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WHY AREN’T WE MANAGING WATER QUALITY TO PROTECT ECOLOGICAL HEALTH?

Russell Death[1], Adam Canning[1,2], Regina Magierowski[3] and Jonathan Tonkin[4]

[1]Innovative River Solutions, School of Agriculture & Environment, Massey University,
Private Bag 11-222, Palmerston North 4442, New Zealand.
[2]Present address: Wellington Fish and Game, P O Box 1325,
Palmerston North 4440, New Zealand.
[3]Department of Ecology, Environment and Evolution, La Trobe University,
Melbourne, Victoria, Australia 3086.
[4]Department of Integrative Biology, Oregon State University, Corvallis, OR 97331, USA.
Email: r.g.death@massey.ac.nz

Abstract

Eutrophication of waterbodies is a major stress on freshwater ecosystems globally and New Zealand is no exception. Expanding agricultural intensification is increasing nutrient levels in rivers throughout the country and as a response the New Zealand Government has established a policy of freshwater management (NPS-freshwater management) where waterbodies are managed within four states ranging from high to low ecosystem health (states A, B, C and D). However, the National Policy Statement for freshwater management does not currently have attributes to manage the two main stressors of lotic ecosystem health: deposited sediment and nutrients. It does have attribute states for nitrate (the dominant form of the nitrogen nutrient), but only at levels where it acts as a toxin. Levels at which nitrate acts as a toxin are however considerably higher than those where it can adversely impact on ecosystem health. There are currently no dissolved reactive phosphorus (DRP) attribute states for ecosystem health of rivers.

We compiled a large range of data sources and used a weight-of-evidence approach to objectively determine nitrate and dissolved reactive phosphorus limits to manage rivers and streams into the four ecological states. This established that the critical nutrient concentrations differentiating rivers in each of the states are 0.11, 0.58 and 1.66 mg/l for nitrate and 0.006, 0.015 and 0.054 mg/l for DRP.

While ecological health of rivers is affected by a range of interacting stressors we believe the evidence supports the view that managing to these nutrient thresholds will provide for better ecological condition in New Zealand’s rivers and streams. It seems strange to us that these nutrient attributes are currently present in the NPS-freshwater for lakes but not for rivers and streams, when the data for them is readily available. If we truly want to manage ecosystem health we must surely consider the most important determinates of its condition so that informed, objective decisions can be made on the implications of particular actions.

Introduction

Eutrophication is among the most widespread and problematic stressors of New Zealand freshwater ecosystems. High nutrient levels are associated with the loss of biodiversity, reduced recreational and property values and increased costs for drinking water treatment

(Foote, Joy & Death, 2015). Eutrophication of freshwaters, therefore, not only comes with a cost to the organisms that inhabit these systems but also financially to the agencies managing them (Jarvie *et al.*, 2013; Dodds *et al.*, 2009; Pretty *et al.*, 2003). The main culprits of eutrophication requiring the greatest attention for management and policy development are nitrogen and phosphorus (Carpenter *et al.*, 1998; Elser *et al.*, 2007).

As in most developed countries there has been considerable concern over the declining water quality, ecological health and biodiversity of many of New Zealand's freshwater bodies (Parlimentary Commisioner for the Environment, 2013; Verburg *et al.*, 2010; Foote, Joy & Death, 2015; Joy & Death, 2014; Joy, 2015; Ballantine & Davies-Colley, 2010). Over the last 25 years many measures of water quality have declined at monitored sites throughout the country, particularly in lowland rivers with catchments dominated by agriculture (Ballantine & Davies-Colley, 2010; Unwin & Larned, 2013; Foote, Joy & Death, 2015; Ministry for the Environment and Statistics New Zealand, 2015; Davies-Colley & Nagels, 2002). Most sites in lowland pastoral catchments and all sites in urban catchments exceed safe swimming standards for pathogens and 60% of sites have increasing nitrogen levels (Larned *et al.*, 2004; Ministry for the Environment and Statistics New Zealand, 2015). Thirty-two percent of monitored lakes are now classed as polluted with nutrients and 84% of lakes in pastoral catchments are the same (Verburg *et al.*, 2010). Groundwater ecosystems are less well monitored, but at 39% of monitored sites nitrate levels are rising and at 21% pathogen levels exceed human drinking standards (Daughney & Wall, 2007).

