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Diffuse contributions dominate over point sources of soluble nutrients in two sub-catchments of the Manawatu River, New Zealand

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Nitrogen and phosphorus concentrations in the Manawatu River, New Zealand, are among the highest nationally. To target policies to address these nutrient levels effectively, this study sought information on relative contributions of soluble nutrients from point and diffuse (non-point) sources at various river flows and in relation to concentration-based regulatory targets using load calculations. In the upper Manawatu and Mangatainoka sub-catchments of the Manawatu River, measured nutrient loads were 55–154% greater than target nutrient loads. Measured loads were predominately from diffuse sources, which contributed 98% or more of the soluble inorganic nitrogen (SIN) and 84–88% of the dissolved reactive phosphorus (DRP) at all flows. At low flows, point source inputs contributed up to 64% of the DRP in the upper Manawatu sub-catchment. This study suggests policy to manage nutrient enrichment in these areas should target inputs from diffuse sources at all flows, along with management of point sources at low flows.

Keywords: water quality targets; nitrogen; phosphorus; nutrient loads; point source; non-point source; diffuse; river flow; load calculation; nutrient management policy

Introduction

In New Zealand, central government legislation (the Resource Management Act 1991) directs local government agencies, known as regional councils, to manage freshwater resources in their regions. To achieve this, regional council functions include the control of discharges into or onto land, or into water and control of land use for the purposes of maintaining and enhancing water quality. The policy guidance for implementing these controls is set by regional councils through regional policy statements and regional plans (Richmond et al. 2004). New central government legislation, the National Policy Statement for Freshwater Management (NPS 2011), directs regional councils to set water quality limits to provide for freshwater objectives, and that where these objectives are not met, time-bound targets for water quality are to be specified and policy and plans implemented to ensure these are met in the future.

Policy development to achieve these requirements can be informed by an understanding of how current water quality relates to the objectives, limits and targets and the relative contributions of the sources of contamination. This study aims to determine the relative contributions of point and diffuse sources to nutrient levels in relation to regulatory targets and flows in two sub-catchments of the Manawatu catchment. This information was sought by the Manawatu–Wanganui Regional Council as a part of policy development to update the existing Plans into an integrated planning document known as the 'One Plan' a combined regional and coastal policy statement and regional plan.

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Management of nutrients in waterways of the Manawatu catchment is primarily to reduce nutrient concentrations to levels that decrease the proliferations of plant and algal material collectively known as periphyton. At nuisance levels, these proliferations adversely affect the ecological, recreational, aesthetic and cultural values of rivers and streams by changing the physicochemical properties of the water, reducing the availability and quality of aquatic habitat and covering the substrate with unsightly algal growths (Biggs 2000a, 2000b). In severe cases, periphyton-induced changes in physicochemical and habitat properties of a river can be lethal to invertebrates and fish (e.g. via lowering dissolved oxygen concentrations; Dean & Richardson 1999). Some forms of soluble nutrient are also managed in the Manawatu, as they can be toxic to freshwater water aquatic species at high concentrations, for example ammonia (Hickey & Vickers 1994; Richardson 1997; Richardson et al. 2001) and nitrate (Hickey & Martin 2009).

There are several mechanisms available to control the proliferation of periphyton. The primary control of maximum periphyton biomass in unshaded rivers is the frequency of flushing flows that reset the growth of periphyton through physical removal and scouring of the river bed (Biggs 1990, 1995, 2000a, 2000b) and this has been proven effective as a management tool (Biggs et al. 2008). River channel shading can also be a useful periphyton control for smaller tributary streams and rivers, slowing growth by reducing light inputs and lowering water temperatures (Davies-Colley & Quinn 1998; Boothroyd et al. 2004; Quinn et al. 2009). However, flow manipulation and shading are impractical for the management of periphyton in large, non flow-regulated channels like the main-stem of the Manawatu River. The primary mechanism for control of periphyton growth in the Manawatu River is limitation of the plant available nutrients, soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP).

Several studies have determined the need to control both SIN and DRP to manage the growth of periphyton in New Zealand rivers (Biggs 2000a; Wilcock et al. 2007; McDowell & Larned 2008; Roygard & McArthur 2008; Roygard 2009; McArthur et al. 2010). For example, McDowell & Larned (2008) studied nutrient ratios (SIN:DRP) at 1100 regional council water quality sites and determined that 76% of sites were phosphorus limited, 12% nitrogen limited and 12% co-limited. They concluded that the prudent approach to nutrient management was to mitigate both nitrogen and phosphorus inputs. Subsequent studies in the Manawatu catchment found that the limiting nutrient can differ within a sub-catchment on the same day and that nutrient limitation at a particular site can change with time and flow (Roygard & McArthur 2008; Roygard 2009; McArthur et al. 2010). Studies also recommended management of SIN and DRP year round at flows below flood flows in the Manawatu–Wanganui and Hawkes Bay regions of New Zealand (Wilcock et al. 2007). Prior to these studies, the previous regional Plan that managed water quality in the Manawatu catchment, the Manawatu Catchment Water Quality Regional Plan (MCWQRP 1998) managed nutrient enrichment through limits on DRP concentrations at flows below the half the median flow for point sources. The concentration based targets in the One Plan for the two study sub-catchments of the Manawatu catchment discussed in this study were set at 0.444 g SIN/m^3 and 0.010 g DRP/m^3. These targets apply year round at all flows less than the 20th flow exceedance percentile (highest 20% of flows) with flows greater than this level defined as ‘flood flows’. The 20th flow exceedance percentile threshold was selected as an approximation of the flushing flows required to remove periphyton (Roygard 2009; Kilroy et al. 2010; McArthur 2010).

Nutrient concentrations in the Manawatu catchment regularly exceed the One Plan targets and ANZECC (2000) trigger values and are ranked amongst the highest in New Zealand when compared with data from the National Rivers Water Quality Network (MfE 2007, 2009; Ballantine & Davies-Colley 2009a; Ballantine et al. 2010a). Nitrogen concentrations increased at all three National Network sites in the Manawatu catchment between 1991 and 2008, whereas phosphorus trends were more variable (Ballantine & Davies-Colley 2009a, 2009b; Ballantine et al. 2010a, 2010b). Overall, nutrient trends indicated degrading water quality at the Manawatu sites between 1991 and 2008 (Ballantine & Davies-Colley 2009a).

