International Water Association

Specialist
Conferences

14th International Conference,
IWA Diffuse Pollution Specialist Group:

Diffuse Pollution
and **Eutrophication**

ISSUES AND SOLUTIONS TO DIFFUSE POLLUTION

Selected papers from the 14th International Conference of the IWA Diffuse Pollution Specialist Group, DIPCON 2010

Editors by

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Conference sponsored
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Design : www.bussierescom.com

Diffuse pollution and freshwater degradation: New Zealand Perspectives

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Abstract

Recent opinion surveys point to water pollution, primarily from pastoral agriculture, as the largest environmental issue in New Zealand. With a prognosis for increased land use intensification, further water quality degradation seems highly likely. This paper outlines five major aspects of the diffuse pollution issue: 1. Characterisation of diffuse pollution and the shift from point to diffuse sources. The 'universal' diffuse pollutants: nutrients, fine sediments, and pathogens, all of which are mobilised by livestock, predominate in New Zealand waters. There has been a shift over the last 40 years from point sources to diffuse sources as the major contributors of pollution, with point sources now accounting for only 3.2% of the total nitrogen, and 1.8% of the total phosphorus fluxes to the sea. 2. Pathways of diffuse pollutants. Diffuse pollutants move into waters through: overland runoff; direct access to waters by livestock; and leaching to groundwater (often with associated legacy issues reflecting groundwater residence times). These pathways are discussed illustrating the importance of understanding processes – particularly for targeting Beneficial Management Practices (BMPs). 3. Attenuation of diffuse pollutants through interception mechanisms and BMPs adjacent to, and in, streams. Attenuation is discussed for riparian zones, and in-stream processing. 4. Modelling of diffuse pollution has been done in New Zealand through mechanistic, stochastic and statistical approaches, and management-accessible models are described. 5. Managing diffuse pollution needs to recognise that catchments are the most appropriate spatial management unit. Managing diffuse nutrient loads has recently been initiated in New Zealand through regulation by setting load limits (nutrient caps) on catchments, and through identified nutrient concentration targets.

Keywords

Faecal microbial pollution; management; Nitrogen; nutrient loads; Phosphorus; sediments

INTRODUCTION

New Zealand has much natural landscape with mountains and natural forest occupying *ca.*43% of the land surface. These areas contain near-pristine rivers, lakes and wetlands. The remaining land area comprises planted forest (5%) and pastoral and arable land (52%) and the country's lowlands are almost devoid of natural landscape (Elliott, 2005; Davies-Colley, 2009). Given the large area of pastoral farming, it is not surprising that New Zealand suffers considerable diffuse water pollution, and the link between pastoral intensification and declining water quality is increasingly acknowledged by the Government (New Start for Freshwater, 2009). This decline has been rated the country's number one environmental problem in several opinion surveys. Water pollution, now overwhelmingly from diffuse sources, has been well documented and the management of diffuse pollutants is currently receiving considerable attention (Ministry for the Environment, 2009; Land and Water Forum, 2010). There has been government recognition of the "strong link" between land use intensification and water quality decline (Ministry for the Environment, 2009). The reasons for this attention relate to public pressure and changing perceptions of the value of natural waters. Behind these are the continuing drives by international primary commodity markets for the documentation of sustainability practices. A significant pressure for cleaner waters has come from the indigenous Maori (Polynesian) people of Aotearoa/New Zealand. Maori recognise freshwater as a taonga (treasure) and have an obligation of guardianship of the landscape including waters (Land and Water Forum, 2010).

The challenge facing New Zealand is how to cope with the economic drive for increased pastoral production while demonstrably minimising contaminant loss to both freshwater and the coastal zone. Detailed reviews of the extent of, and impacts of, diffuse pollutants on the New Zealand aquatic environment have appeared frequently over the last decade as concern has increased over the impacts of pastoral agriculture on them (McDowell, 2009; Quinn et al., 2009). This challenge is significant. The most recent OECD Environmental Review of New Zealand (OECD, 2007) highlights that water quality in lakes and rivers has declined in those areas dominated by pastoral farming and the OECD has recorded the following changes in the 15 year period, 1990-2005:

- Change in agricultural production: NZ ranked 1st out of 28 OECD countries, with the highest % increase in agricultural production.
- Change in total phosphate fertiliser use: NZ had the 2nd highest % increase in phosphate fertiliser use out of 29 OECD countries, while 23 countries decreased their P-fertiliser use.
- Change in total nitrogenous fertiliser use: NZ had the highest % increase out of 29 OECD countries, while 21 countries decreased N-fertiliser use. (The actual net application of N-fertiliser (2.1 tonnes /km2 of agricultural land) in NZ is now close to the OECD average of 2.2 tonnes/km2 of agricultural land.)

International and New Zealand-specific experience shows that such changes are likely to be accompanied by increases in diffuse pollution (Wilcock, 2009). The New Zealand Office of the Parliamentary Commissioner for the Environment has argued for “a paradigm shift in farming practices for New Zealand to become environmentally sustainable”.

