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Quantifying the Ability of Detainment Bunds to Attenuate Sediments and Phosphorus By Temporarily Ponding Surface Runoff in the Lake Rotorua Catchment

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Introduction

Lake Rotorua, in the Bay of Plenty Region on the North Island of New Zealand, is recognised as a 'taonga', or treasured natural resource, and provides valuable ecosystem services (Burns et al., 2005). Anthropogenic nutrient loading has caused ecological degradation, eutrophication and toxic algal blooms in the lake (Environment Bay of Plenty, 2009). Targets have been set to reduce nutrient loading from the catchment in order to improve lake water quality (Bay of Plenty Regional Council, 2012). To achieve these water quality objectives, models have estimated anthropogenic total phosphorus (TP) loading from the catchment would need to be reduced to 8–13 t P y^{-1} (Hamilton et al., 2015). An estimated 71-79% of P delivered to the lake from anthropogenic sources in the catchment is sediment bound (Hamill, 2018).

Pastoral dairy and drystock farms cover ~48% of Lake Rotorua's 42,000 ha surface area catchment, and contribute 67% of the total nitrogen (TN), and 43% of the total phosphorus (TP) loading from the catchment (Bay of Plenty Regional Council, 2012). Storm generated surface runoff leaving grazed pastures in the catchment is responsible for a significant portion of the annual nutrient loads delivered to Lake Rotorua (Environment Bay of Plenty, 2009).

Detainment bunds (DBs) are a mitigation strategy targeted at reducing nutrient losses from pastures in the Lake Rotorua catchment by increasing surface runoff residence times by impeding stormflow and temporarily ponding water (Fig. 1). A DB 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. A DB can be purpose-built, or constructed by modifying an existing structure, such as a raised raceway that divides a paddock.

Figure 1: Photo of a pond formed on pasture by a detainment bund impeding the flow of surface runoff generated during a storm event. The fencing protects sampling equipment from livestock.

The 'Detainment Bund Handbook' used to advise parties interested in implementing the strategy, describes features specific to DBs to include an upstand riser connected to an outlet pipe that passes through the bund and discharges ponded runoff on the downstream side of the DB (Paterson & Clarke, 2013) (Fig. 2 and 3). The upstand riser is a ~1 m diameter vertical pipe reaching to ~20 cm below the lowest point of the DB, installed near the bund at the low point of the ponding area. Ponded water may be discharged from the outlet pipe if the pond height exceeds that of the riser (Fig. 4). During large runoff events that overwhelm the pond storage capacity and discharge rates from the upstand riser, water may be discharged via an 'emergency spillway' at the lowest point of the DB. The surface of the spillway is protected by either a mat material, compacted substrate, or stable grass cover.

Figure 2: Photo of an upstand riser installed in the ponding area of a detainment bund. The riser is connected to an outlet pipe that passes through the bund, which discharges ponded runoff on the downstream side.

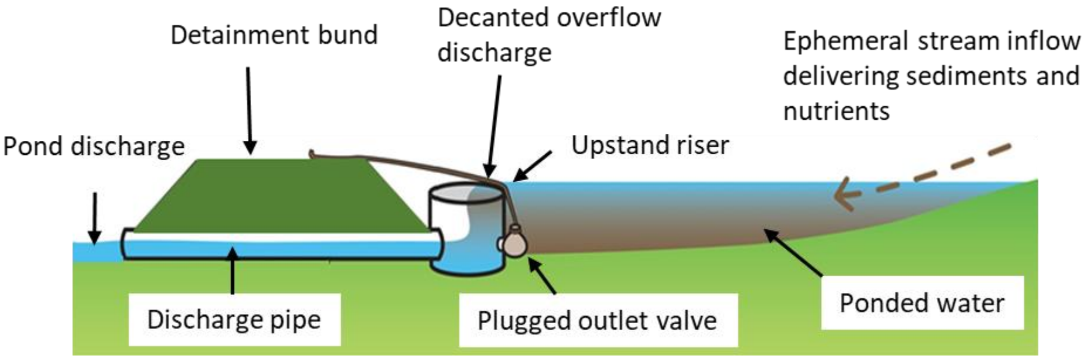

Figure 3: Cross-section of ponding area showing the ephemeral stream inflow delivering sediments and nutrients, and ponding behind a detainment bund. If the pond height exceeds the height of the upstand riser then 'decanted overflow' is discharged via a pipe passing through the bund wall.

