Wetland Nutrient Attenuation Assessment for Inflows to Te Waihora / Lake Ellesmere

Prepared for Whakaora Te Waihora

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Executive summary

Wetlands include a diverse range of ecosystems that exist at the nexus between land and water. They are commonly referred to as the "kidneys of the landscape" because of their ability to intercept, store, assimilate and transform contaminants lost from the land on their pathways through catchments. Extensive drainage in the lower reaches of the Te Waihora (Lake Ellesmere) catchment to facilitate agricultural land use has resulted in substantial loss of natural wetlands from the landscape. Ongoing drainage and stream channelization has lowered local water tables and disconnected many of the remaining wetland areas from the drainage system. This has resulted in a significant loss of functionality of these remnant wetlands, reducing their ability to intercept, attenuate and ameliorate the flux of sediments and nutrients into Te Waihora.

As the first stage in determining the feasibility of re-introducing wetlands to reduce the impact of land-use on the water quality, ecology and cultural values of Te Waihora, the Whakaora Te Waihora partners (Ngāi Tahu, Environment Canterbury and the Ministry for the Environment) commissioned NIWA to evaluate the areas of wetlands in the catchment that would be needed to meet nitrogen load reduction targets of 20% and 40% in surface inflows to the lake. Potential locations in the Te Waihora catchment suitable for restoration or creation of wetlands were also to be identified. In addition to conventional surface-flow wetlands, we were asked to assess the potential use of floating treatment wetlands (FTWs), and to identify potentially suitable locations in the lake for their deployment.

It should be noted that the assessments made in this study are based on theoretical calculations only. The potential sites identified are hypothetical examples that have only been superficially assessed without any specific knowledge of ownership, legal status (e.g., reservation protection), or access to geotechnical or ecological information. They have been included to provide a preliminary indication of the sort of areas and scale of wetland restoration or creation that would need to be considered to achieve meaningful nutrient reductions relevant for the rehabilitation of Te Waihora. They do not represent propositions for wetland creation at sites indicated in the report; no landowners have been consulted and any proposed wetland creation would require full collaboration with Ngāi Tahu, the Department of Conservation and landowners and go through an appropriate consenting process.

Environment Canterbury data on the flow and water quality of major surface inflows to the lake was analysed to determine the mean dry- and wet-season flows, and concentrations and loads of nitrogen and phosphorus entering the lake in the nine key inflows, and the mean concentrations of nitrogen and phosphorus present in the lake itself.

Modelling was performed for each inflow on a seasonal basis to determine the areas of surface-flow wetland that would be required to meet the annual nitrogen reduction targets. A total of 593 ha of suitably-designed surface-flow wetland was predicted to be needed to reduce the annual nitrogen loads in all the major surface inflows to the lake by 20% and 1,782 ha of wetland to reduce the annual load by 40%.

The modelling predicted that surface-flow wetlands achieving these TN reduction targets would concurrently also reduce TP loads in these inflows by 11–35% and 25–76% respectively. Substantial reductions in sediment loads and microbial contaminant peaks concentrations would also be achieved. Such wetland areas, strategically placed to intercept major inflows before they entered the lake, would occupy less than 0.3% and 0.9%, respectively, of their apparent catchment areas. This is a substantially smaller proportion of the catchment required in wetlands compared to relative areas identified for other (predominantly rain-fed) dairying regions of the country (1-3%) which generate greater runoff yields.

Required wetland areas for the nine different inflows ranged from 16–142 ha for 20% TN load reduction, and from 44–324 ha for 40% TN load reduction. In many cases, 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. However, in order to intercept the modified drainage flows and avoid flooding of upstream and adjacent land, construction of lake edge wetlands would in most cases require extensive excavation to depths of 1-2 metres. Although the excavated material could potentially be used to raise the level of adjacent marginal farm-land and enhance its agricultural usability and productivity, the potential economic costs and payback of such re-engineering needs further assessment.

Many of the remnant wetlands currently present in the landscape have retained or developed special natural character which would be markedly impacted by reconnection and rehabilitation for contaminant interception. However, a range of other options, including construction of lake-edge, riparian and farm edge-of-field wetlands would also be possible in suitable areas of the catchment.

The potential use of marginal littoral areas of the lake for wetland creation is likely to be controversial, but also offers another possible option to achieve wetland treatment of lake inflows. Construction of engineered embankments and wave protection measures would be required to reconfigure such littoral areas as wetlands. The extreme exposure to wind and wave action and fluctuating water levels experienced in such areas of Te Waihora, would make this a challenging undertaking. The practical feasibility of such options and their attendant risks and costs would need to be further investigated, in addition to net impacts on cultural and ecological values.

FTWs are a relatively new technology, and their nutrient removal capabilities are not as well understood, particularly in large exposed lakes such as Te Waihora. From a review of available New Zealand and international research and based on the current concentrations of TN and TP present in the lake, we estimate that, to achieve 20% and 40% reduction of surface inflow loads to Te Waihora, around 440 or 880 ha of FTW would be required respectively. This is 74% and 49%, respectively, of the area of conventional surface-flow wetlands estimated to be required to achieve these targets.

Predicted concomitant TP removal for 440 or 880 ha of FTW would be ~22.4 and 44.7 Tonnes TP/yr (~96% and 191% of the TP loads to the lake). These predictions suggest that FTW may be more effective per unit area than conventional surface-flow wetlands. However, there are greater uncertainties associated with the FTW estimates, and the costs of deploying suitably engineered FTWs is likely to be considerably higher per unit area than for land-based wetlands. Comparative overall costs of in-lake (FTW) vs land-based wetland options will depend on the costs of land acquisition or lease, or (where the area of land or water is in public or iwi ownership) foregone opportunity costs for the use of the land or lake (e.g., lost economic, recreational or cultural values).

Taking into account lake level fluctuations and the results of wave height modelling, we determined that ~72 ha of Te Waihora would potentially be suitable for deployment of FTW. This is only 16% and 8%, respectively of the areas required to meet the 20% and 40% target reductions in annual inflow TN load to the lake. Because the long-term efficacy of FTW installations have not been tested thus far, and there are significant challenges and risks involved in their use in such a large and exposed lake, we consider further research is needed before large-scale application would be appropriate.

In conclusion, our investigations and modelling suggest that wetlands would be able to provide substantial reductions in surface water inflow nutrient loads into Te Waihora, readily achieving annual TN load reductions of 20% and feasibly as high as 40%. Importantly, such proportional reductions in N load would also be likely to be maintained if, as forecast, inflowing N concentrations increase in the future. Suitably designed wetlands could also provide marked reductions in sediment and associated particulate P loads to the lake, and a wide range of other ancillary benefits (e.g., wildlife habitat and biodiversity). The investment costs for wetland construction, plant establishment and maintenance, and foregone opportunity costs for use of the land would, however, be substantial, and some existing ecological, social and/or cultural values would inevitably be compromised. In addition, a range of other potential disbenefits, such as flooding risks, and effects on fish passage, lake access and greenhouse gas emissions would need further consideration.

We consider that surface-flow wetlands located on the edge of the lake, in river/stream riparian zones, or targeting farm run-off offer the most feasible, low-risk wetland option to reduce nutrient loads in surface inflows to Te Waihora. Currently there is limited relevant information available on the costs involved in constructing wetlands of this scale in situations similar to Te Waihora. We therefore recommend development of conceptual wetland designs and associated construction methodologies at 2-3 representative sites in the catchment to enable preliminary engineering investigations and provision of realistic cost estimates. These would provide a reliable basis for preliminary cost:benefit comparisons with other mitigation options and sourcing of appropriate funds to undertake field-scale demonstration trials on priority nutrient inflows into Te Waihora.

1 Brief

The Whakaora Te Waihora partners (Ngāi Tahu, Environment Canterbury and the Ministry for the Environment) commissioned NIWA to identify and assess potential areas in the Te Waihora (Lake Ellesmere) catchment where restoration or creation of wetlands could feasibly be located to reduce nutrient loads, in particular nitrogen. In addition to conventional surface-flow wetlands, we were asked to assess the potential use of floating treatment wetlands deployed within the lake. NIWA would also assess potential nitrogen load reductions achievable and predict wetland areas that would be required to achieve two agreed nitrogen load reduction targets (i.e., 20 and 40%) for monitored inflows to the lake. Potential co-benefits and disbenefits of the various options on other key ecosystem services and values would also be identified.

Note of Caution

The assessments made in this study are based on theoretical calculations only. The potential sites identified are hypothetical examples that have only been superficially assessed without any specific knowledge of ownership, legal status (e.g., reservation protection), or access to geotechnical or ecological information. They have been included to provide a preliminary indication of the sort of areas and scale of wetland restoration or creation that would need to be considered to achieve meaningful nutrient reductions relevant for the rehabilitation of Te Waihora. They do not represent propositions for wetland creation at sites indicated in the report; no landowners have been consulted and any proposed wetland creation would require full collaboration with Ngāi Tahu, the Department of Conservation and landowners and go through an appropriate consenting process.

2 Introduction

Te Waihora is a large (~20,000 ha), shallow (1.4m average depth) brackish coastal lake located southeast of Christchurch City between the Rakaia River and Banks Peninsular. It is Canterbury's largest and New Zealand's fifth largest lake, and is an important aquatic resource with high cultural significance to Tangata Whenua. The development and use of its 276,000 ha catchment over the last century, including: 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 decline in water quality, and cultural and ecological values (Hughey et al. 2013; Hughey & Taylor 2008).

2.1 Wetlands for water quality improvement

A practical means to reduce the flux of sediment and nutrients into the lake is by passage of inflowing surface waters through wetlands. Wetlands possess a number of features which facilitate pollutant removal. Typically they consist of broad shallow areas where water velocities are reduced, allowing settling of suspended sediments. Wetland plants take up nutrients, and the dead foliage they drop forms an organic litter/mulch in the base of the wetland. This ready supply of organic carbon in wetlands, combined with low oxygen conditions in the litter and saturated sediments, promotes bacterial conversion of nitrate-N into gaseous forms (predominantly $N_{2)}$ which is released back to the atmosphere (comprising ~79% N_2). Phosphorus may be sequestered in association with accumulating sediments and wetland plant matter, and also taken up into plant tissues. Although plant P uptake is finite and, unless the plants are harvested and removed[1], will be returned to the wetland when plants die and decay, a proportion remains bound to accumulating organic matter in the wetland. Wetlands can therefore perform an important role in reducing the movement of nutrients from land to downstream water bodies.

Where natural wetlands are absent due to unsuitable landscapes or land drainage activities, constructed wetlands can perform equivalent roles. However, retrofitting wetlands into extensively-drained, low gradient agricultural landscapes can be expensive, often entailing substantial excavation (to maintain drainage of upstream and adjacent agricultural land) and planting costs, as well as the loss of potentially valuable farm land. In this report we focus on the potential well-engineered wetlands could have to reduce nutrient fluxes from major catchment areas into Te Waihora.

2.1.1 Surface-flow wetlands

Surface-flow (or free-water surface) constructed wetlands are the most appropriate wetland type for interception and treatment of agricultural run-off. Essentially comprising shallow impoundments or channels planted with emergent wetland plants, similar to natural swamps and marshes (Figure 2-1), surface-flow wetlands are the simplest and cheapest type of wetland to construct. Their simplicity, robustness under highly variable flow conditions, and ability to cope with sediment loads that would rapidly clog the media of wetland types reliant on subsurface-flow make them widely applicable. Their ability to remove sediments and nutrients from diffuse agricultural runoff is now well established (Crumpton et al. 2006; Díaz et al. 2012; Hey et al. 2012; Jordan et al. 2003; Kadlec 2012; Mitsch et al. 2005; Tanner & Sukias 2011).

[1] Plants contain about 1/10th of the P found in normal wetlands, thus harvesting is not usually employed as a sustainable P removal mechanism, although is sometimes used to maintain plant vigour.

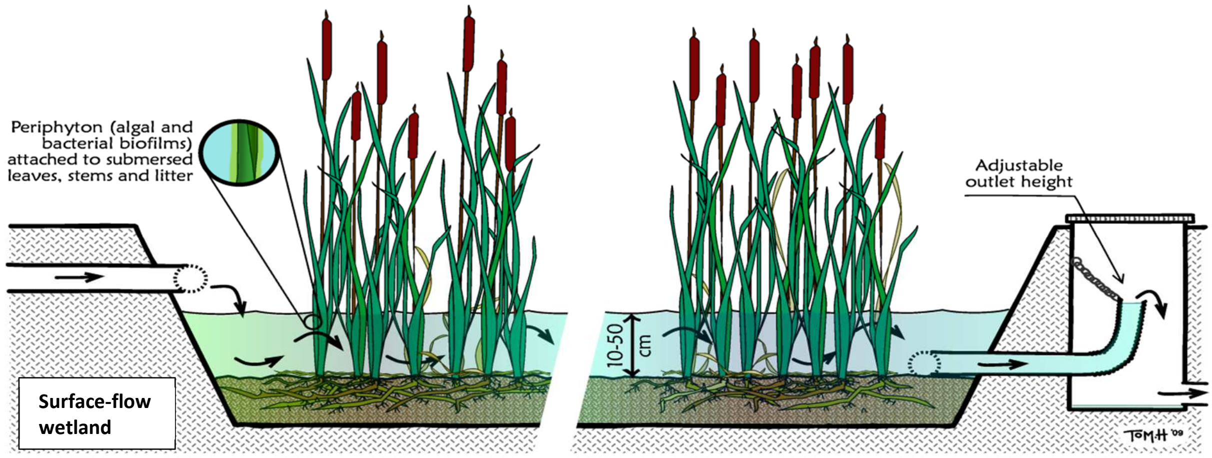

Figure 2-1: Typical cross section of a surface-flow constructed wetland. The wetland may also include deeper open-water zones. A range of alternative inlet and outlet structures are possible to disperse flows and maintain desired water levels (illustration by Tom Headley).

Surface-flow wetlands such as these can provide effective nitrate-N removal via microbial denitrification supplemented by plant uptake and accretion in sediments. Generally the larger the wetland the better the treatment achieved, but with diminishing returns. Nitrate removal performance is temperature sensitive, and will generally be poorer during winter than summer. Nitrate removal via denitrification is promoted by close contact with organic sediments and wetland plants that provide anoxic conditions and organic matter (decomposing plant litter) for denitrifying microbes. Such conditions may also be created or supplemented through the addition of organic amendments such as cereal straws or wood chips/sawdust.

Wetlands can generally provide good removal of particulate-associated phosphorus, but only low level removal of dissolved P. Particulate P removal occurs predominantly by settling, which is promoted in quiescent conditions such as occur in deep water and in areas within vegetated zones. Soluble P removal occurs via reversible soil sorption (which eventually becomes saturated) and uptake by bacterial biofilms, algae and macrophytes. Cycling through growth, death and decomposition returns much of the biotic uptake, but an important residual contributes to long-term accretion of P in newly formed sediments and soils (Reddy et al. 1999). P removal may also be promoted by the use of P-sorbing media, including iron and calcium-rich materials (Ballantine & Tanner 2010), but such materials generally have a finite life, after which they must be replaced.

Previous studies in New Zealand (McKergow et al. 2007; Tanner et al. 2010) and around the world (Kadlec & Wallace 2009; Mitsch & Grosslink 2007) have identified the need for wetland areas of 1-5% of the contributing catchment to provide reasonable levels of nutrient attenuation in humid-climate agricultural landscapes. Depending on the specific attributes of suspended solids, smaller wetland areas in the range of 0.1-1% of contributing catchment can often achieve satisfactory suspended sediment removal.

