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Sizing constructed wetlands to help meet instream DIN concentration targets in the Tukituki catchment

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Abstract

Massey University was asked to estimate the wetland areas required to lower the mean DIN concentrations below 0.8 mg N/L at seven sub-catchments of the Tukituki river (an additional criteria being to reduce the mean concentration during spring and summer below 0.3 mg N/L). Monthly river quality data was provided by HBRC (Hawkes Bay Regional Council) for seven locations. Unfortunately, the flow rate was not available for three of these locations and it was therefore not possible to predict the wetland treatment efficiency at the associated streams. For each remaining location (henceforth referred to as Managaonuku, Kahakakuri, Porangahau, and Tukipo), the wetland areas required to meet the annual mean downstream concentration of 0.8 mg/L was iterated by calculating the monthly wetland and downstream concentrations for the selected area using monthly stream flow, water temperature, and nitrate concentration. The model used was selected and calibrated based on monitoring data obtained under relevant conditions (Pekapeka) and the literature (e.g. 'plug flow areal' model with k_{20} = 82 m/yr and ϕ = 1.09). The hydraulic loading rate (HLR, m/d) was capped to 0.27 m/d based on the literature, in order to prevent wetland damage during high flow events. A safety factor (SF) of 20% was finally applied to the computed wetland area required to meet targets (based on analysis of temporal variability and uncertainty).

Based on this methodology (i.e. 20% SF included), the wetland area required to meet the annual target was determined to be 163, 179, 17.4, and 21.5 ha at Mangaonuku, Kahakakuri, Porangahau, and Tukipo, respectively. These wetland areas represent 0.45, 2.2, 0.24 and 0.10% of their respective total catchment areas (35984, 8026, 7256, and 22040 ha, respectively). These fractions tend to be lower than the general rule of thumb of requiring 1-5% of the catchment area to reduce annual loads, and highlights that wetlands may be more cost effective than currently expected when the target reductions relate to concentrations rather than loads.

Larger area would be required to meet the spring & summer target at Managaonuku (170 ha), Kahakakuri (198 ha), and Tukipo (23.6 ha), while this target was already achieved at Porangahau.

The Capital and O&M costs were estimated to \$165,000-167,000/ha and \$36,533/ha, respectively. These relate to expected capital costs of \$22.5M, \$24.6M, \$2.4M and \$3.0M for the Mangaonuku, Kahahakuri, Porangahau and Tukipo, respectively. The costs per kg of N removed decreased from \$45/kg at Tukipo, a low nitrate concentration location, to \$16/kg, \$13/kg, and \$7.7/kg at Mangaonuku, Porangahau and Kahahakuri (where nitrate concentration was generally high). These wetlands are therefore predicted to provide cost-efficient removal. Targeting nitrogen concentration

reduction therefore appears to provide cost efficient nitrogen removal, especially in streams where nitrate concentration is high. Given the high uncertainty associated with the model calibration, we recommend the approach to be tested at Porangahau as this would require a relatively modest investment.

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1. Introduction - background:

In 2017 Massey University was contracted by Hawkes Bay's Regional Council (HBRC) to develop a model capable to predict Dissolved Inorganic Nitrogen (DIN) concentration following stream treatment using wetlands. Focusing on the Taharua and Tukituki catchments and nitrate (at nitrate represents > 97% of the DIN), an additional objective from this work was to determine if the cost-efficiency of using wetlands to reduce nitrate concentration could improve by targeting certain streams at certain times. For this purpose Massey University was provided with monthly data (e.g. flow rate, temperature, and nitrate concentration) to compute yearly and seasonal averages used in the model. Based on the literature, Massey University initially developed two models (areal and volumetric, see Appendix) predicting wetland area and costs based on the targeted downstream river concentration, water column depth, packing porosity, and other inputs and assumptions based on the literature. Some of the key findings from this analysis were that 1) significant reductions in area and costs may be achieved by targeting nitrate concentration reduction during warmer seasons only; 2) cost-efficiency is higher when instream nitrate concentration is high; and 3) treating only a fraction of the instream flow onto the wetland decreases cost-efficiency[1]. Treatment costs may also be reduced 5-10 folds by using a free surface wetland (FSW) over sub-surface wetland (SSW), not using a liner, and using natural plant recruitment. There was however considerable variation (nearly 5 fold) in area and cost predictions due to variability and uncertainty in data and model inputs.

Following this first study, Massey University was asked to estimate the wetland areas required to lower the annual mean DIN concentrations below 0.8 mg/L at seven sub-catchments of the Tukituki river (an additional criteria being to reduce the mean concentration during spring and summer below 0.3 mg/L). Local data was also provided to calibrate the model and reduce uncertainty. The present report provides 1) results from initial site selection and preliminary wetland area and cost computation; 2) an analysis of

[1] The last 2 conclusions are logical based on the mechanistic modelling assumption that nitrate removal rate is of first-order kinetics (Appendix 2).

temporal variability based on daily concentration profiles at two locations; and 3) a sensitivity analysis based on model inputs and discussion of findings.

2. Methods

2.1. Wetland type

Constructed Wetlands can be classified as Free Water Surface (FWS) wetlands and Subsurface Flow (SSF) wetlands. FWS wetlands are made of one or more vegetated shallow basin, with soil to support vegetation and appropriate inlet and outlet structures. Subsurface wetlands include vertical flow wetlands and horizontal subsurface flow (HSSF) wetlands. In the latter, water flows horizontally in a porous media where vegetation is planted and water is thus found between an impermeable layer and the surface. Media is composed by gravel, sand or soil, with different porosity. Because FWS are allegedly less costly to construct (no need for porous media) and more efficient at removing nitrate than HSSF[2], only this configuration was designed and costed in the following.

2.2. Data analysis

Monthly river quality data was provided for seven locations. Unfortunately, the flow rate was not available for three of these locations and it was therefore not possible to predict the wetland treatment efficiency of the associated streams. For each remaining location, the wetland areas required to meet the annual mean downstream concentration of 0.8 mg/L was iterated by calculating the monthly wetland and downstream concentrations for the selected area using monthly stream flow, water temperature, and nitrate concentration, as described below. The same procedure was used to determine the areas required to meet the spring and summer target of 0.3 mg/L.

Following this, daily profiles of flow, water temperature and nitrate instream concentrations were generated by linearizing monthly data for two locations. The wetlands areas required for each targets were then estimated again as described above.

[2] Crites et al. (2014) noted that FWS remove nitrate more efficiently than HSSF due to the organic carbon released by plants (despite the larger interface area provided in HSSF), but to our knowledge it is unclear if FWS or HSSF wetlands will be better for treating river effluents.

2.3. Model selection description

Various mathematical expressions have been used to predict or describe wetland performance (Crites et al., 2014; Lin et al., 2008). An 'areal' model was preferred here as it appears to be more frequently used in the literature than the 'volumetric' approach, and because it does not require inputting packing porosity and water depth. Although the 'well-mixed' expression of the areal model showed similar fitness to the 'plug-flow' expression during calibration (Appendix 2), the 'plug flow' does not need to input an hydraulic factor and is therefore less inherently uncertain. The two models nevertheless generated very similar results.

Following model selection and calibration, the following methodology was used to compute the nitrate removal efficiency associated with a given wetland area (A, ha). For this purpose, a theoretical hydraulic loading rate (HLR_{th}, m/d) thorough the wetland was calculated assuming the entire stream flow was diverted onto the wetland (Q_w, m^3/d) as:

$HLR = Q_w/A$ (1)

To prevent hydraulic shocks, it is however important to cap the actual hydraulic loading rate (HLR) below a maximum value (HLR_{max}, m/d) above which only a fraction on the stream was diverted onto the wetland. Thus:

$HLR = Q/A$ and $Q_w = Q$ when $Q/A < HLR_{max}$ then (the entire stream is treated)

$HLR = HLR_{max}$ and $Q_w = HLR_{max} \cdot A$ when $Q/A \geq HLR_{max}$ (only a fraction of the stream corresponding to $f = Q_w/Q$ is treated).