Nutrient trends in the Manawatu are consistent with the strong increasing trends in nitrogen and phosphorus reported nationally (Scarsbrook 2006; Ballantine & Davies-Colley; 2009b; Ballantine et al. 2010a, 2010c). Increasing national trends in nutrient concentration were attributed to the expansion and intensification of pastoral agriculture with all studies concluding that environmental gains in terms of reduced point source pollution of waters in New Zealand were being overshadowed by increasing diffuse source pollution (Scarsbrook 2006; Ballantine & Davies-Colley 2009b; Ballantine et al. 2010a, 2010c). These studies are supported by the findings of Elliot et al. (2005), who modelled nationwide loads of total nitrogen (TN) and total phosphorus (TP) from the New Zealand land mass to the sea and showed that 3% of the TN and 1.8% of the TP could be accounted for by known point sources. However, there is little data about the specific relative contributions from different sources of nutrient to rivers and lakes in New Zealand (PCE 2010). This is a critical information gap for policy makers seeking to address nutrient enrichment. The few studies that do exist are primarily for lakes and have focused on total nutrient concentrations rather than soluble nutrients, which are more important in river nutrient management.

Regulatory targets for nutrients are typically expressed as concentrations to limit nuisance plant growth and ensure ammonia and nitrate are not toxic to aquatic life. Management of nutrient concentrations can be informed by determining nutrient loadings that are the nutrient flux (concentration multiplied by the flow) over a period of time. Nutrient concentration outcomes can be achieved by managing the combined loads from point and diffuse sources. For example, point sources are often managed by daily limits on discharge volume, contaminant load or concentration. Diffuse sources are more typically managed over annual time scales using nutrient budgeting tools that estimate losses from farming systems. Relating the annual losses determined by these tools to nutrient loadings and concentrations in waterways requires knowledge of the areas of different land uses and the total nutrient losses from each of these land uses accounting for any nutrient losses and timing delays as the nutrient moves from the area of the land use to waterways (Roygard 2009). Management of losses from farming systems via annual nutrient budgets has been incorporated into regulatory water quality management approaches for lakes in New Zealand (Ledgard et al. 2001; Quinn et al. 2009). These approaches have utilised the OVERSEER® model that predicts long-term average annual nutrient losses from farming systems (Wheeler et al. 2003, 2006) and is the most commonly used tool to assist farmers to meet voluntary dairy-industry nutrient budgeting requirements and for fertiliser recommendations on sheep, beef and dairy farms (Ledgard et al. 1999; Wheeler et al. 2007).

A first step to achieve the regulatory target concentrations in rivers is to determine the relative contributions from point and diffuse sources at a range of flows. This is complicated by the regulatory targets applying only at certain flows. To provide answers relevant to the varying mechanisms of contamination (point and diffuse sources) and the management of these, this study sought to develop and apply a calculation framework to two sub-catchments of the Manawatu catchment to determine:

(1) The translation of concentration-based soluble nitrogen and phosphorus targets as annual loads;
(2) How annual loads change when flood flows (periods where the targets do not apply) are excluded;
(3) The measured annual loads of nitrogen and phosphorus in the river and how these relate to the regulatory targets;
(4) The relative contributions from point and diffuse sources to these annual loads;
(5) How the relative contributions from point and diffuse sources change with river flow for each nutrient; and
(6) How the relative contributions compare with target loads at various flows.

Materials and methods

Study sub-catchments

The two study sub-catchments, the upper Manawatu and the Mangatainoka, are in the upper reaches of the Manawatu catchment (Fig. 1) and have a combination of point and diffuse pressures on water resources.

Water quality in the upper Manawatu sub-catchment is measured at the Manawatu at Hopelands site, which has a catchment area of approximately 127,000 ha. Land use in the upper Manawatu is estimated to be 58% sheep and/or beef farming, 16% dairy farming, 8.4% native cover, 3% plantation forestry, 0.4% cropping with other land uses (including urban areas) making up the remaining 14% (Clark & Roygard 2008). The major point source discharge is from the sewage treatment plant of the Dannevirke Township (population 5510 in Census 2006) and is located approximately 24 km upstream of the Hopelands site.

Water quality in the Mangatainoka sub-catchment is measured at the Mangatainoka at State Highway Two (SH2) site, which has a catchment area of approximately 42,000 ha. Land use upstream of the SH2 site is estimated to be 47% sheep and/or beef farming, 30% dairy farming, 21% native cover, 2% plantation forestry and 1% urban and other land uses (Clark & Roygard 2008). The Mangatainoka has one of highest proportions of dairy farming in the wider Manawatu catchment (Clark & Roygard 2008). The major point source discharge in the Mangatainoka is from the sewage treatment plant of the Pahiatua Township (population 2559 in Census 2006).

Over the study period, discharges of farm dairy effluent to water in the two sub-catchments have significantly, reduced as regulations of the MCWQRP (1998) required a transition to land-based effluent discharge. Other point source discharges are present in both sub-catchments. However, the SIN and DRP contributions from these to overall measured loads are considered minor (McArthur & Clark 2007; Clark 2010).

Data sources

Nutrient data were sourced from the monthly sampling at the Manawatu at Hopelands site (over 15 years) and the Mangatainoka at SH2 site (over 12 years) and flow data were provided by long-term hydrological monitoring records. Nutrient data from the Dannevirke sewage discharge was from compliance monitoring upstream and downstream of the discharge ($n = 30$). Estimations of nutrient loads for the Pahiatua sewage discharge were from averages of available nutrient concentration ($n = 60$) and discharge volume data (McArthur & Clark 2007).

Contaminant load calculations

Nutrient loads can be calculated in several ways (Richards & Holloway 1987; Ferguson 1986, 1987; Richards 1998; USEPA 1999; Guo et al. 2002; Aulenbach & Hooper 2006; Rhode & Suhr 2007) each of which tries to resolve a fundamental question: 'What were the loads at times when water quality was not measured?' Load calculation methods fit four main categories summarised by Aulenbach & Hooper (2006):