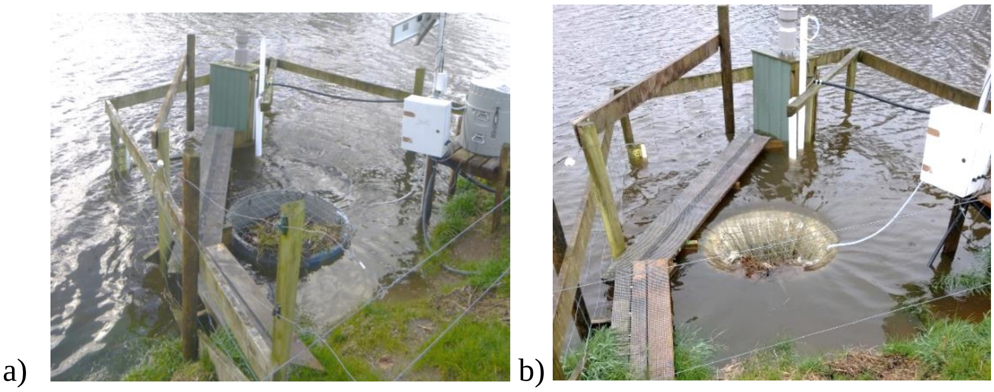

Figure 4: Photos of detainment bund pond below the height of the upstand riser (a), and breaching the upstand riser (b). Ponded water may be discharged from the outlet pipe on the downstream side of the bund if the pond height exceeds that of the riser.

A preliminary study, which served as a proof-of-concept for the strategy, found that DBs facilitated sedimentation and retained P enriched sediments (Clarke, 2013). Prior to the research reported in this study, there was no definitive quantification of the impact of the DB strategy on annual sediment and P losses from pastures in the Lake Rotorua catchment. This present study aimed to provide insight into the DB strategy's function and viability as an option available to pastoral farmers attempting to mitigate nutrient losses that contribute to eutrophication in Lake Rotorua.

Since contaminant loads in surface runoff are determined by the volume of runoff and the concentrations of contaminants, it was hypothesised that the DBs' ability to effectively mitigate nutrient losses from the DB catchments would be affected by multiple processes. First, increasing the residence time of surface runoff, by impeding stormflow on well-drained soils prevalent in pastures in the Lake Rotorua catchment, would facilitate significant soil infiltration, and therefore decrease runoff volumes and dissolved nutrient loads discharged from the DB catchments. Secondly, impeding stormflow would reduce the kinetic energy of flowing water, causing sediment deposition in the ponding area and a decrease in the concentration of sediment-bound nutrients. Lastly, increasing the residence times of runoff could allow greater time for chemical processes such as sorption to occur, that would decrease the concentration of dissolved reactive P (DRP).

Materials and methods

Achieving the research objectives required field monitoring and sample collection at 2 DBs located on pastures in the Lake Rotorua catchment for one calendar year. A digital elevation model derived from LiDAR data (2 m resolution) was used to identify appropriate locations to construct the DBs, measure catchment and pond areas, and determine pond slopes. Site selection criteria for this study stipulated that a single main ephemeral stream delivered runoff to the DB ponding area in a manner that allowed for accurate measurements of inflow volumes. The 2 DBs varied in catchment size but had similar pond storage volume: catchment size ratios (Table 1).

Table 1: Characteristics of detainment bund (DB) sites.

Characteristic	**Hauraki**	**Awahou**
Grid Reference	38°00'21"S 176°11'03"E	38°01'43"S 176°07'54"E
Year DB constructed	October 2011	June 2012
Topography of catchment	Flat, rolling and hill	Mainly rolling
Size of DB entire DB catchment (ha)	55.0	19.7
Area of DB catchment downstream of inflow monitoring (ha)	8.3	1.8
Height of bund at spillway (m)	1.56	1.80
Height of upstand riser (m)	1.36	1.60
DB pond volume ($m^{3)}$	4,894 m^3 at upstand riser 7,110 at m^3 at spillway	1,652 m^3 at upstand riser 2,244 m^3 at spillway
Ratio of pond volume: catchment area (m^3: ha)	89:1 at upstand riser 129:1 at spillway	84:1 at upstand riser 114:1 at spillway
Pond area at pond filled to upstand riser and spillway (m^2)	9,564 m^2 at upstand riser 12,221 m^2 at spillway	2,610 m^2 at upstand riser 2,940 m^2 at spillway
Average slope of ponding area (degree)	0.76°	1.64°

A detailed hydrological analysis was carried out for every storm-generated runoff event that took place during the year-long study period at the 2 DB sites. Water balances were calculated and used along with runoff sample analyses, to determine contaminate loads delivered to, and discharged from the DBs for each storm event. The data from each event was used to quantify the strategy's cumulative effect on annual loads of suspended sediments and phosphorus generated and discharged from the DB catchments.