Once the actual HRL was calculated, the nitrate concentration exiting the wetland (C_w, mg/L) was estimated using the areal plug flow model (Appendix 2) described as:

$C_w = C_{up} \cdot \exp(-k_T/HLR)$ (2)

Where C_{up} is nitrate concentration upstream of the wetland (mg N/L) and k_T is the 'areal' rate constant (m/yr) at temperature T calculated as:

$k_T = k_{20} \cdot (\phi)^{(T - 20)}$ (3)

Where k_{20} is the rate constant at 20°C (m/yr), ϕ is the temperature coefficient, and T is the stream temperature at the time considered. Equation (2) also implies that the impact of nitrate background concentration, evaporation, and rain precipitation were neglected in our computations.

The concentration of nitrate downstream of the wetland was calculated as:

$C_{down} = [Q_w \cdot C_e + (Q_{in}-Q_w) \cdot C_{in}]/Q_{in}$ (4)

Wetland area was manually adjusted to achieve each target for a given set of model input and location.

2.4. Calibration and other design considerations

Calibration of K_{20} and ϕ: The base-case value of K_{20} was set to 82.0 m/d based on the literature and our calibration and this parameter was varied by – 20% and + 20% as worse and best cases, respectively. The value of ϕ was set to 1.09 based on the literature (Kadlec and Wallace, 2009; Kadlec, 2005).

Setting HLR_{max}: Kadlec and Wallace (2019) reported a median HLR of 0.071 m/d across 72 "nitrate dominated FWS", with median influent and effluent concentrations of 4.0 and 1.4 mg N/L, respectively. The same authors also describe several FWS operated at HRL ranging from 0.008 up to 0.65 m/d, for a median of 0.13 m/d. HLR values near 0.1 m/d were reported in a study conducted under instream nitrate concentrations of 1.3-2.5 mg N/L (Beutel et al., 2009). In a study conducted at high influent concentration (20 mg N/L), Lin et al. (2008) reported that nitrate removal efficiency (%) dropped when HLR was increased from 0.02 to 0.25 m/d but that the nitrogen removal load increased up to 332 g N/m^2-yr at 0.12 m/d. A value of 0.27 m/d has been cited as maximum value (Halling et al. 2014) and this value was used as default HLR_{max} value in the following.

Nitrate loading rate (NLR, g/m^2-yr), and nitrate removal rate (NNR, g/m^2-yr): While not used for wetland area determination, it is preferable to keep the NLR and NNR within the observed ranges of published studies during calibration. Based on 72 "nitrate dominated FWS", Kadlec and Wallace (2009) reported a median NRR of 51 g N/m^2-yr, with 60% of the data being 10 and 156 g N/m^2-yr. In another set of data, the same authors also reported FWS operation at NLR ranging from 5 up to 950 g/m^2-yr for a median of 168 g m^2/d. Beutel et al. (2009) reported good performance at NLR and NRR of 47-50 and 42-45 g/m^2-d, respectively, at inlet nitrate concentrations of 1.3-1.4 g N/L (HLR of 0.1 m/d).

2.4. Costs

Construction costs were estimated based on recommendations and data from Kadlec and Wallace (2009), assuming the free surface wetland will neither be lined (i.e. no liner cost) nor planted (i.e. use natural recruitment) in order to reduce costs. Land purchase was also not included as it is very case specific and because its value may appreciate over lifetime (no salvage value was therefore considered at the end of the project). The direct construction (capital) costs considered were therefore site investigation costs (topographic survey, US$ 250/ha, and hydrogeological investigations, US$750/ha), earthwork (US$ 7.56/m^3), purchase of coarse stones to protect berm slopes (US$ 47.59/m^3), water control structures and piping (US$ 0.57 per m^3/d of flow rate treated), and site work[3] (US$ 2/m^2). Indirect costs were computed based on total direct costs and included engineering (12.5% of direct costs), construction observation (5%), start-up services (5%), non-construction costs (5%), and contingency (20%). Operational and maintenance (O&M) costs were estimated to US$ 2000/ha-yr based on the same authors. The present worth of future O&M costs over the 25 years life were then computed assuming a discount rate of 8%. All 2006 USD costs listed above were converted in 2018 NZD using a USD/NZD conversion rate of 1.38 and a 2006 to 2018 inflation index of 1.248 (https://www.usinflationcalculator.com/). The volume of coarse stone required was assumed to represent 2.5% of the total wetland volume.

3. Results

3.1. Site selection and wetland area prediction

As can be seen in Table 1, the “Mangaonuku Strm US Waipawa Rv” and “Kahahakuri stream at Lindsay Rd” sites (henceforth referred to as ‘Mangaonuku’ and ‘Kahahakuri’ for simplicity) were characterized by comparatively high flows and nitrate concentrations at all times (yielding considerable winter loads). In comparison, the “Porangahau Strm at Oruawhara Rd” and “Tukipo Rv at SH50” sites (henceforth referred to as ‘Porangahau’ and

[3] Kadlec and Wallace (2009) cite a median cost of US$46.06/m^2 for site costs but this figure is high and inconsistent with other estimates provided by the same authors. A value of US$ 2/m^2 was therefore inputted based on an example from these authors for FWS costing.

‘Tukipo’) were characterized by comparatively low flows and nitrate concentrations (yielding low summer loads) but high seasonal temperature variations. The mean annual and mean spring-summer nitrate concentrations were therefore above HBRC’s targets at all locations. A more complete data set is provided in Appendix 1.

Table 1: Comparison of spring/summer and fall/winter mean flow (m/s), nitrate concentration (g N/m^3), temperature (˚C) and nitrate load (kg N/d) at the four locations selected.

Period (sample size)	Flow (m^3/d)	Nitrate (g N/m^3)	Temperature (˚C)	Nitrate load (kg N/d)
		Mangaonuku Strm US Waipawa Rv		
Nov-April (37)	150,684	1.73	16.2	255
May-Oct (40)	436,243	2.07	11.6	865
Year (77)	299,027	1.91	13.8	572
		Kahahakuri Strm at Lindsay Rd		
Nov-April (17)	112,328	2.70	16.0	314
May-Oct (10)	301,484	3.43	11.8	1023
Year (27)	182,386	2.97	14.4	836
		Porangahau Strm at Oruawhara Rd		
Nov-April (57)	18,293	0.89	17.1	24.1
May-Oct (55)	66,918	2.16	10.8	168
Year (112)	42,171	1.51	14.1	174
		Tukipo Rv at SH50		
Nov-April (57)	65,280	0.68	16.2	52.3
May-Oct (55)	199,113	1.41	9.72	304
Year (112)	131,001	1.04	13.0	187

Table 2 lists the wetland areas predicted at the four locations selected for the two criteria provided by HBRC. Larger areas are required at Mangaonuku and Kahahakuri than at Porangahau and Tukipo, which is logical given the differences in nitrate loads received (Table 1). The average Nitrate Loading Rate (NLR) and Nitrate Removal Rate (NNR) remained within ‘typical’ values (NLR of 94-135 g N/m^2-yr and NNR of 16-82 g N/m^2-yr), expect at Tukipo, where NLR was high (283-373 g N/m^2-yr) due to data bias (the median was 72-96 g N/m^2-yr). At all locations considered, a significant fraction of the stream could not be treated due to the HLR capping.

Table 2: Wetland area required (ha) to maintain the required mean downstream nitrate concentration targets.

