Levine, B., Burkitt, L., Horne, D., Tanner, C., Condron, L., and Paterson, J., 2019. Phosphorus Mitigation Project: Quantifying the ability of detainment bunds to attenuate phosphorus and sediment loads in surface runoff from grazed pasture in the Lake Rotorua catchment. In: *Nutrient loss mitigations for compliance in agriculture*. (Eds L.D. Currie and C.L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 32. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 9 pages.

PHOSPHORUS MITIGATION PROJECT: QUANTIFYING THE ABILITY OF DETAINMENT BUNDS TO ATTENUATE PHOSPHORUS AND SEDIMENT LOADS IN SURFACE RUNOFF FROM GRAZED PASTURE IN THE LAKE ROTORUA CATCHMENT

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Introduction

Lake Rotorua is located in the Bay of Plenty Region of the North Island of New Zealand. Water quality impairment due to excess nutrients entering the lake has been recognised since the 1960s (Edgar, 2008). The Lake Rotorua Nutrient Management Plan drafted in 2012 has set a target to reduce anthropogenic phosphorus (P) inputs to the lake by 10 t/y from the ~39 t/y baseline to address water quality degradation (Bay of Plenty Regional Council, 2012).

Dairy and drystock farming accounts for ~43% of the 42,000 ha lake catchment (Bay of Plenty Regional Council, 2012). Pastoral agriculture is commonly associated with eutrophication and the deterioration of freshwater ecosystems in New Zealand (Verburg et al., 2010). This reflects that the concentration of P considered critical for accelerated lake eutrophication is an order of magnitude lower than the P concentration in soil solution critical for pasture growth (~0.2-0.3 mg/L) (Daniel et al., 1993).

The quantity of sediment and P transported from pastures to receiving water bodies is dictated largely by the volume of runoff (Braskerud et al., 2000; McDowell, 2008). Dissolved P and sediment-bound P transported from pastures by storm generated surface runoff has been identified as a significant driver of Lake Rotorua eutrophication (Burger et al., 2007; Tempero et al., 2015). Therefore, storm events present a significant opportunity to mitigate sediment and P loss from pastoral agriculture in the lake catchment (McDowell et al., 2013)

Identifying appropriate, cost-effective ways to manage nutrient loading into Lake Rotorua is a priority of the Bay of Plenty Regional Council (BPRC) and local communities, because poor water quality is impacting the aesthetic, cultural, economic and recreational values provided by the lake (Bay of Plenty Regional Council, 2012). The BPRC has been developing Detainment Bunds (DBs) as a mitigation strategy to address sediment and P transport from pastoral agriculture in the Lake Rotorua catchment since 2010 (Clarke, 2013).

Detainment Bunds are low, earthen storm water retention structures constructed in targeted low-order ephemeral streams, capable of temporarily ponding large quantities of runoff within the agricultural sub-catchment (Figure 1). The DB construction protocol promotes a minimum pond storage to contributing catchment area ratio of 120:1 m^3/ha (J Paterson, pers. comm.).

The DB design utilises an upstand riser that is located at the low point of the ponding area. Connected to the upstand riser is an outlet pipe that passes through the bund, allowing for downstream discharge. The riser can release ponded water in two ways. First, it performs a skimming action when the pond height exceeds the height of the riser, enabling the uppermost layer of the ponded water to be decanted and released (Figure 2,a). Second, a restricted drain hole at the base of the upstand riser may be released to completely drain the pond (Figure 2,b). Participating farmers are tolerant of up to three days of ponding, since longer inundation results in pasture quality deterioration (J Paterson, pers. comm.).