The condition of New Zealand's freshwater has become such an issue that both national and regional government have responded with a large variety of regulatory, non-regulatory and funding initiatives in an attempt to improve water quality (Ministry for the Environment, 2004; Ministry for the Environment, 2014; Joy, 2015; Cullen, Hughey & Kerr, 2006; Hughey, Kerr & Cullen, 2010). However, the regulation and/or limit setting with respect to waterbody nutrient levels has become one of the most contentious issues in improving New Zealand's water quality (Rutherford, 2013; Wilcock *et al.*, 2007; Chisholm *et al.*, 2014). This is undoubtedly because of the perceived negative economic consequences associated with constrained nutrient discharge to waterbodies, particularly by the dairy farming industry, although the cost of preventing nutrients reaching waterways is considerably less than trying to remove them once they are there (Foote, Joy & Death, 2015; Joy, 2015; USEPA, 2015). The government has established total nitrogen and phosphorus criteria for lakes, but it only establishes nutrient criteria (i.e. nitrate) for rivers at toxic levels, not to manage ecological health (Ministry for the Environment, 2014; Ministry for the Environment, 2010). Despite the obvious and extensively documented links between high nutrient levels in rivers and declines in ecological health (Biggs, 1996; Biggs, 2000; Clapcott *et al.*, 2012; Collier *et al.*, 2013; Death, Death & Ausseil, 2007; Death *et al.*, 2015), current government policy does not provide mechanisms to manage nutrients to safeguard ecological health.

In this study we adopt the weight-of-evidence approach (Smith & Tran, 2010) to develop nitrogen and phosphorus nutrient limits for New Zealand rivers and streams to protect ecosystem health. We adopt the New Zealand Ministry for the Environment approach detailed in the 'National Policy Statement' where a number of measures (termed attributes: nitrogen and phosphorus in this case) are identified by numerical thresholds into one of four states (from A to D). State D is termed the 'National Bottom Line' or 'minimum acceptable state' (actually an unacceptable condition of impairment), with the intention that waterbodies will need to be improved to at least the national bottom lines over time (Ministry for the Environment, 2014). This approach differs from that in the USA where nutrient limits are derived for impaired / not-impaired waterways (USEPA, 2000; Dodds & Welch, 2000), but is similar to that of the European Union Water Framework Directive, which also characterise water bodies as belonging to one of five states of ecological status from bad to high (European Commission, 2000; Birk *et al.*, 2012; Poikane *et al.*, 2014).

Materials and methods

There are four established methods for identifying nutrient limits (Smith & Tran, 2010; USEPA, 2000). These are 1) division of known nutrient measures into equal classes (percentile analysis); 2) identification of significant change points in the relationship between nutrient values and ecosystem health metrics (Smith & Tran, 2010; Baker & King, 2010; King & Richardson, 2003); 3) identification of signification relationships between nutrient values and ecosystem health metrics at predetermined points; 4) experimental manipulation of the effect of nutrient values on ecosystem health metrics. For this study approaches 1 and 3 have been used to set thresholds for both nitrate and dissolved reactive phosphorus (DRP). A combination of real and modelled data were sourced from a variety of publications and agencies and threshold limits were determined by weighting each line of evidence based on whether the effects were direct or indirect. More detail on the data sources used and the methodology to derive the nutrient thresholds can be found in (Death *et al.*, in prep).

