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Assessment of Strategies to Mitigate the Impact or Loss of Contaminants from Agricultural Land to Fresh Waters

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Assessment of Strategies to Mitigate the Impact or Loss of Contaminants from Agricultural Land to Fresh Waters

Report prepared for MfE

June 2013

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1. Background

Freshwater management in New Zealand is going through its most comprehensive reform in a generation. Advice on reform has been sought from the Land and Water Forum, which included representatives of primary industry, electricity generators, recreational groups, environmental organisations, and iwi, with active observers from regional councils and central government. Consistent with the Forum's advice, the National Policy Statement for Freshwater Management 2011 (NPS-FM; MfE, 2011) was introduced. The NPS-FM provides central government direction to regional councils on water management. In summary, the NPS-FM requires that regional councils:

- state management objectives for waterbodies that reflect national and local needs;
- ensure objectives are achieved by setting flow, allocation and water quality limits;
- efficiently allocate resources to users within those limits;
- avoid over-allocation and address existing over-allocation;
- manage land use and water in an integrated way; and
- involve iwi and hapū in freshwater decision-making and planning.

The NPS-FM also includes a provision that gives regional councils the choice of either completing implementation of the NPS-FM by 31 December 2014, or if the council considers this impracticable, completing implementation as promptly as is reasonable in the circumstances and by no later than 31 December 2030.

The Government released its proposals for freshwater reform in March 2013. The document *Freshwater reforms 2013 and beyond* (MfE, 2013) proposed covering: 1) planning as a community; 2) the National Objectives Framework; and 3) managing within quality and quantity limits. The reforms are focussed on advancing the Government's Business Growth Agenda (MBIE, 2013) within environmental constraints.

Over the past 30 years a great deal of research has been conducted to quantify the processes, transformations and effects of contaminant loss from land to water (e.g. Di and Cameron, 2007; McDowell et al., 2004). A similar effort has been expended in designing strategies (which include technologies and better management practices) to mitigate either contaminant losses or their effects on fresh water (e.g. McDowell and Nash, 2012; Monaghan et al., 2007). This report compiles a list of current mitigation strategies available in New Zealand and provides a quantitative commentary on their relative cost-effectiveness and some context in their likely use or variability in contributing to the NPS-FM's requirement to maintain or improve fresh water quality.

2. Introduction

2.1 Variability

Agriculture emits significant amounts of nutrients, notably nitrogen (N) and phosphorus (P), faecal matter and sediment to New Zealand waterways (Howard-Williams et al., 2011). Whilst the N and P emissions may not be large by agronomic standards, the transfer of these pollutants from land to water can result in significant water quality impairment (Sorrell and Elliott, 2002; Monaghan et al., 2008; Howard-Williams et al. 2011). The proportions of N and P entering New Zealand streams and rivers, and coastal waters, from different land uses are shown in Tables 1 and 2 (Elliot et al., 2005).

Table 1. Proportions of New Zealand land area and total nitrogen (TN) load by source type. The loads have been estimated using the SPARROW model and exclude point sources discharging directly to the coast (from Elliott et al., 2005).

Source type	Load entering streams	Load to coast	Land use area
Fraction of total			
Point source	1.8%	3.2%	–
Dairy	37.8%	36.7%	6.8%
Forestry	19.7%	24.8%	39.2%
Sheep+beef	38.9%	33.3%	31.9%
Other non-pasture	1.8%	2.1%	22.1%
Total	373,900 t yr^{-1}	167,700 t yr^{-1}	263,500 km^2

Pastoral agriculture on steep, erosion-prone land and mobilisation of sediment stores deposited during deforestation are major sources of sediment to aquatic ecosystems (Elliott and Basher, 2011). Faecal matter inputs to New Zealand waterways are predominantly from pasture, with surface runoff, cattle crossings and drains being major sources (Wilcock, 2006). Mitigating these losses presents a challenge because of the diversity of geographical conditions (*viz*. climate, soils and slopes), and farming practices that vary between regions. Thus, mitigation methods for decreasing agricultural pollution of water bodies must take into account both natural and anthropogenic causes of variability and their respective proportions (McDowell et al., 2013).

Table 2: Proportions of New Zealand land area and total phosphorus (TP) load by source type. The loads have been estimated using the SPARROW model and exclude point sources discharging directly to the coast (from Elliott et al. 2005).

Source type	**Load entering streams**	**Load to coast**	**Land use area**
Fraction of total			
Point source	1.2%	1.8%	–
Dairy	9.9%	8.4%	6.8%
Sheep+beef	21.9%	17.0%	31.9%
Non-pasture	17.7%	19.5%	61.2%
Unknown sediment	49.3%	53.2%	–
Total	143,403 t yr^{-1}	63,057 t yr^{-1}	263,500 km^2

2.2 Natural variations

Mitigation methods are mostly based on natural processes to remove targeted contaminants and fall into three classes: (i) land-based treatment of contaminants at source, (ii) interception of contaminants along hydrological pathways, and (iii) bottom-of-catchment methods that treat contaminants within receiving waters. Each mitigation method will perform differently and vary in efficacy according to its location and the contaminant loading; at annual and seasonal time scales. The natural physical features (geography) of each location will differ spatially and temporally (Figure 1). For example, vegetated buffer strips used for intercepting and decreasing the loss of particulate contaminants have different treatment efficiencies according to the land slope, vegetative cover, seasonality and intensity and volume of rainfall, and soil drainage properties (Collins et al., 2005). Between-year and seasonal variations in rainfall affect both the amount and timing of surface runoff and mobilised particulate material and hence, the efficiency of buffer strips. The degree of slope will govern the buffer strip width required for a given trapping efficiency. Thus, a vegetated buffer strip of constant 5 m width will vary spatially in its efficiency for removing sediment, particulate P and *E. coli*, as the slope of the land varies (Collier et al., 1995).

Mitigation methods may also be classified according to their scale of operation, as being either farm-scale (e.g. stock bridges across streams and restricted grazing of winter forage crops), or catchment-scale (e.g. lower catchment wetlands, lake sediment capping). New Zealand's changeable weather patterns (e.g. droughts, tropical storms and El Niño/La Niña cycles) affect the timing and amount of runoff and hence the capacity of farm-scale mitigations to remove contaminants. Larger catchment-scale processes are affected by the volumes of water entering or flowing through them. For example, in deep lakes there is limited mixing of the epilimnetic (upper) and hypolimnetic (bottom) waters through the warm stratified period (c. 8-9 consecutive months), but active turbulent mixing occurring during the colder period (3-4 months). River uptake and transformation of contaminants varies according to the size of the river and distance of a given location from the contaminant sources (Alexander et al. 2002). For treatments involving groundwater there may be substantial lag-times. Thus, one part of a catchment may be hydrologically quite responsive, whereas another sub-catchment may have lag-times of up to 100 years (e.g. Lake Rotorua; Morgenstern and Gordon 2006).

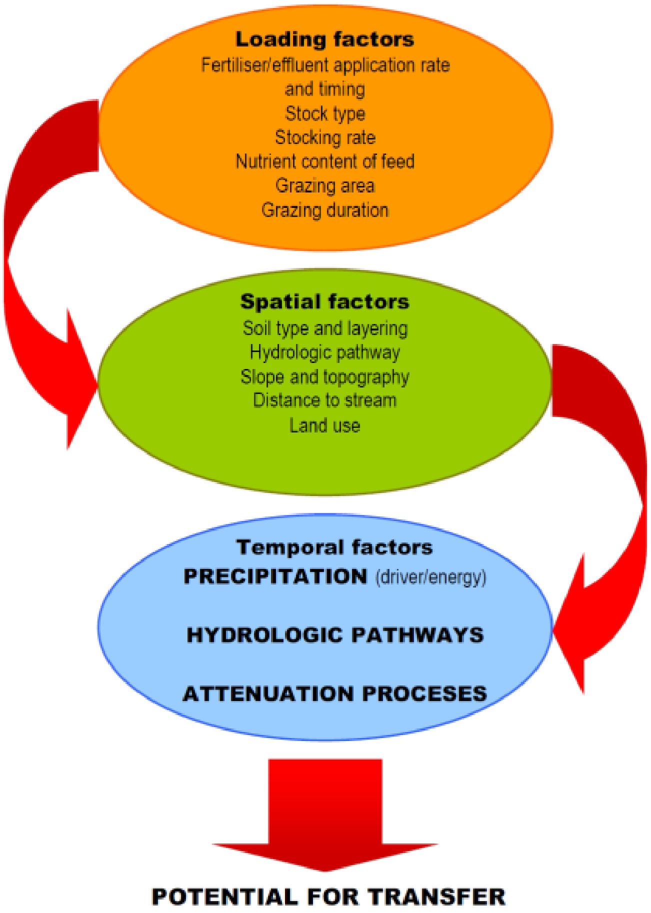

Figure 1. Controls governing pollutant transfer from pasture (from McKergow et al., 2007a).

2.3 Variability in management

Within any given region there will be a range of farming management methods used to achieve profitability. These methods are adapted to local conditions, thereby influencing the effectiveness of mitigation tools and how they interact. For example, the lower fertiliser-P losses arising from the use of low water-solubility products (e.g. reactive phosphate rock) over those in soluble forms (e.g. superphosphate) may leave more in the soil but enhance the effect of vegetated buffer strips to mitigate soil-P in surface runoff. Similarly, differences in the amounts of supplementary feed used on on-paddock in dairy farms will affect production and N leaching losses, and hence, mitigation efficacy.

Temporal variations in management include interannual changes driven by climate or financial conditions. Changes in land use (e.g. dairy conversions or changes in cropping) and irrigation (conversion from dryland to irrigated farming and changes in irrigation method) affect runoff characteristics and thus, mitigation effectiveness. Highly efficient irrigation systems that minimise water use enable more intensive forms of agriculture that may change the timing and nature of contaminant release to water bodies. Border-dyke irrigation systems with low efficiencies emit regular pulses of surface runoff of contaminated runoff, whereas highly efficient sprinkler systems may result in a build-up of nitrate that is only released spasmodically when soils are saturated.

2.4 Catchments and connectivity

Depending on the contaminant, different hydrological pathways may be taken for it to reach a water body. As a consequence, contaminant concentrations are modified and mitigated differently according to the interactions they have with soil, plants and microbes. Particulate contaminants (e.g. fine sediment and associated nutrients like P, and pathogenic microbes in animal dung) are mainly transported in surface runoff or via coarse macropores to shallow groundwater, whereas dissolved contaminants (e.g. nitrate and dissolved reactive phosphorus) are transported via surface and subsurface pathways (Figure 2). Surface and subsurface drains collect shallow surface water at depths within the top 1 m of the soil surface and transport it rapidly to nearby streams, often with very little attenuation (Monaghan et al., 2007). Drain waters pose special problems for surface waters because they often discharge directly into streams without the benefits of attenuation by riparian processes.