Event types were differentiated according to the mode(s) in which ponded water was discharged from the DB. 'Overflow Events' occurred during larger runoff events when inflow continued to be delivered to the pond after the pond height exceeded the height of the upstand riser, generating 'overflow discharge' (Fig. 3). After 3 days of ponding, any residual ponded water was evacuated when the outlet valve was opened, creating 'release discharge'. Therefore, 'Overflow Events' had both 'overflow discharge' and 'release discharge' components. In contrast, ‘Non-overflow Events’ were smaller storms that did not contribute enough runoff to overtop the upstand riser.

Results and discussion

Storm generated surface runoff resulted in 18 ponding events at the Hauraki site, and 19 ponding events at the Awahou site. However, not all of the measured inflow contributed to measurable ponding events. On occasion, inflow yields were relatively small and presumably the soil was sufficiently dry to accommodate this inflow without generating measurable ponding, and the entire inflow was considered to infiltrate the soil. Ponding events occurred most prevalently during the winter months (~50% of the events at both sites) compared to the other seasons (Table 2).

Table 2: Number of each type of ponding event occurring during each austral season at the two study sites (H= Hauraki site, A= Awahou site).

		Site	**Number of Overflow Events**	**Number of non-Overflow Events**	**Total number of events**
Summer	Dec-Feb	H	0	5	5
		A	0	3	3
Autumn	Mar-May	H	1	1	2
		A	1	2	3
Winter	June-Aug	H	1	8	9
		A	1	9	10
Spring	Sept-Nov	H	0	2	2
		A	0	2	2
Total number of events		H	2	16	18
		A	2	17	19

The total annual inflow runoff yield at the Hauraki site was 167 mm (91,801 m^3) compared to 114 mm (22,404 m^3) at the Awahou site (Fig. 5). The total annual discharge yield from the Hauraki DB was 116 mm (62,969 m^3), and 65 mm (12,807 m^3) at the Awahou DB. The ~50 mm difference occurring between annual inflows and discharges at both sites was attributed to soil infiltration occurring in the ponding area.

Two high runoff magnitude Overflow Events occurred during the study period at each site in which ‘overflow discharge’ was generated when the pond height exceeded the height of the upstand riser and then the emergency spillway (Fig. 5). The combined inflow yield of these two Overflow Events was 114 mm (62,938 m^3) at the Hauraki site, and 54 mm (10,571 m^3) at the Awahou site, which accounted for 69% and 47% of the total annual inflow at the sites, respectively. Rare, large storm events have been found to be responsible for the majority of runoff, and sediment and nutrient loads delivered to surface waters in the Lake Rotorua catchment (Abell et al., 2013; Dare, 2018).

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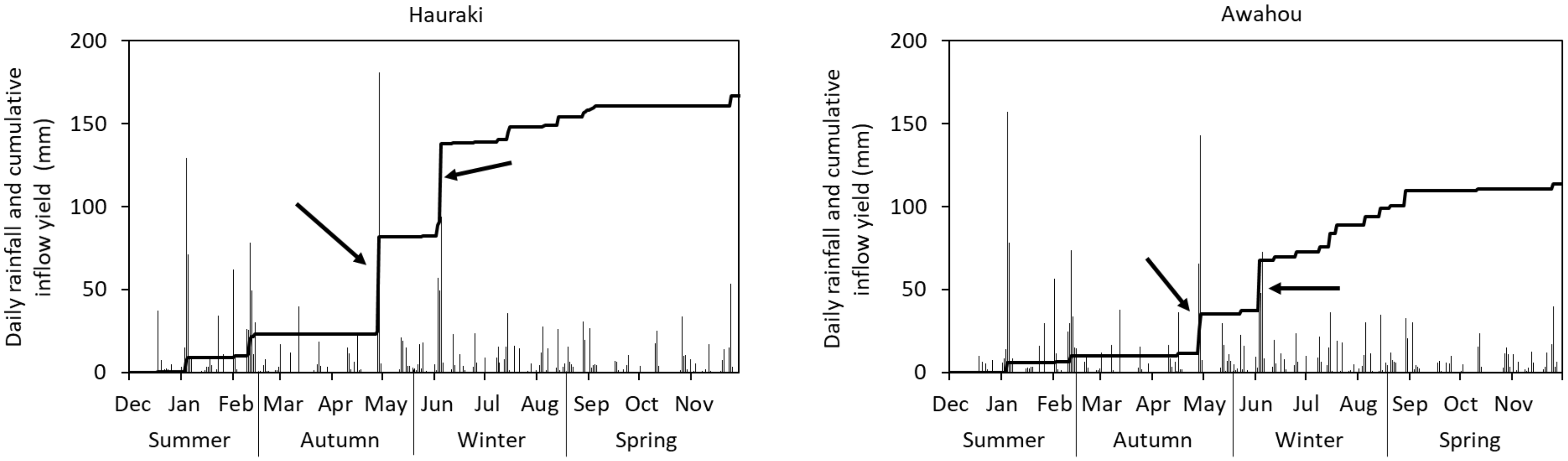