Each regression of the datasets was used to determine the numerical nutrient limits for each ecological state (Table 1). The final nutrient limits were determined by calculating a weighted average of those nutrient limits for each dataset / line of evidence multiplied by their allocated weighting. Following (Smith & Tran, 2010), direct linkage relationships between ecosystem health measures and nutrients were allocated a weighted value of 2 in the analysis and purely statistical or less direct linkages were allocated a weighted value of 1 (e.g. percentile analysis and Fish IBI). Where relationships were not significant they were not included as a line of evidence i.e. they were allocated a weighted value of 0.

Results

Numerical nutrient thresholds

Table 2 presents the numerical nutrient thresholds for the A, B, C and D states derived from each line of evidence. This yielded nitrate concentrations of 0.11, 0.39 and 1.66 mg/l, and DRP concentrations of 0.006, 0.015 and 0.054 mg/l for the A, B, C and D states (Table 2). Criteria from each individual line of evidence (where these were significant) were remarkably consistent across all the lines of evidence (Standard Error = 0.02, 0.05 and 0.29 for the three nitrate criteria and 0.001, 0.003 and 0.020 for the three DRP criteria). The only real exception was that criteria derived from the percentile analysis were generally lower than those from the regression analysis. The percentage of New Zealand river reaches with median nitrate or DRP levels from (Unwin & Larned, 2013) in each of these attribute states is given in Table 1.

Table 1. Percentage of river reaches in each nutrient attribute state. NPS state = New Zealand National Policy Statement for freshwater state.

NPS state	NO_3-N (mg/l)	Percent	DRP (mg/l)	Percent
A	< 0.11	60.1	< 0.006	37.5
B	$0.11 \leq x < 0.58$	27.1	$0.006 \leq x < 0.015$	44.0
C	$0.58 \leq x < 1.66$	12.0	$0.015 \leq x < 0.054$	18.5
D	> 1.66	0.81	> 0.054	0.04

