The performance of Detainment Bunds (DBs) for attenuating phosphorus and sediment loss from pastoral farmland

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Abstract

New Zealand relies upon phosphorus (P) to sustain agricultural productivity. However, P loss from farming systems to freshwater ecosystems can promote eutrophication; a global problem. A disproportionate amount of P and sediment is transported from farm systems to freshwaters via ephemeral streams (overland flow) during short of periods of time. Ephemeral streams flow over landscapes (e.g. depressions in paddocks which are usually dry) during intense rainfall events which produce surface runoff. Treating the sheer volume of water leaving a catchment during these events presents a challenge and many mitigation approaches struggle to cope with such large discharges over short periods of time.

The objective of this MSc research was to quantify the performance of a new type of detainment bund (DB) being trialled in the Lake Rotorua catchment that was designed to intercept surface runoff by ponding it behind a low profile earth bund (c. 1.5 m high). The aim was to promote settling of suspended sediments and associated particulate P (PP) in the DB basin (onto the pasture). Ponded water was released slowly (via a floating decant structure) until the pond was completely drained; residence time of water was no more than three days to ensure pastoral production in the ponding area was maintained.

Three detainment bunds were constructed on private dairy farms within three sub catchments (Waiteti, Hauraki and Awahou) of Lake Rotorua (Bay of Plenty, New Zealand). The DBs have been initiated as part of a collaboration of Bay of Plenty Regional Council, DairyNZ and Rotorua catchment farmers in a wider P mitigation programme known as the ‘Rotorua P-Project’.

Sampling was undertaken from March - September 2012 during which eight rainfall events produced ponding in the DBs. Synthetic grass mats and sediment trays were deployed across the ponding area of each DB to capture sediments which were deposited during ponding periods. Grab samples of in– and out–flowing water were collected at various stages during storm events and analysed for total suspended sediments (TSS), particle size distribution, total P (TP), dissolved reactive P (DRP), total nitrogen (TN) and dissolved inorganic nitrogen to determine changes in water quality over the ponding periods. Water level was recorded to calculate the volume of ponded water and estimates of the mass of sediment and P deposited per event were derived.

Total P concentrations of up to 1.6 mg L^{-1} were recorded in ephemeral stream flow. Results showed that there were significant reductions in TSS concentrations throughout the ponding events. The fastest settling rate (73% reduction in TSS over 43 h) occurred when ponded water comprised a large percentage inorganic material, slower settling rates were associated with high % of organic SS. Particulate nutrient concentrations of water leaving the DBs decreased at fastest rates within the first 20 h of ponding (up to 36% of PP and 42% of PN at Awahou DB) when TSS concentrations were high (>100 mg L^{-1}). Similar reductions were observed at the other sites (with lower TSS) but settling rates were typically half this maximum observed rate.

The sediment retained by the three DBs in this study was enriched with P (average 2080 mg P (kg dw)$^{-1}$) relative to the benthic sediments of Lake Rotorua and the alluvium of the Waiteti Stream. Phosphorus in the deposited sediments was associated with metal cations such as Fe and Mn; this indicates that such PP which is present in redox–sensitive forms is potentially bioavailable in Lake Rotorua during periods of lake stratification which lead to anoxia in the hypolimnion. The largest retention of sediment and P (2,749 kg and 6.08 kg respectively) during the study period occurred when a large rainfall and runoff event in July coincided with the recent complete removal of vegetation in an upstream paddock sown with a winter forage crop. The setting of the Hauraki DB was the most representative of a typical dairy farm and the average deposition per sampled event was 0.261 kg P^{-1}. Using this figure it was estimated, that over a 20 year period, 28 kg of P could be retained (given the same hydrological and catchment characteristics as 2012). This equates to a saving of c. $28,000 if the P was to be removed by in-lake restoration methods.

Detainment bunds did not attenuate dissolved nutrients (DRP and DN) during ponding in most cases; however, DRP was inversely correlated with TSS when the TSS concentrations were high. In some ponding events DRP increased, this was likely due to net desorption from suspended sediments.

An investigation of the soil P concentrations around the ponding area of an old (12 y) detainment dam built for flood control revealed a significant decrease in Olsen P with distance from the dam wall, indicating that historic ponding had deposited sediment enriched with P in the ponding area (Olsen P ranged from 119 mg L^{-1} inside to 41 mg L^{-1} outside of the ponding area). There is a potential for DB ponding areas to be a P source at certain times if DRP is desorbed from P enriched soils to overlying water, however, in the long term the investigation indicated that they are likely to be a P sink and there may be no need for addition of P fertiliser in the ponding area.

Adequate water storage capacity was identified as critical to the design of future DBs. Observations during this research showed that storage ratios should be based on a minimum ratio of 120 m^3 of water storage per 1 ha of contributing catchment (to the concrete riser). It is important that the floating decant structures used to drain DBs are designed specifically for the volume of each DB to allow ponded water to drain from the DB within the desired time of ponding. Land owners have tolerated three days ponding with no impact on pastoral production.

Detainment bunds can play a pivotal role in moderating the hydrological pathways at the catchment scale by prioritising headwater catchments and slowing down water flow to reduce the loss of nutrients and sediment from pastoral farmland during intense rainfall and runoff events. The level of DB implementation within pastoral landscapes will depend on the willingness of landowners to incorporate them into farm systems. A win-win situation is possible where water quality is improved and pastoral production within the ponding areas is maintained.

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Chapter 1: Introduction

This chapter introduces the key contextual features of this thesis. Firstly it outlines the importance of agriculture in New Zealand (NZ), and demonstrates the link between pastoral agriculture and water quality. Secondly it describes the transport mechanisms by which nutrients and sediment leave farms, and identifies the factors that affect nutrient and sediment loss. This chapter will introduces Detainment Bunds (DBs) in the context of existing mitigation tools currently used for treating ephemeral streams. To compliment this, Lake Rotorua is introduced, along with reasons why DBs are being trailed in the Rotorua catchment as a potentialmitigation tool for phosphorus and sediment loss to assist with the improvement of lake water quality. Lastly, the aims and objectives of this study are stated, along with corresponding hypotheses.

1.1 Background

1.1.1 The rise of agriculture in New Zealand

Pastoral agriculture is often regarded as the 'backbone' of NZ'seconomy and rural culture (Clark et al. 2007). Over 50% of the landmass of NZ is covered by pasture, making it NZ's primary land use (Taylor 1997). New Zealand's landscape was once covered by native ecosystems, including indigenous forest and wetland systems(Craig et al. 2000). These provided a range of ecosystem services, including soil production and water purification, with wetlands acting like kidneys in the landscape.

New Zealand's land cover has changed dramatically over the last 700 years as a consequence of anthropogenic activities by both early Maori (fires) and Europeans (timber extraction), and more recently, land conversion to agriculture (Craig et al. 2000). Indigenous forests have been reduced from 85% to 23% of total land cover and wetlands to less than 10% of their pre-European area (Taylor 1997). Land conversion to pastoral farmland has been the largest contributor to this land cover change and has occurred mainly within the past 100 years(Craig et al. 2000). New Zealand pioneers 'broke in the land' by converting forest and wetland ecosystems into productive pastoral farmland with the addition of fertiliser, grass seed and exotic mammals (as seen in Figure 1.1).

Figure 1.1:Pioneer settlers converting New Zealand to pastoral farmland by adding grass seed to cleared forest. From PCE (2012, p.17) (reproducing photography from this source is approved by the author; primary source: Northwood Collection, Alexander Turnbull Library, Wellington).

Vegetation clearance to create pastoral farmland has altered hydrological regimes. Rainfall has a higher tendency to result in surface runoff on pasture than on forested land. Connectivity between land and water determines the potential sensitivity of receiving waters to surrounding land management practices (Brierley & Fryirs 2005).

Agriculture has continued to expand and intensify, especially the dairy industry (primarily grass–based milk production) which has grownto meet strong international demands for NZ’s world class dairy products. In 2003, New Zealand produced almost one–third of the world’s internationally traded dairy products (Ministry of Agriculture and Forestry 2010). Conversions from forestry and dry stock (sheep, beef, cattle, and deer) to dairy farms have occurred nation-wide. The NZ dairy herd has more than doubled in the past 30 years, reaching 6.5 million cows in June 2012, a 23% increase over five years (Statistics New Zealand 2012). The dairy industry contributes to NZ’s economy (Schilling et al. 2010) with yearly export earnings up to $12.5 billion dollars as of June, 2012 (Statistics New Zealand 2012). Farm intensification has exacerbated environmental stressors for many downstream receiving water bodies throughout NZ (Abell et al. 2011; Clark et al. 2007; Parliamentary Commissioner for the Environment 2012).

In recent times, there has been increasing concern for the integrity of freshwater ecosystems (Parlimentary Comissioner for the Environment 2004) This concern has led to the promotion of the adoption of more sustainable farming practices by farmers to safeguard the economic productivity and environmental integrity of NZ for future generations, for example see: the Dairying and Clean Streams Accord 2003 (Dairying and Clean Streams Accord between Fonterra Co-operative Group, Regional Councils, Ministry for the Environment, and Ministry of Agriculture and Forestry 2003); National Policy Statement on freshwater (Ministry for the Environment 2013); BoPRC Regional water and land Plan (Bay of Plenty Regional Council 2013); Land and Water Forum (Land and Water Forum 2010); and the One Plan (Horizons Regional Council 2012).

1.1.2 Soil loss in NZ

New Zealand's landscape was converted to agriculture recently (c. last 150 y), and the effects soil loss are ongoing in the landscape today (Boulton et al. 1997; Cumberland 1944). Vegetation once helped to stabilise much of NZ's geologically young soils, however, deforestation exposed this soil to erosive forces (e.g.. rain water and subsequent runoff) and hill slope processes such as slips and slumps resulted in nationwide soil loss issues throughout New Zealand, especially on steep topography (Campbell 1974; Cumberland 1944). New Zealandstill looses soil at an unsustainable rate, accounting for 1% of the world's total sediment loss to sea per year, despite taking uponly 0.2% of Earth's total landmass(Sharpley et al. 2008).Once lost, this soil which has developed over thousands of years will never return to the same extent when under pastoral land use (Campbell 1974).

Soil erosion can be seen as a loss to the country's productive potential and to the integrity of downstream aquatic environments (Campbell 1974; Cumberland 1944). Soil loss and transport via waterways often leads to excess sedimentation in water bodies. Sediment is an insidious contaminant once in aquatic ecosystems; it can degrade habitat, directly impact fauna and can act as a conduit for nutrient transport (Parliamentary Commissioner for the Environment 2012).

Historical soil loss still burdens aquatic ecosystems today, as sediment continues to fill interstitial spaces (known as the hyporheic zone) between substrata in gravel bed rivers(Boulton et al. 1997; Stanford & Ward 1988). The hyporheic zone is an important habitat for many native freshwater species where individuals can burrow several metres under the substrate, however, sedimentation of these spaces and reduce the ability of species to use this crucial zone (Boulton et al. 1997; Stanford & Ward 1988).(Boulton et al. 1997) studied the hyporheic zone of streams draining pastoral and forested land and found less diverse invertebrate fauna communities in pastoral catchments, in conjunction with greater sediment deposition. The widespread, erosion-driven sedimentation in NZ’s streams is a likely contributing factor to the decline in native fish abundance (Allibone et al. 2010).

1.1.3 Nutrients

Nutrient fertiliser

Fertiliser application is an integral component of agricultural production in NZ and internationally. Nutrients, mainly nitrogen (N) and phosphorus (P), are applied in the form of superphosphate, urea, chicken manure and dairy effluent, among others, to sustain plant growth. Without fertiliser, pasture based production would be significantly lower. Fertiliser has been applied to NZ soils at an increasing rate (Parlimentary Comissioner for the Environment 2004)since the arrival of Peruvian guano in 1860, superphosphate in the 1880s, and aerial topdressing in the 1950s (Campbell 1965), especially in recent years with the increased numbers of intensive dairy farms (Clark et al. 2007; Statistics New Zealand 2012). Plants inevitably do not use all the nutrients that are applied to agricultural land. Some (the extent varies depending on management) will end up in downstream water bodies, where they can have detrimental effects on ecosystem functioning(McDowell et al. 2009). The relevant process is described in the following subsection.

1.1.4 Eutrophication of freshwaters

Overview

Just as nutrients limit terrestrial plant growth, they can also be the main limiting factorfor productivity in freshwater aquatic ecosystems (Schindler 1974). Productivityrefers to the rate at which biomass is generated in an ecosystem, for examplephytoplankton (algae), periphyton (algae, bacteria, fungi and protozoa)and macrophytes(vascular plants with roots and stems larger than 0.5 mm)(McDowell et al. 2004),all of which are primary producers at the base of aquatic food webs. Freshwater ecosystems at temperate latitudes are typically limited by either nitrogen or phosphorus, or sometimes both nutrients (Abell et al. 2011; Schindler et al. 2008). When the limiting nutrient of that particular system becomes increases, primary production (such as growth of algae biomass) increases. The process of increasing productivity is known as eutrophication, an environmental issue worldwide(Smith 2003) which can have detrimental impacts on humans and wildlife (Johnson et al. 2010). Additions of nutrients can cause excessive plant growth (when requirements for other limiting factors such as light and temperature are met) and can result in nuisance algae and/or bacterial blooms which are often toxic (Smith 2003). There are many negative effects associated with eutrophication, such as health risks to humans (and livestock); loss of the water body's amenity value (e.g. associated with swimming and fishing); large scale death of aquatic fauna and promotion of internal nutrient loading (Johnson et al. 2010; Vant 1987).

1.2 Nutrient-loss pathways

1.2.1 Point and diffuse source pathways

Nitrogen and P are the two main nutrients of concern to freshwater managers. These nutrients can enter waterways from both point sources or diffuse sources (non-point) in upstream catchments (Carpenter et al. 1998). 'Point source' refers to concentrated discharge sourced from a specific location, such as factory waste, city waste water effluent discharge, or runoff from a dairy shed or inadequately designed farm dairy effluent management system. Regulation has addressed most point source discharges in NZ, however, diffuse source pathways are much harder to control and manage as they can originate from a range of sources over a large area (McKergow et al. 2007). Diffuse pathways are currently the predominant way that nutrients and sediment enters waterways in NZ (Parliamentary Commissioner for the Environment 2012).

Diffuse pathways can be split up into three categories: ground water, subsurface and overland flow. Nitrogen and P have different transport pathways from farm systems to receiving water bodies. Nitrogen leaves farmland predominantly as nitrate (NO_3) which is negatively charged so readily leaches through negativly charged soil particles into ground water and sub-surface systems. Conversely, P is commonly transported by overland flow in particulate form associated with soil particles (McKergow et al. 2007), but is also transported as dissolved P (Hart et al. 2004). These are the main pathways but they are not mutually exclusive. Phosphorus can be also transported in subsurface and ground water systems, and N can be transported via overland flow. Both nutrients (N and P) have the ability to change form (i.e. between dissolved and particulate form) several times *en* route (McDowell & Sharpley 2001a; Sharpley et al. 2001). This thesis focuses on diffuse nutrient transport in storm water overland flow from pastoral farmland.

1.2.2 Phosphorus retention and internal nutrientcycling

Internal nutrient loading is another pathway by which P can enter the water column of water bodies in a bio-available form. Phosphorus adsorbs (attaches) to and desorbs (releases) from sediment depending on a series of microbial processes (Istvanovics 1993); nutrient gradients between sediment and solution; and, redox conditions of surrounding water. Sediment which accumulates in water bodies can have high levels of attached P depending on historic land use and geology in the surrounding catchment (Trolle et al. 2008). Under oxic (oxygen–present) conditions, P can form redox–sensitive associations with metals cations such as manganese (Mn) and iron (Fe). Phosphorus attached to Mn oxide and Fe hydroxides can be released during anoxic conditions (Davison 1993). This can be abiotically-mediated and also driven by anaerobic organisms (bacteria) which use Mn and Fe cations as electron acceptors during anaerobic respiration, resulting in the release of P, which then becomes bio-available (Reynolds & Davies 2001). Internal P loading can be part of a positive feedback loop where nutrient release triggers increased primary production, which promotes a biochemical oxygen demand for respiration of microorganisms and bacteria as they mineralise dead organic material originating from this production. This can lead to anoxic conditions which trigger redox-mediated P release, and hence releases more P to the system which initiates the feedback loop again (Trolle et al. 2008).

Freshwater ecosystems can be extremely sensitive to P inputs well beyond the time of initial transport into that system, so it is important to encourage good land management practices as they will have an important influence on the integrity of water bodies in the future.

1.2.3 Overland flow

The simple definition of surface runoff is rain that runs off rather than infiltrating into or remainingon the surface where it lands. During high intensity rainfall, not all water will infiltrate through the soil. Excess water will pond and runoff via overland flow.

There are three main mechanisms producing overland flow:

1. Infiltration excess overland flow. This occurs when rain cannot infiltrate through the soil fast enough. This is a function of soil permeability and rainfall intensity (Horton 1933)and usually occurs during short but intense rainfall events (McDowell & Srinivasan 2009).

2. Localised infiltration excess overland flow. This occurs in specific areas where soil is saturated, such as the base of hills where water accumulates (Beston 1964). Livestock can exacerbate localised infiltration excess overland flow through compaction around areas such water troughs, races, and gateways (McDowell & Srinivasan 2009).

3. Saturation excess overland flow. This occurs where soil is saturated and no infiltration is possible(Dunne & Black 1970). This is a function of antecedent soil moisture conditions (Cappus 1960; Hewlett & Hibbert 1967).Runoff usually occurs by saturation excess during large storms (McDowell & Srinivasan 2009).

1.2.4 Ephemeral streams

An ephemeral stream is essentially water travelling as overland flow, but specifically refers to water discharge down a natural flow path as a result of combined overland flow.Ephemeral streams flow over otherwise dry land with flow durations lasting from minutes to days depending on precipitation intensity and soil characteristics. Rainfall events can yield large volumes of water over short periods of time, hence ephemeral streams can have high discharge volumes and fast flow velocities (Figure 1.2). Ephemeral streams can potentially transport a disproportionally large amount of sediment and nutrients from a farmed catchment over a short period of time (Hart et al. 2004). They are the main pathway for storm water transport from land (e.g. paddocks) to receiving water bodies such as streams, rivers or lakes.

Figure 1.2: A typical ephemeral stream with potential to transport sediment and nutrients. This paddock has no surface water for most of the time. (Upper Hauraki Stream, Lake Rotorua catchment). Photo: D. Clarke, May, 2012.

1.2.4.1 Phosphorus transport in ephemeral streams

Water is a conduit for P transport (McKergow et al. 2007). Ephemeral streams transport both dissolved and particulate forms of P, either through desorption of soil P to overlying water, or direct transport of P-enriched soil (McDowell & Sharpley 2001a). The dissolved reactive P (DRP) fraction is defined as P measurable in solution that passes through a filter with a nominal pore size of 0.45 µm. Particulate P (PP), is any P which would otherwise be retained by a 0.45 µm filter and can be determined by measuring total P (TP) in an unfiltered sample that has been digested in hot acid, and subtracting DRP. Potential P loss in overland flow is directly related to the catchment characteristics (e.g. geology, infiltration capacity, topography, climate), land use (e.g. dry stock or dairy)

(McDowell & Wilcock 2008), and management practices (recent fertiliser application, soil P concentration, soil compaction/ disturbance) in the contributing catchment prior to the runoff event (Hart et al. 2004; McDowell & Nash 2012).

Generalisations about the predominant fraction of P (PP or DRP) transported by overland flow cannot be applied to all ephemeral streams given these dynamic site-specific variations in controlling factors which influence P loss from agricultural land (Hart et al. 2004). This is reflected in the literature as research findings can vary significantly depending on the specific characteristics of the studied sites and events (Hart et al. 2004). However, insights can be obtained from the literature about the key driving factors which influence P transport in surface runoff. These are summarised below in two sections: before event and during event controlling factors. Interrelations between the two are also discussed.

Catchment conditions before an event

Conditions before an event influence how water will run off the land and what is entrained. Firstly, antecedent soil moisture will influence the degree to which water will infiltrate and run off. Wet soils (i.e. especially during winter and spring) are prone to compaction and soil disturbance from stock activity. Grazing during these conditions will strongly increase the potential for soil erosion and hence sediment transport in overland flow (Elliott et al. 2002; Nguyen et al. 1998). Grazing events increase the likelihood of P loss from pastoral farmland (McDowell et al. 2006). Soil loss is further exacerbated by lessoverall pasture cover during winter months. In contrast, dry soil conditions (i.e. during summer and autumn) are less prone to stock disturbance, however, pasture growth is limited by water availability, so soluble P is under-utilised. This can increase the potential for DRP loss to surface water (McDowell & Sharpley 2004).

There are spatial variations in P sources across pastoral farmland. A large proportion of annualP and sediment export can come from a small proportion of the landscape, during only a few large storm events(Pionke et al. 2000). These contributing areas are called critical source areas (CSA) defined as the combination of a transport mechanism (i.e. ephemeral stream) and a contaminant source (i.e. soil with elevated P concentration) (McDowell et al. 2004; McDowell

& Srinivasan 2009). Critical source areas can contribute up to 80% of a contaminant load, even though they often only occupy a small proportion (c. < 20%) of the contributing catchment (Gburek & Sharpley 1998). Examples of CSAs are raceways, water troughs, animal wallows, pugged areas, grazed forage crops and tilled paddocks. Critical source areas are often compacted by stock activity, so infiltration excess overland flow is exacerbated, increasing the likelihood of transport during rainfall. Phosphorus load conveyed in ephemeral streams is directly related to whether or not they are connected to CSAs.

Fertiliser applications (timing, rate and type) are key driving factors affecting quantity of P loss (Sharpley & Syers 1983). Rainfall directly following application can lead to excessive event-specific losses (Hart et al. 2004). Historical fertiliser regimes are important, as over-enriched soil has a higher potential to release (desorb) P and also a greater potential environmental impact if suspended and transported downstream (McDowell & Sharpley 2001a). Maintaining soil at optimal Olsen P levels (the level necessary for optimal plant growth) for that particular soil type can have huge benefits for downstream water quality and farm economic performance (Hart et al. 2004; McDowell & Sharpley 2001c; McKergow et al. 2007; Monaghan et al. 2008). It is important to note that even with optimal soil P levels, P will still be potentially lost from pastoral farmland (Sharpley et al. 2000), but not to the same extent as if the soils are over-enriched and have high Olsen P levels.

Phosphorus dynamics during a runoff event

Several factors drive P transport during a runoff event. Firstly, the quantity and intensity of rainfall determines the discharge volume, flow velocity and duration of runoff. These, in addition to the P concentration, are the driving forces behind total load exported during an event. The initial flow period is referred to as the ‘first flush’ and can account for a disproportionally high percentage of the total P export in ephemeral stream water draining pastoral farmland, especially in summer when there is unutilised soluble P in the soil and when fine soil particles are selectively entrained (McDowell et al. 2004). Fine soil particles (i.e. < 13 µm) can potentially hold large amounts of P due to large surface area: volume ratios which increases their ability to adsorb P (Stone & Mudroch 1989). Fine particles such as clays and organic material are easily transported by low flow velocities (i.e. first flush water). The settling velocity of a particle through a standing body of water is defined by Stokes law which incorporates the density and diameter of the particle, the density and viscosity of the fluid medium, and gravitational acceleration (Hsü 2004).If particles have the same or lower density than water, they may stay in suspension for extended periods.

Total DRP export can peak during initial flow stages (commonly known as the first flush) because highly mobile P can be released (desorbed) from soil to solution almost instantaneously (McDowell & Sharpley 2001c). The rate of P desorption is a function of the surface area of soil exposed to water and the P concentration of the soil (McDowell et al. 2004). Conversely, total PP export can be well correlated with water discharge, especially if there is an abundant source of mobile sediment such as from sloping ground that has been cultivated or heavily grazed or disturbed paddock. Sediment transport and deposition in unidirectional flow is a function of flow velocity and sediment size (Hjulstrom 1935). The transportation of sediment is dependent on the critical shear stress (i.e. flow velocity) required to initiate soil particle movement. Clay particles have a higher shear stress than sand, but are more easily transported once in suspension. Rainfall intensity can directly dislodge particles and contribute to SS load in overland flow, which can have a direct effect on PP concentrations entering downstream water bodies (Fraser et al. 1999).

A peak in discharge volume can drive a peak in SS and P transport, depending on the P concentration of the SS (Hoare 1987; McDowell & Wilcock 2007). Suspended sediments can adsorb dissolved P from solution during storm flow (Sharpley et al. 1981), However, SS can also desorb it depending on the concentration gradients of available P and sorption capacity of the sediment.

1.2.5 Ephemeral stream mitigation

1.2.5.1 Farm management

When managing P, a combination of both appropriate soil management and prioritised site-specific considerations is necessary (Sharpley et al. 2000; Withers et al. 2000).Alterations to farm management practices are by far the most cost effective strategy for mitigating P loss from farms (McDowell & Nash 2012). Some of these include; wise nutrient application (type, timing and rate), appropriate stock management (minimising overgrazing and soil disturbance) and stock exclusion from waterways (Sharpley et al. 2001). Strategic grazing of ephemeral flow paths (i.e. for restricted times during suitable soil conditions) can reduce the direct transport of soil and nutrients downstream (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012).

1.2.5.2 The ephemeral stream mitigation tool box

There are several tools which can be used to treat ephemeral stream water (directly or indirectly) during low to medium discharge rates. Treatments are more practical to apply in upper catchment areas. Lower catchment ephemeral streams are subject to much greater volumes. Ephemeral streams that form following intense rainfall events with high discharge volumes are harder to treat due to the sheer volume of water. The available mitigation tools, and issues associated with them, are discussed below. Each tool has a specific function and different tools can be used in different situations, or in combination with others to achieve a desired outcome (McKergow et al. 2007; Monaghan et al. 2008).

Riparian buffer strips are vegetated areas adjacent to waterbody margins. They can be effective tools for attenuating sediment and nutrients (particularly particulate forms) (Cooper et al. 1995; Vought et al. 1995; Williamson et al. 1996). Grass filter strips are areas of dense grass which can filter out particulates (Collins et al. 2004; Smith 1989). Grass filter strips can be in riparian or in paddock settings. Restrictive grazing techniques (i.e. carefully timed short term ‘crash grazing’) (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012)can be used to maintain grass filter strips along ephemeral flow paths within paddocks (Ministry for the Environment 2001). Grass filter strips work best in catchment areas with low gradients when water flows through on a broad front (i.e. not channelised) below the height of the grass (Cooper et al. 1990). However, both riparian buffers and grass filters can be inefficient during extreme rainfall when water converges and flows rapidly through the attenuation area with minimal treatment (Cooper et al. 1990; Owens et al. 2007; Verstraeten et al. 2006).

Sediment traps are excavations in the bed of a watercourse designed to promote sediment settling (Hudson 2002). Coarse sediment traps are designed to attenuate large sediment particles including medium silt size classes. If regularly maintained they can trap up to 90% of fine sand which is transported as bed load, however, they are less efficient at retaining fine particles which are transported in suspension (Hudson 2002) which, as discussed above, can potentially contain large quantities of P (Stone & Mudroch 1989). The efficiency of in-channel sediment traps is often compromised by inadequate storage volume to catchment area ratios; research into the optimal design of sediment traps is currently underway in NZ.

Wetlands, both natural and constructed, can be extremely effective at attenuating sediment, P and N in both particulate and dissolved forms (McKergow et al. 2007; Tanner et al. 2005; Tanner & Sukias 2011). However, during large floods, water can pass through wetlands with minimal residence time, or in the case of constructed wetlands, flood water is often deliberately bypassed to reduce wetland damage (Tanner 2003). This highlights the importance of integrating storm water attenuation and mitigation tools in the upper catchment areas, such as controlling flood flows to increase wetland performance through increased residence time.

Effective treatment of flood water is the key challenge which all of the above tools struggle with. It is during heavy rainfall that P is predominantly exported from farmland, in particulate form, attached to sediment (Hart et al. 2004; Sharpley et al. 2001). Therefore, attenuation efforts need to focus on altering hydrological regimes, such as slowing down flood water (McKergow et al. 2007). McDowell & Nash (2012)concluded in a review of the performance of P mitigation tools for New Zealandand Australia that alteration to a drainage system cannot be relied on for P mitigation until further studies are conducted. The sheer volume of water transported by ephemeral streams is the key challenge to mitigating diffuse sourced nutrients and sediment in overland flow both in NZ and overseas. Consequently it is important to attenuate ephemeral flows as close to their originating sources as possible i.e. prioritise the upper catchment areas.

1.2.5.3 Integrating knowledge

Lessons can be learned from other management contexts to help develop mitigation tools for agricultural landscapes. For example, the construction industry works within strict guidelines to minimise sediment loss from earthwork sites and these activities are regularly monitored (M. Cooper, Goodmans Contracting, *pers. comm.*, 2012). A range of sediment retention tools are used on earthwork sites including: silt fences, mulch, hydro-seeding, hay bale filters and sediment retention ponds (SRPs) (Auckland Regional Council 1999; