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CONSTRUCTED WETLAND ATTENUATION OF NUTRIENT INFLOWS TO TE WAIHORA / LAKE ELLESMERE

James P. S. Sukias, Chris C. Tanner, Mary de Winton and Scott Larned

NIWA-Hamilton, PO Box 11-115, Hamilton 3251

Abstract

Diffuse nutrient losses from agricultural land often require integrated approaches to manage and mitigate effects. Wetlands can be a useful tool to land owners due to their natural capacity to reduce nutrient fluxes to downstream water bodies by capturing phosphorus and removing nitrogen via denitrification. In the Te Waihora/Lake Ellesmere catchment (Canterbury), extensive drainage to facilitate agricultural land use has resulted in substantial loss of these natural wetlands from the landscape. Ongoing drainage and stream channelization has lowered water tables and disconnected many of the remaining wetlands from the drainage system, reducing their ability to intercept and attenuate the flux of sediments and nutrients into Te Waihora. NIWA was commissioned to undertake an assessment of the areas of wetlands in the catchment that would be needed to meet nitrogen load reduction targets of 20% and 40% in the 9 major surface inflows to the highly eutrophic lake. Modelling predicted a total of 593 ha of suitably-designed wetland would be needed to reduce the annual nitrogen loads by 20% and 1,782 ha of wetland to reduce the annual load by 40%. Substantial reductions in sediment and phosphorus microbial contaminant loads would also be achieved. Such wetland areas intercepting major inflows before they entered the lake, would occupy less than 0.3% and 0.9%, respectively, of their apparent catchment areas. Required areas of wetland for different inflows ranged from 16–142 ha for 20% TN load reduction, and from 44–324 ha for 40% TN load reduction. Appropriate areas of potentially suitable land for wetland creation were able to be identified near the outlets of major inflows to the lake edge and/or in shallow littoral areas of the lake. Surface-flow wetlands strategically located in these areas offer feasible, low-risk options to reduce nutrient loads and change the freshwater landscape of Te Waihora.

Introduction

Te Waihora, a shallow (1.4m average depth) and brackish coastal lake is New Zealand’s fifth largest lake (~20,000 ha), located southeast of Christchurch City. Its 276,000 ha catchment has undergone extensive drainage and channelization of waterways, intensification of irrigated pastoral grazing, and artificial opening of the lake to the sea to control water levels, has been associated with a gradual but continuous decline into very poor water quality, and degraded cultural and ecological values (Hughey and Taylor 2008, Hughey et al. 2013). Goals for improving water quality include 20% and 40% reductions in Total Nitrogen entering the lake. Environment Canterbury commissioned NIWA, with assistance from EC staff, to identify potential wetland areas within the major contributing catchments that could, if converted to well-functioning wetlands, theoretically achieve the 20% and 40% N-reduction targets. Wetland types included conventional surface-flow wetlands, river-side swales, and in-lake floating treatment wetlands. Modelling of potential removal was based on inflows and nutrient concentrations provided by Environment Canterbury, with removal based on the P-k-C* first-order kinetic modelling approach as proposed by Kadlec and Wallace (2009).

Methods

Sites within each catchment which retained appropriate wetland characteristics were visited by NIWA and EC staff as part of an initial scoping exercise. Sites included spring heads, river side swales, near lake flood plains (littoral wetlands) and in-lake locations which were potentially suitable for wetland restoration/creation. No consideration was made of current use or ownership, and thus the exercise was purely theoretical, and was an attempt to understand the scope of landscape changes which would be required to achieve the TN reduction goals.

Modelling of the nutrient attenuation of surface flow wetlands was based on the P-k-C* model of Kadlec and Wallace (2009), and represented by the following equation:

$$\frac{C_o}{C_i} = \left(1 + \frac{k}{Pq}\right)^{-P}$$

where:

C_i	=	inlet concentration (g m^{-3})
C_o	=	outlet concentration (g m^{-3})
k	=	temperature dependant first order removal rate constant (m y^{-1})
P	=	hydraulic efficiency parameter
q	=	hydraulic loading (m y^{-1})

Mean k rates and modified Arrhenius temperature coefficients for nitrate-N removal were derived from a comprehensive recent review of available international (Kadlec 2012) and New Zealand data for wetlands treating nitrate-rich waters with low organic matter content (Tanner and Sukias 2011). The specific modelling approach used accounts for all key species of TN (nitrate, nitrite, ammonium and organic) and associated nitrification of ammonium-N and mineralisation of organic-N during passage through the wetland in addition to direct removal of nitrate-N (the dominant form of N in the surface inflows to the lake) via microbial denitrification and plant uptake.

Annual average Total Phosphorus (TP) removal was also predicted by the same approach, using the median removal rate constant reported for 282 surface-flow wetlands by Kadlec and Wallace (2009), although data should be considered preliminary.

Mass loading to Te Waihora from its major inputs (Selwyn, L2, Halswell and Kaituna Rivers, and Hart's Creek, (see Figure 1) and some minor inputs were calculated (seasonal and annual loads) using gaugings and water quality data supplied by Environment Canterbury as inputs to the model (Table 1, annual loads only displayed).

Table 1: Major surface inflows and their mean annual nutrient contributions to Te Waihora.

Inflow	Mean daily average flow ($m^3 d^{-1}$)	% of mean lake inflow	Dry flow: wet flow %	TN load ($t y^{-1}$)	% of annual TN load to lake	TN flow-proportional concentration ($g m^{-3}$)	Dry TN Load: wet TN Load %	TP load ($t y^{-1}$)	% of annual TP load to lake	TP flow-proportional concentration ($g m^{-3}$)	Dry TP Load: wet TP Load %
Harts Creek @ Timber Yard Rd	126,576	14%	69%	281	20%	6.1	67%	2.4	10.3%	0.05	12%
Doyleston Drain @ d/s Lake Rd	14,861	2%	19%	20.6	1.5%	3.8	9%	0.5	2.3%	0.09	23%
Selwyn River @ Coe's Ford	260,928	29%	25%	482	34%	5.1	26%	8.5	36.4%	0.09	4%
L2 River @ Pannetts Rd	193,882	21%	69%	281	20%	4.0	70%	2.9	12.5%	0.04	34%
Halswell River @ Ryans Bridge	71,971	8%	64%	90.8	7%	3.5	58%	2.0	8.5%	0.08	32%
Kaituna River @ Kaituna Valley Rd	48,298	5%	24%	3.81	0.3%	0.2	15%	0.9	3.8%	0.05	34%
Boggy Creek @ Lake Rd	18,835	2%	40%	43.5	3%	6.3	36%	0.5	2.0%	0.07	22%
Hanmer Rd Drain @ Lake Rd	22,982	3%	26%	28.0	2%	3.3	17%	0.7	3.0%	0.08	25%
Irwell River @ Lake Rd	52,272	6%	52%	30.0	2%	1.6	21%	2.2	9.2%	0.12	108%
Small tributaries	104,630	11%	38%	144	10%	3.8	31%	2.8	12.1%	0.07	28%
Total	915,235		44%	1410		4.2	42%	23.4		0.07	18%

Nitrogen removal by floating treatment wetlands (FTWs) is based on fewer New Zealand (Headley and Tanner 2012, Sukias et al. 2010a, Sukias et al. 2010b) and international studies, thus a simplistic aerial removal rate was derived using a power regression as shown in Figure 2. A similar approach was taken to derive likely TP removal rates. Inputs to calculate likely nutrient concentrations experienced by floating treatment wetlands (FTW) were supplied using in-lake values from the lake mid-point. Mean and median mid-lake values for TN were similar at 2.1 and 1.9 g m^{-3}, and for TP are 0.25 and 0.22 g m^{-3} respectively. Other important factors in determining potential FTW locations were suitable depth requirements and acceptable (not excessive) wave action.

Figure 1. Environment Canterbury water quality monitoring sites in Te Waihora.

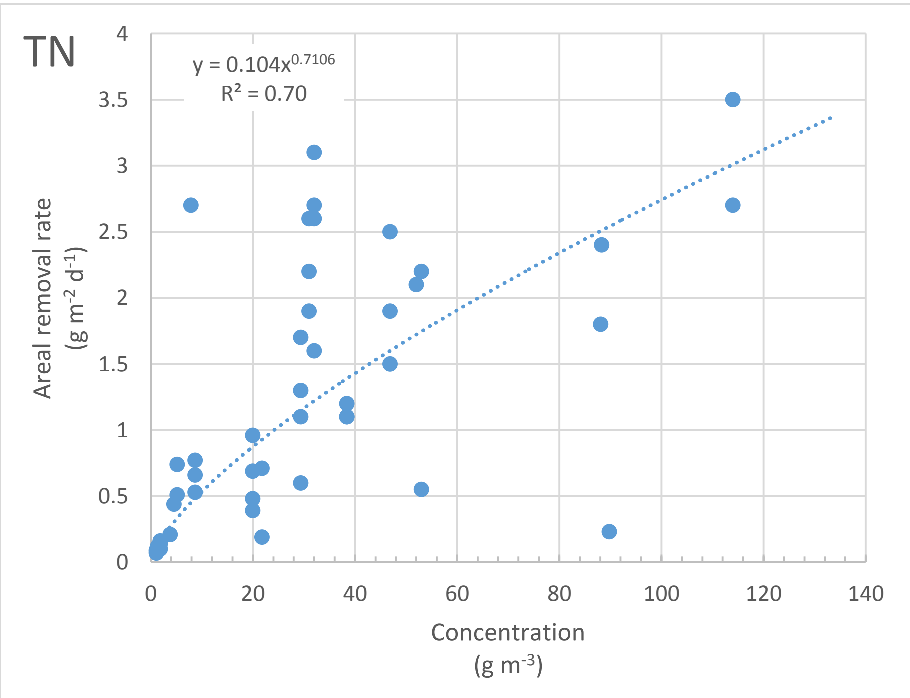

Figure 2. Floating treatment wetland total nitrogen areal removal rate. Power regression and correlation coefficient for TN areal removal vs ambient water concentration. One extreme data point for areal removal lies beyond the range shown.

Results and Discussion

The hydrological characteristics of the Te Waihora catchment are similar to many in the Canterbury region. Rainfall is lower than the national average due to the "rain shadow" of the Southern Alps. In addition, gravely soils permit significant infiltration into relatively unconfined aquifers. Thus streamflows in the foothills can quickly disappear as they arrive at the upper parts of the floodplains, only reappearing as a series of springs in the lower half of the catchment.

Spring head wetlands

There are a large number of areas where springs arise in the catchment creating small wetland areas. The Five Springs site is in the agriculturally developed headwaters of Silver Stream, a tributary of the Selwyn River. The area outlined in yellow in Figure 3 (i.e., within the fenced boundary) is approximately 10,560 m^2.

Figure 3. Google Earth location for Five Springs. Photo of springs inset. Significant areas within the fenced boundary being "dry" land.

In this one example, much of the area around the spring did not have "wetland characteristics". Modifying the area into a wetland was likely to improve the nutrient removal capacity of this area (see Table 2), however at the risk of damaging potentially unique flora and fauna associated with the springheads. In general it was considered advisable to target remediation measures further downstream.

Table 2. Potential nutrient removal at Five Springs reserve if fully functioning as a wetland.

Period	Area (ha)	Flow ($m^3\ d^{-1}$)	% TN removal	% TP removal
Wet	1.05	3,456	11%	7%
Dry	1.05	873	49%	24%
Annual			18%	8%

Riparian river sites

Some sites alongside the Selwyn River were investigated as potential riparian wetland locations.

With suitable excavation and connection to river flows, riparian areas such as these could be converted into constructed wetlands. Alternatively, some of the river-side areas (see Figure 4) could be used as ephemeral wetlands/embayments, only receiving water during high flow/flood events (areas delineated are compiled in Table 3).

Table 3. Potentially available riparian areas adjacent to the Selwyn River near Coe's Ford.

Coe's Ford A (ha)	Coe's Ford B (ha)	Coe's Ford C (ha)	Coe's Ford D (ha)	Coe's Ford E (ha)
11	15	13	10	14

The efficacy of such wetland systems is not well characterised, particularly as inflows were not defined in this instance. Thus we have not attempted to calculate nutrient removal. While they may be effective in reducing nutrient flux to the lake, they should be considered a supplementary tool until their performance is better understood.

Surface flow wetlands

Modelling based on seasonal mean flows and nutrient concentrations shows that a total of 593 ha or 1,782 ha of wetland would be required to reduce the annual nitrogen loads in all the major surface inflows to the lake by 20% and 40% respectively (Table 4). Such proportional reductions in N load would also be likely to be maintained if, as forecast (as noted in Gibbs and Norton 2012, ECAN predicts nutrient increases of up to 35% from current land intensification), inflowing N concentrations increase in the future. In general the wetland areas required to achieve the higher 40% TN reduction target are around 2.5–3 times larger than for the lower 20% TN reduction target. This reflects the diminishing returns achievable as nutrient concentrations decline during passage through a wetland system (Kadlec 2012; Tanner & Kadlec 2013).