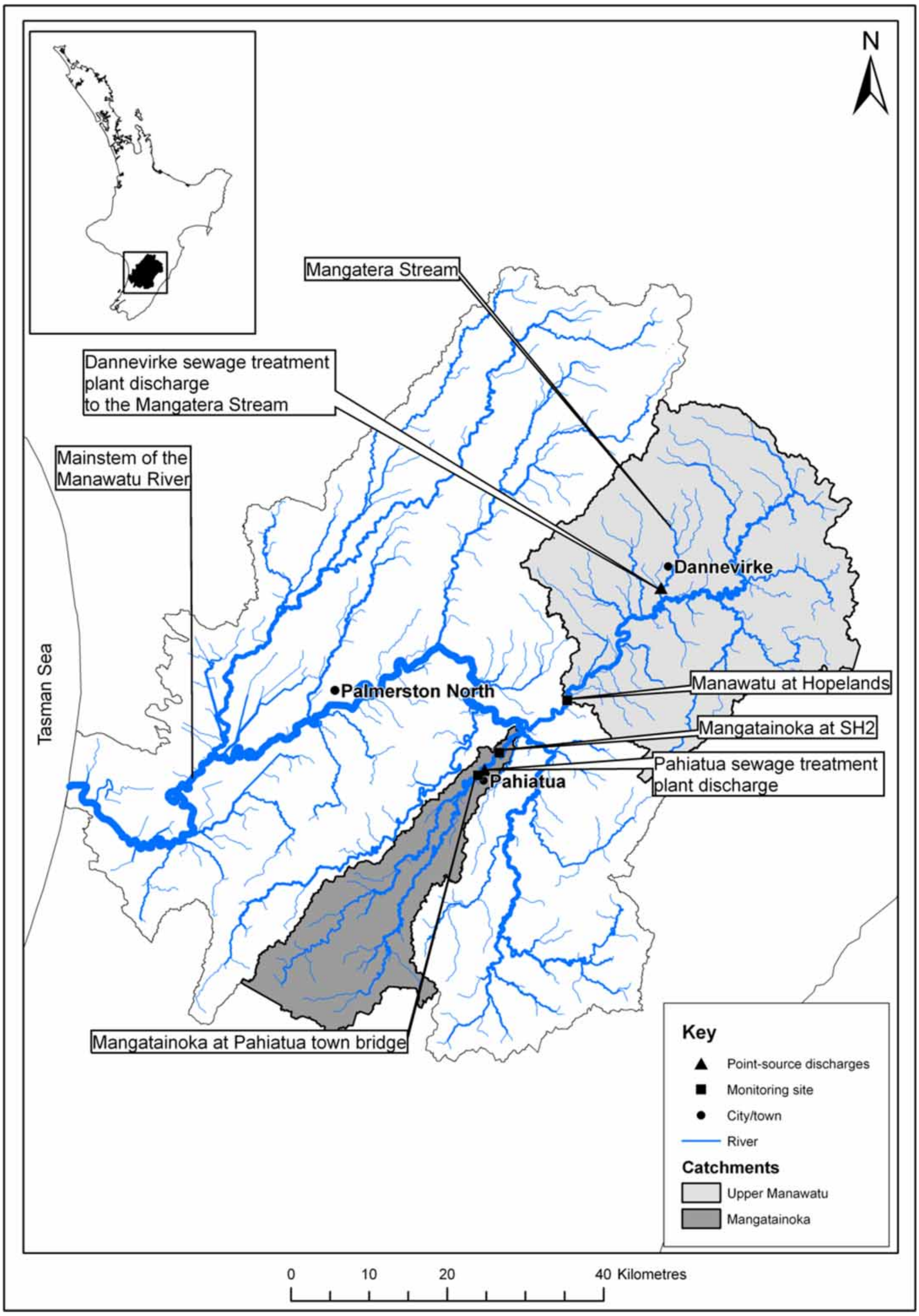

Figure 1 The Manawatu River catchment showing the water quality and flow recording sites of two study catchments: the upper Manawatu and the Mangatainoka.

(1) Regression/rating curve approaches: the regression relationship (or visualised rating curve) between flow and measured nutrient concentration is used to estimate a representative concentration for time between samples, from which a load for the period is calculated.
(2) Averaging approaches: various forms of average concentration and average flow over the same time period are multiplied to calculate loads.
(3) Period-weighted approaches: measured nutrient concentrations are representative of a period of time around which the sample was collected and are multiplied by a measure of flow during that period (e.g. a single monthly nutrient result is multiplied by the average monthly flow). This approach is highly sensitive to sample size.
(4) Ratio estimators: the average load is calculated for days with nutrient concentration observations and adjusted proportionally by a variable that is more frequently measured (i.e. flow).

United States Environmental Protection Agency guidance on calculating pollutant loads identified that regression approaches can be subject to retransformation bias because raw data does not fit a linear regression model (Richards 1998). This can lead to large errors in load calculation (Richards 1998).

Accuracy and precision in load calculation is highly influenced by sampling frequency (Richards 1998; Aulenbach & Hooper 2006). In New Zealand, monthly water quality sampling is the most common sampling frequency with the National Rivers Water Quality Network (Ballantine et al. 2010c) and most regional councils sampling monthly. Monthly sampling programmes for simple load estimation yielded estimates, which were biased low by 35% or more, 50% of the time in load simulation studies for some tributaries of the Great Lakes in the United States (Richards & Holloway 1987). These underestimates may in part be related to inaccurate calculation of some of the key components of the annual load. For example, it is not uncommon for more than 80–90% of an annual load to be delivered over 10% of the time during the highest flows (Richards 1998). Richards (1998) noted that the accuracy and precision of loading estimates from averaging approaches increased when stratification was employed and an additional approach, such as a ratio estimator, was used within strata. Aluenbach & Hooper (2006) also advocated a composite method to increase accuracy in loading estimates.

Following the recommendations of Richards (1998) and Aluenbach & Hooper (2006) our study employed a composite load calculation method which incorporated flow stratification (period-weighted) in addition to an averaging approach to nutrient concentration within each of the strata (defined below). Stratification was achieved by defining 10 flow categories based on the percentage of time flow was within a certain range. Ten equal time-based categories (flow decile bins) were defined using flow distribution statistics. By design, these were period weighted, as each flow decile bin represented a range of flows for 10% of the time over the length of the flow record.

The flow-stratified averaging approach potentially reduces bias resulting from monthly sampling, which does not representatively sample the full range of flows (e.g. either very high or very low flows). This stratification also provided a framework to answer the questions of this study as it enabled the relative contributions of nutrient load from point and diffuse sources to be calculated for each flow stratification category to determine how these sources varied at certain flows.

Conversion of concentration-based targets to annual loads

Conversion of concentration-based targets to annual target loads was completed using each 15-min flow observation multiplied by the concentration based targets. These loads were then assigned to the appropriate flow decile bins for each year. Data in each flow decile bin for all years were then summed and divided by the number of years of record to determine the average-annual target load for the period of record.

Exclusion of flood flows

Loads at flows below the 20th exceedance percentile flow were calculated by removing the loads assigned to the two flow decile bins that represented data for the highest two flow decile bins (0–10th and 10th–20th exceedance deciles) from the annual load calculations.

Measured loads

River flow at the time of sampling and concentration of the nutrient sample were multiplied to characterise an instantaneous load (flux). This load was then applied as a representative sample for the flow decile bin within which the flow at the time of sampling fell. These representative samples were used to calculate the averages for the flow decile bins, which were then multiplied by the frequency of occurrence of the flows within the bins (10% of the record, i.e. 36.5 days of the year on average). These totals were then summed to calculate a long-term loading estimate over an annual period.

