Technical guidelines for constructed wetland treatment of pastoral farm run-off

Prepared for DairyNZ

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DairyNZ and NIWA are working to develop a practitioner-focused version of these guidelines that incorporates feedback from a Technical Advisory Group and ongoing consultation with endusers and stakeholders

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Executive summary

This report has been produced as part of the INTERCEPTOR project – accelerating the uptake of constructed wetlands and riparian buffers, a joint initiative between DairyNZ and NIWA. This project aims to provide robust, science-based practical guidance and improved performance understanding to accelerate wide-scale implementation of constructed wetlands and targeted riparian buffers as tools for managing farm and catchment contaminant loads in New Zealand.

Constructed wetlands (CWs) are used internationally to reduce the losses of sediments and nutrients from agricultural landscapes into downstream waterways. They provide a practical tool that farmers can use, alongside other on-farm nutrient management actions, to minimise their environmental impact while maintaining profitability and productivity. This report is designed to form the basis for the preparation of practical guidelines for the use of CWs for treatment of runoff (both surface and sub-surface) from agricultural pastures. It was produced to provide sufficient guidance and certainty of expected contaminant reductions within CWs to enable farmers to incorporate this technology within farm nutrient management plans and for regulatory agencies to assess their expected efficacy.

An extensive review of New Zealand and international scientific literature regarding CW performance was undertaken in order to develop the sediment and nutrient reduction performance predictions that are presented in this technical guide. For the review, only CW sites with conditions broadly similar to New Zealand climatic and agricultural conditions were included in the data analysis. Results of the data analysis and derivation of performance graphs are presented in a companion document (Woodward et al., 2020). Performance expectations fall within bands which encompass the range of expected variability. Performance will vary due to factors such as the pattern and intensity of rainfall and run-off, and also from site to site depending on local conditions and specific CW design and implementation factors. Performance is determined principally by the size of a CW relative to its contributing catchment, but performance estimates have moderately high uncertainty arising from climate, landscape and design characteristics. For some specific contaminants and soil conditions or flow pathways where current data is seriously lacking and the uncertainty too high, we have restricted the applicability of our performance estimates.

The report provides guidance on procedures for the siting, preparation and construction of CWs appropriate for New Zealand farms. Plant species selection and procedures for planting, maintenance and care of the wetland are also outlined. Correctly designed, constructed, planted and maintained wetlands conforming to these guidelines should be able to achieve the contaminant reduction estimates provided.

1 Introduction and project brief

The project "INTERCEPTOR – accelerating the uptake of constructed wetlands and riparian buffers" is a joint initiative between DairyNZ and NIWA aimed at providing robust, science-based practical guidance for improved management of nutrients and sediment in agricultural landscapes. This includes gaining an improved understanding of, and confidence in, the expected performance of constructed wetlands. The intended outcome is that such guidance will facilitate appropriate wider-scale implementation of constructed wetlands resulting in significant reductions of contaminant loads in dairy catchments. This report addresses one of the key project aims: to develop constructed wetland performance criteria and design guidelines for use by landowners and regional councils. It is informed by a companion report which reviews the field-scale performance reported in the peer-reviewed scientific literature for constructed wetlands intercepting diffuse agricultural run-off and drainage flows (Woodward et al. 2020).

To address current knowledge gaps on constructed wetland performance, the project "INTERCEPTOR – accelerating the uptake of constructed wetlands and riparian buffers" also involves the establishment and monitoring of a range of constructed wetland systems across New Zealand to quantify and compare performance in different landscape and climate settings. It is planned to use this information as it becomes available to refine, validate and update the performance and design guidance currently proposed.

2 Purpose and limitations

This guide provides:

1. Recommendations for the design, construction and planting of surface-flow constructed wetlands to reduce contaminant loads from pastoral farms.
2. Performance predictions of reductions in sediment, nitrogen and phosphorus loads in constructed wetlands conforming to these recommendations.

The spatial scale of the pastoral landscape treated using CWs ranges from field-scale to small sub-catchment scale (i.e., <50 ha). While the principles for treating larger catchment areas and stream flows are similar, engineering requirements and risks, such as ensuring embankment integrity under flood flows and maintenance of fish passage, require specialist geotechnical, structural and ecological input and are beyond the scope of this document.

Every CW application and landscape, including geology, soils, climate and associated run-off characteristics, is unique. Additionally, wetland treatment performance is primarily driven at the scale of minutes and hours by the rate at which water and contaminants arrive, so that contaminant reduction performance (efficacy) is highly dynamic in time. Thus, even at a single site, performance will often vary across and between seasons and years in response to variations in rainfall intensity, duration and frequency.

Although much is known about how CWs function, quantitative data on their treatment performance at field and catchment scale over multiple years is sparse. This is particularly so for pastoral land-uses and for climates similar to New Zealand's. These technical guidelines are, therefore, based on the expert opinion of those working on CWs in New Zealand together with analysis of the available international data (Woodward et al., 2020). Estimates are provided for the reductions of sediment and nutrient expected under New Zealand conditions for wetlands comprising between 1% and 5% of their contributing catchment areas.

The generalised guidance provided in this document needs to be adapted to local site conditions and applied judiciously, incorporating local knowledge, and appropriate experience and expertise (see Section 6.1 for discussion of council rules).

3 Why surface-flow constructed wetlands?

There are three main types of constructed wetlands: i) surface-flow wetlands; ii) sub-surface flow wetlands; and iii) floating wetlands. Surface-flow or free-water-surface wetlands are the most appropriate type for treating agricultural runoff[1]. As the name suggests, water flows across the surface of the wetland soil through beds of emergent aquatic plants such as sedges and bulrushes (see Figure 1). Surface-flow constructed wetlands generally comprise channels or a series of vegetated shallow impoundments and operate similarly to natural swamps and marshes.

Surface-flow CWs are the simplest and lowest-cost type of wetland to construct, and their ability to remove sediments and nutrients long-term from diffuse agricultural runoff is well established (Woodward et al., 2020). Their simplicity, robustness under highly variable flow conditions, and ability to cope with sediment loads make them widely applicable across a range of farm types and landscapes.

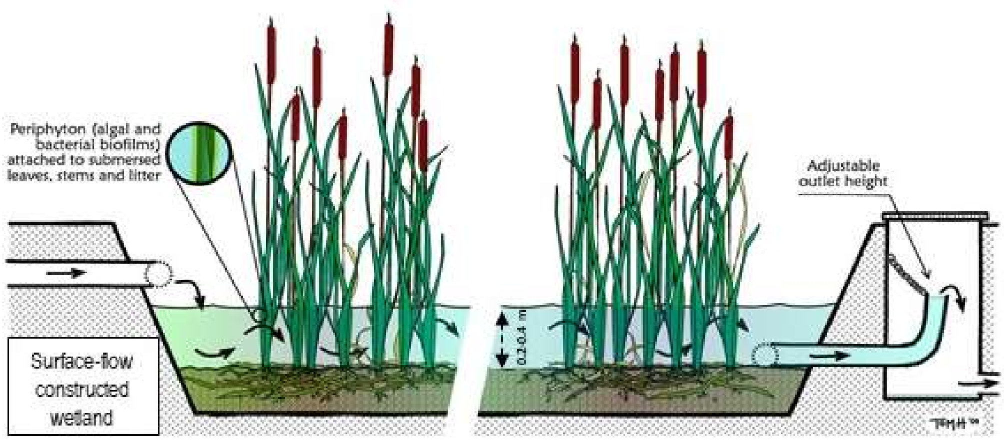

Figure 1: General characteristics of a surface-flow constructed wetland. Deeper, open-water areas are also recommended to redistribute flow, provide re-aeration and increase sunlight exposure to promote inactivation of faecal microbes.

[1] The other major types of wetland are: 1) Sub-surface flow wetlands, where water flows horizontally or vertically through porous sand or gravel beds vegetated with emergent wetland plants (i.e. below the surface); and 2) Floating treatment wetlands, where water flows through the roots of emergent wetland plants supported on floating mats. These wetlands are generally more expensive to construct and less suited to highly variable diffuse agricultural flows and contaminant loads. Sub-surface flow wetlands in particular are vulnerable to clogging by suspended sediments, while floating treatment wetlands require relatively expensive floating platforms and do not cope well with extended dry periods during the year (e.g. droughts). These alternative types of wetland are not dealt with in this guideline.

4 Types of runoff and contaminants

A surface-flow constructed wetland can treat flows entering it from a range of sources. These include storm-generated overland flow (surface runoff), sub-surface (tile) drains, open drainage channels, and small streams or creeks. The advice provided in these guidelines is only relevant to small-scale, edge-of-field and sub-catchment situations; that is, discharge from drains or streams of first-order or less, involving waterways generally smaller than one metre wide and 0.3 m deep at base-flow. Generally, this means catchments no larger than about 50 ha in extent.

In general, runoff arriving at a constructed wetland from surface sources (drains or overland flow) will carry a large proportion of contaminants in particulate forms, including soil particles, plant litter and/or dung mobilised from the soil surface. In contrast, runoff arriving from sub-surface sources (tile drains or groundwater seeps) will mostly carry dissolved contaminants such as nitrate and phosphate. The presence (or absence) of sediment in inflow water has implications for design of CWs, namely the potential need for an initial sedimentation pond to trap and remove coarse sediment.

5 Wetland contaminant reduction processes

Wetlands reduce sediment and nutrient loads in farm run-off by a range of physical, chemical and biological processes. Hydrology (the flow characteristics and quantity of water entering the wetland) and hydraulics (the uniformity and path of water flow through the wetland) are crucial to the sustainable functioning and contaminant reduction performance of CWs. Flow should be dispersed evenly across the wetland cross-section, minimising short-circuiting and preferential flow, which can markedly reduce retention time and treatment performance. To achieve this, elongated or multi-stage wetlands are required, providing a long flow path between the inlet and outlet. Deeper open-water areas at the inlets and at defined regions within the wetland can help slow and disperse flows through shallower zones of emergent wetland plants.

Water depths of around 0.3 m are needed (0.2-0.4 m) for establishment and survival of dense growths of emergent vegetation over the majority of the wetland (i.e. >70% coverage). Deeper open water zones (>1 m) help disperse flow across the width of the wetland. These zones need to be sufficiently deep (typically 0.5-1.0 m) and large to prevent colonisation by emergent plants (e.g. rushes, sedges) and encroachment by sprawling plants (e.g. water cress). Where inflows receive run-off and drainage containing suspended sediments, sedimentation ponds (1.0-1.5 m deep) are required at the wetland inlet to capture coarse particulates with periodic mechanical removal of accumulated sediment. This is especially important where the wetland receives run-off with high suspended sediment loads from farm races, forage cropping, and areas impacted by livestock pugging.

Sedimentation ponds and open-water zones can help disperse flows and trap sediments.

5.1 Reduction of nitrogen

Nitrogen (N) is removed by several processes, the most important of which are the microbial processes that convert dissolved inorganic nitrogen (nitrate-N and ammoniacal-N) into nitrogenous gases. This is carried out by bacteria and fungi which are naturally present in wetland environments. By comparison, uptake of dissolved inorganic nitrogen by plants (including algae) is a relatively small sink in most wetlands. Plants, however, are important in the overall functioning of wetlands, because they are the main source of carbon (i.e. energy) fuelling microbial denitrification. Nitrate reduction rates in constructed wetlands via denitrification may continue to increase for several years after its construction as organic matter gradually accumulates in the wetland sediments. Denitrification (and also plant uptake) rates generally increase with increasing temperature, so wetland N reduction rates are typically higher in warmer climates.

5.2 Reduction of suspended sediment and phosphorus

Suspended sediment and particulate-associated phosphorus are predominantly removed by settling and deposition. Larger or denser particles (e.g. sands and soil aggregates) will deposit in inlet zones, while finer particles (silt and clay-sized particles) will be dispersed through the wetland where they may be removed by adhesion to biofilms (microbial slimes) that grow on the surfaces of plants and detritus in the wetland, and by flocculation processes. Very fine unaggregated clay particles are extremely slow to settle, requiring long residence times, so their reduction in CWs is limited.

