Environment Canterbury

SEDIMENT BUNDS IN WAITARAKAO WASHDYKE LAGOON CATCHMENT

SEDIMENT BUNDS REVIEW

30 AUGUST 2024

CONFIDENTIAL

SEDIMENT BUNDS IN WAITARAKAO WASHDYKE LAGOON CATCHMENT

SEDIMENT BUNDS REVIEW

Environment Canterbury

WSP
Christchurch
12 Moorhouse Avenue
Christchurch 8011
New Zealand
+64 3 363 5400
wsp.com/nz

REV	DATE	DETAILS
1	21/08/2024	Revision 1
2	30/08/2024	Revision 2

	NAME	DATE	SIGNATURE
Prepared by:	Bertie Strickland	21/08/2024	
Reviewed by:	Glen Treweek	21/08/2024	
Approved by:	Andy Johnson	21/08/2024	

Our ref: 3-9C729.13

29 August 2024

Chris Fauth
Environment Canterbury
75 Church Street
Timaru, 7910

Dear Chris Fauth

Sediment Bunds in the Waitarakao Washdyke Lagoon Catchment

Thank you for the opportunity to present our review of existing sediment bund literature and recommendations for the adoption of sediment bunds in the Waitarakao Washdyke area.

We have undertaken a literature review of sediment bunds and other offline treatment systems. This has been done to understand the efficacy of these systems and how they may apply to the Waitarakao Washdyke catchment.

Bertie Strickland

WSP
Christchurch
12 Moorhouse Avenue
Christchurch 8011
New Zealand
+64 3 363 5400
wsp.com/nz

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Waitarakao Washdyke Lagoon Catchment, located north of Timaru, is a significant ecological, cultural, and historical site. Over the years, the lagoon has drastically reduced in size and health due to coastal flooding, erosion, and climate change. A key source of pollution is Washdyke Creek and its tributaries, which carry high nutrient concentrations from agricultural runoff.

Four sediment and nutrient mitigation systems have been identified for use in the catchment area. A literature review of these mitigation systems has been undertaken to understand their efficacy for sediment and nutrient removal, benefits and disadvantages for the catchment.

Recommendations:

- Retention Ponds and Small Farm Dams: Encourage their use in upper reaches and well-defined tributaries.
- Sediment Bunds: Apply in upper reaches where feasible.
- Fencing and Riparian Planting: Implement along all rivers in the catchment.
- Wetland Management: Fence and actively manage natural wetlands.

These measures will improve the health of the Waitarakao Washdyke Lagoon by reducing sediment and nutrient inflows, thereby enhancing the ecological and cultural value of the area.

A number of research gaps were identified for this report. One significant gap is the long term impacts of sediment and nutrient capture on the settlement area and underlying ground water.

An example drawing outlining the key requirements for sediment bund construction has been included in Appendix A.

1 PROJECT BACKGROUND

1.1 INTRODUCTION

The Waitarakao Washdyke Lagoon Catchment is located just north of the Timaru township. The lagoon is important from a native ecological habitat, biodiversity, cultural and historical perspective.

The lagoon is a brackish, shallow, coastal lagoon that serves as a nationally significant wildlife sanctuary for both flora and fauna. It holds significance for mana whenua, local residents, and visitors to the area. In the past, the lagoon was an abundant mahinga kai (food gathering) hub for local mana whenua and visiting iwi from across the South Island. However, in recent decades, the lagoon has shrunk from about 250 hectares in 1881 to less than 10 per cent of that today, and its health, as well as the habitat for wildlife, has declined. Coastal flooding, erosion, and the impacts of climate change pose a major risk to the lagoon, the farmland and the industrial area in the surrounding catchment.

A key source of incoming flows and pollution is Washdyke Creek and its major contributing tributary streams. By reducing the incoming sediment and nutrients from this source it is expected to help improve the lagoon health.

1.2 LAGOON CATCHMENT

The Washdyke Waitarakao Lagoon Catchment includes four main tributaries: Papaka, Rosewill, Kings Road and Oakwood Streams. These streams are highly modified with stream re-alignments, shaping and bridges. The streams are noted to be very flashy - discharging flood runoff out of the catchment very quickly and losing stream connectivity, carrying very low flows in "average" or dry conditions.

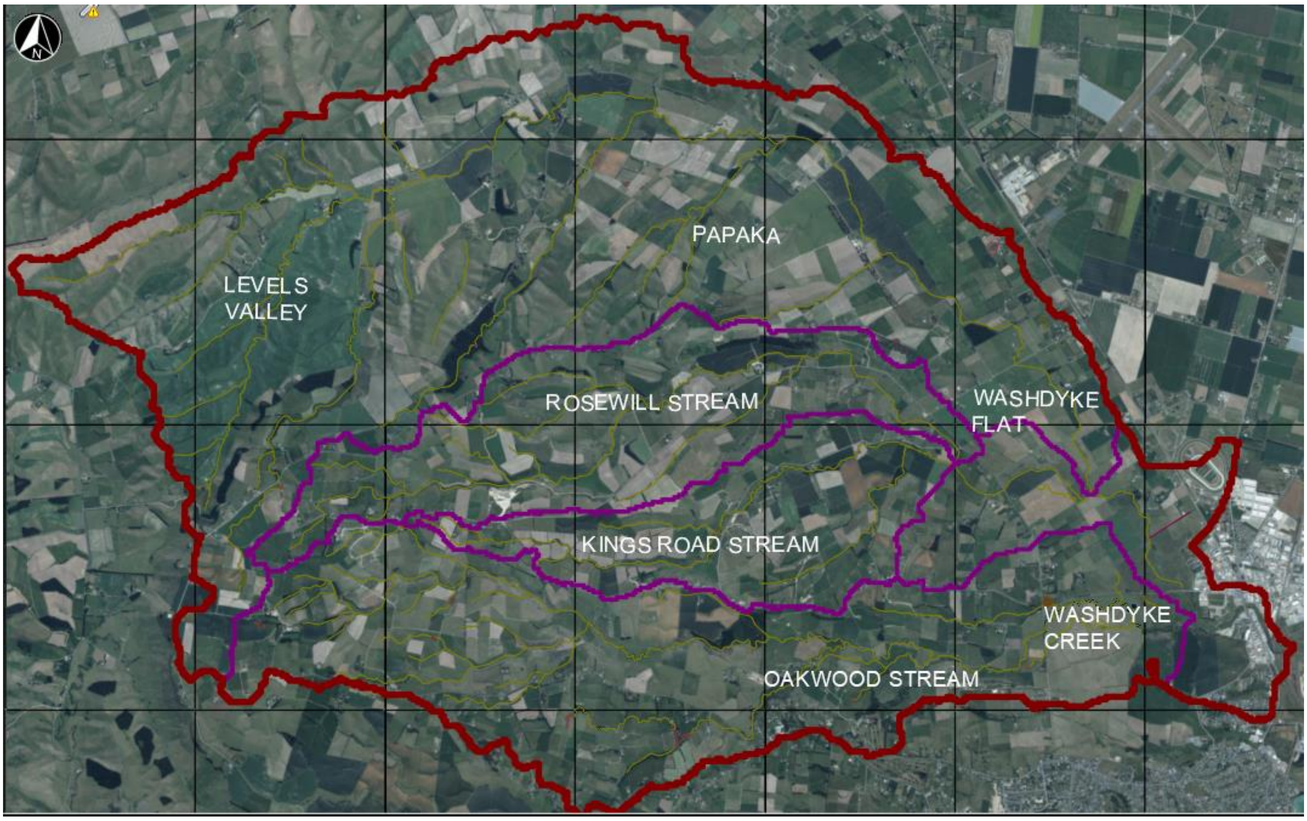


Figure 1. Overall Waitarakao Washdyke catchment.

The lagoon also appears to have catchments stemming from drainage canals in the Levels and Seadown areas. These areas have not been considered in this report and the focus is on the tributaries, lower order rivers, and four main rivers feeding into Washdyke Creek at State Highway 1.

The contributing rivers convey high nutrient concentrations (phosphorus and nitrogen) consistent with agricultural runoff (Our Waitarakao: Washdyke Lagoon Catchment, 2024).