From a practical point of view, optimal wetland treatment conditions for both N and P removal are created through provision of wetland areas, depths and length to width ratios that provide sufficient wetland assimilative area, efficient hydraulic characteristics and conditions suitable for establishment of dense growths of emergent vegetation. Wetlands fully vegetated with emergent plants have been shown to provide greater N removal per unit area than equivalent partially vegetated wetlands, algal-dominated open water or areas colonised by submerged vegetation (Bastviken et al. 2009; Kadlec 2008).

For systems constructed to treat stream flows, provision must also be made for management of storm and low flows, siltation, and fish passage. Wetlands built off-stream (Figure 2-2) have significant advantages in this respect, because the original stream channel remains intact and can be used to convey a proportion of flood flows. However, off-stream wetlands are not always practically achievable, requiring provision for routing of flood-flows around (or through an armoured floodway within) the wetland. Wetlands receiving flood flows may require more frequent maintenance and specific rehabilitation after large flood events.

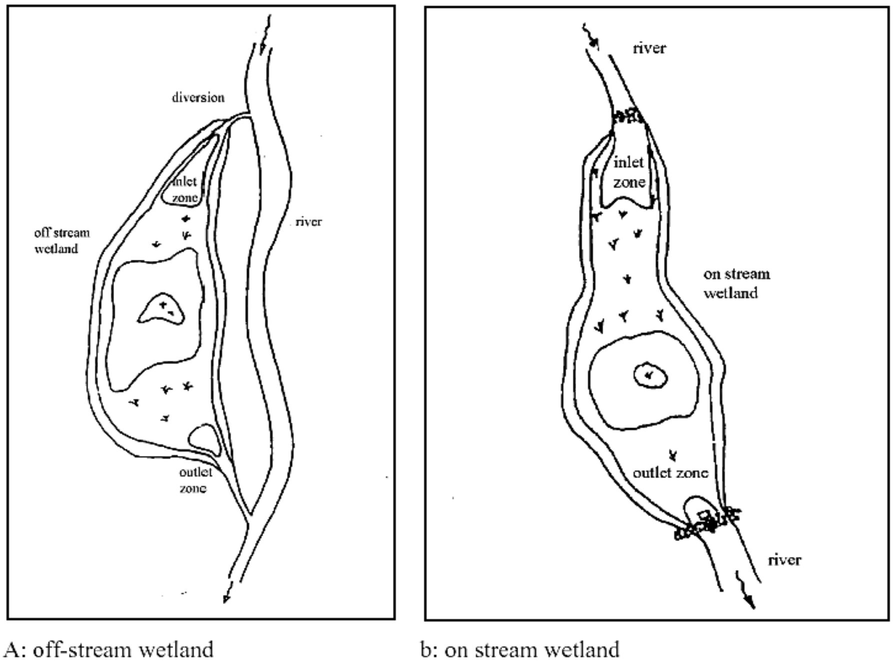

Figure 2-2: Comparison of (a) off-stream (in parallel) and (b) on-stream (in-channel) treatment wetlands. (Bendoricchio et al. 2000).

2.1.2 Floating treatment wetlands

A recent development in wetland technology is the use of floating islands, rafts or platforms (Figure 2-3). These Floating Treatment Wetlands (FTWs) employ emergent plants growing on a buoyant mat on the surface of the water, rather than rooted in the sediments. They can be deployed within existing water bodies to provide a combination of wetland functions and pond/lake removal processes (Headley & Tanner 2012; Tanner & Headley 2011; Tanner et al. 2011).

The plant roots hanging beneath the floating mat provide an extensive surface area for attached biofilm growth and entrapment of fine suspended particulates. Because the plants are not rooted in soils in the base of the wetland, they are forced to acquire their nutrition directly from the water column, which may enhance rates of nutrient and element uptake into biomass. Their buoyancy enables them to tolerate wide fluctuations in water depth and cope with light wave action. Along with the water quality benefits they provide, they can also be used to enhance the aesthetic and wildlife values of water bodies.

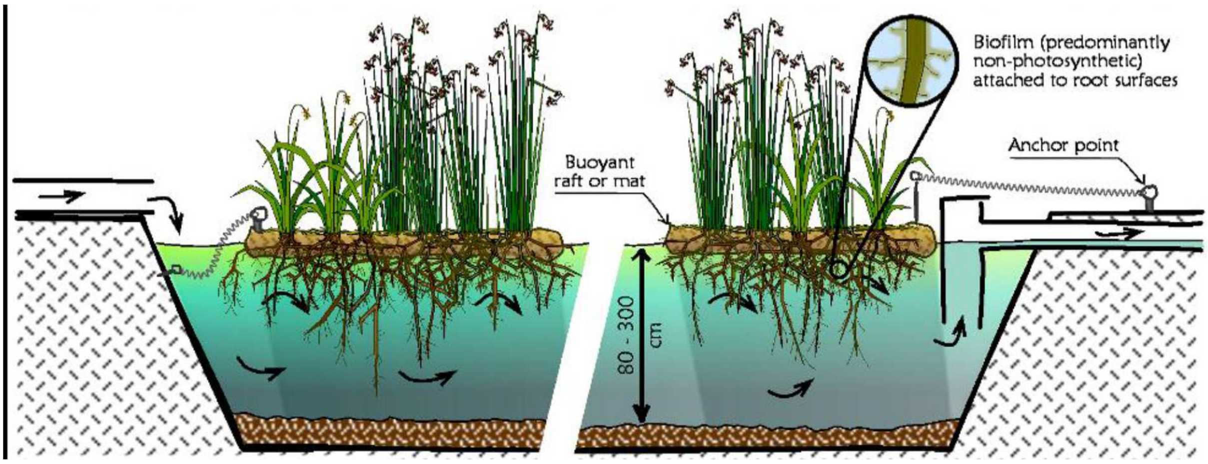

Figure 2-3: Cross-section of FTWs in a treatment pond. (from Headley and Tanner, 2012).

2.2 Opportunities and challenges for interception and wetland treatment of inflows to Te Waihora

Within highly developed agricultural catchments, particularly those such as Te Waihora which have undergone extensive drainage and channelization to lower water tables and control flooding, natural wetland areas become drier and more ephemeral, and are reduced in areal extent or eliminated. Remnant natural wetlands often become hydrologically disconnected and may be left "perched" above natural drainage flows. Furthermore, drains are often cut through such remnant wetland areas, causing waters that do flow into them to pass rapidly through them, short-circuiting much of the potential wetland area. This can substantially reduce the potential of remnant natural wetlands to provide pollutant removal services. Within an agricultural context, such modifications have allowed development of large areas of river flood plains and natural wetland areas around the lake which would otherwise be unsuitable for conventional agricultural production. Such agricultural developments were generally undertaken within a historical context when the sediment removal and nutrient attenuation capacities of wetlands were poorly understood and appreciated. In fact, even in current times, when the benefits of natural wetland to the agricultural industry and wider community is much better understood, small wetlands are still disappearing from farming areas due to both active and passive[2] drainage (Myers et al. 2013; Tanner et al. 2015).

With the forthcoming introduction of environmental limits for agricultural land uses, there is now the potential to utilise the pollutant removal potential of existing wetlands and/or construct new wetlands on lower-value land to provide equivalent sediment and nutrient attenuation services. However, widespread drainage and channelization within agricultural catchments and the concomitant lowering of the overall water table across the whole landscape creates challenges for re-integrating wetland treatment processes. Because current groundwater and surface water levels are generally maintained substantially below ground surface levels, constructed wetlands would need to be excavated to depths of 1-2 metres in order to intercept normal drainage flows and avoid flooding of upstream and adjacent land (see Figure 2-4). This can impose substantial costs for the construction of wetlands. However, if the excavated material is used to raise the level of adjacent marginal farm-land it could result in significant reduction in the flood risk of this land and, by providing for improved drainage (greater elevation above groundwater table), enhance the agricultural usability and productivity of this land. The feasibility and potential economic payback of such re-engineering needs to be assessed if such options are to be considered further.

Despite the challenges outlined above, there are still many opportunities to utilise wetlands within the Te Waihora catchment. Due to the generally flat landscape in the vicinity of the lake, there are still substantial areas of remnant natural wetland around the edge of the lake. Although many of these wetlands have drainage channels (or channelized natural streams and rivers) running through them, they have maintained a substantial degree of wetland character and vegetation. Utilisation of these areas to reduce the flux of sediment and nutrients into the lake is likely to require some re-engineering, but appears feasible. In some circumstances, there will be risks of additional flooding risks to farmland "behind" the wetland areas, unless the wetlands are either excavated deeper into the landscape, or possibly bunded and drainage inflows pumped into them.

A further consideration in some circumstances may be the need to protect high value or unique wetlands from the inputs of sediment and nutrients in low quality drainage water where this would result in their degradation or loss of values. Examples may include wetlands with rare or endangered

[2] e.g. where water is diverted around wetland areas or drains are dug along the edge of wetlands.

plant or animal assemblages, or where they provide aesthetic or recreational opportunities to the public in their present form (e.g., Five Springs or other spring sites).

Additionally, there are remnant wetlands on farms that have either been intentionally preserved, or have resisted drainage attempts thus far. These wetland may be providing (perhaps un-realised) benefits to land owners (Tanner et al. 2015). Such benefits are likely to be enhanced by rehabilitation and improved linkage of these wetlands to drainage flows. It is likely that these opportunities will only be grasped if a financial benefit/value can be gained by land owners (e.g., attenuation functions recognised in farm nutrient budgets).

Lastly, although likely to be controversial, there are potential opportunities to utilise marginal littoral areas of the lake itself to either construct wetlands or deploy floating treatment wetlands. Inflows to the lake would then need to be diverted through such wetland areas to reduce pollutant loads before they entered the main lake. Depending on perspective, the potential advantage of using these areas may be that productive and high-cost agricultural land would not be sacrificed, or that wetland treatment may be able to be provided where other opportunities are limited. On the other hand, the existing ecological and cultural values of these areas would be lost (albeit with provision of alternative values associated with the new wetland ecosystems created). Given the extreme exposure to wind and wave action and fluctuating water levels in such marginal areas of the Te Waihora lake shore, the practical feasibility of such options and their attendant risks and costs would need to be fully investigated. Construction of engineered embankments and wave protection measures would be required to reconfigure these littoral areas as wetlands (see Figure 2-5).These in addition to other cultural considerations may in the end rule-out the use of such areas, but if there is serious intent to reduce pollutant loads to the lake to restore its water quality and wider values, then we consider the potential use of such areas is worth some consideration.

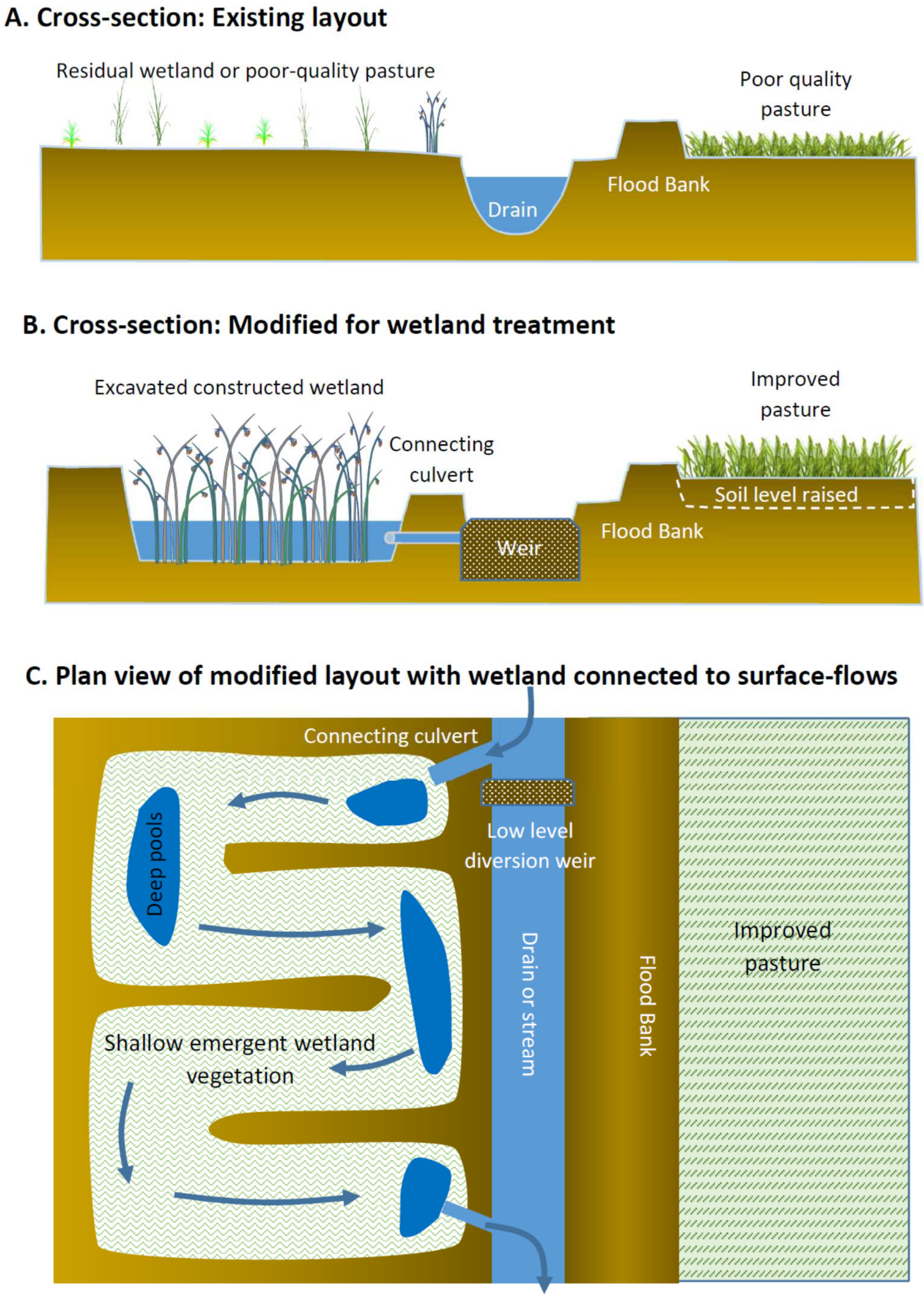

Figure 2-4: Conceptual plan for potential wetland construction in lake-edge areas currently perched above surface-water flows. Excavated soil materials from wetland construction could be used to raise the ground level of adjacent farm land to reduce flood risk and improve drainage, thereby increasing the agricultural value of this land.