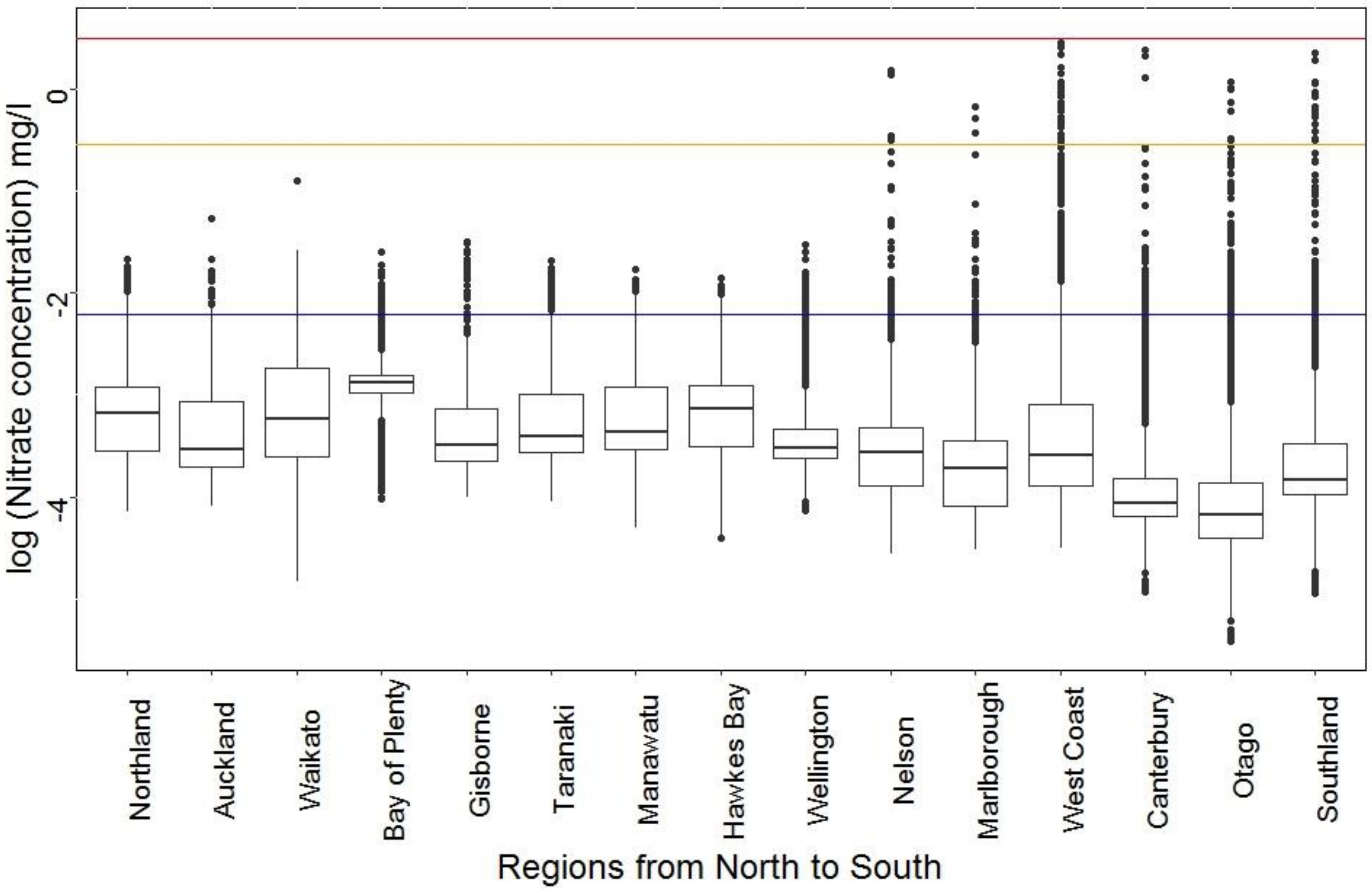
Table 2. Numerical nutrient thresholds (mg/l) for annual median nitrate and DRP concentrations for inclusion in the National Policy Statement for freshwater state (A-D) derived from multiple lines of evidence. Weighting of each piece of evidence is provided along with regression statistics (F statistic, degrees of freedom, probability value and r^2) when relevant. PCI = public conservation land, MCI = Macroinvertebrate Community Index, QMCI= Quantitative Macroinvertebrate Community Index, EPT animals=Percent animals that are Ephemeroptera, Plecoptera or Trichoptera, EPT taxa=Percent taxa that are Ephemeroptera, Plecoptera or Trichoptera, IBI = Fish Index of Biotic Integrity, Chl a = Chlorophyll a concentration.

Ecological metric	n/a	n/a	MCI	QMCI	MCI	QMCI	EPT animals	EPT taxa	MCI	QMCI	MCI	QMCI	IBI	n/a	Chl a	Chl a	
NO_3																	
Relationship Equation	n/a	n/a	ln y = ln (x+1)	ln y = ln (x+1)	y = ln x	y = ln x	y = ln x	y = ln x	y=lnx	y=lnx	y=x	y=lnx	y=lnx	n/a	log10(max Chl a) = x	See Matheson et al 2016	Weighted mean
Weight of evidence	1	1	2	2	2	2	2	2	2	2	2	0	1	2	2	2	
A/B threshold	0.03	0.08	0.02	0.00	0.11	0.10	0.11	0.20	0.06	0.09	0.00	0.00	0.00	0.17	0.12	0.43	0.11
B/C threshold	0.06	0.12	0.45	0.29	0.58	0.34	0.30	0.47	0.53	0.33	0.60	0.13	0.21		0.43	2.77	0.58
C/D threshold	0.28	0.20	1.22	0.77	3.01	1.09	0.87	1.09	4.36	1.20	1.60	9.10	1.54	0.44	0.90	4.84	1.66
r^2			0.53	0.54	0.35	0.27	0.28	0.29	0.37	0.27	0.08	0.04	0.09		0.3		
F			632224	653084	513	363	377.6	390.6	51.72	32.66	6.78	3.85	3775				
df			1,566548	1,566548	1,961	1,961	1,961	1,961	1,86	1,86	1,62	1,62	1,392543				
p			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.01	0.05	<0.0001				
DRP																	
Relationship Equation	n/a	n/a	ln y =x	ln y =x	ln y = x	ln y = x	ln y = x	y=x	y=lnx	y = lnx	y=x	Y=lnx	lny=lnx	n/a	$\log_{10}$(max chla) = x	See Matheson etal 2016	Weighted mean