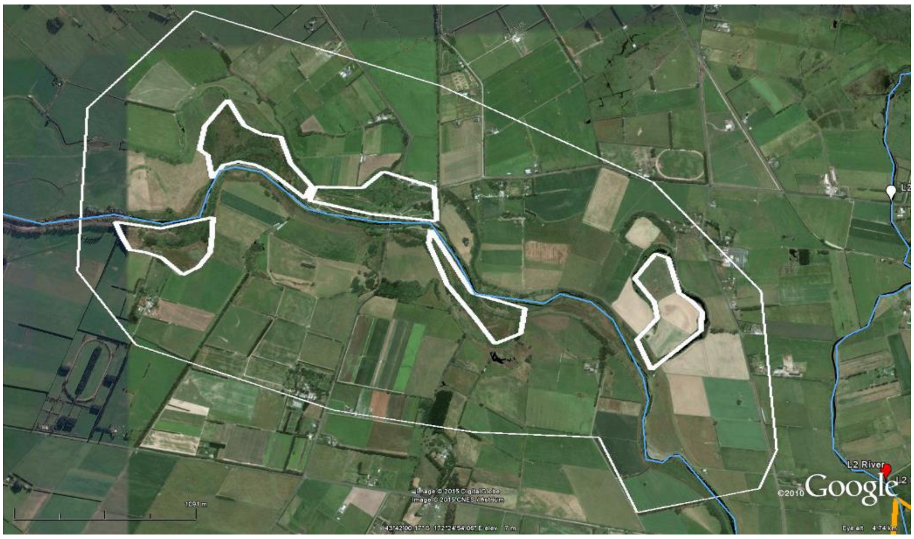

Figure 4. Potentially suitable riparian areas of the Selwyn River. Photo of river side reserve at Coe's Ford inset.

Table 4. Calculated surface-flow wetland areas and percentage of apparent catchment area required to achieve 20% and 40% annual TN load reductions from main inflows. Corresponding TP removals and indicative maximum sustainable wetland areas during the dry season are also presented.

Inflow	Apparent catchment area (1000s of ha)	Wetland area to achieve 20% annual N load reduction (ha)	Percentage of apparent catchment area for 20% annual N load reduction	Percent annual TP load reduction for 20% annual N load reduction	Wetland area to achieve 40% annual N load reduction (ha)	Percentage of apparent catchment area for 40% annual N load reduction	Percent annual TP load reduction for 40% annual N load reduction	Maximum sustainable wetland area under dry season flows[1] (ha)
Harts Creek @ Timber Yard Rd	39.1	70	0.18%	11%	172	0.44%	25%	2076
Doyleston Drain @ d/s Lake Rd	2.1	16	0.76%	21%	44	2.10%	42%	96
Selwyn River @ Coes Ford	95.8	142	0.15%	9%	417	0.44%	23%	2106
L2 River @ Pannetts Rd	27.7	130	0.47%	13%	324	1.17%	28%	36**
Halswell River @ Ryans Bridge	29.1	38	0.13%	12%	99	0.34%	26%	1116
Kaituna River @ Kaituna Valley Rd	4.6	97	2.11%	35%	478	10.39%	75%	384*
Boggy Creek @ Lake Rd	1.3	20	1.54%	17%	50	3.85%	35%	2.4**
Hanmer Rd Drain @ Lake Rd	4.8	27	0.56%	17%	68	1.42%	35%	2.4**
Irwell River @ Lake Rd	2.9	53	1.83%	18%	130	4.48%	36%	8.4**
Total for above inflows	**207.5**[2]	**593**	**0.29%**		**1,782**	**0.86%**		

[1]As a preliminary indicator of potential problems sustaining wetland ecosystems under dry season flow conditions we have assumed that minimum water flows sufficient to maintain ≤60 d nominal hydraulic residence time are required at average dry season flow (not allowing for rainfall, evapotranspiration, or losses to or gains from groundwater); The number of asterisks indicate level of desiccation risk; *potential problem for wetland sized to achieve 40% annual TN removal; **potential problem for wetland sized to achieve 20 and 40% annual TN removal.
[2] Small tributaries, in addition to those noted above, are estimated to collectively account for a further 42.6 thousand ha of catchment.

Our modelling predicts that wetlands achieving the proposed 20% and 40% TN reduction targets would likely also reduce TP loads in these inflows by 11-35% and 25-76%, respectively.

