activities within waterways. Attenuation in RBZs occurs as a combination of:

- Physical retention - deposition, filtering, and infiltration of particulate and dissolved contaminant forms.

- Biological - plant uptake, microbial processing, and uptake and immobilisation in soil organic matter (dissolved contaminants).

- Biogeochemical processes - microbially-driven removal (e.g., denitrification of nitrate-N, which is soluble), adsorption of phosphorus to particles, and chemical precipitation (see McKergow et al. 2007).

1.3.1 Surface runoff

When surface runoff enters an RBZ there are opportunities for three mainly physical processes to occur (Figure 4):

1. Vegetation roughness slows the water down, allowing debris and coarse-textured soil particles to settle in ponded water at the filter face and within the initial few metres of the filter strip (Robinson et al. 1996; Hussein et al. 2007).
2. If soil conditions are suitable, a proportion of the runoff will infiltrate, reducing the potential for runoff to transport sediment by decreasing the volume of flow and allowing solutes to enter the soil (Dillaha and Inamdar 1996).
3. Large soil aggregates and debris may be filtered or sieved by the filter vegetation (Dillaha and Inamdar 1996).

In addition to the main physical processes, filter vegetation may also reduce erosion risk, improve soil structure, uptake nutrients and provide surfaces for adhesion (McKergow et al. 2004a; Dosskey et al. 2010). Plants may improve soil structure by increasing the soil permeability (e.g., those previously compacted by stock) allowing greater infiltration to occur. Infiltrating water may move rapidly via macropores created by plant roots, fauna and soil desiccation (Orozco-López et al. 2018) or slowly through the soil matrix. Plant roots may also reduce soil erosion within RBZs by strengthening the soil during specific soil moisture conditions, such as when the soil is saturated and water is forced to the surface by positive pore water pressures (e.g., McKergow et al. 2004a). Plants can remove soluble nutrients from runoff that infiltrates within the RBZ (notably DRP, Sharpley and Rekolainen 1997). Adhesion of clays onto filter vegetation has been observed in operational filter strips but the efficacy of this removal process is yet to be quantified.

Surface runoff is not uniform on hillslopes because runoff generation and flowpaths are controlled by vegetation, soil properties, microtopography and other less well understood factors such as storm dynamics (see Bracken et al. 2013). Surface runoff often converges into channels and then either overwhelms or bypasses RBZs (Dosskey et al. 2002; Verstraeten et al. 2006). Consequently, during extreme events, filter strips may be overwhelmed by runoff, resulting in low removal efficacy (e.g., Daniels and Gilliam 1996) and scouring and/or re-entrainment of previously deposited material (e.g.,McKergow et al. 2004a). Extreme rainfall-runoff events make determining filter performance under field conditions difficult. Relatively few extreme events may disproportionately contribute to and dominate annual loads, despite adequate performance by the filter strip during smaller events. In soil erosion research it is recognised that a large number of monitored events (75 to 100) may be needed to “dilute” or reduce the impact that a single extreme event may have on average or annual performance estimates (González-Hidalgo et al. 2009).

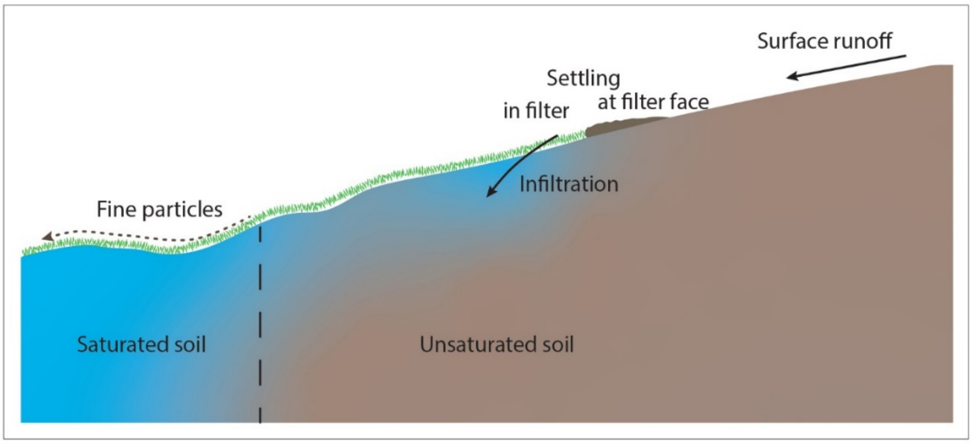


Figure 4: **Main processes by which filter strips retain suspended sediment and associated nutrients.**

Retention of nutrients associated with coarse particulate materials carried in surface runoff occurs by settling, and retention of nutrients associated with fine particulates and in dissolved form occurs by infiltration. Infiltration brings DRP, nitrate and fine particulates into contact with active sites on the surface of soil particles and plant roots. Deposition of coarse particles and organic matter at the filter face and within the filter will also remove nutrients associated with these particles from runoff. Clay and other fine particulates have very low settling velocities and may not be deposited - associated contaminants (notably phosphorus) may pass through the filter (Syversen and Borch 2005; Owens et al. 2007). Fine particulates in subsurface flow may be removed by sorption to soils, but over time P solubility and equilibrium P concentrations in riparian soils may increase, increasing the risk of future DRP release (Roberts et al. 2012). Riparian buffer zones should therefore be considered as “delivery modifiers” that provide temporary storage of phosphorus; P may be retained, but may also be released at a later date, possibly in a different form. Short- to medium-term studies and studies that focus on “total phosphorus” (TP, comprising soluble and particulate forms of P) may not give a true picture of long-term P retention or RBZ performance efficacy for phosphorus retention.

1.3.2 Subsurface flow

Water flows laterally through subsurface RBZ soils when a shallow impermeable soil layer (<3 m deep; Hill 2019) limits the depth of vertical water movement. This subsurface flow will generally carry dissolved nutrients (e.g., nitrate and dissolved phosphorus) but may also carry colloidal P (associated with fine particulates <1 µm in size) (Heathwaite et al. 2005), and microbes.

Riparian buffer zones are often sinks for nitrate and phosphorus as a result of plant uptake from water flowing through the root zone, and microbially-driven removal (e.g., denitrification) from subsurface flow (Figure 5). Phosphorus retention in RBZ soil depends largely on soil chemistry (Roberts et al. 2012).

Plant uptake converts inorganic nutrients to organic forms which are often less bioavailable to algae in the receiving environment. Plant uptake in RBZs can be significant, but widely variable, from less than 10 to 350 kg N/ha/y (Mander et al. 1997). In environments dominated by deciduous vegetation, plant uptake is only a temporary nutrient store, with litterfall returning more than 80% of total plant uptake (Peterjohn and Correll 1984). Plant uptake will vary with species, access to subsurface water, season and plant age (Naiman and Décamps 1997). Recent New Zealand research suggests that grass-like native plants may be better at storing nitrogen than similarly-aged shrubs. Grass-like plants such as pukio (*Carex virgata*), toetoe (*Austroderia richardii*) and Tī kōuka/cabbage tree (*Cordyline australis*), and harakeke (*Phormium tenax*) have high root densities, high biomass and high growth rates – all these traits are beneficial for nitrogen uptake (Franklin et al. 2019). Pukio and Tī kōuka also have leaf litter that is less likely to decompose, immobilising nitrogen in plant debris.

Microbes use nitrate as an energy source and three main microbially-driven processes occur in RBZs when conditions are suitable:

i. When soils are saturated (and low oxygen conditions prevail), denitrifying microbes convert nitrate-N into N-containing gases using carbon as an additional energy source. Denitrification can be a major nitrate removal pathway in many RBZs.

ii. In some anoxic (no oxygen) soils, some microbial species use nitrate and ammonium for metabolism, leading to formation of N-containing gases via the anammox process (see Burgin and Hamilton 2007).

iii. Other microbes can convert nitrate to ammonium under anoxic/anaerobic conditions (Dissimilatory nitrate reduction to ammonium; Burgin and Hamilton 2007).

These microbially-driven processes occur under similar conditions - low oxygen and saturated soils.

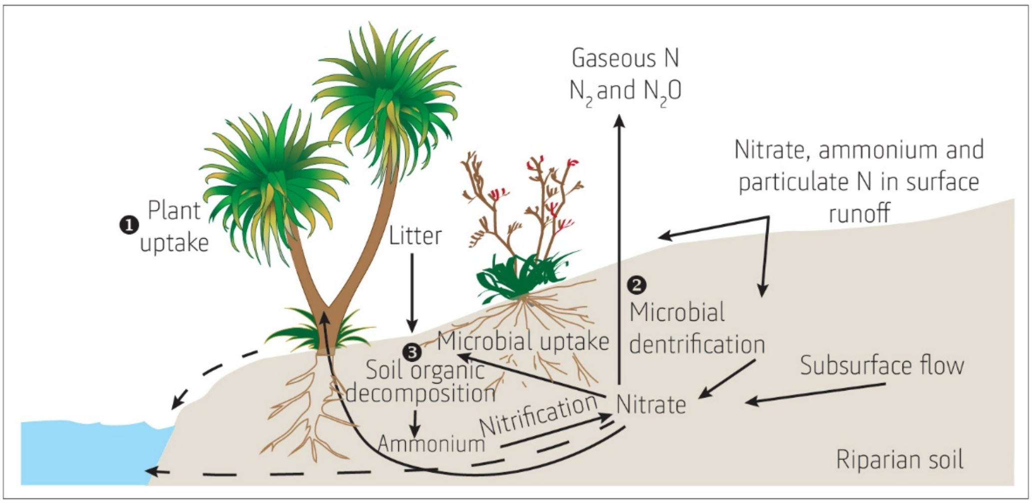


Figure 5: Nitrogen cycling and attenuation in RBZs. The main processes that retain or reduce nitrogen in riparian zones are (1) uptake through roots into plant tissues, (2) microbial denitrification and (3) immobilisation in soil organic matter (after Franklin et al. 2019).

Phosphorus transported in subsurface flow is retained in RBZs by plant- and microbial uptake (biological processes), and may be retained in the soil by physico-chemical processes such as sorption, precipitation and occlusion (Roberts et al. 2012). Plants derive their P requirements from the soil solution using exudates and enzymes (see Roberts et al. 2012) and plant P requirements vary with plant age, plant species, season and P inputs (Dosskey et al. 2010). While the refractory fraction of phosphorus may be retained in biomass and soil, the labile fraction may be remobilised. The key factors controlling geochemical retention of P in soils include soil chemistry, redox conditions, the presence of other solutes (e.g., sulphate), and wetting and drying cycles (Hoffmann et al. 2009; Vidon et al. 2019). So rather than being the final sink for P mobilised from hillslopes, RBZs may alter the timing, extent and chemical form of P eventually delivered to waterways (Roberts et al. 2012).

1.4 Assessing performance

RBZ **attenuation efficacy** may be calculated using concentration, load (total mass per unit time, typically annual) or flux (instantaneous mass per unit time) differences between the inflow and outflow (relative to the inflow, expressed as %). The use of load or flux is preferable for inter-system comparisons because they reflect both the amounts of contaminant and water and represent a known time period. For subsurface flows, changes in concentration are commonly measured and this approach is appropriate if flow does not change markedly or is quantified with an inert tracer. Different methods are required to quantify attenuation efficacy in surface runoff and subsurface flows. Many studies choose to focus on one flowpath through an RBZ, few measure both flowpaths simultaneously (e.g. Smith 1989; and Cooper 1990; McKergow et al. 2006b; Duchemin and Hogue 2009).

Measurement of surface runoff requires directing flow to a collection/ measurement point and two experimental designs are commonly used:

1. Measuring inflow to and outflow from the same site (input-output style).
2. Measuring outflow at adjacent sites (control and treatment style).

The adjacent site approach assumes that there is little spatial variability in runoff characteristics between the sites (unless explicitly tested e.g., Søvik et al. 2012). The same site approach assumes good dispersion after inflow measurement and may over-estimate the true buffer effect because even without a buffer there may be a difference between the inflow and outflow due to infiltration or drainage (Dosskey 2002). At the plot scale (up to ~450 m²) runoff is confined and can be measured using barriers and flumes, but on larger hillslopes surface runoff is typically sampled at multiple gutters (typically >50 cm wide) that represent parts of the overall hillslope.

Removal of nutrients from subsurface flow by RBZs is typically assessed by comparing inflow and outflow concentrations combined with a thorough understanding of site hydrology. Flowpaths and transit times must be identified to ensure that the same water parcel is being measured at the inflow and outflow, and allowance must be made for any dilution by deeper groundwater. Many field studies compare changes in nitrate concentration relative to changes in a conservative tracer. Chloride is frequently used as an natural tracer to detect dilution by upwelling nitrate- and chloride-poor groundwater (e.g., Böhlke and Denver 1995). Conservative tracers, such as bromide, can also be used to characterise the hydrogeology (and denitrification rates) of a single piezometer using the push-pull technique (see Addy et al. 1999). Although flux-based attenuation calculations are becoming more common, measuring subsurface flow rates remains challenging (see Blume and van Meerveld 2015); in many studies measurement are made only at discrete points or by altering flowpaths. Site hydrology is typically investigated using piezometer nests (used to measure hydraulic head) and wells (depth to water table) at short time intervals (5 minutes – hourly). Concentrations are usually measured discretely at weekly to monthly intervals.

As a consequence of these difficulties and other factors, determining and reporting attenuation efficacy is inconsistent in the literature. In particular, time frames over which assessment occurs and reporting styles vary considerably:

- Studies vary from experimental evaluations of one or a few events to short-term monitoring (<4 y), with very few long-term (>4 y) studies (Liu et al. 2017).
- Gall et al. (2018) used a model to demonstrate the difference in calculated efficacy obtained using the average attenuation from each surface runoff event over a year versus the total annual load reduction, and it was shown to be as large as 20% for soils with high clay content.
- Assessments that focus on percentage reductions and annual values can omit important changes to the characteristics of pollutant concentrations and loads, such as reductions in peak values during large events and reduced variability in magnitude of contaminant loads (see Viaud et al. 2004).

In this report, attenuation efficacy (%) is reported as follows:

1. **Surface runoff** – load reductions calculated over reported time frames (typically annual).
2. **Subsurface flows** – concentration reductions calculated for each sampling occasion and reported as an average representing a time frame (typically 1-2 y).

2 Previous literature reviews

2.1 Introduction

Riparian buffer zones have been studied intensively since the late 1980's and there are numerous reviews of attenuation efficacy. Early reviews were narrative, and typically limited to one process, pathway or contaminant. More recently, systematic reviews, using secondary data from existing literature, synthesised findings either qualitatively (e.g., summarised as narratives in tables) or quantitatively (e.g., derived from statistical relationships).

We have summarised and critically examined recent (since 2007) reviews relating to the sediment, N and P attenuation performance of RBZs (Table 2). Our aims were to:

1. evaluate the body of evidence around attenuation efficacy, and
2. identify critical factors that control attenuation by RBZs at the hillslope-scale.

2.2 Filtering surface runoff

Attenuation of contaminant loads from surface runoff by RBZs is variable – although they are sinks for sediment, total N (TN) and total P (TP) most of the time, they may become sources of contaminants under specific conditions (discussed in section 1.3.1). Sediment trapping is typically high; using data representing field conditions, Sweeney and Newbold (2014) reported a 65% reduction in median sediment load, while Gumiere et al. (2011) found sediment reductions ranged between 24 and 100% (over a range of experimental and field conditions).

Filter strips perform inconsistently with respect to soluble P (Hoffmann et al. 2009; Roberts et al. 2012; Stutter et al. 2019). Short duration (1 h to 2 d) experimental studies show that P attenuation increases with filter width (Roberts et al. 2012), whereas analyses which include longer term studies reveal greater variability in performance (-71 to 95%; Hoffman et al. 2009), suggesting that P may be retained but is susceptible to re-release.

Nitrate removal from surface runoff is less frequently reviewed (Table 1) because research on nitrate removal processes has focused on subsurface flow. Valkama et al. (2019) found a wide range of removal efficacies (-55 to 90%) and suggested that attenuation increased with increasing N concentration and according to the source of the pollution (higher for feedlots and cereal production than grass production). They also identified that N removal efficacy decreased with increasing filter age and suggested this may be due to intensive nutrient uptake when plants are actively growing (immediately after establishment).

Filter width and vegetation type are the factors most commonly evaluated in systematic reviews (Table 2), because they can be manipulated during RBZ design (and research) and are routinely reported (see Liu et al. 2008; Roberts et al. 2012). Intuitively, increased filter width is anticipated to improve the interception and processing of contaminants, particularly physical retention of sediment and particulate nutrients by adsorption, deposition and infiltration. However, width-attenuation relationships are affected by many site-specific characteristics and processes which lead to poor overall correlation (e.g., Mayer et al. 2007; Gumiere et al. 2011). These factors include:

- High deposition at the filter face (Karssies and Prosser 1999b; Hussein et al. 2007), and decreasing deposition along the length of the filter as the sediment particles remaining in suspension become increasingly finer.

- Contributing land characteristics such as area, pollution source, soil texture, transported particle size, infiltration capacity, slope form, runoff generation process.
- RBZ characteristics such as vegetation density and infiltration capacity.

Systematic reviews are ambiguous about the role of vegetation; this may be an artefact of the limited information about the vegetation component of RBZs provided in primary research data, or reflect factors such as vegetation/litter densities and the presence of surface sealing in some studies (e.g., McKergow et al. 2006a). However, there is a consensus that grass is equally or more effective than woody vegetation at removing particulates because of the high stem density provided at ground level (Dosskey 2001).

Attenuation of surface runoff is less frequently examined as a controlling factor in systematic reviews – this is a major shortcoming because information regarding changes in surface flows can help identify the role of infiltration in attenuating contaminant losses to water. Sweeny and Newbold (2014) include runoff in their quantitative relationships for SS attenuation.

