Estimation of water quality contaminant loads and the likely effect of fencing in Taranaki.

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Executive Summary

A national model was developed to estimate the load of contaminants (suspended sediment (SS), nitrate+nitrite nitrogen (NO_3-N), ammoniacal-N (NH_4N), total N (TN), filterable reactive phosphorus (FRP), and total P (TP)) in all catchments classified by the River Environment Classification. The Taranaki Regional Council wished to know if contaminant load from streams currently proposed to be fenced from stock access would be different to that proposed by the Land and Water Forum, which focuses on larger, deeper streams in flat catchments. Across the region the LAWF recommendation applied to streams that carried from 10 (for SS) to 16% (for DRP) of contaminant load across all landuses in Taranaki. When focused on pasture-landuse, more contaminant load was captured (from 14% for SS to 20% for DRP). Hence, 84 to 90% of contaminants across all landuses and 80 to 86% of contaminants generated in pastoral catchments would not likely be captured by LAWF fencing recommendations. Assuming a median reduction in contaminant load (varying from 10% for NO_3-N to 52% for TP), loads under the Taranaki recommendation, which requires all streams to be fenced irrespective of size or location, would be substantively less than those under LAWF recommendations. However, it should be recognised that the effectiveness of fencing-off stock as a strategy to mitigate contaminant loads is highly site- and contaminant-specific, ranging from highly effective in flat areas and where contaminants are particulate-associated to very ineffective in steeper areas and where contaminants are mobile.

Scope of work

The Taranaki Regional Council (TRC) asked for data on the following points:

1. To produce estimate of contaminant loads in streams of the Taranaki region. Contaminants considered are suspended sediment (SS), nitrate+nitrite nitrogen (NO_3-N), ammoniacal-N (NH_4N), total N (TN), filterable reactive phosphorus (FRP), and total P (TP).
2. Loads will be estimated and summed according to stream order across the region (all), in pastoral landuse only (pasture) and only encompass the recommendations of the Land and Water Forum (LAWF). The difference between pasture and LAWF represents the load that is covered by fencing rules of the TRC.
3. An estimate (median and range) will be given of the efficacy of fencing to decrease contaminant load.

Methodology

Data

A database comprising concentrations of: SS, nitrate+nitrite nitrogen (NO_3-N), ammoniacal-N (NH_4N), total N (TN), dissolved reactive phosphorus (DRP), total P (TP) and *E. coli* was collated from McDowell et al. (2013a) and (Larned et al., 2016). The database included 728 sites that are routinely sampled by Regional Authorities from as early as the late 1970s. However, to reduce issues related to changes in water quality analyses and temporal trends I used data from 1998-2009. Data within the database varied widely in reporting formats, reporting conventions, contaminant names, and sampling frequency or flows. To consolidate these data into a uniform structure and minimise the potential for error, I used a modified version of a MS-Access database (Ballantine and Davies-Colley, 2010) and adopted the following filtering conventions for data quality:

1. Sites were only included in the database if there were 50 or more measurements of a contaminant during the period of record, to ensure reasonable coverage of the flow range at the site;
2. Contaminant concentrations less than the indicated detection limit were set at half the detection limit. The percentage of sites where the median concentration was below the stated detection limit was generally <1% except for SS (3.4%), DRP (4.3%) and NH_4-N (17.4%). For contaminant concentrations greater than a censored value, such as *E. coli* (>20000 MPN 100mL^{-1}), the numerical extreme was used;
3. Total N was calculated (where possible) as the sum of NO_3-N plus total Kjeldahl N for regions that did not specifically report this variable; and
4. Sites in estuarine waters were omitted to avoid biasing our dataset.

The frequency of sampling varied across the sites represented in the dataset from fortnightly to quarterly. In addition, constraints and objectives associated with the design of regional sampling programmes mean that geographical and environmental coverage of the sites is uneven and variable (Figure 1). The sites in the dataset therefore tended to represent locations where there is a known or anticipated change in water quality due to land use impacts.

I used the New Zealand River Environment Classification (REC) (Snelder and Biggs, 2002) to classify the sites according to the environmental characteristics of the upstream catchment that are strong determinants of their water quality. The first four hierarchical levels of the REC discriminate differences in catchment character based on spatially averaged measures of climate, topography, geology and land cover respectively. The spatial framework for the REC is a digital representation of the New Zealand river network comprising 576,688 segments (between confluences) and catchments with a mean length of ~700m that is contained within a Geographic Information System (GIS). The REC has been shown to discriminate differences in flow regimes (Snelder et al., 2005), nutrient concentrations (Snelder et al., 2004a), general water quality (Larned et al., 2004), and invertebrate community composition (Snelder et al., 2004b). Being hierarchical, the REC enables the classification of all streams and rivers in New Zealand at varying levels of classification detail and associated spatial scales.