Target	**Mean annual = 0.8 mg N/L**			**Mean sprint & summer = 0.3 mg N/L**		
Site	Best	Base	Worse	Best	Base	Worse
Mangaonuku	115	136	169	118	142	177
Kahahakuri	124	149	185	137	165	206
Porangahau[a]	12.3	14.5	17.9	5.6	6.6	8.2
Tukipo	15.8	17.9	21	17.1	19.7	24

a The mean spring and summer target was already achieved when the wetland was sized for the annual 0.8 mg/L target

3.2. Costs

The 2018 NZD costs of wetland treatment logically increased with size, ranging from $2,399,104 at Porangahau up to $24,579,527 at Kahahakuri (Table 3). However, the costs per wetland area varied little, ranging from $165,000-167,000/ha for capital costs and $36,533/ha for operational costs (lifetime of 25 years, 8% discount rate). This is explained by the methodology used as nearly all costs were based on area (depth was fixed at 0.5 m) and the water flow rate was only used to compute the costs associated with water control structures, which never exceeded 1.4% of the total direct costs. Based on data from 84 wetlands, Kadlec and Wallace (2009) reported that the total construction costs of FWS could be estimated as a function of wetland size (A, ha) NZ$ $332{,}000 \cdot A^{0.690}$, when adjusting for inflation and exchange rate. Based on this formula, the construction costs of the two large wetlands at Mangaonuku and Kahahakuri should be nearly 50% of the values listed in Table 3 (the costs of the smaller wetlands better agreed with predictions from the general formula). However, Kadlec and Wallace (2009) also reported near 10-fold variations in the costs of wetlands of similar size in the 1-100 ha range. In New Zealand, Hamill et al. (2014) recently costed 16 small wetland (0.04-6.25 ha) for N removal in the Tarawera and Rotokakahi catchments and reported total construction costs ranging from $36,718 –

201,200/ha, for a median of $80,651/ha[4], which is considerable lower than our estimates. In an earlier study, Hamill et al. (2010) reported total construction costs of $188,565-273,875/ha for 3-10 ha wetlands[5] (2010 NZD) and maintenance costs of $4,000/ha-yr (against $6,328/ha-yr in our estimates) for N-removing constructed wetlands, which is comparable to the data shown in Table 3. There is however considerable uncertainty in all costs provided.

Under the assumptions used (free surface wetland without liner using natural plant recruitment, no land purchase cost, 0.5 m water depth), direct capital costs were mainly contributed by earthwork (57% of total direct capital costs) and site work (30%). Indirect costs represented 50% of the direct costs, or 32% of total capital costs. Earthwork costs may be proportionally reduced by reducing water depth (i.e. reducing water depth by 20% reduces earthwork and associated indirect costs by 20%) but this should also reduce the denitrifying rate K_T by a similar factor. Thus, reducing water depth by 20% from 0.5 m to 0.4 m reduces overall wetland construction by nearly 20%, but the wetland area required increases by approximately by 17-24% (see changes from "base" to "worse" in Table 2), thus yielding similar costs for a larger treatment area. It may therefore be useful to consider increasing depth in order to reduce land requirement (while keeping costs approximately constant). This approach however remains to be demonstrated experimentally, and shallow water wetlands (average water depth less than 0.4 m) are expected to remove nitrogen more efficiently than deeper water wetlands[6]. Costs may be reduced by increasing lifetime and reducing indirect capital expenses.

[4] These costs excluded land purchase or leasing, but included earthwork @ $2,320-47,150/ha (median of $10,735; compared to $64,683/ha in our estimates); structures @ $3,200-50,000/ha (median of $12,693; compared to $12,000-13,000/ha in our estimates when including coarse stones), planting @ $18,265-40,273/ha (median of $32,142; not included in our estimates) and fencing @ ($3,073-33,214/ha, median of $12,397; against $34,224/ha for site work in our estimates). Indirect costs represented 30% of direct costs (47.5% in our estimates), and maintenance was estimated as 30% of total (O&M costs represented approx. 22% of total construction costs in our estimates).

[5] These authors used Kadlec and Wallace (2009) formula adjusted as total cost = $\$38{,}500 \cdot Area^{0.69}$

[6] Personal communication from Dr Hicks

Table 3: Wetland construction and O&M costs to achieve mean of 0.8 mg N/L.

Location	Cost	Best	Base	Worse
Mangaonuku	Capital	$ 19,081,475	$ 22,538,811	$ 27,958,461
	O$M life	$ 4,201,336	$ 4,968,536	$ 6,174,137
	Total	$ 23,282,811	$ 27,507,347	$ 34,132,597
	Capital/ha	$ 165,926	$ 165,727	$ 165,435
	O&M life/ha	$ 36,533	$ 36,533	$ 36,533
	$/ kg NO3-N removed	$ 12.8	$ 15.1	$ 18.6
Kahahakuri	Capital	$ 20,481,576	$ 24,579,527	$ 30,476,287
	O$M life	$ 4,530,136	$ 5,443,470	$ 6,758,670
	Total	$ 25,011,711	$ 30,022,997	$ 37,234,957
	Capital/ha	$ 165,174	$ 164,963	$ 164,737
	O&M life/ha	$ 36,533	$ 36,533	$ 36,533
	$/ kg NO3-N removed	$ 6.25	$ 7.40	$ 9.12
Porangahau	Capital	$ 2,036,714	$ 2,399,104	$ 2,958,223
	O$M life	$ 449,360	$ 529,734	$ 653,947
	Total	$ 2,486,074	$ 2,928,837	$ 3,612,170
	Capital/ha	$ 165,587	$ 165,455	$ 165,264
	O&M life/ha	$ 36,533	$ 36,533	$ 36,533
	$/ kg NO3-N removed	$ 11.0	$ 12.8	$ 15.7
Tukipo	Capital	$ 2,634,331	$ 2,982,511	$ 3,496,043
	O$M life	$ 577,227	$ 653,947	$ 767,200
	Total	$ 3,211,558	$ 3,636,459	$ 4,263,243
	Capital/ha	$ 166,730	$ 166,621	$ 166,478
	O&M life/ha	$ 36,533	$ 36,533	$ 36,533
	$/ kg NO3-N removed	$ 44.4	$ 48.6	$ 54.3

3.3. Impact of wetland area on downstream nitrate river concentration

The Mangaonuku and Kahahakuri sites were selected for more in-depth analysis as these locations have significantly higher loads of nitrate at the catchment level (Table 1). For this purpose the monthly monitoring data provided by HBRC was linearized to generate daily profiles and used to predict the impact of wetland area on downstream nitrate concentration for different model inputs.

The impact of wetland area on the mean downstream nitrate concentration predicted for the worse, base, and best values of K_{20} is illustrated on Figure 1. As can be seen, the mean downstream concentration logically decreases when wetland area increases and uncertainty on the kinetic coefficient K_{20} generates considerable uncertainty in the required wetland area. For example, the wetland area required to maintain a mean nitrate concentration below 0.8 mg N/L varies from 125-153 ha (base case of 148 ha) at Mangaonuku, and 121-182 ha (base case of 145 ha) at Kahahakuri. Wetland area has a stronger impact on mean downstream nitrate concentration at Kahahakuri than Mangaonuku and this is most likely due to the higher nitrate concentration at Kahahakuri. Interestingly, the areas predicted using simulated daily data were 0-9% higher than the values predicted from experimental monthly data. A safety factor of 10% could therefore be applied to the areas listed in Table 2. Figure 2 illustrate changes in concentrations and flows for the year 2008 at Managaonuku.

