Received: 24 February 2020 | Accepted: 10 July 2021
DOI: 10.1002/hyp.14309

RESEARCH ARTICLE

WILEY

The ability of detainment bunds to decrease sediments transported from pastoral catchments in surface runoff

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Funding information
Balance AgriNutrients Ltd; Bay of Plenty Regional Council; Beef and Lamb NZ; DairyNZ; Deer Industry NZ; Environment Canterbury; Horizons Regional Council; Ministry of Primary Industries, Grant/Award Number: Sustainable Farming Fund; National Institute of Water and Atmospheric Research, Grant/Award Number: Strategic Science Investment Fund; Waikato Regional Council

Abstract

Erosion leading to sedimentation in surface water may disrupt aquatic habitats and deliver sediment-bound nutrients that contribute to eutrophication. Land use changes causing loss of native vegetation have accelerated already naturally high erosion rates in New Zealand and increased sedimentation in streams and lakes. Sediment-bound phosphorus (P) makes up 71–79% of the 17–19 t P y^{-1} delivered from anthropogenic sources to Lake Rotorua in New Zealand. Detainment bunds (DBs) were first implemented in the Lake Rotorua catchment in 2010 as a strategy to address P losses from pastoral agriculture. The bunds are 1.5–2 m high earthen stormwater retention structures constructed across the flow path of targeted low-order ephemeral streams with the purpose of temporarily ponding runoff on productive pastures. The current DB design protocol recommends a minimum pond volume of 120 m^3 ha^{-1} of contributing catchment with a maximum pond storage capacity of 10 000 m^3. No previous study has investigated the ability of DBs to decrease annual suspended sediment (SS) loads leaving pastoral catchments. Annual SS yields delivered to two DBs with 20 ha and 55 ha catchments were 109 and 28 kg SS ha^{-1}, respectively, during this 12-month study. The DBs retained 1280 kg (59%) and 789 kg (51%) of annual SS loads delivered from the catchments as a result of the bunds' ability to impede stormflow and facilitate soil infiltration and sediment deposition. The results of this study highlight the ability of DBs to decrease SS loads transported from pastures in surface runoff, even during large storm events, and suggests DBs are able to reduce P loading in Lake Rotorua.

KEYWORDS
mitigation strategy, pastoral agriculture, sediment deposition, surface runoff, suspended sediments, water quality

1 | INTRODUCTION

Land use developments and the clearing of native forests have accelerated the already naturally high erosion rates across New Zealand and caused significant sedimentation in lakes and streams (Ministry for the Envrionment, 2019). Rainfall and surface runoff cause erosion and transport suspended sediments (SS) to downstream surface waters, delivering sediment-bound nutrients that may contribute to eutrophication (Dare, 2018) and cause sedimentation which degrades aquatic ecosystems by disrupting habitats and food webs (Howard-Williams et al., 2010). Pastoral agriculture in New Zealand is responsible for much of the native forest clearing and is strongly associated with eutrophication and degraded freshwater ecosystems (Verburg et al., 2010). Treading by grazing animals increases the likelihood of surface runoff and erosion in pastoral farming systems by physically disturbing the soil, decreasing infiltration rates and porosity, and impairing plant growth (Bilotta et al., 2007; McDowell et al., 2003; Ward et al., 1985). Year-round grazing and high stocking rates used to graze crops are common practices in New Zealand and contribute to increased erosion rates (Monaghan et al., 2007). Addressing erosion is a challenge for pastoral farmers in New Zealand, particularly those with sloping landscapes, who commonly face variable precipitation patterns associated with very wet winters, and dry summers interspersed with highly erosive storm events, and (McDowell et al., 2013). Additionally, erosion is likely to be intensified by the more dramatic hydrological conditions caused by climate change (Ministry for the Envrironment, 2019; Ockenden et al., 2016).

Since the 1960s water quality in Lake Rotorua has declined in part, because of nitrogen and phosphorus (P) inputs from residential, commercial, industrial and agricultural developments in the catchment in the Bay of Plenty Region of New Zealand's North Island (Environment Bay of Plenty, 2009). An estimated 42% of the annual P delivered to Lake Rotorua comes from pastoral dairy and drystock farms (Hamill, 2018) which cover ~48% of the 42 000 ha surface catchment (Bay of Plenty Regional Council, 2012). Between 71 and 79% of the anthropogenic P delivered to the lake is sediment bound (Hamill, 2018), with a portion of that becoming biologically available and contributing to lake eutrophication when anoxic conditions episodically occur in Lake Rotorua (Abell & Hamilton, 2013). The 2012 Lake Rotorua Management Plan has set a target to reduce annual P loads delivered from the catchment 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 multiple nutrient mitigation strategies and may benefit from the development of new technologies (McDowell, 2010). Effectively reducing erosion and the transport of SS should contribute to reductions in P loading from the catchment because of the notable contribution of sediment bound P to annual P loads delivered to the lake. Mitigation strategies that increase stormflow residence time have been found to decrease surface runoff flows, leading to increased sediment deposition by lowering the kinetic energy of flowing water (Dosskey, 2001; McKergow et al., 2007; Stanley, 1996). However, the type of mitigation strategy utilized affects the duration over which sediments are attenuated, as studies have found that sediment retention times are brief (days to months) in concentrated areas such as narrow grass filter strips and constructed treatment wetlands, while strategies where sediments are blanketed over a wide area may have retention times of up to hundreds of years (McKergow et al., 2007).

