A review of contaminant losses to water from pastoral hill lands and mitigation options

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Abstract
Pastoral hill lands deliver a range of contaminants to receiving environments that are of concern to the wider sector stakeholder community: principally sediment, phosphorus, nitrogen and faecal micro-organisms. Thermal energy may also be considered a contaminant. Pastoral waterways generally have higher concentrations of suspended sediments, nutrients, faecal micro-organisms, and water temperature relative to forested waterways. These effects can be quantitatively linked to animal stocking rates and management. The large variation in the micro-climates, parent materials, soil types and vegetation resources inherent in hill country is the major driver of spatial and temporal dynamics of contaminant losses. This variation is modified by animal behaviour and physiology. Stores of contaminants in surface or sub-surface flow paths create important temporal lags resulting from land use and management change. The concept of critical source areas has become a key focus for the development of mitigation options. A wide range of biophysical options are now available, covering multiple scales and levels of cost-benefit. The use of farm planning tools is critical in balancing the implementation of mitigations with farm system objectives to improve whole-system sustainability. More research is needed on long-term impacts, given spatial and temporal variation in drivers and known spatial and temporal lag effects. There will be ongoing demand for mitigations that have been developed through co-innovation processes.

Keywords: environmental mitigations, erosion, hill country, nutrient loss, pastoral, sediment export

Key messages

- Pastoral hill landscapes do show increased losses of sediment, nutrients and faecal coliforms to waterways, and elevated water temperatures, relative to forested landscapes
- Low-altitude steeplands have high spatial and temporal variation in the delivery of contaminants to receiving environments, due to vegetation structure, animal behaviour and climatic factors – all driven by topographic diversity
- Effective mitigations across various scales do exist – e.g. tree-planting, riparian zones, wetlands, cattle grazing management, fertiliser placement and type – but with variable cost-effectiveness
- Future research attention should focus on nitrogen and faecal microbial dynamics, long-term effectiveness of mitigations and the improvement of integrated tools to clarify trade-offs and synergies.

Introduction

The purpose of this review is to summarise the New Zealand research literature covering the major contaminant losses to water from hill country pastoral land and the effectiveness of mitigations in this context. While there is no universally accepted definition of "hill country", the landscapes in scope for this review include those low altitude lands (<1000 m a.s.l.) that feature rolling and steep slopes (>15º), are not regularly cultivated on a large scale, are dominated by diverse pasture systems (but may include various woody vegetation components) and are managed for mixed livestock operations (mainly sheep, cattle and deer). The area covered by this loose definition is about 5.2 million ha (Mackay 2008) or approximately 20% of New Zealand. Most of this landscape has been developed into productive pastures from indigenous broadleaf-podocarp forest over the last century, but in many cases the prevailing vegetation has seen cycles of reversion to scrub or establishment of plantation forestry as the economic and social drivers have shifted over decadal scales. These vegetation types have often provided comparators for the quantification of the contaminants delivered to receiving environments (e.g. McColl *et al*. 1977; Cooper & Thomsen 1988; Fahey & Marden 2000; Quinn & Stroud 2002). The significance of the vegetation changes relates to a) the stability of the underlying pedology, based on soft-rock parent materials (Blaschke *et al*. 1992); and b) the energy balance of streams in terms of incident radiation (Davies-Colley & Quinn 1998) and organic matter inputs (Scarsbrook *et al*. 2001).

In addition to vegetation change, the establishment of productive grazing enterprises has involved two major drivers for contaminant loss: a) the enhanced input of plant nutrients mainly phosphorus (P), nitrogen (N), sulphur (S) and potassium (K) to support

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pasture growth; and b) the introduction of livestock with characteristic grazing, excretion and recreational behaviours.