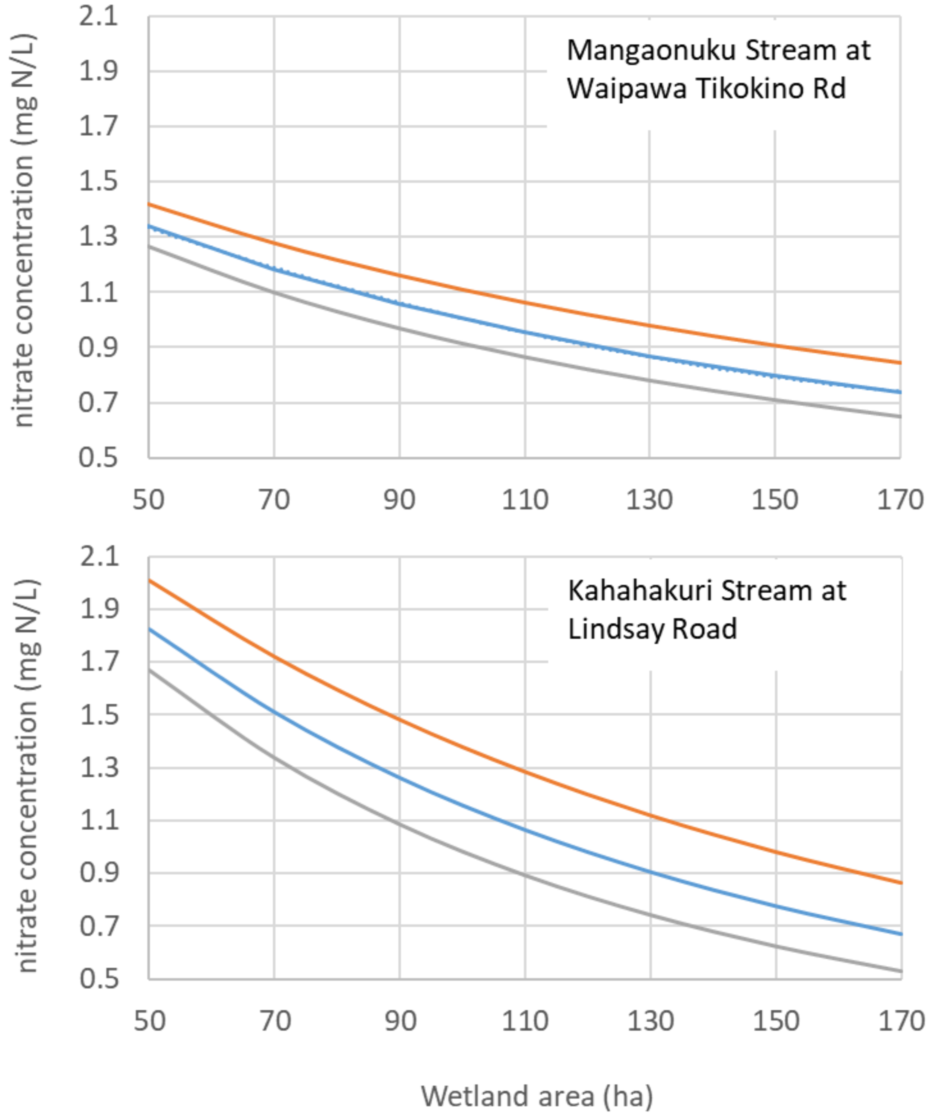
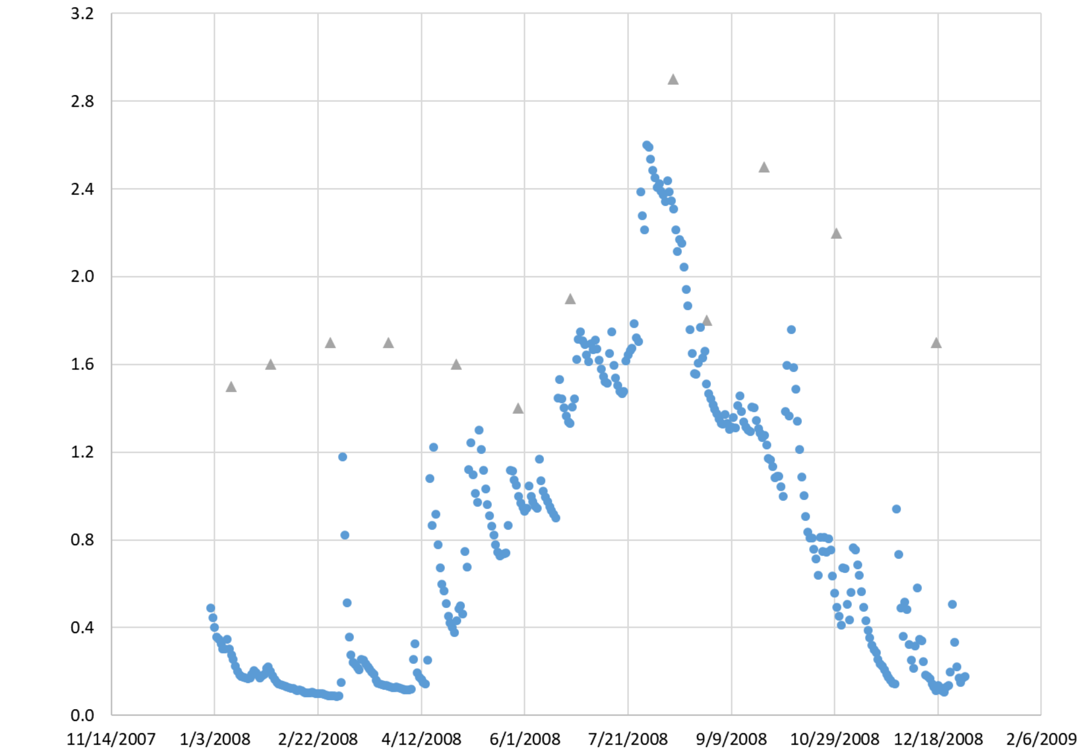


Figure 1: Changes in mean downstream river concentration against wetland area (ha) under base (blue), worse (red), and best (grey) scenarios.


3.2
2.8
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1.6
1.2
0.8
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11/14/2007
1/3/2008
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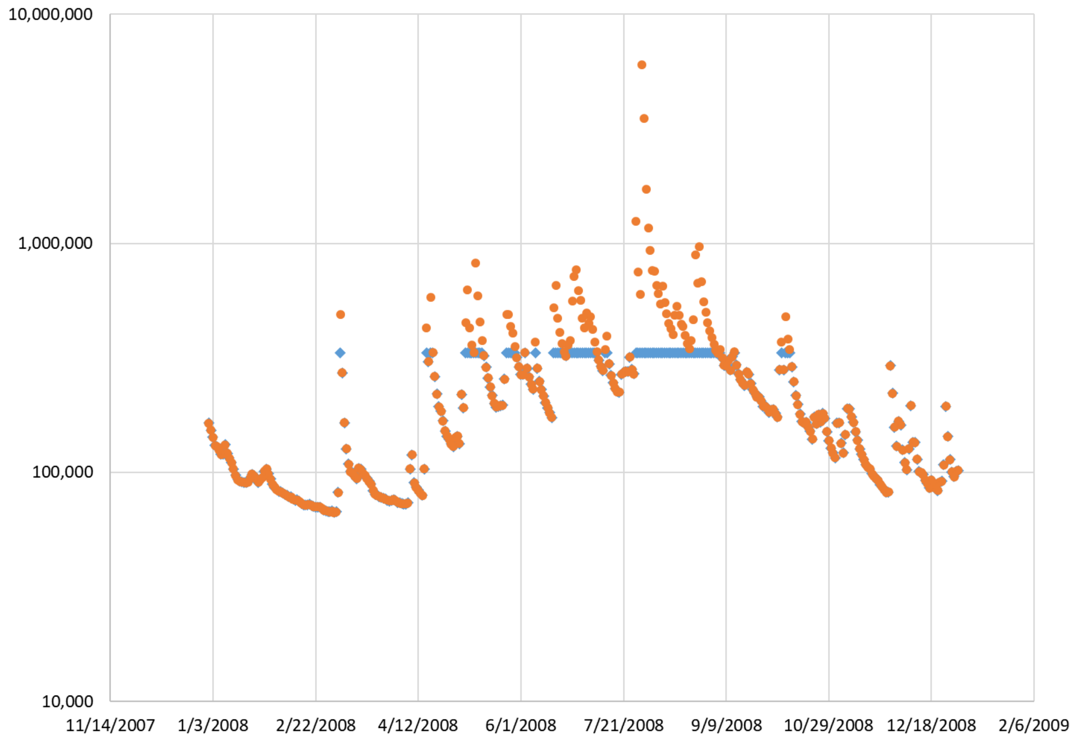
12/18/2008
2/6/2009