Stormwater detention areas (SDAs) are natural or manmade depressions, ponds, and reservoirs, commonly used for flood protection, but are increasingly being used for water quality mitigation strategies in agricultural and urban settings (Shukla et al., 2017; Stanley, 1996). 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 et al., 1981; Harper et al., 1999; Levine et al., 2019; McDowell et al., 2006; Stanley, 1996). Detainment bunds (DBs) are a type of SDA that temporarily pond up to 10 000 m^3 of surface runoff by impeding stormflows with an earthen storm water retention structure constructed on pastures across the flow path of low-order ephemeral streams. The DB strategy was first implemented in Lake Rotorua headwater catchments in 2010 to mitigate P losses from pastures (Clarke, 2013). It is important to note the location of DBs in the headwaters of catchments because pastures in low-order stream catchments have been found to account for an average of 84% of the annual sediment loads delivered to small streams in New Zealand (McDowell et al., 2017). Also, studies of various catchment sizes have found that locating mitigation strategies in catchment headwaters could be especially important because hydrochemical conditions in downstream waters are strongly connected to distant landscape characteristics and may respond relatively quickly to uptstream nutrient mitigation strategy implementation (Alexander et al., 2007). Preliminary studies of DBs in the Lake Rotorua catchment found that P enriched sediments were deposited in DB ponding areas (Clarke, 2013), and a DB effectively decreased runoff volumes, and sediment and P loads discharged during three non-consecutive ponding events (Levine et al., 2019). Additionally, a concurrent study focused on the hydrology of the same ponding events at the same two DB sites as this present study reported 31 and 43% of the annual runoff delivered to the DBs infiltrated the soil in the ponding areas, and noted that deposited sediments could be developing a less permeable surface soil layer and/or clogging soil pore spaces leading to a decline in infiltration rates in the ponding areas (Levine et al., 2021).

Although erosion is recognized for its potential impact on aquatic ecosystems, there is a need to progress our understanding of the transport and fate of sediments lost in runoff from intensively managed pastures (Haygarth et al., 2006). While there is currently no definitive research quantifying the impact of the DBs on annual sediment loads transported from pastures in the Lake Rotorua catchment, previous studies on DBs and related mitigation strategies suggest ponding surface runoff facilitates sediment deposition. Therefore, to determine if DBs provide a viable strategy for pastoral farmers to improve Lake Rotorua water quality, it is important to quantify the strategy's ability to decrease SS loads delivered downstream from pastures located in the catchment headwaters. The main objective of this study was to, for the first time, quantify the effect of the DB strategy on SS concentrations and yields delivered to two DBs for an entire year, and identify the factors influencing the results. The DBs were constructed on productive pastures downstream of 55 and 20 ha catchments mainly used for pastoral agriculture that both drain to Lake Rotorua. We hypothesized that ponding surface runoff will facilitate sediment deposition and result in lower SS discharge concentrations, which combined with decreased runoff outflows identified by Levine et al. (2021), will result in decreased annual SS loads discharged from the DB catchments.

2 | MATERIALS AND METHODS

2.1 | Site descriptions

The two DBs investigated in this study were located on pastoral dairy farms in the Hauraki Stream and Awahou Stream catchments (sites denoted with respective catchment names), in the north-western portion of the Lake Rotorua catchment (Figure 1). The catchment area of the Hauraki site was 55.0 ha with flat, rolling and hill topographies, compared to 19.7 ha at the Awahou site which has a mainly rolling topography (Table 1). The Oropi series soils at the Hauraki site, and Waiteti series soils at the Awahou site are both free draining, with >72 mm/h permeability in the slowest horizon (Rijkse & Guinto, 2010). The measured infiltration rates in the contributing catchment outside of the DB ponding areas at both sites were considerably lower than the permeability for similar soil reported by Rijkse and Guinto (2010) (Table 1), which likely reflects the effect of treading damage under intensive dairying on soil infiltration rates (McDowell et al., 2003).

2.2 | Event types

The study analysed surface runoff that resulted from storm events occurring during a full calendar year, from 1 December 2017 to 30 November 2018. Event types were differentiated according to the course ponded water was discharged from the DB. 'Overflow Events' are defined as runoff events in which inflow continued to be delivered to the pond after the pond height exceeded the height of the upstand riser and the DB spillway (i.e., the lowest point of the DB; Figure 2). Ponded runoff discharged by going over the riser and DB is referred to as 'overflow discharge'. 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 that had either no ponded water remaining, or a small portion of residual ponded runoff to discharge by the unplugging the outlet valve (release discharge) at the end of the 3-day treatment period.

2.3 | Equipment and sampling

Isco (California) 6712 portable auto-samplers, capable of filling 24 x 1 L bottles collected inflow and outflow samples at each site when triggered by 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 et al., 2002). Calibration and maintenance of the monitoring equipment followed standard quality controls (NIWA, 2004).

Inflow auto-samplers were installed upstream of the DBs in the course of the ephemeral stream path that flowed during rain events that were sufficient to generate surface runoff. The inflow auto-samplers were programmed to collect a 1 L sample every 20 min for the first 10 samples, then one 1 L sample/h thereafter (Harmel et al., 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 sample the initial flush of

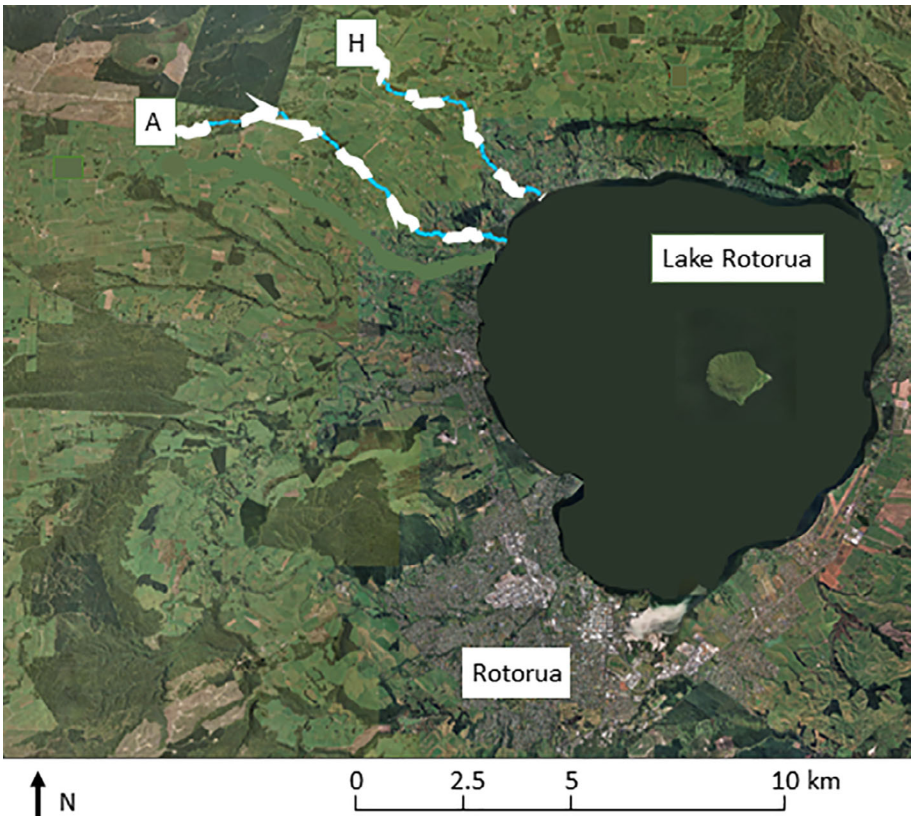

FIGURE 1 Overhead map of Lake Rotorua with study sites labelled with initials for Awahou (A) and Hauraki (H) catchments. White and blue dashed lines show path of runoff from detainment bund site to Lake Rotorua

