

The ability of detainment bunds to decrease sediment loss from pastoral catchments in surface runoff: Investigating a novel stormwater mitigation strategy

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Abstract

Erosion leading to sedimentation in surface water may deliver sediment-bound nutrients that contribute to eutrophication. Loss of native vegetation driven by land use changes have accelerated the naturally high rates of erosion in New Zealand and increased sedimentation in streams and lakes. Water quality in Lake Rotorua, in the Bay of Plenty region, New Zealand, has declined since the 1960's due to land use developments contributing to nutrient loading and eutrophication. Anthropogenic P loads delivered to the lake are 17-19 t P y⁻¹, 71-79% of which are sediment-bound. Lake sediments release an estimated 48% of the total annual P load. Detainment bunds (DBs) were first implemented in the Lake Rotorua catchment in 2010 as a strategy to address P losses from pastoral agriculture. Detainment bund are 1.5-2 m high earthen stormwater retention structures, constructed on productive pasture across the flow path of targeted low-order ephemeral streams. The current DB design protocol recommends a minimum pond volume of 120 m³ ha⁻¹ of contributing catchment with a maximum pond storage capacity of 10,000 m³. No previous study has investigated the ability of DBs to decrease annual suspended sediment (SS) loads leaving pastoral catchments. Annual SS yields delivered to 2 DBs, with 20 ha and 55 ha catchments, during this 12-month study, were 109 kg SS ha⁻¹ and 28 kg SS ha⁻¹, respectively. Results suggest that the DB strategy decreased annual SS loads discharged from the DB catchments by 1280 kg (59%) and 789 kg (51%) as a result of the bunds' ability to impede stormflow and facilitate soil infiltration and sedimentation. The results of this study highlight the DB strategy's ability to consistently decrease SS loads leaving pastures in runoff, even during rare, high magnitude storm events, and suggests DBs are likely able to reduce P loading in Lake Rotorua.

Introduction

Suspended sediments (SS) are organic and inorganic particles transported in suspension by water (Bilotta et al., 2009). Rainfall and surface runoff cause erosion, leading sedimentation in surface waters and causing aquatic ecosystem degradation by disrupting aquatic habitats and food webs (Howard-Williams, Davies-Colley, Rutherford, & Wilcock, 2010), and by delivering sediment-bound nutrients that contribute to eutrophication (Dare, 2018). Land use developments clearing native forests have accelerated the already

naturally high rates of erosion across New Zealand and caused significant sedimentation in lakes and streams (Ministry for the Environment, 2019).

Pastoral agriculture in New Zealand is strongly associated with eutrophication and degraded freshwater ecosystems (Verburg, Hamill, Unwin, & Abell, 2010). Treading by grazing animals physically disrupts the soil, and increases the likelihood of surface runoff and erosion by decreasing infiltration rates and porosity, and impairing plant growth (Bilotta, Brazier, & Haygarth, 2007; R. W. McDowell et al., 2003; Ward, Talbot, Denne, & Abrahamson, 1985). Year-round grazing and high stocking rates used to graze crops are common practices in New Zealand and contribute to increased erosion (Monaghan et al., 2007). Addressing erosion is a challenge for pastoral farmers in New Zealand, particularly those on sloping landscapes, due to variable precipitation patterns with very wet winters, and dry summers interspersed with large storms (R. McDowell, Wilcock, & Hamilton, 2013). Erosion is likely to be intensified by climate change causing more dramatic hydrologic conditions (Ministry for the Environment, 2019; Ockenden et al., 2016).

Since the 1960's water quality in Lake Rotorua, in the Bay of Plenty Region on the North Island of New Zealand, has declined due to nutrient inputs from residential, commercial, industrial and agricultural developments (Environment Bay of Plenty, 2009). An estimated 43% of the annual total phosphorus (P) delivered to the lake comes from pastoral dairy and drystock farms which cover ~48% of the 42,000 ha Lake Rotorua surface catchment (Bay of Plenty Regional Council, 2012). Between 71-79% of the anthropogenic P delivered to the lake is sediment bound (Hamill, 2018), and a portion of that may become biologically available under anoxic conditions which occur in Lake Rotorua and contributes to lake eutrophication (Abell & Hamilton, 2013). Lake sediments release an estimated 36 t P y⁻¹, accounting for ~48% of the total annual P loading (Bay of Plenty Regional Council, 2012). Intensified anoxic conditions during periods of warmer temperatures have caused significantly greater contributions to annual P loads by lake sediments (Burns, McIntosh, & Scholes, 2005).