The Lagoon catchment is intensively farmed with few isolated forestry areas in the Papaka catchment, most of which appears to be plantation forestry. The Oakwood Stream catchment is more developed with a large number or lifestyle blocks close to Timaru. The Washdyke Flat area appears to be the most intensively farmed area, likely as it is fertile flood plains.

The rivers and major tributaries are intermittently fenced. Most of the rivers in the Washdyke flat area appear to have been fenced off. Many of the tributaries and lower order streams are cultivated. Cultivation can encourage sheet erosion due to the presence of bare ground (Basher, 2013). Typical rates of erosion under arable cropping are higher than other land uses (Cullen, Takatsuka, Wilson, & Wratten, 2004).

2 LITERATURE REVIEW

2.1 BACKGROUND

Agricultural expansion and intensification are recognised as key causes of increased erosion, nutrient losses, soil damage and sediment loss (Smith & Muirhead, 2023). It is one of the main sectors contributing to sediment and nutrient pollution of freshwaters, particularly in the form of diffuse pollution (Ockenden, Deasy, Quinton, Surridge, & Stoate, 2014).Large rainfall events, or rainfall events with high kinetic energy, can result in runoff via ephemeral flow paths across swales in the landscape where water does not normally flow. Such ephemeral flow paths are the main pathway for overland flow from land to receiving water bodies (Smith & Muirhead, 2023).

Sediment, phosphorus and organics are the most common contaminants in flood flows as they are suspended in the water column. Nitrate nitrogen losses occur whenever infiltration occurs and high soil moisture conditions enables leaching and delivers nitrate to the groundwater (Paterson & North, 2022). This makes nitrogen more difficult to capture as it is generally not present in high concentration in overland flows, though nitrogen in shallow subsurface can be recaptured by vegetation.

The primary purpose of any water retention system is to significantly slow the water velocity. Slowing the water velocity encourages heavy particles such as sediment, nutrients and organic matter to settle out of the water column, depositing them at the base of the treatment system. Constructed systems can be used to help to control and treat the flood flows. Four systems have been selected for further analysis:

- Sediment bunds,
- Exclusion zones,
- Constructed wetlands,
- Small farm dams and retention ponds.

The primary focus of this review is sediment and nutrient reduction where the ephemeral tributaries and rivers, and overland flow paths deliver diffuse pollution. However, wetlands, both offline and inline have also been considered.

All of these systems work by slowing the water velocity. Deposition begins once the flow velocity falls below the settling velocity of a particle. Settling velocity is closely related to particle size and density, so that the coarse and dense particles are deposited first, with finer and lower density particles settling later, often only as the flow velocity falls (McKergrow, Tanner, Monaghan, & Anderson, 2007). This is done by either using ponding water in the case of sediment bunds, wetlands and ponds, or by natural barriers such as vegetation in exclusion zones.

Other methods, such as farm use, and land management changes have not been developed as part of this report. However, these methods are closely interlinked with the constructed systems and cannot be discarded from the discussion.

2.2 POLLUTION MITIGATION SYSTEMS

2.2.1 SEDIMENT BUNDS

A sediment bund is an earthen, stormwater retention structure, approximately 1.5-2 m high and 20-80 m long, constructed on pastures across the flow path of targeted low-order ephemeral streams (Levine, et al., 2020). The bund temporary impedes the flow of water allowing sediments, nutrients and other contaminants to settle out while reducing the peak flow on the downstream receiving environment. Detainment Bunds PS[120], a sediment bund developed in New Zealand by the P-Project and the Bay of Plenty Regional Council, has been used as the basis for the sediment bunds discussed here (Patterson, Clarke, & Levine, 2019).

The period of time the stormwater is impeded can vary but no more three days is generally accepted to be the optimal length to allow for settlement of large particles while also preventing permanent damage to the pasture immediately upstream of the bund (Levine, et al., 2020). Any longer than three days leaves the pasture oxygen deprived and can cause the plants to die off. The water is released by opening the primary spillway orifice and draining the stored water through the bund via a drainage pipe. This can be done from the top of the bund with a length of rope or chain. Additionally, under saturated and flood conditions, denitrification can occur as microbes look to alternatives to oxygen to survive. This leads to rapid loss of nitrogen from the soil and can cause stress in the plants.

Sediment bunds are similar in nature to retention ponds, where the water is detained for a period and released in a controlled fashion. Sediment bunds differ from retention ponds as they deliberately retain existing pasture in the ponding area. Sediment ponds also differ from retention ponds where the full volume of captured stormwater is released at a controlled rate after every event. Retention ponds retain a continuous volume of water at all times with fluctuating levels during storm events.

Trials on sediment bunds have been undertaken by the Phosphorus Mitigation Project in the Rotorua area with encouraging results, showing on average sediment and total phosphorus reductions of 30% and 20% (Levine, et al., 2020).

2.2.1.1 LOCATION

Sediment bunds work best in flat to rolling country where low order streams are present. Low order streams are defined as headwater streams (Stream order 1 and 2) with little upstream storage (Snelder, Biggs, & Weatherhead, 2010). Stream order increases from the confluence of two or more tributaries of the same order.

Sediment bunds are located on ephemeral streams and natural low draining areas that only flow during or shortly after rain events. Ephemeral streams are characterised by an area of land where there is concentrated flow for short periods of time during and/or after rainfall but is otherwise dry for most of the time (Storey & Wadhwa, 2009). They do not have stream like features, such as natural ponds, well defined channels or a channel invert clear of vegetation as seen in intermittent streams. Ephemeral streams are also unlikely to require fish passage to be considered as part of the design due to the lack of permanent water features and flows.

Sediment bunds offer the opportunity to retain existing pasture in the retention area so there is minimal loss of productive area after construction is completed. This makes the prospect more appealing to farmers who do not want to lose productive land.

Lower order streams offer key locations for diffuse source contamination control as they have fluxes of water and water borne constituent (e.g. sediment) move rapidly through with little attenuation (Snelder, Biggs, & Weatherhead, 2010). By slowing these flashy catchment channels, the downstream effect can be substantial. Both the peak flood levels and contamination levels can be reduced.

These lower order stream areas in flat to rolling country often form natural basin areas, which are ideal for sediment bunds. Steeper hill country areas can still be utilised where natural basins and gully inverts are present. Existing topography should be used where possible as it reduces the volume of earthworks required, and hence the cost, to form the bunds.

The catchment area for sediment bunds is generally relatively small, less than 40 ha in total. This provides several advantages such as:

- Restricting the volume of storage to well below classifiable dam levels.
- Reduces earthworks required to capture the flood flows.
- Allowing the use of rational method to quickly and reliably calculate the anticipated peak flood flows.
- Is unlikely to require fish passage.

2.2.1.2 CONSTRUCTION

Sediment bunds are typically formed from local or imported soil material and formed in a similar fashion to small earth dams with keying in of the fill base, small compaction lifts, and an emergency spillway.

The impounded volume is dictated by the catchment area, recommended to be >120 m^3/ha (Smith & Muirhead, 2023).

Further, the bund height at its lowest elevation should preferably be <4 m, being the vertical distance from the bund crest to the lowest downstream outside limit of the constructed bund. The bunded area should also impound a maximum stored volume of less than 20,000 m^3. (Note that this volume does not include stored water that is lower than the natural ground level or stream level at the lowest downstream outside limit of the dam.) Where feasible, exceedance of both these measurements should be avoided as the structure will become classifiable as a 'large dam' and be subject to the *Building (Dam Safety) Regulations*.

Bunds and dams should be designed and constructed in general accordance with the *New Zealand Dam Safety Guidelines*, 2023 (NZ Society on Large Dams (NZSOLD)).

Generally, the bunding should be over engineered to allow for erosion, stock damage and poor pasture cover conditions to ensure safety over the operational lifetime.

Installation and construction will need to comply with relevant Regional and District plans. For designs with storage exceeding 1,000 m^3, design and construction must be certified by a recognised engineer. Early involvement in the project by an experienced earthworks engineer is recommended. The *Canterbury Land and Water Plan* in rules 5.154 to 5.158 sets out further requirements for Dams and Damming.

2.2.1.3 OPERATION

The bunds retain water in storm events and either continuously but slowly release the retained water or are vented after a defined period to release the water. Sediment bunds installed in the

Lake Rotorua catchment are manually vented after three days of sediment settlement. The three days allows for good settlement of contaminants without causing permanent pasture damage (Levine, et al., 2020).