Key factors controlling attenuation performance by filter strips (Table 2) identified in the reviews include width, slope and runoff attenuation. Other factors, including soil type and properties, filter hydrology and pollution source were identified as potential controlling factors, or were of secondary importance.

2.3 Nitrate removal from subsurface flow

Attenuation of nitrate in subsurface flow by RBZs has been researched widely and summarised in several systematic reviews (Mayer et al. 2007; Sweeney and Newbold 2014; Valkama et al. 2019; Hill 2019; Table 2). Nitrate attenuation varies between -60 and 99 %, with arithmetic means of ~ 70% reported in reviews.

Nitrate removal is strongly influenced by site hydrology – this is the key factor controlling efficacy identified in the reviews. Sweeny and Newbold (2014) found that nitrate attenuation is inversely related to subsurface water flux (L/m/d) and suggest that for sites with high subsurface water flux (>50 L/m/d), RBZs of greater width perform better. Sweeny and Newbold (2014) proposed a model linking nitrate removal rates (%/m) and subsurface fluxes which explained 36% of variation in nitrate removal from 30 RBZ sites. Hill (2019) included subsurface water flux and soil texture in his analysis and concluded that RBZs with a sediment depth of <4 m above an impeding layer can lower the nitrate concentration by more than 90% within 30-60 m (sandy soils) and 10-20 m for finer textured soils. RBZ width is a less important factor for subsurface N removal (Mayer et al. 2007; Sweeney and Newbold 2014; Valkama et al. 2019) – nitrate removal is dependent on whether or not conditions are suitable for biogeochemical processes, rather than RBZ dimensions. Hill (2019) argues that it is important to measure and evaluate studies that include groundwater fluxes to distinguish between RBZs that are major or minor nitrate sinks.

2.4 Summary

The reviews examined many primary datasets, chosen using varying criteria by the authors. The efficacies of RBZs and optimal conditions for attenuation are summarised in Table 1.

While RB research is maturing, summarising the many trials quantitatively is challenging owing to the absence of key information in published literature. All papers provide buffer dimensions and some description of vegetation type, but many other useful details are omitted or inadequately reported.

In addition, particularly for studies where filtering of surface runoff is important, there is a disjunct between controlled experiments at the small scale and larger plot/unconfined plot research. Controlled experimental studies with short timeframes on small plots (typically with simulated rainfall or runoff) can demonstrate the role of RBZ design characteristics on contaminant attenuation. However, in multi-year research where experimental sites receive natural rainfall, the relative influence of design characteristics (such as width) on contaminant attenuation may be disguised by factors such as changing source characteristics, filter characteristics that change over time, extreme events and variable rainfall characteristics.

Using empirical data from the literature to guide RBZ design is not ideal, but for this project is necessary given the absence of results from local studies and verified models. Most reviews do not include sufficient parameters to fully characterise either the experimental design or the contributing hillslopes in their analysis. The reviews also frequently provide a single measure of efficacy (e.g., 50% removal) but the period of time represented by the performance measure is not consistent (e.g., multiple years, annual, monthly, weekly). An exception is the study undertaken by Valkama et al. (2019), who include the standard deviation in their meta-analysis and the study duration. In addition, percentage removal without reference to incoming load/flux may be misleading. For example, 50% removal from a low concentration, large volume flowpath may be a more environmentally significant than a 50% removal from a high concentration, low volume flowpath (e.g., Weaver and Summers 2014). For studies where subsurface flow represents a significant proportion of the load, care is required to include only studies that include a thorough investigation of site hydrology, particularly dilution. There has been no systematic analysis of attenuation of surface runoff (i.e., infiltration), despite it being a frequently measured and reported variable.

Table 1: Summary of systematic review findings regarding the impact of RBZs on contaminant attenuation and optimal conditions required for attenuation.

Contaminant + delivery flowpath	RBZ impact on contaminant attenuation and optimal conditions for attenuation
sediment + surface runoff	*Attenuation:* variable, but >40 % in most cases *Optimal conditions:* dense vegetation at ground surface, high infiltration, unsaturated soil
TP/TN + surface runoff	*Attenuation:* sink for particulate P/N, may be source of soluble P/N, source of particulates in floods. *Optimal conditions:* dense, young vegetation, high infiltration, unsaturated soil
nitrate + subsurface flow	*Attenuation:* consistently nitrate sinks (>70%). *Optimal conditions:* organic carbon, anaerobic conditions, saturation, higher temperature
DRP + subsurface flow	*Attenuation:* sink or source *Optimal conditions*: aerobic conditions, unsaturated soils

Table 2: Summary of results from recent international reviews of RBZ systematic, narrative and meta- analyses. This summary utilises reviews published since 2007.

Author	Target contaminants & flowpath	Method	Findings	Criticisms and comments
Mayer et al. (2007)	N in subsurface flow and surface runoff	systematic review -80 RB from 45 studies; linear and exponential regression	- width-efficacy relationship complex; 65 subsurface flow studies no relationship with width, add 25 surface runoff studies and 9% explanatory power - other factors beyond width e.g., vegetation and root depth, saturated areas -some narrow buffers can consistently remove N	- compared RBZ studies of different durations directly
Liu et al. (2008), Zhang et al. (2010)	sediment, N and P in surface runoff	systematic review -80+ articles; using linear regression related attenuation (%) to soil, width, area ratio, flow, buffer slope, rainfall intensity and vegetation -fitted power model constrained between 0 and 100%	- sediment, N, P trapping increases with width, maximum trapping around 10 m, most studies < 10 m width - sediment trapping increased to ~10% slope, then decreased, suggest slope 8-12% attenuation-width relationship starts to plateau -vegetation - grass or tree RB sediment trapping similar; N & P removal trees > grass - sediment model with width + vegetation + slope explained 66% variation in data; model with width + vegetation explained 50% N and 48% P removal - model suggests increasing RB width from 5 to 10 m would improve sediment removal by 10-15%	- include experimental plots and artificial rainfall (Sweeny and Newbold, 2014); - few streamside RB included -ignore runoff reduction in regression and rely on regression models (Fox and Sabbagh 2009) - slope threshold criticised as being a data artefact (Fox and Sabbagh 2009) - compares RBZ studies of different durations directly
Hoffman et al. (2009)	P in surface runoff	narrative review -includes range of experimental designs, durations (1 h to 10 y) natural & simulated rainfall	- variability for TP (median 67%, range 32-93%) and DRP (median 65%, -71 to 95%) -summarised critical factors as soil type (sorbents, redox state, pH), degree of P saturation, width, vegetation, management, source area, buffer area:source area - mechanistic view critical chemical variables determining long-term efficacy related to P sorption: Fe:P ratios, content of reducible iron oxides, concentration of redox stable sorbents, Fe(III) oxide reduction during anoxic periods, pH, alkalinity, presence of completing sorbates and precipitation agents	- reviewed a wide range of experimental designs
Gumiere et al. (2011)	sediment in surface runoff	narrative review -includes field and flume experiments -49 studies; 147 values	- sediment removal efficacy 24 to 100% - no relationship between sediment removal and width or slope or unit discharge - relationship between sediment removal and runoff reduction	
Roberts et al. (2012)	P in surface runoff	narrative review	-summarise short term (1 hr to 2 days) experimental studies – P retention generally increases with width, decreases with high flow -still a need to identify exact plant traits that maximise physical retention -suggest RB soils do not seem to become saturated with P, but show elevated P solubility and EPC_0 in surface soils; increased water extractable P represents increased risk of dissolved P leaching from surface soils - lack of long-term studies and data on different P forms (DRP, DUP, orgP) confound attempts to identify seasonal patterns (remobilisation)	- useful model of P retention processes & remobilisation - argue RB soils do not become P saturated - suggest RB are "delivery modifier" – potential to alter P form from articulate P to dissolved P - lack of long-term studies and fractions of P
	sediment in surface runoff & N in subsurface flow	narrative review + quantitative relationships; subsurface nitrate and sediment trapping	- sediment: -optimal width 20 m (78% removal), gains beyond 20 m modest -nitrate: demonstrate large influence of water flux; group areal loadings <2 mm/d efficiencies > 80%, sites with > 2 mm/d had lower efficiencies	- limited natural rainfall studies with sediment trapping data below 10 m width available - compares RBZ studies of different durations directly
Valkama et al. (2019)	N in surface runoff and subsurface flow	meta-analysis	- surface runoff: - mean attenuation range -55 to 90%; 33% reduction in nitrate (n=25) and 57% reduction in TN (n=16)	-compares RBZ studies of different durations directly

Author	Target contaminants & flowpath	Method	Findings	Criticisms and comments
		- 1980-2017 (used MetaWIN[2]) - limited to studies with adjacent control sites - surface runoff 22 studies (14 natural), 41 obs. - subsurface flow 25 studies, 38 obs. -some included manure application; some simulated rainfall	- increasing N retention with increasing N concentration - no effects of buffer width or buffer slope (only one study had slope >10%) - main factor for variation in N removal was pollution source - cereal and feedlot sources had higher removal than grass production - surface runoff N removal efficiency decreased with increasing buffer age - subsurface flow: - mean reductions compared to controls 5 to 95%, mean 70% (n=38) - double N greater retention than surface runoff; trees reduced nitrate	
Hill (2018, 2019)	N in subsurface flow	narrative review - summarised 39 studies by hydrogeologic setting	- some RBZ have large water fluxes (>100 L/m/d) while others with fine-textured loess/alluvial sediments 1-30 L/m/d. - subsurface flow can become parallel to stream or flow from the stream to RBZ - subsurface flow when confining layer <3 m deep; deeper GW has limited/no interaction with RBZ -measurement of N subsurface flux is critical to distinguish between major and minor N sinks	

[2] https://www.swmath.org/software/24643

3 Re-analysis of previously published data

We have re-examined published primary data (1984-2016) on RBZs to identify the role of inter-annual variability and site hydrology on attenuation performance, and to develop preliminary guideline values. These collated data will be used for model verification at a later date.

The key question we address is: *How is contaminant attenuation by riparian buffers zones affected by landscape drivers and design characteristics?*

Our re-analysis is classified according to flowpath – surface runoff or subsurface flow.

3.1 Searches, eligibility criteria and data extraction

Our initial search for data examined the studies reviewed in the previous section (Table 2). We also performed a supplementary literature search using ScienceDirect, Web of Science and Google Scholar. Only one peer-reviewed hillslope scale riparian study (Scotsman Valley, Waikato; Smith 1989; Cooper 1990) is available for New Zealand agricultural landscapes.

Each of the RBZ studies that were included in this analysis met the following criteria:

- Natural rainfall event monitoring (irrigation was acceptable if it was usual practice).
- Measured water flow. Studies using erosion mats, passive samplers and sediment tracers were not included.
- Contaminants were derived from diffuse agricultural sources (excludes feedlot runoff and septic tank wastewater treatment systems).
- Contaminants were attenuated by a RBZ at the edge-of-paddock (excludes studies of riparian wetlands and in-field RBZs).
- For subsurface flow:
  - Evidence of thorough hydrological investigation (e.g., multiple piezometer/wells to assess flow direction and/or chloride concentration to assess and correct for dilution).
  - Corrections were applied where nitrate-N: chloride ratio provided evidence of dilution.
  - Information was provided regarding the depth to an impermeable soil layer.
- For surface runoff:
  - Loads (or average flow weighted concentrations) were reported.
  - Reductions in concentration were compiled but were not used.
  - For some studies, annual performance data were not available; multiple year summary values were used for a period up to a maximum of 3 years.
- The minimum duration of a study period was one growing season (spring-autumn). Winter monitoring is uncommon in cold temperate environments where snow cover exists for part of the year.

For surface runoff studies we extracted the following information (where available):

- Study design (inflow on adjacent sites vs same plot, confined vs unconfined), equipment, duration, number of runoff events, number of replicates.
- Site, location, climate, annual rainfall.
- Annual load and annual attenuation efficacy of runoff (as metric of infiltration), SS, N forms and P forms.
- Source area characteristics – slope, soil texture, soil particle sizes, hillslope length, land use, area, runoff: rainfall ratios, applied irrigation, fertiliser application, surface sealing and presence of aggregates.
- RBZ characteristics – width, slope, soil drainage class, and vegetation type and species, age, desired grass length, infiltration rates, grass density and maintenance.

For diffuse subsurface flows we extracted the following information (where available):

- Study design, presence of a control site, equipment (type, number of transects, monitored depths), study duration, sampling frequency.
- Site, location, climate, annual rainfall.
- Annual attenuation efficacy of N forms and P forms (%), average/median concentration reductions.
- Source area characteristics – land use, soil texture, hillslope length, potential contributing area.
- Hydrology – depth to impermeable layer, groundwater flux, duration of hydrologic connection between source area and buffer, absence of dilution (estimated using the chloride to nitrate ratio), minimum and maximum water table depths, saturated hydraulic conductivity.
- RBZ characteristics – width, slope, vegetation type and species.

3.2 Methods

Information was extracted from the primary (original) article(s) and checked against information in secondary references (e.g., reviews) that quoted the primary article.

Some studies evaluated multiple RBZ widths or used replicate RBZs. RBZs were evaluated over their entire width (paddock edge to stream edge), unless the RBZ graded into a riparian wetland. In the latter cases, the data for the unsaturated RBZ were extracted where possible. Data from replicates were aggregated where possible. In some studies, involving multiple sites, data from individual sites that did not meet the criteria were excluded. For example, dilution may have been detected in one transect (excluded), but not in another (included).

Some soils are transported as stable aggregates and their settling characteristics depend on aggregate size. Soil texture for aggregates was estimated using the transported soil particle sizes, rather than the dispersed particle sizes. When soil texture was reported without results from particle size analysis, soil classification information was used to estimate particle fractions.

We categorised the study locations according to the Köppen-Geiger climate classification system (Kottek et al. 2006). Studies were grouped into cold temperate and warm temperate classes.

For each study we calculated several variables for use in our analysis:

- Surface runoff - filter strip width: hillslope length, filter strip area: hillslope area and runoff:rainfall ratio.
- Subsurface flow – attenuation per metre width (%/m) and where possible, nitrate flux (g/m/d) was calculated as water flux (L/m/d) × mean concentration (mg/L).

Analysis was completed in R (ver 3.6.1) using RStudio (ver 1.0.153) and with the support of the following packages: ggplot2, stats, tidyr, dplyr, plyr, rpart, FactoMinR, psych and factoextra. Our datasets were tested for normality. Principal components analysis was used to identify primary continuous variables by forcing as much variation into as few dimensions as possible, without incurring loss of information. Regression trees were used to explore relationships between contaminant attenuation and key landscape and design characteristics of RBZs.

We examined the experimental design of each surface runoff study and checked for a statistical difference between studies that used adjacent control sites versus those that measured the inflow and outflow on the same plot.

3.3 Filtering surface runoff

3.3.1 Dataset

Our surface runoff dataset contains 100 estimates of removal efficacy from 40 sites collected by 19 author groups. The dataset is split between cold temperate (46%) and warm temperate climates (54%). One long-term study has 24 values in the dataset (12 years for 2 different filters). The dataset contains 88 annual values, eight 2-year values and four 3-year values.

The majority (79) were treatment/control studies, while 21 measured inflow/outflow on the same filter. For sediment, TN and TP no statistically significant differences in attenuation were observed between the different experimental designs (Figure 6 b, c, e). However, for runoff, DRP and nitrate, the adjacent site studies with controls had lower median attenuation values. The likely reason is difference in infiltration between treatment and control sites - for well-established filter vegetation differences in soil structure and infiltration characteristics between the control and treatment may exist, whereas inflow/outflow studies were performed on the same site. Given the small number of research sites in the dataset, our approach is to use all sites for sediment, TN and TP (n=100) because attenuation is primarily due to physical processes and to use only the adjacent sites group (n=79) for runoff, nitrate and DRP analysis because attenuation is related primarily to infiltration.

Sixty-four studies were conducted using confined plots (plots with barriers preventing runoff from an adjacent plot entering the study RBZ), and attenuation in confined plots was statistically significantly different from attenuation in unconfined plots for all parameters (.Figure 10 b, Figure 11b, Figure 23b, Figure 24b, Figure 25b, Figure 26b).

The slope of monitored hills ranged from 0.5 to 20% and median hillslope length was 60 m (Table 3). The dataset covered a range of drainage classes – poor (42%), moderate (21%) and well-drained (37%). Sites with silt loam (47%) and clay (24 %) soils dominated the dataset. One study (with five values in the dataset) reported “stable soil aggregates” and was coded as silt loam rather than clay.

Incoming contaminant loads varied widely; for example, TN loads entering filters range between 0.55 and 112 kg TN/ha/y (Table 3).

In our dataset, filter widths ranged from 0.5 m to 20 m, with most less than 5 m wide (Table 3). Filter widths ranged from 1 to 34% of hillslope length, with a median of 11%. Filter vegetation was mostly grass (73%), with 21% tree/shrub and 6% grass and tree/shrub filters. Grass filters were most commonly planted with ryegrass (12) and tall fescue (18), cockspur (6), meadow fescue (18); most contained a mixture of grass species. Few studies reported grass density; some authors reported periods of low grass density (<60% for 9 values). Most grass filters were mown twice-yearly and the cut grass was left in situ. Shrubs and trees were mostly deciduous and included plane trees (8), giant cane (3) and mixed plantings of other trees such as poplar, elm, alder, eucalypts and ash.