TABLE 1 Characteristics of detainment bund sites

Site name		Hauraki	Awahou
Grid reference		38°00′21″S	38°01′43″S
		176°11′03″E	176°07′54″E
Year DB constructed		October 2011	June 2012
Size of DB catchment (ha)		55.0	19.7
Area of DB catchment downstream of inflow monitoring (ha)		8.3	1.8
Percentage of catchment with slope (%)	0°–7.9°	69	69
	8.0°–15.9°	16	19
	16°–25.9°	9	9
	>26°	5	3
Height of bund at spillway (m)		1.56	1.80
Height of upstand riser (m)		1.36	1.60
DB pond volume at spillway		7110 m^3	2244 m^3
Ratio of pond volume to catchment area (m^3: ha)		129:1	114:1
Pond area when pond filled to spillway		12 221 m^2	2940 m^2
Measured infiltration rates inside and outside ponding area[a] (mm/h)		Inside: 19 Outside: 36	Inside: 12 Outside: 37
Soil classifications		New Zealand: Buried-allophanic Orthic Pumice USA: Vitric Hapludand	New Zealand: Typic Orthic Podzols USA: Andic Haplohumod

[a]Levine et al. (2021).

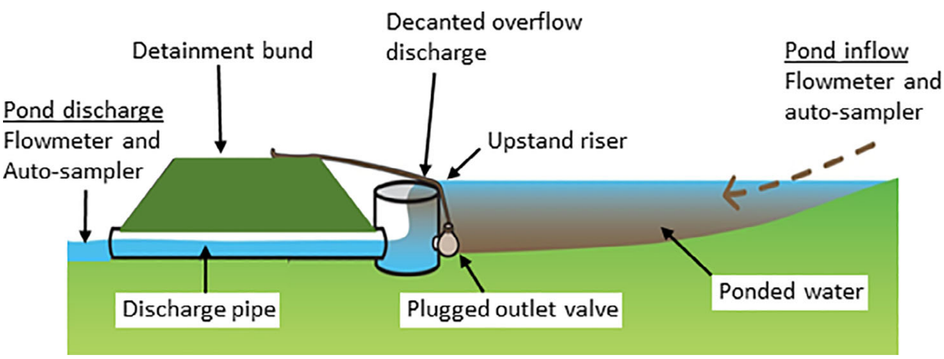

FIGURE 2 Cross-section of the ponding area showing the ephemeral stream inflow ponding behind a detainment bund. If the pond height exceeds the height of the upstand riser then 'decanted overflow' is discharged via a pipe passing through the bund. Inflows and discharges are measured with flowmeters which triggers auto-sampler collections

surface runoff generated before the inflow auto-sampler was triggered. The ping-pong ball bottle sample was used to measure the concentration of initial runoff and used in calculating event inflow yields.

Outflow auto-samplers were programmed to collect 1-L sample/h (Harmel et al., 2003; Stanley, 1996). Sampled outflow was generated if the pond height exceeded the upstand riser height during pond filling (i.e., 'overflow discharge'), and when the valve at the base of the riser was opened to release the ponded water at the end of the event treatment, typically on the third day of ponding (i.e., 'release discharge'; Figure 2).

Throughout all ponding events at both sites, a leak at the connection point of the outlet valve pipe and the base of the upstand riser generated a continual 'leak discharge'. Attempts at sealing this leak during the study period were unsuccessful. The leak volume was similar between the sites during the study, 3302 m^3 at Hauraki and 3267 m^3 at Awahou, but because of the difference in catchment sizes, the proportional contribution of leak discharges to annual outflows differed considerably, accounting for 5% at Hauraki, and 26% at Awahou. The leak flow (~2–4 m^3/h) during at both sites was too low to trigger sample collection by the auto-samplers. However, once the extent of the potential contribution of the leak to the annual outflows was recognized auto-samplers were reprogrammed to enable leak sample collection during five events at Hauraki and two events at Awahou. The collection of leak samples was used to characterize the SS concentrations of the leak discharge and thus contributed to the SS yields outflow calculations.

Water samples were collected from the field within 24 h of the end of the ponding event and kept refrigerated at 4°C prior to subsampling, which occurred within ~24 h of collection. Two subsamples (~30 ml each) were obtained from the field sample to analyse total and dissolved nitrogen and P (results not published). The remaining field sample was refrigerated until being analysed for SS concentrations following the standard procedure from the American Public Health Association (2005).

2.4 | Calculations

2.4.1 | Mean flow proportional concentrations

Event and annual mean flow-proportional (MFP) SS concentrations were calculated by dividing the inflow and outflow loads by their respective volume (Tanner & Sukias, 2011). During the seven events leak samples were collected, the event MFP leak discharge concentration was 3% greater (median: 7% lower) than the MFP inflow concentration. The event MFP inflow concentration value was used as the estimated concentration of the entire leak volume for each respective event in which the leak discharge was not sampled because of the negligible difference between the inflow MFP SS concentration and leak discharge MFP SS concentration during events leak samples were collected. All inflow and discharge MFP concentrations are hereafter referred to as concentrations. Event and annual 'outflows' refer to the combination of each type of discharge, including leak, overflow and release discharges.