2.2.1.4 EFFFECTIVENESS

Field testing of Detainment Bunds PS[120], a sediment bund developed by John Patterson, is being undertaken in the Lake Rotorua catchment. Results recorded from testing in two locations indicate that average sediment and phosphorus reductions of 28% and 20% respectively can be achieved (Levine, et al., 2020).

2.2.1.5 DISADVANTAGES

Sediment bunds require substantial earthworks for construction, this can be reduced by selecting natural basins and gullies but is still a significant investment. The construction will require the area to be removed from active use and will require stripping of topsoil, and the use of site won material or imported material to construct the bund (Patterson, Clarke, & Levine, 2019).

The bund will require active monitoring and requires manual venting by opening the outlet orifice of the primary discharge spillway,

In high sediment areas, such as poor, silty soils and downstream of active forestry, the sediment load may be substantial, and deposits may bury and supress pasture growth. If there is less than 5 cm of silt and the grass has been under water for less than three days, there is a 50:50 chance the existing grass will survive and come through the sediment (Lower North Island Combined Provincial Federated Farmers Storm Group, 2005).

Nitrogen leaching is a concern due the increased nitrogen concentration in the storage area. Levine et al notes that further study is required to understand the long term impacts (Levine, et al., 2020).

2.2.2 EXCLUSION ZONES

Exclusion zones, as the name suggests, removed access to the stream area by fencing the area off from stock and/or cultivation and cropping. This can also include riparian planting to enhance the mitigation and improve stream aesthetics though any vegetation will assist in sediment mitigation. Vegetation reduces sediment by slowing water allowing for sediment capture by settlement or natural filtering (McKergrow, Tanner, Monaghan, & Anderson, 2007).

Grazing of stock in the Timaru Rural Areas 1 and 2 is required to be managed in a way that ensures no rivers, streams or wetlands are significantly contaminated by the activities of stock or their effluent and that the functioning of riparian areas is not significantly inhibited by overgrazing, soil compaction and bank erosion caused by stock (Timaru District Council, 2005). This effectively excludes cattle, deer and pigs from grazing close to any river or stream in the Timaru region.

2.2.2.1 LOCATION

Exclusion zones around waterway edges prevents stock and cultivation in and around the fragile edges of waterways which can reduce the sediment and contamination source immediately around streams and rivers. It can also act as an initial course filter, capturing sediment and nutrients for uptake by riparian plant. The Resource Management (Stock Exclusion) Regulation (New Zealand Government, 2020) states that stock (excluding sheep) must be excluded from wide rivers (>1 m bed width anywhere in the land parcel).

2.2.2.2 CONSTRUCTION

Exclusion zones require substantial investment in fencing. The Resource management (stock exclusion) regulations require a 3 metre set back from wide rivers with either a permanent fence or riparian planting that effectively excludes stock (New Zealand Government, 2020). A permanent fence is defined as:

a) A post and batten fence with driven or dug fence posts; or

b) An electric fence with at least 2 electrified wires with driven or dug fence posts; or

c) A deer fence.

This will incur a cost on the landowner to install this fencing as well as any riparian planting costs. Fencing is generally quick to install and can be completed by the landowner or external contractor.

2.2.2.3 OPERATION

Exclusion zones use vegetation to slow and filter sediment entering flow channels. The vegetation is generally low maintenance but will need to be pruned occasionally to lower the organic matter loading in and around the stream. Maintenance and pruning also removes nutrients from the area and encourages uptake of additional nutrients from the captured sediment.

2.2.2.4 EFFECTIVENESS

Exclusion zones stop stock from entering and depositing faecal matter and urine directly in the river. This provides a substantial reduction of nutrients. They also stop sediment being directly deposited in the stream from stock damaging the river edges (McKergrow, Tanner, Monaghan, & Anderson, 2007). This provides a high initial efficacy compared to not excluding stock.

Exclusion zones also physically trap sediments and slow water encouraging settlement of sediment particles (Philips, Basher, & Spiekermann, 2020). The effectiveness is a factor of a number of factors such as width, vegetation type and cover, slope and upstream catchment (Philips, Basher, & Spiekermann, 2020).

2.2.2.5 DISADVANTAGES

Exclusion zones effectively remove the area from use as productive farmland. The vegetation can be used as fodder but only after the plants are well established and may require removal by hand or limited to sheep only (Philips, Basher, & Spiekermann, 2020).

2.2.3 WETLANDS

Wetlands are permanently or intermittently wet areas, shallow water, and land water margins that support a natural ecosystem of plants and animals that are adapted to wet conditions (Ministry for the Environment, 2024).

Constructed wetlands are structural mitigation measures designed to intercept surface runoff by diverting the flow into a static body of water which has insufficient kinetic energy to keep the sediment in the runoff entrained (Cooper , Battams, Pearl, & Hiscock, 2019). Constructed wetlands are formed using a series of linked pools of varying depths to significantly reduce the water velocity (Cooper , Battams, Pearl, & Hiscock, 2019). Wetlands can also act as retention ponds by restricting the outlet flow and storing flood flows (Deasy, et al., 2010).

2.2.3.1 LOCATION

Wetlands are where the water table is at or near the surface of the land, or where the land is permanently or temporarily (as with the tides) covered by water (Department of Conservation, n.d.).

Wetlands can be implemented at various scales, from headwaters to paddock to farm, and at the bottom of catchments, intercepting water from multiple properties before water enters lakes and estuaries (Matthews, Holland , Maetheson, Craggs, & Tanner, 2024).

Facilitated wetlands are a subset of constructed wetlands that use natural landscape features, such as depressions, to reduce construction costs (McKergrow, Tanner, Monaghan, & Anderson, 2007).

2.2.3.2 CONSTRUCTION

Constructed wetlands often require substantial earthworks to be shaped and formed. They also likely require resource consent due the nature of construction earthworks volume in and around stream bed (Environment Canterbury, 2023). Offline wetlands can also be constructed parallel to existing streams and utilise weirs to redirect the flow once construction is completed.

Wetland areas are typically 1-5% of the contributing catchment area (NIWA, 2020). Constructed wetlands work best with a well-maintained, dense cover of emergent wetland plants (Tanner , Sukias, & Woodward, 2020).

Establishing planting quickly is essential as they absorb nutrients and act to stabilise exposed banks of the wetland reducing erosion and increasing water flow resistance (Cooper , Battams, Pearl, & Hiscock, 2019).

2.2.3.3 OPERATION

A well-established wetland will have only minor maintenance requirements (Tanner , Sukias, & Woodward, 2020). Removal of accumulated sediments from the sedimentation trap/pond will be necessary periodically (Tanner , Sukias, & Woodward, 2020). If the sediment isn't removed, it may be flushed from the wetland during heavy precipitation events (Cooper , Battams, Pearl, & Hiscock, 2019).

Annual maintenance and operational costs comprise of fence maintenance and weed and pest control (Matthews, Holland , Maetheson, Craggs, & Tanner, 2024).

2.2.3.4 EFFECTIVENESS

Wetlands have high sediment retention and high initial phosphorus retention, 60 - 80% and 50 - 80% respectively (McKergrow, Tanner, Monaghan, & Anderson, 2007).

Maintenance is required in order to prevent the wetland becoming clogged with vegetation, remove stored sediment, and prevent the wetland becoming a source for pollution rather than a sink (Deasy, et al., 2010).

2.2.3.5 DISADVANTAGES

Wetlands require a relatively large area of land that is not used for productive farming, approximately 1 – 5% of the catchment area to be effective at sediment removal (NIWA, 2020). This may be mitigated by using already marginal swampy land and existing wetland areas. They also require good fencing to exclude stock from entering the area unmanaged.

Plant uptake is a temporary nutrient store as unless aging plant material is removed from the system (e.g., by biomass harvesting, stock grazing etc) (McKergrow, Tanner, Monaghan, & Anderson, 2007).

2.2.4 SMALL FARM DAMS AND RETENTION PONDS

Small farm dams can be used to help reduce sediment and nutrients as well as creating distributed on farm storage for later use as stock water supply or as an irrigation source (McKergrow, Tanner, Monaghan, & Anderson, 2007). Many hill country farms already utilize farm dams for stock water supply and irrigation but often do not factor in flood storage or retention.