Collectively such wetland areas would respectively occupy less than 0.3% and 0.9% of their apparent catchment areas. This suggests that targets for nutrient reduction from surface inflows could be achieved with a substantially smaller proportion of the catchment in wetlands than has been found in other predominantly rain-fed dairying regions of the country (~1-3%; Tanner & Sukias 2011; Tanner et al. 2010). These much lower area requirements are explained by the low catchment flow yields in the Te Waihora catchment compared with other predominantly rain-fed dairying regions such as the Waikato and Southland, as shown in Woods et al. (2006). For instance Selwyn River at Coe's Ford has a flow of 3020 L s^{-1}, catchment of ~770 km^2 and yield 3.9 L s^{-1} km^{-2} (123 mm yr^{-1} runoff). In contrast, the Waikato River has a yield of 27.7 L s^{-1} km^{-2} (874 mm yr^{-1} runoff) and the Mataura River at Seaward Downs in Southland ~17.6 L s^{-1} km^{-2} (555 mm yr^{-1} runoff). The lower runoff yields for surface-waters in the Te Waihora catchment result primarily from its location in the rain shadow of the Southern Alps, with rainfall ranging from ~400 or less close to the lake to ~800 mm in the inland hills. This compares with rainfalls of 900-1500 mm typical of rain-fed dairying areas in New Zealand. Poorly confined groundwater aquifers and surface-water: groundwater exchanges in places contribute to variability in apparent yields of different tributaries in the catchment, and irrigation water takes and subsequent elevated water loses are also likely to impact on yields.

As indicated by their elevated flow-proportional TN concentrations and moderate seasonality of TN loads, the Selwyn and Halswell Rivers, and Hart's Creek stand out as requiring the lowest percentage of their apparent catchments in suitable wetlands to achieve the 20% and 40 % TN reduction targets proposed. Applying wetland mitigation in these catchments is likely to result in the most favourable cost:benefit ratios per unit of land area mitigated.

Eastern Te Waihora

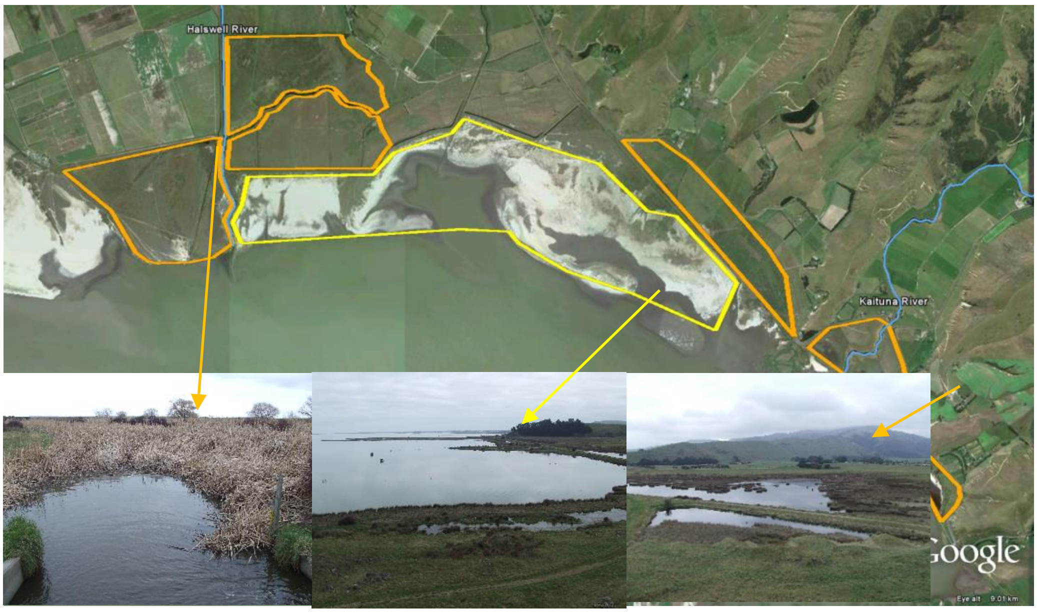

Figure 5. Potential wetland sites, eastern Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow.

Kaituna River

Three lake edge areas at or close to the mouth of the Kaituna River were identified as potential wetland areas (see Figure 5). The areas of each potential wetland are shown in Table 5 along with predicted areas required to achieve 20% and 40% removal of TN. This suggests that the 20% target could be readily met using around 60% of these areas. However, this river has a relatively low yield of TN and would thus appear to be of lower priority for nutrient attenuation than other inflows to the lake. Insufficient area is available to achieve the 40% TN removal, even with all areas combined.