Here we outline five major aspects of the diffuse pollution issue that have wide international relevance: 1. Characterisation of diffuse pollution and the shift from point to diffuse sources; 2. Pollutant pathways; 3. Attenuation of diffuse pollutants; 4. Modelling; 5. Managing diffuse pollution.

CHARACTERISATION OF DIFFUSE POLLUTION

Urban and mining-impacted streams are typically of lowest ‘ecological ‘health’ in New Zealand, as elsewhere, owing to severe physical changes, gross sedimentation, and toxic pollution, but a far greater total length of streams in pastoral agriculture are moderately to severely impacted. The ‘universal’ diffuse pollutants – fine sediments, pathogens and nutrients – all of which are mobilised by livestock, predominate in waters draining the New Zealand landscape.

Fine sediment mostly affects (i) rivers by reducing water clarity and impacting on primary producers and consumers in aquatic food webs, and (ii) coastal areas by reducing water clarity, shoaling by sedimentation and smothering shellfish beds.

Faecal matter (and associated pathogens) affects contact recreation, water supplies and coastal shellfish harvesting from commercial, recreational and traditional harvest sites. In a national study of freshwater swimming sites collated by the Ministry for the Environment 40% of 280 river sites were found to be non-compliant with guideline values for recreation in terms of *E. coli* (http://www.mfe.govt.nz/environmental-reporting/freshwater/recreational/snapshot/freshwater.html#results). Although microbial pollution is of major concern for contact recreation, application of a water quality index for contact recreation to 77 sites in the National Rivers Water Quality Network (NRWQN; Davies-Colley and Ballantine, 2010) suggests that low visual clarity limits contact recreation in NZ rivers more commonly than microbial pollution (high *E. coli*).

In terms of nutrients, New Zealand has a long history of documentation and research on freshwater eutrophication that has affected rivers, wetlands, lakes and estuaries (Burns, 1991; Winterbourn, 1991) with significant deviations from OECD trends (White, 1983). SPARROW modelling calibrated to the NRWQN dataset (Elliott et al., 2005) suggests that point sources account for only 3.2% of the Total N, and 1.8% of the Total P flux to the sea from the New Zealand landmass.

Diffuse pollution has probably been present since widespread land clearance for grazing started in the 19th century in (originally 80% forested) New Zealand, but has gone largely unrecognised until recently. Over the past four decades or so, NZ has been preoccupied with controlling point pollution, with water pollution from diffuse pastoral sources only acknowledged fairly recently – particularly since publication of a landmark paper by Wilcock (1986). Now the gains made from investment in wastewater treatment risk being negated by increasing diffuse pollution from expansion and intensification of pastoral agriculture (Ballantine and Davies-Colley, 2009; Wilcock, 2009; Quinn, 2009). Diffuse pollution (with a few exceptions) seems less amenable than point pollution to control under New Zealand's (effects-based) environmental legislation, the Resource Management Act of 1991.

Correlations between land use and river water quality consistently quantify the relationships between water quality and land use as shown in Table 1. Visual clarity is negatively impacted by land use and is positively related to % native forest in the catchment. Nutrients and *E. coli* concentrations are all positively related to % pastoral land use in the catchment, and negatively to % native forest.

Table 1. Correlation of river water quality variables (medians for the period 2005-08 from NRWQN) and percent of catchment in pastoral, arable and native forest land use types. All correlations are significant at $P < 0.05$. (From Davies-Colley, 2009.)

Parameter	% Pastoral	% Arable + Hort.	% Native Forest
Visual clarity	- 0.45	- 0.24	0.30
Total Nitrogen	0.85	0.45	- 0.39
Total Phosphorus	0.70	0.24	- 0.32
E. coli	0.80	(0.17)	- 0.34

Of the pastoral land use category, which makes up 42% of New Zealand's land cover, dairy farming has the highest diffuse pollution footprint with 36.7% of the Total Nitrogen load entering the sea originating from the 6.8% of the land area occupied by dairy farming (Table 2), while 'other pasture' (sheep, beef, deer etc) provides 38.9% of the Total Nitrogen from 31.9% of the land area (Elliott et al., 2005). This is not surprising given that the nitrogen loss rates from dairy farms are four times higher than from other pasture (*cf.* 39 kg/ha/yr compared with 8 kg/ha/yr from sheep and beef farms, and 5 kg/ha/yr from forest (MAF, 2008; Quinn et al., 2009).

Table 2. Land use area (%) and Total Nitrogen load to the sea as a % of the national total load (after Elliott et al., 2005). NA = Not Applicable. Total area of NZ = 263 500 km^2; total N load to the coast = 167 700 t/yr.