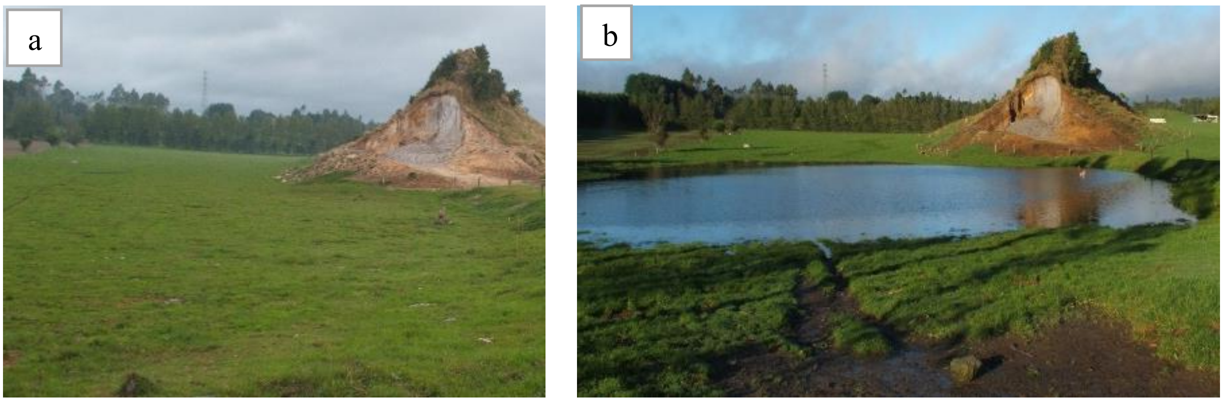

Figure 1. a) Detainment Bund on dry paddock,
b) Water ponded by Detainment Bund at the same site.

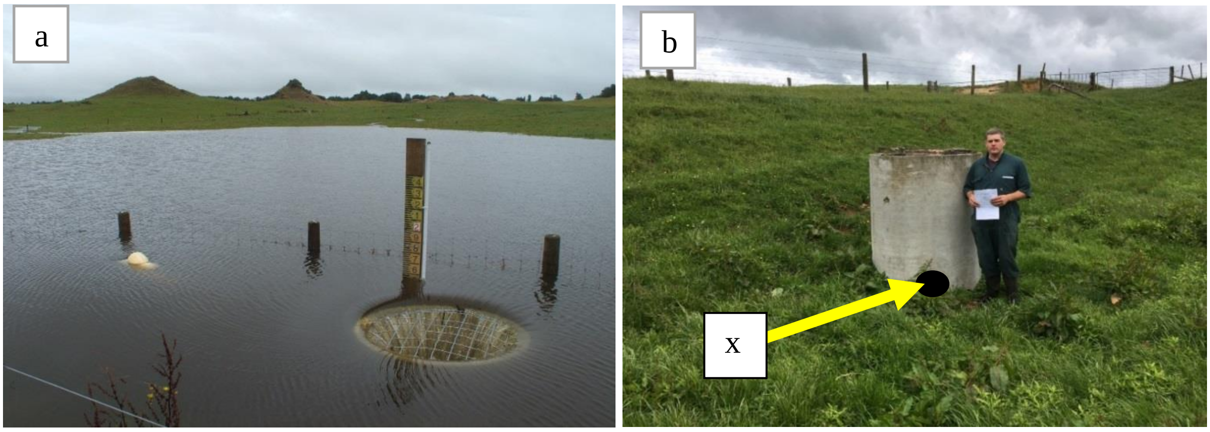

Figure 2. a) Upstand riser skimming uppermost layer of ponded water during Overflow event,
b) Upstand riser and drain hole at base (x).

The Phosphorus Mitigation Project (PMP) is a farmer initiated collaborative effort between national and regional government entities, local farmers, industry, Crown Research institutes and universities, with the goal of advancing the understanding of P mitigation impact through applied research (Clarke, 2013). The PMP has initiated research on the ability of DBs to attenuate sediments and P transported by storm generated surface runoff on productive pasture. Prior research on DBs has shown that P enriched sediments were deposited in the ponding area (Clarke, 2013). Investigations into the performance of sedimentation ponds and basins have found them to be highly effective at retaining P-enriched suspended sediments (SS) (Brown et al., 1981; Edwards et al., 1999; McDowell et al., 2006). Although these related studies serve as a proof of concept for the DB strategy, there is currently no definitive research quantifying the ability of the DBs to attenuate SS and P loads under New Zealand conditions.

This study quantifies the ability of one selected DB to attenuate sediment and P delivered by surface runoff over 12 months (beginning November 2017). Runoff samples and flow measurements were collected during 15 runoff events, upstream and downstream of the DB ponding area. Runoff concentrations and loads of SS, dissolved reactive P (DRP) and total P (TP) were determined in order to examine the efficacy of DBs and identify the mechanisms affecting treatment performance.

Materials and Methods

Site description

The study site is a dairy farm located at 38°01'43.1"S 176°07'54.4"E in the Awahou Stream catchment, which discharges into Lake Rotorua. The DB at this site was constructed in June 2012, and has an annual rainfall that regularly exceeds 2,000 mm/y. The DB pond has one main ephemeral stream channel that delivers surface runoff from a 19.7 ha area of predominantly dairy pasture with rolling topography. The DB has a minimum bund wall height of 2.03 m and an upstand riser height of 1.8 m, relative to the lowest point of the pond at the drainage outlet. The storage capacity of the DB pond is 2844 m^3 and a pond storage:contributing catchment area ratio of 135:1 m^3/ha. Table 1 describes the soil characteristics of the study site.