Surface water–groundwater interactions are important in pollutant transport and hence, mitigation methods that are based on interception methods (e.g. riparian denitrification walls, amended drainage systems having N and P adsorbents). Groundwater is inherently more difficult to treat and often emerges in surface water at a location that is remote from the source. Accordingly, it is best for mitigation methods to focus on decreasing pollutant loadings prior to drainage occurring, or on decreasing excessive drainage. The connectivity of aquatic systems means that impacts of land use affect downstream waters with varying degrees of resilience, *viz*. lakes and coastal lagoons.

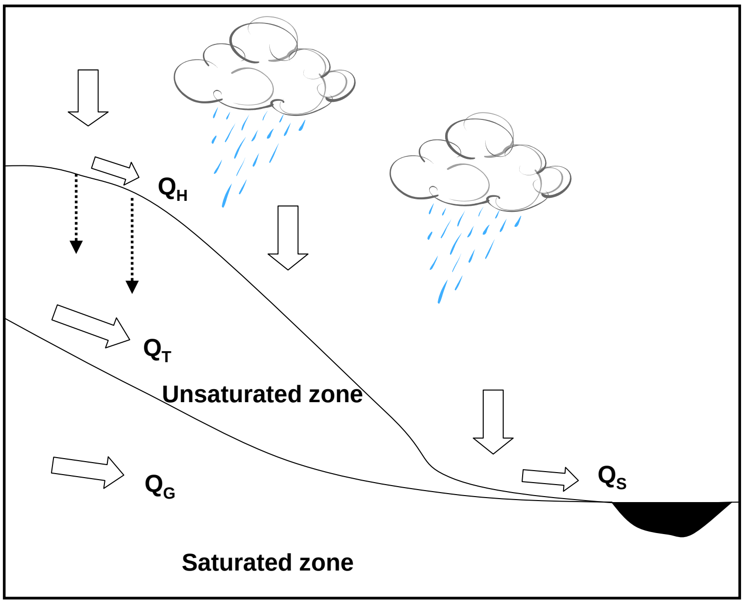

Figure 2. Hydrological processes. Q is flow and the subscripts refer to Hortonian overland flow (H), saturation overland flow (S), throughflow (T) and groundwater flow (G) (modified from Davie, 2004).

2.5 Contaminants

The major water contaminants from agriculture are different forms of N and P, sediment and faecal organisms (usually quantified by the faecal indicator bacteria – *Escherichia coli* [*E. coli*]). Other contaminants of less extensive impact include: oxidisible organic waste, or biochemical oxygen demand (BOD) and pesticides (Table 3). Ammonia in its un-ionised form (NH_3) is highly toxic to aquatic invertebrates and fish and the proportion of NH_3 in ammoniacal-N (NH_4^+) discharges from waste treatment systems increases as pH and temperature rise. Nitrate has recently been found to be toxic to a wide range of aquatic organisms. The current recommended chronic exposure guideline for 95% protection of freshwater species is 2.4 mg N/L (Hickey, 2013). Dissolved inorganic N (DIN) is the sum of ammonia-N and nitrate-N and is a target of many mitigation measures because of its influence in stimulating excessive growth of plants, such as periphyton (Wilcock et al., 2007). A further point to consider is that much of the N entering water bodies is in particulate and dissolved organic forms that are available in the long-term for uptake by plants (Timperley et al. 1985; Parfitt et al. 2006)

Table 3. Point sources and diffuse (non-point) sources of agricultural pollution, and key contaminant indicators.

Pollution source	Pollutant type	Contaminant
Point source		
Surface and subsurface drains	Farm wastes, irrigation water, dairy pond effluent, silage leachate	N, P, sediment, faecal microbes BOD
Industrial discharge	Processing wastes (e.g. abattoir, dairy factory)	BOD, toxic organics, faecal microbes, heat (warm water)
Non-point (diffuse) source		
Surface runoff from agriculture	Particulate pollutants*	P, N, sediment, faecal microbes
Subsurface runoff	Dissolved pollutants**	DIN, DRP
Riparian grazing by livestock (including livestock in channels)	Animal wastes, sediment, reduced streambank stability	Faecal microbes, sediment, N, P
Spray drift	Farm operations	Pesticides, fertiliser

*Surface drains often collect drainage from subsurface drains and hence collect dissolved and particulate pollutants.
**Subsurface drains can convey particulates if there are soil macropores (e.g. soil cracks).

Dissolved reactive phosphorus (DRP) stimulates algae growth at low concentrations. The New Zealand Periphyton Guidelines (Biggs, 2000) have been used to set maximum DRP concentrations to protect aesthetic and recreational values for rivers. Total P and N reflect the sum of the different forms of P and N, and include reactive (bioavailable) forms, and other forms that are not generally immediately bioavailable including dissolved and particulate forms of N and P, and particulate inorganic P.

For lakes the Trophic Level Index (TLI; Burns et al. 2000) has been adopted to indicate trophic state. The TLI grades lakes from “micro-oligotrophic” to “supertrophic” based on surface-water concentrations of total N and P, chlorophyll *a* (indicative of planktonic algae pigment concentrations) and Secci disk (a measure of water clarity).

2.5.1 Limiting nutrients

Excessive periphyton growth on riverbed substrate is a common issue that affects a number of river values, e.g. life-supporting capacity, contact recreation and aesthetics. The New Zealand Periphyton Guidelines (Biggs, 2000) provide some guidance on the acceptable levels of periphyton biomass in relation to protecting different river values and uses. Excessive peak periphyton biomass is dependent on extended periods of stable or low flow, and on the absence of shade from riparian vegetation and low turbidity. Once these conditions are met, the rate of development and peak biomass are most strongly controlled by concentrations of bioavailable N and P in the water. For freshwaters it is common to regard bioavailable N as being DIN, while bioavailable P is taken as being DRP. Both elements are needed for periphyton growth, in an average mass ratio of 7:1 (N:P). In practice, when the DIN:DRP ratio is less than 7, waters are commonly N-limited with respect to periphyton growth. When the ratio is >15 conditions for periphyton growth are commonly P-limited, and ratios of 7-15 may indicate co-limitation by both elements (Wilcock et al. 2007; McDowell et al. 2009). However, it should be noted that these ratios are only to be used as guidelines (i.e. subject to variation) and nutrient limitation should always be confirmed with other techniques such as a bioassay. When both DIN and DRP concentrations are very low (e.g., DIN below 5 parts per billion, DRP below 1 part per billion), then the risk of algal proliferations is low, unless there is a simultaneous discharge of both DIN and DRP into the water body. When both DIN and DRP concentrations are very high (e.g., DIN above 1000 parts per billion or DRP above 50 parts per billion), then N and P availability is probably in excess of algal requirements and increasing the concentration of either nutrient will not elicit a growth response. Under these conditions, light or a different nutrient may limit algal growth and N:P ratios are not informative.

In lakes, concentrations of bioavailable N and P in surface waters can be decreased to very low levels, sometimes below detection limits, and therefore ratios of total N to total P have been used as a more reliable method to indicate potential for nutrient limitation. On average a mass ratio of 7:1 (N:P) should indicate that lake phytoplankton growth is balanced equally by these two nutrients but in practice the ratio varies from 9 to 23 (Oliver et al. 2012). Thus for total N: total P less than 9 it is more likely that N limitation of phytoplankton is prevalent and for total N: total P greater than 23 then P limitation is more likely.

Overall, the limited number of assessments of nutrient limitation in New Zealand freshwater ecosystems has indicated that estuarine systems commonly exhibit N-limitation more than either co-limitation (i.e., N+P) or P-limitation (Larned et al. 2011). In lakes N-limitation and co-limitation occur with greater frequency than P-limitation (Abell et al. 2010; Larned et al. 2011). While in streams and rivers, P-limitation is more common than either co- or N-limitation (McDowell et al., 2009)

Nutrient management is the primary means of mitigating periphyton mats in rivers and phytoplankton growth in lakes and lagoons. Although nutrient ratios may indicate a greater algal response to one nutrient over another, it is quite common to control both N and P in water bodies because of temporal and spatial changes in N:P ratios (Wilcock et al. 2007).

2.5.2 Sediment and faecal microbes

Excessive levels of suspended solids (SS) cause siltation and smothering of river beds that may affect trout reproduction and viability, and may also result in anoxic conditions that preclude sensitive aquatic species, such as mayflies. High SS concentrations reduce visibility and alter the 'visual habitat' (and thus behaviour) of fish and birds, and decrease the amenity value for recreation (Davies-Colley et al. 2003). A black disc visibility of about 1.5 m is sought by most Regional Councils for rivers below median flow. Concentrations of turbidity correlate reasonably well with black disc clarity over a range of flows (Smith et al. 1997). A major reason for mitigating sediment inputs from land to waterways is that a large proportion of P entering natural waters is associated with sediment.

Freshwater faecal pollution is monitored using the usually harmless indicator organism *E. coli* to provide a risk assessment of pathogen infection. New Zealand has a high incidence of Campylobacteriosis by OECD standards, especially in rural areas[1] that is caused by ingestion of the *Campylobacter* bacterium. Other relevant pathogenic organisms of faecal origin are *Salmonella*, *Cryptosporidium*, VTEC/STEC[2] and *Giardia*.

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[1] http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10829263

[2] www.nzpho.org.nz

3. Methods

Information was collated (see Tables 4 and 5) on strategies available in New Zealand to mitigate the loss of contaminants from land to water and within water itself. Two scales of interest were used to define those strategies relevant at a farm and catchment scale. The catchment scale relates to nutrients already within water including where nutrients either enter a lake or are within a lake. Although there are many potential water quality contaminants that may be lost from land (e.g. heavy metals, pesticides etc), our focus was on the four highlighted most often in policy or by the public, namely: nitrogen, phosphorus, sediment and faecal indicator bacteria.

In addition to the authors' knowledge of the field, researchers in Universities and Crown Research Institutes across New Zealand were given the opportunity to provide evidence and commentary on relevant mitigation strategies.

In order to provide a consistent approach across all strategies, the following criteria were strictly applied:

1. The strategy must be published in peer-reviewed literature (grey literature was not accepted), largely from New Zealand or where there are similar agricultural systems (e.g. southeastern Australia) or from countries or ecosystems where the mitigation is likely to perform similarly as in New Zealand. The exception to this was for catchment mitigation strategies where much of the technology has been applied in New Zealand only within the last five years, and the subsequent documentation has not yet been peer reviewed. If so, literature from overseas has been used to describe the wide range of nutrient mitigation strategies;
2. Published data was used wherever possible to define a range for cost-effectiveness;
3. Its relevance to different farming enterprises must be known; and
4. The mode of action and reasons for variability (e.g. soil type, climate) can be succinctly, and simply, described.