Readily available dissolved forms of phosphorus (i.e. dissolved reactive phosphorus, DRP) can be removed by adsorption to sediments and organic matter, and through uptake by algae and plants. However, when the algae die or plant leaves fall and degrade in the wetland, much of this phosphorus may be released. A small proportion becomes trapped in the organic matter that accumulates in the bottom of the wetland. As wetlands mature, net retention of DRP can reduce as uptake by plants reduces to low levels (because of recycling of P accumulated within the wetland and reduced plant growth rates), and retention of particulate forms becomes the dominant long-term reduction mechanism. It is, therefore, important to periodically remove the P-containing sediments that accumulate in the influent zones of the wetland, to maintain trapping efficacy and reduce the risk of remobilisation during high flows or through decomposition and release of soluble P.

There are many different interacting processes that contribute to suspended solids and nutrient reduction in constructed wetlands. As a result, their design and construction must take into account not only individual site factors, but also the key contaminants that are important in the particular landscape and type of flow pathways being intercepted.

6 Wetland design

6.1 Rules and regulations

Before undertaking any excavation work, always check with your local council on regulations regarding earthworks in and around natural waterways and wetlands. Councils generally have rules regarding the height of embankments and dams, the size of the catchment impounded and the total volume or area of earthworks. Fish passage may also need to be maintained where areas of suitable habitat occur upstream. Specific consent may be required under the Resource Management Act (1991)[2] and dam provisions of the Building Act (2004)[3]. It is important to seek advice from appropriate regulatory agencies (generally regional or territorial councils) before any earthworks commence.

Check rules, regulations and permit requirements with your regional council

6.2 Location

Choosing an appropriate site to construct a wetland will depend on where natural or engineered flow pathways can best be intercepted, as well as land availability and productive value. Highest contaminant reductions will generally be achieved by targeting areas of elevated contaminant discharge and by maximising the proportion of discharge able to be captured. Figure 2 shows a range of constructed wetland configurations for sites where surface and sub-surface drains flow directly into stream channels.

CWs are often best located in natural swales, depressions and gullies that provide the dominant pathways for water flow (and associated contaminant loads). These areas also provide suitable landforms to contain the wetland with minimal excavation and earthmoving, and are often of lower agricultural value. In addition, channel straightening and realignment activities often create channel cut-offs and meanders which prove difficult to properly drain. These patches of low-productivity land can provide good sites for wetland construction with minimal impact on pasture production.

CWs can be built at the base of ephemeral watercourses and drainage networks where flow is intermittent, or further downstream where flows are more consistent. They can either be constructed directly in the flow path (in-stream; e.g. by modifying open drains to convert them into wetlands), or alongside the flow path (off-stream; e.g. to minimise damage to a natural stream channel) (see

Figure 3). An off-stream wetland can be engineered to accept the majority of flow during normal flow conditions while allowing a proportion of the water to bypass the wetland during higher flow periods, passing along the existing stream channel. This approach provides more consistent flows to the wetland, allows fish passage along the existing stream channel, and minimises damage to the

[2] RMA (1991) http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html
[3] Building Act (2004) http://www.legislation.govt.nz/act/public/2004/0072/latest/DLM306036.html

wetland during flood flows. However, any water that does not pass through the wetland will not be treated.

On-stream wetlands, which are subject to flood flows, will require provision for routing flood-flows around the wetland or through an internal flow-way to reduce damage to the wetland. Wetlands receiving flood flows may require more frequent maintenance and replanting and rehabilitation after large flood events.

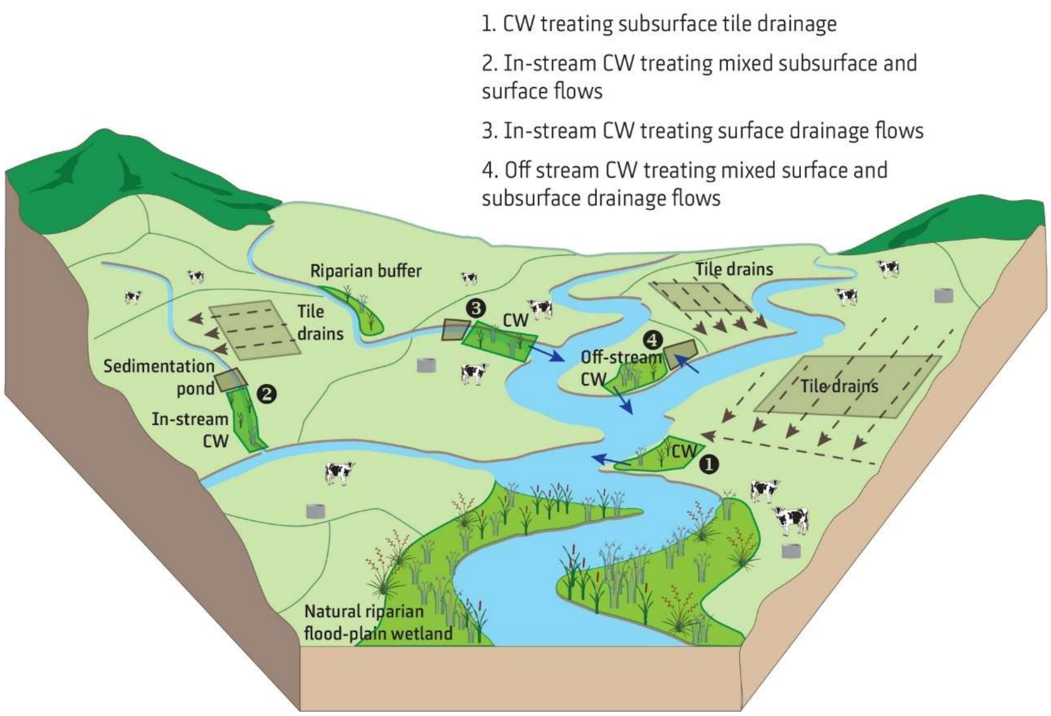

Figure 2: Potential locations of surface-flow constructed wetlands intercepting run-off and drainage flows in a pastoral catchment.

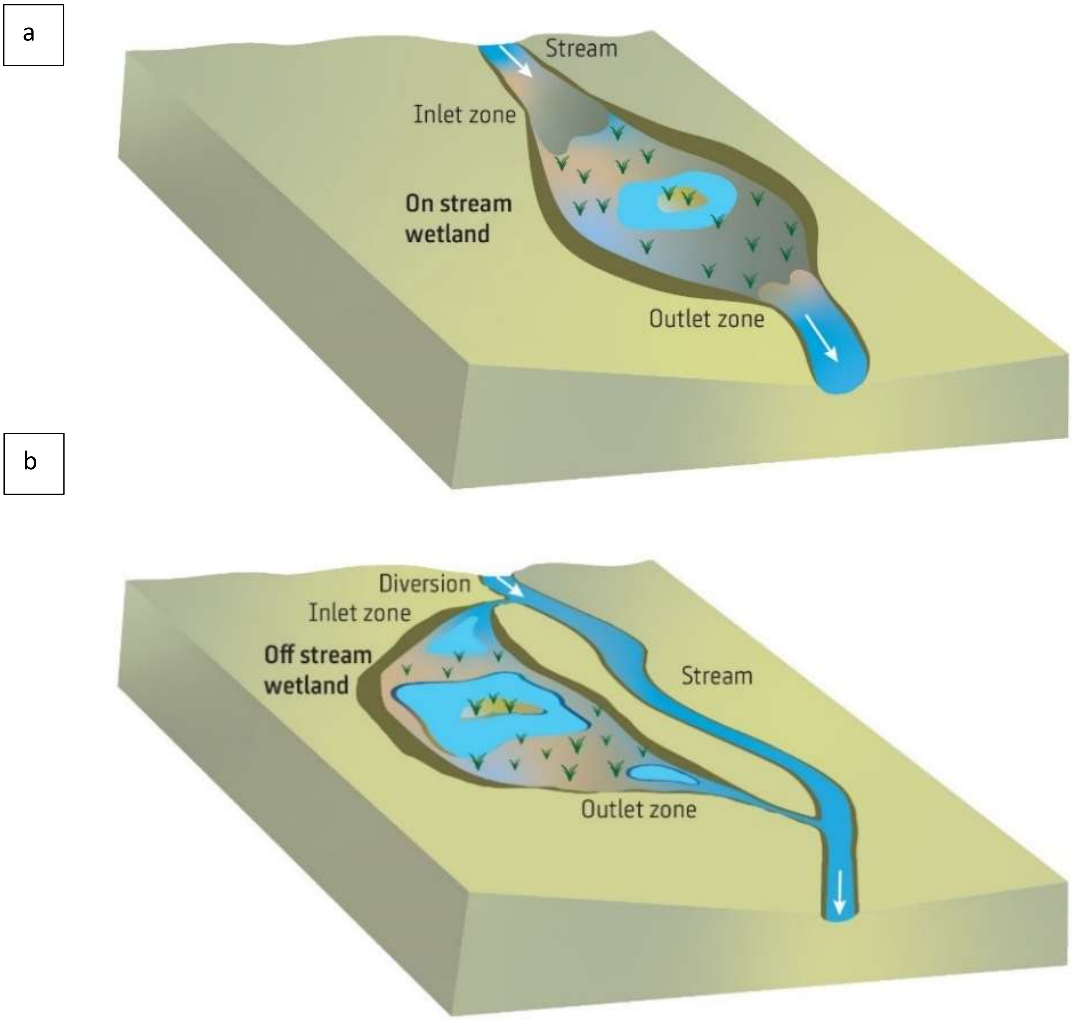

Figure 3: Comparison of (a) on-stream and (b) off-stream (parallel to the channel) treatment wetlands.

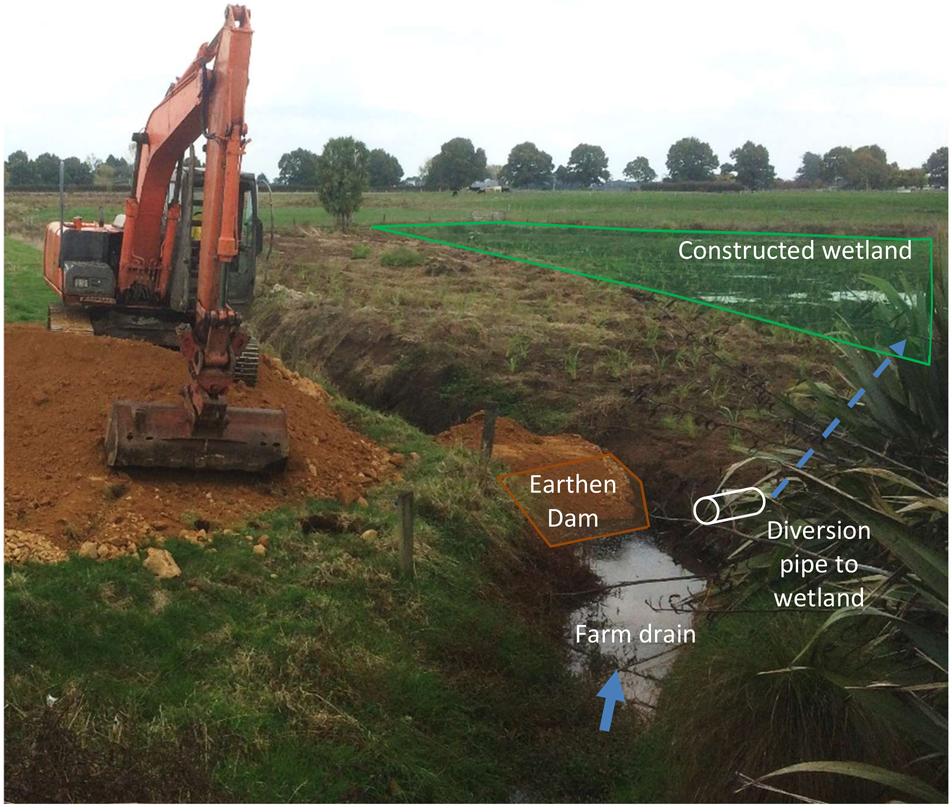

Figure 4: An off-stream wetland (in background) being connected to flow from a drain. An earthen dam (to be armoured with geotextile) has been constructed to block the existing drain. A pipe will be installed to divert the impounded water to the constructed wetland. Another pipe will be installed further downstream to feed this water back to the drain after passage through the wetland. Excess storm flows can still flow over the dam and down the drain.