Retention ponds differ slightly from farm dams where the primary focus is retaining and releasing water at a controlled rate. Retention ponds generally operate with 30% permanent pond volume and 70% operating volume (Auckland Regional Council, 2016) (Environment Canterbury, n.d.). Water captured in the operating volume is released over a period of time. 3 L/sec/ha is the recommended rate (Barber, 2014).

2.2.4.1 LOCATION

Small farm dams and retention ponds can be in gullies, ephemeral streams and on lower order streams (Smith & Muirhead, 2023). Ponds or dams situated in depressions and valleys and areas where surface waters pass can serve as very effective sediment traps as well as being useful for stock water (Ministry for the Environment, 2001).

Many farms in hill and rolling country already utilise dams as distributed water sources for stock water rather than relying on reticulated and pumped systems. The dams and retention ponds can be installed is similar locations to sediment bunds but differ in maintaining a permanent water volume for most or all of the year, reducing pasture cover area.

2.2.4.2 CONSTRUCTION

Retention ponds, while like dams, are primarily used for sediment capture and have a decanting outlet, where the outlet is above the pond invert. The low water velocity encourages settlement of larger sediment particles, and any water above permanent water volume is discharged from the water surface level, helping prevent reactivation of the settled sediment (Environment Canterbury, n.d.).

Small farm dams and ponds do not generally need to meet classifiable dam criteria as set out in the *New Zealand Dam Safety Guidelines* (NZSOLD). However, these guidelines should be considered good practice and dams should be built in general accordance with them, including providing sufficient freeboard and a constructed emergency spillway for flood events.

Further investigation, design and construction guidance for small dams can be found in the IPENZ/EngineeringNZ, *Practice Note 21: Farm Dairy Effluent Ponds* (PN21). Design and construction principles as commented on for sedimentation bunds in section 2.2.4.3 above, are also applicable to small farm dams and retention ponds.

Both farm dams and retention ponds are recommended to be fenced to prevent stock from damaging embankments, camping and stirring up sediment as discussed in the Exclusion zones section. Vegetation on the edges is also encouraged to improve bank stability and provide additional sediment and nutrient removal from the overland flow prior to entering the dam or pond.

2.2.4.3 OPERATION

Small farm dams refill by default during storm events and tend not to discharge water into the downstream environment unless overtopped as the water is repurposed for other uses. They have minimal operational requirements but do require intermittent clearing out to maintain storage volume.

The sediment retention pond design is such that very large runoff events will receive at least partial treatment and smaller runoff events will receive a high level of treatment. To achieve this, the energy of the inlet water needs to be low to minimise re-suspension of sediment and the decant rate of the outlet also needs to be low to minimise water currents and to allow sufficient detention time for the suspended sediment to settle out (Shaver, 2009).

2.2.4.4 DISADVANTAGES

Retention ponds, especially smaller ponds are less inclined to capture smaller particles such as silts and clays due to shorter settlement times (Smith & Muirhead, 2023).

Farm dams are primarily used to detain water for other purposes and water is not discharged into the downstream environment except where overtopping occurs. This can help reduce peak flood flows when the dam is empty but not during periods when the dam is already full, generally winter and early spring. They are often not sized to match the catchment and generally have an operating range as large as possible when supplying irrigation or stock water. They capture sediment and nutrients as a by product

Both retention ponds and farm dams use space that may otherwise be productive farmland.

2.2.5 LAND USE CHANGE, PRACTICE CHANGE AND REGULATION

The primary source of sediment in streams is from overland flow where the stormwater suspends particles and/or transports them, along with any contaminants into tributaries, streams, rivers, ponds and lakes, and eventually the ocean.

Land use in the tributaries and along the edge of waterways can have significant effect on the sediment load of overland flow. WSP undertook a preliminary review of aerial imagery of the Waitarakao Washdyke catchment which showed a number of cultivated and cropped fields intercepting ephemeral streams. Cultivation and removal of permanent pasture disturbs and loosens the soil surface encouraging sediment transport at both a micro and macro level. Cultivation methods can be modified to reduce sediment issues such as contour farming where cultivating is parallel to streams. Contour farming mitigates erosion by slowing down water movement, enhancing infiltration and preserving soil structure (New Zealand Association of Resource Management, 2024).

Land use change is a controversial and contentious issue and is not further discussed in this report. However, land use change does overlap with the edge of field mitigation where streams of any order are fenced and vegetated.

Figure 2. Cultivation perpendicular to lower order stream alignments

2.3 SEDIMENT AND NUTRIENT REDUCTION

The primary purpose of any water retention system is to significantly slow the water velocity. Slowing the water velocity encourages heavy particles such as sediment, nutrients and organic matter to settle out of the water column, depositing them at the base of the treatment system. Smaller particles, such as fine silts and clays, may never settle out of the water column despite the low velocity and are difficult to capture. Unfortunately, smaller particles tend to contain higher contamination levels. This is due to the larger surface area to volume and therefore more potential binding sites for nutrient per mass of sediment (Ockenden, Deasy, Quinton, Surridge, & Stoate, 2014).

Sediment bunds, wetlands and small dams work by capturing a large body of water, effectively lowering the water velocity through the system to near zero. This allows sediment to settle out of the water column and on to the base of the treatment system. Grassed swales and edge of field mitigation use the vegetation to slow water down, promoting settlement and physically capture sediment prior to entering waterways.

2.3.1 SEDIMENT REDUCTION

Sediment reduction in streams is strongly linked to nutrient reduction as many nutrients are bonded to soil particles. Reducing the sediment particles entering the waterway and capturing them once entered can help reduce downstream pollution effects.

Table 1. Sediment reduction estimates

Mitigation system	Estimated sediment reduction (%)					
	(McKergrow, Tanner, Monaghan, & Anderson, 2007)	(Smith & Muirhead, 2023)	(Paterson & North, 2022)	(Cooper , Battams, Pearl, & Hiscock, 2019)	(Philips, Basher, & Spiekermann, 2020)	Average
Sediment bunds		42 - 61%	51 - 59%			53%
Exclusion zones	30 - 90%					60%
Retention ponds	77 – 98%	70 - 94%			23-99%	76%
Wetlands	60 – 80%			69%		70%

Sediment reduction varies across the differing mitigation options with retention ponds and wetlands being the most efficient at sediment removal of suspended sediment. Exclusion zones can be extremely efficient at preventing sediment entering rivers by reducing erosion and bank damage and capturing sediment prior to entering the waterway. However, they do little to reduce sediment already in the waterway.

Sediment bunds and reasonably efficient at sediment removal and allow the temporary ponding area to be retained as pasture. This trade-off offers a good balance between sediment removal and farm use. However, caution is needed in high sediment areas to prevent significant sediment build up leading the smothering of pasture. If the pasture has been completely covered in silt (5 - 25 cm) it will not survive (Lower North Island Combined Provincial Federated Farmers Storm Group, 2005)

2.3.2 PHOSPHORUS REDUCTION

Phosphorus tends to stick to finer sediments such as silts and clays (Ockenden, Deasy, Quinton, Surridge, & Stoate, 2014). This fine sediment can be difficult to remove from the water column as it only tends to settle at very low water velocities and is easily re-suspended.

Table 2. Phosphorus reduction estimates.

Mitigation system	Estimated Phosphorus reduction (%)						
	(McKergrow , Tanner, Monaghan, & Anderson, 2007)	(Tsai, Zabronsky, Zia, & Beckage, 2022)	(Buskerud, 2002)	(Fink & Mitsch, 2004)	(Paterson & North, 2022)	(Cooper , Battams, Pearl, & Hiscock, 2019)	Average
Sediment bunds					47 – 68%		58%
Exclusion zones	15 - 40%	54.5%					37%
Retention ponds	72%						72%
Wetlands	50-80%		21 - 44%	56.2%		35%	48%

Retention ponds and wetlands are the most efficient at phosphorus removal, likely to their ability to significantly slow the water velocity. However, wetlands can saturate with phosphorus and eventually become a source rather than a sink. There does not appear to be much research regarding how long this takes, or the remediation process required to prevent this.

Sediment bunds show good potential for phosphorus removal and includes plant uptake between events helping to reduce re-suspension in following events.