The 2012 Lake Rotorua Management Plan has set a target to reduce annual TP loads delivered from the catchment by 10 t P y⁻¹ by 2022 from the estimated 39 t P y⁻¹, in order to restore lake water quality (Bay of Plenty Regional Council, 2012). Achieving Lake Rotorua water quality targets by addressing P loading from pastoral agriculture will require combining multiple appropriate nutrient mitigation strategies and potentially developing new technologies (R. W. McDowell, 2010).

Mitigation strategies that increase stormflow residence time have been found to decrease surface runoff flows, leading to increased sediment deposition by decreasing the kinetic energy of flowing water (Dosskey, 2001; McKergow, Tanner, Monaghan, & Anderson, 2007; Stanley, 1996). However, the type of mitigation strategy affects the duration sediments are attenuated. Studies have found that sediment retention times are more brief (weeks to months) where sediments accumulate in more concentrated areas, such as narrow grass filter strips and constructed treatment wetlands, compared to strategies where sediments are blanketed over a wide area, which may have retention times of up to hundreds of years (McKergow et al., 2007).

Previous research has found that ponding surface runoff can decrease discharge concentrations and loads of sediments and particulate bound P by decreasing the kinetic energy of flowing water (Brown, Bondurant, & Brockway, 1981; Harper, Herr, Baker, & Livingston, 1999; Levine et al., 2019; R. W. McDowell et al., 2006; Stanley, 1996). Detainment bunds (DBs), are earthen storm water retention structures constructed on pastures across the flow path of targeted low-order ephemeral streams capable of impeding stormflow and temporarily ponding up to 10,000 m³ of surface runoff. The structures were implemented in the Lake Rotorua catchment in 2010 as a mitigation strategy to target P losses from pastures (Clarke, 2013). A concurrent paper by Levine et al., (In review) investigating the strategy's effect on stormwater volumes leaving the same DB catchments during the same storm events as this current study presents further detail on DB design and function.

Preliminary studies of DBs in the Lake Rotorua catchment have found that P enriched sediments were deposited in DB ponding areas (Clarke, 2013), and that a DB effectively decreased runoff volumes, and sediment and P loads, discharged during 3 non-consecutive ponding events (Levine et al., 2019). A concurrent

study investigating the same ponding events at the same DB sites as this present study reported 31 and 43% and noted that deposited sediments could be developing a less permeable surface soil layer and/or clogging soil pore spaces and causing infiltration rates to decline in the ponding areas (Levine et al., In review).

Although erosion is recognised for its potential impact to aquatic ecosystems, there is room to progress our understanding of the transport and fate of sediments from intensively managed pastures (Haygarth et al., 2006). To determine if DBs could provide a viable strategy for pastoral farmers to improve Lake Rotorua water quality, it is important to quantify their ability to decrease SS loads. The main objective of this study was to measure the effect of the DB strategy on SS concentrations and yields delivered to 2 DBs with 55 ha and 20 ha catchments, located on pastures in the Lake Rotorua catchment, and identify the factors influencing the results. Previous studies on DBs, and related mitigation strategies, suggest ponding surface runoff facilitates sedimentation, although there is currently no definitive research quantifying the impact of the DBs on annual sediment loads transported from pastures in the Lake Rotorua catchment. We hypothesised that ponding surface runoff will facilitate sedimentation and result in lower discharge concentrations, which, combined with soil infiltration lowering runoff discharge volumes reported in a concurrent study by Levine et al. (In Review), will decrease annual SS loads discharged from the treatment catchments.

Materials and Methods

Site descriptions

The 2 DBs investigated during this current study, along with concurrent studies investigating the effect of DBs on hydrology and nutrients during the same storm events from 1 December 2017 to 30 November 2018, were located on pastoral dairy farms in the north-western portion of the Lake Rotorua catchment. Table 1 describes site characteristics reported by the concurrent studies. The Oropi series soils at the the Hauraki site, and Waiteti series soils at the Awahou site are both free draining, with >72 mm/h permeability in slowest horizon (Rijkse & Guinto, 2010).