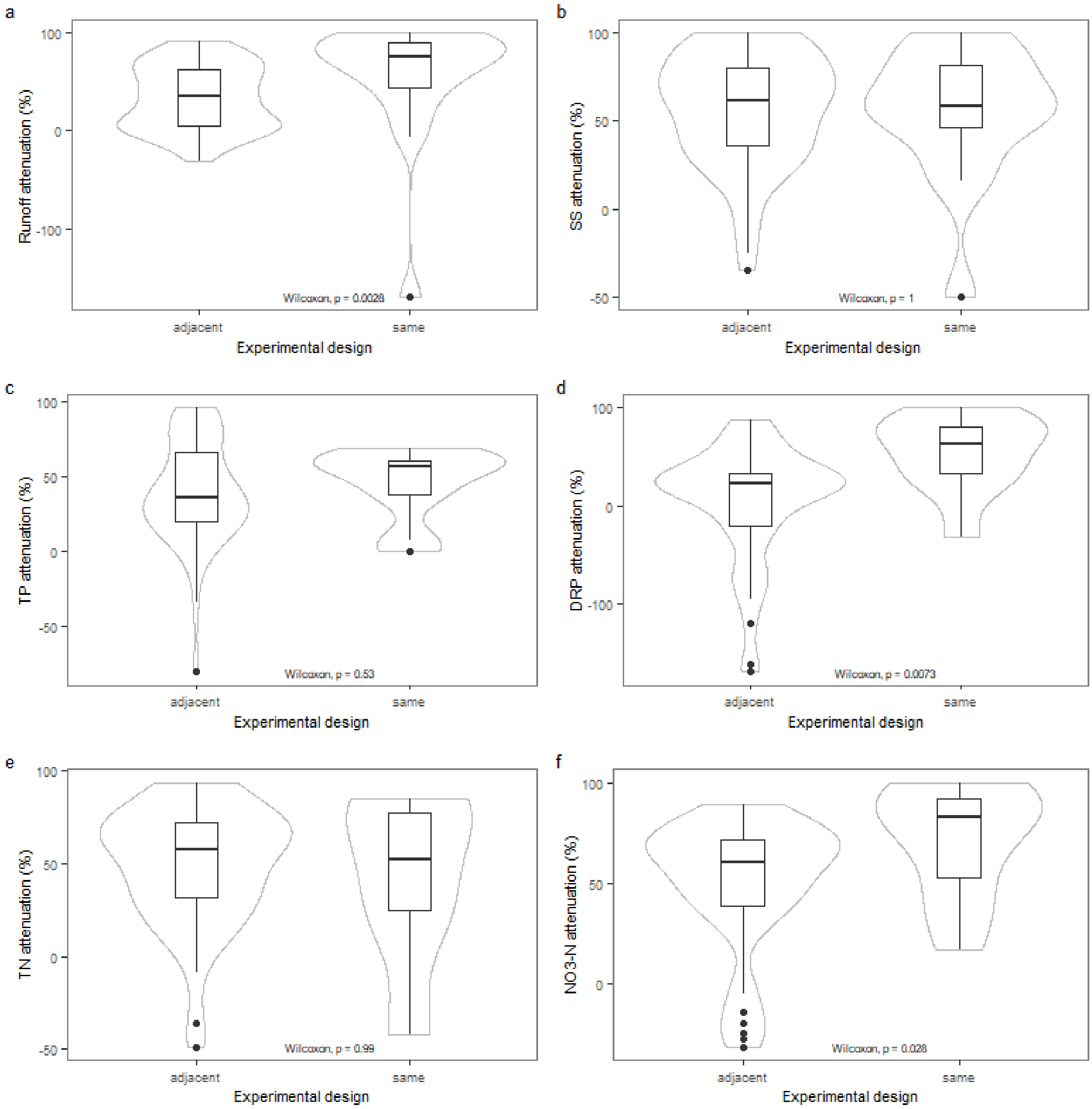


Figure 6: Comparison of experimental design by attenuation parameter. The "adjacent" group all have adjacent control sites; the "same" group measure inflow and outflow on the same plot. The box defines the interquartile range with median, the whiskers are the 10 and 90th percentiles, outliers are dots. The violin plots show the data densities - wider zones contain more data points.

Table 3: Summary statistics for monitored filters in the review dataset (all available data).

Parameter	Minimum	Median	Mean	Maximum	Number of data values
Hill slope (%)	0.50	6.0	8.1	38	100
Hillslope length (m)	22	60	78	380	100
Filter width (m)	0.50	2.0	4.5	20	100
Hillslope length: filter width	0.01	0.11	0.12	0.34	100
Age	0	4	6.5	30+	100
Silt (%)	15	48	45	77	100
Clay (%)	4	20	29	58	100
Annual precipitation (mm)	220	750	820	2030	100
Runoff: rainfall ratio	0.013	0.15	0.18	0.57	71
Inflow (mm)	5.0	93	100	480	65
Sediment load in (kg/ha/y)	7.2	700	1480	21340	63
TP Load in (kg/ha/y)	0.013	0.99	2.2	26	48
DRP Load in (kg/ha/y)	0.0069	0.14	0.38	2.0	43
TN load in (kg/ha/y)	0.55	5.3	9.1	112	44
Nitrate-N load in (kg/ha/y)	0.013	1.8	2.3	8.7	44

3.3.2 Results

All sites

With few exceptions, filters were sediment sinks; SS attenuation ranged from -50 to 99%, with a median of 59% (Figure 8). Loads entering the filters varied from 7 to 21340 kg/ha/y, with a median of 700 kg/ha/y. SS attenuation was positively correlated with inflow load and %silt, and negatively correlated with %clay and filter age (Table 4).

The majority of filters attenuated TP (range -80 to 95%, median 36%; Figure 23). Inflowing P loads varied between 0.01 and 26 kg TP/ha/y and 0.007 and 2 kg DRP/ha/y (Table 3; Figure 23). Monaghan et al. (2007) summarised annual P losses from New Zealand dairy pasture and reported a range of 0.2 to 3.4 kg TP/ha/y, with most studies indicating losses smaller than 0.9 kg TP/ha/y. TP attenuation was negatively correlated with age and %clay (Table 4).

Nitrogen loads arriving at the filter face also varied widely; inflowing TN yields ranged from 0.55 to 112 kg TN/ha/y and the median load was 5 kg TN/ha/y (Figure 7). The filter strips demonstrated a median TN attenuation of 57% (-49 to 94%, Figure 25). Total N attenuation was negatively correlated with %clay and positively correlated with incoming load (Table 4).

Adjacent sites dataset

The adjacent sites dataset had 79 values from 33 sites and 15 research groups. Cold temperate sites dominate the dataset (46 values). Soil textures in the adjacent sites group are mostly clay (29) and silt loam (34). The filters in the adjacent sites group were predominantly grass (58). The mean buffer width was 6 m (0.5-38 m) and hill slopes ranged from 0.5 to 20% (median = 2%).

Runoff:rainfall ratios were available for 50 data values and ranged from 0.013 to 0.57, with a median of 0.16 (Figure 9, Table 3). Although runoff:rainfall ratios indicate how much rainfall becomes runoff and hence the amount of water entering the RBZ, the reported numbers are only indicative because it can be challenging to estimate the area contributing runoff in unconfined hillslope studies.

Some of the filters were source areas with negative attenuation for runoff, DRP and nitrate (Figure 9). Runoff attenuation in the filters varied between -31% (runoff source) and 90% (good infiltration), with a median of 35% (Figure 9). Median DRP load reduction was 22% (-170 to 88 %; Figure 24). Nitrate load attenuation ranged from -31% to 90%, with a median of 60% (Figure 26).

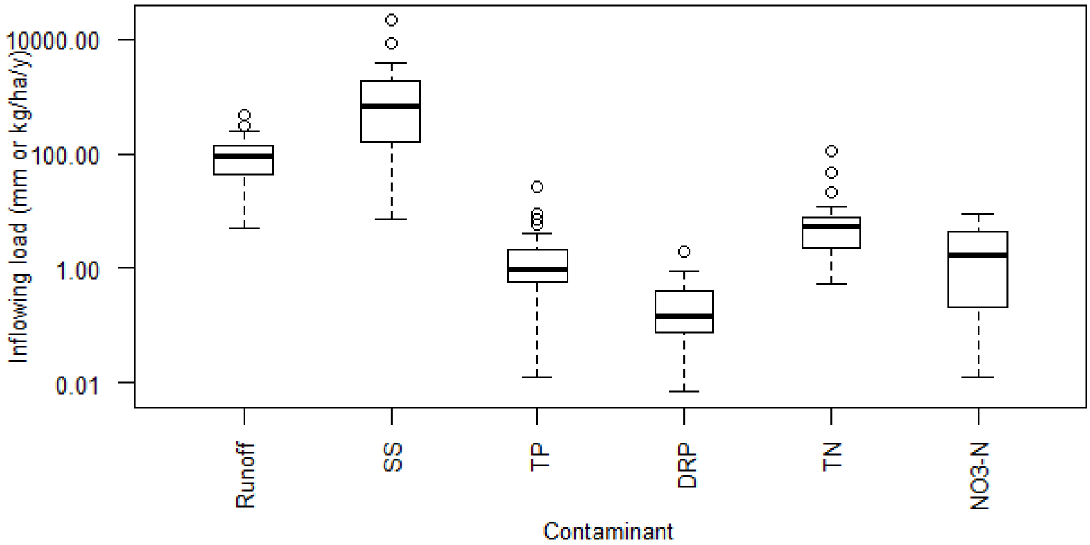


Figure 7: Boxplots showing filter incoming runoff and contaminant load data characteristics. All data (n=100 data values), but not all parameters were measured in all studies.

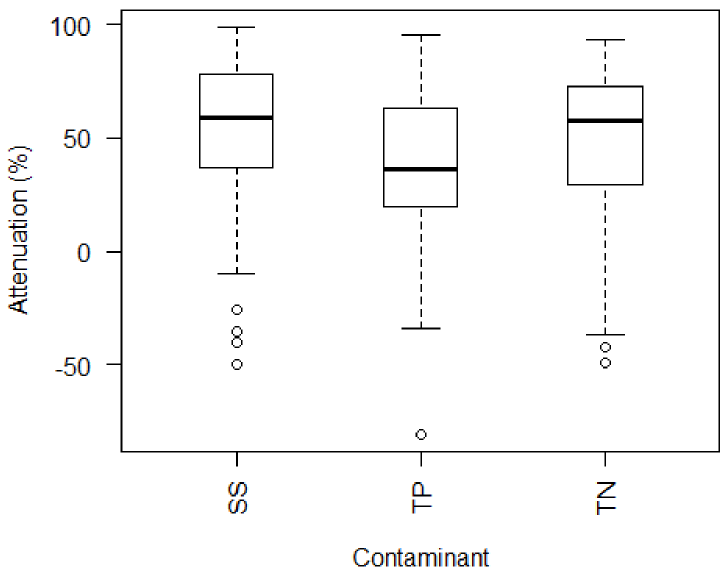


Figure 8: Boxplots of filter contaminant attenuation data (all data, n=100 data values).

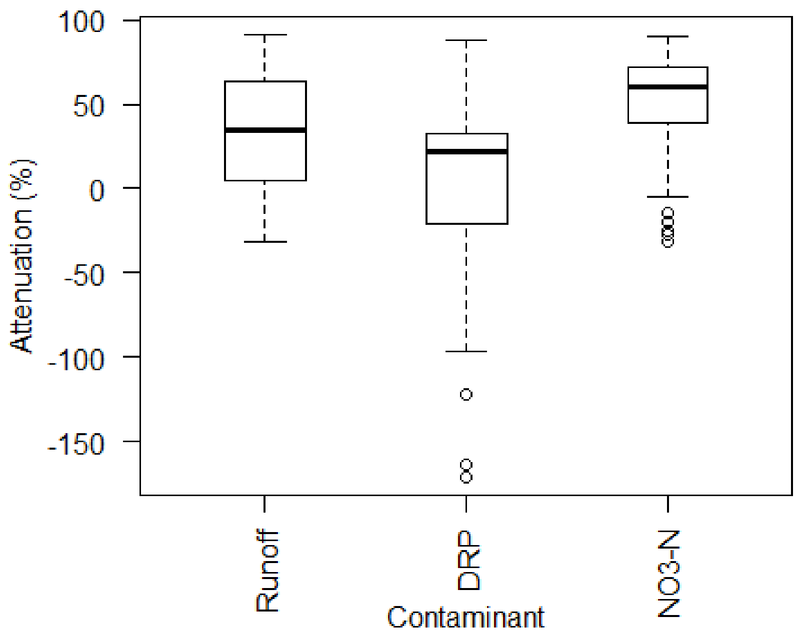


Figure 9: **Boxplots of filter contaminant attenuation (adjacent data, n=79 data values).**

Table 4: **Kendall correlation on ranks coefficients for attenuation vs hillslope and filter physical properties.** Statistically significant correlations are shaded; green are positive and blue are negative correlation coefficients. Cells with "." did not have a significant (p<0.05) correlation coefficient.

Parameter	Runoff attenuation (%)	SS attenuation (%)	TP attenuation (%)	DRP attenuation (%)	TN attenuation (%)	NO3-N attenuation (%)
Dataset	**Adjacent**	**All**	**All**	**Adjacent**	**All**	**Adjacent**
Filter width: hillslope length ratio		.	.	.	.	.
Filter width (m)		.	.	-0.40	.	.
Hill slope (°)		.	.	0.15	.	.
Inflow load (mm or kg/ha/y)		0.16	.		0.24	0.17
Filter age		-0.19	-0.31	.	.	-0.18
Clay (%)	-0.41	-0.39	-0.15	-0.59	-0.35	.
Silt (%)		0.16.	.	0.41	.	.
Sand (%)		.	.	0.05	.	.

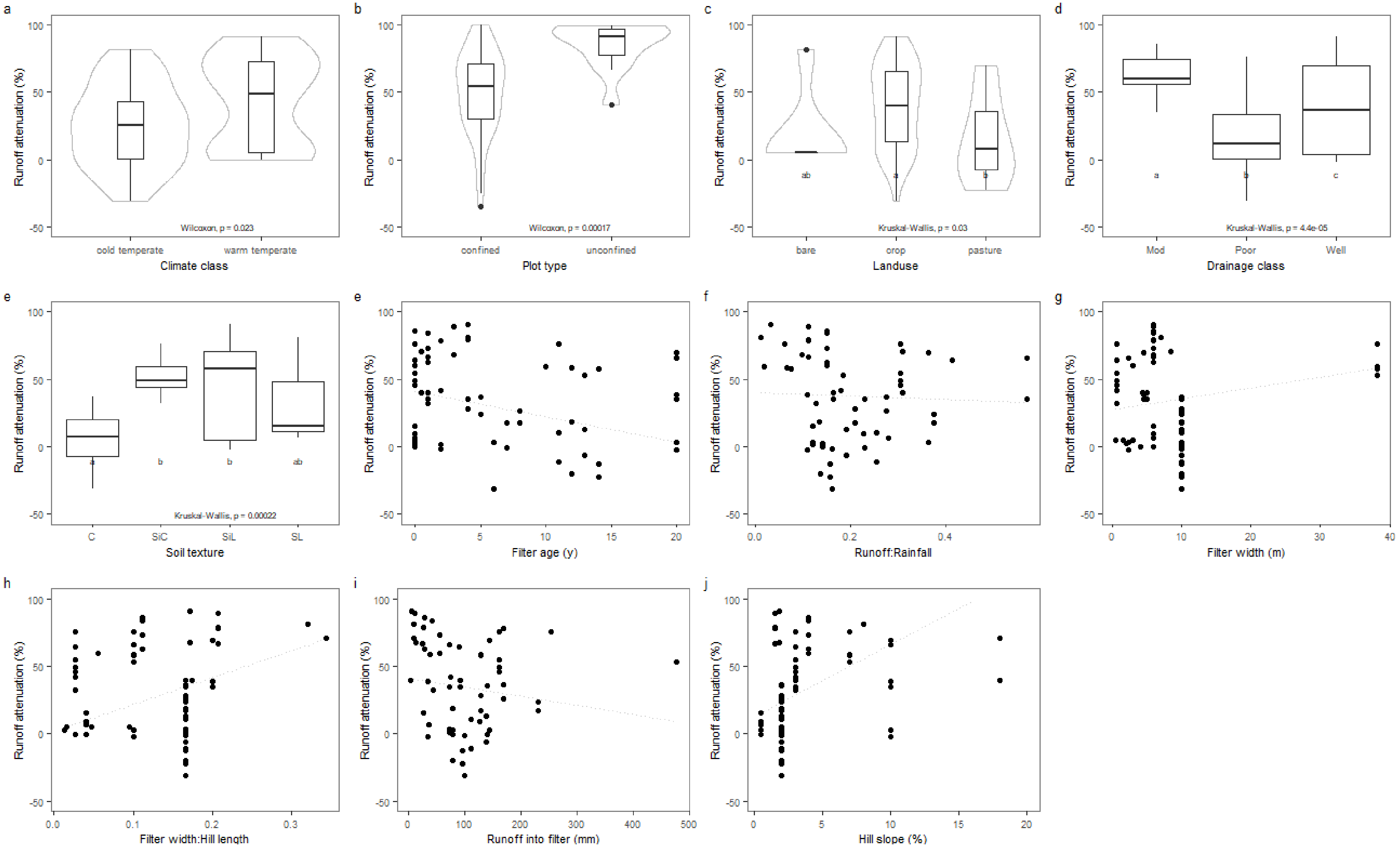


Figure 10: Plots summarising runoff attenuation in filters (adjacent studies only, outlier removed). Grey dashed lines on scatterplots are 0.5 quantile regression lines - half of the data are above and half below the line. The box defines the interquartile range with median, the whiskers are the 10 and 90th percentiles, outliers are dots. The violin plots show the data densities - wider zones contain more data points.