Geographic co-ordinates and names were used to assign each water quality monitoring site to a REC class at the first four levels (climate, topography, geology, and land-cover) based on the network segment on which it was located (Table 1).

Table 1. Defining characteristics, categories, and membership criteria of selected classes within the River Environment Classification at each level.

Level	Defining characteristic (level)	Categories	Notation	Category membership criteria
Level 1	(Climate)	Warm-extremely-wet	WX	Warm: mean annual temperature $\geq$ 12°C
		Warm-wet	WW	Cool: mean annual temperature < 12°C
		Warm-dry	WD	Extremely Wet: mean annual effective precipitation[1] $\geq$ 1500 mm
		Cool-extremely-wet	CX	Wet: mean annual effective precipitation > 500 and < 1500 mm
		Cool-wet	CW	Dry: mean annual effective precipitation $\leq$ 500mm
		Cool-dry	CD	
Level 2	Topography[2]	Glacial-mountain	GM	GM: M and % permanent ice > 1.5%
		Mountain	M	M: > 50% annual rainfall volume above 1000m ASL
		Hill	H	H: 50% rainfall volume between 400 and 1000m ASL
		Low-elevation	L	L: 50% rainfall below 400 m ASL
		Lake	Lk	Lk: Lake influence index[2] > 0.033
Level 3	Geology	Alluvium	Al	Category = the spatially dominant geology category unless combined Soft-Sedimentary geological categories exceed 25% of catchment area, in which case class = SS.
		Hard sedimentary	HS	
		Soft sedimentary	SS	
		Volcanic acidic	VA	
		Volcanic basic	VB	
		Plutonics	P	
		Miscellaneous	M	
Level 4	Land-Cover	Bare ground	B	Class = the spatially dominant (> 50% of catchment area) Land-Cover category, unless P exceeds 25% of catchment area, in which case class = P or U exceeds 15% of catchment area, in which case class = U.
		Indigenous forest	IF	
		Exotic forest	EF	
		Pastoral	P	
		Scrub	S	
		Urban	U	

[1] Effective precipitation = annual rainfall – annual potential evapotranspiration.

[2] Called "source of flow" in Snelder and Biggs (2002).

[3] See Snelder and Biggs (2002) for a description.

Flow estimation

Contaminant load calculations require stream flow data; both the flow at the time each water quality sample was taken (e.g., mean daily flow) and a representative time series or flow distribution at the site. However, 447 of the 728 water quality monitoring sites did not have flow observations at the time of sampling or with continuous flow gauging records. I used the methods of Booker and Snelder (2012) to estimate flow duration curves (FDC) and mean daily flows on the date corresponding with each water quality sample at each water quality monitoring site. Briefly, the following steps were taken:

1. A hydrological dataset was acquired from the New Zealand national hydrometric database that consisted of time-series of daily mean flow measured at gauging stations distributed throughout the country (Pearson, 1998). Data was obtained from gauging stations with five or more years of data and that were free from flow modification due to abstractions and dams (n = 379).
2. A flow duration curve (FDC) was generated for each site. For all sites, a generalised extreme value (GEV) distribution was fitted to describe the distribution of flows.
3. The parameters of the GEV distributions were fitted to available catchment characteristics using a random forest model and the model was used to estimate FDCs for all 728 water quality monitoring sites.
4. Mean daily flows corresponding to sample dates were estimated for each water quality monitoring site by substituting flows observed at geographically close gauging stations with similar catchment characteristics (i.e. having the same REC class).

Load and yield calculation

Two methods were used to estimate contaminant yields for each site: regression (viz. rating) and ratio method. Loads were estimated for each site first and then converted to yields by dividing the loads by the area of the catchment upstream of each water quality monitoring site (kg/ha/yr).

The regression method fitted models to the log of concentrations against the log of flow. Following bias correction to account for back-transformation (Ferguson, 1987), regression model predictions were used to in-fill concentrations at each flow percentile of the FDC. The load associated with each percentile of the FDC was calculated as the product of the corresponding estimated concentration and flow. These individual loads were summed and multiplied by a constant to account for the change of units to produce an annual site load (kg/yr).

The ratio method calculated an annual site load, based on the mean of the product of concentration and flow for days when concentrations were observed (Beale, 1962). This average load was then adjusted by the ratio of the mean flow for all days from the FDC to the mean flow on days when concentrations were observed (Webb and Walling, 1985; Quilbé et al., 2006).