The key contaminants for hill land waterways, in a suggested order of decreasing impact are: sediment, P, N and faecal micro-organisms. Thermal energy is also considered, since it is known to have substantial impacts on aquatic fauna (Quinn *et al.* 1994; Richardson *et al*. 1994). Sediment loss from large-scale erosion events, in terms of both the immediate and ongoing quantities of soil loss, is undoubtedly the biggest environmental management issue for hill country. Phosphorus is included ahead of N as most surface waters appear to be more P-limited than N-limited (McDowell *et al*. 2009) and total P losses in hill environments are strongly linked to sediment (Parfitt *et al.* 2008). In general, relative to waterways in forested catchments, those draining pastoral-dominant catchments have greater water yields, peak flows, nutrient concentrations, suspended sediment concentrations, faecal coliform concentrations, water temperatures, faunal densities, in-stream plant and vertebrate productivity, but lower faunal diversity (Davies-Colley 1997; Quinn *et al*. 1997; Quinn & Stroud 2002; Donnison *et al*. 2004). Table 1 shows data on sediment, N and P export from some of the major influential catchment-scale studies in hill country that have compared vegetation cover effects (see also Dodd *et al.* 2009). The data show a high degree of variability reflecting local lithology, climatic variability and farm management. In this context, one of the key challenges the sector faces is the establishment of quantitative contaminant loss targets that are both relevant to, and achievable by, pastoral-dominant systems; yet also acceptable to the wider stakeholder community as meeting sustainability goals.

The outstanding feature of hill country, in comparison with lowlands, is the high degree of spatial and temporal variation – in both landscape structure and in system processes. Specific driving factors include a high density of waterways per unit land area, rapid downslope flows of contaminants, large micro-climatic differences due to slope and aspect, animal redistribution of nutrients and multiple erosion processes. Studies consistently show that, far from being characterised by "diffuse source" pollution, the majority of contaminant losses occur over short time scales and/or from small areas of the farm where areas of high contaminant sources and rapid transport processes coincide (McDowell & Srinivasan 2009). These areas are called critical source areas (CSAs) and examples include tracks, troughs, gateways, headwater seeps and gullies and can generally be identified from farm mapping resources (Betteridge *et al*. 2013).

Much public and policy attention has been directed at lowland intensive agriculture (in particular dairying) in terms of the degree of contribution to waterway contamination at regional and national scales. Certainly, the extent of research activity in waterway contamination appears to be dominated by lowland studies, based on the number of articles returned from a simple SCOPUS literature search using the terms "Zealand and water and (sediment or phosphorus or nitrogen or faecal or

Table 1 Export of sediment and nutrients from catchments of various sizes and vegetation types reported in New Zealand hill land studies (rounded figures, kg/ha/year).

Location	Source	Scale (ha)	Vegetation	Sediment	Nitrogen	Phosphorus
Taita	McColl *et al.* 1977	4	Pasture		1	0.3
Ballantrae	Lambert *et al.* 1985	1.5	Pasture	1100-2700	8-12	0.7-1.5
Purukohukohu	Cooper & Thomsen 1988	11	Pasture		12	1.7
Tuapaka	Bargh 1978	180	Pasture	1400	5	1.6
Tamingimingi	Fahey & Marden 2000	795	Pasture	259-650		
Whatawhata	Quinn & Stroud 2002	259	Pasture	990-3200	10-23	1.5-3.2
Scotsmans Valley	Cooke 1988, Cooke & Cooper 1988	16	Pasture		7	1.3
Ballantrae	Parfitt *et al.* 2009[1]	8	Pasture		1-44	0.3-1.0
Whatawhata	Quinn & Stroud 2002	266	Pasture+Pine+Native	2600	7	1.3
Purukohukohu	Cooper & Thomsen 1988	34	Pine		1	0.1
Pakuratahi	Fahey & Marden 2000	345	Pine	64-185		
Taita	McColl *et al.* 1977	4	Planted forest+scrub		<0.1	<0.1
Taita	McColl *et al.* 1977	11	Native		<0.1	0.2
Purukohukohu	Cooper & Thomsen 1988	28	Native		4	0.1
Whatawhata	Quinn & Stroud 2002	300	Native	320	2	0.6

[1]Note also correspondence on methodology in this study (Monaghan 2009 and reply).