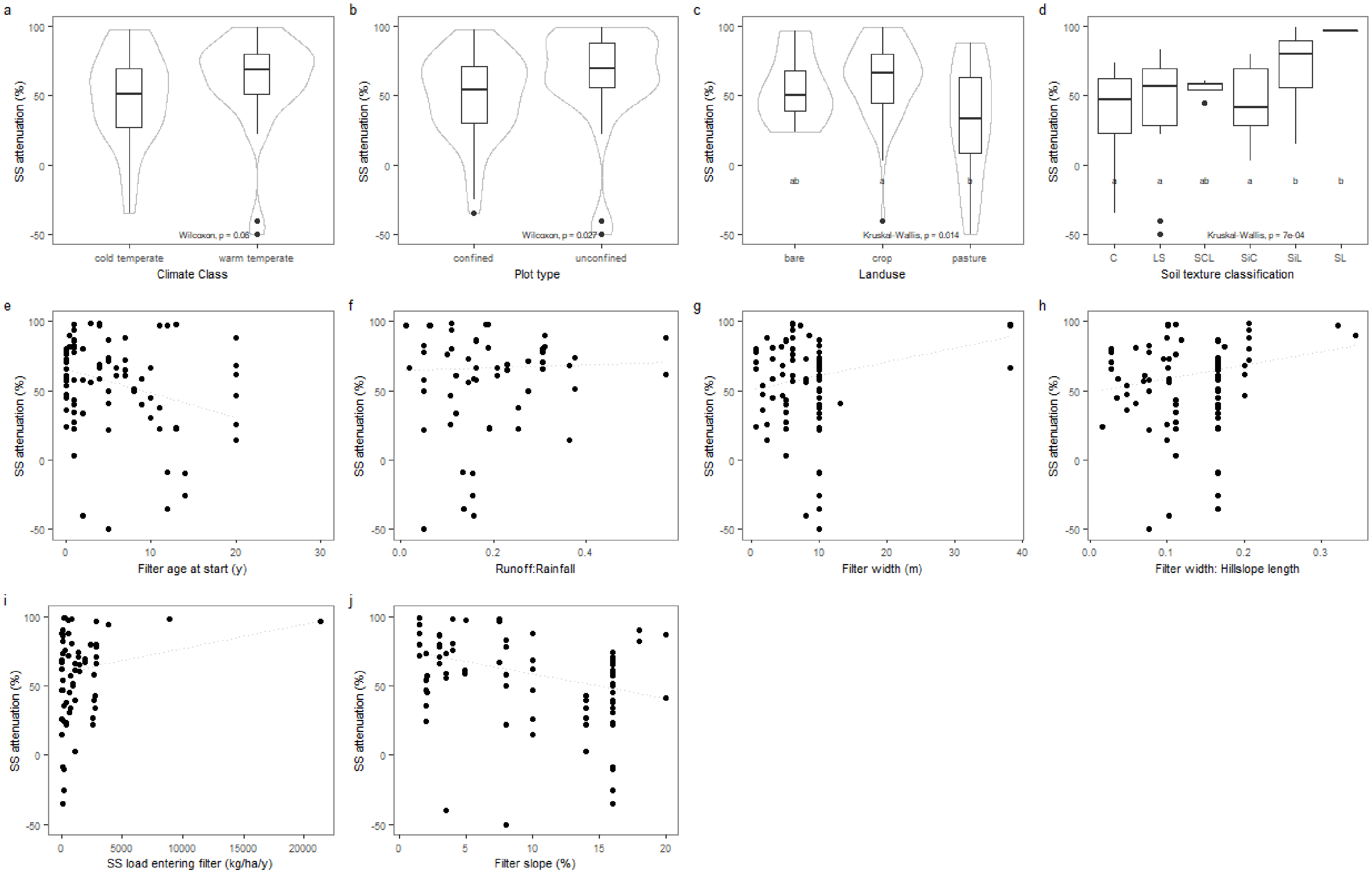


Figure 11: Sediment attenuation in filter strips summary plots according to climate class and physical properties (all data values). Grey dashed lines on scatterplots are 0.5 quantile regression lines - half of the data is above the line and half below. The box defines the interquartile range with median, the whiskers are the 10 and 90th percentiles, outliers are dots. The violin plots show the data densities - wider zones contain more data points

3.4 Nitrate removal from subsurface flow

3.4.1 The dataset

The subsurface flow dataset was selected to explore site hydrology and nitrate concentration attenuation relationships. The dataset contains 52 sites from 30 research groups. The sites cover North America (34), Europe (16) and Australasia (2); most of the sites have warm temperate (39) climates.

The dataset has 19 annual values, twenty 2-year values and nine studies were 3 to 7 years duration. Eight studies had control transects with no riparian vegetation. Many studies had one transect (18) and most had less than 4 transects (41). Sampling intervals were typically monthly (32) or fortnightly (13).

Information on depth to impermeable layer in the riparian zone was provided in all studies and was evenly split into classes (18 studies 0-2 m, 18 studies 2-4 m, 16 < 12 m). Information on hillslope depth to impermeable layer was provided in half of the studies (8 in 0-2m, 4 in 2-4 m and 15 in 4-15 m). The contaminant source was typically cropland (42), with 10 buffers in the riparian zones of pastoral farms.

The RBZs ranged in width from 5 to 220 m, with a median width of 26 m. Most RBZs contained trees and shrubs (34), and mature trees were common (29+). At four RBZs monitoring started within four years of establishment. RBZ soil textures were dominated by coarser-textured soils (38 sites have sandy loam, loamy sand, sand or gravel).

3.4.2 Results

Mean nitrate concentrations entering RBZs ranged from 0.15 to 45 mg/L, with a median of 8.1 mg/L. Nitrate attenuation varied between 0 and 100% and the median reduction in concentration was 87%. A Kendall correlation matrix revealed one significant correlation - between nitrate attenuation and depth to impermeable layer in the RBZ (-0.22, $p<0.05$, Figure 12 e).

Water flux data were available for 31 sites and ranged from 0.5 to 800 L/m/d (Figure 12 b); saturated hydraulic conductivity ranged from 0.005 to 24 m/d (n=33, Figure 12 g).

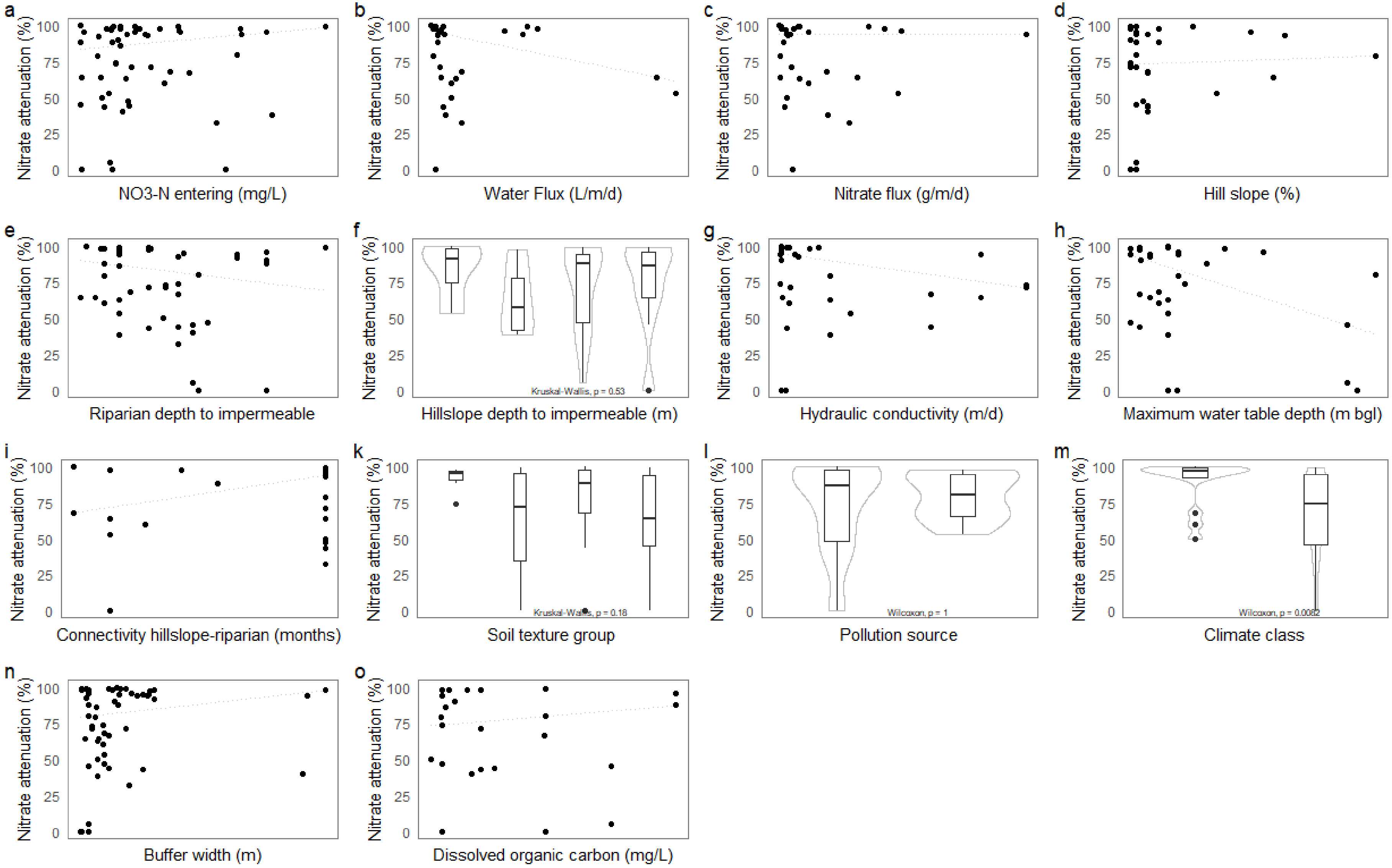


Figure 12: Nitrate attenuation in subsurface flow in RBZs according to climate class and physical properties. Grey dashed lines on scatterplots are 0.5 quantile regression lines - half of the data is above the line and half below. The box defines the interquartile range with median, the whiskers are the 10 and 90th percentiles, outliers are dots. The violin plots show the data densities - wider zones contain more data points.

4 Guideline development

4.1 Filtering surface runoff

4.1.1 Existing guidelines

Many guidelines are available for designing filters for sediment attenuation on cropped land. Most guidelines are designed for annual average annual attenuation, but some are structured around design storms (e.g. Dosskey et al. 2008; Dosskey et al. 2011). Some guidelines relate attenuation to filter width and others to contributing area ratio. Contributing area (or length) ratios are powerful because the area (or length) is a surrogate for the load/runoff volume size and filter area (or width) is a surrogate for attenuation in the filter (Bren 1998, Dosskey et al. 2011). This enables findings to be extrapolated so that site-specific (or variable width) filters may be designed.

The USDA supports an extensive filter guidelines and certification programme. The certification documents specify minimum widths for sediment or dissolved contaminant attenuation (using a points system), runoff criteria (sheet flow >60% of source area, treated concentrated flow), vegetation condition and maintenance. Filter design is typically achieved using models: RUSLE2, an empirical model or VFSMOD, a physically based model. The RUSLE2 model estimates average annual sediment delivery to the filter, and then predicts the contributing area: filter ratio required to accumulate <15 cm of sediment over 10 years at the filter face.

Filter guidelines from Australia also apply to cropped lands (Karssies and Prosser 1999a; Prosser and Karssies 2001), and emphasise the role of sediment settling in the pond created at the filter face. For clay soils that are transported as aggregates, a range of widths are presented for kikuyu filters receiving soil losses ranging between 1 and 70 t/ha/y on slopes from 1 to 10%.

The DOC Riparian Guidelines (Collier et al. 1995) were developed explicitly for filtering surface runoff from pasture in New Zealand. Collier et al. (1995) provide an approach to estimate average annual sediment attenuation based on slope class, soil drainage class and clay content (Table 5). Long term predictions of average efficacy were developed using the CREAMS model, verified at a site in the Waikato (Cooper and Bottcher 1993). The *optimal* width for a filter is defined as the point where the attenuation efficacy (%) versus filter width: hillslope length curve begins to flatten (i.e., the point beyond which limited attenuation gains may be anticipated despite increasing width). It does not mean that the optimal width is the desired width.

We have plotted the DOC guideline optimal points for moderate clay content soils (Figure 13) and fitted a curve to the data point using a negative exponential equation, with an origin of 0,0 and two pairs of estimated points. For the narrow filters with high modelled attenuation a straight line was fitted; straight lines could also be added for other classes with narrow filters (represented as small % of hillslope length). For example, landscapes with code MLM (Table 5) having slopes in a range from 8-15° that are poorly drained, with 20-40% clay, the design which provides a sediment attenuation of 70% requires a filter width sized to be 7% of hillslope length (Figure 13). For filter dimensions with MLM less than 7% of hillslope length, we know that trapping is less than 70%, but cannot quantify by how much less with certainty. Each of the 27 DOC guideline points has a steeper curve to the left and gentler curve to the right of the given point. Curves were not provided in the original guidelines because limited data existed to verify their accuracy.

The DOC guidelines method can be used at paddock-scale and catchment scale for designing variable-width RBs (see Collier et al. 1995). Generally, the buffer widths required to achieve a given sediment removal performance increase as slope length, hillslope angle and clay content increase; at optimal widths (1 to 15% of slope length), estimated performance was classified as high (>70%) for the majority of slope-drainage-soil combinations.

The Riparian Management Classification (RMC; Quinn et al. 2001) provides an alternative, qualitative field-based approach for assessing the current state and likely outcomes of multiple potential riparian management functions (including filtering of overland contaminants, denitrification and nutrient uptake by riparian plants) at both catchment and hillslope scales. This approach has been applied in Waikato (Quinn 1999), Canterbury (Quinn 2003; McKergow et al. 2015) and Wellington (Quinn and Bird 2007). Elements of the RMC can be used to guide field assessment of riparian zones.

Table 5: DOC overland flow filter guideline table. Shaded lines are plotted in Figure 13 (Collier et al. 1995)

Site characteristics			Filter width (% hillslope length)	Attenuation efficacy (%)
Slope category L=0-7°, M=8-15°, H=≥16°	Drainage category L=≤4, M=5-65, H=≥66 mm/h	Clay category L=<20%, M=20-40%, H>40%.		
L	L	L	1	95
L	L	M	5	90
L	L	H	9	80
L	M	L	1	95
L	M	M	2	90
L	M	H	4	80
L	H	L	1	95
L	H	M	1	95
L	H	H	3	85
M	L	L	2	90
M	L	M	7	70
M	L	H	15	50
M	M	L	1	95
M	M	M	4	80
M	M	H	11	55
M	H	L	1	95
M	H	M	2	85
M	H	H	4	60
H	L	L	5	45
H	L	M	15	30
H	L	H	30	20
H	M	L	3	60
H	M	M	7	50
H	M	H	13	35
H	H	L	3	75
H	H	M	4	70
H	H	H	11	50

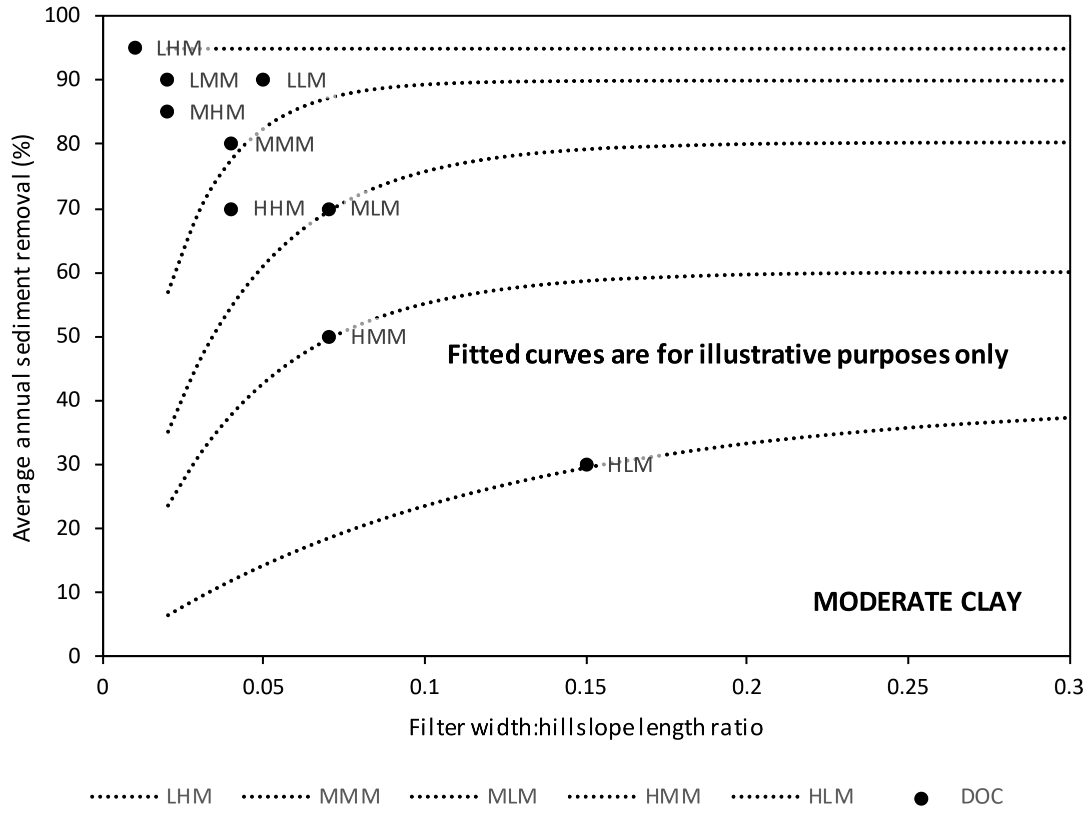


Figure 13: DOC guidelines for sediment removal from overland flow for moderate clay content. Shown are "optimal" points for well-designed and maintained filter strips on soils with MODERATE clay content. After Collier et al. 1995. Fitted curves are for illustrative purposes only. Data points are labelled with L (Low), M (moderate) and H (high) for slope, drainage and clay categories. Point MLM is for filters on moderate slope, with low drainage and moderate clay.