Event types

Event types reported on in this, and concurrent studies, were differentiated according to the mode(s) 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 (**Fig. 1**). 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 and release discharge components. In contrast, ‘Non-overflow Events’ were smaller storms that did not contribute enough runoff to overtop the riser. Non-overflow Events included events when at the end of the 3-day treatment period, either had a portion of ponded runoff to discharge by opening the release valve, or all ponded runoff leaked and infiltrated the soil so there was no water left to discharge.

Equipment

Isco[®] (California, USA) 6712 portable auto-samplers, capable of filling 24 x 1 L bottles collected inflow and discharge samples at each site when triggered by a telemetered UNIDATA[®] Neon[®] 2013 F 3G External Memory Metering Module data loggers linked to UNIDATA[®] 6527 Starflow[®] QSD flowmeters. The auto-samplers were triggered to collect 1 L samples when flows exceeded 7 L/s (Harmel, King, Wolfe, & Torbert, 2002). Calibration and maintenance of the monitoring equipment followed standard quality controls (NIWA, 2004).

Inflow auto-samplers collected a 1 L sample every 20 min for the first 10 samples, then one 1 L sample/h thereafter (Harmel, King, & Slade, 2003; Stanley, 1996). The mouth of a rain guarded 750-mL self-sealing

bottle using a ping-pong ball inside the bottle, was installed at ground level near the pond outlet valve to capture a sample of the initial flush of surface runoff generated before the inflow auto-sampler was triggered. The ping-pong ball bottle sample was used as the concentration of the initial runoff and used in calculating event inflow yields

Discharge auto-samplers were programmed to collect a 1-L sample/h (Harmel et al., 2003; Stanley, 1996). Sampled discharge flows were generated if the pond height exceeded the upstand riser height during pond filling (i.e. ‘overflow discharge’) (**Fig. 1**), and when the valve at the base of the riser was opened to release the pond at the end of the event treatment, typically on the third day of ponding (i.e. ‘release discharge’).

Throughout all ponding at both sites an intractable leak at the connection point of the outlet valve pipe and the base of the upstand riser generated a continual flow of $\sim 2\text{--}4\text{ m}^3/\text{h}$. Attempts at sealing this leak during the study period were unsuccessful. Under normal sampling conditions, the leak flow was too low to trigger the auto-samplers, although leak samples were collected during 4 events at the Hauraki site, and 1 event at the Awahou site, in order to characterise the SS concentrations of the leak discharge.

Water samples were collected from the field within 24 h of the end of the ponding event and kept refrigerated at $4\text{ }^\circ\text{C}$ prior to subsampling (within ~ 24 h of collection). Two separate subsamples (~ 30 mL) were taken from the field sample after vigorously shaking the bottle, to analyse total and dissolved N and P. The remaining field sample was kept refrigerated until being analysed for SS concentrations used in this current study, following the standard procedure from the American Public Health Association (2005).

Calculations

Mean flow proportional concentrations

Event and annual mean flow-proportional (MFP) SS concentrations were calculated by dividing the inflow and discharge loads by their respective volume (Tanner & Sukias, 2011). The average difference between the event MFP inflow and leak samples collected during 5 events was +3%, with no consistent increase or decrease. Due to the negligible difference between the MFP inflow and leak concentrations, the MFP inflow concentration was applied to the entire leak volume for each respective event in which the leak discharge was not sampled. The applied leak concentration was used to calculate the event MFP discharge concentrations and event discharge loads. All inflow and discharge MFP concentrations will be referred to only as inflow and outflow concentrations.

Loads and yields calculation

Loads of SS in inflows and each discharge type were determined for all ponding events. Inflow loads of SS were calculated by multiplying the measured concentration of the runoff samples collected by the ping-pong ball sample bottle and auto-samplers, and using interpolated concentrations based on the linear rate of change between measured concentrations, by the interval flow volume measured every 5 minutes. Inflow loads were corrected on a pro rata basis (15% increase at the Hauraki site and 9% increase at the Awahou site) to account for the small catchment area between the inflow monitoring site and the DB (**Table 1**).