Additional commentary on the likelihood of uptake and co-benefits (within or outside the field of water quality) was invited on the understanding that this information is qualitative and may not be proven.

Although our approach is consistent, it has clear drawbacks such as: the exclusion of new, but unpublished, data from the synthesis of farm mitigation technologies; or the failure to capture the full range of costs or effectiveness for a strategy under different variables (e.g. soil type or climate, lake mixing regime). Hence, where mechanistic models are available to estimate the effectiveness and cost of particular strategy (e.g. Overseer$^{®}$) they should be used to inform decisions before using our estimates. However, the majority of strategies outlined in this report are not captured within current modelling frameworks.

In the case of catchment mitigation technologies, cost and effectiveness could only be broadly approximated. For example, in contrast to farm-scale strategies, most catchment mitigation strategies leave nutrients within the water body, inactivating them through chemical adsorption and precipitation processes, and sedimentation (e.g. through flocculation, floating wetlands, discing, destratification or oxygenation). One potential strategy to mitigate poor water quality in lakes, not listed in Table 5, is to increase flushing rates (Howard-Williams, 1987). The increase in flushing rate is achieved by more discharge to the lake, which may increase nutrient load to the lake. Cost-effectiveness on the basis of $ per kg of N (for example) removed is therefore problematic. Instead, costs are given on an areal basis ($ per hectare in, for example, a lake) and percentage effectiveness is evaluated relative to the most expensive (100%) mitigation strategy.

For catchment mitigation technologies, we included only those mitigations that were specific to nutrient control and not other mitigations that addressed symptoms of excess nutrients such as algal blooms. Excluded were well-established techniques such as algaecides (e.g., copper sulphate; Steffensen 2008) and other less well-proven technologies for algae control such as dyes for shading planktonic algae (Ludwig et al. 2010), ultrasonic or UV irradiation to lyse algae cells (Rajasekhar et al. 2012), and barley straw (e.g. Everall and Lees 1997) and additions of bacteria (e.g. Peng et al. 2003) to inhibit algae growth or break down cell walls. We also excluded biomanipulation because its association with nutrient mitigation is tenuous. However, we also note that in shallow lakes, submerged macrophyte weed beds, when present at moderate to high densities, tend to suppress growth of planktonic algae and may confer some degree of resilience to increases in incoming nutrient and sediment loads (Schallenberg and Sorrell 2009). Furthermore, other biomanipulation techniques such as seeding of mussels (*Hyridella menziesi*; Ogilvie and Mitchell 1995), planktivorous fish such as silver carp (e.g. Ma et al. 2012), and filter-feeding zooplankton may be beneficial in decreasing the effect of nutrients. There is some evidence to suggest that recent unintentional introductions of large-bodied herbivorous zooplankton may now exert some control on planktonic algae populations in some New Zealand lakes (Balvert and Duggan 2009).

Information on the range of cost-effectiveness ($ per kg of nutrient or sediment retained per hectare) and percentage effectiveness were used to rank farm mitigation strategies within a contaminant and categorised into quartiles (low, medium, high and very high). The output is presented in Tables 4 and 5 and in a matrix for each contaminant showing the range of cost (e.g. per kg of N retained relative to the most costly strategy; y-axis) and effectiveness (x-axis) (Figures 3 to 5). It is recognised that categorization into quartiles could, depending on the number of strategies, lead to some strategies that the reader may interpret as mis-categorized. The two metrics are given to the reader to aid a decision on whether or not to mitigate purely on cost-effectiveness or to promote a few strategies that are highly effective, quick or require little labour/maintenance. The reader should also note that those strategies listed in Tables 4 and 5 represent only those that are currently published, there are many more in various stages of development that may come “on-line” in 2-10 years time.

This method is counter to the objective of other land-based nutrient mitigation technologies to reduce sediment and nutrient loads. This example demonstrates why it is difficult to adopt a cost-effectiveness matrix similar to that for farm-based mitigation technologies (Figures 3 to 5) in the case of catchment-scale technologies. On the other hand, given that dredging and weed harvesting remove nutrients from a lake, a similar approach to the farm-based mitigation technologies may be applicable in these cases. In general terms, however, we consider that costs for catchment-wide technologies may be best quantified on a per unit area basis.

4. Detailed tables of strategies

Table 4. Information applicable to the application of farm-scale technologies (strategies) to mitigate the loss of water quality contaminants to water.

Target	Range of applications	Strategy	Description of function	Lead research agency	Effective-ness	Relative cost[1]	Reasons for variability	Factors limiting uptake	Co-benefits	References
Multiple	All farming enterprises	Bridging stock stream crossings	Avoid direct entry of faeces, urine and entrained hoof mud, and substrate disturbance during stream crossings	NIWA	Low [N]; Low [SS]; Medium [*E. coli*]	Medium [N]; Medium [SS]; Medium [*E. coli*]	Highly dependent on stream length, width and number of crossings per farm.	Too many crossings	Avoiding stock losses in high flows.	Davies-Colley et al. (2004); Nagels et al. (2011)
Multiple	All farming enterprises	Constructed wetlands	Modification of landscape features such as depressions and gullies to form wetlands. Slow water movement encourages deposition of suspended sediment and entrained contaminants (e.g. P). Compared to many natural wetlands, constructed wetlands can be designed to remove contaminants from waterways by: 1) decreasing flow rates and increasing contact with vegetation – thereby encouraging sedimentation; 2) improving contact between inflowing water, sediment and biofilms to encourage contaminant uptake and sorption; and 3) creating anoxic and aerobic zones to encourage bacterial nitrogen processing, particularly denitrification loss to the atmosphere. Performance varies depending on wetland size and configuration, hydrological regime, and contaminant type and form. An adaptation has seen the inclusion of floating wetlands (emergent wetland plants grown hydroponically on floating mats) to remove significant quantities of dissolved P from artificial urban stormwater compared to unplanted mats. However, it is also noted that while the regular harvesting and removal of plants growing on wetland sediments may increase P removal from the wetland, unless the biomass has an economic value, harvesting is not a cost-effective strategy. Although relatively easy to construct and maintain, constructed wetlands also remove land from production, which impairs their cost-effectiveness.	NIWA	Very high [N]; Medium [P]; High [SS]	High [N]; Very high [P]; Medium [SS]	Wetland performance depends on intercepting the maximum amount of run-off from the catchment at the right flow rate.	No suitable areas on farm (i.e. catchment lies outside of farm area).	Flood attenuation, wildlife habitat and biodiversity	Headley and Tanner (2007); McKergow et al. (2007a); Tanner et al. (2005).
Multiple	All farming enterprises	Natural seepage wetlands	Natural seepage wetlands at the heads and sides of streams, commonly known as seeps, flushes, valley bottom or riparian wetlands. Wetlands slow water movement through them and encourage the deposition of suspended sediment and entrained contaminants (e.g. P). Wetlands, depending on factors such as loading rates and layout, can be sinks or sources of P. The retention of particulate bound P is usually large via sediment deposition. However, with time the ability of wetlands to retain particulate bound P decreases as the wetland becomes choked with sediment. Furthermore, as the wetland becomes reductive (anoxic) P in sediment becomes soluble, resulting in dissolved P release. The lifespan of natural seepage wetlands therefore depends on where they are located in the catchment. Locating them in places to optimize the retention of particulate bound P, together with the planting and harvesting of wetland plants may enhance their P retention.	NIWA	Very high [N]; Low [P]; High [SS]	Very high [N]; Very high [P]; Very high [SS]	Wetlands have diverse characteristics and intercept differing proportions of run-off depending on landscape, hydrogeology and human modification. Some evidence suggests that the water quality of shallow wetlands can be significantly affected by livestock access, but deeper (>0.4m) wetlands subject to less livestock incursion are not.	Price of permanent fencing >> temporary fencing.	Flood attenuation, wildlife habitat and biodiversity	Hughes et al. (2013); McKergow et al. (2007a; 2012); Nguyen et al. (1999)
Multiple	All farming enterprises	Sediment traps	Stock pond or earth reservoir constructed at natural outlet of zero-order catchment. In-stream sediment traps are useful for the retention of coarse sized sediment and sediment-associated N and P, but do little to retain N and P bound to fine sediment. As the P sorptive capacity of fine particles is much greater than coarse particles (w/w basis), sediment traps can be ineffective at decreasing P loss if the soil in finely textured and/or surface runoff is dominated by fines.	AgResearch, Landcare Research, Plant and Food, NIWA	Low [P]; Very high [SS]; Low [*E. coli*]	Very high [P]; Very high [SS]; Very high [*E. coli*]	Although design can be modified to maximise removal via settling, traps are ineffective at high flows when most sediment is transported	May require resource consent	Potential to buffer storm events and therefore potential downstream flooding.	Hicks DL (1995); Hudson (2002); McDowell et al. (2006)