4.1.2 Guideline development for sediment, TN and TP in surface runoff

Currently we do not have a verified model for hillslope scale estimation of annual sediment, TN and TP attenuation by filters for current pasture management systems in New Zealand. Our approach is to use the datasets collated from the review described above to provide semi-quantitative information about the landscapes suitable for good filter performance and an indication of their likely efficacy.

We retain the approach of the DOC guidelines (Collier et al. 1995) by using the filter width to hillslope length ratio as the primary design variable. Without including this design variable directly into the guidelines, it may be possible for users to overlook the role (and importance) of the contributing hillslope when designing an effective filter.

Most of the studies in our dataset are for planar slopes (i.e., where little flow convergence or divergence is anticipated), so the filter width: hillslope length and hillslope area: filter area relationships are highly correlated (1 outlier). Our dataset contains one study where the filter was designed for convergent flow. Helmers et al. (2012) monitored three small convergent cropped catchments (with paired controls) on 7.5 % slopes with well-designed filter strips, 38 m wide. Data reported to date suggests these filters can remove >67% of sediment in runoff.

Our dataset includes more values for runoff and sediment attenuation than for N and P. We have adopted an approach used by Dosskey et al. (2011). There is strong correlation between SS, TN and

TP in the datasets and “rules of thumb” were derived using linear regression to estimate TN and TP removal from SS removal data.

The dataset does not contain any high slope (>34% degrees) studies and contains 10 moderate slope values.

Relationships between attenuation (%) and filter width: hillslope length are affected by variables such soil type, age, rainfall, hill slope, hillslope land use, runoff and flow convergence (Figure 11, Figure 23, Figure 25). We used Principal Components Analysis (PCA; R stats prcomp function) to identify primary continuous variables by forcing as much variation into as few dimensions as possible without incurring loss of information. Variables included in the main PCA were those available for all 100 studies (filter width:hillslope length, clay%, hill slope, sand%, silt%, age, rainfall). Sand% and filter age dominated PCA Dimension 1, while silt% and annual rainfall and %clay dominated Dimension 2 (Figure 14). Slope dominated Dimension 3 and filter width: hillslope length dominated Dimension 4 (Table 6).

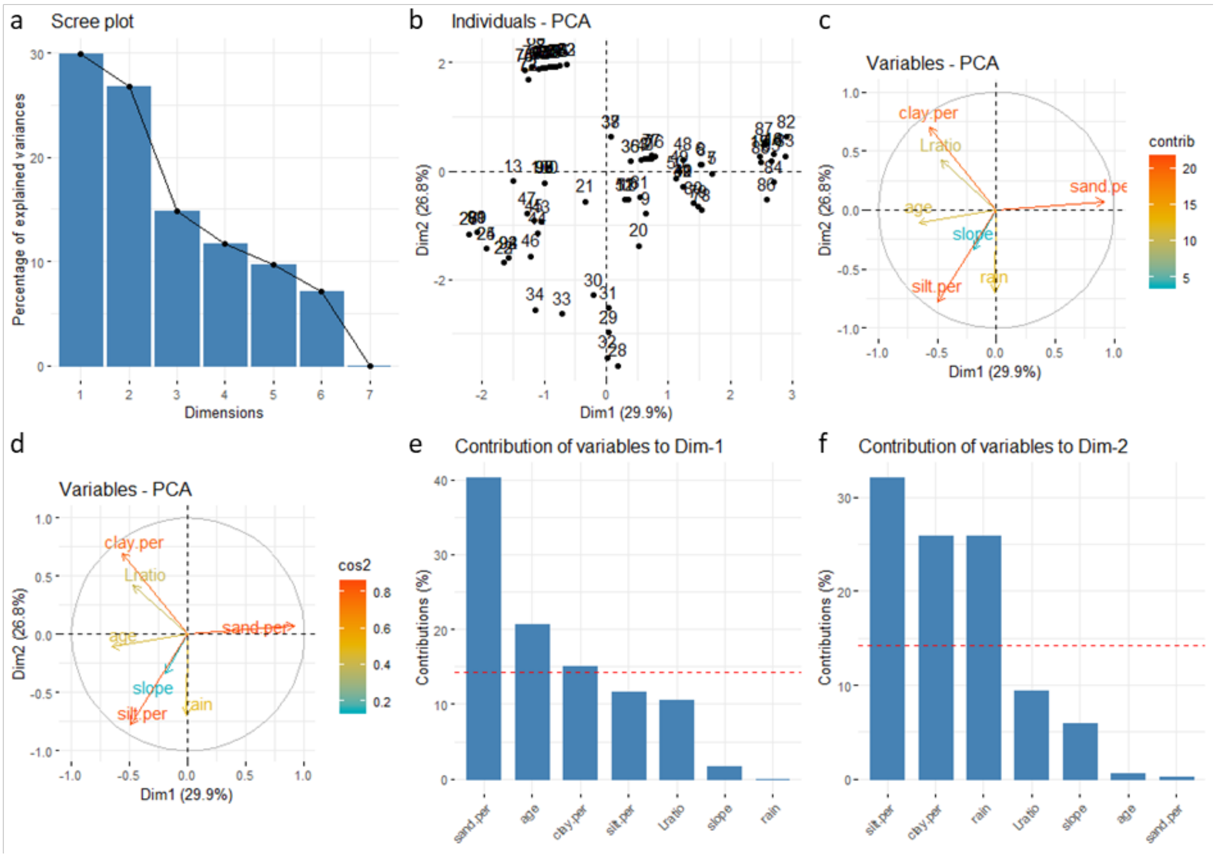


Figure 14: Results of Principal Component Analysis for key continuous filter and hillslope parameters for the whole dataset (n=100 data values). Lratio is filter width:hillslope length. (a) bar graph of the percentage variance explained by the 7 PCA dimensions ordered from highest to lowest, (b) graph of individual data values plotted on Dimensions 1 and 2. Individual data values with similar profiles are grouped together, (c) variable correlation plot - positively correlated variables point to the same side of the plot, negatively correlated variables point to opposite sides of the plot, (d) a cos2 correlation plot for Dimensions 1 and 2 - a high cos2 indicates a good representation of the variable on the dimension, (e) bar graph of the contribution of each variable to Dimension 1. The red dashed line indicates the expected average contribution, and (f) contribution of each variable to Dimension 2.

Table 6: Contribution (%) of variables to Dimensions 1 to 7 indicated by Principal Component Analysis. In the Parameter column, ".per" indicates proportion expressed as a percentage.

Parameter	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5	Dim.6	Dim.7
Lratio (filter width: hillslope length)	10.6	9.4	16	36.2	0	27.8	0
clay.per	15.1	25.9	0	7.3	16.7	5.2	29.8
hill slope	1.7	5.9	71.1	1.8	1.5	17.9	0
sand.per	40.2	0.3	0.8	15	1.7	2.1	39.9
silt.per	11.6	32.1	0.7	3.3	6.6	15.3	30.3
filter age	20.7	0.6	11.4	26.1	10.2	31	0

After identifying key variables from the PCA (sand%, silt%, clay%, age, rain and slope), a regression tree was used to develop possible rules to guide separation of the dataset into subsets. Regression trees are simple and non-parametric. Regression trees partition the data into a set of "boxes" defined by threshold values. These "boxes" have a simple prediction model, in the simplest case a value of the response variable. The reduced sediment dataset contained 73 values. The R function rpart, with a minimum bucket of 8, was used. The regression tree explained ~44% of variance in the dataset (1 - relative model error ~ variance explained, relative model error = 0.56).

The primary dataset (n=73) was split at 28.5% clay content (Figure 15) to create two categories: clayey soils (30) and sandy/loamy/silty soils (43). The clayey dataset contained only three studies; this reduced the confidence we might have in a predictive relationship because a limited number of sites and landscapes were represented, and a limited range of filter width: hillslope length ratios were studied. Consequently, we excluded clayey soils from our filter guidelines.

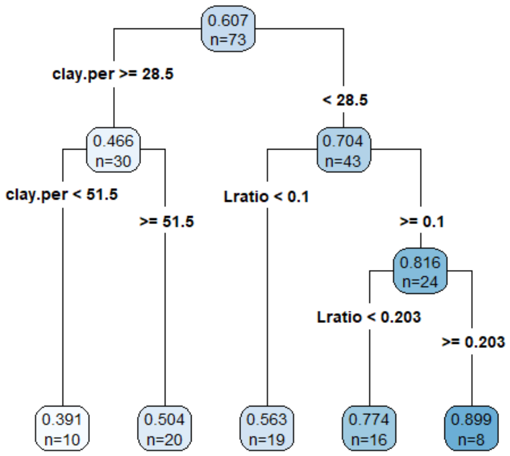


Figure 15: Suspended sediment attenuation regression tree. The results are summarised as a series of "if-then" statements. Each node (box) contains the predicted value (upper number) and number of data values. Node 1 contains the average SS attenuation for the 73 data values. The colour indicates a gradation of SS attenuation from low (light blue) to high (mid blue).

A negative exponential regression (Equation 1) was fitted between % removal of SS and filter width: hillslope length ratio. In a negative exponential regression the relative rate of increase is not constant, but is maximum when $y=0$ and decreases as y increases, and the curve passes through the origin (0,0). This curve reflects filter physical processes – for a given hillslope length an increase in filter width initially results in a large gains in attenuation efficacy (sediment deposition at the filter face and in the initial segment of the filter). After the initial effect, attenuation gains start to plateau with increasing filter width (increasing filter width: hillslope length ratio). This form of equation has worked well with other filter strip datasets (e.g. Dosskey et al. 2011).

Equation 1: Negative exponential regression equation. y is the predicted variable (e.g., SS attenuation) and x is the explanatory variable (e.g., filter width:hillslope length ratio).

$$y = a(1 - e^{-bx})$$

The equation was fitted to 43 data points with clay % < 28.5% collated from the published literature using the R nls function. Confidence intervals were calculated using R package nlstools, confint2 function. The curve fit was poor; the equation explains 7% of the total variation in sediment attenuation and the 95% confidence intervals are large (Figure 16).

The upper bound provides an estimate of % sediment removal likely under ideal conditions. Sediment attenuation (%) on soils with <28.5% clay is unlikely to be less than the lower bound except under exceptional circumstances (e.g., loss of filter vegetation and/or stem density, surface conditions reducing/preventing infiltration).

However, it must be stressed that Figure 16 provides only semi-quantitative information for four reasons:

1. Although the data upon which it is based were derived from published studies, many are from cropping studies in the northern hemisphere. New Zealand pastoral systems differ from the reported studies in several ways, but we do not know how these differences affect sediment attenuation.

2. The data include conditions outside the likely range likely for New Zealand pastoral conditions. Growing season data from cold temperate climates has been included.

3. Extreme events may have a larger impact on annual sediment attenuation (%) in cropping systems (no to low proportion of groundcover), where big storms move lots of sediment that overwhelms the filter. In these systems, lower annual sediment attenuation is likely. Well-grassed pasture RBZs may behave differently.

4. Different study designs and measurement systems may introduce additional variability into the dataset.

The New Zealand data from Smith (1989) are the two largest blue squares and they provide us with some confidence that the lines are reasonable bounds for New Zealand conditions. There is limited data at low filter width:hillslope length ratios and so we have lower confidence in the values predicted for these conditions.

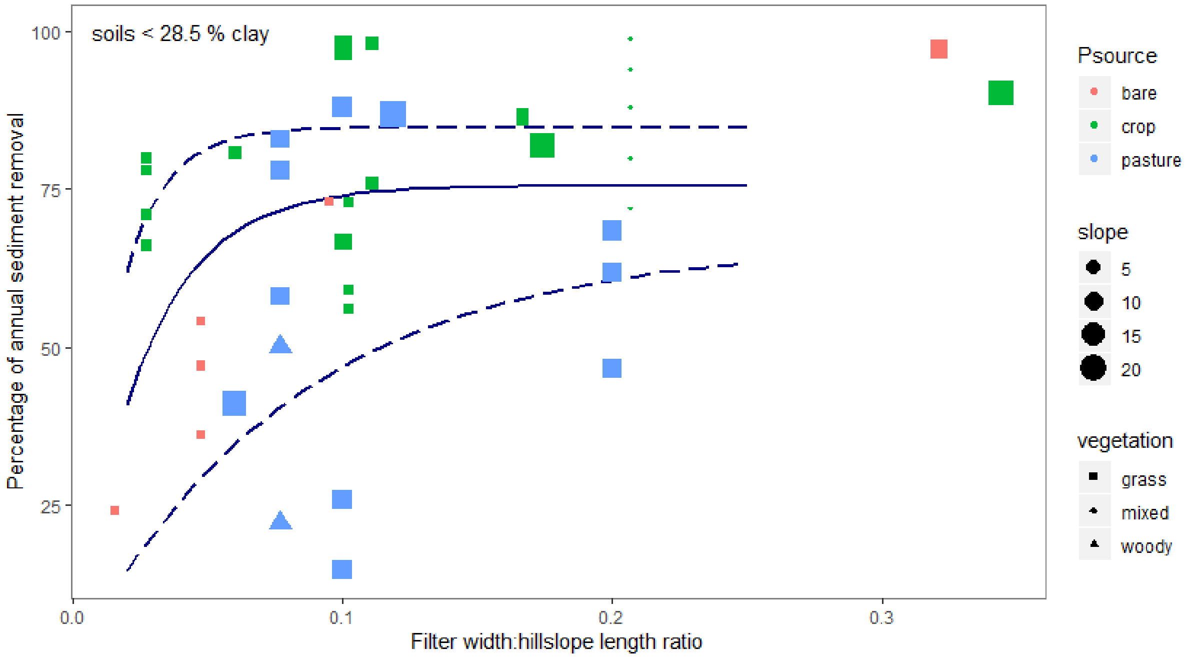


Figure 16: Negative exponential equation (solid) with upper and lower 95% confidence intervals (dashed) and data points from well designed and managed filters on soils with <28.5% clay and on flat-rolling slopes (≤20%). Data points are coloured by source, sized by hill slope (%) and shaped by filter vegetation. For example, the largest blue square (at 85%) is from a filter receiving runoff from pasture, on a moderate (~20%) slope with a grass filter.

Users of this guideline figure may need assistance to evaluate which curve appropriately approximates the filter under evaluation or being designed. It should also be noted that this guide is suitable for low clay (<28.5%) soils on flat-rolling slopes only.

Surface runoff can carry particulates ranging from fine gravels (>1000 µm) to silts (2-50 µm) and clays (<2 µm). Fine particulates, silts and clays, are more difficult to trap than coarser particles; their settling velocities are low, and they are more easily eroded and transported by runoff. These small particles also carry a large fraction of the total load of nutrients (notably phosphorus) because of their high surface area:volume ratio (Syversen and Borch 2005). For fine particles, infiltration is a key attenuation mechanism. Soils transported as aggregates behave like larger particles, settling more rapidly; clay soils transported as aggregates can be trapped by filter strips (McKergow et al. 2004b; Syversen and Borch 2005; Shiono et al. 2007).

A well designed and maintained filter will intercept shallow surface runoff across the filter face. In reality, on many hillslopes flow converges into channels as it moves down slope. If flow approaches the filter in one or more narrow channels it may pass straight through the filter, reducing its effectiveness. Examples from the literature where the effect of concentrated flow on filter performance was assessed include:

- Dosskey (2002) modelled SS removal on 4 hillslopes with and without concentrated flow; predicted removal decreased from 45-90% without concentrated flow to 20-50% with concentrated flow.
- McKergow et al. (2004) measured 40% SS reduction on a moderately convergent cropped hillslope in the wet tropics (excluded from our dataset), but highly convergent channels were prone to scour (i.e., likely to generate sediment).

- Daniels and Gilliam (1996) monitored several convergent channels under hardwood riparian forest using data collected from multiple channels to estimate performance; scouring in both channels increased sediment load. In channel 2 however, it was possible to trap sediment after the initial scouring as water flowed through an additional 50 m of filter.
- (Helmers et al. 2012) found that well-designed buffers on a cropped convergent catchment (7% slope) with a 10% hillslope area:filter area removed >70% SS.

Infiltration can be a key removal process in many filters; infiltration losses will be reduced by:

- Hydrophobic or water repellent soils (McKergow et al. 2006b).
- Surface sealing, for example, when aggregates breakdown under raindrop impact (e.g., Le Bissonnais et al. 2004) the fine particles may clog soil pores.
- Soil saturation (McKergow et al. 2006b).
- Compaction, for example during grazing (Elliott et al. 2002).

Trapping by sedimentation will be enhanced by high stem density at ground level. Most of the research on filter performance is for dense grass filters (see section 3.3). Trees and shrubs can be part of a filter as long as a dense groundcover is present to provide roughness that slows surface runoff. Patchy grass cover or clumped vegetation may encourage the development of micro-channels, allowing water velocities to increase in the filter. Surface runoff channels through a filter can occur when groundcover is low:

- Smith (1992) observed channels through unconsolidated pine litter in a 25-35 m wide *Pinus radiata* RBZ near Moutere.
- Daniels and Gilliam (1996) found that summer vegetation and litter in an RBZ with an ephemeral channel provided little roughness to slow runoff.

Trees and shrubs with extensive root systems may enhance infiltration of runoff in RBZs, but the treatment efficacy may take time to develop if planting is recent. The ability of water to infiltrate soil at any given time will depend on soil moisture conditions, which vary seasonally and according to antecedent conditions.