Exclusion zones are less efficient at reducing phosphorus. This is likely due to the vegetation tending to catch larger sediment before it enters waterways. However, the efficacy is very dependent on multiple factors such as soil type, width, vegetation and upstream land slope. As such there is mixed estimates for phosphorus reduction.

2.3.3 NITROGEN REDUCTION

Nitrogen tends to leach through soil and into the subsurface water table. This can be captured by plants where shallow subsurface flow occurs close to waterways.

Table 3. Nitrogen reduction estimates

Mitigation system	Estimated Nitrogen reduction (%)				
	(McKergrow, Tanner, Monaghan, & Anderson, 2007)	(Fink & Mitsch, 2004)	(Mayer, Reynolds, McCutchen, & Canfield, 2007)	(Cooper , Battams, Pearl, & Hiscock, 2019)	Average
Sediment bunds					
Exclusion zones	10 – 40%		67.5%		39%
Retention ponds	82%				82%
Wetlands	30-60%	40.2%		29%	40%

Nitrogen reduction is difficult to estimate as it can leach through the soil rather than be captured and stored by mitigation options. Options that capture shallow subsoil run-off such as vegetated drains, riparian planting and planted wetlands are all good ways to reduce nitrogen.

Detention and retention systems have the potential to significantly increase leachate by pooling water and encouraging infiltration. This has potential to negatively affect ground water which can take decades to be measurably noticeable.

3 APPLICATION TO THE WAITARAKAO WASHDYDKE CATCHMENT

3.1 TOPOGRAPHY

The catchment is broadly defined into two topographical areas: the rolling hills of the upper catchment and the lowland river flats.

The lowland river flats will be difficult to manage with offline sediment retention systems, where the sediment treatment is not on the main river alignment. The flat nature of the land means overland flow is extensive and difficult to contain. The low lands are intensively farmed and the river channel is heavily modified, re-routed and shaped. The rivers in the lowland areas are also of a higher order, 2 and above. This makes online, in stream treatment more difficult as fish passage will need to be considered for any mitigation systems However, they are also generally well fenced. The easiest and likely most effective solution in these areas is exclusion and riparian planting.

The upland rolling hills are more suited to offline storage as the catchments are more defined and concentrated. This makes installing a point treatment system easier and more effective. Figure 3 shows indicates River Environment Catchment Order 1 (Ministry for the Environment, 2022) which indicates areas suitable for sediment bunds, retention ponds and other temporary storage systems.

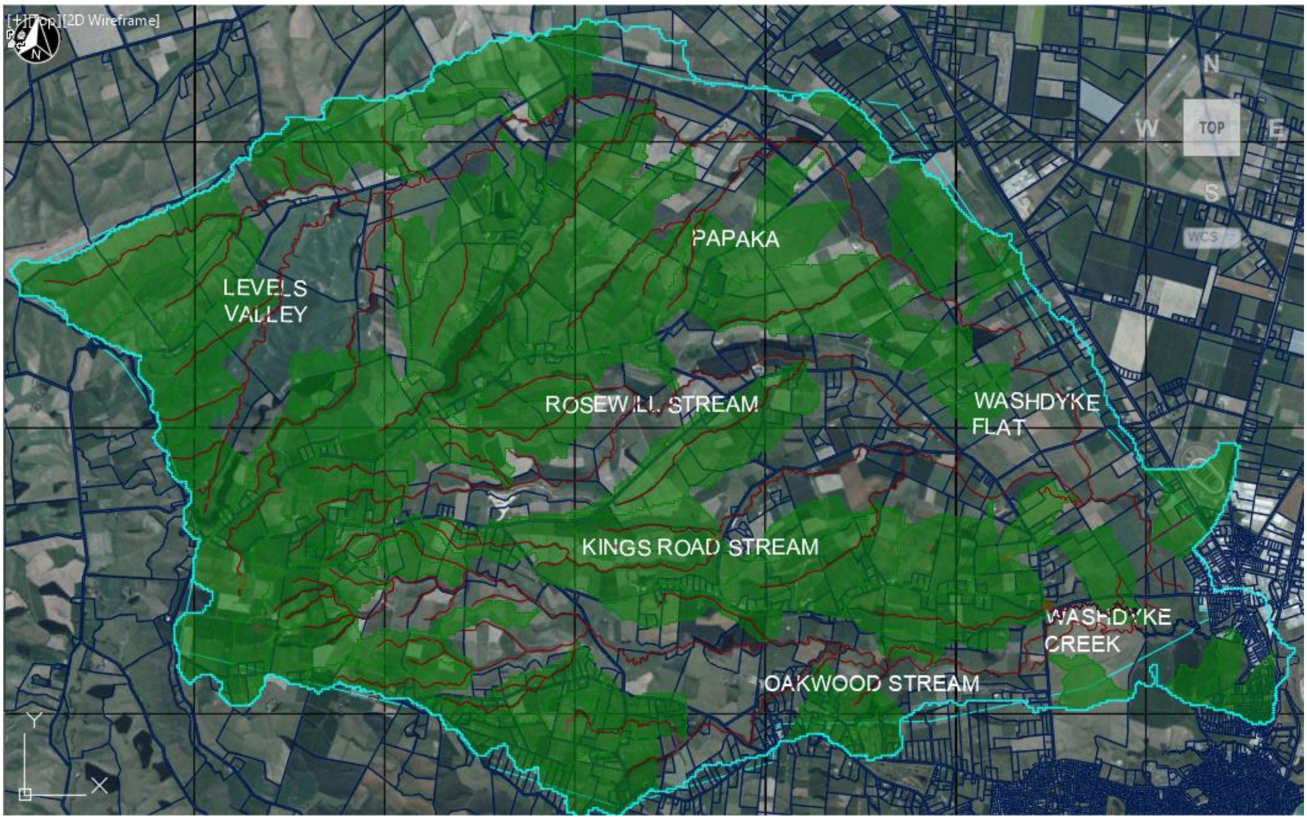


Figure 3. Waitarakao Washdyke catchment. Green indicates River Environment Catchment Order 1 ((Ministry for the Environment, 2022)

3.2 SOIL TYPE

Soils Mapping of the of the catchment area indicates the soil type present in the catchment area is Immature Pallic or Fragic Pallic. This is seen in Figure 4. These Pallic soils typically have slow permeability with limited rooting depth (Landcare Research, 2024). Fragic Pallic soils include a compact pan in the subsoil (Landcare Research, 2024).

The slow permeability of the soil reduces the infiltration of water in sediment bunds. Sediment bunds will still function as expected though losses through infiltration will likely be negligible.

Retention ponds and small farms dams may operate more efficiently for sediment and nutrient removal in this catchment as well as lowering peak flood flows.