temperature)" and "hill" (58) versus "dairy" (144). However, it might be suggested that this is a contrast between the intensity and the scale of contaminant contribution, and it would be naïve to suggest that the impact of the hill country mixed livestock sector is relatively minor, in the absence of a comprehensive regional or national analysis. While most lowland catchments have upland headwaters that contribute to their contaminant load (e.g. Monaghan *et al*. 2007), lowland reaches in general deliver less sediment and thermal energy, but more P, N and faecal micro-organisms to waterways per unit land area (McDowell & Wilcock 2008). National datasets don't clearly distinguish between pastoral sectors but there is good evidence of variation in contaminant concentrations according to stream order (Larned *et al*. 2004) which may bear some relation to enterprise types. McDowell & Wilcock (2008) analysed plot to catchment scale studies conducted since the 1970s to show livestock type effects, which were largely non-significant due to high variability, with the exception of N export (Table 2).

Major contaminant issues (what is the problem?)

It is worth clarifying why the five contaminants that have been highlighted are problematic. Setting aside the loss of productive soil, which has permanent impacts on soil quality and pasture production (Trustrum *et al*. 1984; Sparling *et al*. 2003), sediment entering waterways alters the streambed habitat for aquatic fauna and causes siltation of receiving water bodies. This in turn has widespread economically quantifiable impacts on the severity of flooding, electricity generation capacity, marine traffic and aquatic health and food harvesting. For example, the impacts of a storm localised in the headwaters of the Motueka catchment in March 2005 extended to an area of 180 km^2 offshore in Tasman Bay (Gillespie *et al*. 2011) and continued to be expressed 3 years after the event (Hicks & Basher 2008). Phosphorus and N enrichment of streams enhance algal growth, which may in turn impair drinking water quality (MFE 1992) and, in excess, degrade ecosystem health (Biggs 2000). Microbial contamination can involve a range of zoonotic organisms (cycling between vertebrate animals and man and causing enteric diseases) including *Campylobacter*, *Giardia*, *Cryptosporidium*, *Escherichia* spp. and *Salmonella. Campylobacter* spp. are considered the highest risk and *Escherichia coli* concentrations are commonly used as an indicator organism (Donnison *et al*. 2004). Thermal energy "contamination" refers to the elevated stream temperatures that result from reduced stream shading in pastoral versus forested environments. Lower-order (headwater) streams are the most vulnerable because of their smaller volume and thus lower thermal buffering capacity (Rutherford *et al*. 1997). Many aquatic invertebrates have critical water temperature thresholds for completion of their life cycles (Quinn & Hickey 1990) and their absence in pastoral streams has consequences for aquatic food chains and the abundance of some fish species. In higher order streams, elevated water temperature may have implications for industrial cooling requirements.

It is worth noting that the effects of the pastoral environment on waterways are not all bad from a human use point of view. Elevated temperature and nutrients in streams can lead to increased macrophyte (plant) and aquatic faunal (fish) productivity (Hicks & McCaughan 1997) that provide mahinga kai (e.g. eels, puha and watercress).

Table 2 Mean N and P fertilisation rates, contaminant losses of N, P, sediment and *E. coli*, annual rainfall and elevation – organised by stock type for catchment-scale studies in New Zealand since the 1970s. The significance level of the F statistic and least significant difference (LSD) at the P<0.05 level are given for comparison of data between stock classes. Table reproduced from McDowell & Wilcock (2008).

Land use	P fert. kg/ha/y	N fert. kg/ha/y	P loss kg/ha/y	N loss kg/ha/y	Sediment loss kg/ha/y	*E. coli* loss cfu/ha/y	Rain mm/y	Elevation m
Non-agricultural			0.2	2	174		1641	234
Sheep only	41		0.6	3	598	8.60E+09	1172	268
Sheep/Beef	32	35	1.3	11	1156		1592	214
Deer	32	45	1.5	8	2034	1.80E+11	890	190
Dairy	53	108	1.9	27	299	8.54E+10	1480	67
F statistic[1]	ns	ns	ns	***	*	ns	ns	***
LSD05	22	214	2.6	14	1394	4.52E+11	1029	151

[1]ns = not significant
* = P<0.05, *** = P<0.001; y=year

Major contaminant sources (what causes the problem?)