10,000,000
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2/22/2008
4/12/2008
6/1/2008
7/21/2008
9/9/2008
10/29/2008
12/18/2008
2/6/2009

Figure 2: Changes in instream nitrate concentration (grey triangle), predicted downstream nitrate concentration (blue circles), stream flow (orange circles), and predicted treated flow (blue diamond) at Mangaonuku (k_{20} = 82 m/yr, ϕ = 1.09, and HLR_{max} = 0.27 m/d, A = 123 ha).

According to Dr Hicks, the catchment areas at the Mangaonuku and Kahahakuri monitoring sites are 35,984 and 8,026 ha, respectively. Applying NIWA guidelines for wetland sizing as 1-5% of catchment area for significant nitrogen reduction yields required wetland areas of 360-1799 ha for Mangaonuku and 80 - 401 ha for the Kahahakuri. While our predictions fall in the lower range of 'NIWA-based' estimates for Kahahakuri, they are significantly smaller in the case of Mangaonuku. Significantly smaller nitrate concentration and load reductions were however required at Mangaonuku than at Kahahakuri (Table 4) due to the lower nitrate instream concentrations recorded at Mangaonuku (Table 1). A 490 ha wetland would in fact be needed to remove 59% of the nitrate load at Mangaonuku (base case), which represents 1.4% of the catchment. Currently, 1.4% of the catchment is required to achieve the same objective at Kahahakuri (e.g. 130 ha; Table 4). Considerable savings can thus be achieved by targeting concentration reduction rather than load reduction.

Table 4: Key operational and performance data during simulated stream treatment in free surface wetlands of different areas.

Area (ha)	50	70	90	110	130	150	170
Mangaonuku							
Average HLR (m/d)	0.24	0.22	0.20	0.18	0.17	0.15	0.14
Fraction of flow treated (%)	34%	44%	51%	51%	57%	65%	68%
Nitrate loading rate (g N/m^2-yr)	169	155	142	130	120	110	102
Nitrate removal rate (g N/m^2-yr)	69	66	62	59	56	54	51
Nitrate removal load (t N/yr)	34.4	45.9	56.0	65.0	73.1	80.3	87.0
Average concentration reduction (%)	31%	39%	46%	52%	56%	60%	63%
Total load reduction (%)	14%	18%	22%	26%	29%	32%	35%
Kahahakuri							
Average HLR (m/d)	0.23	0.18	0.15	0.13	0.11	0.10	0.09
Fraction of flow treated (%)	75%	83%	88%	90%	92%	94%	95%
Nitrate loading rate (g N/m^2-yr)	259	209	172	145	125	110	99
Nitrate removal rate (g N/m^2-yr)	110	101	93	86	79	74	69

Nitrate removal load (t N/yr)	55.1	70.8	83.6	94.1	103	110	117
Average concentration reduction (%)	42%	53%	61%	67%	73%	77%	80%
Total load reduction (%)	32%	41%	48%	54%	59%	63%	66%

As evidenced by the data displayed in Table 4, treatment performance logically improved when wetland area increased. Concentration reduction (%) was always higher than load reduction (%), and this is explained by the fact that only a fraction of the instream flow is diverted onto the wetland when flow is high (Table 4). Because the hydraulic loading increases when wetland area decreases (evidence by the average HLR in Table 4), both the areal nitrate loading rate (g N/m^2-d) and the areal nitrate removal rate (g N/m^2-d) increased when wetland area decreased. However, removal also became less efficient and the overall nitrate removal load (t N removed per year) logically decreased when wetland area decreased.

3.4. Temporal variability

Table 5: Yearly upstream and predicted downstream nitrate concentration (mg N/L) at Mangaonuku (base case wetland area of 148 ha).

Year	Upstream (mg N/L)		Downstream (mg N/L)	
	Median	**Mean**	**Median**	**Mean**
2007	1.88	1.92	0.62	0.81
2008	1.73	1.92	0.60	0.74
2009	2.07	2.11	0.77	0.87
2010	1.87	1.88	0.70	0.75
2011	1.92	1.90	0.74	0.83
2012	1.64	1.73	0.67	0.85
2013	1.78	1.82	0.67	0.77
2007-2013	1.87	1.90	0.68	0.80

Table 5 lists the yearly upstream and predicted downstream nitrate concentration (mg N/L) at Mangaonuku when the wetland was sized to achieve a mean downstream concentration at 0.8 mg N/L over the entire assessment period. As can be seen, this threshold was exceeded during 4 years. To achieve a mean downstream concentration below 0.8 mg N/L during all years would require to increase wetland area from 148 to 167 ha under the base case scenario (13% increase).

Table 6: Mean upstream and downstream nitrate concentrations (mg N/L) under selected environmental conditions. RE_C and RE_L represent the predicted percentage concentration and load reduction, respectively.

Metric Criteria	Occurrence[a] %	Upstream mg N/L	Downstream mg N/L	RE_C %	RE_L %
Mangaonuku (148 ha)					
T > Median (14.4˚C)	50	1.73	0.36	79%	52%
Flow < Median (206,155 m^3/d)	50	1.80	0.30	83%	83%
T< Median and Flow < Median	39	1.75	0.22	87%	85%
Kahahakuri (112 ha)					
T > Median (13.9˚C)	50	2.60	0.34	87%	86%
Flow < Media (113,607 m^3/d)	50	2.60	0.36	86%	85%
T > Median and Flow < Median	34	2.45	0.22	91%	91%

[a] Occurrence = number of day the criteria is/are met (e.g. by definition of the median, 50% of the data is below or above the median value).

An additional criteria provided by HBRC was that downstream concentration should be maintained below 0.3 mg N/L during spring and summer. The rationale for this secondary and more stringent criteria is that the ecological impact of nitrate pollution (the triggering of algae growth) is more likely stronger when high sunlight availability and high water temperature boost algae growth. To verify if this secondary criteria was indeed met over the assessment period considered, we estimated for each location the mean downstream nitrate concentration when temperature was above the median temperature and/or below the median flow (as these conditions are typically associated with higher ecological impacts). As can be seen from the data listed in Table 6, the more stringent target (0.3 mg N/L) is well achieved when both conditions are experienced (at both locations). An increase in wetland area of 15% from 148 to 170 ha (base case) is needed to meet the target when either conditions are experienced (occurring 61% of the time over the assessment period) at Mangaonuku. In comparison, a 10% increase (from 145 ha to 160 ha) is required to meet the target when either temperature is high or flow is low at Kahahakuri (66% occurrence). This analysis shows it may be more cost-effective to target a low spring & summer concentration and than a yearly concentration: Requiring a mean concentration of 0.3 mg N/L when temperature is high and flow low, only 124 and 125 ha are required at Mangaonuku and Kahahakuri, respectively (14-16% reduction).