2.4.2 | Loads and yields calculation

Loads (kg) of SS in inflows and outflows (combining leak, overflow and release discharge loads), were determined for runoff events that lead to the development of measurable ponding. Yields refer to the load per unit of contributing catchment area for sediments expressed as kg ha^{-1} and mm for runoff volumes. Inflow loads of SS were calculated using the measured concentration of the runoff samples collected by the ping-pong ball sample bottle and auto-samplers. We interpolated concentrations assuming a linear rate of change between measured concentrations. The measured and interpolated concentrations were then multiplied by the interval flow volume measured every 5 min to obtain the inflow loads. 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 estimated runoff contribution from the small catchment area between the inflow monitoring location and the DB that was unable to be sampled by the inflow flowmeter and auto-sampler (Table 1). We assumed the SS concentrations and runoff volumes of the unmeasured area were equivalent to the rest of the contributing catchment that was measured at the inflow monitoring location for each event because the measured and unmeasured portions of the DB catchment had similar pastoral land use at the sites.

Loads were calculated for overflow discharge (combining upstand riser and spillway breaching that occurred during Overflow Events), release discharge (that occurred during Overflow Events and Non-Overflow Events), and leak discharge (that occurred during all events). The load of each discharge type was calculated from flow measurements and sample concentrations taken from the DB outlet pipe, except for spillway breaching. Spillway loads were calculated by applying the MFP concentration of the ponded water discharged from the outlet pipe after going over the upstand riser to the volume breaching the spillway during Overflow Events. The emergency spillway was breached during the two large Overflow Events that occurred at both sites. Levine et al. (2021) describe in detail how emergency spillway discharge volumes were calculated. Briefly, because both the spillway discharge and soil infiltration were unmeasured, the event average soil infiltration rates were calculated for each of the Overflow Events to determine the volume discharged over the spillway for each respective event. Spillway volume discharges were determined by subtracting the measured leak, upstand riser overflow, and release discharge volumes, and calculated infiltration volumes, from the event inflow.

2.4.3 | Data analysis

Events at each site were analysed to calculate annual results and to compare results between event types. Changes to concentrations were calculated as the percent difference between inflow and outflow concentrations (percent change in concentration = [outflow-inflow]/inflow)*100). Differences between inflow and outflow concentrations are referred to as the 'trapping efficiency'. Differences between inflow and outflow yields are referred to as a 'yield treatment efficiency'. Inflow yield data for each site was organized by austral seasons (i.e., summer from December to February) to compare differences between the sites and identify seasonal patterns for SS inflow yields.

3 | RESULTS AND DISCUSSION

Storm-generated surface runoff resulted in 18 ponding events at the Hauraki site and 19 ponding events at the Awahou site, the majority of which occurred during the winter months (Figure 3). Inflow water samples were analysed for 13 ponding events at the Hauraki site, and 14 events at the Awahou site, with the remainder of the ponding events either not generating sufficiently high inflow rates to trigger auto-samplers or not sampled because of auto-sampler error. Inflow during unsampled events accounted for 3% of the annual inflow at the Hauraki site, and 4% at the Awahou site. Discharge samples were collected during 10 events at the Hauraki site, and 13 events at the Awahou site, because not all events generated high enough discharge flows to generate samples because of insufficient inflow volumes, leakage and soil infiltration.

3.1 | Concentrations

The annual MFP SS inflow concentration was 17 g m^{-3} at the Hauraki site, and 96 g m^{-3} at the Awahou site. Inflow concentrations peaked in the winter months at both sites during this study, although there was no clear temporal trend for inflow concentrations (Figure 3). These results are similar to the findings of Smith (1987) who found that SS concentrations were higher in winter runoff when pasture lengths were low, and concentrations were lower in the spring and

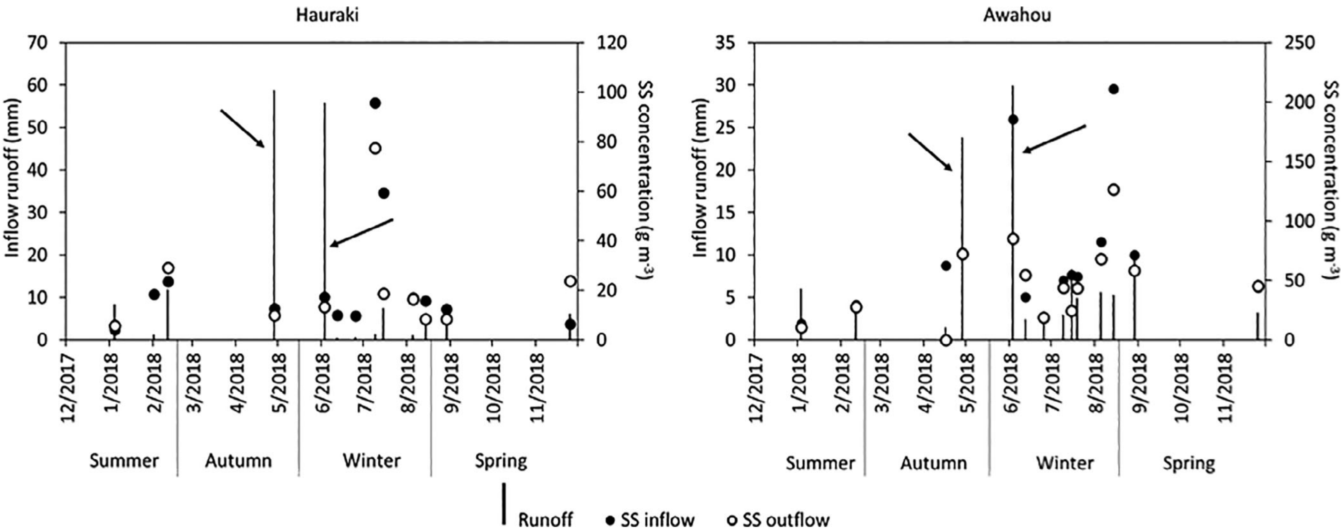

FIGURE 3 Inflow runoff yields (mm) and mean flow proportional suspended sediment (SS) concentrations (g m^{-3}) of inflow and discharge for each event at each site, with arrows pointing to the large Overflow Events. Dates are presented as month and year with austral seasons labelled. *Note:* Both inflow runoff and SS concentration y-axes are different between the sites

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

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

summer when pasture lengths were longer. Event inflow concentrations did not tend to correspond to event runoff magnitudes and varied widely between events (Figure 3).