There is an extensive New Zealand literature on soil erosion processes, ranging from mass movement to sheet runoff, and their contribution to sediment contamination in waterways (Basher *et al*. 2008; Caruso & Jensen 2001). Extreme weather events have a strong influence on contaminant losses in steep hill lands and subsequent impacts on stream ecosystems (Parkyn & Collier 2004; Collier & Quinn 2003). Long-term, erosion rates appear to be declining from high levels after initial forest clearance to a new steady state (Blaschke *et al*. 1992; Kasai *et al*. 2005). The resultant channel infilling creates recent terraces that contribute to the characteristic pastoral stream structure of narrow, swift-flowing channels, in contrast to forested channels which are wider and shallower (Davies-Colley 1997). This only provides a temporary stabilisation of sediment in stream banks, as they are still vulnerable to degradation by cattle treading and stormflow.

Where sediment originates from hillslope areas, rainfall simulator experiments in hill country have demonstrated that soil treading damage and exposure of bare ground to intensive livestock grazing is a key driver of sediment and nutrient input via overland flow (Nguyen *et al*. 1998; Elliott *et al*. 2002). The impacts of grazing on sediment and nutrient losses were less in summer than winter due to less damage to vegetation and greater soil infiltration rates in summer (Sheath & Carlson 1997). Headwater and riparian wetlands play key roles in influencing in-stream concentrations of sediment, N and P (Ngyuen *et al*. 1999). Cattle are attracted to these and their faecal bacteria inputs result in high export during high flows (Collins 2004).

Phosphorus contamination in hill country (in contrast to lowlands) is largely from particulate sources associated with surface runoff, stock management and direct fertiliser application (Gillingham & Thorrold 2000). The P fertility status of the soil influences total P export via erosion (Gillingham & Gray 2006). Phosphorus and N losses via runoff are greater under cattle grazing than under sheep grazing (Lambert *et al*. 1985). However, N contamination is largely from leaching and subsurface flows of nitrate originating from microbial transformation of N deposited in livestock urine patches (Di & Cameron 2002). Studies of N leaching are problematic for hill country with complex topography and hydrology, and only a few lysimeter studies have been attempted, which confirm the relationship between fertility/N inputs/stocking rate and drainage from the root zone (Sakadevan *et al*. 1993). The important role of subsurface flow pathways (particularly for inorganic N) creates time lags between land use changes and receiving water impacts. Groundwater lags have been estimated for the Rotorua lakes (15-110 years) and Taupo catchments (50-80 years) and have disguised the effects of land use changes since the 1940s (Morgenstern 2007). Even in steepland headwater areas, base-flow residence times have been shown to be in the order of 3-9 years (Stewart *et al*. 2007), which has implications for the likely lag effects of increases in N fertiliser use in hill country. Lag times may also exist for phosphorus where in-stream concentrations are influenced by significant stores of sediment deposited by erosion (McDowell 2015).

Microbial contamination is derived from livestock excreta and thus its distribution and abundance is influenced by stock type, stocking rate and animal behaviour (e.g. camping, drinking, Bagshaw *et al*. 2008), with increases associated with greater forage intake in spring and summer (Collins 2004; Donnison *et al*. 2004). However, it should be noted that other non-livestock sources relevant to hill lands have been identified, including feral animals and birds, as evidenced by contamination of non-pastoral waterways (Donnison *et al*. 2004).

While stocking rate and/or fertiliser inputs can be quantitatively linked to contaminant loads (Table 1; Buck *et al*. 2004; Parfitt *et al*. 2009), loads can also be influenced by animal behaviour such as a desire by cattle and deer to stand and wallow, respectively, in waterways. Both cattle and deer defecate more in the stream than out (Davies-Colley & Nagels 2002). Within hill paddocks, cattle are much more likely to camp in low slope areas close to streams, which combined with their greater N loads in urine, increases the risk of N leaching losses to water (Betteridge *et al*. 2010). While sheep do not actively seek out streams, some anecdotal evidence suggests that the rate of defecation is greater in flood zones than further away.