Discharge loads were calculated for overflow discharge (combining upstand riser and spillway breaching), release discharge (which occurred during Overflow events and Non-Overflow events), and leak discharge. The load of each discharge type was calculated from flow measurements and sample concentrations taken from the DB outlet pipe, except for emergency spillway breaching. Emergency spillway loads were calculated by applying the MFP concentration of the overflow discharge generated by ponded water discharged by going over the upstand riser to the volume breaching the spillway calculated by the concurrent study reporting on hydrology. Yields refer to the load per unit of contributing catchment area and expressed as mm for runoff volumes, and kg ha^{-1} for SS loads.

Data analysis

Water sample data analysis

Events were grouped by site, then analysed for overall annual results, and results for each event type. Changes to concentrations were calculated as the percent difference between inflow and discharge concentrations. The percent difference between inflow and discharge yields were reported as ‘yield treatment efficiencies’. Inflow yield data for each site was also organised by austral seasons (i.e. summer from December to February) to compare differences between the sites and identify seasonal patterns for SS inflow yields.

Results and discussion

Storm generated surface runoff resulted in 18 ponding events at the Hauraki site and 19 ponding events at the Awahou site during this 12-month study. Ponding events occurred most often during the winter months compared to the other seasons (**Fig. 2**). Water samples were analysed for 13 of these ponding events at the Hauraki site, and 14 events at the Awahou site, since not all ponding events generated flow rates high enough to trigger auto-samplers. Discharge samples were collected during 10 events at the Hauraki site, and 13 events at the Awahou site, since not all events generated discharge flows to be sampled due to leakage and soil infiltration.

Concentrations

The annual SS inflow concentration was 17 g m^{-3} at the Hauraki site, and 96 g m^{-3} at the Awahou site. Concentrations peaked in the winter at the Hauraki site, while there was no clear temporal trend for inflow concentrations at the Awahou site (**Fig. 2**). Event inflow concentrations did not tend to correspond to event runoff magnitudes and varied widely between events.

The annual MFP SS discharge concentration was 28% lower than inflows at the Hauraki site, and 29% lower at the Awahou site. These results suggest that DBs effectively facilitated sedimentation during ponding, and attenuated deposited sediments in the ponding area. Discharge concentrations were lower than inflows during 7 of the 10 events analysed at the Hauraki site, and 10 of the 13 events analysed at the Awahou site (**Fig. 2**). Inconsistencies in concentration treatment efficiencies were observed between and within event types at both sites (**Table 2**).

The wide range of concentration treatment efficiencies observed in this study were influenced by multiple factors. Treading damage, deposited animal excreta and previously deposited sediments in the ponding area could have contributed to SS discharged from the DB that were not accurately accounted for by the pro rata correction of the contributing catchment area and affected the concentration treatment efficiency results.

Variations in particle sizes delivered to the DBs, which were not measured in this study, could have also been a contributing factor to the varying concentration treatment efficiencies observed between events and the sites in this present study. Large particles that have greater densities settle more readily than smaller sized particles with lower densities, which would be less likely to settle and more likely to be remobilised and discharged from the DBs (R. W. McDowell et al., 2003). A greater number of larger particles, which require more energy to mobilise and transport, could have been delivered to the DBs during higher magnitude runoff events, particularly Overflow Events, and could be partially responsible for SS concentrations decreasing during all Overflow events in this study, while this was not the case for all Non-Overflow Events (**Table 2**).

During Overflow Events at both sites, the SS concentrations between the portions of inflow contributing to ponded water going over the top of the upstand riser and emergency spillway (i.e. overflow discharge) and the overflow discharge, did not decrease to the same extent as the concentration decreased between the between overflow discharge and the following release discharges (**Table 3**). These results are somewhat surprising since we would expect the decanting of the uppermost layer of water performed by the upstand riser (**Fig. 1**

) and emergency spillway would be highly effective at preventing SS discharge. The data suggests however, that longer pond residence times experienced by the release discharge compared to the overflow discharge (an average of 14 hours between overflow discharge and the following release discharge at both sites) allowed for greater sedimentation to occur. Longer retention times have been found to increase sediment removal efficiencies in a study of sedimentation ponds (Brown et al., 1981).