Various factors may have contributed to differences in inflow concentrations between the sites and the lack of a relationship between runoff magnitudes and inflow concentrations. While the Hauraki site had slightly steeper slope gradients which have been found to contribute to higher erosion rates (Kleinman et al., 2006), the higher SS inflow concentrations at the Awahou site was likely caused by some combination of land management factors (Kleinman et al., 2002), storm frequencies affecting source exhaustion at the Haurkai site which experienced greater runoff (Figure 3; Edwards & Withers, 2008), antecedent moisture conditions affecting susceptibility to erosion (McDowell & Sharpley, 2002) and pasture length affecting the transport potential of SS (Smith, 1987).

The annual MFP SS outflow concentration was 28% lower than inflows at the Hauraki site and 29% lower at the Awahou site, suggesting that DBs effectively facilitated sediment deposition. Inconsistencies in trapping efficiencies were observed between and within event types at both sites with apparent no temporal trends (Table 2; Figure 3). Outflow 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 (Figure 3). On average, the concentration decreased 31% at the Hauraki site and 25% at the Awahou site during events in which concentrations decreased. During events in which concentrations increased, the concentration increased an average of 109 and 18% at the at the Hauraki and Awahou site, respectively. The large increase observed at the Hauraki site was the result of a 270% higher outflow concentration compared to the very low inflow concentration (6 g m^{-3}) relative to other events at the Hauraki site. Therefore, a slight increase in outflow concentration resulted in a high proportional concentration increase, causing the average increase in concentration of the three events in which concentrations increased to be so high.

The wide range of trapping efficiencies observed between events in this study (Table 2) were likely influenced by multiple factors. Because the temporary ponding area was still used in livestock production, treading damage, deposited animal excreta (McDowell et al., 2003) and the mobilization of previously deposited sediments in the ponding area (Barber & Quinn, 2012) could have contributed to SS discharged from the DB that was not accurately accounted for by the pro rata correction of the unmeasured contributing catchment

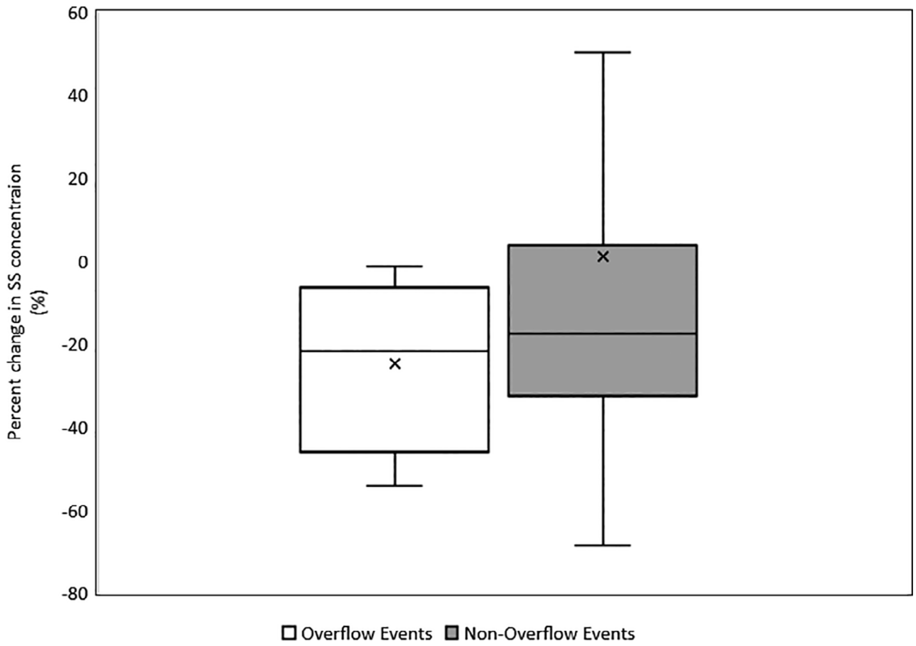

FIGURE 4 Side-by-side box and whisker plot comparing the percent change in suspended sediment (SS) concentration during Overflow and Non-Overflow Events occurring at both study sites during the 12-month study. Centre lines represent the medians, box limits indicate the 25th and 75th percentiles and *x*'s indicate the mean event percent concentration change

area downstream of the inflow monitoring site, and so would have affected the trapping efficiency results. Also, variations in particle sizes delivered to the DBs, which were not measured in this study, could have contributed to the varying trapping efficiencies observed between events and the sites. Heavier particles (i.e., sand) settle more readily than smaller particles (i.e., silt and clay) which more likely to be transported and/or remobilised and discharged from the DBs (McDowell et al., 2003). A previous study of DBs found that sediments deposited at higher elevations in the ponding area typically had greater proportions of coarse size sand particles than lower elevations, suggesting that finer sediments take longer to settle than coarser particles in DBs (Clarke, 2013). During this present study, a greater proportion of large particles were likely to have been delivered to the DBs during higher magnitude runoff events because of greater erosive power, particularly during Overflow Events. Therefore, differential transport of grain sizes 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). While Non-Overflow Events had greater variation in concentration changes than Overflow Events (standard deviation = 21.8 during Overflow Events, 71.3 during Non-Overflow Events), and Overflow Events had greater mean trapping efficiencies, median trapping efficiencies were similar between the two event types (Figure 4). The greater variation during Non-Overflow Events was likely caused by not all of these events having residual ponded water to be released at the end of the 3-day treatment period because of soil infiltration and leakage.

During Overflow Events at both sites, results suggest longer retention times of runoff contributed to increased trapping efficiencies. Specifically, the SS concentration difference between the portions of inflow contributing to overflow discharge, termed Flow A, and the subsequent overflow discharge, termed Flow B, did not decrease to the same extent as the concentration decreased between Flow B and the release discharge generated at the end of the ponding event, termed Flow C (Table 3). These results are somewhat surprising because it might be expected that the decanting of the uppermost layer of water performed by the upstand riser (Figure 2) and spillway would be highly effective at preventing SS discharge. The data suggests however, that the longer residence times of the release discharge compared to the overflow discharge (an average of 14 h between Flow B and Flow C at both sites) allowed for greater settling out of the water column to occur (Table 3). Longer retention times have been found to increase sediment removal efficiencies in a study of sedimentation ponds (Brown et al., 1981). The results from the Overflow Events suggests ponding runoff for longer than 3 days could result in greater trapping efficiencies, however, this could risk damaging pasture productivity (Clarke, 2013). Removing the upstand riser/outlet valve/discharge pipe installation (Figure 2) and allowing all ponded water to infiltrate the soil would prevent the discharge of the bottommost portion of ponded water where SS is likely to be highly concentrated 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. Raising of the outlet valve would also 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 trapping efficiencies could include the use of flocculants that would aggregate SS and facilitate greater sediment deposition.