Relative contributions from point and diffuse sources

Calculations of relative contributions from point and diffuse sources were completed under the conservative assumptions that the point source inputs do not change between the point of discharge and the downstream recording sites, i.e. there is no reduction of soluble nutrients by plant uptake or other processes and no increase in soluble nutrients through transformation of the organic nutrient discharged by the point source. The calculations for diffuse contributions include any changes in soluble nutrient loads through assimilative or transformative mechanisms.

A flow-stratified method was used to calculate load based on river flow data and measurements of nutrient concentrations upstream and downstream of the Dannevirke township sewage treatment plant effluent discharge. Because of an absence of sampling data in the highest two flow decile bins (0–10th and 10th–20th exceedance deciles), concentrations for these bins were estimated using the value for the 20th–30th flow decile bin.

In the absence of adequate data for the flow stratified method, an alternative method was used to determine the point source load in the Mangatainoka catchment. Loads for each flow decile bin were calculated from the average discharge volume and average effluent concentration ($n = 60$). The underlying assumption that flow and concentration (and therefore load) were not correlated requires re-examination when improved data becomes available. Annual diffuse source inputs were determined by subtracting point source loads from the measured load for each flow decile and summing these.

Change in relative contributions with flow

The flow-stratified approach was used to determine relative contributions of point and diffuse sources in each flow decile bin. This was only possible for the upper Manawatu case study where the upstream and downstream monitoring information for the Dannevirke STP discharge was available to determine variation in the point source inputs with flow, providing for the application of the flow-stratified methodology.

Results

Nutrient concentrations compared with water quality targets

Concentrations of soluble nutrient at the Hopelands site regularly exceeded the regulatory targets in all flow categories (Fig. 2). Over all

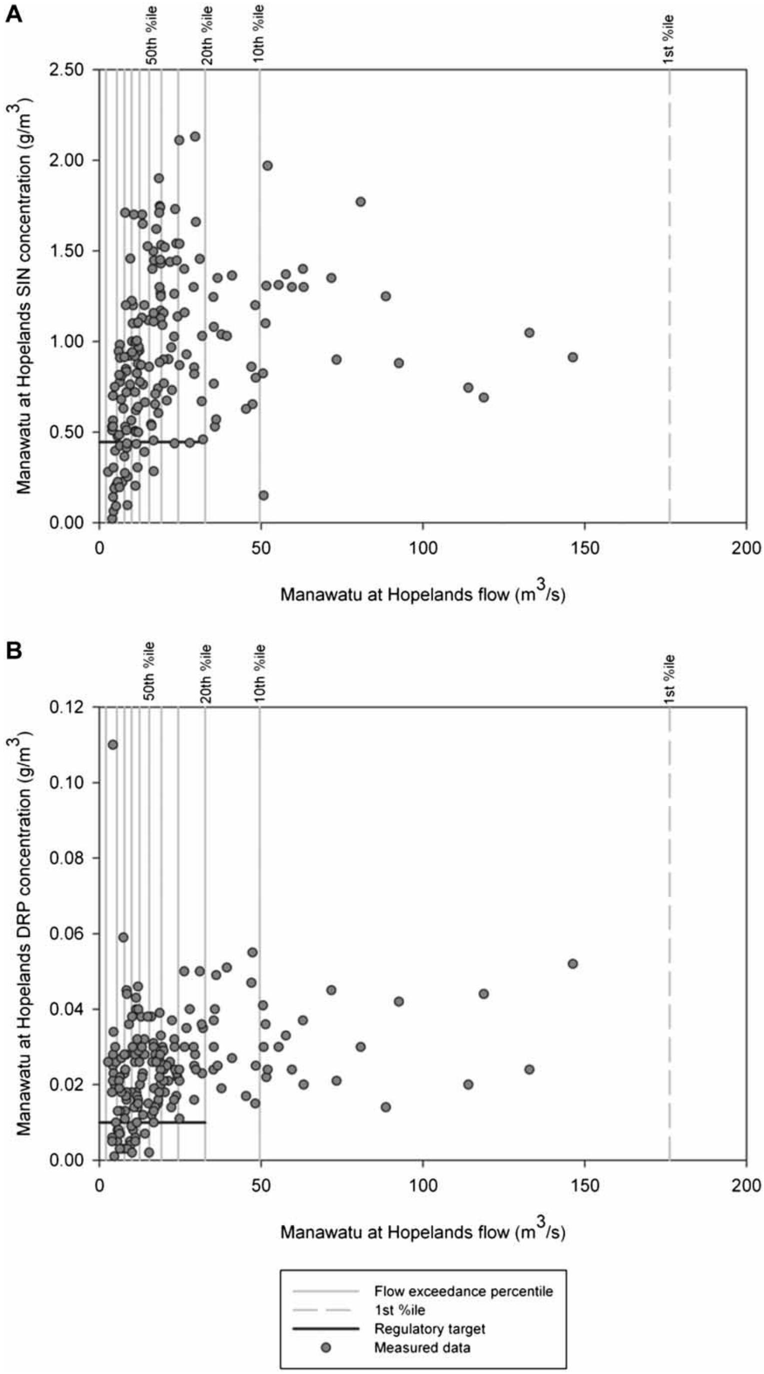

Figure 2 Concentrations of soluble nutrients at the Manawatu at Hopelands site in decile flow bins as defined by exceedance percentiles (%ile) for **A**, soluble inorganic nitrogen (SIN); and **B,** dissolved reactive phosphorus (DRP). Note: the 1st flow exceedance percentile (1st%ile) is shown as a reference to indicate the range of flows, the maximum recorded flow at Hopelands is approximately 1700 m^3/s.

flows, 16% of SIN samples and 13% of DRP complied with (were less than) the regulatory targets. Above median flow, few nutrient samples at Hopelands were within the regulatory target concentrations (4% for SIN and none for DRP). Below median flow, about a quarter of the samples at Hopelands were within the regulatory limits (28% for SIN, 26% of DRP). In the Mangatera tributary, 47% of SIN samples complied upstream of the discharge and this reduced to 7% downstream (Fig. 3A). However, no samples of DRP complied with the regulatory targets upstream or downstream of the Dannevirke STP discharge (Fig. 3B).

Nutrient targets expressed as loads

The concentration based water quality targets of 0.444 g SIN/m^3 and 0.010 g DRP/m^3 were determined to be equivalent to average-annual target loads of 358 t SIN/year and 8.1 t DRP/year at the Manawatu at Hopelands (Hopelands) site, and 268 t SIN/year and 6.0 t DRP/year the Mangatainoka at SH2 (Mangatainoka) site (Table 1).