Pollution Source	Land use area %	Load to Coast %
Point sources	NA	3.2
Dairy	6.8	36.7
Other pasture	31.9	33.3
Trees (Native and plantation forest)	39.2	24.8
Other non pasture (mountains, scrub)	22.1	2.1

A recent study of 112 currently monitored New Zealand lakes (Verburg et al., 2010) found that 49 were eutrophic or worse and 29 were oligotrophic or better. However, bias in the distribution of the monitored lakes was acknowledged in that many lakes in natural areas were not monitored. Statistical extrapolation, accounting for this bias, indicated that 32% of all 3820 NZ lakes of >1 ha in area are eutrophic or worse, while 43% are oligotrophic or better. Of the monitored lakes, 73% of those in the eutrophic or worse category were located in predominantly pastoral land use catchments (Verburg et al., 2010).

Diffuse sources have thus now comprehensively supplanted point sources across the country. For example, at (nitrogen-limited) Lake Rotorua a sewage discharge was diverted in 1991 with an immediate decline in Total N in the lake, but Total Nitrogen levels are now higher than they were in 1991 due to steadily increasing nitrogen loads from catchment streams draining pastoral land (Figure 1).

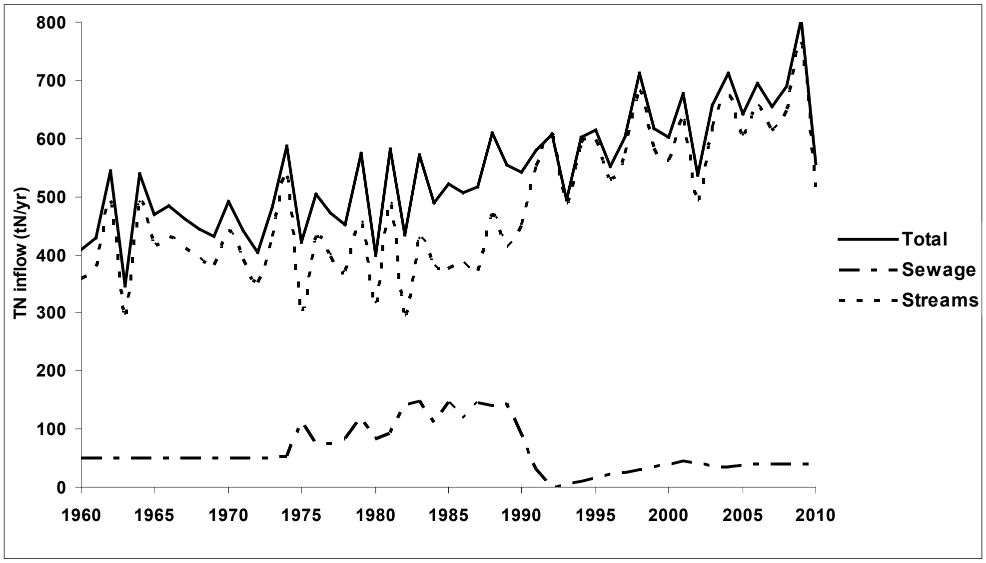

Figure 1. Diffuse pollutants continue to increase as point sources decline. At (N-limited) Lake Rotorua the sewage discharge was diverted in 1991 (Data from Rutherford, 2003 and unpublished) but diffuse inputs from streams continued to increase.

Management of diffuse pollution relies on the estimation for each catchment of the load that has arisen from human activity and is additional to the natural load. We estimate that 75% of diffuse source N & P flux to the sea is from modified landscapes, mostly pastoral and, as such, is theoretically manageable while 25% would be "natural". Lake Taupo, New Zealand's largest lake has a mixed land use catchment with 22% pastoral, 27% as plantation forest and the remaining 51% as native forest, scrub and mountain vegetation. The manageable loads there of Total N and P are only 40% of the natural load as modelled for pre-European times. Nutrient management in the Lake Taupo catchment has been focussed only on that 40%.

New Zealand catchment modelling indicates that the manageable load, as a proportion of the total load, varies not only with time but with distance downstream in rivers. In the case of the Waikato River, the manageable nitrogen load gradually diverges from the 'natural" load as the river progresses downstream to a distance of *ca.* 225 km, and then doubles in the next 50 km while the "natural" load increases by only 16% (Table 3). The manageable load increase is due to the inflows from a major tributary, the Waipa River. The situation for phosphorus is not as clear-cut because the Waipa would have provided a significant natural phosphorus load. In this case the manageable P load doubled below the Waipa junction and the "natural" load also doubled by 0.5 t P/day (Table 3).

Table 3. Waikato River natural nutrient loads and anthropogenic (manageable) loads (tonnes/day) vary with distance downstream from Lake Taupo (0 km). The "natural load" figures are the modelled load for the 1920s before hydropower development but after some limited land use change. 225 km is upstream and 250 km is downstream of the Waipa River inflow

Distance downstream (km)	Total Nitrogen load		Total Phosphorus load	
	1920 'Natural'	2010 Manageable	1920 'Natural'	2010 Manageable
0	1.2	-	0.09	-
75	1.5	3.0	0.2	0.3
170	4.2	6.4	0.4	0.7
225	6.1	9.2	0.51	0.9
Waipa River inflow here				
250	7.1	18.4	1.1	1.8
300	10.5	23.1	1.5	2.5