Target	Range of applications	Strategy	Description of function	Lead research agency	Effective-ness	Relative cost[1]	Reasons for variability	Factors limiting uptake	Co-benefits	References
Multiple	All farming enterprises	Stream fencing	Preventing livestock access to stream, decreases stream bank damage (and sediment inputs via bank erosion) bed disturbance of sediments (and entrained *E. coli*, N and P) and stops the direct deposition of excreta into streams.	AgResearch	High [P]; Low [SS]; High [*E. coli*]	Low [P]; Medium [SS]; High [*E. coli*]	Gain is dependent on the area of the farm currently unfenced and stream density.	Price of permanent fencing >> temporary fencing.	Stream shading decreasing water temperature and light for periphyton and macrophyte growth.	Hicks DL (1995); James et al. (2007); McDowell (2007); Line et al. (2002); McDowell et al. (2006); McKergow et al. (2007b); Muirhead et al. (2011); Muirhead (2013).
Multiple	All farming enterprises	Vegetated buffer strips	Vegetated buffer strips work to decrease contaminant loss in surface runoff by a combination of filtration, deposition, and improving infiltration. The upslope edge of the strip is where most large particles and particulates (sediment and entrained N, P and *E. coli*) are filtered-out, and the speed of surface runoff slows enough that deposition occurs. If the hydrology allows, a more important mechanism that decreases contaminant loss is infiltration (i.e. there is no water for transport overland into streams). This deposits of particulate material onto the soil surface or vegetation and increases the interaction and sorption of dissolved P with the soil.	NIWA, AgResearch	High [P]; High [SS]; Low [*E. coli*]	High [P]; High [SS]; Very high [*E. coli*]	Buffer strips do have major flaws: 1) the strip can quickly become clogged with sediment; 2) they function poorly in areas that are often saturated due to limited infiltration; 3) they function best under sheet flow, whereas most surface runoff tends to converge into small channels that can bypass or inundate strips; and, 4) grassed buffer strips function best when the number of tillers is greatest, which generally occurs where biomass is harvested (i.e. under grazing).	Land adjacent to stream may not be available or suitable for a buffer strip.	Potential to stabilise stream banks.	Longhurst (2009); McKergow et al. (2007a,b;); Redding et al. (2008); Smith (1989)
Multiple	All farming enterprises with forage crops	Restricted grazing of winter forage crops	Winter grazing of a forage crop leads to large losses of N in drainage and P, sediment and E. coli in surface runoff. Restricting the time spent grazing a forage crop to 3-4 hrs so animals get maintenance feed requirements can decrease losses via erosion and excretal deposition compared to plots where animals are left in-situ.	AgResearch	High [P]; Medium [SS]	Medium [P]; Low [SS]	See above.	Must be accompanied by a stand-off area that has no connection to a waterway (e.g. runoff/effluent is captured).	Decreased soil and pasture damage caused by animal treading will help increase pasture yields and decrease N_2O emissions and denitrification rates.	McDowell and Houlbrooke (2009); McDowell et al. (2003; 2005)
Multiple	Dairy	Greater effluent pond storage and deferred irrigation	The risk of waterway contamination via land application of farm dairy effluent (FDE, otherwise known as dairy shed effluent) is high on soils with a propensity for preferential flow, rapid drainage via artificial drainage or coarse structure, or surface runoff via an infiltration or drainage impediment or application to rolling/sloping land. Deferred irrigation, which involves storing FDE in ponds when soil moisture is close to or at field capacity and applying FDE to land otherwise, has proven effective at decreasing N, P and *E. coli* losses.	AgResearch, Massey University, Landcare Research, DairyNZ; Aqualinc	Medium [N]; Medium [P]; Medium [*E. coli*]	Medium [N]; Low [P]; Medium [*E. coli*]	Depends on the number of cows, size of pond required, material and suitable location to build a pond. Inaccurate pond size can result in applications during wet periods and N and P losses. Differs with soil types and drainage status.	The requirement for storage is dictated by local climate and if too wet may make practice unrealistic.	Added water and carbon during summer and decreased (but unquantified) *E. coli* losses. Land treatment of dairy effluent culturally favoured over direct pond discharge to streams.	Houlbrooke et al. (2004); Houlbrooke et al. (2008); McDowell et al. (2005); Muirhead et al. (2011); Muirhead (2013).
Multiple	Dairy	Greater effluent pond storage and low rate effluent application to land	Coupling pond storage with low rates of effluent application can decrease P loss by minimising the potential for surface runoff and sub-surface losses via preferential flow. Some research has also shown low-rate application to be somewhat effective at decreasing P losses in sump-and-spray systems compared to a travelling irrigator.	AgResearch, Massey University, Landcare Research, DairyNZ	Medium [N]; High [P]; Medium [*E. coli*]	High [N]; Low [P]; Medium [*E. coli*]	The requirement for solid separation (using low-rate sprinklers) and degree of existing infrastructure that is already suitable (i.e. block size and mainline/hydrant layout). Difference soil types and drainage status.	Increased labour requirements compared to travelling irrigator.	Added water and carbon during summer and decreased (but unquantified) *E. coli* losses. Land treatment of dairy effluent culturally favoured over direct pond discharge to streams.	Monaghan et al. (2010); Houlbrooke et al. (2006); Muirhead et al. (2011); Muirhead (2013).

Target	Range of applications	Strategy	Description of function	Lead research agency	Effective-ness	Relative cost[1]	Reasons for variability	Factors limiting uptake	Co-benefits	References
Multiple	Dairy, piggery effluent manage-ment	Enhanced Pond Systems	Enhanced Pond Systems are an option for on-farm effluent treatment prior to land application. The system is designed for both effluent treatment and resource recovery and consists of four types of ponds: 1) Covered Anaerobic Ponds to remove and digest organic suspended solids to methane-rich biogas for energy recovery and reduced GHG emissions; 2) High Rate Algal Ponds for nitrogen and phosphorus removal and recovery as algal biomass; 3) Algae Harvest Ponds for removal of algae for beneficial use (fertiliser, feed, biogas); and 4) Maturation Ponds for further removal of faecal contaminants indicated by *E.coli*.	NIWA	Very high [N]; High [P]; Very high [*E. coli*]	Very high [N]; Very high [P]; Very high [SS]; Very high [*E. coli*]	Removal efficiency varies seasonally so designed for winter performance specifications and have higher performance in summer.	Requires substantial land area (10 to 40 m2/cow)	Energy recovery / production. Separation of effluent nutrient application from hydraulic application. Beneficial use of algae for biofuel and fertiliser or feed.	Craggs et al. (2012); Park and Craggs (2001); Craggs et al. 2008; Craggs et al. (2004); Craggs et al. (2003)
Multiple	Dairy	Restricted grazing and off pasture animal confinement systems	In fully or partially grazed systems, a strategy for minimising N, P, sediment and *E. coli* losses is to avoid deposition of urine and faeces or soil disturbance during periods of high loss risk (especially in spring and late autumn where soils are wet and growth is poor), by either removing the animals from pasture at certain times or by extending the existing housing period. Measurement and modelling of these "restricted grazing" strategies have been shown to decrease N leaching losses and surface runoff losses of P, *E. coli* and sediment. The size of these decreases depends on the duration and timing of the restricted grazing period. Disproportionately greater benefits were observed if grazing was restricted shortly preceding or during periods when losses were likely i.e. when drainage or runoff was occurring. Stand-off pads (preferably covered), herd shelters and wintering barns are some of the infrastructure options that are required for an off-pasture animal confinement system to work effectively.	AgResearch, Massey University, DairyNZ	High [N]; Medium [P]; Low [SS]	Medium [N]; Medium [P]; Very high [SS]	Costs vary widely due to variations in soil type and climate, and on the frequency of use of a restricted grazing strategy. For farms on heavy soil types and in wet locations where standing animals off-paddock is desirable, a small or nil net cost might be assumed. For dairy farms on well-drained soil types with minimal risk of soil treading damage, significant cost might be incurred.	High capital and operational costs and increased management complexity; immature design criteria and management systems that meet animal welfare and manure management requirements; and some risk of 'pollution swapping' by increasing NH_3 or N_2O emissions from the collected effluent and manures.	Decreased soil and pasture damage caused by animal treading will help increase pasture yields and decrease N_2O emissions and denitrification rates.	Cardenas et al. (2011); Christensen et al. (2012); de Klein et al. (2006); Ledgard et al. (2006)
Multiple	Deer	Alternative wallowing	Red deer will use or create areas for wallowing. The wallows are often directly connected to streams thereby providing a direct conduit for excreta deposited and the bed sediment disturbed during wallowing. A solution sees the fencing off or existing connected wallows and the creation of a wallow that is not connected to a stream.	AgResearch	Medium [N]; Very high [P]; High [SS]	Very high [N]; Medium [P]; Low [SS]	Poor performance could occur if runoff from alternative wallow reaches stream in large storms.	There must be an area close by that is suitable for an artificial wallow.	Allowance for natural behaviour may decrease stress (unquantified).	McDowell (2008b; 2009)
Multiple	Deer	Preventing fence-line pacing	This strategy is specifically for red deer who have a tendency to pace and erode fence-lines when stressed, for example, when feed is low or near calving. The strategy involves a combination of tree planting to provide shelter and maintaining sufficient feed.	AgResearch	Low [P]; Low [SS]	High [P]; Low [SS]	Planting, maintenance and effect of tree planting is subject to climatic influences (primarily wind direction).	Supplying sufficient feed to avoid animal stress is dependant on skill of farm manager.	Trees decrease stress and may have anthelmintic properties (if grazed).	McDowell et al. (2004; 2006)
Nitrogen	All farming enterprises	Denitrification beds	Many poorly drained soils used for farming are drained to decrease flooding and saturation of soils. Leaching water can be rapidly transported to subsurface drains and directly discharged into surface waterways. Denitrification beds are large containers filled with woodchips that intercept drain flow before discharge to surface waters. The wood chips support conversion of nitrate in water to nitrogen gas which is released to the atmosphere.	University of Waikato, Landcare Research, NIWA, GNS Science; Aqualinc	Very high	Very high	High cost when bioreactor was underloaded. True value much more likely to be at lower end when systems properly designed	Appropriate hydrology needed - tile/sub-surface drained land or small surface drains.	Might be integrated to support dissolved P removal	Barkle et al. (2008); Christianson et al. (2012); Schipper, et al (2004; 2010)

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Nitrogen	Irrigated land	Precision agriculture	Good design, including the use of novel sensors and automation of crop production, will optimise water and nutrient application according to local crop requirements. Sensors and information usage lead to individual animal based and optimised herd management. By accounting for site specific growth conditions, water demand and emission risks, precision agriculture can improve local production potentials and increase nitrogen use efficiency.	Lincoln Agritech, Landcare Research	High	Low	Varying effects in decreasing nitrate leaching: (i) differences in soil heterogeneity (leaching risks, denitrification capacity, soil fertility) and crop responses to adapted production intensity (variable rates), (ii) weather conditions, (iii) irrigation design practices and skills and (iv) management practices and skills. Varying effects in economic performance: (i) weather conditions, (ii) irrigation design practices and skills and (iii) management practices and skills of farmers.	Insufficient communication and training on benefits.	Improved farm and herd management; improved crop reliability and quality; conservation of water and better labour and management productivity.	Dalgardo and Bausch (2005); Claret et al. (2011); Reiche et al. (2002)
Nitrogen	All pastoral farming enterprises	Change animal type	Animal type influences N leaching due to inherent differences in the spread of urinary N (the major source of N loss in grazed pastures). Increased urinary spread results in a lower rate of N deposited in urine, greater utilisation by plants and less surplus N that contributes to N losses. Research has shown that N leaching from sheep and deer is approximately half that from beef cows at the same level of feed intake. Potentially differences also exist between male and female cattle (losses from male cattle being about two-thirds that of female cattle although there is high uncertainty with this). Similarly, young cattle are assumed to have greater urinary N spread than larger older cattle due to greater animal numbers per unit of feed consumed and greater number of urinations, although again there is limited data on this aspect	AgResearch	High	Medium	Highly variable over time due to changes in relative prices between cattle and sheep meat. As an example, farm profitability from finishing steers or bulls (male cattle) can be at least as great as from female cattle. Indeed, cattle breeding systems are generally less profitable than systems based on purchasing weaned animals and finishing them for meat processing	Changing relative prices between animal types over time; possibly a need for a mix of animals on a farm; and better farm management skills and farm infrastructure (e.g. extent of fencing).	This may also lead to decreased nitrous oxide and greenhouse gas emissions. However, with a change to deer it may (unquantified) lead to greater sediment and P loss.	Betteridge et al. (2005); Hoogendoorn et al. (2011); Williams and Haynes (1994)
Nitrogen	All pastoral farming enterprises	Diuretic supplementation or N modifier	Diuretics such as common salt generally result in increased water consumption by animals with an associated increase in the spread of urinary N by the animals. Potentially, other modifier materials can also either increase N utilisation by animals (e.g. monensin) thereby decreasing the amount of N excreted or decrease the amount of N excreted in urine relative to dung (e.g. tannin-containing materials). However, field proof of effectiveness of the latter materials is limited and some studies suggest animals may adapt to them leading to decreased effectiveness with time (e.g. with monensin). Research on the plot-scale effectiveness of salt as a diuretic is clear with benefits of up to 50% increase in spread of N from its use, although evidence for a decrease in N loss at a field-scale is limited.	AgResearch	Low	Low	Potential adaptation by the animal to supplementation or N-modifier leading to less efficacy of the strategy with time.	Salt is more appropriate in well-structured soils for long-term use since excess sodium in soil can potentially lead to soil structure degradation. Time requirements for supplementation and uncertainty of effects on animal health also limit its use. Not yet in models like Overseer due to limited data.	May also lead to decreased nitrous oxide and greenhouse gas emissions	Ledgard et al. (2007)