3.2 | Yields and loads

The key finding of this 12-month study was that impeding ephemeral stormflows with DBs resulted in the attenuation of 789 and 1280 kg

TABLE 3 Mean change in suspended sediment (SS) concentrations between the portion of inflow contributing to overflow discharge (Flow A), and the runoff discharged over the upstand riser (Flow B), and the mean concentration change between the overflow discharge (Flow B) and the release discharge generated when the outlet valve was opened to drain the pond (Flow C), during Overflow Events at both sites

Mean change in SS concentration between	Hauraki (%)	Awahou (%)
Portion of inflow contributing to overflow discharge (Flow A) and the runoff discharged over the upstand riser (Flow B)	−37	−20
Overflow discharge (Flow B) and release discharge generated upon opening the outlet valve to drain the pond (Flow C)	−41	−84

of SS, equivalent to 51 and 60% of the annual SS inflow loads, in the ponding areas at the Hauraki and Awahou sites, respectively. The proportion of the annual SS loads reduced by the DBs exceeded the proportion of the annual runoff inflow infiltrated the soil in the ponding areas, 31% at Hauraki and 43% at Awahou (Levine et al., 2021) demonstrating that load reductions were a result of the DBs' ability to decrease SS concentrations by facilitating sediment deposition, and decreasing the volume of runoff discharged from the DB as a result of soil infiltration observed by Levine et al. (2021).

The sediment loads deposited in the ponding area in the current study are likely to be lower than the loads prevented from reaching surface waters downstream of the DBs as a result of the mitigation strategy. This is because in addition to some portion of sediments discharged from the DBs could be permanently entrained in the soil which typically occurs in pastures (Smith, 1987), the reduced surface runoff magnitude as a result of impeding stormflows would likely decrease erosion occurring downstream of the DBs. The extent of the effects of impeding stormflows with DBs on downstream erosion was beyond the scope of this study and should be investigated in the future. Additionally, an associated benefit of reducing SS loads discharged from the DB catchments, and potentially mobilized downstream of the DB catchments, is the decrease in particulate P loads delivered to receiving surface waters. Clarke (2013) found that the mean P concentration of sediments deposited in the same DB ponding areas as this present study ranged from ~1.5 to 3 g P kg^{-1} of sediment dry weight. Taking the findings of Clarke (2013) into account, the results of this present study suggest that DBs could decrease particulate P losses delivered to Lake Rotorua by 1.2–2.4 kg y^{-1} (Hauraki DB) and 1.9–3.8 kg y^{-1} (Awahou DB). These findings highlight the potential importance of DBs in the Lake Rotorua catchment because pastures in low-order stream catchments have been found to account for an average of 84% of the annual sediment loads delivered to small streams in New Zealand (McDowell et al., 2017) and locating mitigation strategies in catchment headwaters, where DBs more most likely to fit in the landscape, have been found to be have relatively rapid impacts on downstream hydrochemical conditions (Alexander et al., 2007).

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 et al., 2013). Factors affecting the catchments' hydrological responses to precipitation, including antecedent soil conditions and localized differences in storm rainfall intensity and duration, and differences between the catchment sizes and land use and management factors, affected runoff generation and erosion rates (Dougherty et al., 2004) and likely accounted for the SS inflow yield differences between the sites in this present study and the results reported by Abell et al. (2013).

At both sites during this study, runoff and SS inflow yields were lowest in the spring and increased during each subsequent season, peaking during the winter period (Figure 5). This was not surprising, as the contributing catchment is grazed year-round by dairy cattle, so soil treading damage and erosion was likely to increase when soils were wet during the winter months (McDowell et al., 2003). Additionally, greater SS yields tended to correspond with greater runoff yields, particularly during the large Overflow Events (Figure 6). The positive relationship between event runoff and SS yields contrast with the lack of relationship between event runoff yield and SS concentration, likely due to the effects of source exhaustion and dilution (Abell et al., 2013). The results are consistent with other studies that found greater runoff magnitudes tend to mobilize 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 higher SS yields measured at Awahou while higher runoff yields occurred at Hauraki suggests differences in factors affecting erosion between the catchments at the two sites, such as precipitation patterns, geomorphologies, soil types and land management (Dougherty et al., 2004).

The results of this study demonstrate the DBs at both sites were able to consistently decrease SS loads discharged from the DB catchments, even during rare, large events, despite event outflow concentrations not being consistently lower than inflow concentrations. These results emphasize the important role soil infiltration plays in DBs effectively decreasing SS outflow loads. The greater inflow magnitudes during Overflow Events at the Hauraki site contributed to a greater portion of runoff undergoing overflow discharge compared to the Awahou site, and consequently, the difference in the portion of inflow undergoing soil infiltration and SS yield treatment efficiencies between the sites during the large runoff Overflow Events (Figure 7).

The ability of DBs to consistently decrease SS loads, particularly during large runoff events, is noteworthy because some land management strategies are overwhelmed by hydrologic conditions (Kleinman et al., 2006; McDowell & Sharpley, 2002; McKergow et al., 2007). Sediments were observed to be deposited across the relatively wide DB ponding area during this study, which likely contributed to the