It is worth considering a few of the current trends in pastoral management of hill lands and their likely impact on contaminant delivery to waterways:

1. Small-scale cultivation. An increase in forage cropping on easy slopes within hill country may lead to increased sediment and particulate P losses due to high levels of bare ground and winter grazing with cattle (Orchiston *et al*. 2013). Cultivation, whether for forage cropping or pasture renewal, can also release large amounts of mineral N and lead to increased N leaching over the subsequent year (Betteridge *et al*. 2011).
2. “Spray and Pray”. Increased introduction of new plant material using this non-cultivation technique will similarly increase the risk of sediment and particulate P loss due to a variable period of low or patchy ground cover.
3. Dairy heifer/cow grazing. An increase in cattle:sheep stock ratios is likely to lead to increased erosion, N leaching and sediment delivery due to more

concentrated cattle urine patches on easy slopes (Betteridge *et al*. 2010).

4. Increased tactical N use. An increase in N inputs to the system is likely to lead to greater N leaching losses, although there is little published verification of this for hill country due to the challenges of measuring leaching on slopes. The magnitude of the effect could also depend on whether the additional forage grown is directed at increased stocking rates (with associated increases in N leaching), or increased per head performance.

Major contaminant mitigations (how to fix the problem)

The key challenge for the sector is to mitigate contaminants while retaining a pastoral-dominant landscape with its associated productive enterprises. At most scales, from paddock to farm system to landscape, there is plenty of evidence to suggest that there is scope to decrease contaminant losses without jeopardising the sustainability of pastoral farming systems. McDowell *et al*. (2014) suggest that maximum efficiency from mitigations in the long-term is achieved when they are: 1) chosen on the basis of suitability to the farm; 2) implemented on the basis of cost-effectiveness; and 3) implemented in critical source areas, with the result that 25-50% of some contaminant losses can be mitigated without impairing farm earnings.

A critical first step in meeting this challenge is the application of farm planning tools. Beginning with catchment authority soil and water conservation plans that date from the 1950s and were latterly based on the Land Use Classification (LUC) framework (Lynn *et al*. 2009), a number of farm planning approaches have been developed and applied with varying degrees of success over several decades (e.g., SUBS, Ag-vantage, Project Green, OVERSEER, BOP Environment Programmes; Blaschke & Ngapo 2003). For the hill country sector, the most recent and comprehensive is the Land and Environmental Planning (LEP) Toolkit developed by a team led by AgResearch and promoted by Beef+LambNZ (see: http://www.beeflambnz.com/farm/environment/land-and-environment-planning-toolkit/). This approach has also been a major component of regional government initiatives to implement environmental management policy at the farm level (e.g. Sustainable Land Use Initiative of Horizons Regional Council).

Given the pre-eminence of the soil erosion issue, greater use of woody vegetation must be a key mitigation strategy. There is a wealth of literature confirming the effectiveness of a wide range of tree and shrub vegetation options for reducing erosion and associated sediment loss (Basher *et al.* 2008; Hicks 1995; Hicks *et al.* 2001; Hawley & Dymond 1988). At a paddock scale, shade trees can be used to draw cattle away from vulnerable sites (Betteridge *et al*. 2012). At the whole-farm scale, reconfiguration of land use and management dominated by tree-planting has shown improvement of all contaminants in the short-term (Dodd *et al*. 2008). At a larger scale again, modelling has been used to show that implementation of whole farm plans can potentially reduce sediment loads in the Manawatu River by 8 to 47% (depending on the degree of targeted implementation, Schierlitz *et al*. 2006).