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Nitrogen	All pastoral farming enterprises	Improved N use efficiency	Greater N use efficiency can be achieved by: increasing per animal production with a commensurate decrease in animal stocking rate (replacement rates particularly) to maintain per hectare production and profitability; using less fertiliser N and some, if prices allow, low N feeds; and maximising the N value of farm dairy effluent by applying it to a greater proportion of the farm	AgResearch, Massey University, DairyNZ	Medium	Medium	The ability to decrease N losses to water depends on (i) the existing level of farm intensity and N loss, and (ii) the management expertise to implement required changes in farm practices. As a comparative example, very low input/intensity farms have little scope for decreasing inputs and N losses still further, in contrast to high input farms where less N fertilization is technically quite possible. Farms that are already very expertly managed will also have little scope to further modify farming practices to decrease N losses	Greater management expertise is required to maximise the amount of harvested feed under a low input farming system, while an increase in per cow production (to allow a decrease in stocking rate) will take time as improved genetics is introduced into herds	Decrease emissions of greenhouse gases and an improvement in energy use	Aarts et al. (2000); Beukes et al. (2011); Cardenas et al. (2011); Gourley et al. (2012a); Gourley et al. (2012b); Oenema et al. (2012)
Nitrogen	All pastoral farming enterprises	Nitrification inhibitors (Dicyandiamide, DCD)	N excreted by animals and in particular urine, is the most important determinant of N loss in stocked systems. Urinary-N deposited onto the soil is rapidly mineralised to ammonium-N and transformed by soil bacteria into nitrate. If not taken up by plants, nitrate is vulnerable to be leached. Rates of N deposition in the urine patch range from 400 up to 1000 kg N ha^{-1} (dairy cattle), which far exceeds pasture requirements, and thus leaving surplus nitrate in the soil. DCD slows the oxidation of ammonium (which is sorbed onto soil and less mobile) to nitrate, thereby decreasing the risk of leaching losses when drainage occurs and providing more time for plant uptake of ammonium.	Lincoln University, Massey University, AgResearch, Ballance Agri-Nutrients, Ravensdown	Medium	Medium	The efficacy of DCD depends on how long after the urination event the DCD is applied and once applied, the effectiveness depends on soil type, temperature and moisture.	Currently not permitted for use in dairy systems and there is a lack of proof of efficacy at a farm scale.	DCD decreases the emission of the greenhouse gas nitrous oxide by 40 to 80%	de Klein et al. (2011); Di and Cameron (2007); Gillingham et al. (2012); Houlbrooke and McDowell (2008); Kelliher et al. (2008); Monaghan et al. (2009); Smith et al. (2005)
Nitrogen	All pastoral farming enterprises	Supplementary feeding with low-N feeds	Pastures contain more N than is required by grazing animals and excess N is excreted predominantly in urine which is prone to N losses. Supplementary feeding with low-N feeds such as maize silage can increase animal productivity with little effect on the amount of N excreted in urine and lost by leaching. For example, studies with dairy cows have shown maize silage supplementation to increase milk production by one-third had little effect on the amount of N leached per hectare. Thus, it can increase N efficiency i.e. animal production per kg N leached. However, it is important to account for effects in the areas used to produce the low-N feed and when this is done there may only be small whole-system benefits unless N-efficient practices are used to grow the low-N feed crop. Potentially, this will be most beneficial where the low-N feed is a waste by-product from another sector (e.g. vegetable or fruit waste).	AgResearch, DairyNZ	Low	Low	Highly variable depending on source and price of feed and the efficiency with which it is fed to animals (with critical importance of the need to avoid substitution by the low-N feed for consumption of existing pasture). Thus, it is highly dependent on farmer management skills. On dairy farms in years of high milk payment, it can result in increased farm profitability.	Lack of facilities for feeding out supplementary feed and costs of introducing them; increased workload; requirement for increased skills in feed utilisation; and increased risk, depending on milk payout and feed prices	May also lead to reduced nitrous oxide per unit of productivity but this can be more than countered by increased carbon dioxide production in the production and feeding of the low-N feed sources.	Jensen et al. (2005); Ledgard et al. (2006); Williams et al. (2007)
Phosphorus	All farming enterprises	Low water soluble P fertiliser	Low water solubility P fertilisers decrease P loss by maintaining a smaller pool of soluble P in soil solution soon after application than highly water soluble P fertilisers (e.g. superphosphate), thereby minimising the potential for loss should runoff occur. Among P fertilisers, reactive phosphate rock (RPR) has little water soluble P; has been shown to decrease dissolved P losses by about a third from field plots grazed by dairy cattle and in a 12 ha catchment grazed by sheep in New Zealand. However, reactive phosphate rock should not be used where annual rainfall is < 800 mm and soil pH is > 6, RPR and requires a lead-in time meaning that a third of the applied P becomes available per annum such that it a field with RPR applied will have the same P fertility as a field with superphosphate applied after 3 years.	AgResearch	Medium	Low	Gain compared to highly water soluble P fertiliser is dependent on time of year that fertiliser is applied. Larger gains are evident where the coincidence of surface runoff soon after application is frequent.	Soil pH < 6.0, rainfall > 800 mm. Also cannot be used for capital applications and must gradually replace maintenance highly-water soluble P applications at a rate of one-third per annum (i.e. 100% low water soluble P in year 3)	Has a slight liming effect.	McDowell et al. (2010); McDowell and Smith (2012); Sharpley and Syers (1979)

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Phosphorus	All farming enterprises	Optimum soil test P concentration	The magnitude of P losses from soil via surface runoff or subsurface flow is generally proportional to soil P concentration, so maintaining a soil test P concentration in excess of the optimum for pasture production represents an unnecessary source of P loss. Achieving an Optimal soil test P concentration (e.g. Olsen P) can be done with nutrient budgeting software such as Overseer. The magnitude for P loss mitigation is dependent on how excessive Olsen P is, but if in-excess will always represent a profitable strategy.	AgResearch	Low	Low	Gain is dependent on soils being enriched beyond their optimum	None	None	Nash et al. (2007); McDowell et al. (2003); Gillingham and Gray (2006)
Phosphorus	All farming enterprises	Sorbents in and near streams	Management practices to decrease P in stream flow are limited. Techniques applicable to lakes, such as dosing with modified bentonite clays (e.g., Phoslock®) to sorb P, may not be applicable to streams as they rely on P attached to the adjuvant remaining on the stream bed, or for the material to cap the bed and block P dissolution from sediment. This may not occur as materials can be lost downstream during high flow events and the input and deposition of new P-rich sediment frequently negates the cap's effectiveness. An alternative strategy has been to encase P-sorbing material in a mesh. These "P socks" can decrease DRP and TP concentrations on average 35 and 21%, respectively. However, they are restricted to low flows. Near stream areas, and areas connected to the stream, are important sources of P loss to most waterways which can be decreased by the addition of P-sorbents. Areas include gateways, lanes, and around barns and troughs. One example saw P-rich runoff from a stream crossing where daily traffic by cows to-and-from the milking parlour reached a stream, accounting for 90% of the catchment P load. Installing a P-sorbent on the side of the lane decreased catchment P losses by c. 80%.	AgResearch	High	Very high	Materials may contain different quantities of sorbing materials (e.g. Al, Fe and Ca). The particle size of the material needs to maintain good stream flow but also good interaction with material	Source may be far away and the cost of transport prohibitive. Installation in stream may require resource consent	None	McDowell (2007b); McDowell et al. (2007)
Phosphorus	All farming enterprises with drained land	Tile drain amendments	By-product materials rich in P-sorptive Ca, Al and Fe have been identified as decreasing P loss from soils with varied success. These include, but are not limited to: zeolites, aluminium sulphate, water treatment residuals, and fluidized bed bottom-ash and fly ash from coal fired power plants. Selection criteria include: (1) cost of the material - does it need to be mined or is there a readily available and cheap source? (2) toxicity to the environment - does it contain heavy metals or is the material caustic?, and (3) the efficacy of sequestering P. A mixture of steel melter slag (90%) and basic slag has shown some promise at sequestering P when installed as a backfill above and around a tile drain. Similar work showed that volcanic tephra as a fill for mole channels could also decrease P loss.	AgResearch, Massey University	Very high	Medium	Materials may contain different quantities of sorbing materials (e.g. Al, Fe and Ca). The particle size of the material needs to maintain good flow but also good interaction with material	Source may be far away and the cost of transport prohibitive	Potential to decrease (via filtration) the loss of sediment and faecal bacteria (both unquantified).	Hanly et al. (2008); McDowell et al. (2008)
Phosphorus	Critical source areas in all pastoral farming enterprises	Applying alum to forage cropland	Aluminium sulphate (alum) has been used around the world to flocculate P from water columns, and in the US to decrease the water solubility of P in manures applied to land (Smith et al., 2001) and thus decrease P loss in runoff from grassland plots and catchments. Additional work in New Zealand has shown alum can decrease P losses in surface runoff when applied after animals have grazed a winter forage crop.	AgResearch	Medium	High	Alum may be ineffective in high rainfall environments where it may be washed from the soil and does not affect particulate phosphorus (the dominant form lost from cropland)	Few supplies and competing use as a water treatment additive	None	McDowell and Houlbrooke (2009)
Phosphorus	Critical source areas in all pastoral farming enterprises	Applying alum to pasture	Aluminium sulphate (alum) has been used around the world to flocculate P from water columns, and in the US to decrease the water solubility of P in manures applied to land (Smith et al., 2001) and thus decrease P loss in runoff from grassland plots and catchments. It does not impair pasture growth and ingestion at rates of 10-40 kg Al ha^{-1} yr^{-1} are unlikely to impair animal performance. Alum works by binding P in the topsoil, making it insoluble in water and therefore less available for loss in surface runoff.	AgResearch	Low	Very high	Alum may be ineffective in high rainfall environments where it may be washed from the soil	Few supplies and competing use as a water treatment additive	None	McDowell (2010)