To avoid bias associated with poor representation of very low or high flows, sites were only included where concentrations were available for 90% of the flow range at the site. The regression method was used where the concentration-flow relationship was significant ($P<0.05$) and the amount of variance explained was > 60%, otherwise the ratio method was used, as per Quilbé et al. (2006).

Yield variation with stream order, REC class and accord-type

For each of the REC classes (Climate, Topography, Geology and Land-cover), I fitted a restricted maximum likelihood (REML) model (Genstat Committee, 2015) to the log-transformed yields of each contaminant, with order as a linear term along with REC class and their interaction; non-linear order effects were fitted with smoothing splines (Verbyla et al., 1999) on stream order and the interaction of REC class with stream order.

Across REC classes and stream orders there were 13,230 potential combinations for each contaminant. However, only 2,396 occur across the 576,688 stream segments represented in the REC: for example, there are no 8th order streams of hill topography.

The uncertainty of estimated yields depends on the strength of the relationship between yield and order for each REC class, which is influenced by the amount of data (viz. contributing sites) within each class. The REML model does not produce a coefficient of determination that can be used to check of the goodness of fit of the model. However, goodness of fit was assessed using the frequency with which observed yields fall within the mean yield estimated by the model and 95% confidence interval for a class.

Loads from streams recommended to be excluded from fencing

A GIS was used to define the catchment area of each of the 576,688 stream segments represented by the REC. Load predictions were then made for each catchment using the fitted REML models. The methods of Booker (2010) and Jowett (1998) were used within a GIS to isolate those stream segments that were < 1-m wide, <30-cm deep, or had a contributing catchment with a mean slope greater than 15 degrees (i.e. excluded streams). The predicted yields were multiplied by the catchment's contributing area to generate catchment-specific loads for each segment of the REC. The total load (kg/yr) was calculated for each region and nationally for fenced and excluded streams for each contaminant for all catchments, and for only those catchments that were dominated by the REC pastoral land-cover class, indicative of intensive land use.

Estimates

Uncertainties

After applying data filtering rules, sufficient data was available to estimate yields for between 243 (SS) and 481 (DRP) sites (Table 2). For TP, NO_3-N, TN and SS yields, more sites were estimated using the regression than the ratio method, while for DRP and *E. coli* the ratio method was used more frequently (Table 2). A plot of yields estimated by the two methods across all contaminants yielded a coefficient of determination of 0.98 (regression = $0.94.\text{ratio}^{1.0038}$; $P<0.001$), indicating the outputs from yield calculation methods were, on average, similar.

Table 2. Number and percentage of sites (in parentheses) using the two different yield calculation methods.

Contaminant	Regression	Ratio	Total
DRP	207 (43)	274 (57)	481
TP	233 (50)	229 (50)	462
NH_4N	176 (37)	294 (63)	470
NO_3-N	347 (73)	129 (27)	476
TN	328 (72)	131 (28)	459
SS	158 (65)	85 (35)	243
E. coli	119 (27)	329 (73)	448

Yield estimates were generated across the climate, geology, topography and land-cover REC classes using the REML procedure. The fit of the modelled yields to those calculated for each site is indicated by the frequency with which the data fell within the modelled estimate plus or minus the confidence interval. Across all contaminants, 84% of sites fell within the modelled estimate and respective 95% confidence interval, varying from 80% for *E. coli* to 91% for SS (Table 3).

Table 3. Fit of the restricted maximum likelihood model fitted to each contaminant, expressed as the number and percentage of predicted yields that fell within the mean and 95% confidence interval.

Contaminant	Number of sites with yield data	Number of sites within 95% confidence intervals	Percentage of sites within 95% confidence intervals
DRP	703	589	84%
TP	675	571	85%
NH_4N	687	581	85%
NO_3-N	694	611	88%
TN	670	587	88%
SS	364	332	91%
E. coli	655	526	80%

Contaminant loads

The mean proportional load accounted for all land uses across New Zealand by fenced streams was 16% across all contaminants, varying from around 11% for SS to 21% for NO_3-N; meaning 84% of loads were not captured from excluded streams. Regional variation for the load likely captured by fencing across all land uses was greater ranging from <1% for all contaminants in the West Coast region to 40% for NO_3-N in the Auckland region. The same calculation catchments dominated by pasture land-cover (i.e. intensively farmed), showed more would be captured by fencing, on average 23% across all contaminants. However, this means that in catchments dominated by pastoral land, 77% would not; varying from 73% for DRP and TN to 84% for SS (Figure 1). Inter-regional variation was greater still in pasture-dominated catchments, varying from 48% for DRP and TN in the Otago region to 99% for most contaminants in the West Coast region. Agriculturally productive regions such as Canterbury, Southland, and Hawkes Bay also exhibited large contaminant loads from excluded streams.