Figure 5: Daily rainfall totals (mm) (bars) and the cumulative inflow yield (mm) (line) over the duration of the 12-month study at both sites. Arrows point to high runoff magnitude Overflow Events occurring on the same dates at both sites. Note: austral seasons are labelled with corresponding months.

The fate of discharged runoff must be considered when evaluating the effect of DBs on the proportion of surface runoff inflows reaching downstream surface waters. It is unlikely that any of the overflow discharge (riser overflow and spillway discharges combined) infiltrated the soil downstream of the DBs, since runoff was still being generated in the catchments during this discharge period. In contrast, discharge after runoff generated in the catchment had ceased, including those occurring when the pond outlet valve was opened after the prescribed 3-day period, were expected to infiltrate the well-drained soils downstream of the DB before connecting with a downstream surface waterway.

The combined overflow discharge yields (riser overflow and spillway discharges combined) at the Hauraki site was 92 mm (50,579 m^3) at the Hauraki site, and 37 mm (7,367 m^3) at the Awahou site, which accounted for 80% and 58% of the total annual discharge from the DBs. Infiltration yields during Overflow Events were 16 mm (8,650 m^3) at the Hauraki site, and 12 mm (2,335 m^3) at the Awahou site, accounting 14% and 22% of the Overflow Event inflow yields at each site, respectively. At the Hauraki site, 21 mm (11,622 m^3), or 18% of the annual discharge yield was expected to infiltrate the soil downstream of the bund, and 23 mm (4,603 m^3), or 36% of the annual discharge yield was expected to infiltrate the soil downstream of the Awahou site (Fig. 6). The combined infiltration occurring during the ponding period and downstream of the bund is likely to have prevented 73 mm (40,324 m^3) of surface runoff from reaching downstream surface waters at the Hauraki site, and 72 mm (14,118 m^3) at the Awahou site. The total surface runoff likely to be prevented from reaching downstream surface waters equated to 43% of the inflow at the Hauraki site, and 63% at the Awahou site (Fig. 6).

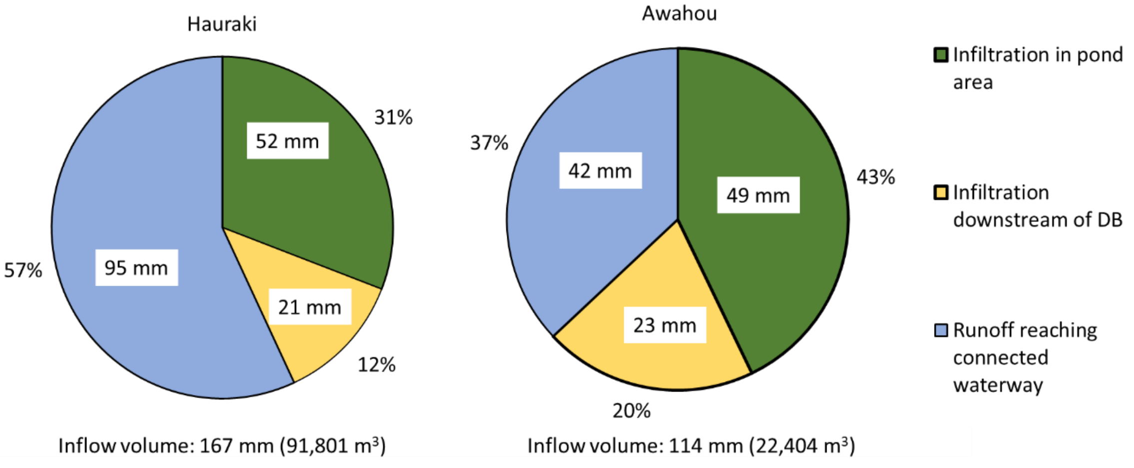

Figure 6: Yield (mm) and proportion of annual inflow infiltrating the soil in the ponding area, infiltrating the soil downstream of the detainment bund (DB), and likely to reach surface waters downstream of the bund.