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Phosphorus	Critical source areas in all pastoral farming enterprises	Red mud (bauxite) to land	Red mud is a by-product of refining bauxite into alumina. It is alkaline (pH 10-13) and contains up to 60% Fe oxide along with lesser amounts of Al, Si and Ca – all of which bind P into water insoluble forms. In Western Australia, red mud is sold as a soil amendment under the name Alkaloam® to increase soil pH and prevent P loss via leaching from sandy soils. There are some concerns over toxicity, largely centred on the presence of heavy metals or radionuclides, but the concentrations, when applied at the recommended rate of up to 20 Mg ha^{-1}, are small and unlikely to be detrimental to livestock. However, any product with a high pH should employ a stand down period of at least 2 weeks before stock can graze pastures otherwise rumen pH could increase adversely affecting the digestion of feed.	University of Western Australia; AgResearch	Very high	Medium	Increases soil pH which may increase P solubility if outside pH range 5.5-5.9.	Few suppliers. If used for liming effect, grazing animals need to avoid treated area otherwise ingestion may impair rumen function.	Alkaline and hence can be used instead of lime.	Summers (2001); Summers et al. (1996; 2002); Vlahos et al. (1989)
Phosphorus	Flood irrigated land	Refurbishing and widening flood irrigation bays	Water exiting flood irrigation bays represents about 20-50% of that applied and carries with it significant quantities of P and other water quality contaminants. Better matching irrigation to soil infiltration rates, re-contouring irrigation bays, and/or preventing outwash/wipe-off from accessing the stream network can decrease P loss.	AgResearch; Aqualinc	Very high	High	Inaccurate level resulting in flow (and outwash) faster than anticipated. Variation in the water supply rates.	A move to spray irrigation is likely to be more cost-effective.	More efficient use of flood irrigation water.	Houlbrooke et al. (2008a); Strong (2001)
Phosphorus	Irrigated land	Dams and water recycling	The use of recycling systems to divert outwash for use in another part of the farm increases nutrient efficiency and, since no water leaves the farm, significantly decreases the load of P lost by a farm.	AgResearch	Very high	Medium	Leakage from infrastructure	Only viable if delivery of irrigation is sporadic/irregular. A move to spray irrigation is likely to be more cost-effective.	More efficient use of flood irrigation water and entrained nutrients (unquantified).	Barlow et al. (2005); Houlbrooke et al. (2008b)
Sediment	All pastoral farming enterprises	Soil conservation farm plan	Combination of retirement and pole planting on highly erodible land. Suitable for pastoral farms which contain some highly erodible hill country. Introduction of tree roots to soil regolith protects soil on steep slopes from mass movement erosion.	AgResearch, Landcare Research, Plant and Food Research	High	High	Depends on severity of erosion	No factors limiting uptake	Decreased P inputs to waterways (unquantified). Increased sustainability of pastoral farming. Increased carbon sequestration. Improved shelter for animals.	Hicks DL (1995). Dymond et al. (2010). Thompson and Luckman (1993).
Sediment	Cropping	Benched headlands	Constructed level bench that runs across the slope of a field. Suitable for use on cultivated soil where slopes are greater than 3 degrees. These encourage infiltration of water on the bench and reduce the slope length of water pathways.	HortNZ	Low	Medium	Depends on infiltration capacity of soil	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Bunds	Earthen barrier constructed along paddock edge to prevent water flowing onto or from field. Suitable for use on cropping land with slope greater than 3 degrees. Creates ponds of water at bottom of field where sediment settles out. Sediment in cropping may be collected and redistributed to the upper land slope areas. Bunds, in concert with riparian strips will further increase effectiveness.	HortNZ	Very high	High	Depends on infiltration capacity of soil	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Contour cultivation	Cultivation along contours of cropping land with slopes greater than 3 degrees. This will reduce the speed of runoff water and thereby reduce the eroding power.	HortNZ	Very high	Low	Depends on infiltration capacity of soil and slope angle	Education	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Contour drains	Temporary drains that run across the slope of a field and into a permanent drain on the side of the field. Suitable for use on cultivated soil where slopes are greater than 3 degrees. These reduce the slope length of water pathways and thereby reduce the eroding power.	HortNZ	Medium	Low	Depends on density of drains	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).

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Sediment	Cropping	Cover crop	Green manure or cover crop which is grown to be ploughed into the soil rather than harvested. Suitable for use on cropping land after harvesting of main crop and sowing of new crop. The cover stabilises bare soil from erosion and improves water penetration and drainage.	HortNZ	Very high	High	Depends on soil structure	Willingness of manager to forgo short term gain for long term gain	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Erosion management plan	General erosion management plan for minimising soil erosion on cropping land according to HortNZ code of practice. Includes design and implementation of specific mitigation measures below.	HortNZ	Very high	High	Depends on the plan design	No regulation	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010).
Sediment	Cropping	Minimum tillage	Range of techniques from direct drilling of seed into stubble or pasture, through reduced number of cultivation passes, to more judicious use of conventional ploughs and harrows. Suitable for use on cropping land. Reduces the proportion of time that land is bare during the growing cycle.	HortNZ; Plant and Food Research	Medium	Low	Depends on the amount of time land is bare	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Silt fence	Material fastened to a wire fence for filtering out sediment from overland flow. Usually a temporary measure used in cultivated growing situations.	HortNZ	Very high	Very high	Variability of material and contracting costs	High cost	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Stubble mulching	Stubble is mulched and left on field if there is direct-drilling the following season. Suitable for continuous cropping. Partial ground cover protects soil from erosion and also reduces the transport of eroded soil in overland flow.	HortNZ	Medium	High	Depends on the amount of partial ground cover	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Wheel track dyking	Series of closely-spaced indentations in wheel tracks created by tillage machinery. Suitable for use on cropping land after the use of heavy vehicles on cultivated soil. Slows surface runoff water down and settles suspended sediment.	HortNZ	Medium	Medium	Depends on the proportion of runoff coming from compacted soil	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Wheel track ripping	Ripping of wheel tracks is suitable for use on cropping land after the use of heavy vehicles on cultivated soil. Ripping allows water to percolate into the soil rather than flow down the tracks.	HortNZ	Medium	High	Depends on the proportion of runoff coming from compacted soil	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	HortNZ (2010). Dymond (2010). Basher and Ross (2002). Basher et al. (1997). Hicks DL (1995).
Sediment	Cropping	Wind break crop	Tall crop in paddock providing shelter for neighbouring cultivated paddock from prevailing wind. Suitable for use in cropping land where wind erosion is a problem. Slows wind speed down at the soil surface and thereby reduces erosive power of the wind.	HortNZ	Low	Medium	Depends on value of wind break crop	Management expertise	Increased sustainability of cropping. Decreased P input (unquantified) to waterways.	Basher and Painter (1997).

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[1] Relative cost breakdowns for each quarter were (low, medium, high, and very high): N (<6.5, 6.5-40, 41-130 and 131-393 $/kg N retained/yr); P (<41, 41-108, 109-245 and 246-360 $/kg P retained/yr); Sediment (<30, 30-75, 76-150 and 151-790 $/kg sediment retained/yr).

Table 5. Information applicable to the application of lake-scale technologies (strategies) to mitigate the effects of water quality contaminants to lakes.

Target	Strategy	Description of function	Lead research agency	Effectiveness	Relative cost	Reasons for variability	Factors limiting uptake	Co-benefits	References
Multiple	Inflow diversion	Diverts nutrient–rich lake inflows downstream.	University of Waikato, NIWA	Ohau Channel inflow to Lake Rotoiti diverted towards Okere Falls outflow in Lake Rotoiti. TLI reduced from 4.45 (2003-2006) to 3.79 in (2008-2011). Sandy Creek diverted to reduce catchment area of Lake Tutira (Hawke's Bay) from 2719 to 844 ha. No evidence of improvement. Consideration given to Hamurana Stream inflow to Lake Rotorua at cost c. $12M.	Ohau Channel wall cost c. $10 million.	Dependent on the relative contribution of inflow to external loads and proximity to outflow. Success varies from apparently highly successful for a large inflow into Lake Rotoiti to moderately or marginally successful for smaller inflows or partial diversions.	Potentially very expensive and may be detract from landscape values.	_	Scholes and McIntosh (2010); Jacoby et al. (1999); Robertson et al. (2000).
Multiple	Hypolimnetic siphoning	Removes poor-quality (e.g. anoxic) water at the bottom of stratified lakes	_	Not used in NZ, but has been used in c. 50 lakes in Europe and N. America where it has proven to be an "effective low-cost restoration technique".	A proposed hypolimnetic discharge from Lake Okareka (BOP) was estimated to remove 21 kg P/ha/yr at a cost of c. $700,000 including construction of a wetland for treatment.	Preferential removal of cool bottom waters can lead to lake warming, increased O_2 consumption and reduce water column stability.	Only suitable for deep, seasonally stratified lakes where there is not a sensitive downstream water body.	_	McIntosh (2004); Nürnberg (2007)
Multiple	Dredging	Removes nutrients and sediments from a lake bed.	University of Waikato	Has not been used at large scale in NZ, but recently carried out in Oranga Lake, University of Waikato campus	Estimated costs vary from $1.6 –352 million for Lake Rotorua (8 050 ha) and $1 million for Lake Okaro (30 ha). Recent application to Lake Oranga (0.69 ha) was $0.1 million.	Multiple: depth of dredging, composition of underlying sediments that are then exposed, evenness of removal across lake; extent of disturbance and resuspension as well as disruption of benthic biota.	Disposal of spoil, disturbance of benthic fauna (invertebrates), potential release of contaminants from sediments.	In some cases spoil may be useful as a soil conditioner.	Klapper (2003) ; Faithfull et al. (2006); Miller (2006)
Multiple	Increased flushing rate	Create sufficient through-flow to physical remove phytoplankton before substantial response to prevailing nutrient concentrations	_	Flushing occurs naturally in many hydro lakes (e.g. along the Waikato River) at rates sufficient to curtail phytoplankton biomass potential, but otherwise few opportunities presented in NZ for this to be effective.	_	Flushing rate has to be reduced to c. 20 days to exert substantial control on phytoplankton biomass. Diverted inflows may otherwise act to enhance phytoplankton biomass due to additional nutrient load.	Few situations where sufficient flushing from inflow diversion is possible.	Could divert nutrient load away from system that was sensitive to this inflow.	Hickey and Gibbs (2009); Howard-Williams (1987)
Nitrogen and phosphorus	Weed harvesting	Removes nutrients assimilated in excess weed growth.	NIWA	Used for nutrient control in Lake Rotoehu, Bay of Plenty.	Hornwort harvesting in Lake Rotoehu (790 ha): $52,800/yr.; estimated at $22/kg N and $165/kg P removal cost.	_	Only suitable where invasive weeds are a problem.	Non-indigenous plant removal. Composting is possible where heavy metals not accumulated in plants (e.g. Waikato River plants not suitable for composting due to heavy metal accumulation).	Bay of Plenty Regional Council, Rotorua District Council, Te Arawa Lakes Trust (2007)
Phosphorus (and nitrogen secondarily)	Sediment capping	Provide a capping layer – either inactive (e.g. sand) or active (e.g. Aqual-P, allophane or zeolite) to decrease nutrient releases from lake bed sediments.	NIWA, University of Waikato	Aqual-P has been used both as a flocculant and to provide an active phosphorus cap on the lake bed.	Cost of Aqual-P is c. $2000 per tonne. Used in Lake Okaro (approximately 100 tonnes over lake area 31 ha).	Other naturally occurring minerals (e.g. zeolite, allophane) are potentially less expensive, but may release bound P under anoxic conditions.	Capping layer may be rapidly buried if catchment sediment load is high. Iwi are generally averse to introduction of foreign minerals into waterbodies.	Some capping materials may induce a partial flocculation of water column nutrients during application process.	Hickey and Gibbs (2009); Özkundakci et al. (2010); see special section of Hydrobiologia: Hamilton &Landman (2010).