In terms of smaller-scale mitigations within farm systems, Table 3 covers a range of practises and indicates relative cost and effectiveness – it is difficult to specify the benefits precisely as so much depends on local factors. In the most effective/most costly domain, fencing and planting of riparian zones impacts all contaminants to some degree, but is most effective in reducing sediment, faecal and thermal contamination (Smith 1989). Riparian fencing prevents direct stock access to waterways and fragile banks, thus reducing sediment and faecal inputs. Woody riparian vegetation provides stream shade and mediates water temperatures, but its continuity in space (along reaches) and time (over harvest cycles) is critical. Herbaceous riparian vegetation is also effective at sediment tapping and nutrient attenuation, though the nutrient storage capacity may become saturated if the herbage is not harvested. Riparian vegetation also provides external organic matter inputs, thus influencing the energy base of the stream ecosystem. However, the effectiveness of riparian vegetation is limited under conditions of extreme weather events and when contaminant flow paths operate via groundwater (e.g. N-leaching). Under heavy rainfall on steep pastoral land, overland flow can transport substantial quantities of faecal bacteria to streams and it is unlikely that vegetated buffer strips will be particularly effective at attenuating such high-energy flow conditions (Collins & Rutherford 2004). Assessment of the efficacy of riparian plantings of various ages up to 24 years showed improvements in water clarity and bank stability but found little improvements in macro-invertebrate communities, attributed to water temperature changes with greater canopy shading (Parkyn *et al*. 2003). In contrast, macro-invertebrate communities showed an improvement towards native forest type within the first 7 years after integrated farm and riparian management was applied to the Mangaotama hill-land experimental catchment, near to sources of invertebrate colonists in adjacent native forest streams (Quinn *et al*. 2009). Studies of water flowing through afforested reaches below pastoral land show strong remediation towards native forest streams in terms of temperature and aquatic fauna over distances of 300-600 m, while sediment and nutrients showed less recovery (Storey & Cowley 1997; Scarsbrook & Halliday 1999), although this will depend on stream order.

Wetlands have an important role in mediating sediment and nutrient export through physical entrapment and denitrification processes, provided there is no stock/mechanical disturbance of these systems (Nguyen *et al.* 1999; Rutherford & Nguyen 2003). Wetlands are a cost-effective mitigation tool for reducing sediment and nutrient inputs to waterways under normal flow conditions. There remains, however, a recognition that for sediment and P they represent a temporary entrainment solution. Removal of 95% of N inflows in the wetlands of the Tutaeuaua sub-catchment of Taupo was attributed to denitrification (Collins *et al*. 2005).

Given that most phosphate fertiliser is aerially applied to hill lands, there is greater potential for direct entry to waterways, though modern aerial precision spreading technologies should largely overcome this for larger rivers (Gillingham *et al.* 2003). Use of less soluble fertiliser products will also reduce losses of dissolved P forms (Hart *et al*. 2004; McDowell *et al.* 2010).

Reducing animal stocking rates, stocking with lighter/younger cattle and decreasing the cattle to sheep stock ratio all have a demonstrable quantitative effect on sediment and nutrient losses and improved water quality. However, since the profitability of farming businesses is highly dependent upon establishing stocking rates that achieve high levels of pasture utilisation, any disruption to that relationship is likely to be a costly strategy for reducing nutrient losses. There is plenty of scope for prudent animal management that accounts for livestock type, slope, vegetation cover and soil moisture in avoiding substantial short term losses during adverse weather. For example, higher grazing residuals have been shown to reduce sediment loss (Russell *et al*. 2001).

An important consideration in evaluating mitigations is the time scale for environmental improvements. These have been shown to vary depending on the indicator of interest and in the short-term (5-10 years), mitigation outcomes were not always as predicted by modelling – e.g. sediment loads declined more quickly than expected in response to livestock exclusion from steep slopes (Quinn *et al*. 2006). Smith (1992) observed increased sediment, P and N export from riparian pine afforestation of pastoral catchments after 9 years, attributed to the lack of riparian wetlands, in-stream vegetation and close riparian ground cover.

Moreover, some long-term studies have highlighted counter-intuitive outcomes. For example, afforestation is expected to decrease contaminant losses in the long term, based on paired catchment studies (McColl *et al.* 1977; Cooper & Thomsen 1988; Fahey & Marden 2000). Observed increases in short-term sediment, P and N exports with afforestation have been attributed to tree shading effects that reduce riparian herbaceous cover and destabilise stream banks, shading effects that reduce instream plant nutrient uptake, and a decline in

Table 3 Relative cost (orders of magnitude) and effectiveness (high/medium/low) of contaminant mitigation practises relevant to hill country mixed livestock systems. Abridged from: http://www.farmmenus.org.nz/en/Drystock-farms/ which includes implementation detail.