3.5. Sensitivity to model inputs

Kadlec (2005) has reported that the mean value of K_{20} was associated with a relative error of less than 10% (34 ± 3 m/yr). In the present study, this uncertainty was increased to 20% to account for the fact that not all the data reviewed Kadlec (2005) may be relevant to the present study. Based on the data reported by these authors, a relative error of 3% was associated to the mean temperature correction factor (ϕ) value used. This uncertainty was increased to 5% in the following analysis. Little data is available to estimate the variability of HLR_{max} and this parameter was allowed to vary by ± 20%.

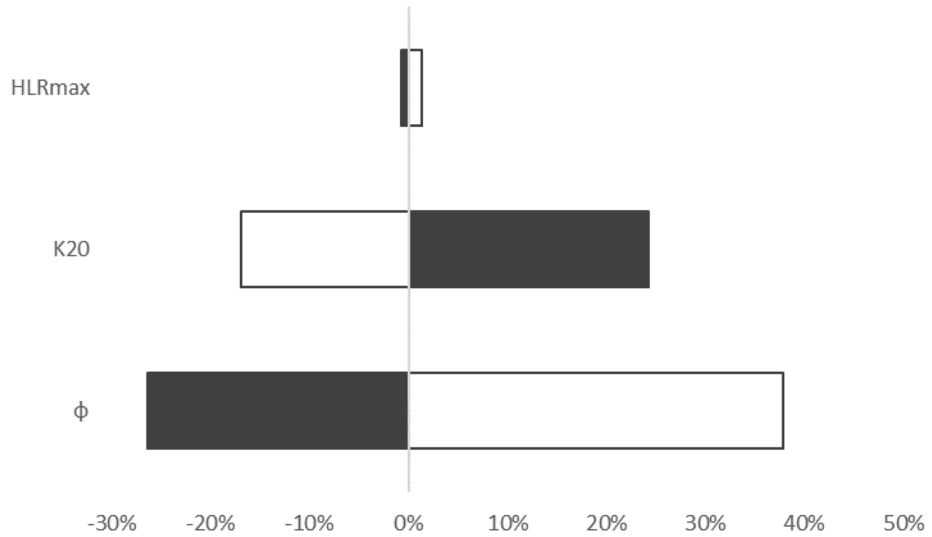

Figure 3: Impact of changes in the values of K_{20} (±20%), ϕ (±5%), and HLR_{max} (±20%) on the wetland area required to reduce downstream mean nitrate concentration to 0.8 mg N/L at Mangaonuku. Black bars shows impact of decreasing the input value and white bar shows the impact of increasing the input value.

As can be seen from the data illustrated in Figure 3, uncertainty on ϕ and K_{20} generated considerable uncertainty on predicted area whereas the impact of HLR_{max} variability was insignificant. The impact of these inputs were similar at Kahahakuri (not shown). The high impact of uncertainty on ϕ mandates for further investigation because it cannot be dissociated from the impact of k_{20}, depending on how these values were obtained from experimental data[7]. While further analysis is beyond the scope of this student, we urge for caution and the inclusion of safety factors. The low impact of HLR_{max} has interesting engineering implications as capping HLR_{max} to a lower value could ease maintenance and improve performance by avoiding hydraulic shocks. How much HLR_{max} can be reduced is however likely location-dependant[8] (further analysis was beyond the scope of this study).

3.6. Safety factors

Based on the results shown above, we recommend to apply safety factors to the computation of wetland areas in order to account for temporal variability and model input uncertainty (this also increases the chance to meet the secondary target, as shown above). Two approaches can be used for this purpose:

1. The area is computed using monthly data and base-case inputs (k_{20} = 82 m/yr, ϕ = 1.09 and HLR_{max} = 0.27 m/yr) and is then increased by 20%.
2. The area is computed using monthly data and base-case inputs but assuming the targeted concentration is 20% lower than required (e.g. 0.64 mg N/L in this study).

Based on the first approach, all locations are impacted similarly although increasing area has different impacts: For examples, increasing wetland area from 136 to 163.2 ha at Mangaonuku causes the average flow treated to increase from 213,270 to 228,282 m^3/d, the amount of N removed to increase from 73,095 to 81,865 kg N/yr, and the mean annual concentration to decrease from 0.8 to 0.71 mg N/L. At Kahahakuri, increasing wetland area from 149 to 178.8 ha causes the average flow treated to increase from 153,906 to 160,458 m^3/d, the amount of N removed to increase from 162,284 to 185,210 kg N/yr, and the mean annual concentration to decrease from 0.8 to 0.66 mg N/L. Given the

[7] A k_{20} value of 81.4 m/yr was obtained by fitting experimental data when ϕ was set to 1.09. However, increasing ϕ by 5% (= 1.1445) causes the calibrated value of K_{20} to increase by 75% to 143 m/yr. Inputting the new values of ϕ and k_{20} in the model actually causes the required area to decrease by 20% at Mangaonuku, instead of increasing it by 38% as shown on Figure 2. Reversely, inputting ϕ = 1.0355 (-5%) in the calibration yields a new K_{20} value of 45 m/yr. Inputting the 2 new values in the model causes the required area to increase by 30%, instead of decreasing it by 26% as shown on Figure 2 (data from daily predictions).

[8] Reducing HLR_{max} by 50% causes the required area to increase by 8% and 2% at Mangaonuku and Kahahakuri, respectively (data from daily predictions).

low impact of the water flow on cost, increasing area by 20% also increases capital and O&M costs by 20%. The impact on the costs per kg N removed varied with locations by was limited (-3 to +7%).

Based on the second approach, the wetland areas required were estimated to 190 (+40%), 183 (+23%), 25 (+72%), and 39 (+118%) ha at Mangaonuku, Kahahakuri, Porangahau, amd Tukipo, respectively. The second approach is therefore more conservative and was not recommended.

4. Conclusions and recommendation

Using a 20% safety factor, the Capital and O&M costs were estimated to approximately $165,500/ha and $36,500/ha, respectively (25 years, discount 8%). The costs per kg of N removed thus decreased from approximately $45/kg at Tukipo, a low nitrate concentration location, to $16/kg, $13/kg, and $7.7/kg at Mangaonuku, Porangahau and Kahahakuri (where nitrate concentration was generally high). These wetlands therefore provide more efficient removal than the $79 kg/N forecasted by Hamill et al. (2010) when investigating various methods for reducing nutrient loads to lake Rotorua and, comparable to the most economical option listed by these authors (protecting natural wetlands, $14/kg N removed).

In light of the high impact of model input of predicted areas (Figure 2), we nevertheless recommend a cautious approach to implementation and possibly the use of a higher safety factor because the data used for model calibration. In particular, the K_{20} value of 82 m/yr was in the higher range of the values reported in the literature[9], and it was derived from data generated under low HLR and NLR conditions in comparison to the predicted values[10]. A potential way forward could therefore be to test the approach at Porangahau as this would only require a (relatively) small land area and therefore investment. The Pekapeka wetland should also be better characterised and more intensively monitored.

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[9] Kadlec (2005) reported 34 ± 3 m/yr compared to 192-196 m/yr by Beutel et al. (2009). Tanner et al. (2005) reported 17-92 m/yr in New Zealand.

[10] The model was mainly calibrated against the data collected from September to December 2017 (Appendix 4). Over this period the NLR varied from 9 to 43 g N/m^2-yr and the HLR varied from 0.03 to 0.11 m/d.