Target	Strategy	Description of function	Lead research agency	Effectiveness	Relative cost	Reasons for variability	Factors limiting uptake	Co-benefits	References
Phosphorus and sediment	Wave barriers	Reduce resuspension of sediments and nutrients in shallow lakes through a physical barrier to reduce surface wave propagation.	NIWA	No known application in NZ. Has been used in Lake Tai (Taihu) in China to reduce sediment resuspension around water treatment plant intakes, with moderate success.	Being considered in Lake Ellesmere to re-establish macrophyte beds (in conjunction with exclosures to prevent swan grazing).	Insufficient information to assess variability. Could potentially create quiescent conditions with higher clarity that may favour blue-green algae blooms.	Applicable to shallow lakes	Water clarity improvements.	Jellyman et al. (2009).
Nitrogen	Floating wetlands	Use wetland plants to take up nutrients, wetland environment to remove N via denitrification.	NIWA	Effectiveness likely to be marginal based on areal uptake rates, especially in a non-flow-through environment such as a stream. Floating wetlands have been established in lakes Rotoehu, Rotorua and Rotoiti.	Approximately $1M in Lake Rotorua (0.4 ha) with only a very small amount of nutrient removed.	Difficult to measure effectiveness of nutrient uptake in lake environment; harvesting of plants for nutrient removal not actively carried out.	Could potentially detract from open-water vista.	Iwi enthusiastic about floating wetlands to enhance habitat for mahinga kai species.	Tanner et al. (2005).
Phosphorus	Oxygenation or destratification or mixing propellers.	Air/O_2 pumped to the bottom of lakes can decrease redox-mediated nutrient releases, particularly PO_4-P which is released under chemically reducing conditions.	University of Waikato, NIWA	Oxygenation is not used in NZ. Destratification with 'air cannons' was first trialled – largely unsuccessfully – in Lake Tutira, Hawkes Bay (1972). Mangatangi Reservoir supplying Auckland city has used destratification successfully to maintain water column mixing and avoid deoxygenation of bottom waters. Destratification recently (2012) implemented for Lake Rotoehu, Bay of Plenty.	Destratification trial in lake Rotoehu (790 ha): $524 000. Overseas, costs for oxygenation of moderate to large lakes estimated at US $ 1M set-up and operational cost of $30% of set-up cost per year (Beutel 2002).	Systems may be under-designed (with respect to air flows) or poorly designed (with respect to bubble plume dynamics).	Systems are generally expensive and may require maintenance (e.g. to prevent blockages from weeds) or blockages of air nozzles.	Can be well received by iwi due to non-use of chemicals.	Hickey and Gibbs (2009); Howard-Williams (1987); Beutel (2002); Beutel & Horne (1999); Antenucci et al. (2005).
Phosphorus	Phosphorus inactivation or flocculation	Chemicals like alum (aluminium sulphate) can 'lock up' dissolved phosphorus in lakes via adsorption and precipitation processes.	NIWA, University of Waikato, Scion	Under evaluation in selected Rotorua lakes, NZ. Has included materials such as alum, Phoslock® and Aqual-P. Alum, and Phoslock® to a lesser extent, have been highly effective in P removal and eutrophication control overseas. TLI in Lake Rotorua was 4.57 (2006-8) and 4.4 (2010-12) following continuous alum application (stream inflows). TLI in Lake Okaro was 5.6 (2002-4) and 5.1 (2010-12) following successive applications of alum and Aqual-P. TLI in Lake Rotoehu was 4.57 (2006-8) and 4.3 (2010-12) following continuous alum application (stream inflow).	Lake Okaro (30 ha) modified zeolite application c. $75,000/yrover 3 years. Alum dosing to two stream inflows in Lake Rotorua (8,050 ha) costs c. $1M/yr	Varying products, dose rates and application methods have been used; e.g. on-off lake aerial application vs. continuous inflow dosing. Buffering to reduce pH variation and optimise effectiveness has been used to varying extents and will be highly dependent on hardness of lake water.	Alum applications have occasionally resulted in catastrophic fish kills through low pH when applications are improperly buffered. Some eco-toxicological concerns about Phoslock® due to subsequent release of P-binding agent lanthanum. Aqual-P has shown little or no adverse eco-toxicological impact but efficacy for P removal is low. Maori/iwi are averse to foreign chemical introduction. May not be suitable for softwater lakes.	Primarily effective for removing PO_4-P from solution but some modified clays (e.g. Aqual-P) with similar function may also remove NH_4-N. Coagulants such as alum also remove fine sediments from the water column via flocculation.	Pilgrim & Brezonik (2005); Paul et al. (2009); Özkundakci et al. (2010); Scholes and McIntosh (2010); Hickey and Gibbs (2009); see special section of Hydrobiologia: Hamilton and Landman (2010).

5. Matrix summaries of farm-scale mitigation strategies

A visual assessment of strategies to mitigate N, P and sediment (but not *E. coli*) can be made by reference to Figures 3 to 5. However, it is important to realise that the data for each strategy are unlikely to capture the full range of cost or effectiveness due to site specific variations in climate, topography, soil type, etc. Hence, a better comparison is given with references to the relative cost and effectiveness columns listed in Tables 4 and 5. A qualitative assessment has also been published by the Waikato Regional Council (see: http://www.waikatoregion.govt.nz/menus).

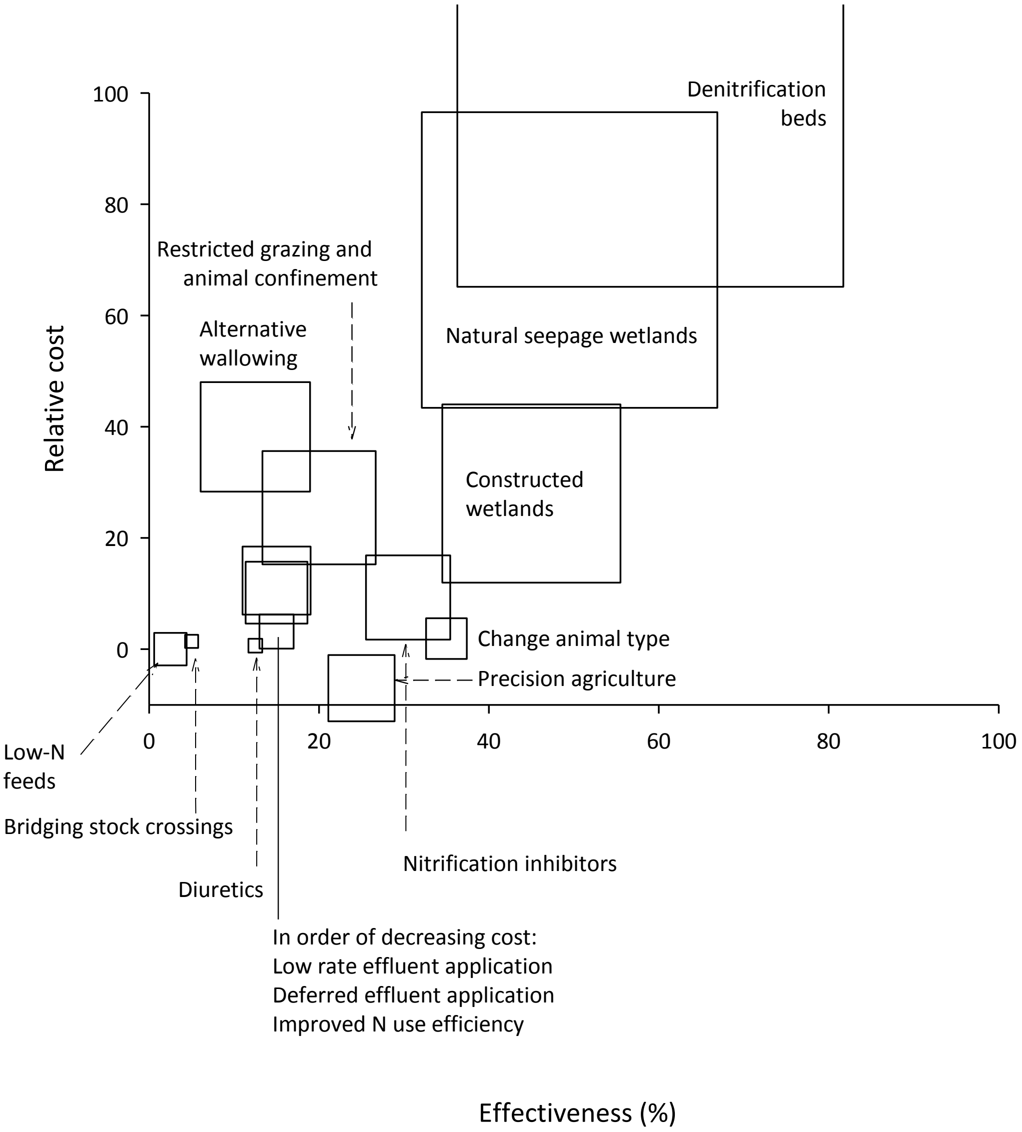

Figure 3. Diagram of the relative cost and effectiveness of strategies to mitigate **nitrogen** losses to water at the farm-scale. Cost is shown as the cost per kg of N mitigated relative to the most expensive strategy - denitrification beds at $393 per kg N retained/ha/yr. The centre of the squares represents the mid-point in the range for each strategy, while the size represents the relative variability of each strategy as the square root of the product of the range in percent cost by effectiveness.