The data suggests ponding runoff for longer than the currently suggested 3 days could achieve greater concentration treatment efficiencies, however, this could risk damaging pasture productivity. Removing the upstand riser/outlet valve/discharge pipe installation (**Fig. 1**), and allowing all ponded water to infiltrate the soil, would avoid discharging the bottommost portion of ponded water where SS are likely to concentrate and/or be stirred up by turbulence when unplugging the outlet valve to drain the pond. Also, placing the outlet valve 10 cm above ground level would enable a small portion of the ponded water left after draining the pond to infiltrate the soil. This later revision would prevent the discharge of a lower portion of ponded runoff, and would decrease the area potentially affected by prolonged inundation, compared to avoiding the release procedure entirely. Lastly, approaches to achieve greater SS concentration treatment efficiencies could include the use of flocculants.

Yields and loads

The key finding of this study was that impeding stormflow with DBs effectively attenuated 789 kg and 1280 kg of SS at the Hauraki and Awahou sites, respectively. The 51% and 60% decrease in annual SS loads discharged from the DB catchments was a result of the DBs' ability to facilitate sedimentation, which often decreased event SS concentrations, and soil infiltration, which decreased the volume of runoff discharged from the DB. These results suggest DBs should be effective at reducing P losses from pastures in the Lake Rotorua catchment, due to the high proportion of sediment bound P delivered to the lake (Hamill, 2018).

Annual SS inflow yields were 28 kg ha⁻¹ at the Hauraki site, and 109 kg ha⁻¹ at the Awahou site, although runoff inflow yields were greater at the Hauraki site than the Awahou site. The annual SS inflow yields at both sites in this study were much lower than the estimated annual SS yields entering streams in the same area of the Lake Rotorua catchment from May 2010 to May 2012 (479-741 kg ha⁻¹ y⁻¹) (Abell, Hamilton, & Rutherford, 2013). Factors affecting the catchments' hydrological responses to precipitation, including antecedent soil conditions and localised differences in storm rainfall intensity and duration, and differences between the catchment sizes, geomorphologies, and land use and management factors, affected runoff generation and erosion (Dougherty, Fleming, Cox, & Chittleborough, 2004), and likely accounted for the SS inflow yield differences between study sites in this present study and the results reported by Abell et al. (2013).

At both sites during this present study, runoff and SS inflow yields were lowest in the spring and increased during each subsequent season, peaking during the winter period (**Fig. 3**). This was not surprising, as the contributing catchment is grazed by dairy cattle soil treading damage and erosion is likely to increase when soils are wet (R. W. McDowell et al., 2003). Additionally, greater SS yields tended to correspond with greater runoff yields, particularly during the high runoff magnitude Overflow Events (**Fig. 4**). These results are consistent with other studies that found greater runoff magnitudes tend to mobilise and transport greater quantities of sediments and nutrients from pastures in New Zealand (Cooke, 1988; Smith & Monaghan, 2003) and the Lake Rotorua catchment, specifically (Abell et al., 2013; Dare, 2018).

The results of this study suggest the DBs at both sites were able to consistently decrease SS loads discharged from the DB catchments, even during rare, high runoff magnitude events. The greater inflow magnitudes during Overflow Events at the Hauraki site contributed to a greater portion of runoff undergoing overflow discharge, and consequently, the difference in the portion of inflow undergoing soil infiltration and SS yield treatment efficiencies between the sites during these high magnitude events (**Fig. 5**).

The results from the high magnitude Overflow Events emphasize the importance of being effective during these high magnitude events since they were responsible for 61% and 66% of the annual SS inflow loads at the Hauraki and Awahou sites, respectively, and 39% and 59% of annual SS yields attenuated. This finding is

important to note since large storm events have been found to be responsible for the majority of SS loading to streams in the Lake Rotorua catchment (Abell et al., 2013).

Although DBs effectively attenuated SS loads during Overflow Events, these large magnitude events still generated 84% of the annual SS discharge yields at the Hauraki site, and 77% at the Awahou site. These results are likely related to the majority of annual runoff discharges also occurring during Overflow Events at both sites (**Table 4**). These results suggest that reducing runoff discharges from DBs by facilitating soil infiltration played a key role in effectively decreasing SS loads, which highlights the importance of optimising DB designs to maximise soil infiltration of ponded runoff and avoiding excess overflow discharge.