6.3 Wetland sizing

Generally, contaminant reduction efficacy increases as constructed wetland area increases, but subject to gradually diminishing returns (see section 6.4 for performance estimates in relation to wetland size). Wetlands intercepting agricultural runoff and drainage flows need to be between 1% and 5% of their contributing catchment (i.e. 100-500 m^2 of wetland per ha) to significantly reduce contaminant loads. Wetlands smaller than this will provide insufficient residence time to enable contaminant reduction and, unless they have a high flow bypass, will be frequently overwhelmed by stormflows. The wetland sizes proposed refer to the actual wetted area under normal flows. They do not include the additional areas required for embankments or marginal plantings. Note that the wetland areas and associated performance estimates in this document refer to the actual wetted area at normal flow incorporating, where necessary, an initial sedimentation pond occupying up to 20% of the wetland area. Area taken up by any associated bunds, embankments and riparian plantings are additional.

While the wetland sizing guide is applicable to the majority of catchments, some locations may require site specific considerations. Where the contributing catchment is larger or smaller than the apparent surface catchment, CW design will need to be tailored to accommodate the actual flows entering it. This may require measurement of existing drain flows to determine appropriate wetland size and predict consequent contaminant reductions, which is outside the scope of the present guidelines.

Size wetlands so that they occupy 1-5% of their contributing catchment area

6.3.1 Predicted wetland contaminant reduction

The performance of constructed wetlands depends to a large extent on the retention time of water within the wetland. This is influenced by the size of the wetland relative to its inflow, and how uniform the flow is as it passes through the wetland. The evenness or efficiency of flow distribution through the wetland is primarily determined by its internal design and distribution of emergent vegetation. In general, to maximise nutrient reduction it is important to maintain the majority of the wetland in shallow planted zones for microbial/plant induced attenuation. Deeper zones target sediment removal and promote an even flow distribution as outlined above[4]. Nutrient reduction processes are also affected by temperature, so performance will vary seasonally and for different climatic regions.

Flows of diffuse agricultural run-off are highly variable from day-day, season to season and year-to-year, so wetland treatment performance will vary according to the frequency, intensity and duration of rainfall and how this interacts with soils, slopes and vegetation across landscapes to generate run-off, drainage flows, and contaminant loads.

The performance of different sized CWs relative to the size of their contributing catchments was assessed by Woodward et al. (2020) using information derived from local and international field-scale monitoring and modelling studies. This information was integrated with expert opinion to derive contaminant reduction estimates for CWs. These estimates were further refined to generate conservative guidelines of long-term performance for appropriately designed, constructed, vegetated and maintained wetlands. They assume typical New Zealand pastoral farming conditions and management practises. They apply only to flat to rolling landscapes (average slopes of 15 degrees or less)[5], and to regions with annual rainfall of 800-1600 mm. They do not apply to areas with highly permeable soils where groundwater is the dominant flow pathway[6]. Some additional limitations are noted below for specific contaminants and flow pathways.

[4] Attempting to increase the wetland residence time by excessive use of deep zones will reduce the effectiveness of nitrogen reduction process which rely on good plant production of leafy material for denitrification as well as oxygen transfer through the water surface for nitrification.

[5] Note that suitable sites for wetland construction will normally require slopes < 7°.

[6] Highly permeable soils limit opportunities for interception of contaminants transported in groundwater and generally provide insufficient reliable flow to sustain wetland vegetation and function.

Sediment

Figure 5 shows the expected long-term performance estimates for reduction of suspended sediments by well-constructed and maintained CWs built according to the guidelines outlined in this report. The solid line defines the 'most likely' performance for different relative wetland sizes. This line indicates that wetlands occupying 1% and 5% of their catchment area should, on average, remove 50% and 90% respectively of the long-term average sediment input. The shaded areas show the expected range of long-term median performance.

Sediments transported in drains or overland flows (e.g. off raceways) will comprise a range of size fractions from fine clays, to sands to larger aggregates of soil and clumps of dung. High intensity rain events will transport large particles, while low intensity events will only transport medium to fine particles. The estimates for reduction are based on annual performance of wetlands, thus during high intensity events when lots of large particles are mobilised, high reduction rates will occur, but only for the coarse particles. In contrast, during less intense events, less sediment will be mobilised, but a greater fraction of finer particles will be transported as flow velocity will be lower. There is insufficient information regarding the potential for reduction of very fine particles in constructed wetlands to enable reliable predictions to be made at this stage. These performance estimates are therefore only applicable to catchments not dominated by clay soils (i.e. < 35% clay content).

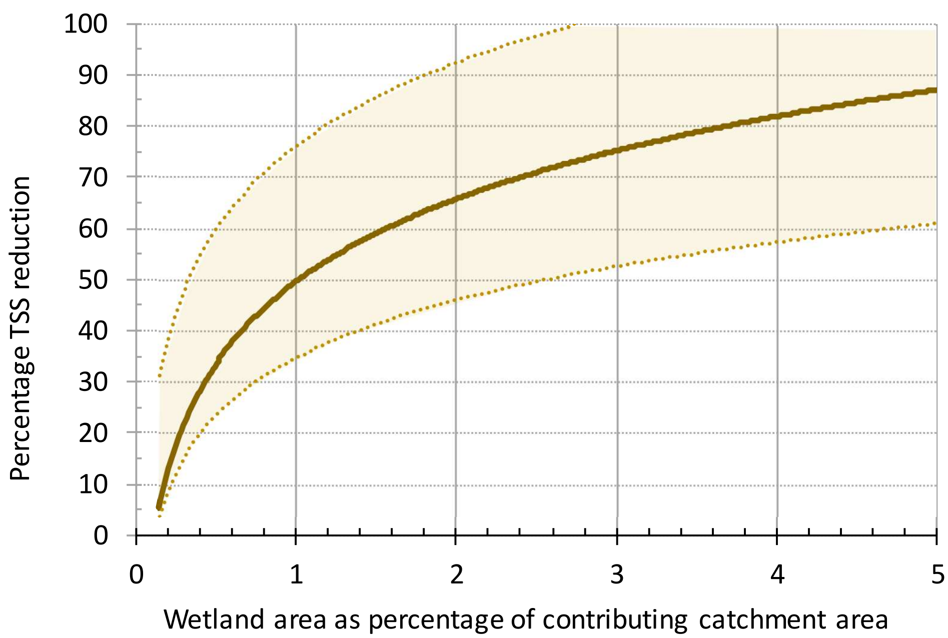

Figure 5: Long-term median annual performance expectations for reduction of Total Suspended Solids. Performance is for appropriately constructed wetlands receiving run-off and drainage from pastoral farmland in New Zealand. Not applicable to areas with clay soils (≥35% clay content) or catchment rainfall outside NZ norms as noted in the text. Solid line shows expected median. Shaded area shows expected range of performance.

Nitrogen

Nitrogen in agricultural runoff and drainage is most likely to be present as dissolved nitrate-N. This is primarily removed in CWs via biological processes (microbial denitrification and plant uptake). Reduction rates generally decrease as temperature decreases. Different performance estimates are, therefore, provided for warm (median annual air temperatures ≥12°C) and cool regions (median annual air temperature 8-12°C) of New Zealand (Figure 6). Median long-term annual temperatures across New Zealand (1981-2010) are presented in (Appendix A) for guidance.

Figure 6 shows the expected long-term performance estimates for reduction of total nitrogen by well-constructed and maintained CWs built according to the guidelines outlined in this report. The solid lines define the 'most likely' performance for different relative wetland sizes in warm and cool regions of New Zealand. They show that wetlands occupying 1% and 5% of their catchment area should, on average, in warm regions remove 24% and 52% respectively and in cool regions 18% and 38% respectively of their long-term average TN inputs. The shaded areas show the expected range of long-term median performance.

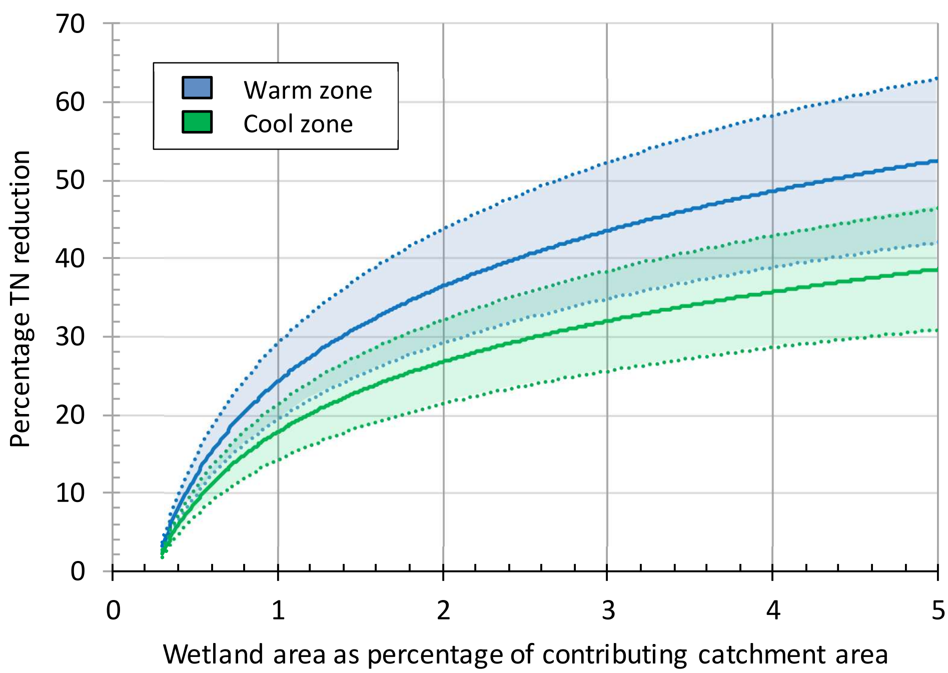

Figure 6: Long-term median annual TN reduction performance expectations. Performance is for appropriately constructed wetlands receiving run-off and drainage from pastoral farmland for warm (median annual temperature >12°C) and cool (median annual temperature 8-12°C) climatic zones and with catchment rainfall within New Zealand norms. Solid lines show expected medians for each zone; shaded areas show range of performance expected.

Phosphorus

Performance estimates for reduction of Total Phosphorus (Figure 7) are applicable to constructed wetlands receiving run-off and drainage flows where P is predominantly associated with particulates (sediments), and in catchments not dominated by clay soils (i.e. < 35% clay content). Figure 7

Figure 5 shows the expected long-term performance estimates for reduction of Total Phosphorus by well-constructed and maintained CWs built according to the guidelines outlined in this report. The solid line defines the 'most likely' performance for different relative wetland sizes. It indicates that wetlands occupying 1% and 5% of their catchment area should, on average, remove 26% and 48% respectively of the long-term average TP input. The shaded areas show the expected range of long-term median performance.

Phosphorus mobilised in sub-surface drainage is mainly in dissolved forms and its reduction by CWs is generally low, can be highly variable and is not covered by these guidelines. New Zealand studies at three sites have shown the potential for dissolved P release from within the CW when P-rich agricultural soils are used as growth media for the wetland plants (Ballantine and Tanner, 2010; Tanner and Sukias, 2011) – so soils with low potential for P release should be selected for use as growth media in the base of wetlands (see Section 7).