PATHWAYS OF DIFFUSE POLLUTANTS

Diffuse pollutants move into waters through three main processes:

i. surface runoff as overland from land to water;
ii. livestock direct access to waters (including wetlands and lake margins);
iii. leaching to groundwaters and subsequent re-emergence as springs.

i. Overland flow is probably the largest source of diffuse pollution in New Zealand and comprises mostly particulate diffuse pollutants (fine sediment, microbes and particulate N and P). It is highly flow-dependent as described above, and is mostly derived from critical source areas (CSAs) for runoff representing often only a small proportion of a catchment (Pionke et al., 2000; McDowell et al., 2004). Because surface runoff mainly occurs during and immediately after rainstorms, diffuse pollution from this pathway tends to correlate positively with stream flow – in sharp contrast to livestock access and groundwater seepage (and point source pollution) that tend to be *diluted* with increasing stream flow. In New Zealand rivers water clarity (inversely related to fine sediment) tends to decline with increase in discharge, while microbes, and total nitrogen and phosphorus concentrations increase with discharge – broadly consistent with the inference that overland flow is the dominant source of diffuse pollution in this country (Smith et al. 1996, Davies-Colley, 2009).

In a comparative study of pasture, pine and native forest catchments, Cooper and Thompsen (1988) found that on an areal basis, the pasture catchment exported about 15 times more P than either of the forested catchments and about 3 and 10 times more N than the native and pine catchments respectively. The proportion of TN export that occurred during stormflow in the pasture, pine, and native catchments was 90%, 52%, and 20%, respectively and similar proportions occurred for TP exports.

In any catchment or farm, identification of Critical Source Areas for priority attention to mitigate or ameliorate pollution in runoff is a necessary first step in diffuse pollution control. These areas can then be set aside for management actions that reduce pollutant runoff such as minimising fertiliser application or livestock exclusion or reduction. Beneficial Management Practices (BMPs) that are most appropriate to overland flow are those that act as 'filters' to intercept diffuse pollutants in the surface runoff. These include contour tilling and planting, grassy strips, wetlands and stream-bank vegetation. Other BMPs include the use of slow release fertiliser such as rock phosphate that minimises soluble fertiliser loss in rains (Hart et al., 2004), and livestock stand-off pads that prevent soil damage from treading compaction during wet weather (Table 4).

ii. Livestock direct access. This widespread pollution source is important in NZ and is a significant area for management attention. Direct livestock access to waters or wetlands adversely affects water quality by:

a. Physical damage by livestock treading and browsing to the vegetation, soils and substrates in and on the edges of lakes, wetlands and streams, increasing their susceptibility to erosion, sediment loss and pollutant runoff;

b. Direct dung and urine deposits in waters, which add nitrogen, phosphorus and faecal microbes.

A study in the Sherry River (http://icm.landcareresearch.co.nz/) has shown that river crossings of dairy herds between milking parlour and pasture up to four times daily approximately doubles average faecal pollution levels (Davies-Colley et al., 2004). The microbial quality of the Sherry River has greatly improved since the fords used for dairy crossings were all replaced by bridges, although the river still falls well short of contact recreation guidelines – mainly because dairy cattle continue to access unfenced channels from pasture.

Studies of direct pollution by sporadic access of cattle to streams have been conducted in New Zealand. Bagshaw et al. (2008) found that beef cattle in hill land spent about 2% of their time in stream channels to which they had unrestricted access, and inferred that a proportional amount of faecal deposition would go directly into stream water, with a further 2% deposited in the 'immediate' riparian zone (from which any rise in stream stage would readily entrain faecal matter). Bagshaw and co-workers also studied dairy cow access to unfenced streams (15 separate observational experiments on 5 different farms) and found that cows spent only about 0.1% of time in the channels, but deposited about 0.5% of faeces (Collins et al., 2007). Monitoring of stream water quality upstream and downstream of the dairy paddocks in 10 of the 15 experiments (Davies-Colley and Nagels, 2008) showed that the stream water was highly polluted with *E. coli* concentrations up to 30 000 cfu/100 mL. The faecal bacterial yield agreed well with observations that 0.5% of faecal deposits directly enter stream water, suggesting a 5-fold amplification of defecation rate water *versus* land.

Thus, fencing of stream banks in pastoral landscapes, ideally with a set-back to create a riparian buffer, is increasingly recognised as the most important BMP to arrest this pollutant pathway, with bridged stream crossings also important on dairy farms where cows move usually twice-daily to milking sheds, often crossing streams.

iii. Nutrients leaching to groundwater and their subsequent emergence in seeps and springs, is a particular issue in New Zealand's alluvial soils and porous volcanic soils where groundwater resources are often significant. This is a particular problem for nitrate entering aquifers in aerobic conditions although microbial pollution of groundwaters can also be significant in the near-field. In the intensively-farmed Waikato region 16% of bores exceed this guideline (Quinn et al., 2009). Recently, Hickey and Martin (2009) analysed acute (short-term) chronic (long-term) nitrate toxicity data in order to recommend freshwater guidelines for nitrate concentrations in natural waters. As a result of this analysis recommended guideline values for chronic toxicity were: a) 1.0 mg NO_3-N L^{-1} in pristine environments with high biodiversity values; b) 1.7 mg NO_3-N L^{-1} in slightly or moderately disturbed systems; and c) 2.4-3.6 mg NO_3-N L^{-1}in highly disturbed systems (i.e. with measurable degradation).