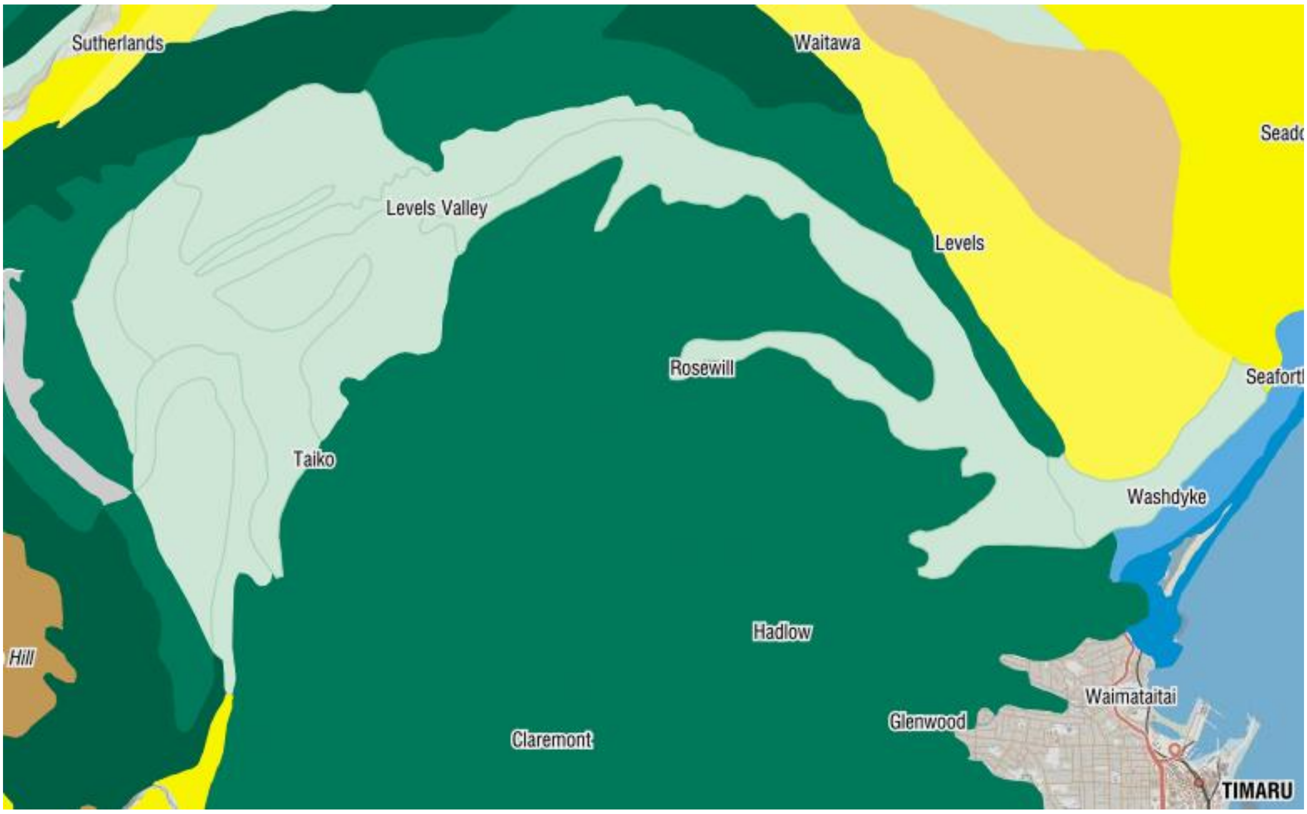


Figure 4. Soils map of the catchment area (Landcare Research, 2024). Green indicates Fragic Pallic soils and light green indicates Immature Pallic.

3.3 EXISTING FLOODING

There is no existing flood imagery of the upper catchment held in Environment Canterbury's Flood Image Register. This is likely due to flood levels rising and falling very quickly making aerial photographs difficult to capture. Figure 5 gives a good overview of the flooding in 2017 on the Papaka Stream alignment. Flooding can be seen in the main stream alignment and on ephemeral tributaries. Ponding is also noted in multiple locations.

Further study of the upper catchment areas to determine suitable locations for sediment bunds and other systems is required. John Patterson (Paterson, 2019) offers guidance for the selection of suitable locations using GIS analysis of catchments. Other systems, such retentions ponds and wetlands will require engineering design for each individual catchment area. Farm dams can be installed with little to no engineering input provided they are less than 1000 m^3, though a basic design and an experienced contractor is recommended.

An example drawing outlining the key requirements for sediment detainment bund construction has been included in Appendix A.

Figure 5. Flooding on Papaka Stream looking towards Rosewill Valley (Source: Flood Image Register, Environment Canterbury)

There are multiple images available on the Flood Imagery Register (Canterbury Maps, 2024) of the lowland river flats showing substantial flooding. The flooding typically breaks out of the existing river channels and on to the surrounding farmland as seen in Figure 6. Flooding also occurs in ephemeral channels and former river channels as seen in Figure 7. However, apart from exclusion zones, sediment and nutrient will be difficult to capture in this area. Reducing the peak flows in the upper catchments will assist in reducing flooding and sediment in the lowland areas

Figure 6. Washdyke flat flooding (Source: Flood Image Register, Environment Canterbury)

Figure 7. Flooding in the Washdyke Flat area (Source: Flood Image Register, Environment Canterbury)

4 RESEARCH GAPS

The research has been limited to high level literature review and looks at the indicative sediment and nutrient reductions that can be achieved.

For some mitigation options, such as wetlands and exclusion zones, their efficacy can increase with size. However, this relationship has not been explored in this report.

While only four mitigation systems have been identified for review, there are many more options available and variants which may improve the sediment and nutrient capture. These may be further explored depending on the system/s deemed most suitable for further development.

Long term impacts of the mitigations systems were not considered. Issues such as increased leaching of nitrogen into groundwater and long term sediment and phosphorus build up in deposition areas and wetlands should be further considered.

Fish passage has not been considered. In most cases, fish passage is unlikely to be required. however, this is dependent on the location of the mitigation system, online or offline to the main stream alignment.

The cost for each mitigation option has not been considered.

5 REVIEW FINDINGS AND DISCUSSION

The literature review indicates that the most effective sediment and nutrient removal is retention ponds. Wetlands and sediment bunds are similar in effectiveness for sediment and nitrogen removal while vegetated drains and exclusion zones have the lowest efficacy. However, all mitigation measures indicate that substantial gains can be made regardless of the system applied. Table 4 shows the average reduction for each mitigation system based on the average of the values determined in Table 1, Table 2 and Table 3.

Table 4. Mitigation system average estimated sediment and nutrient reduction.

Mitigation system	Average estimated reduction		
	Sediment	Phosphate	Nitrogen
Sediment bunds	53%	58%	
Exclusion zones	60%	37%	39%
Retention ponds	76%	72%	82%
Wetlands	70%	48%	40%

Each mitigation system has advantages and disadvantages and cannot be applied in every situation. Sediment bunds, dams and ponds will be difficult to install and operate in low slope areas with poorly defined tributary catchments. They also require some degree of design, earthworks and fencing to be installed and operated. With the exception of sediment bunds, a loss of potentially productive land will be required to operate these systems. Farm dams and retention ponds can offset this loss by providing an irrigation storage volume or stock water volume for later use.

Exclusion zones can be installed at almost any point along streams and tributaries. However, it does come with a cost of loss of productive land which may not be acceptable to the landowner. Depending on the farm use, exclusion zones on wide rivers may be enforceable under the Resource Management (Stock Exclusion) Regulation. This will likely only apply to the lower reaches of the catchment, where the river bed exceeds 1 m.

Wetlands are noted to be a good way to remove sediment and nutrients and can provide flood storage volumes. However, they require design and significant earthworks, planting, monitoring and maintenance to operate efficiently. Wetlands can, and should, be encouraged in natural wetland areas and low lying sections of the streams where productivity is low. Wetlands can also be applied inline to the main stream alignment so can help supply sediment and nutrient mitigation to the typical river flows.

6 RECOMMENDATIONS

WSP recommends the following:

- Retention ponds and small farm dams be encouraged in upper reaches and in well-defined tributaries.
- Sediment bunds be applied to the upper reaches where feasible.
- Fencing, stock exclusion and riparian planting be applied to all rivers in the catchment.
- Natural wetlands be fenced and actively managed.

7 LIMITATIONS

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for Environment Canterbury ('Client') in accordance with the A2E Engagement Terms Engagement number 394, dated 26 June 2024 ('Agreement').

Permitted Purpose

This Report has been prepared expressly for the purpose of literature review of sediment bunds and other offline retention systems for the reduction of sediment, phosphorus and nitrogen in the Waitarakao Washdyke catchment ('Permitted Purpose'). WSP accepts no liability whatsoever for the use of the Report, in whole or in part, for any purpose other than the Permitted Purpose. Unless expressly stated otherwise, this Report has been prepared without regard to any special interest of any party other than the Client.

WSP accepts no liability whatsoever for any use of this Report, in whole or in part, by any party other than the Client. Unless WSP agrees otherwise in writing, any use or any reliance on this Report by a third party is at its sole risk without recourse to WSP. Third parties must make their own enquiries and obtain independent advice in relation to any matter dealt with or any conclusion expressed in this Report.

Qualifications and Assumptions

The services undertaken by WSP in preparing this Report were limited to those specifically detailed in the Agreement and the Report and are subject to the scope, qualifications, assumptions and limitations set out in the Report and/or otherwise communicated to the Client. Except as otherwise stated in the Report and to the extent that statements, opinions, facts, conclusion and/or recommendations in the Report ('Conclusions') are based in whole or in part on information provided by the Client and other parties ('Information'). The Information has not been and have not been verified by WSP and WSP accepts no liability for the reliability, adequacy, accuracy and completeness of the Information.