When calculated for each individual year, the target loads ranged from 54% lower to 45% higher at the Hopelands site and 40% lower to 31% higher at the Mangatainoka site (Table 1). The variation was entirely explained by variation in flow volumes in each year, as constant concentrations were used in the calculations (i.e. the target concentrations).

Excluding flood flows from target loads

Excluding the flood flows (highest 20% of flows) provided loads for the periods when the nutrient concentration targets in the One Plan apply. Removing flood flows reduced the average-annual target loads by 57% at the Hopelands site and 64% at the Mangatainoka site (Table 2). Again, these calculations used constant concentrations so the reductions are related to variations in annual flow volumes. The inference is that at Hopelands 57% of the total volume flows through the site during 20% of the time, at the highest flows. Similarly, for the Mangatainoka 64% of the flow volume occurs 20% of the time.

Variability in target loads

The variability of the annual loads for each individual year around the average-annual target load reduced when flood flows were excluded. At Hopelands, the standard deviations reduced from 89 (Table 1) to 9.5 t SIN/year (Table 2) and from 2 to 0.2 t DRP/year. Similar reductions occurred at the Mangatainoka site, where standard deviations reduced from 54 (Table 1) to 7 t SIN/year (Table 2) and 1.2 to 0.2 t DRP/year. The reductions show flood flows were primarily responsible for the inter-annual variation around the average target loads.

Measured nutrient loads and comparison with target loads

Measured loads were between 55% and 154% greater than target loads for SIN and DRP at the two sites (Table 3). Measured loads at Hopelands were 745 and 20.6 t SIN and DRP/year being 108% and 154% greater than the target loads (Fig. 4). Mangatainoka measured loads were 603 and 9.3 t SIN and DRP/year being 125% and 55% greater than the target loads (Fig. 4; Table 3).

Excluding flood flows from measured loads

In all cases, measured loads still exceeded target loads after the removal of flood flows (Fig. 4; Table 3). The gap between measured loads and targets increased when flood flows were removed from SIN load calculations (Table 3). The gap increased at Hopelands from 108% to 129% and at Mangatainoka from 125% to 190%. The increased gap is attributable to measured SIN loads having higher concentrations below flood flows than above flood flows. This can be concluded as

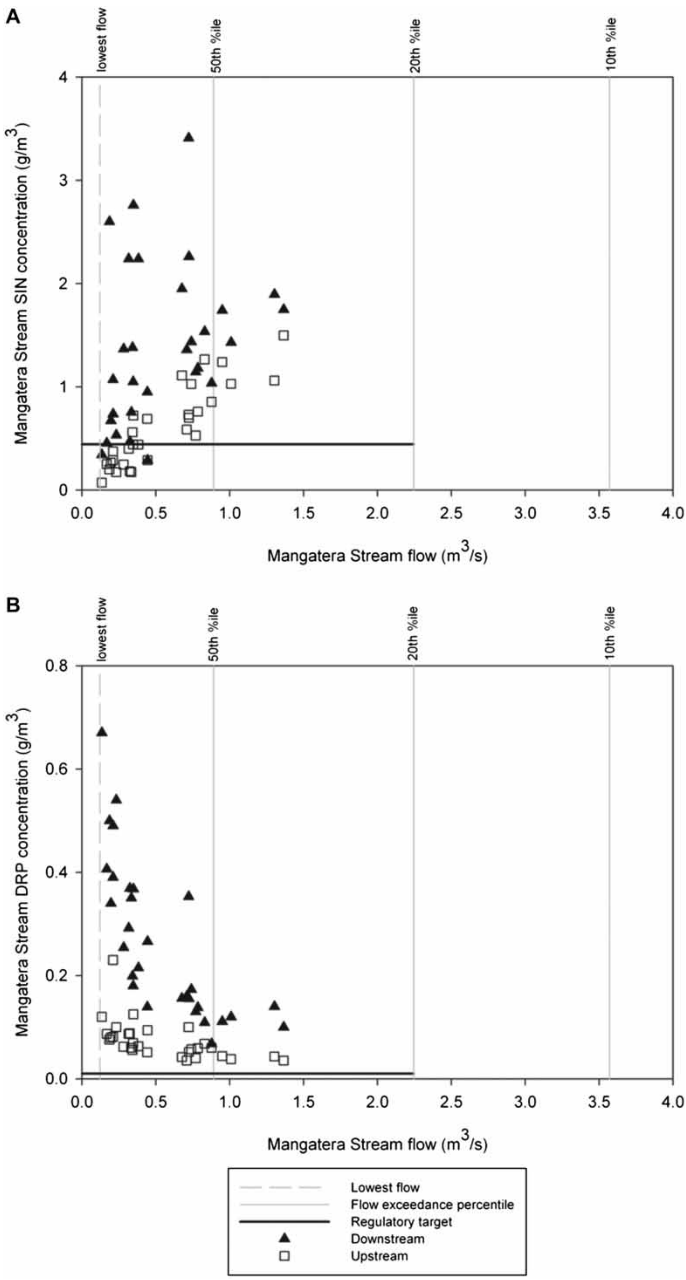

Figure 3 Comparison of soluble nutrient concentrations in the Mangatera Stream upstream (open squares) and downstream (closed triangles) of the Dannevirke Sewage Treatment Plant (STP) discharge for **A**, soluble inorganic nitrogen (SIN); and **B**, dissolved reactive phosphorus (DRP). Flow exceedance percentiles (%ile) indicate the range of flows in the Mangatera Stream. The regulatory targets and flows at which these apply are shown for each nutrient by the black solid line.

Table 1 Comparison of annual target loads from individual years with mean target load limits calculated from all years of record for the Manawatu at Hopelands ($n=15$) and Mangatainoka at SH2 ($n=12$) monitoring sites between 1989 and 2005.