Table 1. Soil characteristics of study site located in the Awahou Stream catchment

Soil classification	**Texture profile**	**Drainage class**	**Topsoil P retention**	**Parent material origin**
Typic Orthic Podzol	Sandy loam	Well drained	Medium (42%)	Tephra

Volume and water sampling

Isco® auto-samplers and Starflow® flowmeters were installed at a pipe channelling the entire main ephemeral stream upstream of the DB ponding area, and in the pond drainage pipe downstream of the pond. The auto-samplers were capable of collecting twenty-four-1 L water samples and were triggered to collect samples when flows exceeded 7 L/sec. The upstream auto-sampler was programmed to sample every 20 minutes for the first 10 samples, then one sample per hour thereafter. The downstream auto-sampler was programmed to collect one sample per hour. Downstream samples were generated when the upstand riser was exceeded during ponding, and during pond release at the end of the event treatment. A persistent leak in the riser structure that generated flows of <2 L/sec occurred throughout ponding. Water samples of the continuous leak were collected during 7 events to characterise the concentration of sediment and P of the leak flow.

Sample analysis

Water samples were collected from the field and kept refrigerated at 4 °C prior to subsampling (~30 mL) for separate DRP and TP concentration analysis. The subsamples for DRP analysis were filtered (<0.45 µm) ~24 h after collection. Both the filtered and unfiltered subsamples were subsequently frozen until analysis. Unfiltered samples were analysed using the alkaline persulphate digestion method of Hosomi and Sudo (1986). Both digested and filtered subsamples were analysed for P concentrations using the FIA with Lachat QuickChem methods 10-115-01-1-A (PO_4^{3-}) (Lachat Instruments, 1998). The remaining volume of each field sample was refrigerated until SS analysis following the standard procedure from the American Public Health Association (2005).

Data analysis

The 15 runoff events over the course of this study were separated into three event types for comparison. Three 'Overflow' events occurred in which the pond height exceeded the height of the upstand riser and a portion of the delivered runoff was discharged via the upstand riser skimming the uppermost layer of water. Eleven 'Release' events occurred in which the pond height did not exceed the height of the upstand riser, but ponded water remained to be discharged when the drain hole at the base of the riser was opened. One 'Non-release' event occurred in which the riser was not exceeded and no water remained in the pond after the prescribed treatment duration due to soil infiltration and leakage. Upstream volumes and contaminant loads were increased by 6.5% to correct for the 1.8 ha catchment area between the US sampling station and the DB.

Volumes

Upstream and downstream water volumes were calculated by multiplying the measured flow rate by the time elapsed between flow measurements (typically 5 min intervals). Ponded water was discharged downstream by potentially three means during each event. Firstly, when the pond height exceeded the upstand riser, secondly, when the valve was opened to drain the pond and thirdly, when a persistent leak in the riser structure generated flows of <2 L/sec which occurred throughout ponding during all events. Combined soil infiltration and evaporation was calculated by subtracting the discharge volume, including leakage, from the corrected upstream volume.

Loads and concentrations

Loads of SS, DRP and TP were calculated by multiplying the volume, determined by the measured flow (5 minute intervals), by the concentration of the runoff sample (20 min or 1 hr intervals) at the corresponding time. Concentrations of flow between sample collection times were assigned values based on the linear rate of change between samples and multiplied by the measured corresponding flow to calculate load. Loads were determined for upstream runoff, and downstream discharge (overflow, leak, release) for each event. Load attenuation for each event was calculated by subtracting downstream loads from upstream loads. Mean load attenuation percentage was calculated by averaging the load attenuation for each event, within each event sub-type.

Upstream and downstream flow-weighted mean concentrations of SS, DRP and TP were calculated by dividing delivered or discharged load by the respective volume for each event. Based on the analysis of leak concentrations from selected events, the mean upstream concentration was applied to the leak concentration for the respective event. Changes between upstream and downstream mean SS, DRP and TP concentrations were calculated for each event. Mean percent change in SS, DRP and TP concentrations for each event type was calculated by averaging the change of contaminant concentration from each event within the event sub-type.

Results

Event hydrology

The range and mean of runoff volume delivered to the ponding area (Inflow), and range and percentage of inflow for each type of discharge (Riser overflow, Infiltration, Leak and Release) were calculated for each event type (Table 2). Infiltration accounted for a higher percentage of inflow when greater volumes of runoff were delivered to the pond. The leak volume accounted for a higher percentage of inflow when low volumes of runoff were delivered to the pond.

Table 2. Volume range and mean of runoff delivered to Detainment Bund pond (Inflow) and discharged from the pond for Overflow, Release and Non-release events. Mean values are in brackets.