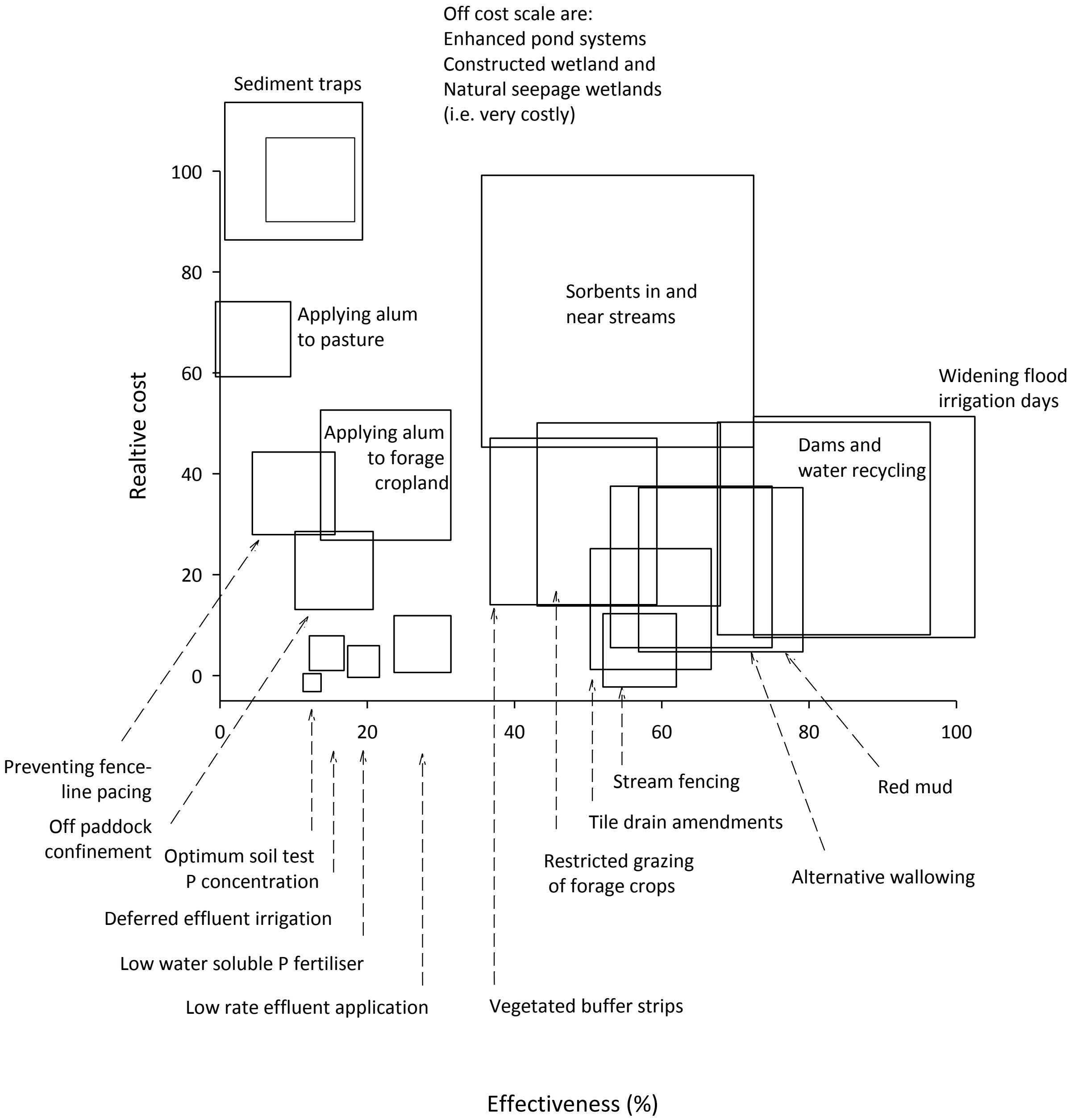

Figure 4. Diagram of the cost and effectiveness of strategies to mitigate **phosphorus** losses to water at the farm-scale. Cost is shown as the cost per kg of P mitigated relative to the most expensive strategy - sediment traps at $360 per kg P retained/ha/yr. The centre of the squares represents the mid-point in the range for each strategy, while the size represents the relative variability of cost-effectiveness for each strategy as the product of the range in percent effectiveness by the range in cost. Enhanced pond systems and the two wetland type were considerably more expensive (1400 – 4000% > sediment traps)

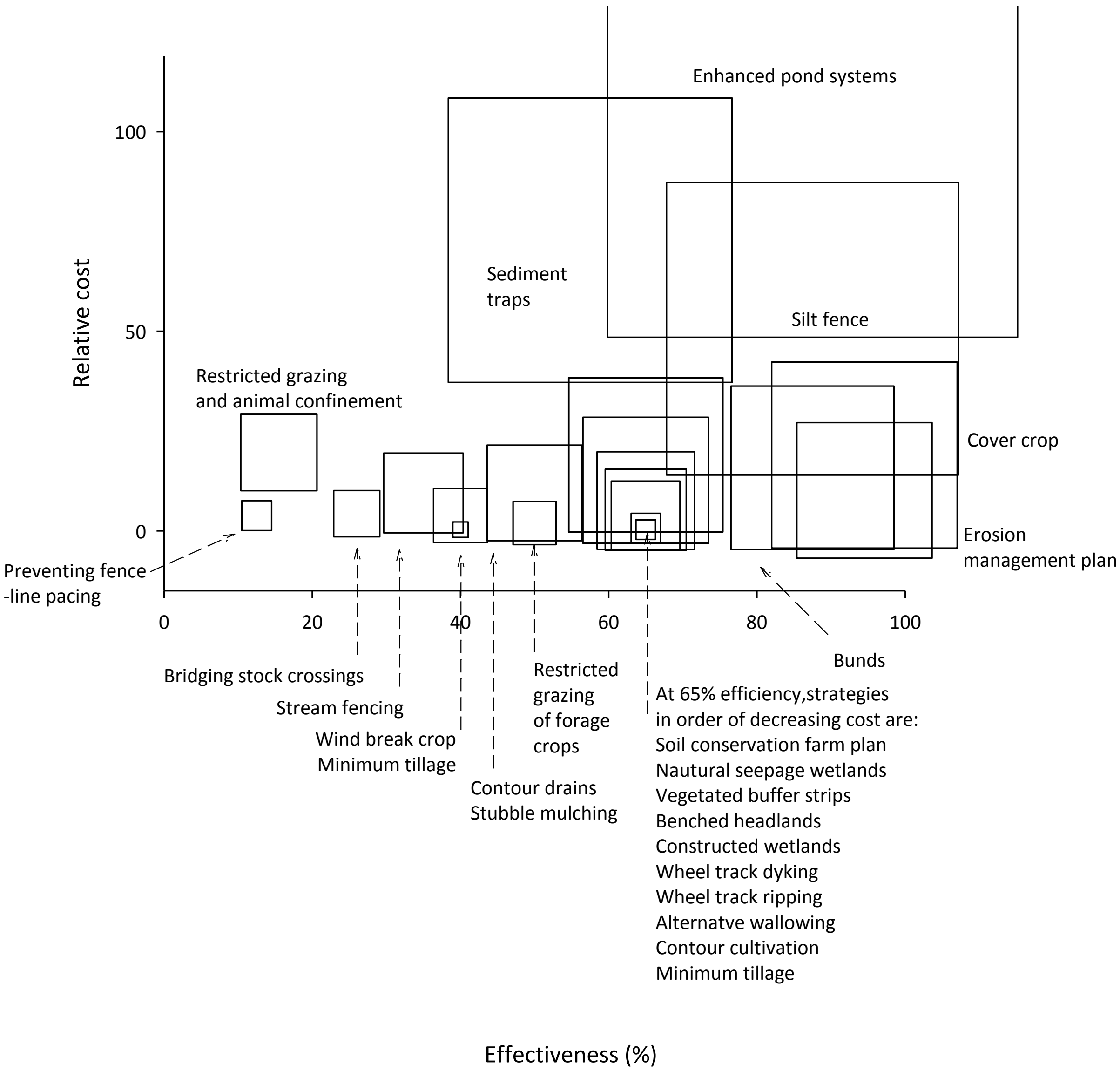

Figure 5. Diagram of the cost and effectiveness of strategies to mitigate **sediment** losses to water at the farm-scale. Cost is shown as the cost per kg of sediment mitigated relative to the most expensive strategy - enhanced pond systems at $790 per kg sediment retained/ha/yr. The centre of the squares represents the mid-point in the range for each strategy, while the size represents the relative variability of cost-effectiveness for each strategy as the product of the range in percent effectiveness by the range in cost.

6. Conclusions and take home messages

A number of caveats apply to the selection, use and ability of mitigation strategies to achieve good water quality outcomes.

1. Although each strategy has a range in price and effectiveness, both may be significantly improved if placed in the right place and at the right time. Each strategy will be different in this regard. However, McDowell et al. (2012) found that in two catchments in Otago the application of strategies to mitigate P losses when applied to critical source areas (viz. areas that account for the majority of contaminant loss, but account for a minority of the area) was 6-7 times more cost-effective than applying the strategies across entire paddocks. Other examples include the consideration of soil type and the capacity of groundwater to assimilate N when putting in new irrigation schemes, or the location of winter forage crops on drier parts of the farm where there is less runoff.
2. There is a wide range of strategies available. Strategies should be chosen according to the contaminant of concern and water quality objective. We suggest that cost effectiveness (also called price efficiency index) is an unbiased metric to do this. However, the selection of multiple strategies that are cost-effective may not be the most optimal mix to meet a water quality objective that is required quickly, in which case decisions may be based on effectiveness alone.
3. The range of strategies presented also allows the user to mix and match the best mix for their property. However, it is also important that the co-benefits be considered as some target multiple contaminants, or could conceivably be antagonistic to one another. For example, the use of alkaline P-sorbing materials in an acid soil could end up releasing more P despite less fertiliser being applied to decrease Olsen P.
4. Using multiple strategies in one location will be less effective due to the diminishing quantity of contaminant to mitigate, than the use of multiple mitigations along the transport pathway. However, in general, it is more cost-effective to mitigate the loss of contaminants at the source than farther down the catchment (Turner et al. 1999).
5. It is unlikely that there will be one strategy that can meet a water quality objective, i.e. there is “no silver bullet”.
6. Even when optimally placed and timed, the use of mitigation strategies may not meet a water quality objective for several reasons:
    a. Natural factors such as catchment characteristics (soil type, climate etc) mean their will always be a water quality issue;

   b. The costs or time involved at the enterprise level in using the number of strategies required to meet a community water quality objective are too great;
   c. There is a lack of motivation or poor skill base by land users to enact mitigation strategies at the source of contaminants, or a lack of community understanding of the processes and timeframes involved in seeing a response in a waterbody.
7. New science (and mitigation strategies) needs to continue to inform the community and land users at the catchment scale to achieve good water quality outcomes.

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