	Manawatu at Hopelands			Mangatainoka at SH2		
	Annual target load (all flows)			Annual target load (all flows)		
Water year	SIN	DRP	Deviation from mean target load	SIN	DRP	Deviation from mean target load
1989	325	7.3	+9%	–	–	–
1990	390	8.8	−9%	–	–	–
1991	388	8.8	−8%	–	–	–
1992	–	–	–	–	–	–
1993	198	4.5	+45%	185	4.2	+31%
1994	406	9.1	−13%	296	6.7	−10%
1995	425	9.6	−19%	295	6.7	−10%
1996	389	8.8	−9%	311	7.0	−16%
1997	276	6.2	+23%	224	5.1	+16%
1998	283	6.4	+21%	294	6.6	−10%
1999	264	5.9	+26%	209	4.7	+22%
2000	307	6.9	+14%	265	6.0	+1%
2001	396	8.9	−10%	225	5.1	+16%
2002	317	7.1	+11%	233	5.2	+13%
2003	553	12.5	−54%	374	8.4	−40%
2004	453	10.2	−27%	301	6.8	−12%
Mean	358	8.1		268	6.0	
Median	388	8.8		280	6.3	
Max	553	12.5	+45%	374	8.4	+31%
Min	198	4.5	−54%	185	4.2	−40%
SD	89	2.0		54	1.2	

Target load limits were determined from concentration-based nutrient targets in the Proposed One Plan (0.444 g soluble inorganic nitrogen (SIN)/m^3 and 0.010 g dissolved reactive phosphorus (DRP)/m^3) and are expressed in tonnes per year (t/year). Water years were 1 July to 30 June.

Table 2 Comparison of mean annual target loads from all years of record separated by flow decile bin for the Manawatu at Hopelands ($n = 15$) and Mangatainoka at SH2 ($n = 12$) monitoring sites.

	Manawatu at Hopelands				Mangatainoka at SH2			
Flow decile bin	Mean target load (all years SIN)	Mean target load (all years DRP)	Total target load in this flow decile bin (%)	Mean target load in this flow decile bin or less (%)	Mean target load (all years SIN)	Mean target load (all years DRP)	Total target load in this flow decile bin (%)	Mean target load in this flow decile bin or less (%)
0–10th	147	3.3	41	100	123	2.8	46	100
10th–20th	56	1.3	16	59	48	1.1	18	54
20th–30th	39	0.9	11	43	31	0.7	12	36
30th–40th	30	0.7	8	32	22	0.5	8	24
40th–50th	24	0.5	7	24	14	0.3	5	16
50th–60th	19	0.4	5	17	11	0.2	4	11
60th–70th	16	0.4	4	12	8	0.2	3	7
70th–80th	12	0.3	3	8	5	0.1	2	4
80th–90th	9	0.2	3	4	3	0.1	1	2
90th–100th	6	0.1	2	2	2	<0.1	1	1
All flows	358.0	8.1	100		267.6	6.0	100	
Flows less than 20th percentile	155.6	3.51	43.5		96.7	2.2	36	
SD	9.5	0.21			7.4	0.17		

Target loads were determined from concentration-based nutrient targets in the Proposed One Plan (0.444 g soluble inorganic nitrogen (SIN) /m^3 and 0.010 g dissolved reactive phosphorus (DRP) /m^3) and are expressed in tonnes per year (t/year). These standards apply at all flows less than flood flows ($<$20th flow exceedance percentile for the site).

Table 3 Comparison of the percentage change in measured and target soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) loads in tonnes per year (t/year) at all flows and with flood flows excluded for the Manawatu at Hopelands and Mangatainoka at SH2 state of the environment monitoring sites in the upper Manawatu River catchment.

	SIN			DRP		
	Measured load (t/year)	Target load (t/year)	Measured load greater than target load (%)	Measured load (t/year)	Target load (t/year)	Measured load greater than target load (%)
Manawatu at Hopelands						
All flows load	745	358	108%	20.6	8.1	154%
Load excluding flood flows	358	156	129%	8.6	3.5	146%
All flows load greater than load excluding flood flows (%)	108%	129%		140%	131%	
Mangatainoka at SH2						
All flows load	603	268	125%	9.3	6.0	55%
Load excluding flood flows	281	97	190%	2.9	2.2	32%
All flows load greater than load excluding flood flows (%)	115%	176%		221%	173%	

Flood flows = all flows less than the 20th flow exceedance percentile.

target loads were calculated using a constant concentration and both measured loads and target loads have the same changes because of the flow component of the load calculation when flood flows are removed. In contrast to the SIN results, when flood flows were removed from the DRP load calculations the gap between measured loads and targets decreased (Table 3). The gap decreased at Hopelands from 154% to 146% and at Mangatainoka from 55% to 32%. The decreased gap is attributable to measured loads having higher DRP concentrations at flood flows, than below these flows. The difference between SIN and DRP concentrations in relation to flood flows likely reflects differing transport pathways for these two nutrients.

Relative contributions from point and diffuse sources

Diffuse sources contributed 98% or more of SIN and 84–88% of the DRP measured loads in the two study catchments (Fig. 5).

At Hopelands, the flow-stratified load calculation method was applied to nutrient concentration data collected upstream and downstream of the Dannevirke sewage treatment plant discharge. The mean annual point source load from Dannevirke was estimated to be 17.1 t SIN/year (Table 4) and 2.56 t DRP/year (Table 5) at all flows. This equated to 2% of the measured SIN load (Fig. 5A) and 12% of the measured DRP load (Fig. 5B). Subtraction of the point source load from the measured load provided a diffuse source load estimate of 728 t SIN/year and 18.06 t DRP/year at all flows, a

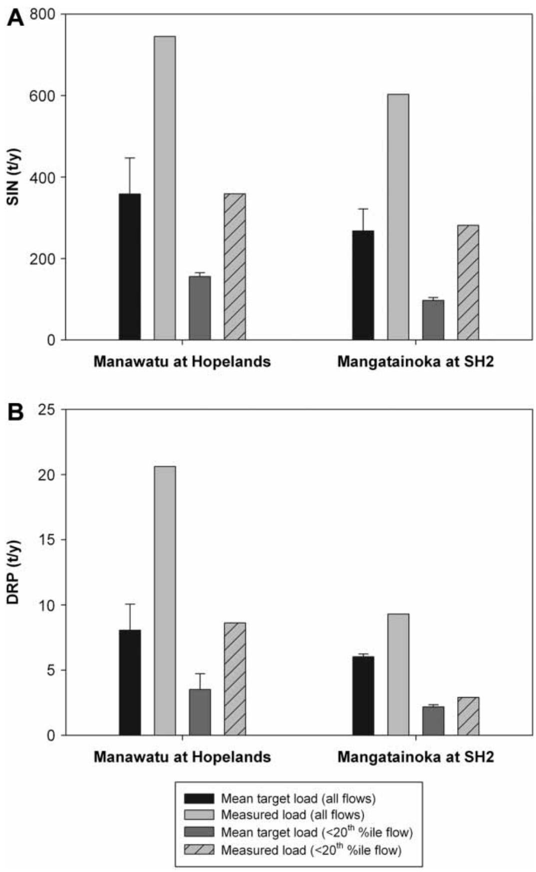

Figure 4 Comparison of regulatory target loads with measured loads in tonnes per year (t/year) at all flows and flows less than the 20th flow exceedance percentile for two study sites in the Manawatu River catchment for **A**, soluble inorganic nitrogen (SIN); and **B**, dissolved reactive phosphorus (DRP). Error bars = + 1SD.

proportional contribution of 98% of the measured SIN load (Fig. 5A, Table 4) and 88% of the measured DRP load (Table 5, Fig. 5B).