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Appendix A: Monitoring data

		Flow (m³/d)	Nitrate (g N/m³)	Temperature (˚C)	Nitrate load (kg N/d)
Tukipo	Average	65,280	0.68	16.15	52
	Min	8,986	0.09	10.20	4
	Q1	17,669	0.45	14.40	9
Nov-April	Q2 (Median)	34,319	0.56	16.00	20
	Q3	53,444	0.72	18.20	43
	Max	655,480	2.60	20.80	950
	N	57	57	57	57
May-Oct	Average	67,260	1.41	9.72	304
	Min	15,492	0.34	4.92	8
	Q1	79,763	0.81	8.10	74
	Q2 (Median)	128,775	1.36	9.80	214
	Q3	198,633	1.95	11.40	341
	Max	1,194,566	3.34	14.25	1,646
	N	55	55	55	55
Mangaonuku	Average	150,684	1.73	16.19	255
	Min	62,586	0.94	14.00	93
	Q1	82,180	1.50	15.20	146
Nov-April	Q2 (Median)	98,732	1.70	16.00	174
	Q3	159,868	1.90	17.30	272
	Max	743,872	2.50	20.40	1,319
	N	37	37	37	37
	Average	436,243	2.07	11.61	865
	Min	74,332	1.40	8.50	143
	Q1	201,492	1.63	9.88	420
May-Oct	Q2 (Median)	345,025	1.98	11.00	698
	Q3	427,591	2.35	13.33	1,026
	Max	2,438,738	3.00	16.16	3,756
	N	40	40	40	40
Porangahau	Average	18,293	0.89	17.15	24
	Min	1,814	0.00	11.80	0
	Q1	3,159	0.20	15.34	1
Nov-April	Q2 (Median)	5,964	0.76	17.30	5
	Q3	10,212	1.40	19.00	15
	Max	233,021	3.10	23.30	513
	N	57	57	57.00	57
	Average	66,918	2.16	10.84	168
	Min	2,913	0.15	5.73	1
	Q1	17,137	1.47	9.17	30
May-Oct	Q2 (Median)	38,042	1.96	10.87	81
	Q3	71,271	2.66	12.40	166
	Max	486,864	6.00	15.92	1,100
	N	55	55	55	55
Kahahakuri	Average	112,328	2.70	15.99	314
	Min	71,054	1.95	13.20	158
	Q1	93,997	2.40	14.90	255
Nov-April	Q2 (Median)	111,084	2.60	16.25	291
	Q3	126,117	3.00	17.25	320
	Max	169,915	4.00	18.40	680
	N	17	17	17	17
	Average	301,484	3.43	11.79	1,023
	Min	106,916	1.92	8.10	242
	Q1	121,767	2.65	10.80	365
May-Oct	Q2 (Median)	168,846	3.40	12.23	709
	Q3	369,660	4.35	13.20	1,014
	Max	953,361	4.80	14.20	2,840
	N	10	10	10	10

Appendix B: Model selection and calibration

In combination with a water mass balance accounting for all inputs (influent, rain) and outputs (effluent, evaporation, evapotranspiration, and infiltration), volumetric and areal loading models have been developed to predict or describe denitrification efficiency in wetlands (Crites et al., 2014). The volumetric and areal approaches used for FWS are conceptually identical because both assume denitrification is limited by nitrate concentration and follows first order kinetics. There are however minor differences in the models as explained below. For simplicity, we henceforth assume that the inflow and outflow are similar (no impact of rain, infiltration and evaporation).

B.1. Volumetric approach:

Volumetric models were developed by Reed et al. (1995) and Crites and Tchobanoglous (1998). With this approach, denitrification efficiency is described by Crites et al. (2014) as:

$$C_e = C_0 \cdot \exp(-K_T \cdot HRT)$$

where C_e and C_0 are the effluent and influent nitrate concentrations (g NO_3^--N/m^3), respectively, K_T is the first-order reaction rate constant (d^{-1}) at water temperature T (˚C) and HRT is the hydraulic residence time (d) calculated as:

$$HRT = n \cdot d \cdot A_s / Q_A$$

where A_s is the wetland surface area (m^2); Q_A is the average flow thought wetland (m^3/d); n is the average porosity (dimensionless); and d is the average water depth (m). K_T is calculated as:

$$K_T = K_{20} \cdot (\Theta)^{(Tw - 20)}$$

where T_w is the average water temperature in the wetland; K_{20} is the first order constant value at 20°C (d^{-1}) and Θ is the temperature coefficient (dimensionless).

There is little data available to parameterize these systems, especially in the case of 'clean' influent with low nitrate concentrations (e.g. river) and Crites et al. (2014) assumed K_{20}= 1.00 d^{-1} and Θ = 1.15. Given the lack of data and need to input water depth and bed porosity (which uncertainty compounds model accuracy), this model was not selected for this study.

B.2. Areal approach in well-mixed systems:

Crites et al. (2014) also proposed to calculate performance as:

$$(C_e - C^*)/(C_0 - C^*) = \exp(-k_T/HLR)$$

where C* is the background concentration (g NO_3^--N/m^3), k_T is the 'areal' rate constant (m/yr) at temperature T (˚C) and HLR is the hydraulic loading rate (m/yr) calculated as:

$$HLR = Q_0/A_s$$

where Q_0 is the influent wastewater flow rate (m^3/yr).

Again, the reaction constant k_T is calculated as:

$$k_T = k_{20} \cdot (\phi)^{(Tw - 20)}$$

where k_{20} is the rate constant at 20°C (m/yr) and ϕ is the temperature coefficient.

Crites et al. (2014) also proposed to use default vales for k_{20} and ϕ of 34 m/yr and 1.09, and these values were likely obtained from Kadlec (2005).

B.3. Areal model in plug-flow systems

In this approach described by Kadlec and Wallace (2009), C_e is predicted as:

$$C_e = C_0 \cdot (1 + k_T/(N \cdot HLR))^{-N}$$

Where N is a constant representing the hydraulics. The reaction constant is again calculated as:

$$k_T = k_{20} \cdot (\phi)^{(Tw - 20)}$$

where k_{20} is the rate constant at 20°C (m/yr) and ϕ is the temperature coefficient.

Based on a large amount of literature, Kadlec (2005) proposes K_{20}, ϕ, and N values of 34 ± 3 m/yr, 1.09, and 4.5. These values have often been used in the literature (e.g. Hamill at al., 2014).