Of special note in relation to the management of nitrate pollution are the legacy issues that relate to extended residence times of polluted groundwater. In the Central North Island, nitrate from groundwater-fed springs and seeps is a major contributor to the total nitrogen load of large (nitrogen-limited) lakes. In the Lake Taupo catchment groundwater ages vary from 2.5 to 80 years (Morgenstern, 2007) with a mean age of water of 9 streams being 37 years, so the lake now receives nitrate from farming activities several decades in the past. The effects of current farming will not show up for several decades into the future. The policy response to this legacy of nitrogen in groundwater has been termed "the load to come"

(Vant and Smith, 2004). Lake protection and remediation programmes in the Central North Island have been required to account for the load to come when calculating nutrient input budgets and time scales of change

ATTENUATION OF DIFFUSE POLLUTANTS

Attenuation of pollutants with distance downstream from the source of flow is an important consideration for modelling (Rutherford, 1987; Elliott et al., 2005) and management. Attenuation of overland flow takes place on land through natural interception mechanisms (and BMPs) as mentioned above and it takes place adjacent to, and in, streams where different nutrient attenuating systems have been identified (Downes et al., 1997). These were:

i. streams receiving lateral flow where nutrient processing occurred in groundwater and in surface runoff adjacent to the stream;

ii. Streams with spring sources where nutrients were attenuated in the stream channel.

In the first case, 'Lateral Attenuation', particulate and dissolved inorganic nutrients are removed when surface and subsurface water flows through riparian vegetation before reaching the stream channel. In the second case 'Instream Attenuation', processes such as plant and microbial uptake (denitrification in the case of nitrate) can remove nutrients from waters within the stream channel itself. Other Instream Attenuation processes such as hyporheic exchange, sediment exchange, microbial pollutant die-off in sunlit channels, long-term storage of sediments (infilling) and nutrient transformations (i.e. from dissolved inorganic nutrients to particulate nutrients and vice versa) have also been demonstrated as important. These processes combined reduce fluxes and the concentrations that would otherwise be encountered in downstream water bodies.

i. Lateral attenuation: Attenuation of runoff through riparian vegetation on stream edges has been the subject of long study in New Zealand with one of the seminal works being that of McColl (1978). He showed then the value of riparian vegetation along pasture streams as nutrient traps for overland flow of phosphorus to stream channels during rain storms. The study provided "strong support for the use of buffer strips of vegetation along stream channels as a means of protecting streams from phosphorus losses".

In a study of faecal coliform attenuation in pasture lands, Collins et al. (2004) found that during large runoff events, and where preferential flowpaths occur, buffer strips need to exceed 5 m in length in order to markedly reduce the delivery of faecal microbes to waterways, but during low-rates of water application to pastures, riparian buffers trapped >95% of *E.coli* in the runoff. Cooper et al. (1995) provided a note of caution in the long-term sustainability of riparian strips for lateral attenuation, suggestion that riparian soils can become saturated with P. The results imply that riparian set-asides may lead to the development of a zone likely to supply runoff to the adjacent stream that is depleted in sediment-bound nutrients and dissolved N but enriched in dissolved P.

ii. Instream Attenuation of pollutants has been modelled as a first order decay process (see Cooper and Botcher, 1993; Hearne and Howard-Williams, 1988; Elliott, 2005) so that downstream concentration $C_z = C_0 e^{-Kz}$, where C_0 is the source concentration, K is the attenuation coefficient (m^{-1}) and z is distance downstream (m). In the case of nutrients, the downstream attenuation coefficient for dissolved nutrients in water (K_w) may also be calculated from $K_w = R_w / F_w$ where R_w is the mass of nutrient removed per unit time per meter of stream length and F_w is the nutrient flux (mass per unit time) in the suite of equations describing nutrient spiralling (Newbold et al., 1981). Most diffuse pollution occurs in small (low order) streams that have the greatest attenuation capability. This is demonstrated by the strong dependence of K_w on stream and river discharge (Rutherford et al., 1987; Figure 2). The information suggests that for optimising nutrient attenuation, attention should be paid to streams that have a K_w of greater than 0.0001/m or > 10% loss of nutrient per km of stream length. These conditions are found in streams with a flow rate of < 0.5 m^3/s (Figure 2).

The nutrient attenuation coefficient (K_w) for mid summer periods in the Whangamata Stream in the central North Island was shown to vary fifty-fold, in a cyclical manner, from 0.03/m to 1.5/m.over a 30 year period. This reflected changes in discharge, in-stream vegetation biomass, stream shade by riparian vegetation, and in-stream plant species composition (Howard-Williams and Pickmere, 2010).