	Volume range ($m^{3)}$	% of inflow
Overflow events n=3		
Inflow	2308-5890 (3669)	
Riser overflow	250-1461	25
Infiltration	1352-4047	64
Leak	83-190	4
Release	182-283	7
Release events n=11		
Inflow	467-2177 (1108)	
Infiltration	252-1666	47
Leak	98-528	16
Release	63-327	37
Non-release event n=1		
Inflow	277	
Infiltration	89	32
Leak	188	68

Event concentrations and loads

Over the course of the yearlong study, 15 runoff events were measured. The average soil infiltration over the 15 events was 61%. The Overflow events had the greatest effect on SS, DRP and TP concentrations and loads (Figures 4 and 5). The settling of sediments and associated particulate P, and the skimming action of the uppermost layer of ponded water, could explain the greater concentration change and attenuation of SS and TP during Overflow events. The lack of change in concentration and the 32% change in load for all parameters during the Non-release event was due to the leak being the only downstream discharge during the event, and the leak being assigned the concentration equal to the upstream mean concentration. Since we assumed no change in concentration between upstream runoff and downstream discharge occurred, a 32% infiltration value generated a 32% load attenuation. Over the course of all 15 events in this study, the DB attenuated a combined 1467 kg (78%) suspended sediments, 5.2 kg (63%) dissolved reactive P, and 11.6 kg (66%) total P over the course of the study (Table 3).

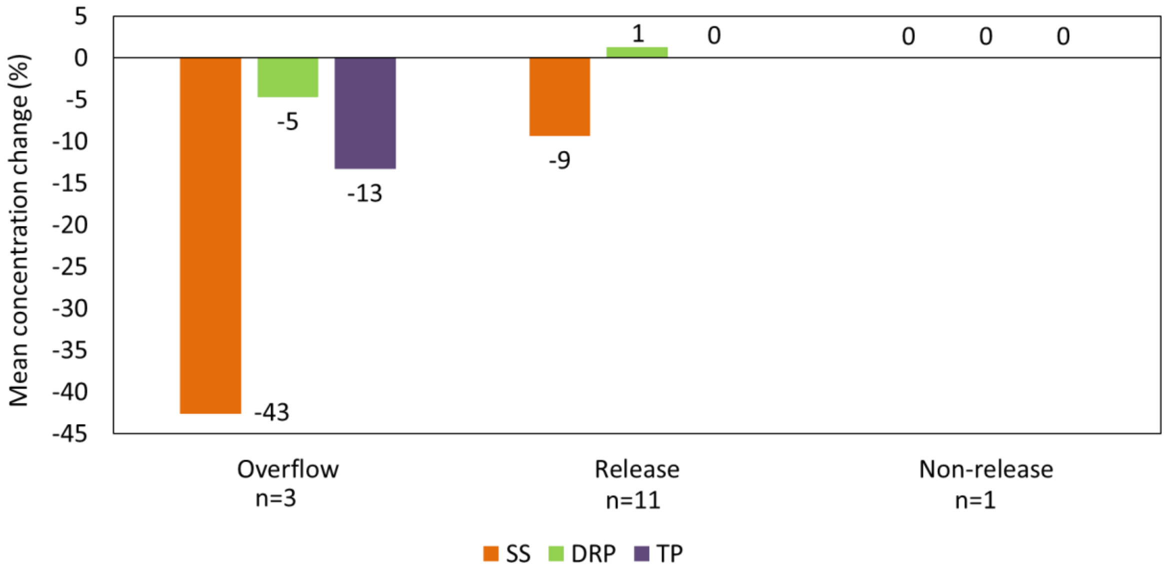

Figure 4. Mean change in suspended sediment (SS), dissolved reactive P (DRP) and total P (TP) flow-weighted concentrations for Overflow, Release and Non-release events.