The data reported and Conclusions drawn by WSP in this Report are based solely on information made available to WSP at the time of preparing the Report. The passage of time; unexpected variations in ground conditions; manifestations of latent conditions; or the impact of future events (including (without limitation) changes in policy, legislation, guidelines, scientific knowledge; and changes in interpretation of policy by statutory authorities); may require further investigation or subsequent re-evaluation of the Conclusions.

Use and Reliance

This Report should be read in its entirety and must not be copied, distributed or referred to in part only. The Report must not be reproduced without WSP's prior approval in writing. WSP will not be responsible for interpretations or conclusions drawn by the reader of the Report. This Report (or sections of the Report) must not be used as part of a specification for a project or for incorporation into any other document without WSP's agreement in writing.

Disclaimer

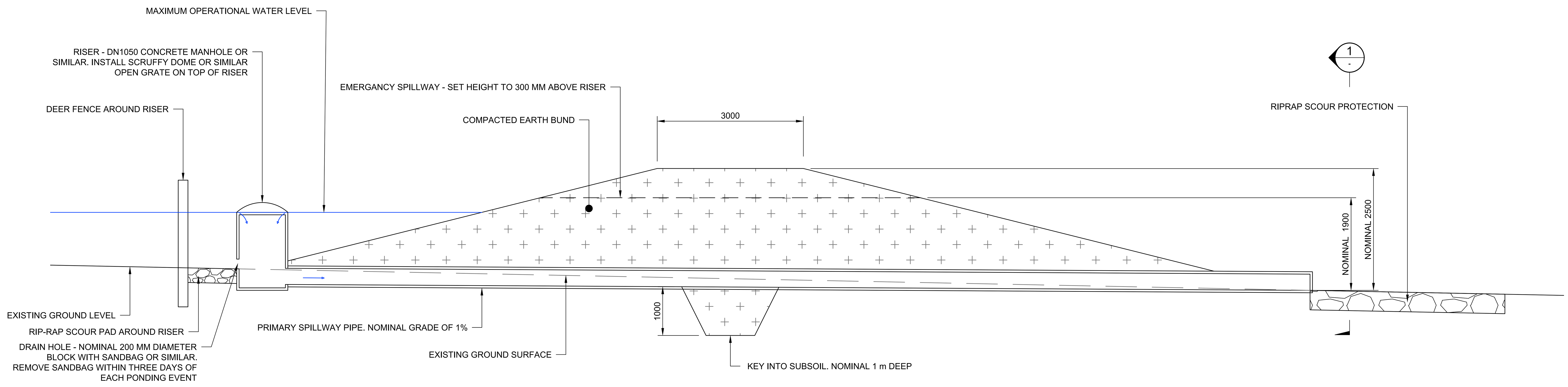
No warranty, undertaking or guarantee whether expressed or implied, is made with respect to the data reported or the Conclusions drawn. To the fullest extent permitted at law, WSP, its related bodies corporate and its officers, employees and agents assumes no liability and will not be liable to any third party for, or in relation to any losses, damages or expenses (including any indirect, consequential or punitive losses or damages or any amounts for loss of profit, loss of revenue, loss of opportunity to earn profit, loss of production, loss of contract, increased operational costs, loss of business opportunity, site depredation costs, business interruption or economic loss) of any kind whatsoever, suffered or incurred by a third party.

APPENDIX A

TYPICAL SEDIMENT BUND EXAMPLE

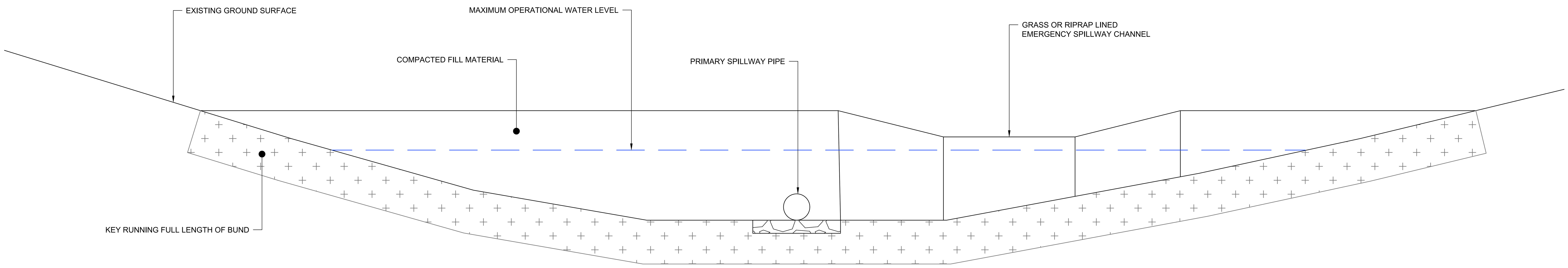
NOTES:

1. CONSTRUCT SEDIMENT DETAINMENT BUNDS AS PER "DETAINMENT BUND[PS120]: A GUIDELINE FOR ON-FARM, PASTURE BASED, STORMWATER RUN-OFF TREATMENT" (PATERSON, CLARKE AND LEVINE, 2019)
2. BUNDS WITH STORAGE VOLUME >1000 m³ REQUIRE DESIGN AND CONSTRUCTION CERTIFICATION BY A RECOGNIZED ENGINEER (ENVIRONMENT CANTERBURY LAND AND WATER REGIONAL PLAN RULE 5.154).
3. ALL CONSTRUCTION MUST BE UNDERTAKEN IN ACCORDANCE WITH THE REGIONAL PLAN REQUIREMENTS.
4. WORKS MODIFYING, DAMAGING OR DESTROYING A PRE 1900 ARCHAEOLOGICAL SITE ARE SUBJECT TO THE HERITAGE NEW ZEALAND POUTERE TOANGA ACT 2014. CONFIRM WITH HERITAGE NEW ZEALAND IF ARCHAEOLOGICAL AUTHORITY IS REQUIRED.
5. GEOTECHNICAL ENGINEER TO CONFIRM EMBANKMENT FILL SUITABILITY, EMBANKMENT FILL ZONES AND CONSTRUCTION REQUIREMENTS. SITE WON MATERIAL MAY BE USED WHERE SUITABLE.
6. REMOVE ALL TOPSOIL FROM CONSTRUCTION AREA AND STORE ON SITE. REPLACE OVER BUND AND ESTABLISH GOOD PASTURE COVER.
7. EMERGENCY SPILLWAY TO BE DESIGNED TO BE SCOUR RESISTANT. SPILLWAY MAY BE RIPRAP OR GRASS LINED. CONFIRM RIP-RAP SIZE WITH ENGINEER. GRASS LINED SPILLWAY SHALL BE INSPECTED REGULARLY AND MAINTAIN SUITABLE VEGETATION COVER.
8. REMOVE SANDBAG FROM DRAIN HOLE AND DRAIN STORAGE VOLUME WITHIN 3 DAYS OF EACH PONDING EVENT.
9. USE DEER FENCING OR SIMILAR AROUND THE RISER TO PREVENT UNAUTHORIZED ACCESS, STOCK DAMAGE AND TO ACT AS A COURSE FILTER FOR LARGE OBJECTS.



TYPICAL SECTION

SCALE 1:50 @ A1



1 - SECTION

SCALE: 1:50

1:50@ A1 / 1:100@ A3 — 0 1 2 3 4 5 m

REVISION	AMENDMENT	APPROVED	DATE
A	DRAFT - NOT FOR CONSTRUCTION		

wsp
Christchurch Office
+64 3 363 5400
PO Box 1482
Christchurch 8140
New Zealand

WATER

SCALES		ORIGINAL SIZE
1:50		A1
DRAWN	DESIGNED	APPROVED
B. STRICKLAND	B. STRICKLAND	A. JOHNSON
DRAWING VERIFIED	DESIGN VERIFIED	APPROVED DATE
A. JOHNSON	A. JOHNSON	2024-08-30

NOT FOR CONSTRUCTION

PROJECT
ENVIRONMENT CANTERBURY
75 CHURCH STREET, TIMARU
WAITARAKAO WASHDYKE CATCHMENT

TITLE
SEDIMENT BUNDS IN WAITARAKAO WASHDYKE CATCHMENT EXAMPLE DRAWING

WSP PROJECT NO. (SUB-PROJECT)	SHEET NO.	REVISION
3-9C729.13	C001	A

BIBLIOGRAPHY

Auckland Regional Council. (2016). *Erosion and sediment control guide for land disturbing activities in the Auckland region.* Auckland: Auckland Regional Council.