In addition to stream attenuation of nutrients there is increasing evidence of high variability in attenuation processes operating in groundwaters particularly for nitrate-N. For instance at Lake Rotorua groundwater appears to be well oxygenated (viz., little denitrification) so attenuation of groundwater N is unlikely. By comparison, at Lake Taupo many groundwaters are anoxic (Hadfield, 2007) and have low nitrate concentrations with an assumption of high denitrification rates on organic-rich layers in the aquifers (Stenger et al., 2009).

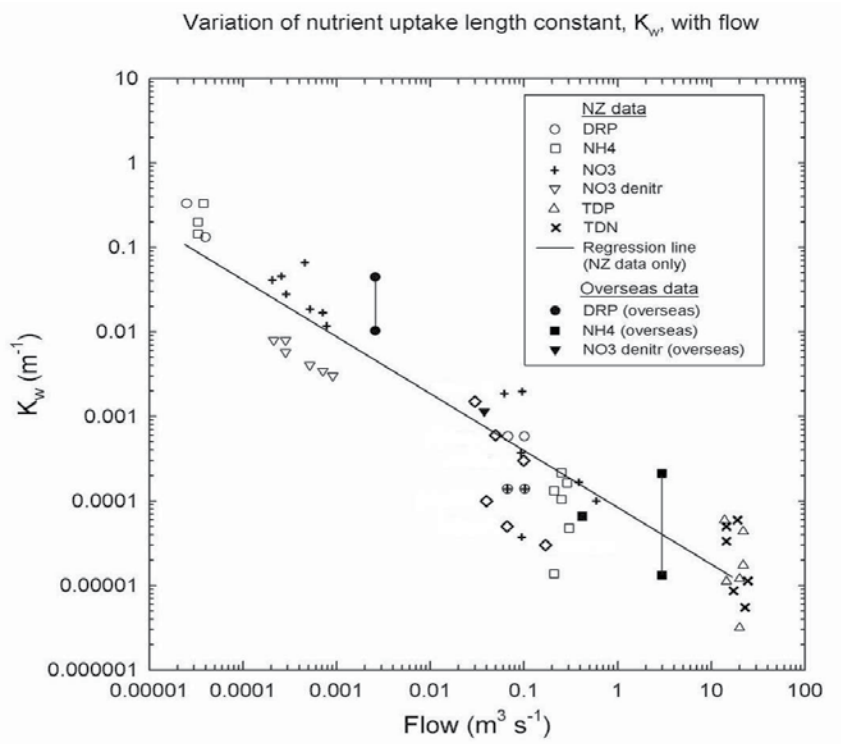

Figure 2. (After Rutherford et al., 1987).
Variation in the downstream attenuation coefficient for dissolved nutrients (K_w) with stream flow

A number of factors affect attenuation (Table 4) and in addition to managing these for nutrient removal, considerable advances can be made by maximising attenuation at diffuse pollution source sites on farms. A comprehensive statement on the effectiveness of on-farm mitigation strategies for managing contaminant sources was provided by Quinn et al. (2009).

Table 4. Mechanisms that enhance attenuation in streams and prevent nutrient loss from farm soils to waters.

Enhancing attenuation in and near waters	Reducing nutrient loss from farms
Riparian strips,	Riparian and farm drain management
Wetland and seep protection	Slow release fertilizers
Maximising aerobic-anaerobic interface for denitrification	Nitrification inhibitors
Constructed wetlands	Constructed wetlands
In-channel vegetation	Nutrient budgets, nutrient mapping
	Feed pads, herd homes, wintering off-site
	Improved weather and climate forecasting
	Nutrient trading/capping

MODELLING

Diffuse pollution modelling in New Zealand has been done through statistical, mechanistic, stochastic and conceptual approaches (e.g. Decision Support Systems and Bayesian Belief Networks) and includes several of the models reviewed for the EU Water Framework Directive (Yang and Wang, 2009). Statistical modelling includes SPARROW (Alexander et al., 2002) which accounts for in-stream attenuation. This has been used to define pollutant loads to the sea across the New Zealand landmass (Elliott et al., 2005) and to focus on more detailed catchment understanding. SPARROW forms the core of a recent model package (Catchment Land Use for Environmental Sustainability – CLUES); which was specifically designed to be used by water managers and combines underlying landuse pollutant spreadsheet approaches such as OVERSEER$^{(TM)}$ with SPARROW to relate catchment pollutant loads on a GIS framework (McBride et al., 2008). The resulting package allows for a map-based delineation of land uses and provides GIS images of seasonal or annual loads of pollutants through the stream network.

Other catchment models that have been used with success are GLEAMS (and GLEAMSHELL) (Cooper and Bottcher, 1993). Catchment nutrient modelling with GLEAMSHELL provided the nutrient inputs to New Zealand's largest lake, Lake Taupo for scenarios that investigated proposals for increased dairy farming in this nitrogen sensitive area. The model, together with an in-lake dynamic ecosystem model (Spigel et al., 2001; Hamilton and Wilkins, 2004), resulted in a Policy Response (Variation 5 to the Waikato Regional Plan) that limits future land-use intensification in the catchment. This includes a nitrogen capping policy that limits inputs to the lake and accounts for "the load to come" of nitrate in groundwater.