Table 5. Wetland area requirements and potentially available areas near the mouth of the Kaituna River.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Kaituna A (ha)	Area Kaituna B (ha)	Area Kaituna C (ha)
97	478	88	50	28

Halswell River

Three areas were identified at the river mouth of the Halswell River (Figure 5) which appeared to be sufficient in area (Table 6) for either 20% or 40% TN annual removal targets.

Table 6. Wetland area requirements and potentially available areas at the mouth of the Halswell River.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Halswell A (ha)	Area Halswell B (ha)	Area Halswell C (ha)
38	99	134	94	88

Central-northern Te Waihora

Figure 6. Potential sites, central-northern Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow. Riparian wetlands are outlined in white.*L2 River*

Two areas near the mouth of the L2 River were delineated for modelling (Figure 6). These areas already have a "wetland character" and thus may be already removing some nutrients passing through them. However, they currently intercept only a small proportion of the water flowing from the L2 and their current layouts are not optimised for nutrient removal. The areas identified appear to be sufficient to meet the annual 20% TN reduction target or about two thirds of the 40% TN target.

Table 7. Wetland area requirements and potentially available areas near the mouth of the L2 River.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area L2 A (ha)	Area L2 B (ha)
130	324	93	128

Selwyn River

A number of sites exist around the outlet of the Selwyn River that appear to have potential for wetland development, however much of the land is already developed for pastoral use, or holiday residences. An embayment alongside the Selwyn River may also be incorporated. In combination these areas would appear to be ample to achieve a 20% TN reduction target, but less than required to reach 40% TN reduction. The existing inflow would need to be diverted into these areas for treatment, possibly with areas of FTWs added. It is likely that a proportion of flood flows would need to be diverted around such wetland areas to protect them and avoid flow restrictions, potentially causing upstream flooding.

Table 8. Wetland area requirements and potentially available areas near the mouth of the Selwyn River

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Selwyn A (ha)	Area Selwyn B (ha)	Area Selwyn C (ha)	Area Selwyn D (ha)
142	417	137	44	54	80

Western Te Waihora

Areas adjacent to the Irwell River and Hanmer Road Drain were identified as shown in Table 9 and Table 10. The areas immediately by the Hanmer Road drain appear to be insufficient to achieve even the lower 20% TN target proposed. As can be seen, the area required to adequately treat the Irwell River identified in this assessment are inadequate to meet the N removal targets.

Table 9. Wetland area requirements and potentially available areas near Hanmer Road Drain.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Hanmer A (ha)	Area Hanmer B Lake-edge (ha)
27	68	12	6

Table 10. Wetland area requirements and potentially available areas near the mouth of the Irwell River.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Irwell C (ha)	Area Irwell D (ha)
53	130	14	19