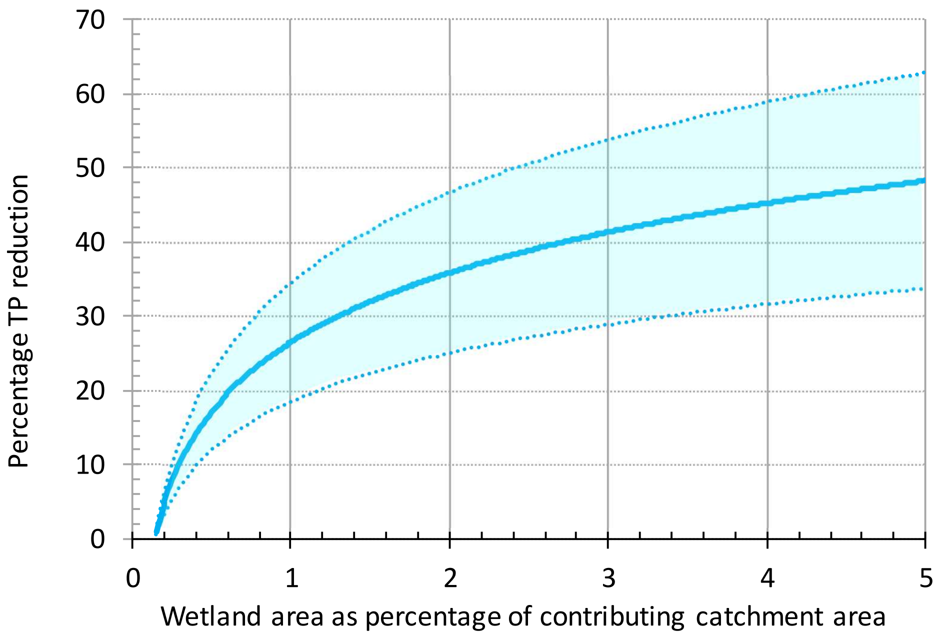

Figure 7: Long-term median annual TP reduction performance expectations. Performance is for appropriately constructed wetlands receiving run-off and drainage from pastoral farmland in New Zealand with catchment rainfall within New Zealand norms. Solid line shows expected median; shaded area shows range of performance expected. These performance predictions do not apply for constructed wetlands whose main source is sub-surface drainage containing predominantly dissolved forms of phosphorus, or where soils comprise ≥35% clay.

6.4 Constructed wetland shape

Wetlands can be constructed as simple rectangles or shaped into curved structures that better mimic nature. Uniform flow distribution across the full width of a wetland (i.e. no preferential flow paths or 'short circuiting'), and consequent contaminant reduction performance, is improved where the overall length to width ratio of the wetland channel is between 5:1 and 10:1 (i.e. 5 to 10 times longer than it is wide, see Persson et al., 1999; and Su et al., 2009 for details). The length to width ratio should not be less than 3:1.

Constructed wetlands may comprise a single elongated channel or a series of smaller cells which flow from one into the next. Length to width ratios and shapes can be varied within the range specified above to fit with the landscape and surrounding farm activities. Land slope and site characteristics will generally dictate whether a single or multi-stage wetland is preferable. It is generally more practical to build a series of smaller wetland cells down a slope, keeping the fall between each cell to no more than ~1-2 m to avoid the need for large bunds/embankments and extensive excavation. Where an embankment must be constructed between modules, this should be constructed using well-compacted subsoil with a high clay content keyed into the substrate beneath.

It is important that slopes on the edges of sedimentation ponds and wetlands are not too steep, creating the potential for erosion and bank collapse. Local excavator operators will generally be familiar with the soil characteristics in your locality and can offer advice. Unless there is evidence that slopes can be steeper, we recommend slope be no more than 2:1 (length: height).

Constructing a wetland in low-gradient areas with intensive networks of surface and/or sub-surface (tile) drains, while retaining effective drainage functioning, will generally require excavation of the wetland base below the depth of the drainage network.

Wetlands, either continuous or multi-celled, perform best when the overall length to width ratio is between 5:1 and 10:1

6.5 Constructed wetland components

6.5.1 Sedimentation ponds

Where constructed wetlands receive surface inflows and associated sediment loads (even infrequently during large storm flows), sedimentation ponds are recommended as the first stage to capture coarse sediments. This will minimise sedimentation and infilling of the shallow vegetated zones of the main wetland, thereby prolonging their effectiveness in removing other contaminants. Accumulated sediment needs to be mechanically removed periodically from the sedimentation pond, so that it never occupies more than half of the original pond depth.

Sedimentation pond size (either as a separate pond or a sediment trap area within the main wetland) is dependent on peak flows that the pond is likely to experience during a storm event. A detailed explanation of sizing criteria is provided in Appendix B. In the absence of specific local rain intensity data, sedimentation ponds should be sized based on the ratios proposed in the following table. For the purpose of estimating treatment performance, initial sedimentation ponds occupying up to 20% can be considered an integral part of the wetland area. If the initial sedimentation pond area exceeds 20% then this additional area needs to be considered as supplemental to the wetland area for estimating performance.

Table 1: Sedimentation pond sizing.

Regional rainstorm intensity (Region)	Sedimentation pond size (m^2 per ha of catchment)
Low intensity (Otago, Southland, Manawatu-Wanganui, Canterbury, Wellington)	40
Medium intensity (Waikato, Marlborough, Taranaki, Auckland, Hawkes Bay)	60
High Intensity (Nelson, Northland, Tasman, Bay of Plenty, Gisborne, West Coast)	80-100

General principles for construction of a sedimentation pond are based on the coarse sediment trap guidelines (Hudson, 2002).

Depth: Sedimentation ponds should be excavated to a depth of 1.5 m below the outlet level.

Width: In general, a sedimentation pond will be constructed using the same type of excavators as will be used to empty them in the future. Thus, width is limited to the reach of the excavator (7.7 – 8.5 m). Where a wider sedimentation pond is required, it can be excavated from both sides (or from within the pond if it dries out sufficiently in summer), although this can make sediment removal problematic.

Length: The length of a sedimentation pond should be greater than its width. Where the required length of a pond is greater than 5 times the width, it is recommended that multiple ponds be constructed in series.

6.5.2 Shallow vegetated wetland zones

The majority (~70%) of a constructed wetland and, in particular, the final 20% of the wetland, should be shallow and densely vegetated. A water depth of 0.3 m is ideal for most emergent wetland plant species, although a mix of shallow (0.10-0.25 m at the wetland margins) and slightly deeper zones (0.35-0.40 m) can be used to provide habitat for different wetland plant species allowing for a more diverse plant selection.

Specific details regarding this zone can be found in Section 7, but briefly, it should have a (200-300 mm) base layer of mixed topsoil and sub-soil as a planting medium for the wetland plants. As noted above, it is important to avoid using high-P soils as a planting medium because they may release DRP. Embankment slopes should be similar to those in ponds (2:1 length: height ratio unless local conditions permit steeper slopes).

6.5.3 Deep open-water zones

Regardless of whether a wetland is receiving surface or sub-surface runoff, deep open-water zones (0.5-1.0 m) within the wetland provide various benefits to wetland functioning. Deep zones are used to encourage water to spread across the full width of the shallow downstream parts of the wetland, thus reducing flow channelization and encouraging flow into all areas of the wetland including corners, especially if it is square or rectangular in shape.

Because of their depth, these zones generally remain unvegetated. They can be an attractive feature of a wetland, enhancing aesthetics and biodiversity by providing a mixture of different habitats.

Because deeper zones have less resistance to flow, they should generally be aligned across the flow path of water (i.e. across the width of the wetland) unless they are being used to direct flow into a low flow zone (e.g. around the outer edge of a corner. See the 'hairpin' wetland in following diagrams). As with all zones, embankments should be sloped to prevent bank collapse (discussed above). These deeper zones (which are separate from the sedimentation pond at the inlet) should comprise no more than 30% of the wetland area and not be located in the final ~20% of the wetland.

Deeper open-water zones orientated across the width of the wetland encourage good flow dispersion

6.6 Constructed wetland configurations

The three key components of constructed wetlands: 1) sedimentation ponds, 2) shallow vegetated and 3) deep open water zones, need to be integrated into a treatment train. The following figures provide an overview of the most common configurations recommended for various situations (Figure 8-Figure 12). Note that there may be a range of suitable wetland configurations depending on site slope and available area.

6.6.1 Low gradient sites (0-3°slope)

Option 1a: Sub-surface drainage (negligible sediment input; focus is on N reduction)

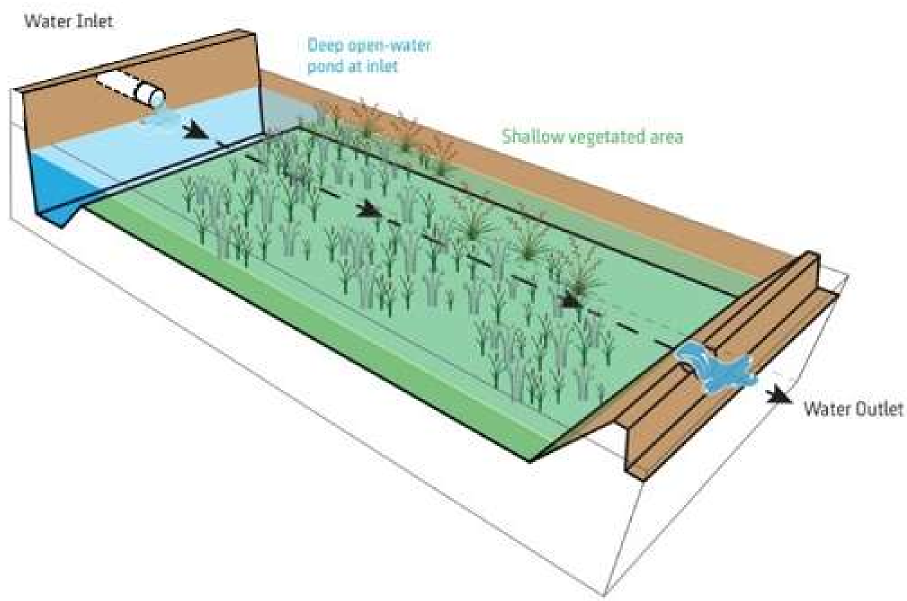

Figure 8: Option 1a: Elongated wetland channel receiving sub-surface tile drainage. This simple design is appropriate for low gradient sites (0-3° slope) with where the primary focus is on N reduction and the input is from a tile drain (i.e. with negligible sediment inputs). There is an initial deep zone to aid spreading of flow across the full width of the wetland. This is then followed by a shallow fully vegetated zone (≥70 % of area) promoting microbial denitrification and plant uptake.

Option 2a Surface and mixed flows (including significant sediment and associated nutrients)

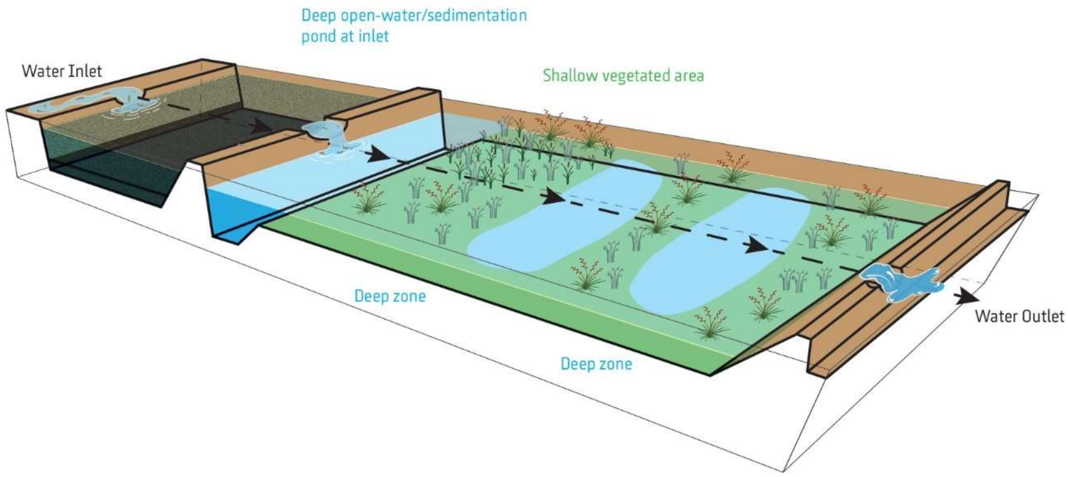

Figure 9: Option 2a: Elongated wetland channel with multiple open-water deep zones receiving surface and mixed flows. This design is suitable for a low gradient site (0-3°) where there is some sediment load to the wetland. The initial sediment pond will capture much of the coarse sediment and associated nutrients. In the main wetland area, there is an initial deep zone to aid spreading of flow across the full width of the wetland followed by alternating shallow vegetated (~70% of area) and deeper open-water zones where microbial processes, plant uptake and sorption processes reduce nutrients. Note that the deep zones need to be orientated across (rather than along) the channel to avoid short-circuiting of flow.