Mitigation practise	**Magnitude of costs / $ per ha**[1]	**Relative effects on:**				
		Sediment	**Phosphorus**	**Nitrogen**	**Faecal coliforms**	**Temperature**
Riparian fencing+planting	10000s	M	M	M	M	H
Riparian fencing	1000s	L	M	L	H	L
Forestry	1000s	M-H	M-H	M	M	H
Wetlands	1000s	M	H	M	M	-
Culverts & bridges	1000s	H	M	L	H	-
Sediment traps	100s	M	M	L	L	-
Hillslope spaced trees	100s	M	L	-	-	-
Water reticulation	100s	M	M	L	H	-
Protection of forage crop CSAs	10s	M	H	L	M	-
Farm nutrient budget	10s	-	L	L	-	-
Precision fertiliser application	nil	-	H	H	-	-
Exit large cattle enterprises	nil	H	M	L	L	-
Contour crop planting on low slopes	nil	M	H	L	-	-
Restricted cattle grazing	nil	M-H	M	L	L	-

[1]Assumes approx. 70 m of waterway per hectare of land.

the extent of wetlands in forests, which reduces their attenuation potential (Hughes & Quinn 2014). In the medium term there is a pattern of reductions in water yield, sediment and nutrient exports and improvement in stream biota over a plantation forest growth cycle (Fahey *et al.* 2004). While temporary (3-5 years) increases in these indicators will occur during the logging and early tree regrowth phases, exports over the whole cycle of a plantation forest are still lower than those observed for pastoral catchments (Fahey & Marden 2006).

Modelling

Systems models have historically been used either at the farm scale for management decision support, or at the landscape scale for regional policy development. With the recent shift in the role of farm-scale modelling to policy implementation it is worth considering what tools are available, their uses and limitations for hill country landscapes. At one level, there are a number of catchment-scale models available to researchers, such as BNZ (Basin New Zealand, Cooper & Bottcher 1993), WAM (Watershed Assessment Model, Collins 2001), NZEEM (New Zealand Empirical Erosion Model, Parfitt *et al*. 2008), SedNet (Schierlitz *et al*. 2006), FIO (Faecal Indicator Organism, Wilkinson 2007), ROTAN (Rotorua and Taupo Nitrate model (Rucinski *et al.* 2006) and SPARROW (Spatially Referenced Regression on Watershed Attributes, Alexander *et al*. 2002). These are generally based on topography and vegetation and can be used to predict contaminant losses but are relatively insensitive to farm-scale variables such as stock type and grazing management. At the farm system scale, decision support models such as OVERSEER and MitAgator have grown out of a focus on traditional farm management parameters (fertiliser inputs, stock types, productivity and profit), to address environmental impacts and the efficacy of on-farm mitigations, but as yet do not deal with all the relevant issues (e.g. sediment, temperature). The only tool operating at this sub-catchment/farm scale and derived from an explicit environmental impact perspective is CLUES (Catchment Land Use for Environmental Sustainability, McBride *et al*. 2008). A modelling framework is needed that deals comprehensively with all the major contaminants and includes the full range of mitigations at a range of scales.

Knowledge gaps

Finally, some brief comments on areas that need more research attention to improve the ability to mitigate contaminant losses in hill lands:

- Improve spatial and temporal data coverage of all contaminants for hill country environments, taking account of the variability in underlying soil/climate/ management contexts. In particular, the dynamics of faecal micro-organisms appear to be the least well understood
- Improve understanding of N leaching on variable slopes and the quantitative connection to N export
- Measure long-term impacts and time scales for effectiveness of mitigations. Investigate trade-offs and synergies between mitigations for water quality and greenhouse gases. Ensure that farm planning tools (including models) are effective at addressing all contaminants in an integrated manner.

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