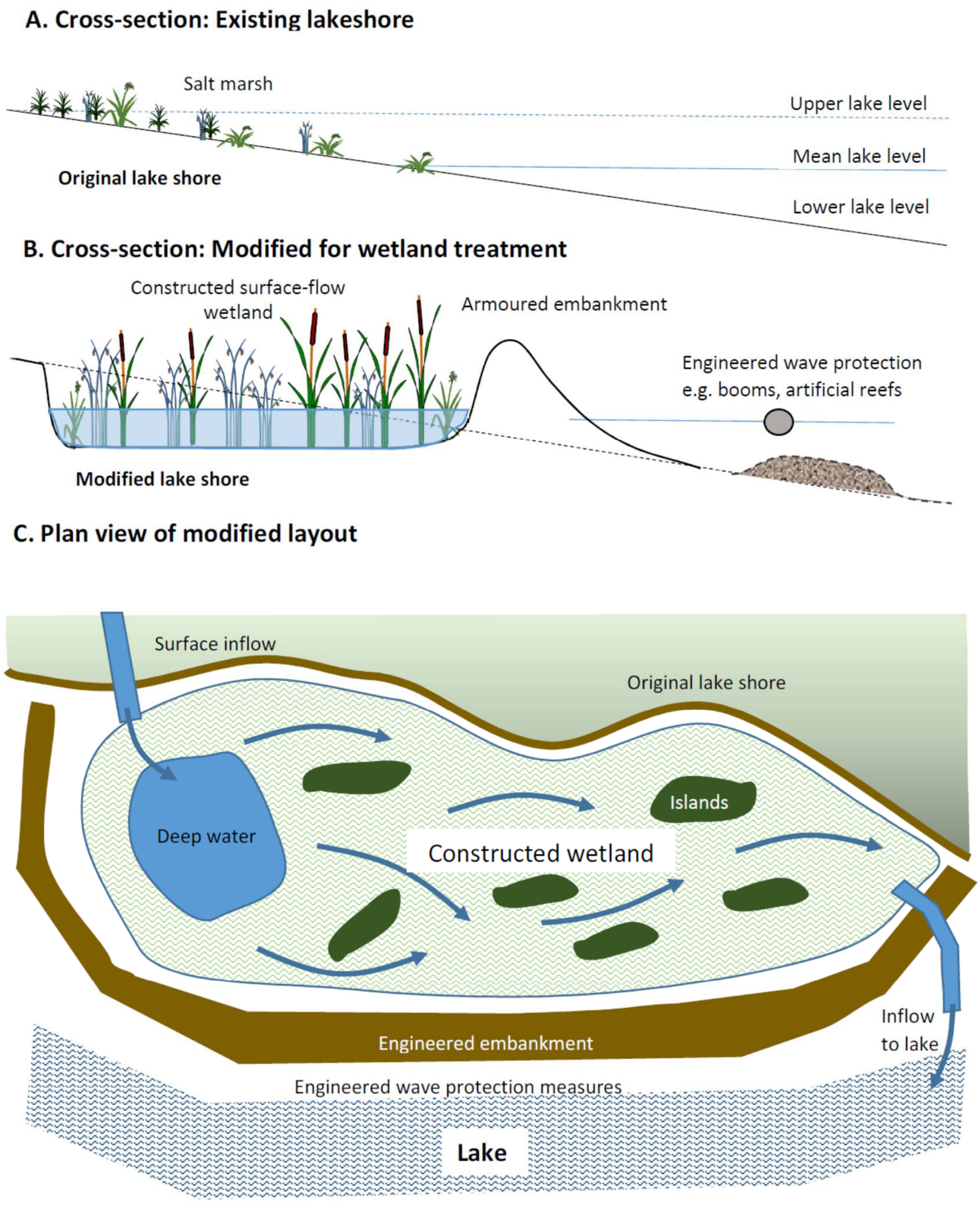

Figure 2-5: Conceptual plan for potential wetland construction in shallow littoral zones of the lake.

3 Methods

3.1 Inflows and nutrient loads

The drainage network entering Te Waihora is extremely complex, with poorly confined aquifers leading to gaining and losing sections of channel. Irrigation takes and applications across large areas and drainage further modifies the natural drainage regime. This makes it difficult to reliably delineate catchments. Apparent catchment areas have, however, been calculated for major inflows based on the NIWA River Environment Classification (REC) to provide an indication of wetland extent relative to catchment area.

Estimates of nitrogen, phosphorus and suspended solids loadings to Te Waihora were calculated from monthly water quality data combined with hydrological data from flow recorders supplied by Environment Canterbury. Where flow records were not available, flow estimates were generated from spot measurements of flow and a regression model presented in an Environment Canterbury technical report (Horrell & Clausen 2007). Because of significant seasonal differences in flow, water quality and water temperatures, the data was divided into dry (Nov-Apr) and wet (May-Oct) season periods for wetland performance modelling. A more detailed explanation of analytical and statistical techniques, site locations and further data summaries are presented in the Appendix A.

3.2 Lake water quality

Lake water quality and physico-chemical data from regular monthly monitoring of the lake supplied by Environment Canterbury was used to assess the potential nutrient removal rates for floating treatment wetlands deployed in the lake. Figure 3-1 shows the points where water quality is sampled in Te Waihora, and shows the major inflows to the lake. Long-term and more recent data is summarised separately, the later on a seasonal basis. Further details and analysis are provided in Appendix A. In this study we have chosen to use means for long-term data for the Mid-Lake monitoring site to represent the overall lake water quality status, but refer to data for other sites where relevant.

3.3 Identifying potential locations for nutrient attenuation wetlands

3.3.1 Potential surface-flow wetland locations

Site visits to gain an understanding of the nature of the catchment and identify potential locations for wetland remediation or construction were undertaken by NIWA with guidance from Environment Canterbury staff (19-20 Aug, 2014). Where sites showed obvious wetland potential, we have delineated the areas available and modelled potential nutrient removals in the same manner as above. It should be noted, however, that all the sites identified are hypothetical examples, and have been only superficially assessed without any specific knowledge of ownership, legal status (e.g., reservation protection), or access to geotechnical or ecological information. They have been included to provide a preliminary indication of the sort of areas and scale of wetland restoration or creation that would need to be considered to achieve meaningful nutrient reductions relevant for the rehabilitation of Te Waihora. For each of the major types of wetland remediation system we have chosen to illustrate a few potentially suitable examples, with abbreviated details for other similar sites.

Figure 3-1: Environment Canterbury water quality monitoring sites in Te Waihora.

3.3.2 Floating treatment wetland locations

We considered the two main factors constraining the areas within Te Waihora where FTWs could be deployed were:

1. Suitable depths to avoid root anchorage in the lake sediments.
2. Acceptable (not excessive) wave action to limit risks of damage to the floating islands/platforms, anchorage systems and plants.

Given the significant variations that occur in the water level of the lake, we determined suitable minimum depths and maximum levels of wave action for deployment of FTWs, based on the results of mesocosm experiments and our profession judgement. We then used records of lake bathymetry (Irwin et al. 1988), water level range and wave modelling under the two wind exposure directions common in Te Waihora to determine suitable areas in the lake that met our criteria. Extracted GIS layers for streams and rivers, drainage systems, lake polygons and coastline were derived from Koordinates (https://koordinates.com/).

Te Waihora has a large fetch and relatively high wind exposure. The strongest winds at the lake are south-westerly. Maximal wind gusts of 148 km hr^{-1} are expected at Taumutu with a 25 year return period and 158 km hr^{-1} at a return period of 50 years (Taylor 1996). Storm force north-easterlies are not very frequent, however, gusty north-west winds are known to be strong enough to damage structures in the vicinity of the lake (Taylor 1996). Very strong south-west winds have been known to raise the lake on the leeward side at Kaituna by 0.6 to 0.9 m, with over a 2 m rise from wind combined with flood waters recorded during the 1968 Wahine storm (Taylor 1996). By contrast strong winds affected levels at Taumutu by -0.6 to +0.2 m (Taylor 1996). This effect is most obvious at the lake margins but there is no information about the area offshore that may be affected by this wind seiche.

We used modelling of wave conditions on Te Waihora undertaken using the SWAN numerical wave model (Jellyman et al. 2008). This model assumed a constant strong wind (20 m s^{-1}) and considered two scenarios; wind from the north-east, or from the south-west, the two predominant wind directions for the area. The model generated expected mean wave height and direction, and identified areas of high relative wave energy along shorelines.

3.4 Predicting wetland nutrient removal

3.4.1 Surface-flow wetlands

Seasonal treatment performance of surface-flow wetlands was predicted for average wet and dry season flows and TN concentrations using the *P-k-C** first-order kinetic modelling approach as proposed by Kadlec and Wallace (Kadlec & 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 & 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). It should be noted that this can only be considered as a preliminary indication of likely TP removal. Wetland TP removal is likely to be substantially affected by the form of P in inflows (particularly particulate compared to dissolved fractions) and the geochemistry of the particulate fraction (as it affects the potential for subsequent P desorption under ambient wetland conditions).

For initial assessment purposes we have assumed that rainfall and evapo-transpiration for the wetland areas are essentially equal, and that losses or gains from groundwater are negligible. Although higher net rainfall during winter and elevated evapotranspiration rates during summer dry periods will likely add to the day to day variability of wetland treatment performance, it is not expected to make a marked difference to the overall treatment performance.

The hydraulic efficiency of the wetlands was assumed to be equivalent to that of well-designed and vegetated surface-flow constructed wetlands with approximate length to width ratios between 3:1 and 4:1 (hydraulic efficiency parameter of 3). However, it should be noted that wetland systems show a range of nutrient removal performance depending on their specific flow and loading regime, design, age, vegetation type and cover, and local climate and site conditions (Kadlec 2012; Tanner & Kadlec 2013).

Wetland areas within a catchment required to achieve annual TN load reductions of 20% and 40% have been modelled for each monitored inflow to Te Waihora. Expected corresponding load reductions of TP at these wetland areas have been included for each scenario. In addition, a number of the inflows are subject to large seasonal variations in flow, drying up or stopping flowing during the dry season. The maximum realistic area at which a wetland would remain sufficiently "wet" to sustain a wetland ecosystem has therefore been estimated based on mean dry season inflows. For preliminary guidance we have assumed that a wetland would require a flow providing a nominal hydraulic residence time no greater than 60 d during the dry season to be able to sustain viable wetland vegetation and function. Where the area of wetland required to achieve this is smaller than the modelled size required to achieve the desired water quality targets, we predict the wetland will likely become too dry during summer, resulting in problems sustaining viable wetland vegetation and/or substantially reducing treatment function during subsequent wet seasons.

3.4.2 Floating treatment wetlands

Most of the information available quantifying the nutrient removal potential of FTWs is based on relatively short-term and small-scale mesocosm studies, as summarised by Headley and Tanner (2012). In New Zealand NIWA has examined the nutrient attenuation performance of floating treatment wetlands (FTWs) planted with the emergent wetland macrophytes (*Cyperus ustulatus, Juncus edgariae* and *Schoenoplectus tabernaemontani*) (Sukias et al. 2010a). Treating artificial eutrophic lake water at nutrients concentrations relevant to eutrophic Rotorua lakes, we found mean areal mass attenuation rates ranged from 638 to 762 mg m^{-2} d^{-1} for total nitrogen, however the additional amount specifically attributable to the FTWs (in excess of controls without FTWs) was 339 mg m^{-2} d^{-1} with other in-lake processes contributing the remainder. This FTW only rate is similar to that for equivalently loaded conventional constructed wetlands with sediment-rooted vegetation. Mean areal mass attenuation rates for TP and DRP of 54 to 58 mg m^{-2} d^{-1} for DRP and 57-64 mg m^{-2} d^{-1} for TP were recorded. The additional amount specifically attributable to the FTWs (in excess of controls without FTWs) ranged from 30 and 16 mg m^{-2} d^{-1} respectively for TP and DRP, with in-lake processes adding a further 39 and 44 mg m^{-2} d^{-1}. Nutrient attenuation mechanisms appeared to be dominated by plant and algal uptake, and subsequent algal settling beneath the FTWs. Denitrification within the FTW matrix was also apparent when nitrogen was supplied as nitrate, but was generally limited by a lack of organic carbon available for microbial processing. These small-scale experiments demonstrated considerable potential for FTWs to reduce nutrients from eutrophic lake water, but further larger-scale trials were recommended to evaluate their effect in larger lakes and waterbodies.

NIWA also undertook a 9 month pilot-scale lake-side study in a modified large shipping container to evaluate the potential removal of nutrients from an inflow to Lake Rotoehu (Sukias et al. 2010b) which showed mass removal rates, for low and high loading rates respectively, of 157 and 239 mg TN m^{-2} d^{-1} (77 and 45% reduction) and 2.3 and 5.4 mg TP m^{-2} d^{-1} (32 and 35% reduction). Apart from this, relevant and reliable field-scale research using FTWs to treat eutrophic lake water in NZ or anywhere else is rather limited. Because many of the nutrient removal processes associated with FTWs are indirectly mediated via depth- and scale- dependant sedimentation processes and impacts on physic-chemical conditions (e.g., dissolved oxygen depletion promoting microbial denitrification) in the root mass and beneath the floating mat (Tanner & Headley 2011), there are significant uncertainties as to the long-term nutrient removal performance of FTWs at field-scale. Our ability to predict performance in a very large exposed lake such as Te Waihora is therefore also limited.

For this preliminary assessment we have used the best information available to us, including the results from New Zealand trials and relevant published data from overseas studies. Data summarised by Headley and Tanner (2012) was compiled and a range of common regression relationships tested to provide an estimate of TN and TP areal mass removal performance at the in-lake nutrient concentrations recorded for Te Waihora. A power regression was found to provide the smallest least squares residual error for both TN and TP reduction (r^2 of 0.70 for both nutrients). There was still a considerable scatter of performance around the regression lines for both TN and TP mass removal, suggesting that FTW performance can vary significantly depending on factors such as the plant species used and the specific conditions in which they are operating (Tanner & Headley 2011). However, as can be seen later (Section 5.2), the removal performances derived by this method were generally consistent with those from other pilot-scale trials carried out in New Zealand (Sukias et al. 2010b). Predicted areal mass removal rates thus derived were then compared with desired annual mass removals from the total annual surface inflows to achieve the annual 20% and 40% TN reduction (in influent tributary loads) to provide a preliminary estimate of necessary FTW areas.

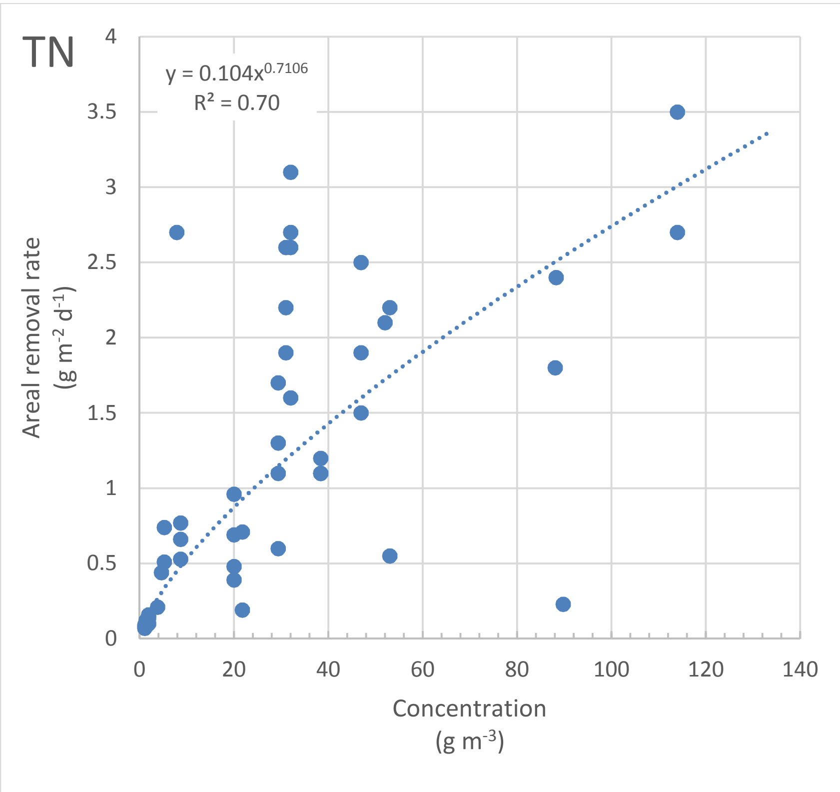

Figure 3-2: Floating treatment wetland total nitrogen areal removal rate. Power regression and correlation coefficient for TN areal removal vs ambient water concentration. One extreme data point for areal removal lies beyond the range shown.