Weight of evidence	1	1	2	2	2	2	2	2	2	2	0	0	1	2	2	2	
A/B threshold	0.004	0.011	0.004	0.003	0.008	0.006	0.005	0.015	0.005	0.008	0.000	0.000	0.002	0.009	0.002		0.006
B/C threshold	0.008	0.014	0.016	0.012	0.022	0.015	0.009	0.021	0.038	0.025	0.023	0.008	0.007		0.007	0.110	0.015
C/D threshold	0.012	0.021	0.032	0.024	0.040	0.027	0.016	0.028	0.275	0.079	0.066	0.024	0.014	0.100	0.014	0.018	0.054
r^2			0.38	0.39	0.18	0.15	0.18	0.18	0.54	0.420	0.02	0.04	0.04		0.3		
F			349187	357979	210.3	165	217.80	211.10	99.83	63.89	2.160	3.610	15770				
df			1,566548	1,566548	1,961	1,961	1,961	1,961	1.86	1,86	1,62	1,62	1,392543				
P			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.001	0.15	0.06	<0.0001				
Ecological metric source	n/a	n/a	(Clapcott, Goodwin & Snelder, 2013)	(Clapcott, Goodwin & Snelder, 2013)	(Death *et al.* 2015a)	(Death *et al.* 2015a)	(Death *et al.* 2015a)	(Death *et al.* 2015a)	(Death 2013)	(Death 2013)	(Unwin and Larned 2013)	(Unwin and Larned 2013)	(Joy 2009)	n/a	(Biggs 2000a)	(Matheson, Quinn & Unwin, 2016)	
Nutrient concentration source	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Death, 2013)	(Death, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Unwin & Larned, 2013)	(Davies-Colley, 2000)	(Biggs, 2000)	(Matheson, Quinn & Unwin, 2016)	

Are national or regional criteria more appropriate?

New Zealand is geologically active with high mountains, frequent earthquakes, geothermally active areas and volcanoes. This geological activity in turn results in a spatially variable geology that might suggest regional nutrient criteria will be necessary to account for the natural differences in ‘pristine’ environmental conditions. However, a plot of the median and range of nutrient values from Unwin & Larned (2013) in catchments with predominantly (>80%) native vegetation (Fig. 1) indicates that although the median is lower and range greater as one moves south, there are no dramatic regional differences. Furthermore, all regions have 75% of ‘pristine’ reaches well below the A band upper nutrient threshold (see below for derivation), and all reaches are well below the B band upper threshold, except for a few outlying points in the South Island (Fig. 1). Given the greater simplicity and understanding associated with one set of national criteria, rather than multiple regional criteria, we have opted for the former.


log (Nitrate concentration) mg/l
0
-2
-4
Northland
Auckland
Waikato
Bay of Plenty
Gisborne
Taranaki
Manawatu
Hawkes Bay
Wellington
Nelson
Marlborough
West Coast
Canterbury
Otago
Southland
Regions from North to South