The addition of woody vegetation to a filter must be considered carefully; it may be suitable if deposition of sediment is not a key removal process, and if particulate material cannot easily be resuspended from beneath trees during events (e.g., McKergow et al. 2004b).

Table 7: Likely adjustment of the attenuation line required for non-ideal filter strips.

Category	Probable curve	Justification
Concentrated flow - more likely on longer hillslope lengths and steeper slopes.	Lower bound more likely to represent the average performance curve.	Concentrated flow forces runoff through a narrow zone of the filter face, reduces efficacy.
Low infiltration conditions, such as compaction, surface sealing, crusting, hydrophobicity.	Lower bound more likely to represent the average performance curve.	Infiltration will be reduced to zero, reducing efficacy.
High infiltration	Upper bound more likely to represent the average performance curve.	Infiltration will be a major removal process, increasing efficacy. Check for soils susceptible to bypassing.
Low vegetation density	Lower bound more likely to represent the average performance curve.	Lower bound for tree and shrub filters or poor grass cover as water will be able to move around between plants in channels, reducing efficacy.
Aggregates	Upper bound more likely to represent the average performance curve.	Soils may be transported as aggregates and behave more like coarser sediment, improving efficacy.
Large storms	Lower bound more likely to represent the average performance curve.	Large storms can overwhelm filter strips, reducing annual efficacy.

Limited data are available for sediment attenuation on clayey soils (≥ 28.5% clay), which we considered inadequate to develop reliable design parameters and performance guidelines. Nevertheless, collated data are shown in Figure 17 and compared with the guidelines in Figure 16. Sediment attenuation on clay soils is likely to be lower due to long settling times for clay particles. The group of points at 0.11 filter width:hillslope length ratio in Figure 17 are from one study on clayey soils where soils became saturated and surface sealing occurred (Søvik et al. 2012). Those at 0.17 are from a long-term study (Uusi-Kämppä and Jauhiainen 2010) that examined different RBZ vegetation covers and sources; the RBZs were most effective at decreasing TS and TP from paddocks subject to conventional tillage, less so with direct drilling and least effective where grazing occurred.

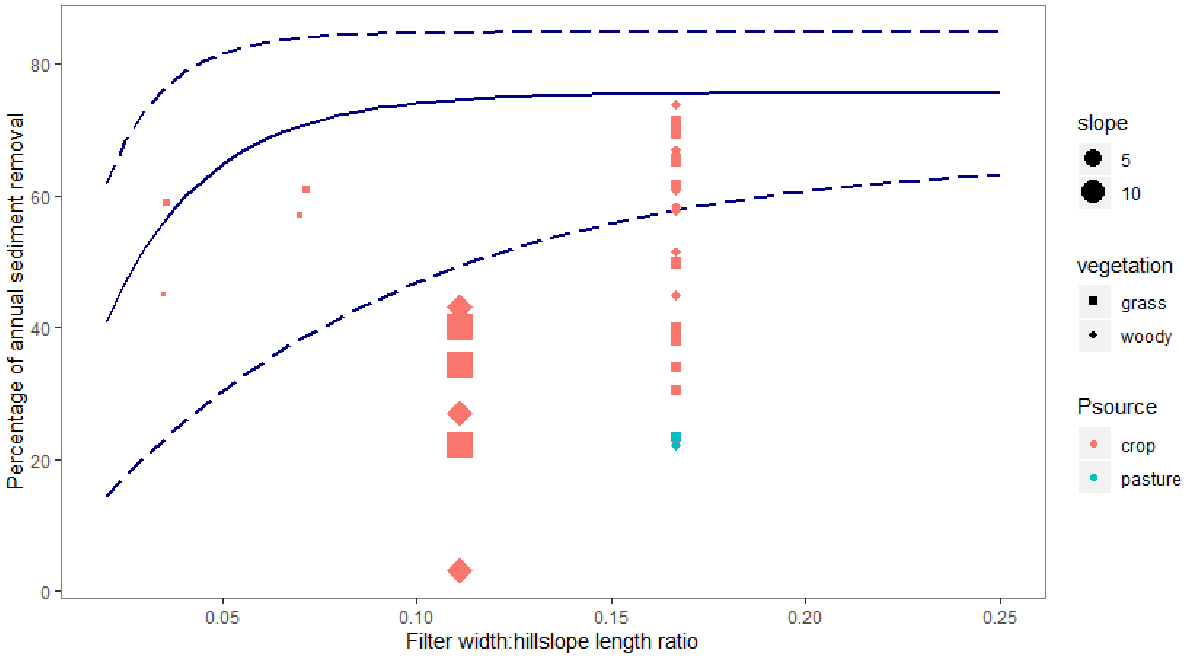


Figure 17: Negative exponential equation (solid) with upper and lower 95% confidence intervals (dashed) from Figure 16, and data points from well-designed and managed filters on soils with >28.5% clay on flat-rolling slopes (≤20%). Data points are coloured by source, sized by hill slope (%) and shaped by filter vegetation.

The TP and TN datasets are smaller than the sediment dataset; TN and TP attenuation values were estimated by using SS attenuation as a surrogate. Linear regressions were developed in R between SS attenuation and TN and TP attenuation (Appendix B - Figure 18 and Table 8).

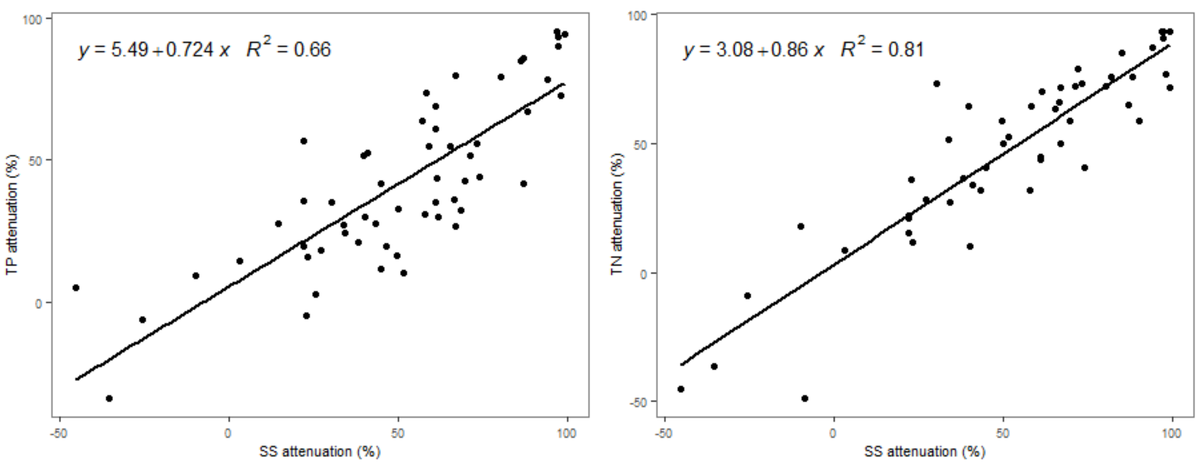


Figure 18: "Rule of thumb" linear regression plots for TP and TN against SS (whole dataset).

Table 8: Rules of thumb for estimating TP and TN removal from SS removal.

	Measured (SS) and predicted (TP, TN) contaminant attenuation		
	SS (%)	TP (%)	TN (%)
Equation		TP = 5.49 + (0.724 × SS)	TN = 3.08 + (0.86 × SS)
		r^2 = 0.66	r^2 = 0.81
Values	30	27	29
	40	34	37
	50	42	46
	60	49	55
	70	56	63
	80	63	72
	90	71	80

Filters are dynamic systems with several characteristics that change over time (e.g., species composition, vegetation height, root biomass, organic matter content). Contributing area characteristics also change over time (e.g., pasture growth, grazing, cropping). The complex, time-varying and inter-related nature of these factors influence filter efficacy, which is not constant over time either. Careful observation of filters during runoff events, response to observed performance and maintenance is important to ensure filters perform at their best.

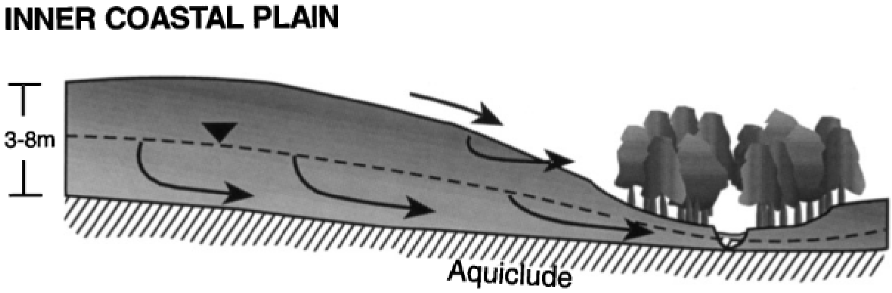
4.2 Subsurface flow in planted riparian buffers

4.2.1 Existing guidelines

Existing guidelines for nitrate attenuation from subsurface flow in planted riparian buffers are narrative, qualitative (high, medium or low performance) or quantitative. Examples include narrative guidelines developed by Prosser et al. (1999) and qualitative guidelines for Chesapeake Bay (Lowrance et al. 1997). Those guidelines that incorporate some level of performance assessment use a physiographic or hydrogeomorphic approach to identify flowpaths, and investigate whether plants may improve denitrification rates in RBZs.

The DOC Riparian Management Guidelines (Collier et al. 1995) do not contain a section on nitrate removal by planted riparian buffers. Instead, they focus on protecting seepage wetlands where research has showed that denitrification rates are likely to be high (Cooper et al. 1990). By encouraging protection and retention of existing seepage wetlands, the guidelines facilitate interception of nitrate-rich emerging groundwater with existing and easily identified organic soils likely to provide the biogeochemical conditions required for effective denitrification.

There is a history of designing buffers for nitrate removal by hydrogeomorphic units (e.g. Lowrance et al. 1997). The Chesapeake Bay qualitative guidelines (Lowrance et al. 1997) were developed by a group of researchers using best professional judgement based on sound biogeochemical and physical principals. Using local research data, typical groundwater flowpaths influencing riparian buffer attenuation performance were identified for physiographic regions. For each physiographic region a series of consensus statements were developed that summarised the best professional judgement on expected level of buffer function, factors likely to constrain performance, and critical management actions (Figure 19).



Water Quality Function	Expected Level	Critical Constraints	Restoration/ Enhancement
Removal of nitrate from groundwater	High, most water moves in or near root zone.	Bypass due to artificial subsurface drains. Organics in Zone 2.	Important on all streams. Rapid restoration of dentrification function. Ground cover in Zone 3.
Removal of sediment and sediment-borne pollutants	High/Medium	Convert concentrated flow to sheet flow.	Restore in all areas. Enhance existing forest with Zone 3 speaders.
Removal of dissolved phosphorus	Medium/Low	Control of dissolved P in surface runoff and groundwater is limited.	Restore in areas with major P load in surface runoff. Enhance existing forest with Zone 3.

Figure 19: Chesapeake Bay Riparian Guideline schematic for the Inner Coastal Plain. Schematic includes idealised flow system, expected level of RB function, critical cons constraints and management factors critical to achieving the function (Lowrance et al. 1997).

Hunter et al. (2006) present narrative guidelines and suggest that site-specific performance should be assessed using their Riparian Nitrogen Model. The Riparian Nitrogen Model estimates removal of nitrate by denitrification in situations where shallow groundwaters interact with riparian soils (Rassam et al. 2005). Hunter et al. (2006) also identify protection of bio-available organic carbon resources as a management option additional to those identified by Lowrance et al. (1997), suggesting that this is best achieved by maintaining a mix of vegetation types, minimising soil disturbance, and by incorporating site-specific design that recognises the influence of landscape, hydrology and soil type.

4.2.2 Guideline development

Moving beyond qualitative guidelines is challenging. We have explored the semi-quantitative hydrology framework developed by Vidon and Hill (2004). This framework was initially developed with field data for eight riparian buffers on glacial till and outwash, which were subsequently modified using international literature (Hill 2018; Hill 2019). The hydrology framework combines depth of permeable sediment (depth to impeding layer), water flux and soil texture to estimate widths required for 90% nitrate removal (Figure 20). The primary axes on the framework are hillslope depth of impermeable layer (left vertical axis), riparian depth of permeable sediment (right vertical axis), and the main horizontal axis is slope. The N input flux, distance of 90% removal and magnitude of the riparian N sink are qualitatively indicated from various combinations of values for the primary axes. Conditions leading to large continuous N fluxes (circled in Figure 20) are most likely to occur when subsurface flow from a thick upland soil (>2 m deep and underlain by an impermeable layer) flows into a shallower (2-6 m deep) riparian soil.

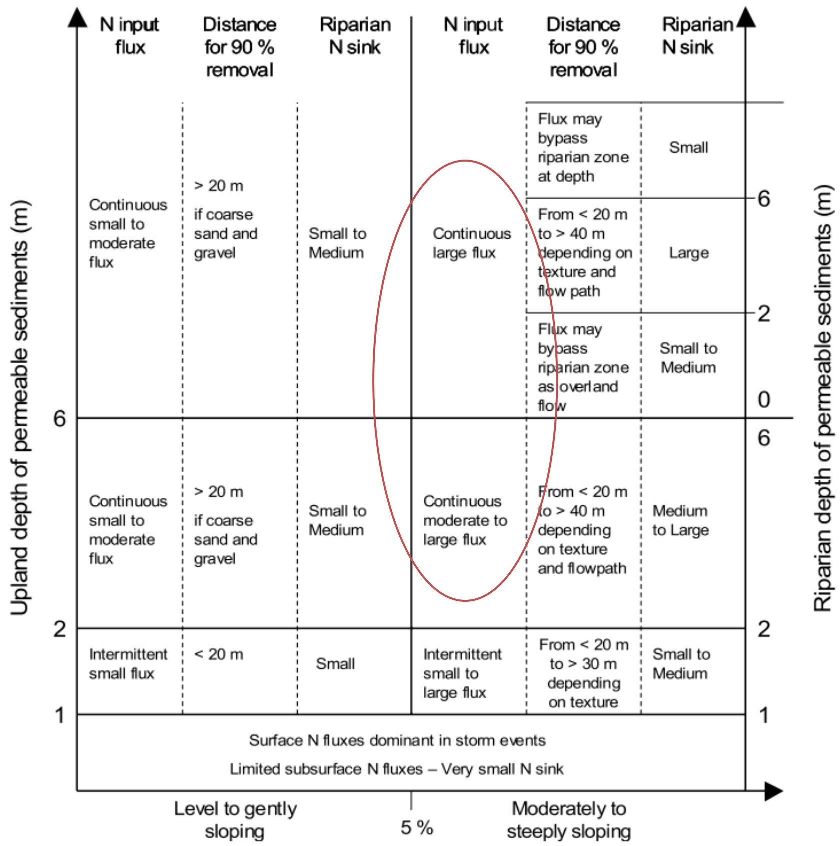


Figure 20: Conceptual model linking nitrate removal to landscape characteristics (Vidon and Hill 2004). Landscape characteristics include depth of hillslope permeable soil (m), the riparian depth of permeable sediments (m), topography and riparian soil texture.

There is insufficient data to verify this framework with adequate confidence for the development of guidelines. We do however recognise the interaction of key characteristics and guiding principles summarised in the framework of Vidon and Hill (2004). Accordingly we provide an attenuation range (Figure 21) for planted riparian buffers with shallow (<2 m) impeding layers, and identify features of landscapes that would tend to represent the higher and lower ends of the range. This information is incorporated in the guidelines.

There is one New Zealand study in this dataset, that of Cooper (1990). Cooper (1990) studied nitrate removal in mineral soils along the pasture riparian zone at Scotsman Valley in the Waikato. In the mineral soils, which occupied 88% of the headwater stream's border (both banks), the average nitrate removal was 64% (the olive green point at 64% in Figure 21 c), but nitrate-N removal accounted for <44% of total N removed in the riparian zone. Most of the nitrate removal occurred in the anoxic organic soils which were seepage wetlands and represent a particular set of biogeochemical conditions. We have specifically excluded seepage wetlands from this analysis. At Scotsman Valley seepage wetlands occur at the base of hollows where most (37-81%) of the subsurface flow is directed, and high denitrifying activity was measured.