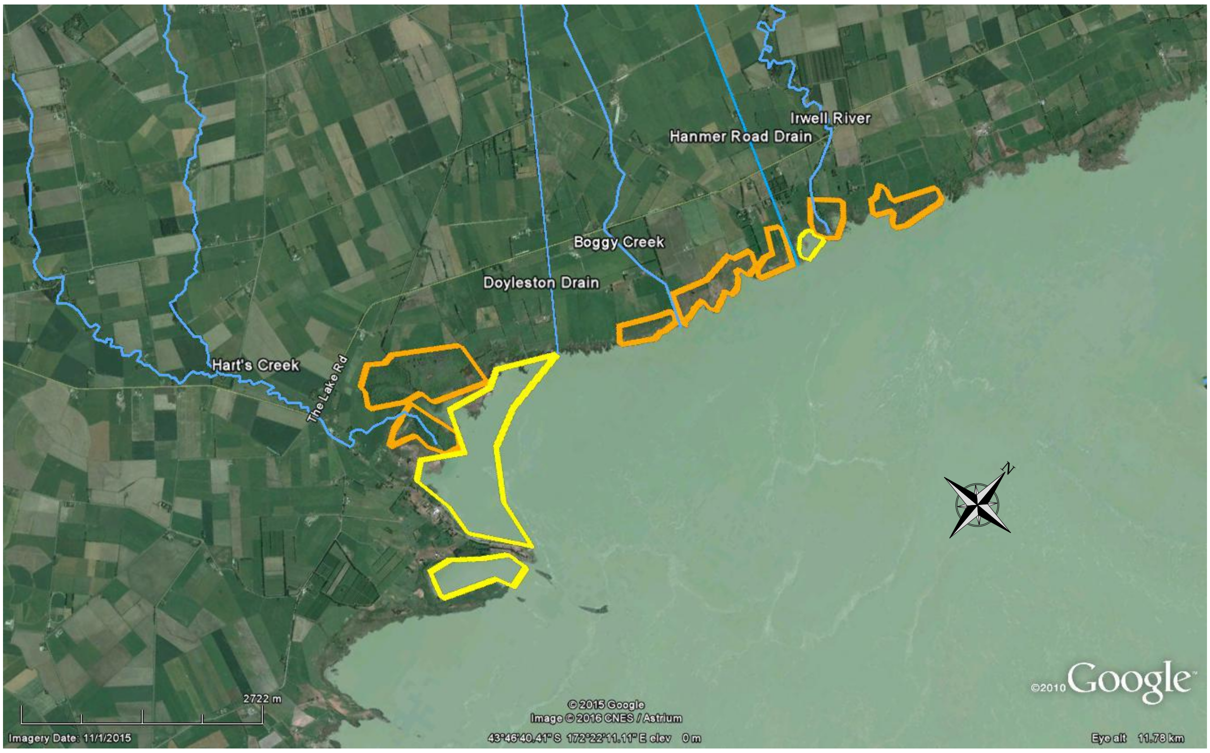

Figure 7. Potential wetland sites, western Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow. Note orientation of image.

Two areas at the mouth of Boggy Creek could achieve the 20% TN reduction target for this inflow, but even combined would be insufficient to fully achieve a 40% TN reduction target

Table 11. Wetland area requirements and potentially available areas near the mouth of Boggy Creek.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Boggy Creek A (ha)	Area Boggy Creek B (ha)
20	50	28	12

A raupo dominated wetland area was present at the mouth of Hart's Creek which would require some minimal re-engineered to provide improved treatment of inflows from Hart's Creek. Further areas of relatively protected shallow littoral zone within the lake may also be appropriate for wetland construction, although this would likely conflict with current recreational use in these areas. The potential wetland areas identified exceed those required to achieve the 20 % and 40% TN removal targets (Table 12).

Table 12. Wetland area requirements and potentially available areas near the mouth of Hart's Creek.

Area required for 20% TN removal (ha)	Area required for 40% TN removal (ha)	Area Hart's Creek A (ha)	Area Hart's Creek B (ha)	Area Hart's Creek C (Lake-edge) (ha)	Area Hart's Creek D (Lake-edge) (ha)
20	50	65	22	126	32

Floating treatment wetlands

Suitable depth ranges for FTWs are influenced by water level fluctuation during artificial lake opening. In this instance we would recommend a depth range between 1.0-1.2m at 0.8m a.m.s.l. Also wave height should be less than 0.35m wind (based on modelling results of Jellyman et al., 2008). On this basis, suitable areas are shown in Figure 8. Map of potential locations for FTW (in red) based on area intercepts between depth criteria and modelled wave heights of <0.35m.

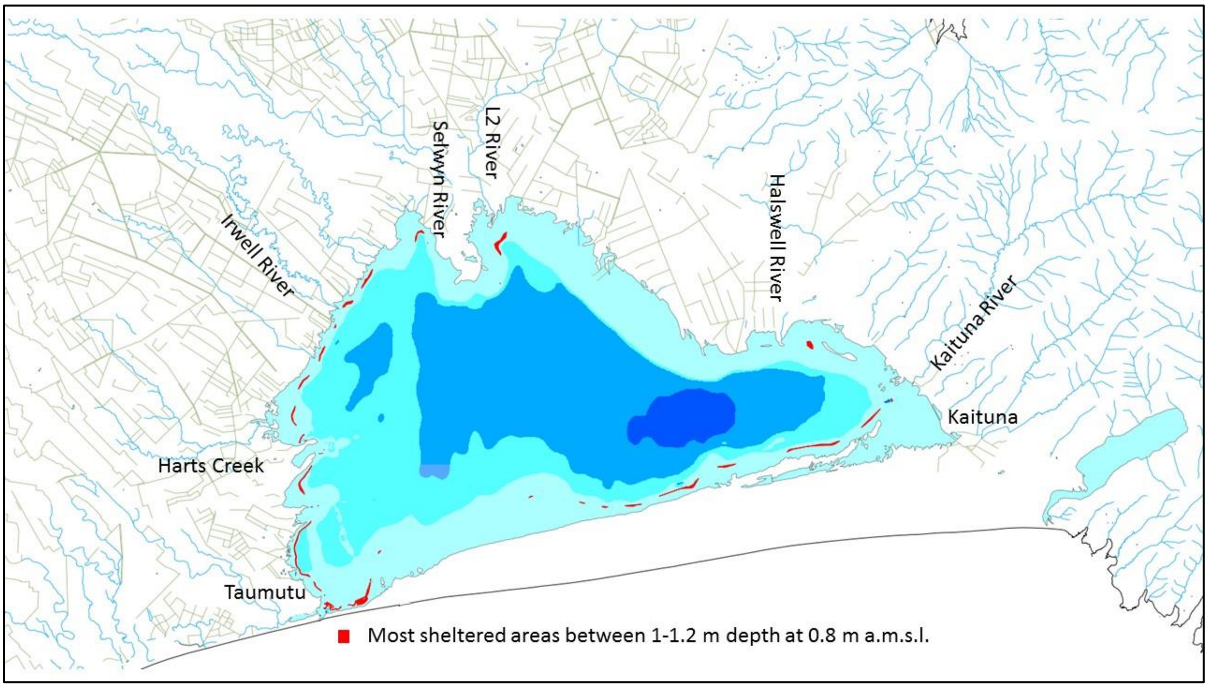

Figure 8. Map of potential locations for FTW (in red) based on area intercepts between depth criteria and modelled wave heights of <0.35m. Bathymetry increments shown as 0.5 m depth intervals from 0 m a.m.s.l. in increasingly darker shades of blue.

Using mean lake water concentrations and the relationships from the power regressions, we would expect nutrient removals from FTWs of 176 mg TN m^{-2} d^{-1} (643 kg TN ha^{-1} y^{-1}), and 14 mg TP m^{-2} d^{-1} (51 kg TP ha^{-1} yr^{-1}). This areal TN mass removal rate is intermediate between those found in the high and low-loaded mesocosm studies treating Maero Stream inflows to Lake Rotoehu (Sukias et al. 2010b). The areal TP mass removal rate is at least double the rate found in the Rotoehu mesocosm study, corresponding with the markedly higher (3.7-fold) TP concentrations in Te Waihora.

Annual influent surface loads of TN and TP to Te Waihora are 1,410 tonnes and 23.4 tonnes respectively (Table 1). Based on the FTW nutrient removal rates noted above, 439 and 877 ha of FTW would be required to remove 20% and 40% of the annual influent loads of TN. Suitable areas shown in Figure 8 only equate to 71.5 ha (i.e. ~16% of the area required to remove 20% of the annual TN load and 8% of that required to remove 40% of the annual TN load to Te Waihora).

Predicted TP removal would be ~22.4 and 44.7 Tonnes TP yr^{-1} (~96% and 191% of the TP loads to the lake).

Summary

Te Waihora/Lake Ellesmere is highly nutrient impacted. Environment Canterbury commissioned NIWA to undertake a modelling exercise on wetland areas required to achieve 20% and 40% TN reductions entering the lake, using actual areas adjacent to the major inflows as conceptual wetland locations. In general, these nearby areas were large enough to achieve the 20% TN reduction target. However, only the Halswell River and Hart's Creek had sufficient area nearby to achieve the 40% TN reduction target, although other inputs were close to achieving this.

Suitable areas for FTWs in Te Waihora only equate to 71.5 ha (i.e. ~16% of the area required to remove 20% of the annual TN load and 8% of the necessary area required to remove 40% of the annual TN load. This is due to the extreme exposure to wind and waves and fluctuations in water level likely to be experienced in the lake. There are also uncertainties related to the long-term treatment performance of FTWs and risks associated with their use in such a large and exposed lake.

Recent limit setting studies for Te Waihora predict that an even higher decreases (50%) in the current load of both nitrogen (TN) and phosphorus (TP) would be needed to improve water quality to achieve a TLI (Trophic Level Index) score of 6.0 in the mid lake (Norton et al. 2012). A 50% reduction in the internal load of P (i.e., the legacy load of P contained in lake bed sediments from historic land use) would also be required to achieve this goal. Given the current degree of nutrient enrichment in Te Waihora and the likely increases in nutrient load yet to come, a suite of mitigation measures will be required to meet the nutrient targets required to achieve desired water quality and ecological values for the lake (Gibbs & Norton 2012). Such a multi-pronged approach would include:

- minimising nutrient losses at source (e.g., good to best possible land use practice)
- capturing nutrients where possible as they move through the catchment (e.g., riparian and wetland management), and
- Implementing a range of in-lake remediation and restoration measures.

While it is clear that areas of wetland required to achieve nutrient reduction targets are probably not available, in combination with other mitigation measures, they may perform an important role in lake water quality remediation.

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