Option 2b Surface flows (including significant sediment, alternative configurations)

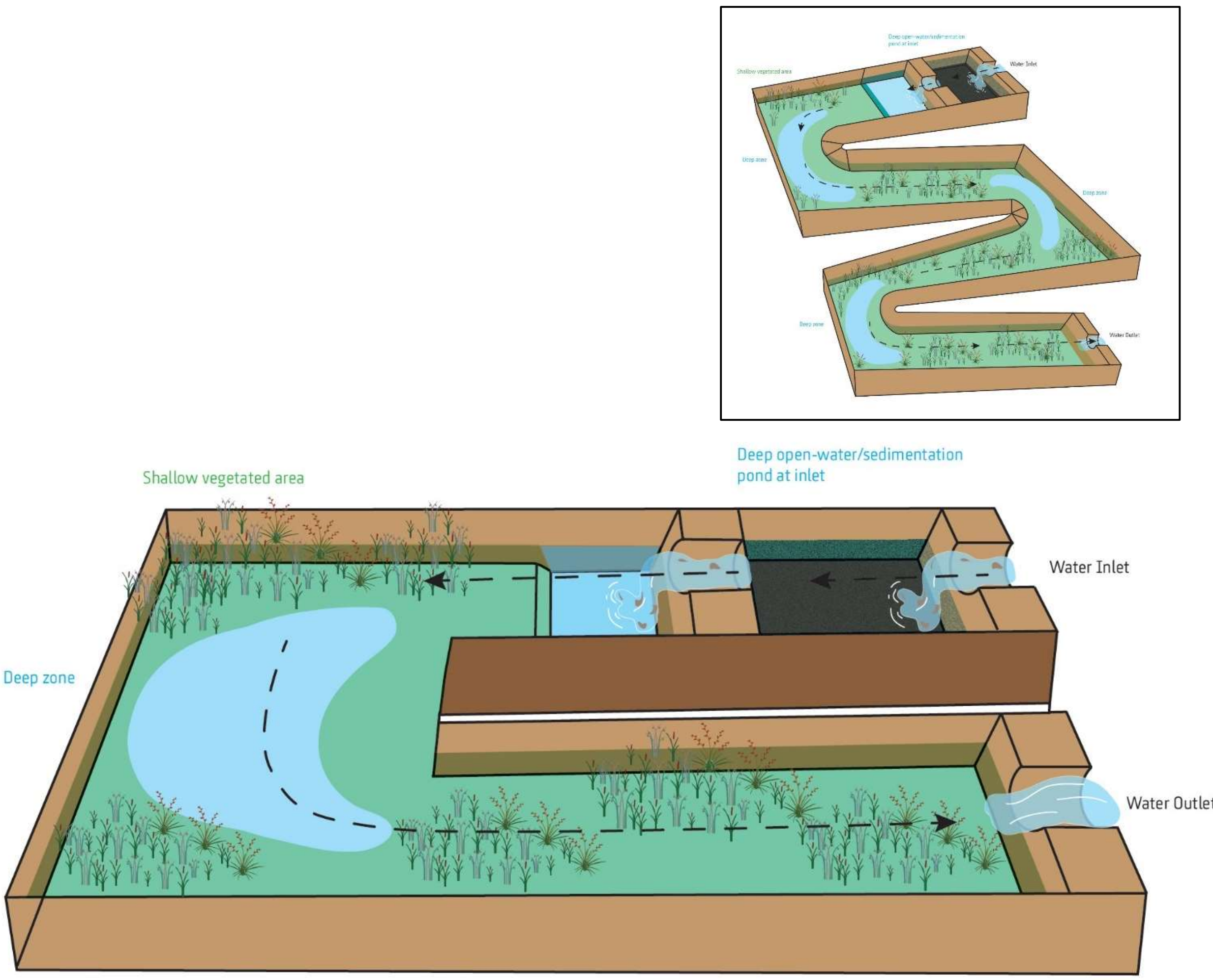

Figure 10: Option 2b: 'Hairpin' wetland. An alternative option for low gradient sites (0-3°). This wetland has the same features as the straight "elongated channel" wetland above, but the hairpin reduces the fall from the inlet to the outlet. The deep zone around the outside of the hairpin helps reduce short circuiting around the corner. Shallow vegetated zones should still occupy ~70 % of the wetland area. Multiple 'hairpin' continuations can also be used creating a serpentine wetland (see inset).

6.6.2 Moderate gradient sites (4-7° slopes)

Option 3a: Longitudinally stepped multi-stage wetland

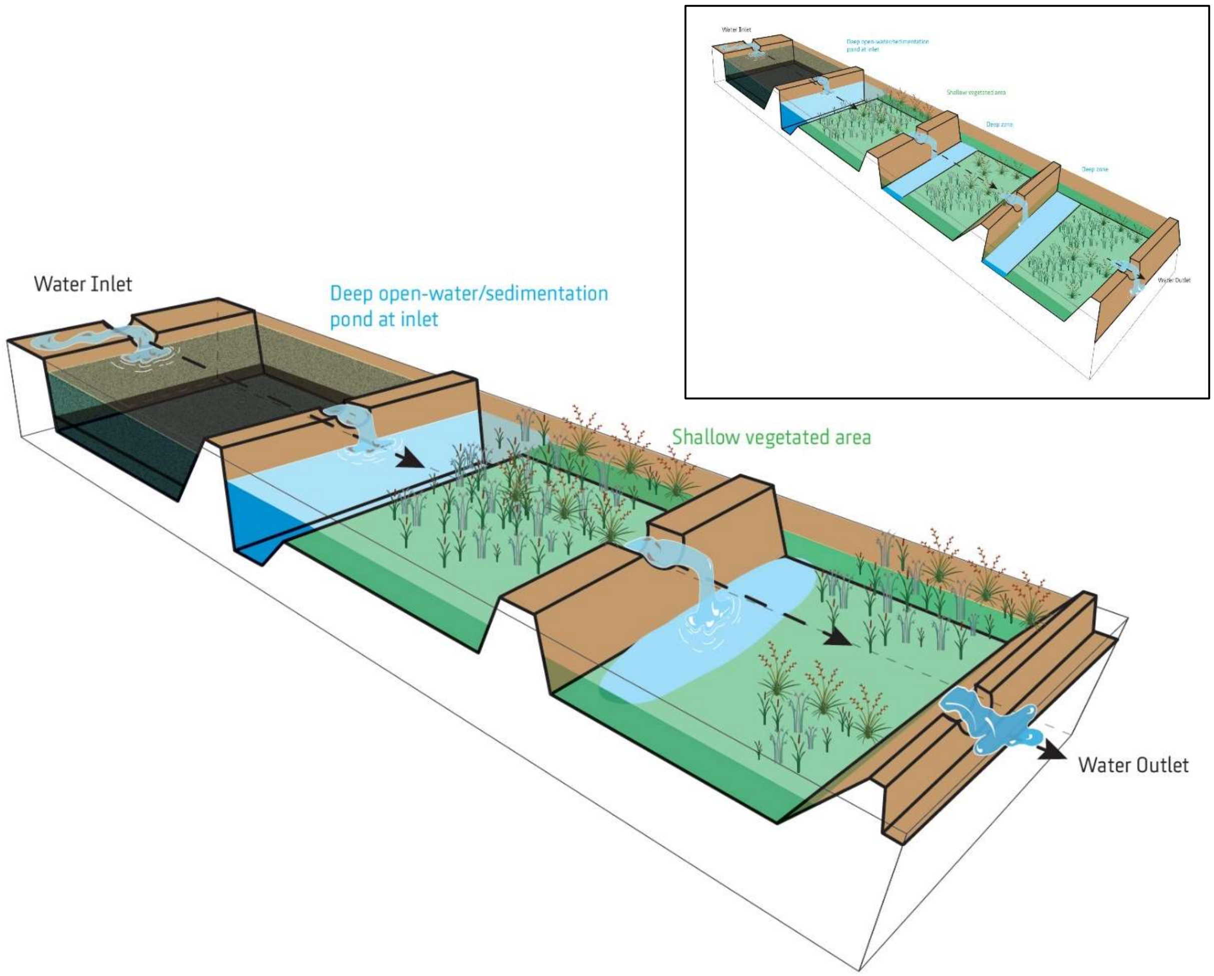

Figure 11: Option 3a: Longitudinally stepped multi-stage wetlands. This is appropriate for moderate gradient sites (4-7°). Multiple cells in series, stepping down the slope result in lower bunds and flow velocities between cells and less potential for erosion of inlet and outlet zones. A deep open water zone is recommended at the inlet to each cell of the wetland. The wetland can include as many steps as necessary to achieve the required wetland area (see inset). Shallow vegetated zones should still occupy ~70 % of the wetland area.

Option 3b: Transversely stepped multi-stage wetland

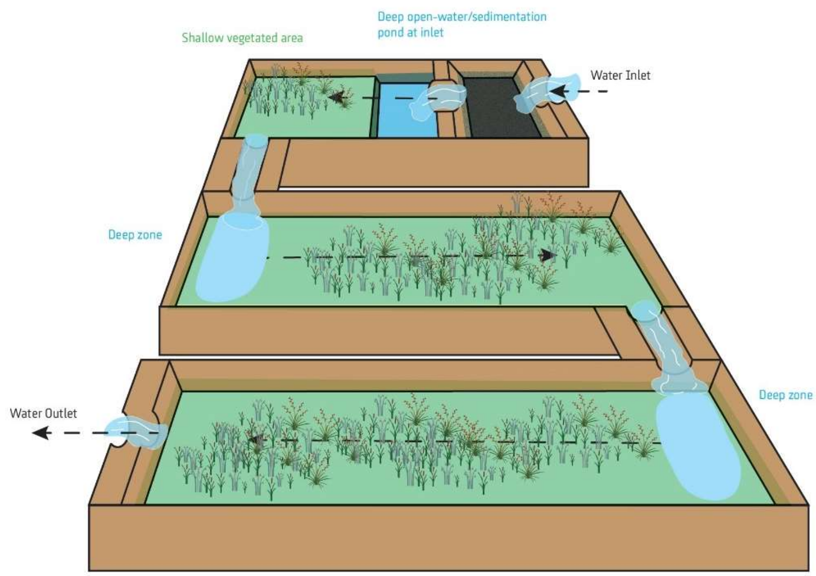

Figure 12: Option 3b: Transversely stepped multi-stage wetland. This alternative is suitable for moderate gradient sites (4-7°+). The wetland can include as many steps as necessary to achieve the required wetland area.

Figure 13: Example of a multi-cell wetland prior to planting. By creating multiple cells with a serpentine design, the bund height between cells is kept to a minimum. The design allows treatment of three major drain/stream inputs as well as runoff from the raceways. Use of curved edges to the wetland cells creates a natural appearance. Note also Figure 14.

Figure 14: The same wetland shown in Figure 13 after four years of plant establishment. The landowners have also done extensive planting around the wetland margins.

6.7 Ancillary wetland values

6.7.1 Biodiversity and aesthetics

To enhance biodiversity, a variety of native plant species can be used in and around the wetland (e.g. to provide food and nesting opportunities for native birds). Figure 15 illustrates how wetland shape can be modified to provide a more natural fit with the surrounding landscape whilst still keeping within the general guidelines (e.g. length : width ratio). Open water areas are attractive and can enhance wildlife habitat values, improve flow dispersion, increase sediment deposition, and can increase faecal bacteria inactivation following exposure to sunlight. Wildfowl are often attracted by open water areas. Their feeding and breeding activities may disturb sediments deposited within the wetland, and they may contribute faecal microbes, impacting on the water quality leaving the wetland waters. To limit such impacts, open-water areas should not be located near the outlet point. Instead the final ~20% of the wetland should comprise a shallow, densely vegetated filter zone.

Figure 15: A wetland constructed in a retired area of restored native bush. The curved shape winding between the trees gives a more natural appearance. (Wetland plants are just becoming established).

7 Construction

7.1 Timing and construction sequence

Wetland construction is generally best undertaken in late spring or summer when soils become dry enough for heavy earthmoving (see Appendix C for a proposed timeline). Undertaking construction as early as possible in the dry season also makes it possible to plant the wetland during an optimal growth period (e.g. spring and early summer). Where conditions are very dry over the summer and early autumn period, plants may need to be watered during the first season to ensure their survival and establishment. Alternatively, planting may need to be postponed until moist conditions return. Because many wetland plants are dormant over winter, in many cases it will be preferable to wait until early in the following spring to undertake planting (with prior weed control). Plants are an important and costly component of any wetland, and poor plant establishment and weed invasion is difficult to correct once water levels within the wetland are at normal operating levels.