The ability of DBs to consistently decrease SS loads, particularly during high magnitude runoff events, is also significant because some land management strategies may be overwhelmed by extreme hydrologic conditions (Kleinman et al., 2006; R. W. McDowell & Sharpley, 2002; McKergow et al., 2007). Sediments deposited as a blanket across the relatively wide DB ponding area was observed during this present study, and likely contributed to the consistency in DB performance during this study (**Table 1**) (McKergow et al., 2007). Importantly, it is likely sediments deposited in the DB ponding area will be attenuated for longer periods of time than other mitigation strategies, such as buffer strips and treatment wetlands, that have more concentrated sediment deposition areas and are susceptible to flushing during high magnitude events (McKergow et al., 2007). The ability of the DB to impede the stormflow of each runoff event reduced the kinetic energy of water, which enables the transfer and/or remobilisation sediments, and particularly the ‘first-flush’ of the initial runoff, could have had a major influence on the DBs’ ability to decrease SS loads transported in surface runoff during each event in this study (Bierozza et al., 2019).

The role of soil infiltration in annual SS yield treatment efficiencies is important to note. The concurrent study by (Levine et al., In review) found lower infiltration rates in the ponding area than outside the ponding area (**Table 1**). The decreased soil infiltration rates in the ponding area could be due to a combination of factors including treading damage in the lower lying and wetter areas (R. W. McDowell et al., 2003), the large volumes of water moving through the soil causing stress and deterioration in soil structure, and sediments deposited in the ponding area clogging soil pores and/or forming a less permeable surface soil layer (Hendrickson, 1934; Reddi, Ming, Hajra, & Lee, 2000; Rice, 1974). Therefore, the data suggests infiltration rates, and consequently SS yield treatment efficiencies, may be highest in newly constructed DBs, and may decrease over time. Also, soil infiltration rates, and consequently SS yield treatment efficiencies, could decline more rapidly if DBs are located in areas where erosion is more intense and a greater amount of sediments are deposited in the ponding area compared to this present study, if deposited sediments are responsible for infiltration rate declines. Causes of declining soil infiltration rates in the ponding areas, as well as methods of mitigating soil infiltration rate declines, such as aerating the pond area soils or employing subsoil amendments, should be investigated.

During this study, event discharge concentrations were lower than inflows more often than higher, and SS yield treatment efficiencies were greater than runoff yield treatment efficiencies (**Fig. 5**). These results indicate that sedimentation facilitated by impeding stormflows with DBs caused lower SS discharge concentrations. Therefore, DBs would likely be able to decrease SS discharge yields in areas where soil infiltration rates and pond storage to catchment area ratios are lower than those in this present study. Other factors influencing the proportion of runoff infiltrating the soil and sediment sizes delivered to the DBs would affect yield treatment efficiencies.

Lastly, revising the DB design to remove the upstand riser/outlet valve/discharge pipe installation would prevent SS leak and release discharges, which could be remobilised and delivered to downstream surface waters in subsequent runoff events. We calculated that applying this revised DB design would have prevented an additional 147 kg of SS from being discharged from the Hauraki site, and an addition 216 kg at the Awahou site, increases of 16% and 14% of the annual load attenuated at each site, respectively. The costs and benefits of revising the DB design should be considered since the increased inundation period could damage pasture productivity.

Conclusion

The results of this current study found that DBs located on pastures in the Lake Rotorua catchment attenuated 789 kg SS at the Hauraki site, and 1280 kg SS at the Awahou site, accounting for 51% and 59% of the annual inflow SS loads, respectively. These findings demonstrate that DBs are an effective strategy available to pastoral farmers attempting to mitigate their contribution to Lake Rotorua eutrophication, since and the majority of P transported from the catchment is sediment-bound and has the potential to become biologically available.

Large portions of the annual SS yields attenuated by the DBs occurred during rare, high runoff magnitude events, which delivered the greatest surface runoff and SS yields to the bunds during this study. Identifying the ability of DBs to effectively decrease SS yields during these rare, high magnitude storm events is important since large but less frequent runoff events have been observed to contribute significant sediment loads to streams in the northwest portion of the Lake Rotorua catchment where this study was conducted.

The annual SS yield treatment efficiencies observed in this present study were related to changes in SS concentrations through sedimentation, and the portion of runoff infiltrating the soil in the ponding area. Greater SS yields were discharged from the DBs with greater discharged runoff volumes, which emphasises the importance of optimising DB design to maximise the amount of runoff infiltrating the soil. Still, the impoundment of runoff generally decreased event SS concentrations, suggesting that DBs may effectively decrease SS loads where soil infiltration rates, and pond storage to catchment area ratios, are not as high as those this present study.