B.4. Model calibration

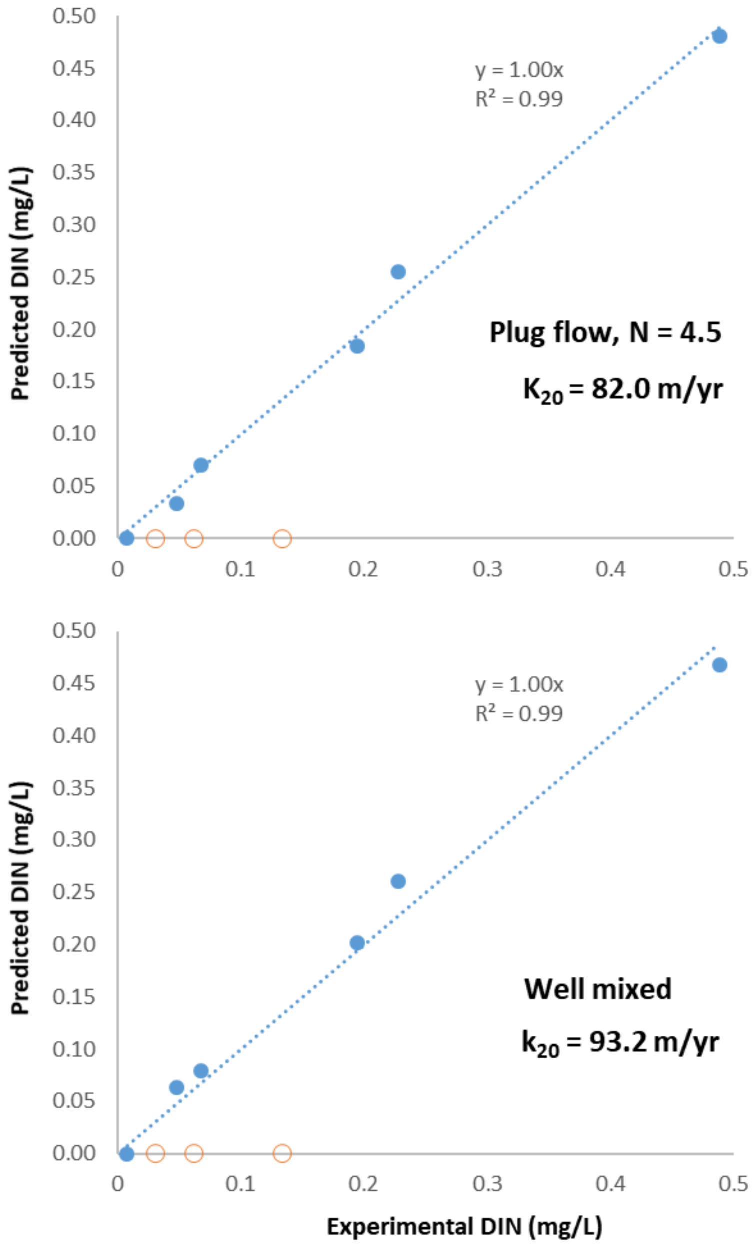

Figure A2.1: Comparison of predicted versus experimental concentrations using monitoring data from Pekapeka. Red circles show data excluded from the calibration. The values of K_{20} were manually adjusted to achieve a regression factor of 1. In both model the value of ϕ was 1.09 and in the plug-flow model the value of N was 4.5.

As can be seen from Figure A2.1 the two areal models yielded similar accuracies, albeit with slightly different k_{20} values. Both values were significantly higher than the median value of 34 m/yr reported by Kadlec (2005), but they are also lower than the 192-196 m/yr reported by Beutel et al. (2009) under similar conditions. They also fall within the range of 17-92 m/yr reported by Tanner et al. (2005) in New Zealand.

Appendix 3: wetland effluent vs downstream N concentrations

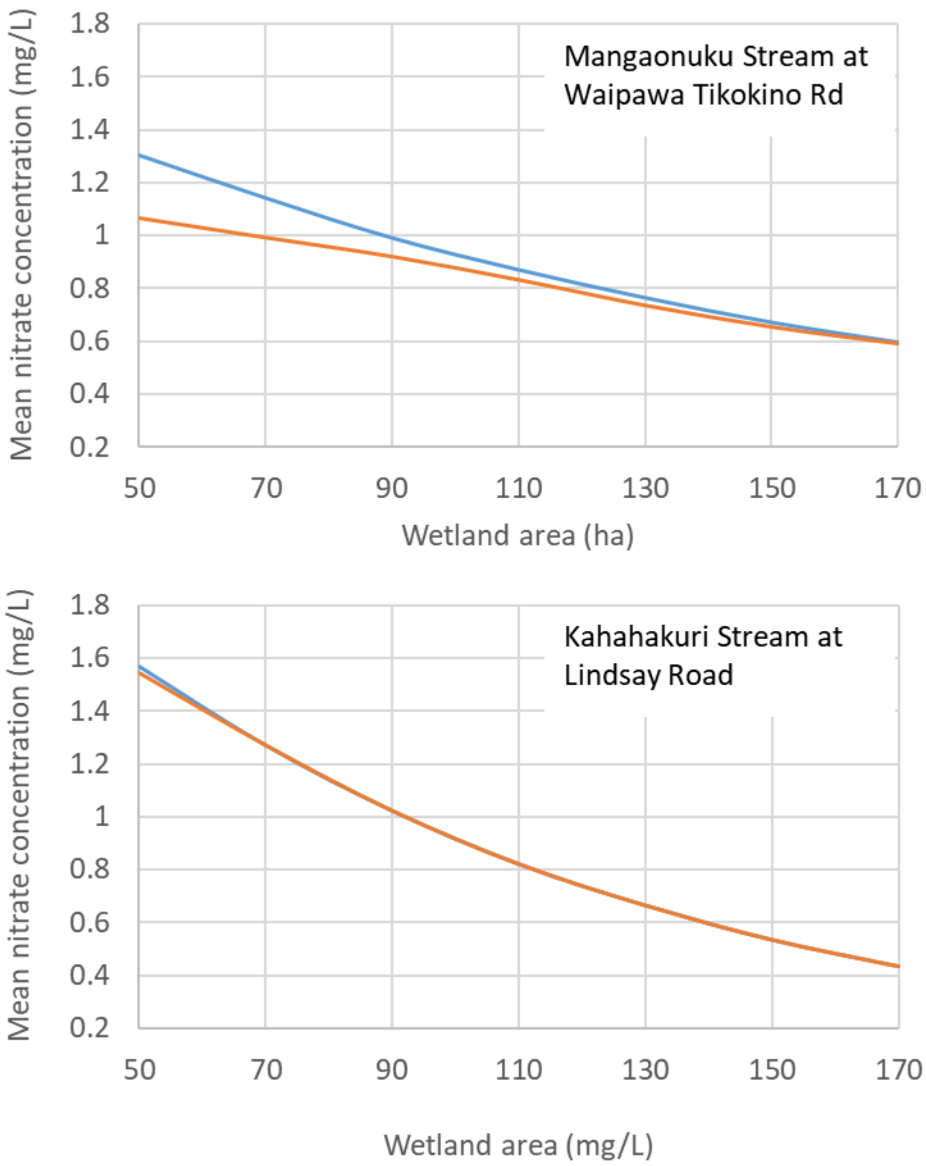

Figure A3.1: Change in predicted wetland effluent (red) and downstream (blue) median nitrate concentration (mg/L) against wetland area (ha) for the base case.

Appendix 4: Calibration data

		Upstream (Te Mahanga Road)			Downstream (Stock Road)			Treatment Efficiency	
Sample Date	Flow (l/s)	DIN(mg/L)	T (oC)	Load In (kg/d)	DIN (mg/L)	T (oC)	Load In (kg/d)	Kg N removed/ha-d	RE (%)
11/17/2016	90	0.4731	17	3.68	0.0617	15.4	0.48	11.9	87.0
12/6/2016	30	0.3123	19	0.81	0.134	19.2	0.35	1.72	57.1
1/13/2017	9.5	0.1564	17.6	0.13	0.0073	17.6[a]	0.01	0.46	95.3
2/9/2017	9.5	0.1982	15.7	0.16	0.0306	15.9	0.03	0.51	84.6
3/2/2017	14.6	0.558	18	0.70	Data missing	18.4	-	-	-
4/6/2017	890[b]	9.409[b]	16.5	724[b]	2.093[b]	15.9	326[b]	1482[b]	55.0
5/9/2017	320	1.077	10.5	29.8	0.0475	10.4	1.31	106	95.6
6/12/2017	500	0.9984	7	43.1	0.1949	7.2	8.42	129	80.5
7/6/2017	690	0.936	7.2	55.8	0.2278	7.9	13.6	157	75.7
8/7/2017	1250	1.06	9	114	0.4884	9	52.8	230	53.9
9/12/2017	650	0.4278		24.0	0.0677	11[c]	3.80	75.3	84.2

a) Data missing to assumed equal to upstream temperature
b) Clear outlier (upstream sample withdrawn on 4/5/2017 with flow of 1800 l/s)
c) Data missing and extrapolated based on seasonal trend