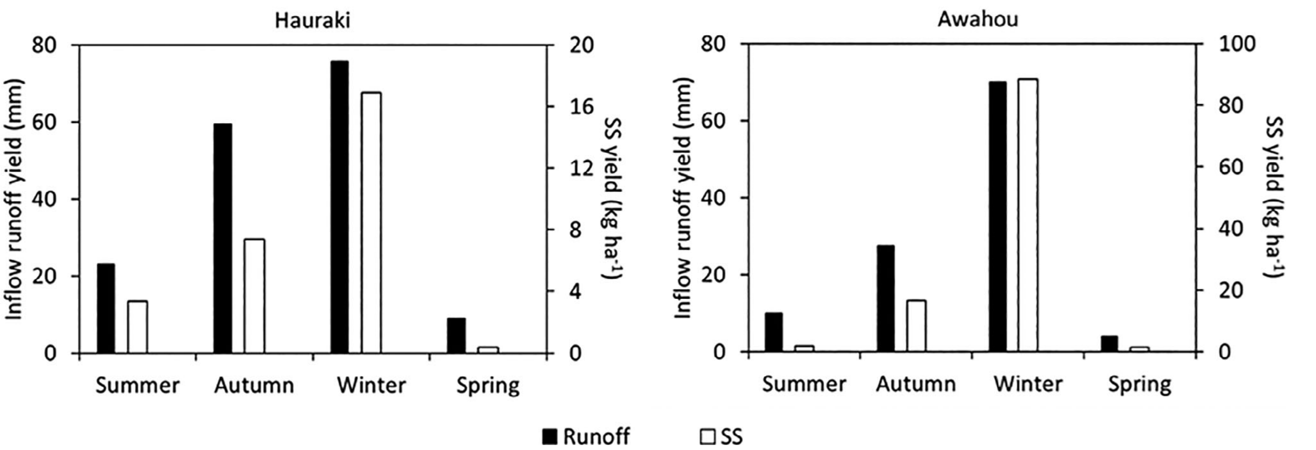

FIGURE 5 Cumulative seasonal runoff inflow (mm) and suspended sediments (SS) inflow yields (kg ha^{-1}) for each season at each site. *Note:* Difference between the 'SS yield' *y*-axis between sites

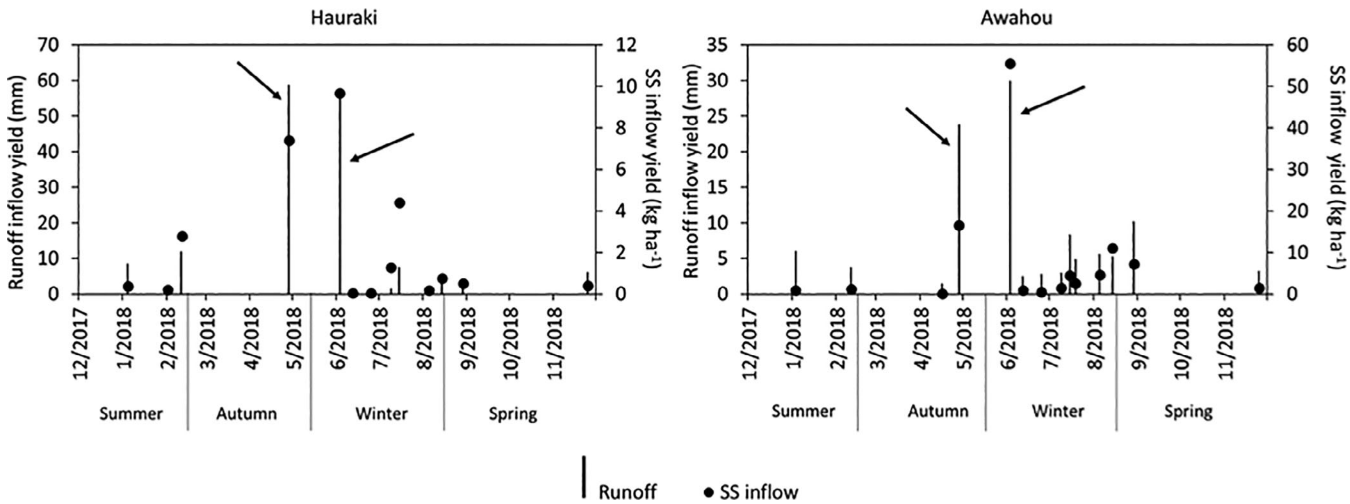

FIGURE 6 Event inflow runoff yield (mm) and suspended sediment (SS) yields (kg ha^{-1}) at both sites, with arrows pointing to high runoff magnitude Overflow Events. Dates are presented as month and year with austral seasons labelled. *Note:* Both runoff inflow and SS inflow yield *y*-axes are different between the sites

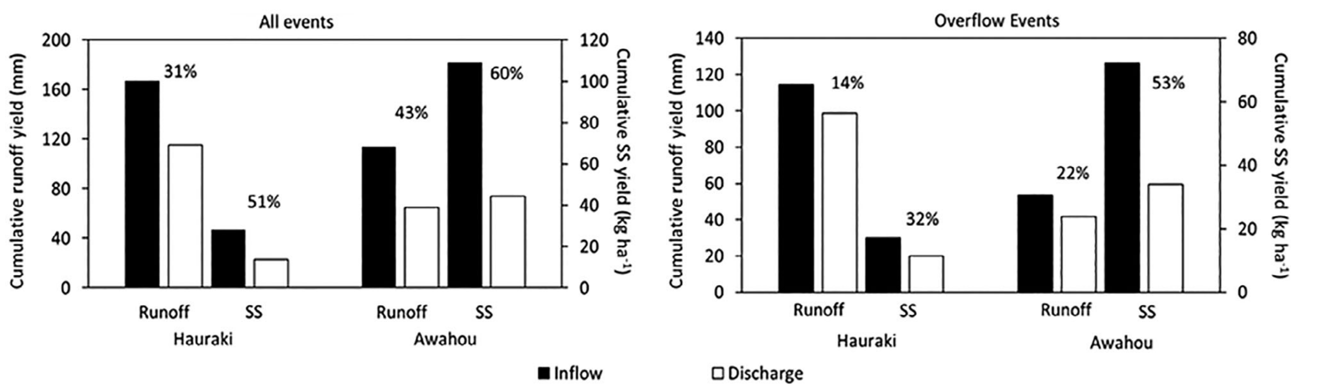

FIGURE 7 Cumulative annual, and Overflow Event only, inflow and discharge runoff yields (mm) and suspended sediment (SS) yields (kg ha^{-1}). Percentage decrease in runoff and SS outflow is also shown (%). *Note:* Both runoff and SS yield *y*-axes are different between the sites

consistency in DB performance as it is likely sediments deposited in the DB ponding area will be attenuated for longer periods of time compared to other mitigation strategies, such as buffer strips and treatment wetlands, that have more concentrated sediment deposition areas and are susceptible to flushing during large runoff events (McKergow et al., 2007). The ability of the DB to impede the stormflow of each runoff event, particularly the 'first-flush' of the initial runoff, reduced the kinetic energy of water and therefore the ability of the runoff to mobilize and transfers sediments, which likely had a major influence on the DBs' ability to decrease SS loads transported from the DB catchments during each event in this study (Bieroza et al., 2019).