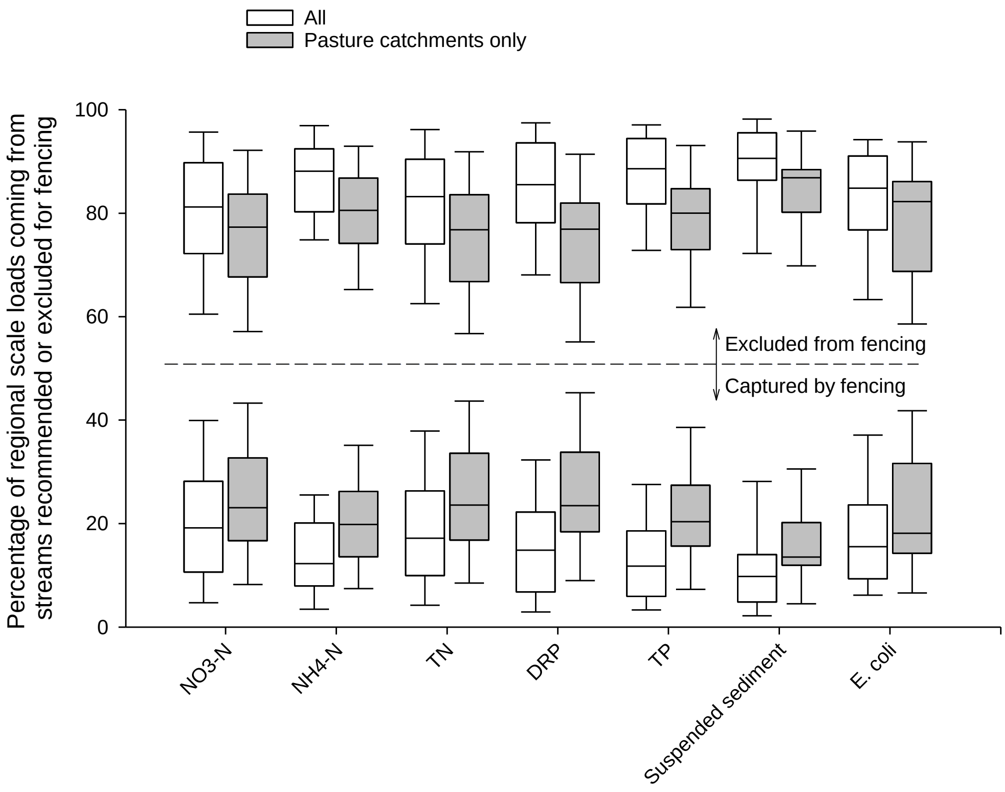

Figure 1. Box plots showing the percentage mean loads contributed by all streams recommended (captured) and excluded for fencing-off from stock access for all land uses and only those under pasture across the 16 regional authorities of New Zealand. The 25th and 75th percentiles as the lower and upper end of the box, with 10th and 90th percentiles as whiskers.

The LWAF fencing recommendation captured from 10% for SS to 16% for DRP across all landuse in Taranaki, while the pasture-specific component varied from 14% capture for SS to 20% for DRP (by difference in Figure 2). This means that 84 to 90% of contaminants across all landuses and 80 to 86% of contaminants generated in pastoral catchments were not likely captured by the fencing recommendations (Figure 2). Taranaki accounted for between 3 and 7% of the national load of contaminants (Table 4).