Recently the statistical ROTAN model (Rutherford et al., 2009) has been developed to quantify the role of groundwater lags in delaying the response to landuse changes of nitrogen inputs to lakes Rotorua and Taupo. ROTAN is currently being used to calculate how quickly lake inputs will decrease if nitrogen exports from land are reduced in different parts of the Lake Rotorua catchment – so that the mitigations including land purchase and retirement can be targeted where they will be most cost-effective and timely. An empirical approach to modelling diffuse pollution is that of Unwin et al. (2010) who make use of the spatial framework tool, the "River Environment Classification" (Snelder and Hughey, 2005) to model water quality.

Mechanistic models for exploring microbial diffuse pollution have been reported by Collins and Rutherford (2004). These have highlighted the very different 'microbial regime' of baseflows compared to (microbially polluted) stormflows when microbes are entrained by flood currents and washed into waters with overland flow – resulting in polluted storm plumes affecting downstream waters and coasts. A stochastic approach of increasing interest in New Zealand is quantitative microbial risk assessment (QMRA) to investigate health risks to humans of microbial pollution of recreational or drinking waters or bivalve shellfish under different pollution scenarios (McBride, 2007).

MANAGING DIFFUSE POLLUTION

Management of diffuse pollution involves approaches at several levels: reductions of nutrients at source (i.e. by reducing animal stocking rates); retiring, or not permitting certain activities on, sensitive land in sensitive catchments and by widespread application of mitigation methods. It is widely accepted that there is no single mitigation option for diffuse pollution reduction (e.g. Stevens and Quinton, 2009 and Quinn et al., 2009 for arable and pastoral systems respectively). Diffuse pollution management is receiving attention at four levels: i). national government; ii). regional government; iii). rural industry promoted standards and iv). community-led initiatives. Several management instruments are currently being evaluated involving combinations of the above. Regulating for diffuse pollution is not the single answer, even if this were (to become) politically tenable. In the UK, the National Farmers Union rejected regulation as an answer to diffuse pollution stressing the need for advice-based voluntary approaches (Whyte, 2004), a sentiment also strongly expressed by the various agricultural sector groups in New Zealand where a recent Government panel has recommended a matrix of governance and management approaches to the problem (Land and Water Forum, 2010). These approaches range in scale from national to local in the following sequence:

- defining national objectives based on values setting for water quality;
- establishing limits and standards at regional scales but based on spatial frameworks to account for natural landscape and waterway variability; and
- collaborative processes at catchment scales (“integrated catchment management”) that involve both industry and local stakeholders.

Key to this last point is strong rural industry engagement to provide credibility, advice and incentives, as well as the introduction of adaptive management and audited self management as tools for promotion and validation of BMPs. Across all these scales in New Zealand are the interests of the indigenous Maori (‘first nation’) people who have traditional obligations to protect freshwater so as to “leave a worthy inheritance for future generations” (Land and Water Forum, 2010). Negotiations on the role of Maori in freshwater management up to and including full co-management of water bodies (e.g. Collier et al. 2010) are currently underway.

Regional governments in New Zealand have been increasingly active in the last decade in promoting water protection. In Taranaki the Regional Council provides a riparian planning service “to maintain water quality in the region”.

Since the late 1990s it has:

- Prepared (free of charge) more than 2 000 farm riparian management plans, focussed mainly on fencing and planting ;
- Promoted 500 km of stream fencing and 425 km of stream bank re-vegetation which, when added to existing fencing and planting means that 60% of stream bank, on the lowland “ring” plain under a riparian plan, is fenced, and 43% is vegetated.;
- Supplied 1.5 x106 plants (300 000 plants in 2010 alone) at cost;
- Detected a 30% improvement in stream ecological health using a Stream health Monitoring and Assessment Kit (SCHMAK), and in this time no negative trends have been detected in the monitored streams.

In two sensitive lake catchments deemed to be of national significance, Lakes Taupo and Rotorua, the last decade has seen national government intervention to assist with lake restoration initiatives that have established nutrient load limits. These have been set following extensive scientific consultation advice and modelling in conjunction with broad community consultation. Thus, in the case of Lake Taupo, the legislated “Regional Plan Variation 5 (Lake Taupo)” imposes a cap (a Nitrogen Discharge Allowance or NDA) on nutrient loads leached from individual farms which is based on the load in their "best" recent farming year. A NDA can be traded between farmers. A 20% reduction in the manageable loads is to be achieved over a 10 year period to accommodate the "load to come" through the purchase and retirement of farms by the Lake Taupo Protection Trust (www.laketaupoprotectiontrust.org.nz).