After a suitable site has been selected, the excavator would normally:

1. Scrape off the soil surface and associated vegetation and discard this portion.
2. Scrape away and stockpile the remaining topsoil.
3. Mark-out and excavate the wetland area to the required depths, maintaining suitable batters on excavated margins. Compact clay subsoils in the base of the wetland or utilise a liner.
4. Utilise suitable excavated subsoils to make necessary embankments.
5. Mix stockpiled topsoil and subsoil (50:50) and spread as a planting medium (~200-300 mm deep) in the base of the wetland.

7.2 Embankments and lining

Embankments need to be keyed into the subsoil and battered at an angle of around 2:1 to 3:1 to minimise the potential for bank slumping. Local contractors will normally have sufficient experience with local soils to ensure that appropriate bank slopes and levels of compaction are maintained. Embankments should be solidly constructed and water-tight, requiring use of well compacted clay. Use of a heavy sheep's-foot roller or similar may be needed. Alternatively, the excavator operator can "track roll" thin layers of subsoil onto the embankment, building up successive well-compacted layers[7]. Some councils have limits on the height that a bund may be before requiring engineering design and council consent. Consenting requirements related to specific wetland designs and locations should be identified early in the planning process, prior to starting construction.

Embankments should be made from well compacted clay or subsoils, NOT from topsoil which will erode.

[7] Despite being heavy, tracked excavators have low ground pressures (e.g. 35 kPa) allowing them to operate on soft ground. For comparison, a standard car has a ground pressure of around 205 kPa.

Where present, cohesive clays can be used to line the base and sides, with appropriate compaction. This will help retain water during dry periods. Where soils are highly permeable (e.g. sands), water retention may be insufficient to maintain adequate water levels during dry periods – use of a synthetic liner may be necessary to retain water. Where water retention is limited, it may not be possible to establish wetland vegetation during dry summer months. In those circumstances, it will be essential to establish the plants in early spring.

In the shallow CW areas identified for planting, a layer of 200-300 mm of non-compacted soil is required. It is important to realise that improved farm top-soils which have received fertilizer for many years are likely to have high phosphorus status, which can lead to release of P when the soil is permanently saturated in the wetland. We recommend using a mixed (50:50) topsoil and subsoil layer[8] in the planting areas (i.e. not in the sedimentation pond or in deep flow dispersion zones). Where P reduction is a specific target for wetland construction, specialised testing of the soils being used is recommended to assess the risk of P loss under saturated wetland conditions. Addition of appropriate P-retaining materials may be warranted to enhance P reduction performance (Ballantine and Tanner, 2010).

7.3 Wetland outlets

The water depth in the wetland (e.g. shallow planted areas or deeper sedimentation basins) is controlled by the height of the outlet – either the bottom of an outlet pipe, or the crest of an outlet weir. The embankment should be made first to ensure it is properly compacted, and then excavated to fit the outlet pipe or weir structure at the appropriate depth (in most instances 30 cm above the wetland base once the topsoil layer has been added to the wetland). Provision is required for future adjustment of the outlet height, as sediment and plant material build up in the wetland. This can be done by adding a 90° pipe bend that can be swivelled to adjust the level of the outlet, or adding another section to raise the weir crest. Care should be taken if using slotted boards in a weir to ensure that slow leakage does not result in the drying out of the wetland over summer causing plant die-off.

A high-level overflow and spillway is also required for on-stream wetlands to cope with large storm flows or outlet blockages. The lip of the spillway needs to be sufficiently wide and shallow to keep flow velocities low. The spillway crest, chute and exit need to be suitably armoured with geotextile and rock riprap to resist erosion and avoid undermining of embankments.

Where the wetland is off-stream, it is common to construct the entire wetland (and sometimes to plant the wetland) prior to connecting it to the main inflow (using an inflow pipe or by diverting the main channel). Inlet and outlet structures need to be sized appropriately to accommodate the flows anticipated. Where the inlet is from a single sub-surface drain, specialised inlet or outlet structures are probably not required, provided the water flow is not likely to cause erosion of any embankments, or short-circuit the structure. Where flows are larger, such as from open drains or from streams, deeper open pond areas are required to slow and dissipate flows and allow suspended sediments to settle.

[8] Subsoils are generally less impacted by fertilisation and have residual phosphorus sorption capacity available.

8 Plants

8.1 Role of plants

Constructed wetlands work best with a well-maintained, dense cover of emergent wetland plants. Plants are crucial to the functioning of constructed wetlands because they:

- provide the physical structure that supports the growth of microbial biofilms, which are important in their ability to retain contaminants
- produce litter which become the fuel for denitrification and other microbial processes
- shade the water surface to reduce algal growth
- dissipate wind and wave action to reduce erosion
- enhance wildlife and aesthetic values.

You should start organising the plants early on in your planning. Eco-sourced plants grown from seed collecting in your region are recommended[9]. It is likely you will need to order at least some of your plants from a specialist wetland nursery which may have to specifically grow them for you. You may also be able to harvest wetland plants for transplanting from existing drains and wetland areas on your farm. Ensure you do not damage valuable natural wetlands, or transfer weeds along with the intended species, particularly in the soil around the plant roots.

Organize plant supply early to ensure availability when you need them

[9] Eco-sourced plants are grown from seeds collected from naturally occurring vegetation in a locality close to where they are replanted. Plant ecotypes growing locally are more likely to be suited to the local climate and soil types, and therefore more likely to survive. By using eco-sourced native plants, you will also help maintain the unique genetic characteristics of the local flora.

8.2 Planting zones

Within the planted areas of a wetland[10], water depth will dictate which plants are suitable. There are three different planting zones within the constructed wetland:

1. the main shallow (20-40 cm deep) flooded zone
2. the wet margins (0-20 cm deep)
3. the embankments (dry margins).

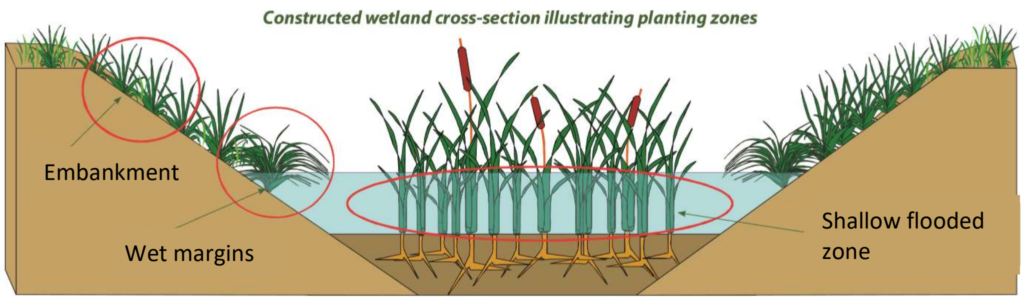

Figure 16: Different planting areas within a wetland.

The plants in the flooded zone are primarily responsible for water treatment while the plants on the margins and embankment stabilise the edges, help exclude weeds, contribute organic matter (carbon) and promote biodiversity.

8.3 Plant selection: Key species for the shallow flooded zone

The tall, emergent plant species listed below grow well within the flooded zone of constructed wetlands. Eco-sourced native species adapted to your locality are recommended. Where nitrate-N reduction is a priority, species such as raupo (*Typha orientalis*) are valuable due to their high productivity which provides a source of organic matter. However other species may find it hard to compete with them. Other hardy tall-growing sedges such as purei/makura (*Carex* spp.) and rushes (*Juncus* spp.) can be planted in shallow zones, and kapungawha (lake club-rush), soft-stem bulrush (*Schoenoplectus tabernamontani*), mokuautoto (jointed twig-rush, *Machaerina articulata,* upper North Island), kuta (tall spikerush, *Eleocharis sphacelata*) can be planted in deeper zones.

The main areas of the wetland should be planted with robust tall-growing emergent native species.

We recommend sourcing plants from a reputable specialist wetland plant supplier who can advise on suitable native species/varieties for your area. The number of plants and planting density depend on the grade of plant used. Robust seed-propagated plants in 1-2 L pots (e.g. PB1.5-PB3) are recommended, offering good survival after planting but lower cost than larger plants.

[10] This does not refer to the deep-water dispersion zones or the sedimentation pond if one is used.

Table 2: Key native plant species for the shallow flooded zone.

Plant species	Common name	Natural range	Description	Depth range
Typha orientalis	raupo, bulrush equivalent to: cumbungi (Aus), reed mace (UK), cattail (N. America)	Throughout New Zealand.	1.5–3 m tall. Dull green, erect leaves arising in clumps from green spongy rhizomes. Thick, cylindrical brown seed heads (cat-tails) borne on tall shoots. Leaves die back strongly in winter. Generally dominant emergent wetland plant in fertile lowland New Zealand swamps.	0–0.4 m
Machaerina articulata (formerly known as *Baumea articulata*)	mokuautoto, jointed twig-rush	From Northland to Levin.	1.8 m tall. Green year-round. Dark green, 'leafless', stiff, cylindrical shoots with obvious joints when mature. Red-brown pendulous seed heads borne on separate fertile shoots.	0–0.4 m
Eleocharis sphacelata	kuta, tall spike-rush, spike-sedge	Throughout NZ (common in North Island, uncommon in Canterbury).	0.8–1.3 m tall. Stout, bright green 'leafless', hollow shoots with transverse internal septa, arising from thick rhizome. Seed heads forming at tip of shoots.	0.2–0.6 m
Schoenoplectus tabernaemontani (formerly known as *Scirpus or Schoenoplectus validus*)	kapungawha, soft-stem bulrush, lake clubrush	Northland to Westland and Canterbury.	0.6–1.8 m tall. Shoots die back over winter, except in northern coastal areas. Erect green to blue-green, 'leafless', cylindrical shoots with white central pith, arising from horizontal rhizome. Brown seed heads form tuft just below the shoot tip. Shoots die back in winter at inland sites.	0–0.4 m

Figure 17: ***Typha orientalis*** **(raupo, bulrush).**

Figure 18: ***Machaerina articulata*** **(mokuautoto, jointed twig-rush).**

Figure 19: ***Eleocharis sphacelata*** **(kuta, tall spike-rush).**

Figure 20: ***Schoenoplectus tabernaemontani*** **(kapungawha, soft-stem bulrush).**

8.4 Plant selection: Key species for wet margins and embankments

These species are suitable for planting in wet margins and on dry embankment slopes to reduce bank erosion and weed ingression, and enhance plant and habitat diversity. For identification of these species, see 'Wetland Plants in New Zealand' (Johnson and Brooke, 1989).

Table 3: Key native plant species for wet margins and embankments.

Plant species	Common name	Natural range	Description	Planting position	Comments	Photo
Bolboschoenus fluviatillis and *B. medianus*	purua grass, kukuraho, ririwaka, river bulrush, marsh clubrush	Northland to Westland and Canterbury	1–1.8 m tall. Leafy sedges with stems, (triangular in cross-section), emerging from woody, bulbous tubers.	Shallow water to 0.3 m depth.	Common in coastal areas. Fast-growing in spring and early summer, dies back over winter. Provides seasonal diversity.	
Carex secta	purei, makura	Throughout New Zealand	1–1.5 m tall. Drooping harsh tussocks forming trunk-like base when mature. Green year-round.	Moist lower embankments and shallow water to 0.2 m depth.	Establish initially in moist conditions or shallow water, can grow in deeper water if gradually acclimatised. Classic New Zealand plant of wetland and stream margins.	
Other *Carex* spp.; especially *C. germinata,* *C. lessoniana* and *C. virgata*	rautahi, carex	Throughout New Zealand	0.5–1.5 m tall. Harsh leafy sedges. Green year-round.	Moist lower embankments and shallow water to 0.2 m depth.	Taller-growing species mentioned are likely to be the most robust and able to compete with weeds. Valuable for wildlife.	