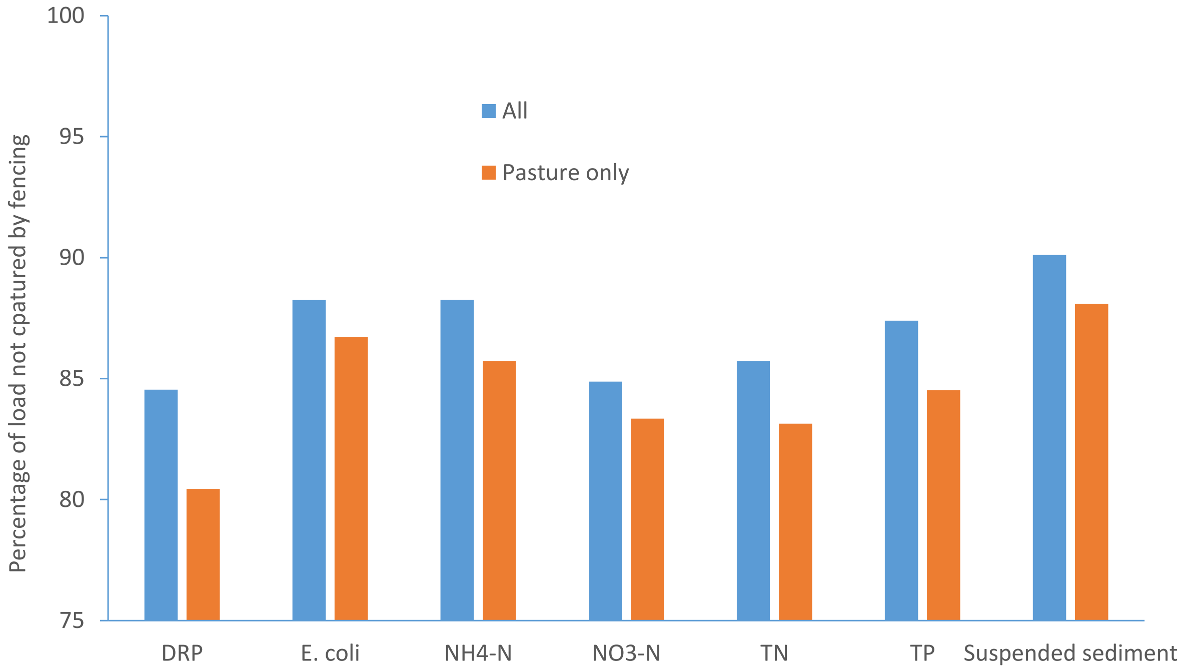

Figure 2. Percentage of contaminant load not likely to be captured by the LWAF fencing recommendation under all landuses and only in pasture-dominated catchments.

A previous stocktake of strategies to mitigate contaminant loads identified the potential for stream fencing to decrease the loads of N, P, SS and *E. coli* (McDowell et al., 2013b). A wide range of effectiveness has been recorded caused by different edaphic conditions (e.g. slopes, soil types), varying number of already-fenced streams and stream density among measurement sites. These data (range and median decreases) were applied to the load of N and P fractions and suspended sediment generated from streams and rivers in Taranaki. This is compared to the load potentially mitigated under the LAWF recommendations for all landuses and in catchments dominated by pasture (Table 4). Loads under the Taranaki recommendation, which requires all streams to be fenced irrespective of size or location, would be substantively less than those under LAWF recommendations. However, it should be recognised that the effectiveness of fencing-off stock as a strategy to mitigate contaminant loads is highly site- and contaminant-specific, ranging from highly effective in flat areas and where contaminants are particulate-associated to very ineffective in steeper areas and where contaminants are mobile (McDowell et al., 2013b).

Table 4. Contaminant loads (tonnes) as reduced by fencing according to regulation proposed by the Taranaki Regional Council and those recommended by the Land and Water Forum (Land and Water Forum, 2015).

	Taranaki load (% of NZ load)	Taranaki load	% Effectiveness of fencing[1]	Load under Taranaki recommendations	Load under LAWF recommendations (All landuses)	Load under LAWF recommendations (Pasture only)
DRP	4.7	133	52 (32-82)	64 (91-24)	122 (127-112)	120 (125-112)
E. coli[2]	6.8		38 (10-65)			
NH_4-N	4.2	129	15 (5-25)	110 (122-97)	127 (128-124)	126 (128-124)
NO_3-N	4.8	4050	10 (2-15)	3645 (3969-3443)	3989 (4038-3949)	3983 (4037-3949)
TN	4.5	5995	15 (5-25)	5095 (5695-4496)	5866 (5952-5742)	5843 (5944-5742)
TP	4.1	317	52 (32-82)	152 (215-57)	296 (304-277)	291 (301-277)
Suspended sediment	3.3	97098	35 (20-50)	63113 (77678-48549)	93735 (95176-91316)	93051 (94785-91316)

[1] Median percentage effectiveness and range (in parentheses) taken from (Hicks, 1995; Line et al., 2000; James et al., 2007; McDowell, 2007; McKergow et al., 2007; McDowell, 2008; Muirhead et al., 2011; Basher, 2013).

[2] Loads for *E. coli* are not carried through into recommendations as the percentage mitigation effectiveness relates only to median concentrations, not loads.

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