Results from the 2 largest storm events during this current study, which were responsible for large portions of the annual inflow runoff and contaminant yields, point to the importance of sedimentation and chemical processes such as sorption in the ponded area, in mitigating contaminant losses during these very large storm events. Although only relatively small portion of the inflow runoff volumes infiltrated the soil in the ponding area during these large Overflow Events (14 to 22%), the quantities of sediments and nutrients attenuated in the ponding area were, by contrast, approximately twice as large (24 to 56%) (Table 3). Additionally, significant portions of the annual sediment and nutrient loads attenuated at both sites occurred during these large events (Table 3). The ability of DBs to perform effectively during high magnitude storm events will become more important over time since climate change is likely to increase the number and/or the intensity of large storms, and increase runoff and associated erosion and nutrient losses (Ministry for the Environment, 2019; Ockenden et al., 2016). Also, the results from Overflow Events highlight the importance of placing DBs in locations that maximise the pond storage: catchment size ratio in order to minimise overflow discharges during large runoff events that are responsible for the majority of contaminants that are discharged from the DBs (Table 3).

Table 3: Summary of the proportion of annual inflows delivered to detainment bunds during Overflow Events (%), the percentage of loads attenuated during these events (%), the proportion of the annual load attenuated during Overflow Events (%), and the percent change in mean flow proportional contaminant concentrations between inflow and discharges during Overflow Events (%).

	Hauraki				**Awahou**			
	Runoff	**Suspended sediment**	**Total P**	**Dissolved reactive P**	**Runoff**	**Suspended sediment**	**Total P**	**Dissolved reactive P**
Proportion of annual inflow during Overflow events (%)	69	61	68	72	47	66	54	51
Overflow Event attenuation (%)	14	32	24	29	22	54	56	44
Proportion of annual load attenuated during Overflow Events (%)	31	39	42	51	24	59	50	43
Percent change in contaminant concentration (%)		-22	-12	-18		-41	-43	-29

Results of this study suggest DBs were effective at reducing the annual sediment and phosphorus loads from being discharged from the DBs (Table 4). Multiple factors, including soil infiltration, sedimentation , and chemical processes, contributed to the DB’s ability to decrease the runoff yield and contaminant loads transported in surface runoff from being discharged from the DBs and from reaching surface waters downstream of the bunds (Tables 4 and 5). The ability of DBs to decrease surface runoff volumes by increasing the residence time of runoff on the relatively well-drained soils in the ponding area is an important finding since contaminant loads delivered to surface water in runoff are the product of the concentration of contaminants and the volume of runoff. Additionally, the ponded runoff released from the DBs after approximately 3 days of detention was likely to have infiltrated the soil downstream of the bund. During the 3 days of ponding between the storm front and releasing the ponded water, the soil downstream of the DB was likely to have dried and have restored reasonably rapid soil infiltration capabilities.

Table 4: Summary of the cumulative annual runoff yields (mm) and contaminant loads (kg) delivered to the detainment bunds in inflow, and discharged as overflow, and combined release and leak discharges. The cumulative annual runoff yield and contaminant loads attenuated in the ponding area, and the estimated load prevented from reaching Lake Rotorua are presented, as well as the proportion of annual inflow runoff and contaminants estimated to have been prevented from reaching the lake (%).

	Hauraki				**Awahou**			
	Runoff (mm)	**Suspended sediment (kg)**	**Total P (kg)**	**Dissolved reactive P (kg)**	**Runoff (mm)**	**Suspended sediment (kg)**	**Total P (kg)**	**Dissolved reactive P (kg)**
Inflow	167	1543	95	78	114	2151	18	8
Overflow discharge (riser and spillway)	92	607	47	37	37	634	4	2
Release and leak discharge (all events)	22	147	12	9	28	216	3	2
Load attenuated in the ponding area	51	789	37	32	49	1280	11	4
Load prevented from reaching Lake Rotorua	72	789	44	40	72	1280	12	6
Percentage of annual inflow prevented from reaching Lake Rotorua	43	51	47	51	63	59	68	71

Table 5: Percent change (%) in annual mean flow proportional contaminant concentrations as a result of the detainment bund treatment.