For the Mangatainoka, the average annual loads for the Pahiatua sewage discharge were estimated to be 3.4 and 1.5 t SIN and DRP per year, respectively, comprising 0.6% of the total measured SIN load (Fig. 5A) and 16% of DRP load (Fig. 5B). Removal of the point source contribution from the measured load provided a diffuse source estimate of 600 t SIN/year and 7.8 t DRP/year, a proportional diffuse source contribution of 99.4% of the measured SIN load (Fig. 5A) and 84% of the measured DRP load (Fig. 5B).

Change in relative contributions with flow

Relative contributions of nutrients calculated for the flow deciles at Hopelands showed point sources contributed between 1% and 10% of measured SIN load (Table 4; column 6) and were between 1% to 14% of the target load (Table 4; column 8). The proportion of DRP from point sources ranged from 4% to 64% of the measured load (Table 5; column 6) and from 9% to 170% of target load (Table 5; column 8). Point source contributions were less than the target load for both SIN and DRP in all flow deciles except the lowest flow decile for DRP. This shows management of point source DRP inputs will be important to meet targets at

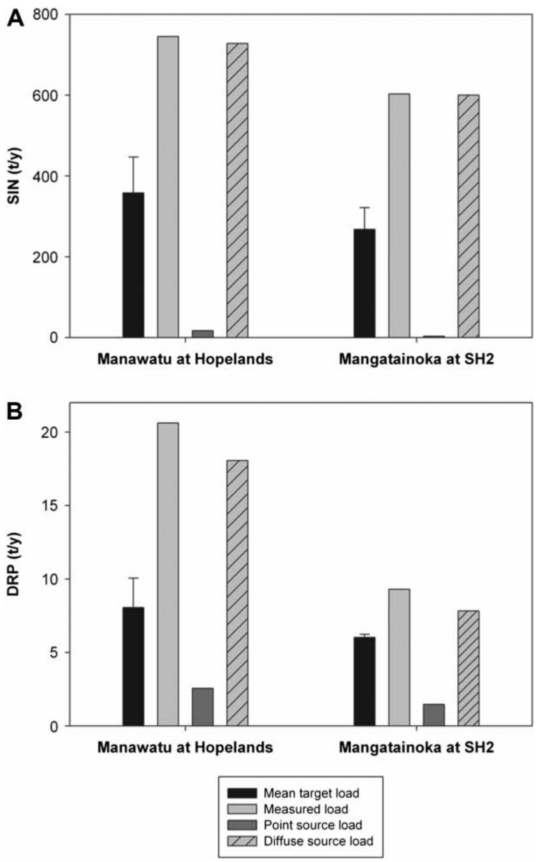

Figure 5 Summary of relative contributions of soluble nutrients from point and diffuse sources for the Manawatu at Hopelands and Mangatainoka at SH2 study sites, in comparison with target and measured loads for **A**, soluble inorganic nitrogen (SIN); and **B**, dissolved reactive phosphorus (DRP). All loads are expressed in tonnes per year (t/year). Error bars = + 1SD.

low flows. Diffuse source contributions were greater than the target load for SIN in all flow deciles except the lowest. For DRP, diffuse inputs exceeded the target loads in all flow deciles except the two lowest. This shows management of diffuse sources of SIN and DRP inputs will be important to meet targets during most flow conditions.

Discussion

There are few studies in New Zealand that define the contributions of nutrients to rivers from various sources (PCE 2010). This study has developed and applied a calculation framework to determine the relative contributions of point and diffuse sources to measured nutrient loads in comparison with the regulatory targets at the flows where these apply. The methodology has provided a way to show how relative contributions from point sources and diffuse sources change at various flows in the two study catchments providing guidance for the setting of targets as required by the NPS (2011). The framework also enables development of regulatory and non-regulatory methods to achieve these targets through management of point and diffuse source nutrients and could easily be applied to other catchments.

Table 4 Comparison of relative loads of soluble inorganic nitrogen from point and diffuse sources at different flows calculated in tonnes per year (t/year) for the Manawatu at Hopelands state of environment monitoring site in the upper Manawatu River catchment.

Flow decile bin	Mean target load (t/year)	Mean measured load (t/year)	Mean point source load (t/year)	Mean non-point source load (t/year)	Point source contribution to measured load (%)	Non-point source contribution to measured load (%)	Point source contribution to target (%)	Non-point source contribution to target (%)
0–10th	146.7	267.4	2	265.4	1	99	1	181
10th–20th	55.7	119.2	2	117.2	2	98	4	211
20th–30th	39.3	104.3	2	102.3	2	98	5	260
30th–40th	30.1	76.5	3.5	73	5	95	12	243
40th–50th	24	65.8	1.3	64.5	2	98	5	269
50th–60th	19.4	45.9	1.9	44	4	96	10	226
60th–70th	15.5	30	2.2	27.7	7	93	14	179
70th–80th	12.3	18.9	0.4	18.5	2	98	3	150
80th–90th	9.2	12.4	1.3	11.1	10	90	14	121
90th–100th	5.7	4.7	0.5	4.2	10	90	9	74
All flows	**358**	**745.1**	**17.1**	**728**	**2**	**98**	**5**	**203**
Flows >20th percentile	202.4	386.6	4	382.6	1	99	2	189
Flows <20th percentile	155.6	358.5	13.1	345.3	4	96	8	222
Flows <50th percentile	62.2	111.9	6.3	105.6	6	94	10	170
Flows <80th percentile	14.9	17.1	1.8	15.3	10	90	12	103
		Percentage of total load						
All flows	100%	100%	100%	100%				
Flows >20th percentile	57%	52%	23%	53%				

Table 4 (*Continued*)

Flow decile bin	Mean target load (t/year)	Mean measured load (t/year)	Mean point source load (t/year)	Mean non-point source load (t/year)	Point source contribution to measured load (%)	Non-point source contribution to measured load (%)	Point source contribution to target (%)	Non-point source contribution to target (%)
Flows <20th percentile	44%	48%	77%	47%				
Flows <50th percentile	17%	15%	37%	15%				
Flows <80th percentile	4%	2%	10%	2%				

Application of the framework has provided specific information on the size of the nutrient issue in the Manawatu Catchment relative to the concentration based regulatory targets of the One Plan. The information provided goes beyond identification of the issue, confirming the level of current over-allocation of the resource relative to nutrient targets. Diffuse contributions were the predominant reason for over-allocation of the resource, providing the majority of nutrient to the study catchments and exceeding the regulatory targets in nearly all flow categories. These findings identify the management of diffuse sources will be key to managing cumulative inputs of nutrients to achieve water quality targets in these sub-catchments. This is consistent with the recommendations of other commentators on this topic (PCE 2004; Hill Young Cooper 2006; Monaghan et al. 2007b; Quinn et al. 2009). For the Manawatu catchment, this finding is significant as the previous catchment plan (MCWQRP 1998) did not address cumulative nutrient effects and only regulated point sources. Management of point sources will continue to be important particularly at low flows where point source contributions were identified as being most significant in these study catchments.