While this study found DBs consistently decreased SS yield discharged from the DBs, identifying methods to improve concentration treatment efficiencies, such as integrating flocculants, or allowing the bottommost layer of the pond to infiltrate the soil rather than be released, would improve yield treatment efficiencies. Also, cost:benefit analyses should be conducted to determine whether removing the pond drainage mechanism (i.e. riser/outlet valve/discharge pipe unit) would be beneficial, keeping in mind this might affect pasture productivity. Longer-term studies should also be conducted on more DBs in the Lake Rotorua catchment to further understand the potential of the strategy to effectively mitigate pastoral farming's impact to surface water quality. Studies should also investigate the cause of declining soil infiltration rates in the ponding area and methods for maintaining or rehabilitating infiltration rates in order to maintain SS yield treatment efficiencies over the life of the DB.

Data Availability Statement

Data is available upon request from the corresponding author.

Conflict of interest

The authors declare no conflict of interest.

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Tables

Table 1. Characteristics of detainment bund sites.

Site name	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 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 at spillway	7,110 m ³	2,244 m ³
Ratio of pond volume to catchment area (m³:ha)	129:1	114:1
Pond area when pond filled to spillway	12,221 m ²	2,940 m ²
Measured infiltration rates inside and outside ponding area^a (mm/h)	Inside: 19 Outside: 36	Inside: 12 Outside: 37

Site name	Hauraki	Awahou
Soil classifications	New Zealand: Buried-allophanic Orthic Pumice USA: Vitric Hapludand	New Zealand: Typic Orthic Podzols USA: Andic Haplohumod

^a Levine et al. (In review)

Table 2. Mean flow proportional (MFP) concentrations of suspended sediments (SS) for inflow and discharges across all events, ranges for each event type, and changes to concentrations comparing discharges to inflows.

Site	Event type	MFP SS concentration (g m ⁻³)	MFP SS concentration (g m ⁻³)	Percentage change (%)
Hauraki	All events	Inflow 17	Discharge 12	-28
	Overflow Event range	13 – 17	10 – 13	-22 – -21
	Non-Overflow Event range	4 – 96	6 – 77	-69 – +270
Awahou	All events	96	68	-29
	Overflow Event range	74 – 186	73 – 85	-54 – -1
	Non-Overflow Event range	14 – 211	11 – 127	-55 – +50

Table 3. Mean change in suspended sediment (SS) concentrations between the portion of inflow contributing to ponded water going over the top of the upstand riser and emergency spillway (i.e. overflow discharge) and the overflow discharge, and the mean concentration change between the overflow discharge and the release discharge generated upon opening the outlet valve to drain the pond during Overflow Events at both sites.

Mean change in SS concentration between:	Hauraki (%)	Awahou (%)
Portion of inflow contributing to overflow discharge and overflow discharge	-37	-20
Overflow discharge and release discharge generated upon opening the outlet valve to drain the pond	-41	-84

Table 4. Percentage of annual inflow yields and suspended sediments (SS) which occurred during Overflow Events at each site.

	Runoff (%)	SS (%)

			Runoff	SS
Hauraki	Hauraki	Inflow	69	61
		Discharge	85	84
Awahou	Awahou	Inflow	47	66
		Discharge	64	77

Figure legends

Figure 1. Cross section of the ponding area showing the ephemeral stream inflow 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. Inflows and discharges are measured with flowmeters which triggers auto-sampler collections.

Figure 2. Inflow runoff yields (mm) and mean flow proportional suspended sediment (SS) concentrations (g m^{-3}) of inflow and discharge for each event at each site, with arrows pointing to high runoff magnitude Overflow Events.

Figure 3. Cumulative seasonal inflow runoff (mm) and cumulative suspended sediments (SS) inflow yields (kg ha^{-1}) for each season at each site.

Figure 4. Inflow runoff yields (mm) and suspended sediment (SS) inflow yields (kg ha^{-1}) for each event at each site with arrows pointing to high magnitude Overflow Events.

Figure 5. Cumulative annual event and Overflow Event runoff (mm) and suspended sediment (SS) yields (kg ha^{-1}) for inflows and discharges at both sites. Percent decreases between discharge and inflows is also shown.