In the case of Lake Rotorua, a target of 435 t N/yr has been set for the nitrogen input to the lake – the input during the 1960s before there was widespread concern about algal blooms in the lake. Currently nitrogen export within the catchment totals 825 t N/yr, of which >80% originates from pastoral farming. Streams have a large groundwater component and the mean "age" of groundwater ranges from 15 to 110 years which means that even if nitrogen leaching losses from pasture were reduced immediately, it would take several decades for the input to the lake to reduce. Internal releases of nutrient from the lakebed during summer stratification are also likely to delay lake recovery. Measures are currently being considered to reduce nitrogen exports and to reduce internal lake loads.

Significant approaches to water governance at regional and local levels and combining regulation and voluntary action have been proposed in the last few years; Regional government initiatives include the Horizons council's "*One Plan*" that will see the establishment of Water Management Zones with specific controls over landuse intensification of farming activities at catchment and sub-catchment scales, and a mix of 'persuasion, advice and rules to manage water quality within the Management Zones'. Using a similar approach, the Canterbury Regional Council's recent approval of the *Canterbury Water Management Strategy* will see a combination of regulatory action set at regional level, to deal with environmental problems complemented with incentive mechanisms that progressively drive efficiency in the use of water and responsible land management practices. This will be done through ten Water Management Zones sufficiently large to enable the management of surface and groundwater systems to be integrated with the management of the areas where the water is used but also small enough to avoid becoming remote from local catchment issues. Water management zones are seen as spanning the divide at the right scale between regulation and community and industry voluntary action.

As detailed in the water planning frameworks for many countries, catchments are usually the best spatial management unit. In New Zealand, Beneficial Management Practises in dairy farming areas have been quantitatively evaluated over the last decade through a set of five "Best Practise Dairy Monitor Catchments", which demonstrate the efficacy of BMPs (Wilcock et al., 2007) in different dairy-dominated catchments in five regions of the country with varied climate and soils. In the Whatawhata Hill Country experimental farm, retirement of much riparian and steepland in the Mangaotama Catchment has improved water quality and aquatic ecological health in less than a decade (Dodd et al., 2008), although some expected benefits are expected to take longer owing to 'legacy' effects to do with nitrogen in groundwater and stored sediment in streambanks.

As part of the Primary Sector Growth Partnership in New Zealand, "the fertiliser industry is responsible for meeting its commitments to ensuring the sustainable use of freshwater resources in the primary sector. These commitments include: by 2013 80% or nutrients applied to land nationally are managed through quality assured nutrient budgets and nutrient management plans…" (Land and Water Forum, 2010). The dairy industry has signed the voluntary 2003 '*Dairying and Clean Streams Accord*' that had achieved the following by 2008-09: 1. Dairy cattle are excluded from streams, rivers and lakes -80%; 2. Regular race crossing points have bridges or culverts -97%; 3. All dairy farms have in place systems to manage nutrient inputs and outputs -97%; 4. All dairy farm effluent discharge complies with resource consents and regional plans -60%. These data need to be treated with some circumspection as one influential report disputes industry claims about the percentage compliance with the "Accord" (Deans and Hackwell, 2008). Whatever the final numbers, the industry intervention is producing positive environmental outcomes from existing dairy farms. However, of on-going concern is continuing degradation as a result of conversions from sheep and beef farming to dairying (Environment Waikato, 2008).

Managing diffuse nutrient loads through regulation by setting load limits (nutrient caps) on catchments, and through identified nutrient concentration targets (regional planning standards) in downstream waters needs to be directed by government (central and regional) regulatory agencies. This should be combined with co-operative approaches with the rural industry sectors and rural communities to work through voluntary mechanisms (Codes of Conduct, Audited Self Management (ASM) schemes, adaptive management) to implement good management practise.

FUTURE DIRECTIONS

Further improvement in management of diffuse pollution needs attention by science and by government agencies at several scales of policy and regulation, by industry and by communities in catchments.

Science attention should focus on:

- Definition of pollutant pathways,
- Understanding of attenuation mechanisms (including for targeting BMPs),
- Modelling spatial extent, levels and sources of "manageable loads", with user accessibility to models fostered to maximise information transfer,
- Assess effectiveness of BMPs, taking natural spatial variability into account.

Policy, Regulation, incentives and community actions in relation to water resources in New Zealand are currently being re-examined by several agencies (Land and Water Forum, 2010). These include:

- National objective setting, including national environmental standards, is needed to ensure consistency of values and approaches
- Setting of regional standards based on values of receiving waters in a spatial context, and on system time lags. Setting limits (and targets if there is a need to claw back diffuse pollution) is currently a mechanism that regulators have to reduce cumulative impacts of landuse and prevent further diffuse pollution at catchment scales.
- Work with industry landowners and catchment stakeholders, increasingly in ICM-type frameworks, to promote mitigation methods and local-scale management (incentives, BMPs, audited self management, community restoration schemes).

ACKNOWLEDGEMENTS

We thank the OECD for sponsorship for one of us (C.H-W) and the National Institute for Water and Atmospheric Research for travel funding (for R.D-C and R.W) to the DIPCON 2010 Conference in Quebec. Drs. John Quinn and Sandy Elliott provided considerable intellectual input to this review.

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