Catchment specific analysis is recommended to determine the overall importance of diffuse and point sources as wastewater discharges remain a key influence on water quality in some areas (McArthur & Clark 2007; Ministry for the Environment 2007). This study has lead to the Manawatu–Wanganui Regional Council upgrading its monitoring programme to enable catchment specific analyses. The monitoring programme now measures upstream and downstream of the major point sources on the same day as sampling river water quality at state of environment monitoring sites (Roygard 2009). The revised monitoring programme provides information for reporting on the effectiveness of managing point sources and diffuse sources over time. This effectiveness will be able to be reported separately (e.g. has management of

Table 5 Comparison of relative loads of dissolved reactive phosphorus from point and diffuse sources at different flows calculated in tonnes per year (t/year) for the Manawatu at Hopelands state of environment monitoring site in the upper Manawatu River catchment.

Flow decile bin	Mean target load (t/year)	Mean measured load (t/year)	Mean point source load (t/year)	Mean non-point source load (t/year)	Point source contribution to measured load (%)	Non-point source contribution to measured load (%)	Point source contribution to target (%)	Non-point source contribution to target (%)
0–10th	3.30	7.80	0.28	7.52	4	96	9	228
10th–20th	1.25	4.20	0.28	3.92	7	93	22	313
20th–30th	0.89	2.70	0.28	2.42	10	90	32	273
30th–40th	0.68	1.66	0.42	1.24	26	74	62	182
40th–50th	0.54	1.34	0.22	1.12	16	84	40	207
50th–60th	0.44	0.96	0.24	0.72	25	75	54	165
60th–70th	0.35	0.80	0.27	0.53	33	67	76	152
70th–80th	0.28	0.47	0.18	0.29	38	62	65	105
80th–90th	0.21	0.34	0.18	0.17	52	48	86	80
90th–100th	0.13	0.34	0.22	0.12	64	36	170	96
All flows	**8.06**	**20.62**	**2.56**	**18.06**	**12**	**88**	**32**	**224**
Flows > 20th percentile	4.56	12.01	0.56	11.44	5	95	12	251
Flows < 20th percentile	3.50	8.61	2.00	6.61	23	77	57	189
Flows < 50th percentile	1.40	2.92	1.08	1.84	37	63	77	131
Flows < 80th percentile	0.34	0.69	0.40	0.29	58	42	118	86
		Percentage of total load						
All flows	100.0%	100.0%	100.0%	100.0%				
Flows > 20th percentile	56.5%	58.2%	21.9%	63.4%				

Table 5 (*Continued*)

Flow decile bin	Mean target load (t/year)	Mean measured load (t/year)	Mean point source load (t/year)	Mean non-point source load (t/year)	Point source contribution to measured load (%)	Non-point source contribution to measured load (%)	Point source contribution to target (%)	Non-point source contribution to target (%)
Flows <20th percentile	43.4%	41.8%	78.1%	36.6%				
Flows <50th percentile	17.4%	14.1%	42.1%	10.2%				
Flows <80th percentile	4.2%	3.3%	15.5%	1.6%				

diffuse sources been effective?) and as an overall effectiveness (e.g. has the combined management of point and diffuse sources been effective?). This type of analysis will be informative for future policy development.

To achieve water quality targets, regional councils will need to consider the combined inputs from point and diffuse sources. This type of approach is similar to the Total Maximum Daily Load Approach used by the United States Environmental Protection Agency (USEPA 1999), which caps the amount of contaminant in order to meet a regulatory target. The framework provided by the flow-stratified averaging approach can be used on daily and annual timescales to meet the targets within the various flow categories. For example, point sources could be managed to remove the discharge at times where their influence is most significant i.e. at low flows. This could be achieved by using land based treatment or storage of the effluent at these times. However, this study shows that overall it is management of diffuse sources that is more important to achieve water quality targets in these study catchments.

Reducing nutrient inputs from diffuse sources is not as simple as for point sources and requires consideration of the mechanisms by which nutrients reach waterways, such as run-off during rainfall events, leaching from the root zone of saturated soils and direct inputs (Monaghan et al. 2007a). These mechanisms occur over all flow categories and may differ in their relative contribution as flows increase or decrease. If the outcome sought is reduced diffuse source inputs at low flows, consideration should be given to methods that reduce direct diffuse source inputs such as stock access to water (Quinn et al. 2009) and poorly managed farm dairy effluent (Houlbrooke et al. 2004, 2008), including leakage from effluent ponds (Wilcock et al. 1999; Roygard 2009). Direct diffuse source inputs are obvious mechanisms for nutrient transport; another major pathway is via groundwater. Groundwater can be the primary source of water to rivers during low flows and may provide a considerable proportion of the diffuse nutrient input to the catchment at these flows. These inputs cannot be controlled at particular flows, as there are time lags between diffuse source nutrient losses and this nutrient reaching waterways, which may be in the order of decades in some cases (Hamilton 2005). Reductions in diffuse contributions for particular or all flow categories will therefore require management of year round nutrient losses from the landscape.

Conclusion

Application of the flow-stratified calculation framework determined that diffuse inputs were the predominant sources of nutrient load in the study catchments, but at low flows, discharges were important contributors of phosphorus. The framework enables determination of the reductions required from point and diffuse sources at various flows, in order to meet regulatory targets. When considering reductions in diffuse source contributions in any flow category, entire farm losses need to be managed to account for mechanisms of nutrient transport from the farm to the river. The framework linked management of concentration-based standards to annual target loads, providing targets relevant to management of diffuse sources on an annual basis. High annual variability in the annual target loads for these river systems was found and this was determined to be predominately driven by the frequency of flood flows in any given year. This variability should be considered when setting annual load targets and assessing the effectiveness of actions to achieve these.

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