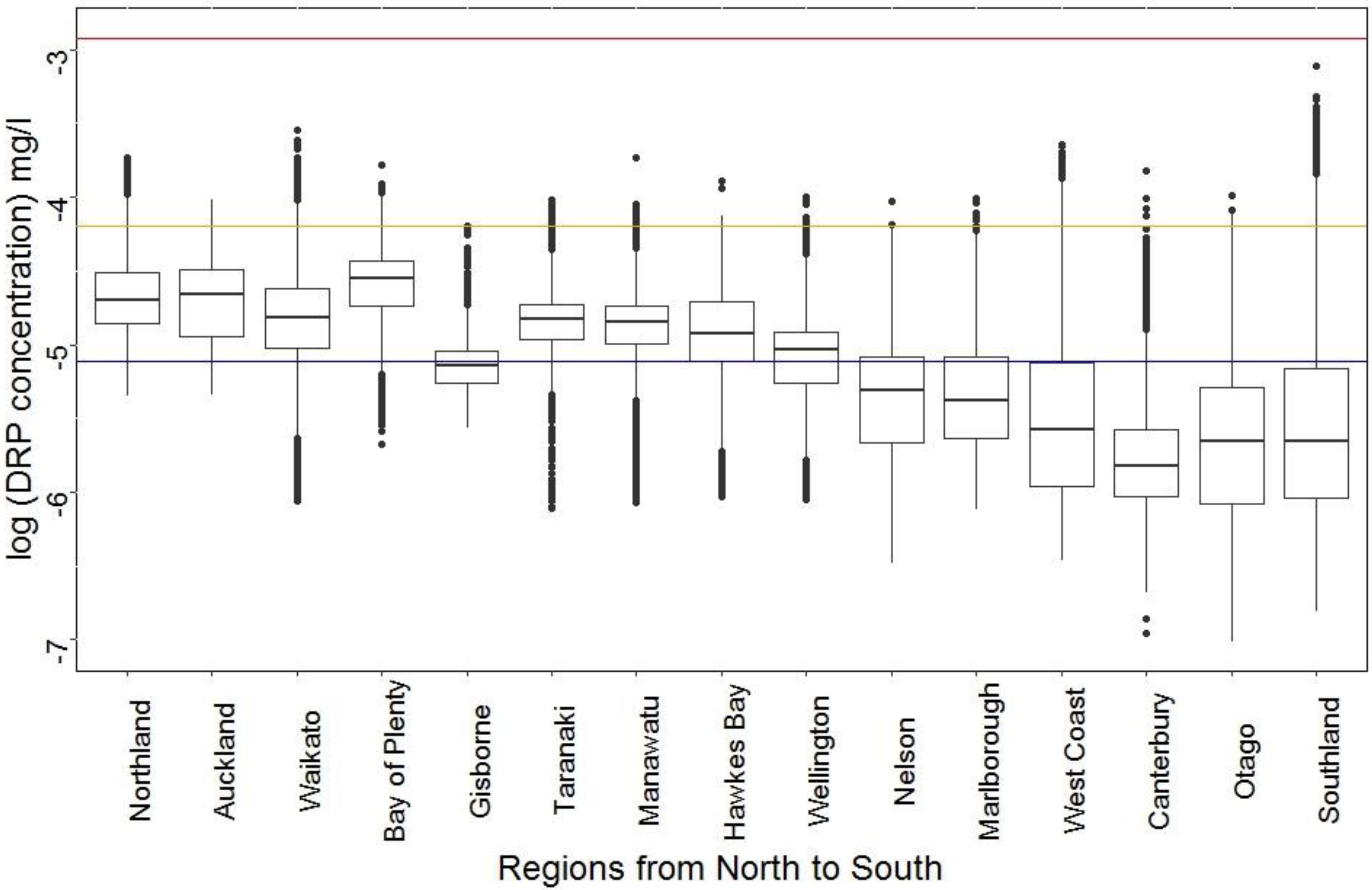


Figure 1 Boxplot of the median and range of log nitrate and dissolved reactive phosphorus concentrations in streams in the Conservation Estate from Unwin & Larned (2013). Blue, yellow and red lines represent the A, B and C/D thresholds derived from the study.