Site	Suspended sediment	Total P	Dissolved reactive P
Hauraki	-28%	-10%	-14%
Awahou	-29%	-30%	-18%

The ability of DBs to facilitate soil infiltration has an obvious impact on the loads of dissolved nutrients discharged from the DB catchments. However, the form of the dissolved nutrient affected whether the DBs ability to decrease the load transported in surface runoff actually resulted in decreased loading in receiving waters downstream. The soils in the Lake Rotorua catchment generally have high anion storage capacities (ASCs) and have the ability to sorb dissolved P that infiltrates the soil (Morgenstern et al., 2015; Reddy & DeLaune, 2008).

Sediments reaching Lake Rotorua may cause aquatic ecosystem degradation by disrupting aquatic habitats and food webs (Howard-Williams et al., 2010), and by delivering sediment-bound nutrients that contribute to eutrophication (Dare, 2018). Sedimentation has been identified as the primary mechanism involved in mitigation strategies affecting surface runoff sediment and nutrient concentrations (Stanley, 1996). During this current study, the DB strategy was found to facilitate sedimentation, decreasing SS concentrations in the majority of ponding events at both sites, and decreasing the loads of sediments discharged from the DB catchments to a greater degree than runoff discharges. Also, sediments attenuated by the DB were blanketed across the relatively wide ponding area, and are therefore more likely to be effectively held behind the DB as opposed to other strategies such as buffer strips and treatment wetlands that may have sediments flushed out during high magnitude runoff events (McKergow et al., 2007).

In order to conservatively calculate the sediments prevented from reaching surface waters downstream of the DBs, we only considered the loads attenuated in the pond, since some portion of the sediments that were discharged on release could eventually be remobilised by future runoff events, especially the high magnitude overflow events that breach the emergency spillway. However, it is also possible that some of these discharged sediments could be permanently entrained in the soil. Since we assumed any sediment-bound P discharged from the DB was likely to reach downstream surface waters, the conservative nature of the sediment load attenuation estimates also pertain to total P (TP) loads reported to be prevented from reaching Lake Rotorua. However, some of these sediments could be permanently entrained, and/or desorption could occur, releasing dissolved P that is taken up by plants and/or is mobilised into water that is then sorbed and retained deeper in the soil due to infiltration.

The investigations in this thesis found that DBs decreased nutrient losses from pastures during every storm event that occurred during the 12-month study period. One potential reason why DBs were able to consistently decrease contaminant loads discharged in runoff is that they impede the flow of even the highest magnitude stormflows, as well as the ‘first flush’ of sediments and nutrients that may have accumulated during inter-storm periods which can be rapidly mobilised when rainfall initiates surface runoff (Bieroza et al., 2019). The proportion of sediment and P loads attenuated in the ponding area was affected by the decrease in surface runoff volume, mainly attributed to soil infiltration, and changes to contaminant concentrations. Therefore, weather patterns, and land use and hydrological conditions influencing the magnitude of runoff and the concentration and form of nutrients delivered to the DB, impacted the quantity of nutrients prevented from reaching Lake Rotorua as a result of the DB strategy.

Conclusion

This study found that soil infiltration, sedimentation, and chemical processes contributed to the DB’s ability to decrease sediment and P loads transported in surface runoff from reaching surface waters downstream of the bunds. Results emphasised the important role decreased runoff volumes discharged from the DBs played in preventing contaminants from reaching Lake Rotorua. While the current study offers a degree of support to the minimum pond volume: catchment size ratio established in the current DB site selection and design protocol, results also suggest that building DBs with greater ratios would contribute to greater treatment efficiencies.

Key findings of this current study, which have advanced our understanding of the function and effectiveness of DBs as a nutrient mitigation strategy, include identifying the key role soil infiltration played in decreasing the contaminant loads from potentially reaching Lake Rotorua, and the ability of DBs to decrease contaminant loads during rare, high magnitude runoff events which have the capability to deliver the majority of annual contaminant loads to surface waters in the catchment. This current study should be expanded to collect longer-term data from more DB locations. Results from this current study, and future studies, should be used in algorithms that estimate runoff and contaminant yields delivered to, and treated by DBs in specific locations, based on hydrologic and landscape conditions. These models should be integrated into nutrient management software such as Overseer®, MitAgator® and others, to increase the adoption of DBs and allow policy makers and farmers to account for the capacity of DB's to reduce nutrient losses to surrounding water bodies.

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