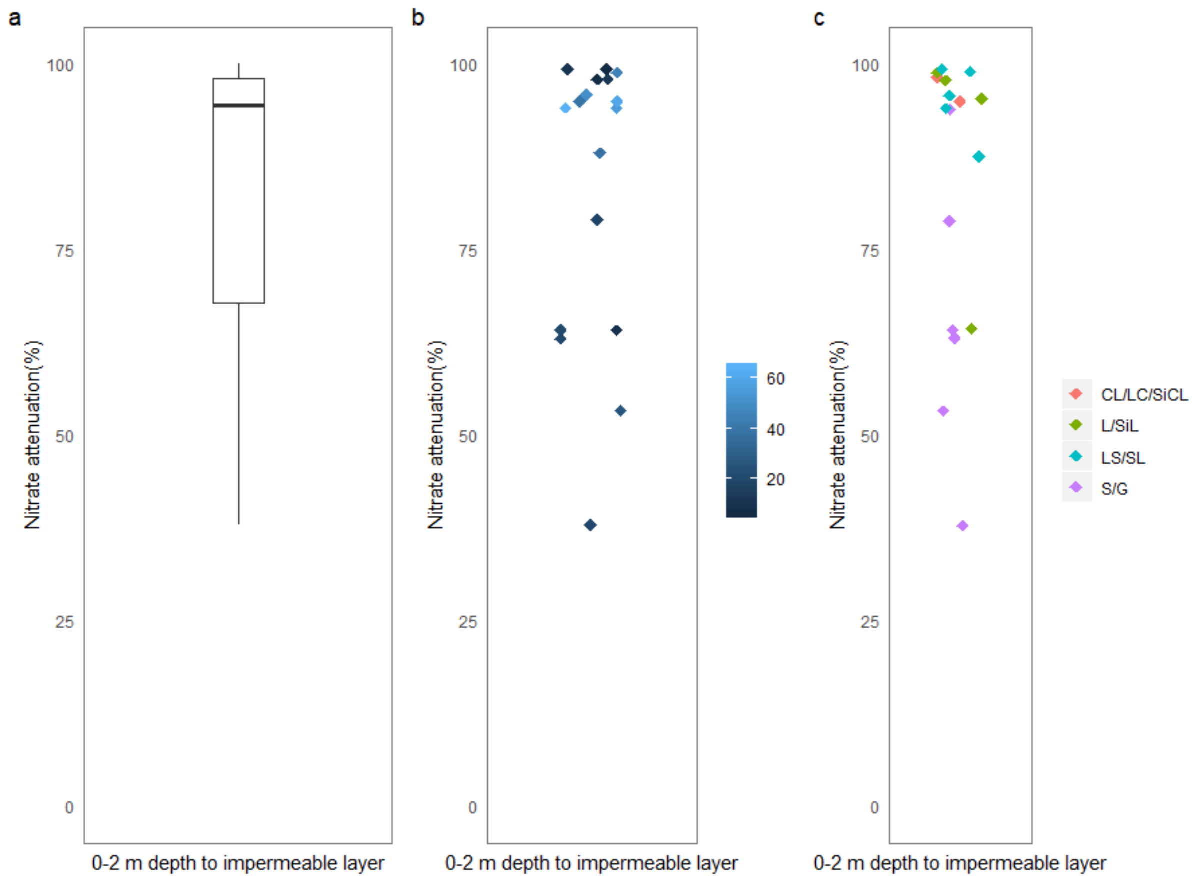


Figure 21: Performance guidelines for nitrate removal from subsurface flow in soils with a shallow (<2m) impermeable horizon. (a) boxplot summary, box contains the 25th to 75th percentiles and median is the dark line, (b) data values with colour gradation of buffer width (m) and (c) data values coloured by soil texture group (S/G = sand/gravel, LS/SL = loamy sand/sandy loam, L/SiL = loam/silt loam, CL,LC,SiCl=clay loam/loamy clay/silty clay loam).

Width is not a strong explanatory variable to nitrate removal from subsurface flowpaths (Figure 12 n). Despite this we are required to provide some guidance on width. We calculated nitrate attenuation (%) per metre width of buffer (Figure 22) and for the 0-2 m depth to impermeable class the median was 2.6%/m width (range 1.5 and 16.5 %/m). We are not including this information in the guidelines as removal occurred in hotspots in many of the studied buffers. In buffers with multiple piezometers in transects hotspots of removal sometimes occurred at the buffer edge, while in others the hotspots are mid-buffer.

We use a pragmatic approach by including the range of buffer widths (Figure 21 b) used for the guidelines. We also use the guidance of Parkyn et al. (2000) on self-sustaining riparian buffers. Parkyn et al. (2000) formulated recommendations on riparian buffers widths for aquatic habitat and concluded that:

- 5-6 m wide buffers would require ongoing maintenance to keep them weed free and would only be suitable for small waterways.
- 10 m should result in a low maintenance buffer, with weed infestations on the margin (1-2 m).

- 15-20 m buffer were highly likely to be maintenance free.

Deep rooting plants are valuable features in RBZs designed to remove nitrate from subsurface flow. Deep roots can forage for water and nutrient supplies and can sequester carbon at depth, which provides a source of labile carbon that may facilitate microbial denitrification (see Pierret et al. 2016). Seasonally fluctuating water tables (observed in many RBZs), may facilitate the establishment and development of deeper rooting systems (Xi et al. 2018). Maintaining a mix of vegetation types (trees, shrubs and grasses), species and ages, will provide a range of rooting depths and architectures, litter types and decomposition rates. In addition to providing nutrient mitigation capability, these characteristics also provide aesthetic and biodiversity values.

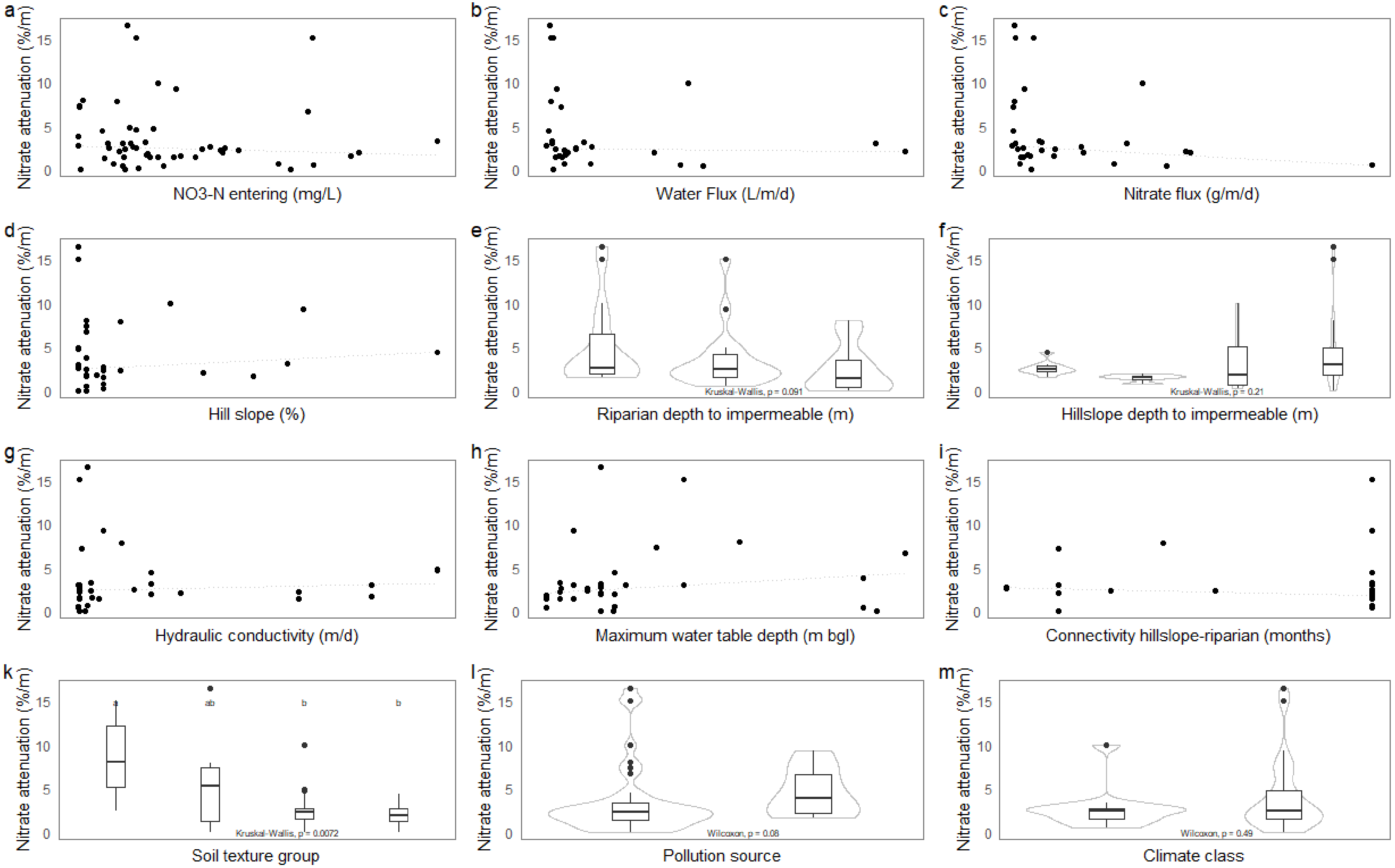


Figure 22: Nitrate attenuation (% attenuation per m buffer width) in subsurface flow in RBZs according to climate class and physical properties. Grey dashed lines on scatterplots are 0.5 quantile regression lines - half of the data is above the line and half below. The box defines the interquartile range with median, the whiskers are the 10 and 90th percentiles, outliers are dots. The violin plots show the data densities - wider zones contain more data points.

5 Conclusion and recommendations

Our systematic review and guideline development has exposed a paucity of New Zealand data on riparian buffer efficacy. By collating international data on annual average removal, we have developed semi-quantitative guidelines for sediment, TN and TP removal from surface runoff and nitrate removal from subsurface flow.

- Our **filter strip guidelines** (developed for soils with <28.5% clay content) suggest that removal of SS in well-designed and maintained filter strips typically ranges from 40-80%. SS attenuation serves as a good surrogate for TN and TP attenuation. Performance data for the latter range from 31-60% TP and 37-72% TN.
  - Landscape and rainfall characteristics may enable surface runoff to bypass or overwhelm filter strips, and lower performance should be anticipated during extreme storm events.
  - Despite ensuring good groundcover and infiltration (which help reduce sediment losses generally), fine-textured soils, particularly clays, are less likely to be removed from surface runoff.
  - Performance of RBZs are likely to be limited by factors such as setback, livestock exclusion and possibly nitrate removal from subsurface flow.
- The **guideline for nitrate removal** from subsurface flow is limited to RBZ with shallow (<2 m) riparian soils underlain by an impermeable layer. This hydrogeologic setting ensures that subsurface flow comes into contact with RBZ soils and plant roots and nitrate removal is likely to be greater than 40%.

Improvement of these guidelines (including better defining the likely performance in complex systems where multiple inter-related processes ultimately determine overall performance) will require further research. Development of these guidelines has enabled us to define how the empirical data required may be obtained, and how these data could be used to develop more effective tools. We have termed these "research opportunities", and identify some of them below:

1. Topographic assessments should be combined with hydrographic data to identify slope thresholds at which concentrated flow occurs, as well as the spatial and temporal prevalence of concentrated flow. This information is required because overland flow is a phenomenon that commonly impairs RBZ performance. Methods could include farmer knowledge, LIDAR and field surveys.

2. Denitrification and plant uptake studies are required to deliver the information required to permit rapid assessment of N removal from subsurface flows across a range of hydrologic and biogeochemical conditions. This is the only realistic way to provide the data required to develop and verify the next generation of guidelines required for New Zealand conditions and farming systems.

3. Examining new research on carbon sequestration in soils may provide useful methods and data that will improve our understanding of rooting depths in RBZs, and the role of plant roots in supplying carbon.

4. There is a general requirement for long-term research to provide the information regarding the processes and performance of filter strips necessary to understand average annual performance, the impact of maturing grass and changing performance with age. This research should include a range of typical RBZs and how they perform when dealing with runoff derived from common crop and pasture practices across a range of climate- and field conditions in New Zealand. This long-term research should also identify the impacts of extreme events on sediment delivery and attenuation.

5. Integration of these data and the processes they describe, at appropriate time scales may only be done using suitable models. Development of verified models will enable better description of the function of RBZs, as well as further development of guidelines such as these. These models will also provide information regarding average annual estimates of performance.

Guidelines (including our accompanying report) are often developed for single contaminant-flowpath pairings. In reality however, each RBZ simultaneously provides some level of efficacy for multiple contaminants and across a range of flowpath conditions. As this review of the literature has shown, the level of efficacy for all contaminants is dependent on multiple inter-related factors, including factors over which the farmer has no control (e.g., season, rainfall, slope, soil type and depth). To ensure that mitigation tools such as riparian buffer zones deliver the water quality outcomes anticipated by farmers, communities and government in a cost-effective manner, tools that address multiple contaminants and tradeoffs across scales are required. These must include appropriate models.

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7 Appendix A – Attenuation plots for TP, DRP, TN and nitrate-N in filter strips

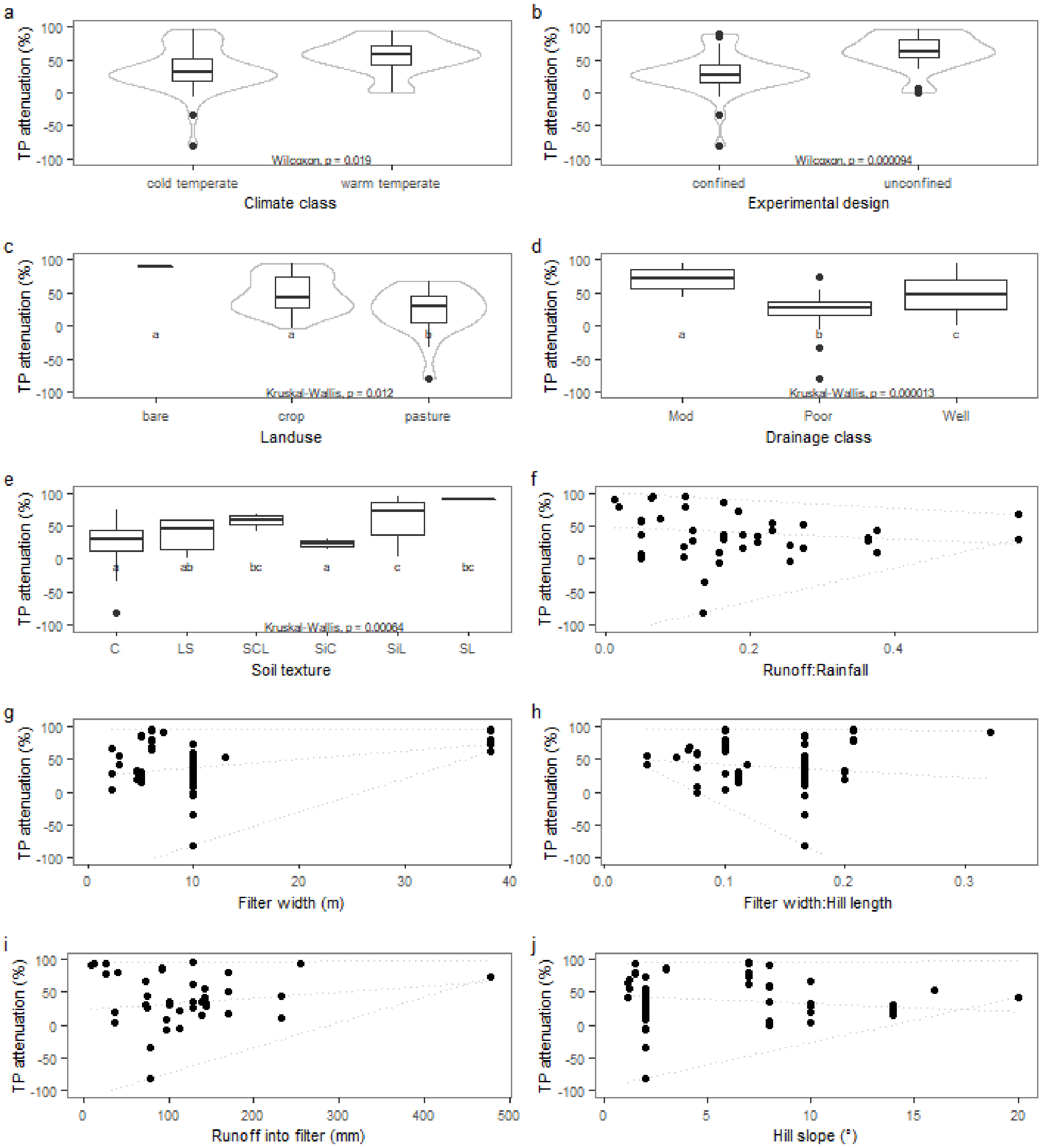

Figure 23: TP in filter strips summary plots for the whole dataset. Grey dashed lines on scatterplots are the 0 (minimum), 50 (median) and 100 (maximum) percent quantiles. n = 100.

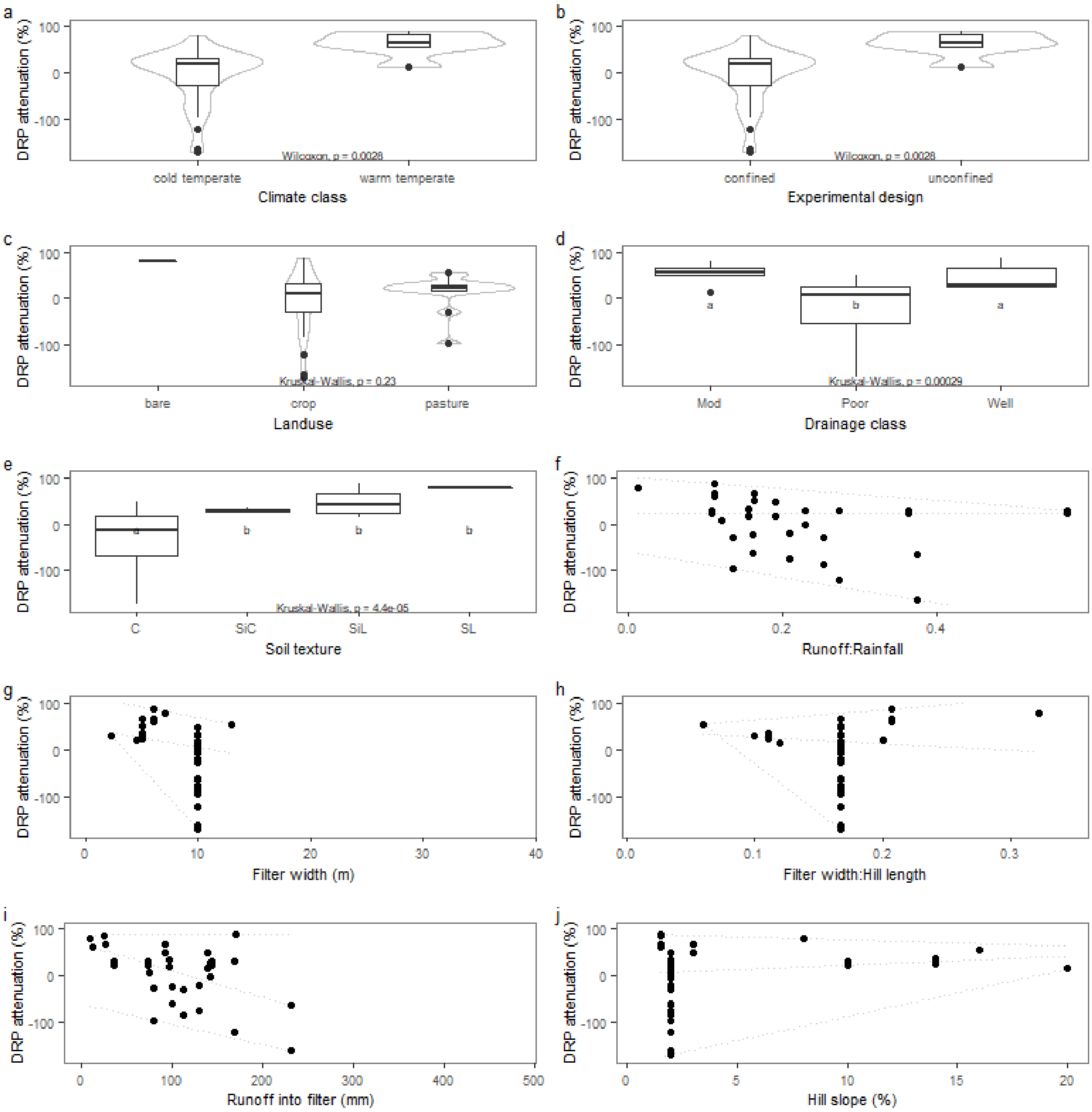

Figure 24: DRP in filter strips summary plots for the adjacent dataset. Grey dashed lines on scatterplots are the 0 (minimum), 50 (median) and 100 (maximum) percent quantiles.