Discussion

Although the ecological health of rivers and streams is determined by a wide range of potentially interacting stressors, it is clear that nutrients are one of the most pervasive and detrimental stressors for the fauna and flora of rivers globally (Allan, 2004; Carpenter *et al.*, 1998; Stevenson & Sabater, 2010). Environmental stress from excess nutrients is particularly detrimental to river health in New Zealand where the dominant land use is agriculture, rather than the heavy industry or manufacturing that dominates in many other places (Foote, Joy & Death, 2015; Weeks *et al.*, 2016; Joy, 2015). The developed nitrate concentrations of 0.11, 0.58 and 1.66 mg/l, and DRP concentrations of 0.006, 0.015 and 0.054 mg/l will therefore be very valuable policy tools to maintain or improve the ecological health of rivers in good, moderate or poor condition.

There is a large amount of data available to draw on to make these decisions and it is surprising that this has not been done before now. We have established nitrogen and phosphorous limits for ecological health in lakes and it is very odd to not have the same attributes in a water quality management document. The weight-of-evidence approach offers an objective, scientifically rigorous, multiple lines of evidence method to compile a variety of data sources to set nutrient thresholds to meet the four attribute states of ecological health adopted by current New Zealand Government policy. Given the large environmental, economic and social costs these limits may create (Foote, Joy & Death, 2015; Weeks *et al.*, 2016; Hughey, Kerr & Cullen, 2010) it is important that they are objectively determined from as wide a range of data and in as robust a manner as possible.

This is the first example we are aware of where fish have been included with periphyton and macroinvertebrates in such an assessment, despite their obvious public interest. Interestingly, the derived nutrient criteria for fish (IBI) were very similar to those for the other taxa. Perhaps one of the impediments has been that a range of variables, besides nutrients, will also impact on river health and thus it is not always easy to determine rigorous relationships between nutrients and indices of ecological health. This is clear in the large amount of data scatter in the relationships used in this study. However, it is reassuring that all the data sets yielded numerics within the same small range.

As with any freshwater resource management adhering to these nutrient limits will not provide a panacea for maintaining good ecological health. Many other factors may interact with, or override the effects of nutrients on river health, however, as a well-established determinant of river food web structure, managing below these nutrient concentrations will certainly be a step in the right direction (Wagenhoff, Townsend & Matthaei, 2012; Wagenhoff *et al.*, 2011; Matthaei, Piggott & Townsend, 2010; Clapcott *et al.*, 2012). Similarly, establishing limits for only nitrate or dissolved reactive phosphorus will not serve to limit adverse environmental effects, as when and where the respective nutrients become limiting changes and is thus often hard to establish (Jarvie *et al.*, 2013; Death, Death & Ausseil, 2007; Dodds & Welch, 2000; Keck & Lepori, 2012).

Perhaps the only concern we have in using this approach is that the established bottom line for MCI/QMCI of 80/4 appears to be too low. Once ecological health reached that point the long flat tail of the relationship along the right of the nutrient axis meant there could be large increases in nutrient levels with only a very small decline in health. In other words, once the ecological health is at the bottom line condition is relatively unaffected no matter how many more nutrients are added. This suggests the bottom line for the MCI/QMCI may be better at a slightly higher level (e.g. 90 or 4.5 for the MCI and QMCI, respectively).

In conclusion we derived the nitrate concentrations of 0.11, 0.58 and 1.66 mg/l, and DRP concentrations of 0.006, 0.015 and 0.054 mg/l which correspond with numerical threshold states A to D (high to low ecological health). We believe these provide rigorous and objective levels at which to set instream nutrient concentrations to protect New Zealand river ecological health. These have been compiled across a range of studies over the full length of New Zealand without any indication of regional differences that might affect the efficacy of these limits in protecting and maintaining the desired ecological state of rivers or streams. Given the pervasive and every increasing eutrophication of waterbodies worldwide, we hope these limits will be adopted by New Zealand freshwater managers as one more tool in the arsenal of techniques to better protect and manage freshwater.

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