Barber, A. (2014). *Erosion and sediment control guidelines for vegetable production: Good management practises* . Auckland: Agrilink.

Basher, L. R. (2013). Eroosion Processes and Their Control. In J. R. Dymond (Ed.), *Ecosytem services in New Zealand* (pp. 363-374). Lincoln. Retrieved from http://www.mwpress.co.nz/__data/assets/pdf_file/0004/77053/2_7_Basher.pdf

Buskerud, B. C. (2002). Factors affecting phophorus retnetion in small constructed wetlands treating agricultural non-point source pollution. *Ecological Engineering*, 41-61.

Canterbury Maps. (2024). *Canterbury Maps* . Retrieved from Flood Imagery Register: https://apps.canterburymaps.govt.nz/FIR#!/1448330.275105875,5085225.7448869515,1460560.1996314866,5094082.885539485,2193

Cooper , R. J., Battams, Z. M., Pearl, S. H., & Hiscock, K. M. (2019). Mitigating river sediment enrichment through the construction or roadside wetlands. *School of Environmental Sciences, 231*, 146-154. doi:10.1016/j.jenvman.2018.10.035

Cullen, R., Takatsuka, Y., Wilson, M., & Wratten, S. (2004). *Ecosystem services on New Zealand arable farms.* New Zealand Agricultural and Resource Economics Society.

Deasy, C., Quinton, J. N., Silgram, M., Stoate, C., Jackson, R., Stevens, C. J., & Bailey, A. P. (2010). Mitigation Options for Phosphorus and Sediment (MOPS): reducing pollution in run-off from arable farms. *The Environmentalist*, 12-17.

Department of Conservation. (n.d.). *Wetlands*. Retrieved August 2024, from Department of Conservation: https://www.doc.govt.nz/nature/habitats/wetlands/

Ekka, S. A., Rujner, H., Leonhardt, G., Blecken, G.-T., Viklander, M., & Hunt, W. F. (2021). Next generation swale design for stormwater runoff treatment: A comprehensive approach. *Journal of Environmental Management*, 1-16. doi:https://doi.org/10.1016/j.jenvman.2020.111756

Environment Canterbury. (2023). *Canterbury Land and Water Regional Plan Volume 1.* Environment Canterbury.

Environment Canterbury. (n.d.). *Sediment control - Sediment retention ponds*. Retrieved from Erosion Sediment Control Canterbury: https://esccanterbury.co.nz/project/retention-ponds/

Fink, D. F., & Mitsch, W. J. (2004). Seasonal and storm event nutrient removal by a created wetland in an agricultura watershed. *Ecologicial Engineering, 23*, 314-328.

Landcare Research. (2024, June). *New Zealand Soil Classification*. Retrieved from Soils Map Viewer: https://soils-maps.landcareresearch.co.nz/

Landcare Research. (2024). *Soils Portal*. Retrieved from Pallic Soils: https://soils.landcareresearch.co.nz/topics/soil-classification/nzsc/soil-orders/pallic-soils/

Levine, B., Burkitt, L., Horne, D., Tanner, C., Condron, L., & Paterson, J. (2020). Quantifying the Ability of Detainment Bunds to Attenuate Sediments and Phosphorus By Temporarily Ponding Surface Runoff in the Lake Rotorua Catchment. *Nutrient Management in Farmed Landscapes*(Occasional Report No. 33).

Lower North Island Combined Provincial Federated Farmers Storm Group. (2005). *Flood Sediment.* Palmerston North: Lower North Island Combined Provincial Federated Farmers Storm Group. Retrieved August 2024, 05, from https://nzva.org.nz/assets/For_vet_professionals/Flood-resources/Flood_Sediment.pdf

Matthews, Y. S., Holland , P., Maetheson, F. E., Craggs, R. J., & Tanner, C. S. (2024). Evaluating the cost effectiveness of green infrastructure for mitigating diffuse agricultural contaminant losses. *Land* , 748.

Mayer, P. M., Reynolds, S. K., McCutchen, M. D., & Canfield, T. J. (2007). Meta-Analysis of Nitrogen Removal in Riperian Buffers. *Journal of Environmental Quality* , 1172-1180.

McKergrow, L. a., Tanner, C. C., Monaghan, R. M., & Anderson, G. (2007). *Stocktake of diffuse pollution attenuation tools for New Zealand pastoral farming systems.* Hamilton: NIWA.

Ministry for the Environment. (2001). *Managing waterways on farms: A guide to sustainable water and riperian management in rural New Zealand* . Wellington : Ministry for the Environment.

Ministry for the Environment. (2022, August 8). *Ministry for the Environment - Maps*. Retrieved from Ministry for the Environment: https://data.mfe.govt.nz/layer/52372-river-environment-classification-catchment-order-1-2010/

Ministry for the Environment. (2024). *Resource Management Act 1991.* Wellington: Ministry for the Environment.

New Zealand Association of Resource Management. (2024). *Land and Soil*. Retrieved from New Zealand Association of Resource Management: https://nzarm.org.nz/resources/knowledge-hub/land-and-soil

New Zealand Government. (2020, August 03). Resource Management (Stock Exclusion) Regulations. Wellington, New Zealand. Retrieved August 01, 2024, from https://www.legislation.govt.nz/regulation/public/2020/0175/latest/whole.html#LMS379869

New Zealand Society on Large Dams. (2023). *New Zealand Dam Safety Guidelines.*

NIWA. (2020). *Constructed wetlands to reduce contimanation loss from pastoral farms.* Hamilton: NIWA.

Ockenden, M. C., Deasy, C., Quinton, J. N., Surridge, B., & Stoate, C. (2014). Keeping agricultural soil out of rivers: Evidence of sediment and nutrient accumulation within field wetlands in the UK. *Journal of Environmental Management*(135), 54-62.

Our Waitarakao: Washdyke Lagoon Catchment. (2024). *Our Waitarakao: Waitarakao Washdyke Lagoon Catchment Strategy*. Timaru.

Paterson, J. (2019). *The DB Application Model: A GIS model for assessing catchments' suitability for the installation of Detainment Bunds PS120 to mitigate stromwater run-off.* Rotorua.

Paterson, J., & North, N. (2022). How Risky is Intercepting Farm Run-off? Assessig the Risk of Proposed StormWater Detainment Bund (PS120) Sites on NZ Farms. *Adaptive trategies for Future Farming*(34).

Patterson, J. H., Clarke, D. T., & Levine, B. (2019). *Detainment Bund PS120: A guideline for on farm, pasture based, storm water run-off treatment.* The Phosphorus Mitigation Project Inc.

Philips, C., Basher, L., & Spiekermann, R. (2020). *Biophysical performance of erosion and sediment control techniques in New Zealand: a review.* Manaaki Whenua - Landcare Research.

Shaver, E. (2009). *Hawke's Bay waterway guidelines: Erosion and sediment control.* Napier: Hawke's Bay Regional Council.

Smith, L. C., & Muirhead, R. W. (2023). A review of the effectiveness of sediment traps for New Zealand agriculture. *New Zealand Journal of Agricultural Research*. doi:10.1080/00288233.2023.2184838

Snelder, T., Biggs, B., & Weatherhead, M. (2010). *New Zealand River Environment Classification User Guide.* Wellington: NIWA.

Storey, R., & Wadhwa, S. (2009). *An assessment of teh length of permanent, intermittent and ephemeral streams in the Auckland region.* Hamilton: NIWA.

Tanner , C., Sukias, J., & Woodward, B. (2020). *Provisional guidelines for constructed wetland treatment of pastoral farm run-off.* Hamilton: NIWA.

Timaru District Council. (2005). *Part D1 - Rural Zones.* Timaru : Timaru District Council.

Tsai, Y., Zabronsky, H. M., Zia, A., & Beckage, B. (2022). Efficacy of Riparian Buffers in Phosphous Removal: A Meta-Analysis. *Frontiers in Water*(4). doi:10.3389/frwa.2022.882560