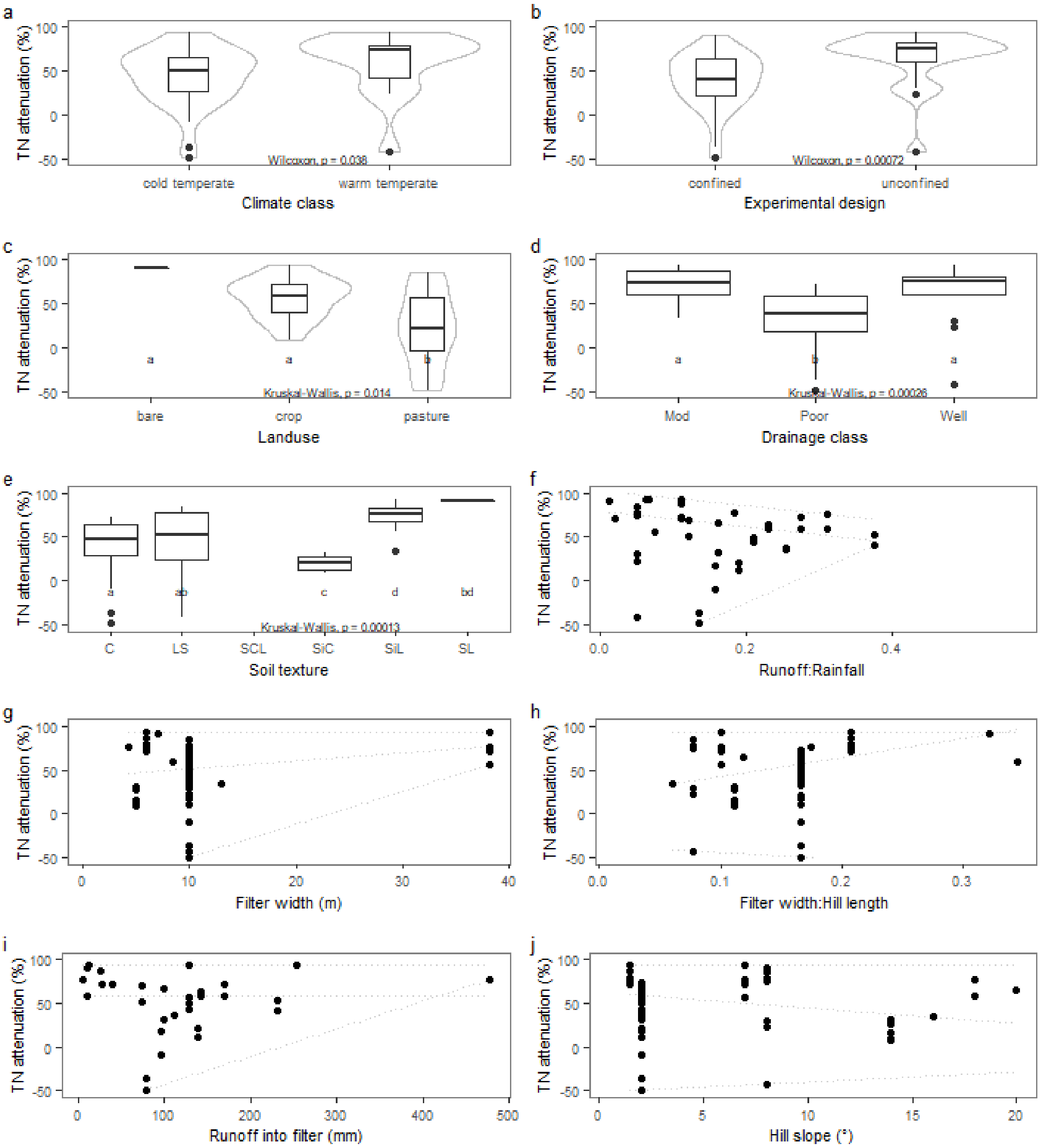

Figure 25: TN in filter strips summary plots. Grey dashed lines on scatterplots are the 0 (minimum), 50 (median) and 100 (maximum) percent quantiles.

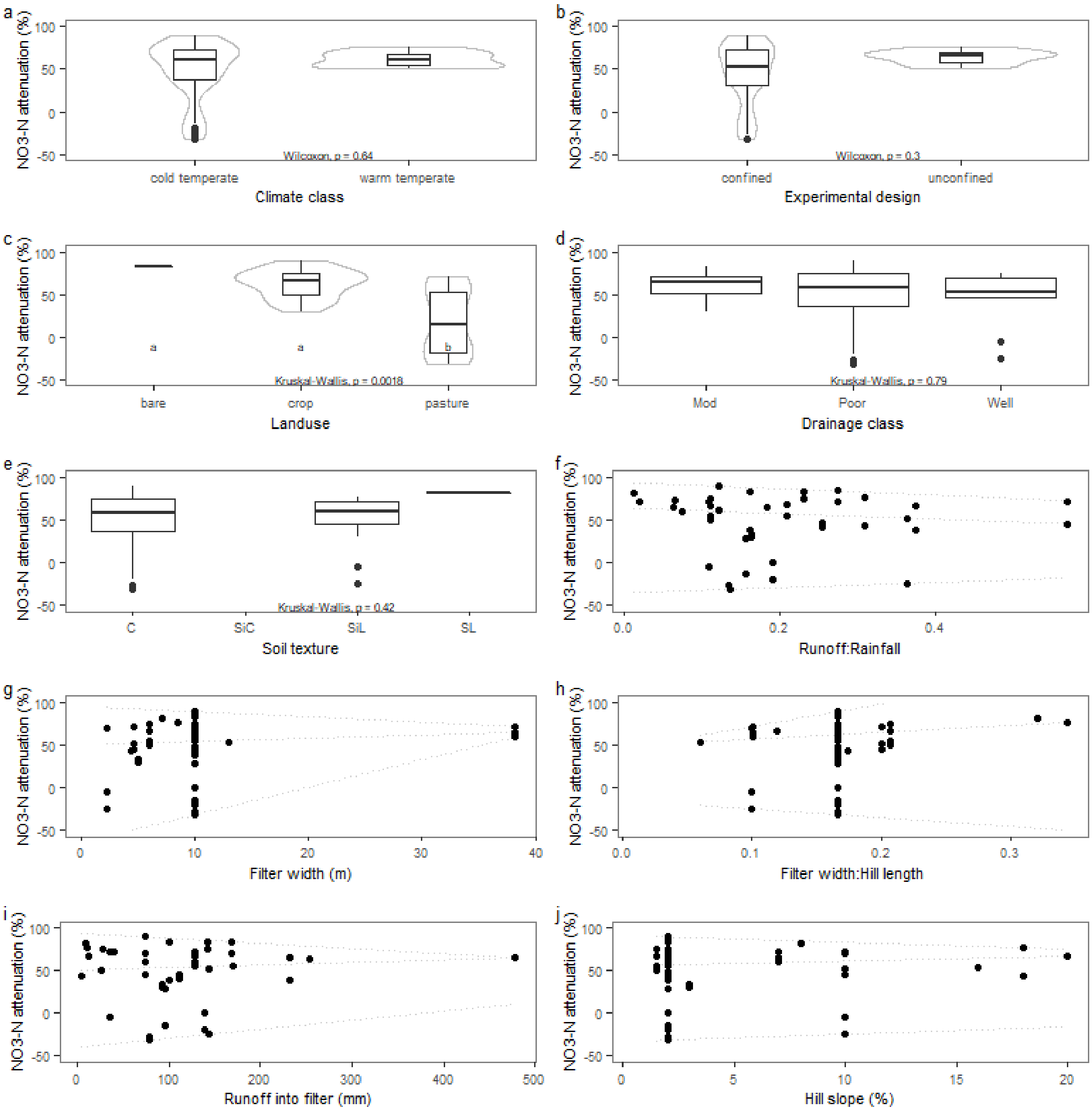

Figure 26: Nitrate in filter strips summary plots for the adjacent dataset. Grey dashed lines on scatterplots are the 0 (minimum), 50 (median) and 100 (maximum) percent quantiles.

8 Appendix B - Guideline plots for filtering surface runoff

"Rules of thumb" were derived using linear regression to estimate TN and TP removal from SS removal data.

An initial linear regression between SS removal and TP removal (n=59) explained ~58% of the variation in the data, but there were two outliers and the residuals did not meet the normality requirement. The model was re-run without the three outliers (n=57) and the final model explains 66% of the variation in the data; residuals are heteroscedastic (Figure 27 a) and the probability plots of standardized residuals show slight departures from normality (Figure 27 b). The p value of the Shapiro Wilk and Anderson Darling normality tests are >0.05 and the standardized residuals are within 2 (Figure 27 b).

The relationship between SS removal and TN removal (n=51) explains 81% of the variation (Table 9) in the relationship. Residuals are heteroscedastic (Figure 28 a) and the probability plots of residuals show slight departures from normality (Figure 28 b). The probability value of both Shapiro Wilk test and Anderson Darling test is > 0.05 for the TN regression so the residual data is normally distributed.

Table 9: "Rule of thumb" regression model summary statistics for SS-TP and SS-TN.

SS-TP linear regression statistics

```
lm(formula = TP_per ~ TSS_per, data = tpss.data)

Residuals:
   Min     1Q Median     3Q    Max 
-32.64 -13.90  -2.06  16.05  35.57 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  5.49427    4.22256   1.301    0.199    
TSS_per      0.72430    0.06933  10.447 1.14e-14 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 17.19 on 55 degrees of freedom
Multiple R-squared:  0.6649,	Adjusted R-squared:  0.6588 
F-statistic: 109.1 on 1 and 55 DF,  p-value: 1.136e-14

Shapiro-Wilk normality test: W = 0.96869, p-value = 0.1458
Anderson-Darling normality test: A = 0.60788, p-value = 0.1089
```

SS-TN linear regression statistics

```
lm(formula = TN_per ~ TSS_per, data = tnss.data)

Residuals:
    Min      1Q  Median      3Q     Max 
-44.543  -9.315   1.728   7.516  43.702 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  3.08441    3.67164    0.84    0.405    
TSS_per      0.85971    0.05866   14.65   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 14.84 on 49 degrees of freedom
Multiple R-squared:  0.8142,	Adjusted R-squared:  0.8104 
F-statistic: 214.8 on 1 and 49 DF,  p-value: < 2.2e-16

Shapiro-Wilk normality test: W = 0.97129, p-value = 0.2501
Anderson-Darling normality test: A = 0.49741, p-value = 0.2027
```

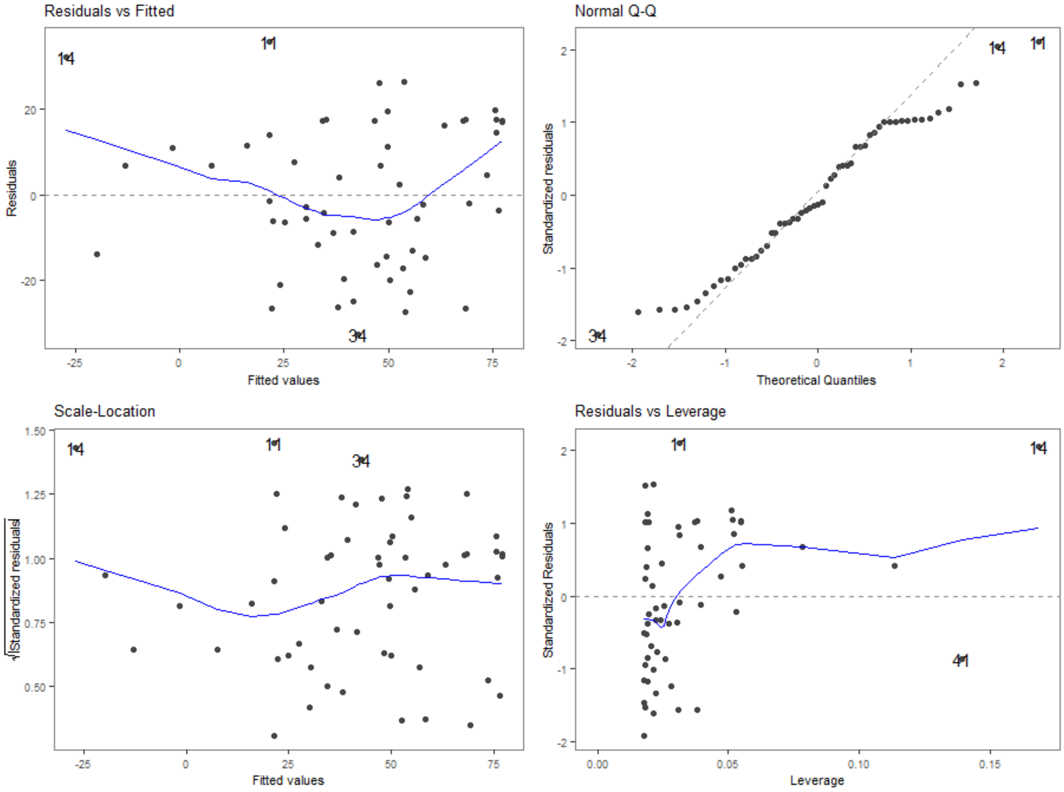

Figure 27: Residual plots for "Rule of thumb" TP attenuation

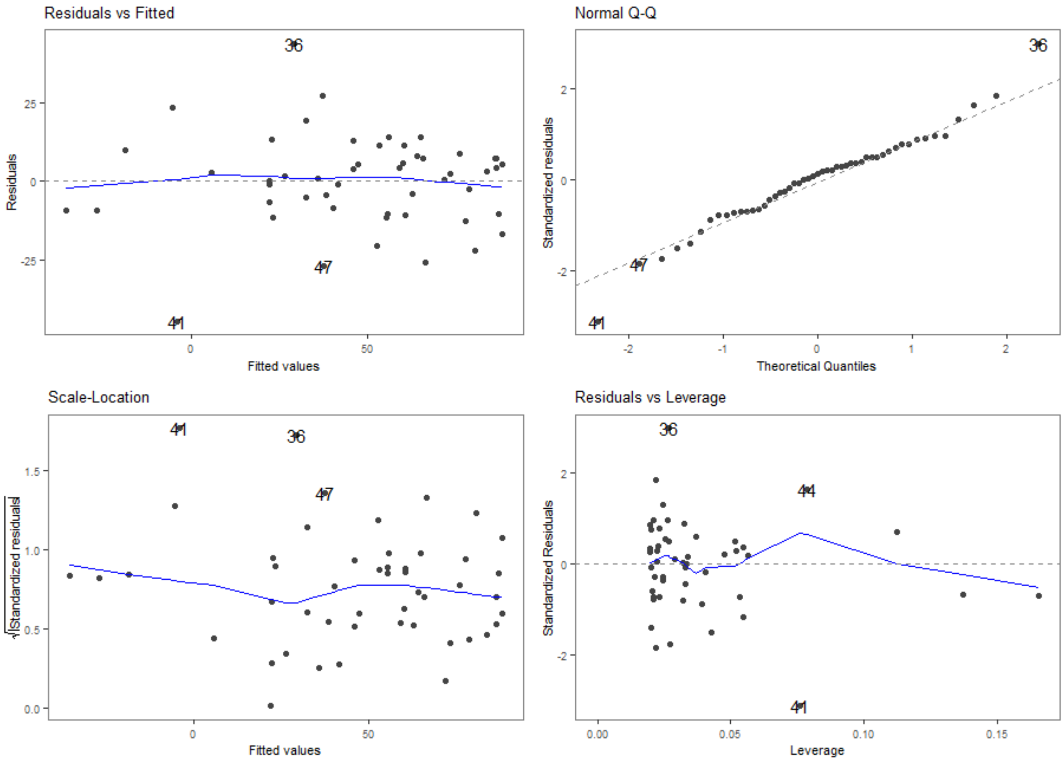

Figure 28: Residual plots for "Rule of thumb" TN attenuation