Although DBs effectively attenuated SS loads during Overflow Events, these large runoff events still generated 84% of the annual SS outflow yields at the Hauraki site, and 77% at the Awahou site. These results are related to the majority of the annual runoff outflow also occurring during Overflow Events at both sites (Table 4). Results from Levine et al. (2021) suggest that soil infiltration played a key role in reducing runoff outflow from DBs which was critical to the reduction of SS loads in the current study, highlighting the importance of optimizing DB design to maximize soil infiltration of ponded runoff to avoid excess overflow discharge during large runoff events.

The contribution of soil infiltration to annual SS yield treatment efficiencies is also important to note because Levine et al. (2021) found infiltration rates in the ponding area to be lower than those outside the ponding area (Table 1). The results of this present study support previous findings that deposited sediments are able to clog soil pores and/or form a less permeable surface soil layer (Hendrickson, 1934; Reddi et al., 2000; Rice, 1974). Therefore, infiltration rates, and consequently SS yield treatment efficiencies, are likely to be highest in newly constructed DBs and will decrease over time and would likely decline faster in locations with higher erosion rates and greater SS loads deposited in DB ponding areas. During this study, outflow concentrations were lower than inflow concentrations in 70 and 77% of the events at the Hauraki and Awahou sites respectively, and SS yield treatment efficiencies were greater than runoff yield treatment efficiencies at both sites (Figure 7). These results indicate that sediment deposition facilitated by impeding stormflows with DBs caused lower SS outflow concentrations. Therefore, DBs would still decrease SS outflow yields in areas where soil infiltration rates and pond storage to catchment area ratios are lower than those in this present study, although yield treatment efficiencies would likely not be as high. Other factors influencing the proportion of runoff infiltrating the soil and sediment sizes delivered to the DBs would affect yield treatment efficiencies.

TABLE 4 Percentage (%) of annual runoff and suspended sediments (SS) inflow and discharge yields which occurred during Overflow Events at each site

Site	Flow type	Runoff (%)	SS (%)
Hauraki	Inflow	69	61
	Discharge	85	84
Awahou	Inflow	47	66
	Discharge	64	77

Revising the DB design to remove the upstand riser/outlet valve/discharge pipe installation would prevent SS leak and release discharges. Removing the leak and release discharge loads from the annual SS outflow loads would have prevented an additional 147 kg of SS from being discharged from the Hauraki site, and an additional 216 kg at the Awahou site which would increase the annual SS load attenuated at each site by 16 and 14%, respectively. The costs and benefits of revising the DB design by removing the leaking upstand riser and plugged outlet pipe should be investigated because the increased inundation period could damage pasture productivity.

Despite hundreds of kilogrammes of sediments being deposited in the DB ponding area during the 12-month study period, and presumably during each of the 6 years since the DBs were constructed, there was no observable build-up of sediments in the ponding area. Although previously deposited sediments may be remobilised in subsequent ponding events, and soil infiltration rates have been found to be decreasing in the ponding areas (Levine et al., 2021), the finding that DBs reduced annual SS outflow loads by 51 and 59% suggests the monitored DBs will be able to continue to effectively attenuate SS well into the future. However, future sediment deposition and potential adoption of innovations that increase trapping efficiencies could, in turn, decrease yield treatment efficiencies in the long-term, because of greater quantities of deposited sediments potentially contributing to further decreases in soil infiltration rates and increased sediment remobilisation. Methods of mitigating declines in the soil infiltration rates such as aerating the pond area soils or employing subsoil amendments should be investigated. Future investigations should also characterize sediment sizes (distribution of sand, silt, and clay) in the DB catchments, mobilized during runoff events, attenuated in the DB ponding area, and discharged from the DB, in order to provide further insight into the ability of DBs to attenuate SS and associated P in the short- and long-term.

4 | CONCLUSIONS

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, equivalent to 51 and 59% of the annual inflow SS loads, respectively. Notably, large portions of the annual SS yields attenuated by the DBs occurred during large runoff events which delivered the majority of annual surface runoff and SS yields to the bunds. As this is the first study quantifying the ability of a relatively novel mitigation strategy to decrease annual SS loads exported from pastures in stormflows, it is important for decision makers in the Lake Rotorua catchment, and other similar settings around the world, to be aware of DBs as a mitigation option and the strategy's efficacy.

The annual SS yield treatment efficiencies observed in this study were related to changes in SS concentrations caused by sediment deposition, and the portion of runoff infiltrating the soil in the ponding area. Greater SS outflow yields occurred with greater runoff outflows which emphasizes the importance of optimizing the DB design to maximize the amount of runoff infiltrating the soil. Also, the temporary ponding of surface 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 at the DB sites in this present study.

While this study found DBs consistently decreased SS outflow yields from the DBs, identifying methods to improve trapping efficiencies, such as integrating the use of 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 pond discharge mechanisms (i.e., the riser/outlet valve/discharge pipe unit) would be beneficial, keeping in mind this might affect pasture productivity and performance longevity. Longer-term studies in a higher number of DB locations should also be conducted in the Lake Rotorua catchment to further understand the strategy's potential to effectively mitigate pastoral farming's impact on surface water quality. Future investigations should also characterize sediment sizes in the DB catchments mobilized during runoff events, attenuated in the DB ponding area, and discharged from the DB, in order to provide further insight into the ability of DBs to attenuate SS in the short- and long-term. 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.

ACKNOWLEDGEMENTS

This applied research on DBs was initiated, and is governed by, the Phosphorus Mitigation Project, Inc. We 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 Agri-Nutrients, Ltd., Beef and Lamb NZ, and Deer Industry NZ. The funders had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication. Thank you to Wayne McGarth and Andrew Starr at NIWA for their instrumentation assistance.

DATA AVAILABILITY STATEMENT

Data is available upon request from the corresponding author.

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How to cite this article: Levine, B., Burkitt, L., Horne, D., Tanner, C., Sukias, J., Condron, L., & Paterson, J. (2021). The ability of detainment bunds to decrease sediments transported from pastoral catchments in surface runoff. *Hydrological Processes*, *35*(8), e14309. https://doi.org/10.1002/hyp.14309