Plant species	Common name	Natural range	Description	Planting position	Comments	Photo
Austroderia richardii, C. fulvida, C. toetoe	toetoe (New Zealand native species only, not to be confused with introduced pampas grasses)	Different species common in different regions	1.5–3 m tall. Coarse green tussocks, with tall feathery flower heads borne on cylindrical stems.	Upper & lower embankments to water edge and surrounds.	Useful, hardy plant suitable for bank stabilisation and screening. Ensure invasive introduced pampas species are avoided.	
Cordyline australis	ti kouka, cabbage tree	Throughout New Zealand	Tall-growing soft-stemmed tree bearing tufts of fibrous leaves.	Upper embankments and surrounding areas.	Classic New Zealand tree common in wet soils.	
Cyperus ustulatus	toetoe upokotangata, giant umbrella sedge	Northland to Canterbury and Fjordland; mainly coastal and lowland	0.5–1 m tall. Harsh pale-green leaves in clumps, with emergent seed-bearing leafy umbells.	Moist lower embankments and shallow water to 0.2 m depth.	Tolerates dry periods. Suitable for wetland margins and embankments, and shallow water.	
Phormium tenax	harakeke, New Zealand flax	Throughout New Zealand	1–3 m tall. Robust clumps of tough robust leaves. Tall dark brown to black flower heads.	Upper & lower embankments to water edge and surrounds.	Does not generally establish well in continuously flooded conditions. An important traditional plant for Māori and important habitat for wildlife.	

A wide variety of riparian species including harakeke (*Phormium tenax*), toetoe (*Austroderia spp.)* and red tussock (*Chionochloa rubra*) are suitable for the wet margins and embankments around wetlands, where they help to stabilise banks and enhance amenity and biodiversity values. Use of a range of plant species within a wetland enhances biodiversity values and can create an aesthetically pleasing farm asset.

A wide range of other natives are suitable for the wetland margins and embankments.

Plants in the wetland should be planted shortly after earthworks are completed. Maintaining shallower water depths (approximately 15 cm) for the first few months after planting is recommended to allow plants to establish. Baseflow (low) water level in the wetland can be maintained by installing holes in the outlet weir (which may be plugged later), so that a deeper wetland depth can be maintained once plants are well-established.

Plants on wetland edges or embankments around the wetlands can be planted in autumn. Further guidance on plant identification and management can be found in Tanner et al. (2009) and Appendix D.

Figure 21: Wetland planting. The wetland has been partially flooded. This makes planting easier and assists with plant survival.

8.5 Planting and establishment

Care is needed to ensure rapid establishment of wetland plants and maximise the survival rate before weeds invade. Below are some tips for successful planting:

1. **Timing of planting**

Most wetland plants do not grow much during winter and for many species the above-ground portions die back over this period. Ideally therefore, planting should take place in spring or early summer (September–December) to promote rapid establishment and to enable growth of a tall dense cover that can outcompete weeds. However, planting at this time is often difficult in practice, because ground conditions remain too wet for construction early in the season.

Later planting in summer (January–February) is possible if larger plant grades are used and a supplementary water source is available to keep the wetland moist. Planting smaller plants later in the season, or when the availability of supplementary water cannot be guaranteed, is not recommended. Instead, it is better to wait until the following spring to undertake planting.

2. **Pre-planting weed and pest control**

If the base of the wetland has been left for sufficient time to allow weeds to establish, manual weeding or spraying with a suitable translocated herbicide such as glyphosate will be required. If large masses of herbicide-killed plant material are subsequently flooded they will decompose creating de-oxygenated conditions detrimental to plant establishment. It is therefore advisable to control weeds at low levels (to avoid build-up of biomass) and/ or physically remove biomass derived from dead plants. Useful resources to help identify and control weeds are noted in Appendix D and Appendix E.

Wildfowl (specifically Pukeko and Canada Geese), can be very destructive to newly planted wetlands and may need to be deterred or controlled during the plant establishment phase. There are a range of bird deterrents that may be useful including gas bangers and flashing lasers. If you intend to dissuade birds by shooting, a hunting permit from The Fish and Game Council will be required, and possibly a special permit to extend control beyond the open game-bird hunting season[11].

3. **Planting**

Select hardy plants appropriate to your conditions (preferably local ecotypes that grow well in your region – see previous section), and plant at 3–4 plants per square metre density (depending on transplant size). The plants should be well firmed into the soil, so they do not float out when water levels are raised or are easily uprooted by waterfowl.

Best establishment and subsequent spread are usually achieved using nursery stock grown from seed. Plants with well-developed roots and rhizomes grown up in 1–2 litre pots (PB 1.5–3) are recommended. Some species (e.g., raupo, harakeke/flax, *Schoenoplectus*) can be successfully grown by dividing up wild-grown plants into bare-rooted cuttings, each with 3–5 shoots trimmed to 0.3 m height. Such propagules tend to establish more slowly however and are more vulnerable to desiccation and uprooting by waterfowl; they need to be planted early in the season and under ideal conditions to establish effectively. Collection permits may be necessary for wild-grown plants, except where materials can be sourced on private land.

[11] https://fishandgame.org.nz/licences/

4. **Water level control**

During establishment water level should be maintained at or up to 15 cm above the wetland soil surface. Plants can be planted into dry topsoil provided enough water can be supplied to cover the topsoil immediately after planting. If inflow to the wetland is insufficient during the initial establishment period, supplementary water may be necessary to avoid desiccation of young plants.

As a minimum, flooding every 5–10 days or periodic spray irrigation may be used to maintain moist conditions. It is important that the water level is not raised above the height of the establishing plant shoots, as these act much like a snorkel, conveying oxygen to the submerged portions of the growing plant. As the plants grow, the water level can gradually be raised.

5. **Post-planting weed and pest control and care**

Competition from weeds and disturbance from waterfowl need to be carefully managed during the plant establishment phase to ensure that tall-growing aquatic species dominate. Useful resources to help identify and control weeds are noted in **Error! Reference source not found.** and **Error! Reference source not found.**. Once properly established (generally after two growth seasons), tall-growing wetland species should be sufficiently resilient to water level fluctuations, predation by wildfowl and other stressors. Plants growing in water-retentive soils should be able to survive normal summer dry periods and recover from moderate periods of drought, re-growing from buried rhizomes. Weed invasion may, however, occur during such episodes requiring additional control and possibly also replanting of badly affected areas.

6. **Get it right first time**

Wetland plant establishment should be relatively rapid and simple if it is carried out correctly right from the start. However, problems can multiply and become difficult to overcome where plant establishment is compromised by factors such as:

- planting at the wrong time of the year e.g., too late in the season
- insufficient or excessive water levels
- competition and suppression by weeds
- damage by livestock or waterfowl.

9 Maintenance

A well-established wetland will have only minor maintenance requirements. Provided the wetland plants prosper at the time of wetland creation, the potential for weed species to enter the wetland and become a nuisance is much reduced. Common "weeds" in wetlands include pasture species such as Yorkshire Fog (*Holcus lanatus*) which can form floating mats on the water surface and can smother young establishing wetland plants. Manual removal or chemical control should be done before the weeds become well established. Herbicides used should only be formulations that are permitted for use in or near waterways. Although both glyphosate and diquat are permitted by EPA, local regional council rules may also apply and should also be checked before using herbicides. Care should always be taken to reduce spray drift onto nearby desirable wetland plants.

Once wetland vegetation has established, wetland maintenance involves periodic checking of inlets and outlets, and clearance of any blockages; checking structural integrity of any embankments, dams and high-level overflows; weed management around the wetland; and maintenance of gates and fences.

Removal of accumulated sediments from the sedimentation trap/pond will be necessary periodically (Figure 22). The frequency of sediment removal is highly dependent upon the size of the sedimentation pond and the quantity of incoming sediment. Sediment removal should be undertaken when the trap is about half full so it will keep working optimally and not be susceptible to erosion and resuspension during stormflows.

Table 4: Requirements during wetland establishment.

Fortnightly action list for first three months	
Plants	Visual inspection of plant health and damage by pukeko or other birds/animals. Check water level and adjust as appropriate (particularly during dry periods or periods of low inflow). Control weeds in wetlands and surrounds by hand-weeding, careful herbicide application, and/or temporary water level increases.
Inlet	Visually check for adequate inflow and identify any blockages or damage.
Outlet	Adjust outlet height so plants are not drowned. Check for blockages and damage. Clear any plants or debris away from outlet to maintain unrestricted flow and optimal water level.
Embankments	Inspect for weeds, erosion, and damage by pukeko, rabbits or other birds/animals.

Table 5: Requirements after wetland establishment.

Seasonal action list	
Plants	Visual inspection of plant health, weed and pest problems, take remedial action as necessary.
Inlet	Visually check for adequate inflow and identify any blockages or damage.
Outlet	Check for blockages and damage, clear any plants or debris away from outlet. Check water level and outflow quantity (is it normal based on recent rainfall levels).
Embankments	Where required, control weeds on inner embankments by hand-weeding or herbicide application, mow, or graze with sheep to control grass on embankments and wetland surrounds. Ensure fence and gate are stock-proof.
Sedimentation pond(s)	Check accumulation of sediment. If the pond is more than 1/2 full of sediment, it requires emptying.

Figure 22: **Emptying a sedimentation pond.**

10 Key indicators of success

A well-functioning wetland will have:

- Low sediment accumulation rates in the main vegetated wetland
- Well-established, flourishing and evenly distributed wetland plants
- Evenly distributed flow, without channelization or short-circuiting
- Appropriate water levels for plant survival and treatment function
- Minimal invasion by weedy plants
- Well-maintained embankments and margins – negligible erosion/bank collapse, low incidence of weeds, controlled stock access
- Outflow water is generally clear, with low odour.

11 Acknowledgements

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12 References

ARC, 1999. Guidelines for stormwater runoff modelling in the Auckland Region: TP108. ARC, Beca Carter Hollings & Ferner Ltd.

Ballantine, D.J., Tanner, C.C., 2010. Substrate and filter materials to enhance phosphorus removal in constructed wetlands treating diffuse farm runoff: A review. AGR08220/ATTE 53, 71–95.

Hudson, H.R., 2002. Development of an in-channel coarse sediment trap best management practice. Report FRM500. Environmental Management Associates Limited, Prepared for the Ministry of Agriculture and Forestry, Christchurch, p. 43.

Melbourne Water, 2005. Water Sensitive Urban Design (WSUD) Engineering procedures: Stormwater. CSIRO Publishing, Melbourne, Victoria.

Persson, J., Somes, N.L.G., Wong, T.H.F., 1999. Hydraulic efficiency of constructed wetlands and ponds. Water Science and Technology 40, 291-300.

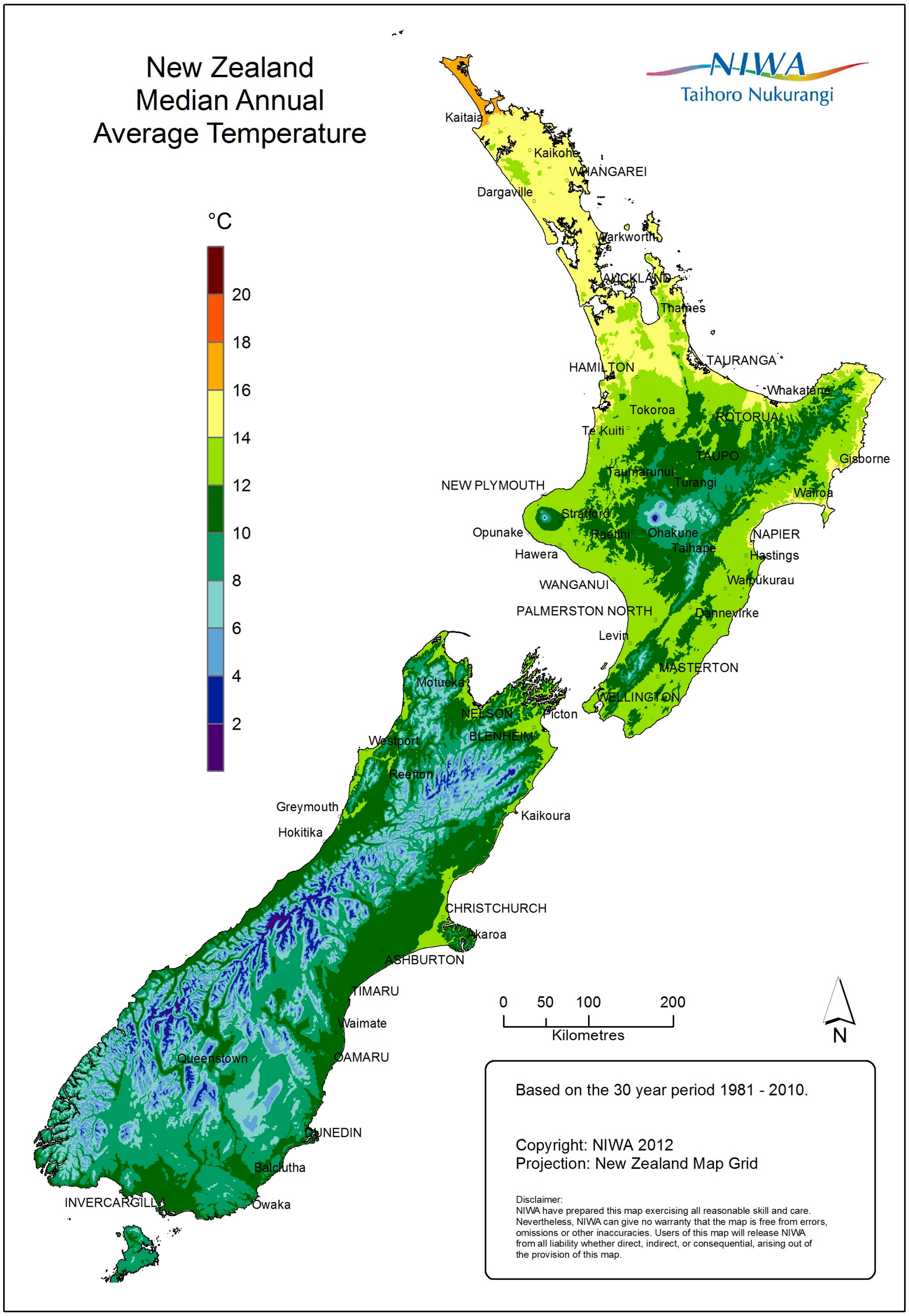
Su, T.-M., Yang, S.-C., Shih, S.-S., Lee, H.-Y., 2009. Optimal design for hydraulic efficiency performance of free-water-surface constructed wetlands. Ecological Engineering 35, 1200-1207.

Tanner, C.C., Sukias, J.P.S., 2011. Multi-year nutrient removal performance of three constructed wetlands intercepting tile drain flows from grazed pastures. Journal of Environmental Quality 40, 620–633.

Woodward, B., Tanner, C.C., McKergow, L., Sukias, J.P.S., Matheson, F.E., 2020. Diffuse-source agricultural sediment and nutrient attenuation by constructed wetlands: A systematic literature review to support development of guidelines. NIWA Client report to DairyNZ, Hamilton, NZ.

Wratt, D., Tait, A., Griffiths, G., Espie, P., Jessen, M., Keys, J., Ladd, M., Lew, D., Lowther, W., Lynn, I., Mitchell, N., Morton, J., Reid, J., Reid, S., Richardson, A., Sansom, J., Shankar , U., 2006. Climate for crops: Integrating climate data with information about soils and crop requirements to reduce risks in agricultural decision-making. Meteorological Applications 13, 305–315.

Appendix A Median annual average temperatures across New Zealand[12]



[12] Wratt et al. Wratt, D., Tait, A., Griffiths, G., Espie, P., Jessen, M., Keys, J., Ladd, M., Lew, D., Lowther, W., Lynn, I., Mitchell, N., Morton, J., Reid, J., Reid, S., Richardson, A., Sansom, J., Shankar , U., 2006. Climate for crops: Integrating climate data with information about soils and crop requirements to reduce risks in agricultural decision-making. Meteorological Applications 13, 305–315.

Appendix B Derivation of sedimentation pond sizing

Sizing of the sedimentation pond component of a constructed wetland receiving surface flows is based on peak flows generated during high intensity rainfall events, targeting particle size and anticipated removal (fraction of inflow load). Clearly the pond cannot be sized to capture all sizes of particles under every set of storm conditions, thus we have chosen target values based on national and international recommendations, adapted to New Zealand conditions.

NIWA has a High Intensity Rainfall Design System (HIRDS) calculator[13] which supplies the user with rainfall information (likely frequency and intensity) for any location in New Zealand. Within each NZ Region, three locations were selected to generate broadly representative rainfall data. Sites were chosen in a semi-random fashion, with the three locations spread as widely as possible within each region, ensuring that none were closer than ~20 km to the boundary of each region. Sites were selected following a visual assessment of terrain and consideration of likely farming activities. Towns/cities were avoided, as well as steep hilly or mountainous areas.

Daily (24 hr) rainfall data for two-year Annual Return Interval (ARI), 10-year ARI and 100-year ARI were compiled. Based on this information, we selected the 10-year ARI as providing a reasonable target rainfall. Average values were generated from these data. This data was input to a model provided by Auckland Council (Guidelines for stormwater runoff modelling in the Auckland Region, ARC, 1999), which allows calculation of peak flows during different storm events. Although this model was designed for Auckland conditions, the model can be adapted for use elsewhere, provided appropriate rainfall information (such as supplied by the NIWA HIRDS calculator) are available[14].

Various international guides (Melbourne Water, 2005, Healthy Waterways 2006) suggest targeting very fine sand particles (125 µm) for removal during peak flows. At flows lower than the peak, a progressively larger proportion of finer particles will be captured.

Using the peak flow data and 125 µm particle size, we calculated required sedimentation pond sizes for each region using the guidelines produced by Hudson (2002) for a nominal 1 ha catchment; the results of this calculation are shown in Figure A1.

From these data, we recommend the following sedimentation pond sizes:

- 40 m^2 per ha of catchment for regions with lower intensity storms,
- 60 m^2 per ha of catchment for the regions where medium intensity storms are likely, and
- 80-100 m^2 per ha of catchment for the regions with higher intensity storms.

For areas with rainfall characteristics outside the normal regional bounds considered here, we recommend site-specific calculations are made instead.

For the purpose of estimating wetland treatment performance using information provided in this guideline, initial sedimentation ponds can occupy up to 20% of the wetland area. Where the initial sedimentation pond area exceeds 20% then this extra area needs to be additional.

[13] (https://www.niwa.co.nz/software/hirds)
[14] Note: the Auckland Council model calculates total as well as peak runoff. Soil type is a key variable for total runoff, however does not affect peak runoff. Thus we have been able to adapt this to each NZ region.

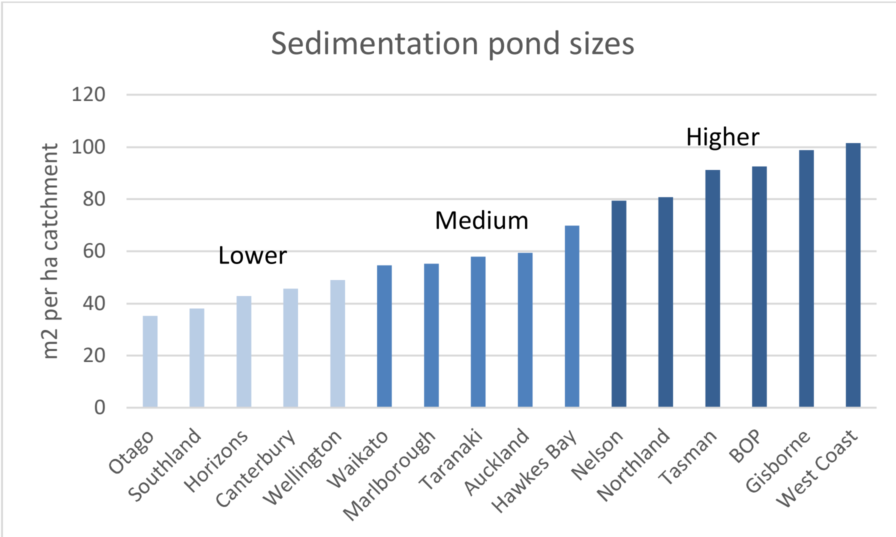


Figure A1: Sedimentation pond sizing based on a nominal 1 ha. catchment for different NZ regions. Different regions are classified as lower, medium and higher intensity rain events.

Appendix C Construction timeline

Task	Planning period	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer
Plan wetland - identify appropriate site, delineate catchment, determine appropriate wetland size and associated contaminant reductions, determine appropriate design configuration, get quotes for construction and planting.																
Check regulations with local Council. Discuss proposed design, supply required information and apply for consent if required.																
Determine construction requirements and book contractor/ machinery hire and any engineering oversight required																
Plant supply - Pre-order plants																
Construct wetland																
Plant embankments																
Plant wetland																
Control weeds pre- and post-planting and manage pests. Irrigate plants if required																
Check and maintain wetland inlets and outlets (water levels), embankments, sedimentation pond																

Appendix D Resources for wetland plant identification and management

Johnson, P.; Brooke, P. (1989). Wetland plants in New Zealand. DSIR Field Guide. DSIR Publishing, Wellington. Reprinted by Maanaki Whenua Press. www.mwpress.co.nz

New Zealand Novachem Agrichemical Manual. Updated annually. AgriMedia Ltd, Christchurch, New Zealand. www.novachem.co.nz

Peters, M.; Clarkson, B. (2010). Wetland Restoration: A Handbook for New Zealand Freshwater Systems. Manaaki Whenua Press, PO Box 40, Lincoln 7640. www.mwpress.co.nz

Popay, I.; Champion, P.; James, T. (2010). An Illustrated Guide to Common Weeds of New Zealand. Third Edition. New Zealand Plant Protection Society, Lincoln, New Zealand.

Popay, I.; Champion, P.; James, T.; Ford, K. (2012). An Illustrated Guide to Common Grasses, Sedges and Rushes of New Zealand. New Zealand Plant Protection Society, Lincoln, New Zealand.

Tanner, C.C.; Champion, P.D.; Kloosterman, V. (2006). New Zealand constructed wetland planting guidelines. National Institute of Water & Atmospheric Research Ltd (NIWA) in association with NZWWA. www.waternz.org.nz

Weedbusters website; an alphabetical guide to weeds and their management. www.weedbusters.org.nz/weed-information/

Appendix E Herbicides for weed control

Target plants to be controlled	Recommended herbicide*	Notes on use
General weed control	glyphosate (e.g., Roundup®)	Non-selective, it will kill most plants. Careful spot application required to avoid impacts on wetland plantings. Generally low toxicity and non-residual, broken down rapidly. Only use formulations recommended for use over water e.g., Roundup Renew, Agpro Green Glyphosate. Also useful for cut stem/stump treatment of woody weeds (e.g., grey willow).
Selective control of grasses	haloxyfop** (e.g., Gallant®)	Generally kills grasses only. Minimal damage to other monocots (sedges, cabbage trees, flax, rushes, etc.), but minimise overspray. Does not kill broadleaf plants, ferns, etc. Foliar active with minimal soil activity, moderately low toxicity, short soil residue.
Selective control of woody broadleaf plants (e.g., blackberry and willow)	triclopyr triethylamine (e.g., Garlon® 360)	Kills many broadleaf species including shrubs, vines and trees. Does not kill grasses, but may cause limited damage to sedges, flax or other monocots or ferns. Moderately low toxicity, short soil residue. Also useful for cut stem/stump treatment.
	metsulfuronmethyl** (e.g., Escort®)	Kills most broadleaf species including ferns, shrubs, vines and trees except *Solanum* species. Generally not effective on grasses or other monocots (e.g., sedges and flax) unless applied at very high rates. Moderately low toxicity, however, short-lived but very active residue, apply with extreme care, works at very low rates. Also useful for cut stem/stump treatment.

The New Zealand Novachem Agrichemical Manual provides detailed information on use of all registered herbicides. Use all herbicides carefully according to label recommendations and avoid overspray of non-target plants.

*Mention of specific herbicides does not constitute specific endorsement, nor mean that other products with equivalent active ingredients will not provide similar results.

**Herbicides not specifically registered for use in waterways, but they can be used by regional and central government agencies under a Permission from the New Zealand Environmental Protection Authority (EPA). Therefore, they should only be used in situations that avoid contamination of waterways. There are no EPA controls over the use of glyphosate where contamination of waterways may occur. However, check with local regional council as you may require specific resource consent (under the Resource Management Act) for use around and in waterways.