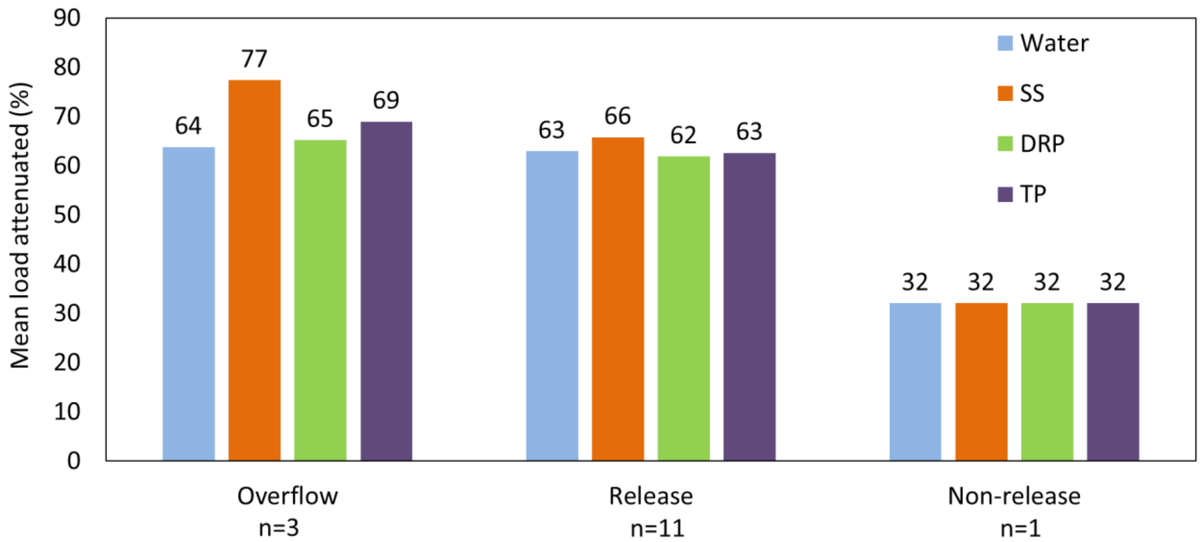

Figure 5. Mean volume, suspended sediment (SS), dissolved reactive P (DRP) and total P (TP) loads attenuated during Overflow, Release and Non-release events.

Table 3. Summary of overall attenuation performance from 15 storm generated runoff events at one Detainment Bund location.

All events n=15	Volume (m^3)	Load SS (kg)	Load DRP (kg)	Load TP (kg)
Delivered	22,400	1,902	8	17
Decrease	14,509	1,476	5	12
% Decrease	65	78	63	66
Decrease/ha[A]	737	75	0.3	0.6

[A] Based on a catchment area of 19.7 ha

Discussion

The results of this study suggest that utilising DBs to temporarily pond surface runoff decreases the volume of runoff and loads of SS, DRP and TP leaving the treatment catchment (Table 3). Data suggests that the proportion of runoff that infiltrates the soil is equivalent to the proportion of P loads being attenuated by the DB strategy over the 12 month study (Table 3). Suspended sediment attenuation was greater in Overflow events in which greater quantities of runoff were delivered to the pond and the pond height exceeded the upstand riser, enabling the riser to skim and release the uppermost layer of water (Figure 5). The data also suggests DBs attenuate greater quantities of TP during Overflow events, which is likely due to the greater attenuation of sediment-bound particulate P. These results might be explained by selective erosion based on the size of runoff events. During larger runoff events, coarser particles that more readily settle during ponding are more likely to erode these, while smaller runoff events will likely have more fine grained particles that do not settle as readily (Braskerud et al., 2000). Also, as greater quantities of runoff are delivered to the pond, the pond surface area increases, which may lead to greater sediment retention as found in studies of constructed wetlands (Braskerud, 2005).

Conclusion

The results of this study suggest the DB strategy is an effective mitigation option able to address sediment and P transported from pastures in surface runoff in the Lake Rotorua catchment. Preliminary results from 15 runoff events showed an attenuation of 1476 kg (77%) of suspended sediments, 5.2 kg (63%) of dissolved reactive P, and 11.6 kg (66%) of total P over the course of a year from a 19.7 ha catchment. The proportion of sediments and P attenuated was similar to the proportion of runoff that infiltrated the soil during ponding over the course of the study. The results of this study suggest that DBs located on pastoral farms with well-drained soils have the ability to reduce the quantity of sediment and P transported by surface runoff. Understanding the treatment mechanisms and quantifying DB performance is necessary for decision makers interested in utilising DBs at a wider scale, and for the potential development of a nutrient attenuation credit program using nutrient management software. Future studies should investigate other DB sites, the impact on nitrogen by DB treatment, longer-term DB performance, the fate of P in the soils of DB ponding areas, and perform a cost:benefit analysis of DBs to compare to other runoff mitigation strategies.

Acknowledgements

This applied research on DBs was initiated, and is governed by, the Phosphorus Mitigation Project Incorporated. We would like to acknowledge the following funding agencies: Ministry of Primary Industries Sustainable Farming Fund, National Institute of Water and Atmospheric Research's Strategic Science Investment Fund, Dairy NZ, Bay of Plenty, Environment Canterbury, Waikato and Horizons Regional Councils, Ballance AgriNutrients Ltd., Beef and Lamb NZ, and Deer Industry NZ.

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