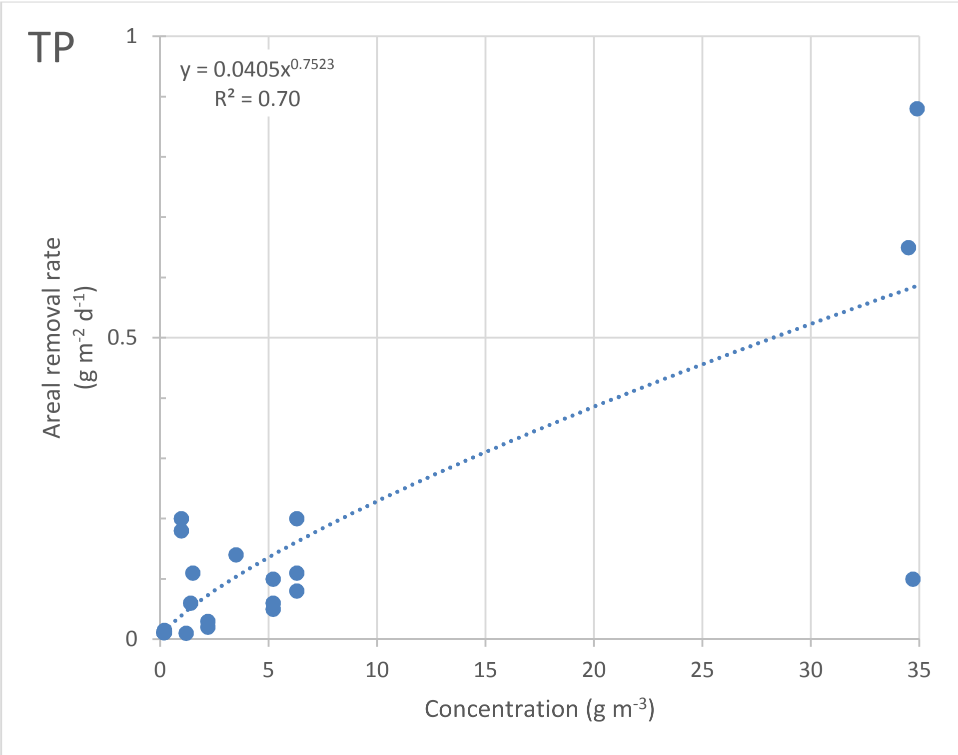

Figure 3-3: Floating treatment wetland total phosphorus areal removal rate. Power regression and correlation coefficient for TP areal removal vs ambient water concentration. Two extreme data points for areal removal lie beyond the range shown.

4 Te Waihora and its inflows

Major surface inflows to Te Waihora include the Selwyn River, L2 River, Hart's Creek, Halswell River and the Kaituna Rivers (Figure 3-1). As identified by Golder Associates Ltd (2011), in-flowing rivers can be broadly split into an upper and lower catchment reaches, upstream and downstream of State Highway 1. Upper reaches are predominantly hill-fed and typically go dry during summer as they cross highly permeable Canterbury Plains' gravels. Lower reaches are spring fed and flow year round in most instances. This distribution of flows strongly determines the potential locations of wetland and riparian remediation interventions. The complex interaction of flows in unconfined aquifers also makes it impossible to define specific catchment areas for most surface-waters in the catchment, so determination of wetland remediation potential cannot be based on percentage of apparent surface catchment areas (e.g., Tanner et al. 2010).

4.1 Surface water nutrient loads

The major inflows have been gauged and sampled for water quality by Environment Canterbury, allowing calculation of seasonal and annual loads[3]. Table 4-1 shows that larger inflows generally contribute proportionally larger nutrient loads to the lake. The Selwyn and L2 rivers, and Hart's Creek collectively contribute 54% of measured surface inflows, 64% of TN load and 59 % of TP load. Flow proportional mean concentrations have been calculated for each inflow by dividing the mean daily load by the mean daily flow. These concentrations indicate the flows that contribute the greatest average nutrient flux per unit of flow. Because wetland mass nutrient removal rates per unit area are related to inflowing concentrations (and temperature in the case of N), the higher flow-proportional concentrations indicate the flows where wetland mass removal efficiency is likely to be optimised. This suggests that Boggy Creek, and the Harts and Selwyn Rivers should be preferentially targeted for wetland N removal, and the Irwell and Selwyn Rivers and Doyleston Drain should be preferentially targeted for wetland P removal. The Kaituna River appears to be an anomaly with a very low flow proportional TN concentration of about 0.2 g m^{-3}, so that despite representing 5% of the flow it only contributes 0.3% of the TN load (and only 3.8% of the TP load). This suggests the Kaituna River would be of low priority for wetland treatment for nitrogen removal.

Seasonality of flow and nutrient loads also influences the nutrient removal ability of wetlands. Wetland nitrogen removal (via nitrification/denitrification) is highly temperature dependant, with higher rates at higher temperatures. However, as can be seen in Table 4-1, dry season flows range between 20%-70% of wet season flows (overall 44%) and represent 9–70% of N load (overall 42%) and 4–108% of TP load (overall 18%), limiting the potential annual TN mass removal of wetlands during the period when conditions are most conducive to TN reduction.

In terms of seasonality, the Doyeston and Hanmer Rd Drains, and Selwyn and Kaituna Rivers show the lowest ratios of dry to wet season flow (19–26%) and dry to wet season TN load (9–26%). However, the L2 and Halswell Rivers, and Harts Creek still export 58–70 % of their TN load during the summer period (approximately consistent with their seasonal flow regime). In contrast, the Irwell River, despite dry season flows being 58% of wet season flows, only transports 21% of its TN load during this period reducing its overall wetland mass removal performance. Although overall mass removal performance will be reduced under such dry season flows, the efficiency of wetland TN reduction (percentage removal) will increase. As phytoplankton growth rates and associated nutrient needs are also likely to be highest during the warmer dry season, resultant reductions in N

[3] Loads were calculated based on wet and dry season flows and nutrient concentrations. These have been used in later calculations, but only annual loads have been presented here for simplicity.

concentrations in inflows may contribute to reduced severity of blooms during these critical periods when risks are greatest.

The reduced TP load during the dry season likely reflects the reduced intensity of rainfall (and greater reliance on irrigation), and resultant reduction in surface run-off and erosive high-flow events in channels during this time, which are typically the dominant transport pathways for particulate P into waterways. The Selwyn River, in particular, appears to export an extremely small percentage of its TP load during the dry season (4% of wet season load). Conversely the Irwell River, despite dry season flows only being around half of wet season flows, exports the greatest percentage of its TP load during the dry season (108% of wet season load). The reasons behind these anomalies requires further evaluation and may provide useful insights into management practices that could reduce nutrient sources in these catchments.

Low relative dry seasonal flows can also result in problems sustaining a viable wetland ecosystem. Depending on the permeability of the soil underlying a wetland (as it affects exfiltration water losses) and possible shallow groundwater influx, low dry season inflows can cause desiccation reducing the growth and survival of wetland plants. It can also provide for rapid aerobic decomposition of organic matter in the wetland, reducing the "fuel-source" subsequently available for N removal by denitrifying microbes (typically the dominant N removal process) when saturated, oxygen-limited conditions are resumed. Nitrification and denitrification processes may also be less metabolically efficient under such conditions leading to increased generation of nitrous oxide (a potent greenhouse gas), rather than innocuous N_2 (Burgin et al. 2013; Burgin & Groffman 2012). Situations where dry season inflows may be insufficient to sustain a wetland ecosystem are identified in Table 4. Boggy Creek, Hanmer Rd Drain and the Irwell River all show significant potential for dry-season wetland sustainability issues, even for the smaller wetland extents required to meet the 20% TN reduction target proposed. Further investigation of flow regimes would be required to assess this issue more fully.

Table 4-1: 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%

4.2 Lake nutrient concentrations

Concentrations of nutrients and chlorophyll-*a* (a measure of phytoplankton abundance) measured in the middle of the lake are summarised in Table 4-2. Dissolved inorganic forms of nitrogen, which comprise on average around 8% of the Total Nitrogen (TN) concentration in the lake, are generally dominated by nitrate (NO_3-N; 82%). Dissolved reactive forms of P (DRP) comprise on average less than 4% of Total Phosphorus (TP). The remainder of the TN and TP is expected to be bound in plankton biomass or associated with particulates suspended in the water column.

Although the instantaneous concentration of dissolved forms of both N and P appears relatively low, we have assumed that there will be a significant ongoing turnover of plankton biomass and hence a significant flux of nutrients mineralised from dead and decaying plankton into available forms. Furthermore we assume that emergent plant roots suspended beneath FTWs located in the lake will be able to successfully compete with phytoplankton for this available nutrient flux.

Table 4-2: Mid-lake long term and recent nutrient and Chl-*a* concentrations. Long term since 1983 and recent (short-term) 2011-2014. Values are mean ± standard deviation.

Parameter	1983 - 2014	2011 - 2014	winter	spring	summer	autumn
NH_4-N (mg/L)	0.03 ± 0.08	0.02 ± 0.04	0.028 ± 0.053	0.013 ± 0.013	0.041 ±0.062	0.017 ± 0.013
NO_3-N (mg/L)	0.14 ± 0.27	0.03 ± 0.06	0.092 ± 0.094	0.020 ± 0.030	0.015 ±0.015	0.008 ±0.005
TN (mg/L)	2.1 ± 0.75	1.7 ± 0.7	1.38 ± 0.52	1.48 ± 0.35	1.82 ±0.64	1.97 ±1.01
DRP (mg/L)	0.008 ± 0.012	0.003 ± 0.002	0.002 ± 0.001	0.003 ± 0.002	0.004 ±0.002	0.004 ±0.002
TP (mg/L)	0.22 ± 0.12	0.17 ± 0.09	0.12 ± 0.09	0.14 ± 0.05	0.22 ±0.06	0.19 ±0.13
Chl-*a* (µg/L)	87 ± 44	47 ± 37	53 ± 27	49 ± 20	26 ±17	54 ± 65

5 Wetland areas required to meet nutrient load targets

5.1 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 5-1). Such proportional reductions in N load would also be likely to be maintained if, as forecast[4] , 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). Conversely, lower wetland TN reduction targets would generally be able to be achieved with proportionally less wetland area; for instance 10% TN reduction with 0.3-0.4 times the wetland area predicted for 20% TN reduction.

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)[5]. 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.

[4] As noted in Gibbs and Norton 2012, ECAN predicts nutrient increases of up to 35% from current land intensification.
[5] Data for Waikato and Mataura Rivers derived from respective Regional Council web pages.

5.2 Floating treatment wetlands

The critical values in interpreting FTW nutrient removal with the data available are the in-lake nutrient levels for Te Waihora. 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. Thus, using mean concentrations and the relationships from the power regressions (see Section 3.4.2), we would expect nutrient removals 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 4-1). Based on the likely 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. Predicted TP removal would be ~22.4 and 44.7 Tonnes TP yr^{-1} (~96% and 191% of the TP loads to the lake). These areas of FTW are around 74% and 49%, respectively, of the total area of surface-flow wetlands predicted to be required to achieve the proposed 20 and 40% annual TN reduction targets for all (except the small tributary inflows) to the lake.

Table 5-1: 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.

6 Potential for rehabilitation of remnant wetlands

Only relatively small areas of natural wetland now occur in the wider Te Waihora catchment, compared with historical wetland extent (Estimated only 7% of original wetland area in Canterbury is still present; Ausseil et al. 2008).

6.1 Remnant lake edge and riparian wetlands

Rehabilitation of significant remnant wetland areas at Ahuriri, Ta-rere-kau-tuku (Yarrs Lagoon), or Motukara specifically for nutrient remediation has not been considered in this report due their very high existing cultural and ecological values (Environment Canterbury 2004; Environment Canterbury 2013) and small current extent. Some other small riparian wetlands are marked on the Canterbury Maps Website (7.10.2014 update) along the Selwyn River and on the Irwell River just north of Brookside. No further information was available to us on these sites and they have not been evaluated in the current study.

The lake edge and littoral-zone wetlands at Kaitorete Spit are located on the seaward side of Te Waihora remote from significant surface-inflows to the lake. These remnant areas of largely intact wetland are regionally and internationally important wildlife habitats (Environment Canterbury 2004). Although they undoubtedly play a role in maintenance of lake water quality and contribute significantly to the ecological and cultural values of the lake, they offer minimal opportunity to intercept and treat nutrient-rich surface-water inflows from the wider lake catchment and so have been also excluded from further consideration.

Many other remnant wetland areas occur around the shores of Te Waihora (Canterbury Maps Website; 7.10.2014 update). These wetlands, which have developed under contemporary land and water management practices, are likely to be highly modified from the wetlands that would have existed here prior to major development across the catchment and active management of lake levels. Agricultural drainage of the surrounding landscape and channelization of associated streams has resulted in most these areas being perched and largely disconnected from surface-flows, except during floods or when lake levels are elevated. We anticipate that creation of wetlands in these areas that would allow for passive gravity-driven entry of existing surface inflows to the lake would require significant excavation and destruction of the existing ecosystems. Thus we consider utilisation of these areas as essentially involving new wetland construction rather than rehabilitation of the current wetlands. Potential redevelopment of these wetland areas for interception and treatment of surface waters is dealt with in Section 7 of this report.

6.1.1 Spring-head wetlands

There are a large number of areas where springs arise in the catchment creating small wetland areas. Many of these areas have been agriculturally developed with the spring flows intercepted by drains. The Five Springs site is in the headwaters of Silver Stream, a tributary of the Selwyn River. The area outlined in yellow in Figure 6-1 (i.e., within the fenced boundary) is approximately 10,560 m^2. This area appears presently to be managed primarily for its habitat, biodiversity and passive recreation values. As can be seen from Figure 6-2, significant areas within the boundary are terrestrial and have been planted with native plants, largely trees and shrubs. We estimate that only around 10% of the area could be considered as wetland and have significant interaction with outflowing water from the spring heads. This limits the water quality functions of the area.

Figure 6-1: Google Earth location for Five Springs.

Figure 6-2: Five Springs. The area is undergoing some restoration, with significant areas within the fenced boundary being "dry" land.

Possible alternative options for intercepting springheads

For spring sites such as Five Springs, the contributing catchment is not able to be readily defined. Flow at Five Springs is not gauged, but was visually estimated at 40 L s^{-1} in the outlet drain at the time of our visit (19.8.14) . For the purpose of this modelling assessment, we have assumed the entire area could be optimised as a surface-flow wetland (essentially involving excavation and replanting with emergent wetland vegetation). Using the 40 L s^{-1} as a wet flow for this site, and applying the ratio of wet:dry season flows and nutrient concentrations from the Selwyn River during wet and dry seasons for this site, we have calculated that this site could achieve reasonable nutrient reductions from these flows, as shown in Table 6-1. A number of other wet areas were obvious in the vicinity of the Five Springs sites where small springs appeared to be emerging. It would conceivably be possible to also excavate these areas to intercept these shallow "spring" flows. Small wetlands could then be constructed downstream of these to treat the nutrient content of these flows before they were directed to waterways. As high water tables often constrain agricultural use of these wet spring-head areas, such management might provide benefits for both agricultural productivity on the surrounding land and water quality. However, In general, unless these spring outflows are specific nutrient hotspots that should be specifically targeted, it may be better to instead construct wetlands further downstream that treat the cumulative flows emerging from these areas. This would protect the unique flora and fauna[6] associated with these springheads.

Further discussion of springhead management will be covered in a sister study of riparian vegetation management in the Te Waihora catchment concurrently being undertaken for ECAN by NIWA.

Table 6-1: 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%

[6] E.g. wetland species and potentially stygofauna.

7 Potential locations for wetland development

Areas identified for potential development of wetlands to reduce nutrient loads from significant surface water inflows to Te Waihora are shown in Figure 7-1–3. As a general convention, we have outlined riparian areas in white, terrestrial lake edge wetland areas in orange and littoral or in-lake wetland areas in yellow.

It is important to reiterate that the sites identified are hypothetical examples that have only been superficially assessed without any specific knowledge of ownership, legal status (e.g., reservation protection), or access to geotechnical or ecological information. They have been included to provide a preliminary indication of the sort of areas and scale of wetland restoration or creation that would need to be considered to achieve meaningful nutrient reductions relevant for the rehabilitation of Te Waihora. They do not represent propositions for wetland creation at sites indicated in the report; no landowners have been consulted and any proposed wetland creation would require full collaboration with Ngāi Tahu, the Department of Conservation and landowners and go through an appropriate consenting process.

7.1 Lake-edge and littoral wetlands

A number of potential locations have been identified along the terrestrial edge of Te Waihora near the outlets of significant inflows. These locations appeared from satellite imagery, and in some cases a rapid visual assessment, to be potentially suitable, lower-value land which retained a wetland character, or were as close to these requirements as were available in the near vicinity of the associated input rivers/streams. We have also identified areas of the lake littoral zone that with significant re-engineering could potentially be developed into shallow surface-flow wetlands to intercept flows from surface inflows before entering the main body of the lake. Many of the areas will have significant ecological and cultural values even in their current highly modified state, which would be lost should they be converted into constructed wetlands. However, constructed wetlands established on such sites would provide an alternative suite of ecological and cultural values.

7.1.1 Kaituna River sites

Three lake edge areas at or close to the mouth of the Kaituna River were identified as potential wetland areas (see Figure 7-4). Areas immediately to each side of the river were somewhat boggy in appearance, although there appeared to be partial agricultural use of the land. Some wetland areas (Figure 7-5) that have formed behind the former railway embankment (now a cycleway) could be connected to river flows, and extended and rehabilitated to provide wetland treatment of this inflow. The areas of each potential wetland are shown in **Error! Reference source not found.**, along with predicted areas required to achieve 20% and 40% removal of TN (from Table 5-1). This suggests that the 20% target could be readily met using around 60% of these areas. However, as noted previously (Section 4.1), 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.

Table 7-1: 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

Figure 7-1: Potential wetland sites, eastern Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow.

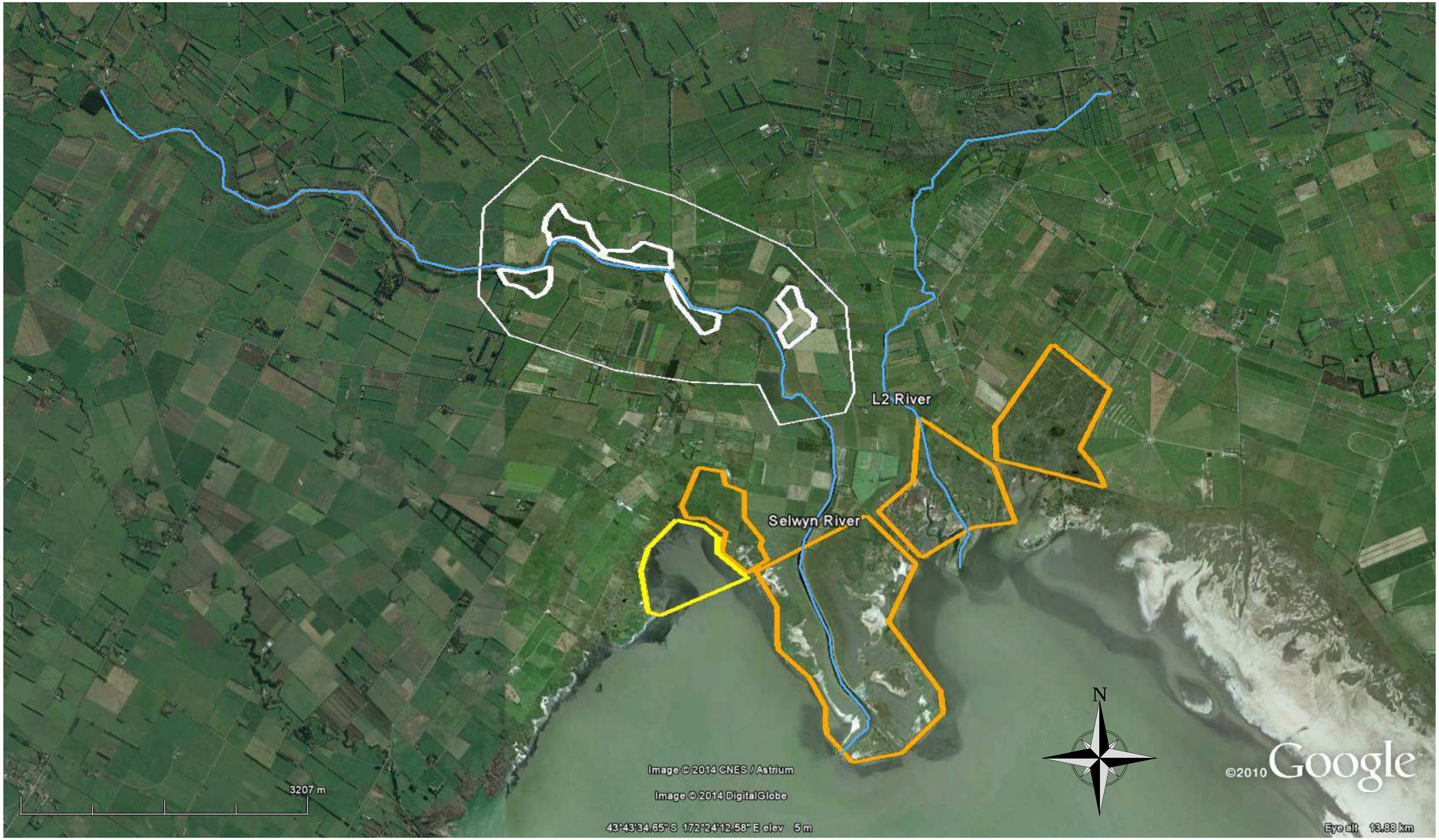

Figure 7-2: Potential wetland sites, central-northern Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow. Riparian wetlands are outlined in white.

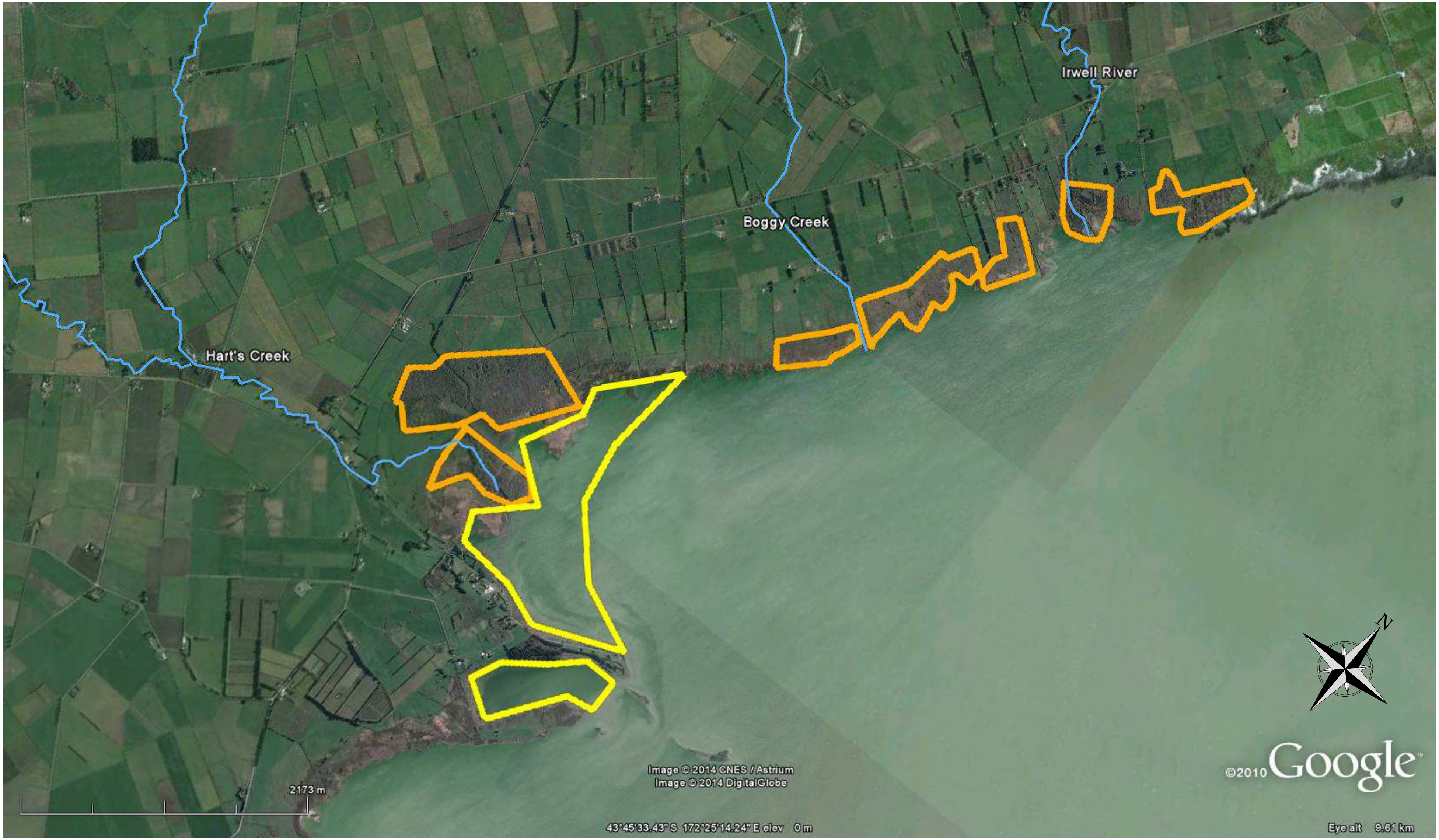

Figure 7-3: Potential wetland sites, western Te Waihora. Lake edge wetlands are outlined in orange. Littoral wetlands are outlined in yellow.

Figure 7-4: Potential areas for constructed wetland development near the mouth of the Kaituna River. Note identified areas are hypothetical examples and would require additional investigations to determine their suitability.

Figure 7-5: Wetlands near the outlet of the Kaituna River. These wetlands have formed behind the former railway causeway (now a popular cycleway). Redirection of flows from the Kaituna River into these areas would allow them to provide greater water quality function.

7.1.2 Halswell River

Three areas were identified at the river mouth of the Halswell River (Figure 7-6) which appeared to be sufficient in area (Table 7-2) for either 20% or 40% TN annual removal targets.

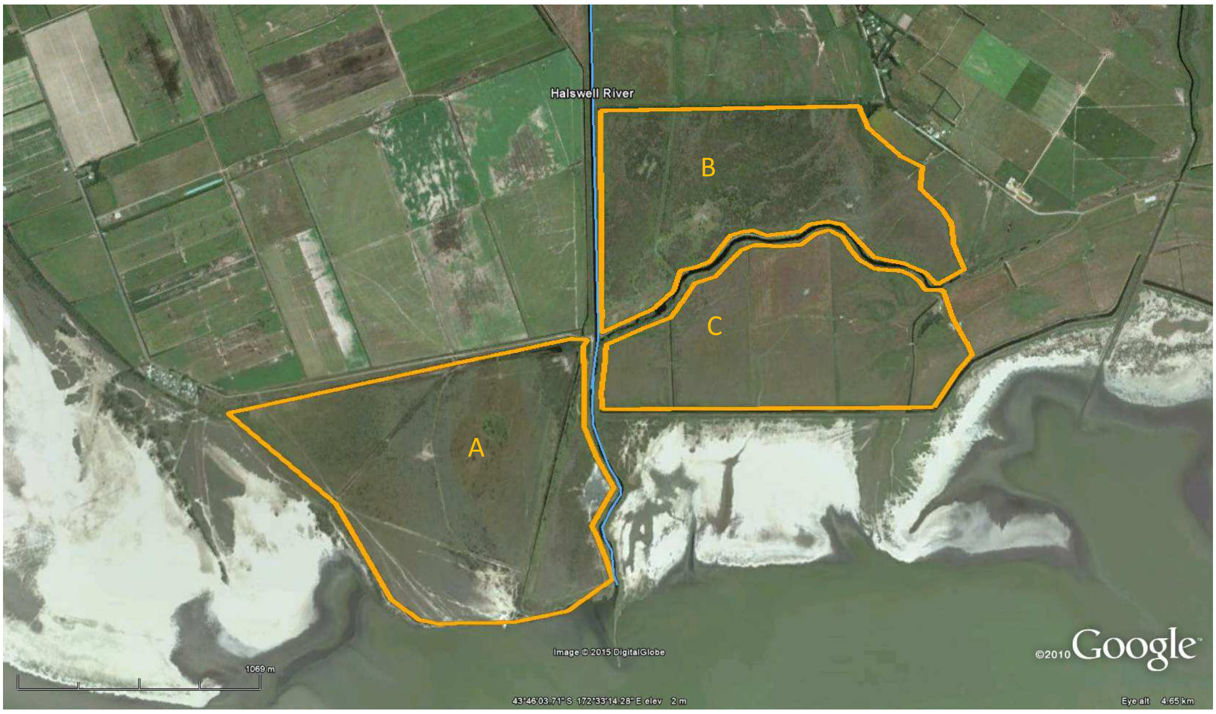

Figure 7-6: Three potential wetland areas at the mouth of the Halswell River.

Table 7-2: 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

7.1.3 L2 River

Two areas near the mouth of the L2 River were delineated for modelling (Figure 7-7). These areas appear from the Google Earth image to 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.

Figure 7-7: Wetland areas near the mouth of the L2 River.

Table 7-3: 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

7.1.4 Selwyn River

A number of sites exist around the outlet of the Selwyn River that appear to have potential for wetland development (see Figure 7-8). 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.

Figure 7-8: Mouth of the Selwyn River showing potential wetland areas identified.

Table 7-4: 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

7.1.5 Irwell River and Hanmer Road Drains

Areas adjacent to the Irwell River and Hanmer Road Drain were identified as shown in Figure 7-9. These are presented together as some of the wetland areas shown could be used for either input. These areas appear to be insufficient to achieve even the lower 20% TN target proposed (Table 7-5 and Table 7-6). The areas identified would need to be extended inland or along-shore, or further wetland areas would need to be found.

Figure 7-9: Areas adjacent to the Irwell River and Hanmer Road drain for modelling of constructed wetland nutrient removal.

Table 7-5: 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 (ha)
27	68	12	6

Table 7-6: 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

7.1.6 Boggy Creek

Two areas were identified at the mouth of Boggy Creek (Figure 7-10). The larger of these areas exceeds the area required to achieve the 20% TN reduction target for this inflow (Table 7-7), but even together these areas would be insufficient to fully achieve a 40% TN reduction target

Figure 7-10: Mouth of Boggy Creek and associated potential wetland areas.

Table 7-7: 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

7.1.7 Hart’s Creek

A raupo dominated wetland area was present at the mouth of Hart’s Creek that appears to be poorly connected with this surface inflow (Figure 7-11). This area has been designated as a Wildlife Reserve (Fig 15, ECAN Navigation Safety Bylaws 2010), which may preclude development of this area as a constructed wetland. However, constructed wetlands could also provide potentially valuable alternative wildlife habitat in this area. Alternatively, the existing wetlands in this area might be able to be minimally 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 (See Figure 7-12; and Fig 15 of ECAN Navigation Safety Bylaws 2010). The potential wetland areas identified exceed those required to achieve the 20 % and 40% TN removal targets (Table 7-8).

Table 7-8: 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 (ha)	Area Hart’s Creek D (ha)
20	50	65	22	126	32

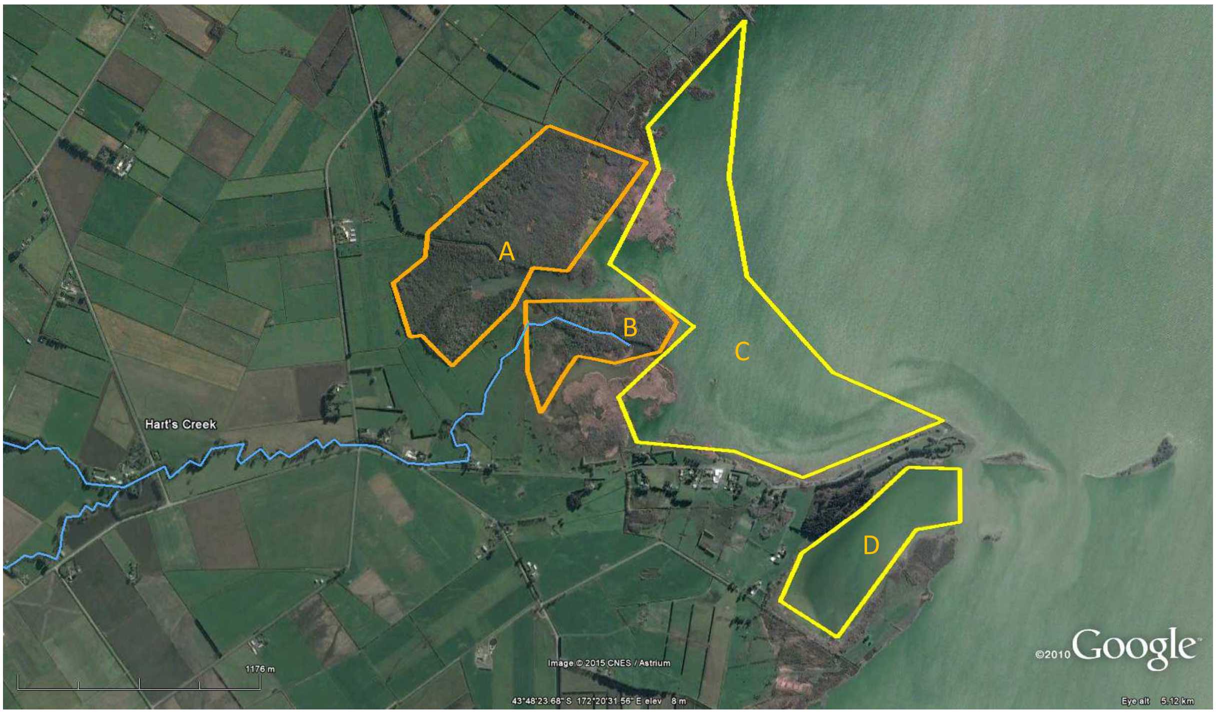

Figure 7-11: Existing and potential wetland areas near the mouth of Hart's Creek and Timberyard point.

Figure 7-12: Sign at Timberyard Point near Hart's Creek outflow showing it is a significant area of recreational use. Development of wetlands in this area, especially in the shallow littoral areas of the lake, would be likely to conflict with these uses.

7.2 Other surface-flow wetland options

7.2.1 Riparian wetlands

In the area immediately downstream of Five Springs, extensive channel widening, re-contouring and riparian planting had been undertaken (see Figure 7-13). In the example photo, it could readily be imagined that contact between water already in the channel and the marginal vegetation would be minimal in most circumstances. Thus the opportunities for remediation of water quality is also limited[7]. Enhanced nutrient removal (and additional biodiversity benefits) might be achieved by adding occasional wider and deeper zones where flow velocities would be reduced, wetland plant species could be planted without reducing the overall drainage capacity of the network, and solids settling, phosphorus sequestering and nitrate removal via denitrification might occur.

Figure 7-13: Channel modifications downstream of Five Springs.

[7] That is not to say that there will not be biodiversity benefits and reduced bankside erosion potential to this design.

Coe’s Ford

There are a number of potentially available areas adjacent to the Selwyn River near Coe’s Ford. These are highlighted in Figure 7-14. Some areas are clearly public reserves while some of the area delineated are probably in private ownership.

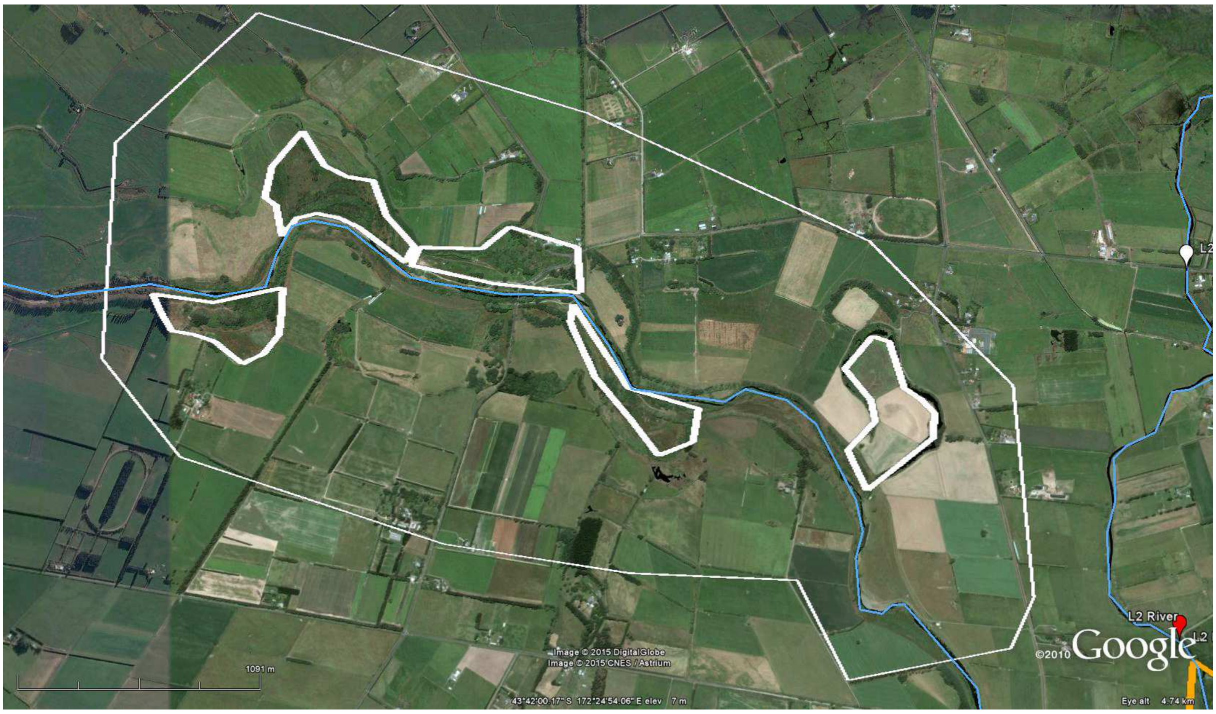

Figure 7-14: Potentially suitable riparian areas of the Selwyn River.

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 7-15) could be used as ephemeral wetlands/embayments, only receiving water during high flow/flood events. Areas of land delineated in Figure 7-14 are compiled in Table 7-9.

Table 7-9: 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

Figure 7-15: River side reserve at Coe's Ford.

7.2.2 On-farm drainage treatment wetlands

At the time of the NIWA site visits, an assessment was made of the potential to treat subsurface drainage at the Lincoln University demonstration farm. In general, the nutrient removal potential of a wetland treating farm drainage is based on the relative areas of the wetland and its contributing catchment, unless there is specific information on flows and nutrient concentrations, which was not the case in this instance. Thus we have relied on extensive data sets of New Zealand and international examples to give likely removal rates (as have been summarised the New Zealand Guidelines for Constructed Wetland Treatment of Tile Drainage, Tanner et al. 2010). In the above example, the general contributing area was in the order of 30 ha. Two wetlands of ~0.5 ha area each were recommended. On this basis, they should provide an average nitrate-N removal in the order of 45% on an annual basis[8].

[8] Note: there is considerable variation in the performance of any one constructed wetland, and values quoted here are averages of a large number of wetlands of this relative size.

Figure 7-16: Preliminary conceptual layout for serpentine wetland at Lincoln University Dairy Farm. Design is overlaid on a Google Earth Image showing the corner of the paddock where this wetland might be situated. Hatched areas show deep open water zones, with shallow sedge wetlands proposed in remaining areas.

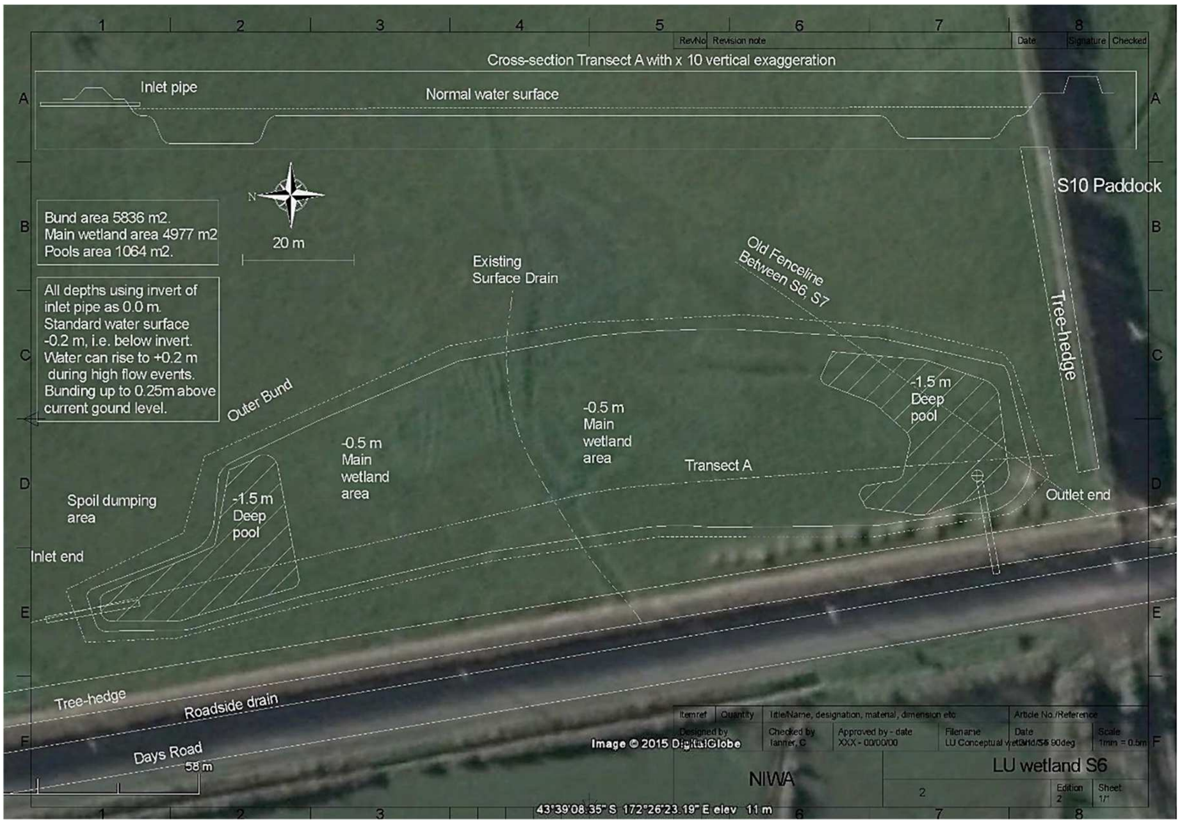

Figure 7-17: Preliminary conceptual layout for linear wetland at Lincoln University Dairy Farm. This paddock edge location lends itself to a more linear wetland design.

7.3 Floating Treatment Wetlands (FTW)

7.3.1 Criteria for deployment of FTW within Te Waihora

Although there is limited information available, based on root growth in previous mesocosm experiments conducted by NIWA, we consider the FTW would require a water depth of approximately 0.8 m depth (minimum of 0.6 m). In shallower water, there is potential for root anchorage into the lake bed which would minimise root uptake of nutrients from the water column, and create potential problems when the lake level rises (e.g., either ripping out of roots or submergence of the FTW anchored by the plant roots). Required installation depths are likely to dictate the distance offshore and location of FTW relative to nutrient inflow sources.

Due to the high energy environment of Te Waihora, FTW will likely need to be located in areas with areas of lower wave action. Although FTW can be tethered to the lake bed using screw anchors, and have reinforced wire cabling through the island structure, their performance and structural soundness within such a high energy environment has not been tested. Thus wave exposure limits we recommend are conservative.

Elements which will influence these two factors include the artificial lake opening regime, lake bathymetry, and wind and wave action. Key locations will also include high nutrient inflows to the lake.

Opening regime

The water level of Te Waihora is artificially managed to prevent flooding of surrounding agricultural land and properties resulting in significant fluctuations in water depth. Openings and their timing are dictated by Resource Consent under the National Water Conservation (Lake Ellesmere) Order 1990. These allow for openings when:

- Lake level exceeds 1.05 m a.m.s.l.[9] during 1st August to 31 March.
- Lake level exceeds 1.13 m a.m.s.l. during 1st April to 31st July.
- Irrespective of lake level between April 1 to June 15 and September 15 to October 15, to allow for fish migration in and out of the lake.
- Or when lake level is below 0.6 m a.m.s.l. allows for the lake to be artificially closed.

In reality, lake levels can only be opened when there is sufficient head of water (greater than 0.9 m a.m.s.l.) and sea conditions permit. To date, the lake has never been artificially closed (Hughey & Taylor 2008).

In contemporary times the lake has been opened on average 3.5 times per year (Taylor 1996). Lake opening results in a rapid drop in lake level, followed by more gradual re-filling. The average closing level is 0.60-0.64 m a.m.s.l. (Taylor 1996), however, evaporation under minimum inflows can cause the lake level to reduce further. Rises in lake level are mostly governed by storm events in the upper Selwyn catchment via Selwyn River inflow (Taylor 1996).

Lake bathymetry

The bathymetry chart for Te Waihora (Irwin et al. 1988) is relative to a lake level of 0.8 m a.m.s.l. and shows a maximum depth of 2.7 m and approximate mean depth of 1.4 m at this datum. Mean lake levels over 1994 to 2008 were approximately 0.832 m a.m.s.l. (Jellyman et al. 2008).

[9] a.m.s.l. = above mean sea level.

Wind action causes tilting of the water surface, with larger level fluctuations observed on the northern side of the lake than on the southern (see wind and wave action below).

Wind and wave action

With a large fetch and relatively high wind exposure, the water level of Te Waihora is variously affected by wind. The strongest winds at the lake are south-westerly. Maximal wind gusts of 148 km hr^{-1} are expected at Taumutu with a 25 year return period and 158 km hr^{-1} at a return period of 50 years (Taylor 1996). Storm force north-easterlies are not very frequent, however, gusty north-west winds are known to be strong enough to damage structures in the vicinity of the lake (Taylor 1996).

Very strong south-west winds have been known to raise the lake on the leeward side at Kaituna by 0.6 to 0.9 m, with over a 2 m rise from wind combined with flood waters recorded during the 1968 Wahine storm (Taylor 1996). By contrast strong winds affected levels at Taumutu by -0.6 to +0.2 m (Taylor 1996). This effect is most obvious at the lake margins but there is no information about the area offshore that may be affected by this wind seiche.

The wave modelling (Figure 7-18) showed the south-western shoreline (Hart's Creek to Taumutu was most sheltered from high wave energy, with the shoreline between the L2 and Selwyn Rivers being relatively sheltered (Jellyman et al. 2008). Sheltered areas under a north-east wind are Kaituna Lagoon and embayments either side of the Selwyn River.

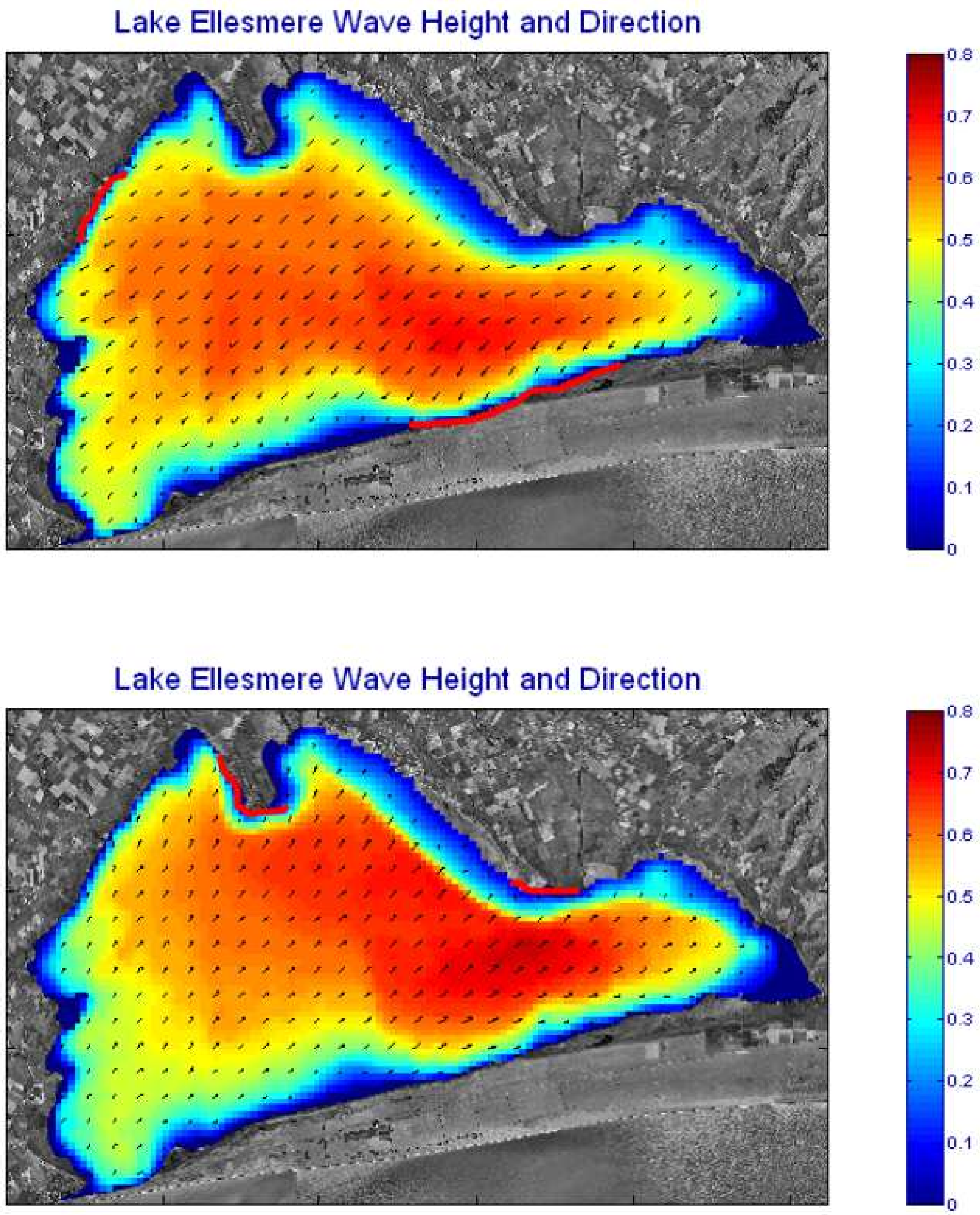

Figure 7-18: Mean wave height and direction generated from a constant wind field of 20 m s^{-1} from the NW (top) and from the SW (bottom). Wave height is in metres. Lake level is taken as 0.8 m a.m.s.l. Red lines along the shore indicated areas of high wave energy. (Taken from Jellyman et al. 2008).

7.3.2 Potential locations within Te Waihora for FTW deployment

Depth ranges

Based on a normal recommended water depth for FTW of 0.8 m (minimum 0.6 m), we suggest a minimum anchoring depth of 1.0 m[10] at a lake level of 0.8 m a.m.s.l.

During an opening event, the lake level could reduce to 0.6 m a.m.s.l. while still providing a depth of 0.8 m beneath the FTW. This provides a further buffer of 0.2 m before reaching the minimum depth beneath the FTW of 0.6 m (which would only occur if the lake level falls below 0.4 m a.m.s.l.).

As noted above, a large wind seiche effect could reduce depth by up to 0.6 m., however, it is unlikely that such an effect would be sustained for sufficient time to desiccate plant roots or allow root systems of wetland plants to grow into the sediment. Potential degree of depth variation, as due to the various opening regimes summarised above would need to be taken into account in determining suitable anchorage systems for FTW in the lake.

Suitable locations

Based on the above limitations, potentially suitable sites within Te Waihora for FTW were extracted from GIS. These were based on:

- Areas within the lake between 1.0-1.2 m depths at 0.8 m a.m.s.l.
- Modelled wave heights of less than 0.35 m under both a predominant north-east and south-west wind (based on modelling results of Jellyman et al., 2008).

The selection of 0.35 m as maximum wave height was arbitrary, but was chosen as representative of lower wave energy areas.

Areas which meet these criteria have been shown in red on Figure 7-19. These areas are loosely similar to areas of the lake that previously supported submerged macrophytes (Miers & Williams 1969), except that macrophytes appear to have also colonised areas along the Greenpark Sands shoreline between the L2 and Halswell Rivers. Areas of suitable depth and wave height are identified in bays either side of the Selwyn River inflow, which is the dominant inflow into the lake, accounting for an estimated 29% of surface water nutrient load to the lake. Other areas marked are along the Kaitorete Spit, along the western shoreline, and near Kaituna Lagoon. Interception of inflows is possible in the vicinity of the L2 River and along the western shoreline.

Our analysis has identified 64 areas, totalling 71.5 ha area that are potentially suitable for deployment of FTWs (Figure 7-19). Based on the expected TN removal rates calculated in Section 5.2., this is ~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. This suggests that FTWs alone are unlikely to be able to achieve the desired water quality targets, but could be used to supplement lake edge and littoral zone wetlands.

[10] Minimum anchoring depth of 1.0 m and a maximum depth of 1.2 m.

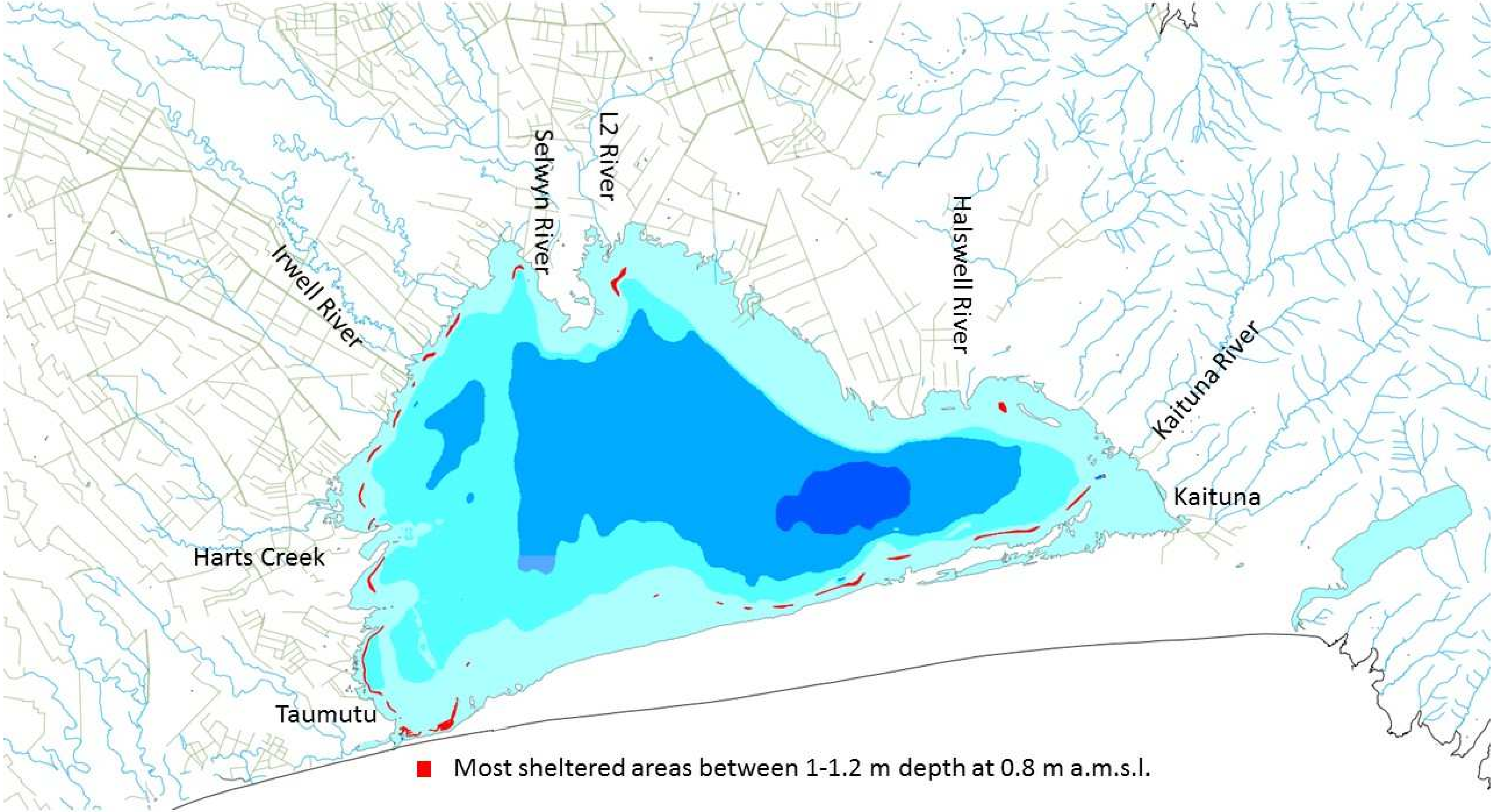

Figure 7-19: Map of potential locations for FTW (in red) based on area intercepts between depth criteria and modelled wave heights of <0.35m. Bathymetry increments shown as 0.5 m depth intervals from 0 m a.m.s.l. in increasingly darker shades of blue.

7.4 Ancillary benefits and disbenefits

Wetlands are well known for the water quality improvements they can achieve when degraded water passes through them. Within the wider context of the Te Waihora catchment, many areas that may previously have been permanent or ephemeral wetlands have now been drained (intentionally or unintentionally), thus creating valuable agricultural land, but at the expense of water quality remediation services. Below we summarise our assessment of potential benefits and disbenefits of either constructing surface-flow wetlands (Table 7-10) to reduce nutrient loads in surface inflows to Te Waihora, or deploying floating constructed wetlands within the lake (Table 7-11).

Weighing up the relative costs and benefits of the options proposed will require community deliberation. In many cases additional information will also be needed to quantify and properly evaluate the consequences and decide on the best way forward.

Table 7-10: Summary of benefits and disbenefits of surface-flow constructed wetlands treating lake inflows.

Benefits
Reduced nitrogen, phosphorus, sediment and faecal microbial loads reaching the lake.
Multiple contaminants able to be managed simultaneously.
Complement on-farm nutrient source reduction mitigations.
Low on-going operational and maintenance costs, while nutrient removal benefits are ongoing.
Sustainable, solar-powered systems not reliant on machinery or external energy-sources.
Can be used to target inflow "hot-spots"; highest contaminant concentrations and loads before they flow into the lake.
Excavated soil materials may be beneficially used to raise adjacent low-lying land to reduce drainage limitations and flooding risk, thereby providing compensatory economic benefits.
Increased shallow wetland swamp habitat for mahinga kai (eels, koura, fish and birds) and other cultural resources (harakeke, kuta, raupo, kapungawha).
Biodiversity enhancement with associated wildlife benefits, fish passage and spawning, and water bird habitat (Hefting et al. 2013; Strand & Weisner 2013; Thiere et al. 2009).
Potential recreational use (e.g., bird-watching, kayaking, hunting) where access and suitable facilities provided.
Enhanced landscape values and aesthetics. Provides for wider community involvement to achieve multiple benefits, including potential cost-sharing and voluntary assistance with planting etc.

Disbenefits
Cost of land acquisition or lease, or (where the area of land or water is in public or iwi ownership) foregone opportunity costs for the use of the land or lake (e.g., lost or changed economic, recreational or cultural values).
Cost of wetland construction and plant establishment.
Additional costs to maintain wetlands (e.g., cleaning of weirs and outlet structures, removal of sediment accumulating in sedimentation ponds, weed control especially during establishment, pest control).
Existing economic, social, cultural and ecological values of re-constructed remnant wetlands will be lost or changed. (e.g., high marsh converted into shallow swamp habitat, lake access and/or recreational uses changed).
Fish passage may be affected for some species.
Lake access may be compromised.
Drainage and flooding risk of some adjacent and upstream agricultural areas may be increased.
Possible elevated greenhouse gas emissions, although comprehensive analysis generally shows the net effect in practice to be either insignificant or beneficial (Burgin et al. 2013; Hefting et al. 2013; Hey et al. 2012; Thiere et al. 2011).

Table 7-11: Summary of benefits and disbenefits of FTWs deployed in the lake.

Benefits
Reduced nitrogen, phosphorus and sediment concentrations in the lake.
Potential to complement other lake remediation measures, managing internal as well as external lake nutrient loads.
FTWs can potentially remove twice as much nutrient per unit area as conventional land-based wetlands.
FTWs deployed in lake can complement on-farm nutrient source reduction and conventional wetland mitigations.
Multiple contaminants able to be managed simultaneously.
Use of lake areas in public and/or iwi ownership (rather than land) could markedly reduce land purchase or lease costs.
No excavation costs, unlike land-based surface-flow wetlands.
Low on-going operational and maintenance costs while nutrient removal benefits are ongoing.
Sustainable, solar-powered systems not reliant on machinery or external energy-sources. Floating mats can be constructed from recycled plastics.
Able to contend with fluctuations in water level in lake; rise and fall with lake level.
No impact on drainage and flooding risk within catchment.
Localised shading of algae, wave buffering and enhanced sedimentation may promote conditions suitable for inshore submerged macrophyte re-establishment.
Creates additional habitat for mahinga kai (eels, koura, fish and birds), plus refuges for zooplankton and fish.
Biodiversity enhancement with associated wildlife benefits, fish spawning and water bird habitat.
No fish passage restrictions.
Potential recreational interest (e.g., bird-watching, kayaking trails).

Disbenefits
Potentially suitable areas of lake limited. Less than 10% of the required area for 20% TN inflow load reduction appear to be suitable for FTW deployment.
Cost of artificial floating platforms is high per unit area relative to construction of conventional wetlands; For example, even allowing for land lease costs, Hamill et al. (2010) estimated FTWs would cost 5.5-fold more per kg of N removed from Lake Rotorua than land-based constructed wetlands, and cost nearly 10-fold higher per kg of P removal than land-based constructed wetlands.
Suitability and nutrient performance in exposed high energy environments has not been definitively demonstrated. Some doubt about winter nutrient extraction performance and plant survival, especially in areas prone to frosts. Potential need for further investigations and development.
Life-time of FTWs likely to be less than for conventional wetlands; Operational life-time of suitably constructed PET–based (Polyethylene terephthalate) floating mats expected to be ~10 years
Significant risk of damage to floating platforms, anchorage or moorings, vegetation, especially during big storms. Additional research and development may be required.
Suitable plant species for high-exposure, semi-saline habitat not tested. Additional research required.
Most trials to date relatively short-term; the sustainability of nutrient removal processes (e.g. need for plant harvesting to sustain plant vigour and optimise nutrient uptake) not fully resolved, and no data available to determine magnitude of net effects greenhouse gas emissions.
Localised depletion of dissolved oxygen may occur underneath FTWs with potential effects on aquatic life and P regeneration from underlying sediments; these considerations are likely to restrict the areal extent of FTWs able to be deployed in a given area of the lake.

8 Recommendations

Recent limit setting studies for Te Waihora predict a 50% decrease in the current load of both nitrogen (TN) and phosphorus (TP) is 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. The lake modelling predicts that TN loads may need to be reduced as low as 30% of current loads (i.e., 70% reduction) to enable the lake to “flip” back towards a submerged macrophyte dominated state. 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.

The results of the present study suggest that surface-flow constructed wetlands could achieve substantial reductions in inflowing nutrient loads to the lake providing reductions of TN in the range of 20–40%. Sediment and associated particulate P loads would also be markedly reduced. The treatment characteristics of surface-flow constructed wetlands are well-researched and similar approaches are widely used internationally for nutrient attenuation. Potentially suitable areas and locations for such wetlands appear to be available on the lake edge, or possibly in shallow littoral zones of the lake, sited predominantly near the mouths of major inflows to the lake. Thus surface-flow wetlands if widely implemented can be considered as a potentially viable means to achieve substantial reductions in TN loads to the lake. They also offer a wide range of ancillary benefits particularly for habitat creation and biodiversity enhancement. However, a range of potential disbenefits will also need consideration, and means to avoid or ameliorate them investigated.

FTWs deployed in the lake would appear to be capable of reducing loads by similar amounts, and require smaller areas than for conventional land-based wetlands. However, our analysis suggests that deployment of FTWs in the lake would only be practically feasible in less than 10% of the lake area required to achieve 40% TN reduction, given 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. Further research and field testing would be needed to resolve the engineering challenges involved with deployment of FTWs in the lake and identify suitable plant species able to deal with salinity fluctuations and levels of exposure. Large-scale field studies would also be recommended to quantify FTW treatment performance in-situ the lake and determine the most appropriate locations, size and layout of FTWs to generate optimal conditions for efficient nitrate-N removal via denitrification, whilst limiting potential negative consequences of localised deoxygenation of waters beneath the floating mats on aquatic life and phosphorus regeneration from underlying sediments.

Small-scale trials of FTWs in Te Waihora are already planned as part of a Whakaora Te Waihora funded study being carried out by NIWA and the University of Canterbury. Under this Ngāi Tahu and Environment Canterbury-led cultural and ecological restoration programme, the feasibility of re-establishing submerged macrophytes in the lake is being investigated. The use of wave barriers and floating treatment wetlands is being trialled as a means to create conditions conducive to reestablishment of transplanted submerged macrophytes in littoral areas of the lake. Although currently not addressing the nutrient removal capacity of FTWs, these trials will provide valuable information on emergent plant growth and survival in FTWs deployed in the lake, and the structural robustness of the FTWs to wind and wave conditions in the lake. Consideration should be given to extending the current monitoring programme for this trial to assess their impacts on in-situ nutrient removal (and possible regeneration processes) in the lake and associated physico-chemical conditions that occur beneath the FTWs.

Overall, we consider that surface-flow constructed or rehabilitated wetlands on the edge of the lake, in river/stream riparian zones, or targeting farm run-off offer the most feasible, low-risk options to achieve nutrient attenuation from surface inflows to Te Waihora. Although we consider the nitrogen attenuation rates predicted for surface-flow wetlands in the current study are reasonably robust, there is more uncertainty around P removal rates. Further consideration of the cost: benefit of such wetland options requires reliable estimates of the costs involved in their construction, planting and maintenance. Currently there is limited relevant information available on the costs involved in constructing wetlands of this scale in situations similar to those that occur around Te Waihora, where significant excavation is likely to be required. Also the potential payback from re-use of excavated materials to improve adjacent land experience needs to be assessed.

Areas of potentially suitable land near to priority inflows to Te Waihora need to be identified that could be suitable for potential development of wetlands. Conceptual wetland designs and construction methodologies then need to be prepared for 2-3 representative sites in the catchment and preliminary engineering investigations undertaken, utilising Lidar elevation data and relevant geotechnical information to enable realistic cost estimates to be determined. These would provide a reliable basis for preliminary cost:benefit comparisons with other mitigation options and sourcing of appropriate levels of funding.

Construction and comprehensive monitoring of a moderate to large-scale wetland targeting a priority nutrient inflow into Te Waihora would, in addition to providing confirmation of wetland nutrient removal performance under local flow and environmental conditions, also provide a real-world demonstration of a wetland designed for nutrient attenuation. Showcasing the range of cultural and ecological values able to be restored and/or created is likely to be particularly important in situations where existing values (despite having arisen under highly modified conditions) are significant, and risk being lost or compromised by creation of nutrient attenuation wetlands.

The available water quality data shows the Kaituna River, which drains from Bank's Peninsular into the northern end of the lake, exhibits a markedly lower relative load and flow proportional TN concentration than the other Te Waihora tributaries and is therefore not a priority in terms of wetland treatment for N removal.

In order of relative N load to the lake, the Selwyn River, Hart's Creek, L2 River and the Halswell River are priorities for N attenuation. All of these plus the Doyleston Drain, Boggy Creek, Hanmer Rd Drain and a range of unspecified small tributaries show elevated flow proportional TN concentrations. This suggests appropriately designed surface-flow wetlands could achieve substantial mass N load reductions from these flows. However, restricted dry season flows appear to be a potential challenge for wetland sustainability in the L2, Boggy Creek, and the Hanmer Rd Drains, and require further evaluation.

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10 Glossary of abbreviations and terms

a.m.s.l	Above mean sea level.
Chl-*a*	Chlorophyll-*a*, the primary photosynthetic pigment found in algae. Used as a measure of algal abundance.
DIN	Dissolved Inorganic Nitrogen. NH_4-N plus NO_3-N; the fraction of TN considered readily available for plant and algal uptake.
DRP	Dissolved Reactive Phosphorus. The fraction of TP considered readily available for plant and algal uptake.
FTW	Floating Treatment Wetland planted with emergent macrophytes.
k rates	A rate coefficient (for removal of a constituent) relative to its concentration.
macrophyte	A large macroscopic plant, includes emergent, submerged, free-floating and sprawling types.
NH_4-N	Ammonium nitrogen.
NO_3-N	Nitrate nitrogen.
TN	Total nitrogen.
TP	Total phosphorus.

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Appendix A Flow and water quality data for Te Waihora

Inflow hydrology

There are approximately 40 tributaries that convey surface water, nutrients and sediment to Te Waihora. The majority are small drains, some of which rarely flow. Volumetric flow data are available from permanent recorders or spot gaugings on at least one cross-section at 35 of the tributaries. Permanent flow recorders are located near Te Waihora on six of the largest tributaries:

- Hart's Creek @ Timberyard Road
- Doyleston Drain @ d/s Lake Road
- Selwyn River @ Coe's Ford
- L-2 River @ Pannett's Road
- Halswell River @ Ryan's Bridge
- Kaituna River @ Kaituna Valley Road

The flow recorders listed above are located 1-6 km from the lake shore (straight-line distance). Longitudinal changes in flow rates between the recorder and the mouth of each tributary are not known, but expected to be relatively minor. Flow time-series for each of the six recorders were acquired from Environment Canterbury. The six sites with recorders are also monitoring sites used in the Environment Canterbury (ECan) State of Environment (SoE) surface-water monitoring programme with nutrient data available for each site.

In addition to the six sites with recorders, there are ECan SoE sites near Te Waihora on three other tributaries that lack recorders, and nutrient data are available for these sites:

- Irwell River @ Lake Road
- Boggy Creek @ Lake Road
- Hanmer Road Drain @ Lake Road

For these three sites, flow-time series for the period 1 Oct 1994 – 31 Dec 2011 were prepared using the regression models in an ECan technical report by Horrell and Clausen (2007). While this time period is not as current at those used for the recorder sites, it was long enough to produce robust summary statistics.

Summary statistics for the nine sites listed above were calculated with TIDEDA software. Each summary statistic was calculated on an annual basis and a season basis, using the period 1 November - 30 April for the dry season and 1 May - 30 October for the wet season.

For the remaining 26 small tributaries that lack both flow recorders and nutrient data, but for which spot gauging data are available, we used the mean annual flow rates estimated for cross-sections near Te Waihora by Horrell and Clausen (2007). We grouped these sites into a single category, "small tributaries" and used the sum of their estimated mean annual flows. To estimate the seasonal flows from the small tributaries, we calculated the average proportions of the mean annual flow for the nine large tributaries that occur in the wet and dry seasons, and applied these proportions to the mean annual flow for the small tributaries.

Inflow nutrient loads

The nine SoE monitoring sites used in this report are sampled monthly by Environment Canterbury staff (Kelly et al. 2013). Concentrations of five nutrient variables are determined in water samples from each site, two forms of dissolved inorganic nitrogen, ammonium-nitrogen (NH_4-N) and nitrate-nitrite-nitrogen (NNN), total nitrogen in unfiltered samples (TN), dissolved reactive phosphorus (DRP), and total phosphorus in unfiltered samples (TP). The dissolved inorganic nitrogen (DIN) concentration in each sample was estimated as the sum of NH_4-N and NNN.

To ensure that nutrient data reflect recent conditions in the Te Waihora tributaries, ECan provided data for the period January 2007 to April 2014 (the latest date for quality-assured data). Data from some sites for the 2013-14 period had not been finalized by ECan database staff, so the ending dates varied among sites from February 2013 to April 2014.

Some nutrient concentrations were flagged in the raw dataset as “below detection limit” (BDL) with no value provided. When the number of BDL entries is small relative to the total number of concentration data for a given variable, the standard treatment is the replace the flag with a fabricated value equal to half the laboratory detection limit (0.5DL). In the water quality dataset used for the present study, the proportion of BDL entries was less than 10% of the total number of NNN, TN, DRP and TP concentrations for each tributary. However, the percent of BDL entries was larger for NH_4-N concentrations at some tributaries. This is a common occurrence because NH_4-N concentrations tend to be relatively low in low-elevation streams in New Zealand, and standard laboratory methods for NH_4-N are imprecise at low concentrations. The percent of BDL entries ranged from 4% in the Halswell River to 22% in the Selwyn River. In tributaries with large percentages of BDL entries, reported NH_4-N concentration were generally < 10% of NNN concentrations, indicating that replacing the flagged entries with 0.5DL would have little effect on subsequent estimates of DIN loading.

Seasonal nutrient concentrations were calculated by dividing the nutrient dataset into the same dry (1 November - 30 April) and wet (1 May - 30 October) seasons used for the flow data. Long-term and seasonal nutrient concentrations in the unsampled tributaries were estimated as the mean concentrations in sampled tributaries.

Annual and seasonal nutrient loading rates were estimated as the products of water input rates and mean nutrient concentrations for each tributary. Total annual and seasonal loads were estimated as the sum of the tributary loads.

Annual and seasonal mass loads to Te Waihora are summarised in. Note that, because masses have been derived from average flows and average nutrient concentrations for each season, annual values may differ from the sum of the two seasonal values. For the purpose of this report, these anomalies were not considered of sufficient magnitude to require deriving mass load data using a different technique. As can be seen by a quick comparison of annual nitrogen total load values in Table A-1 and Table 4-1, these differences only equate to a total of 5 tonnes, or less than 1%.

Table A-1: Annual and seasonal mass loads to Te Waihora (tonnes per annum or tonnes per season). For each group of cells, the annual mass load is in the upper cell, with seasonal mass loads (dry in the left cell and wet in the right cell) in the line below.

	NH_4-N		NNN		DIN		TN		DRP		TP	
Hart's Creek	0.8		267		267		281		0.9		2.4	
Per season	0.3	0.4	109	158	109	159	113	169	0.1	0.9	0.3	2.4
Doyleston Drain	0.3		17		17		21		0.3		0.5	
Per season	0.1	0.2	2	20	2	20	2	23	0.1	0.2	0.1	0.4
Selwyn River	1.4		455		456		482		1.8		8.5	
Per season	0.3	1. 1.3	94	354	94	355	98	381	0.4	1.5	0.4	11.7
L-2 River	1.6		263		265		281		1.8		2.9	
Per season	0.5	1.2	110	154	110	155	117	165	0.5	1.4	0.8	2.3
Halswell River	1.6		82		83		91		0.8		2.0	
Per season	0.4	1.3	31	51	31	53	34	58	0.3	0.6	0.5	1.6
Kaituna River	0.3		2		2		4		0.4		0.9	
Per season	0.1	0.3	0	2	0	3	1	4	0.1	0.3	0.2	0.6
Boggy Creek	0.2		38		39		44		0.3		0.5	
Per season	0.0	0.2	11	28	11	28	12	32	0.1	0.2	0.1	0.4
Hanmer Rd Drain	0.2		25		25		28		0.4		0.7	
Per season	0.0	0.2	4	24	4	24	4	26	0.1	0.3	0.1	0.6
Irwell River	0.8		24		25		30		0.7		2.2	
Per season	0.5	0.2	3	23	4	24	6	27	0.4	0.3	1.0	0.9
Small tributaries	1.2		129		130		144		1.3		2.8	
Per season	0.3	0.9	31	99	32	100	35	112	0.3	0.9	0.6	2.3
Total	8.5		1300		1308		1405		8.8		23.4	
Per season	2.5	6.1	394	914	397	920	421	999	2.3	6.7	4.2	23.3

Lake water quality

Key physico-chemical measures of lake water quality are summarised in Table A-2

Table A-2: Long term (since 1983) and recent short term (2011-2014) physico-chemical variables (mean ± standard deviation) recorded mid-lake.

Parameter	1983 - 2014	2011 - 2014	winter	spring	summer	autumn
Temperature (^{o}C)	13 ± 5	12 ± 5	7 ± 1	12 ± 2	18 ± 2	13 ± 4
Dissolved oxygen (%)	104 ± 9	104 ± 8	108 ± 8	103 ± 4	101 ± 7	103 ± 11
pH	8.3 ± 0.2	no data	no data	no data	no data	no data
Conductivity (mS/m)	1296 ± 588	1798 ± 671	1405 ± 566	1585 ± 325	2114 ± 624	2090 ± 850
Salinity (ppt)	7.1 ± 3.1	10.9 ± 4.3	8.3 ± 23.3	9.4 ± 1.8	12.9 ± 4.3	12.8 ± 5.5
Turbidity (NTU)	116 ± 85	109 ± 93	54 ± 34	99 ± 71	148 ± 69	132 ± 145
Secchi depth (m)	0.12 ± 0.05	0.13 ± 0.08	0.17 ± 0.10	0.15 ± 0.09	0.10 ± 0.03	0.12 ± 0.07
TSS (mg/L)	219 ± 135	154 ± 101	76 ± 39	140 ± 89	250 ± 94	150 ± 95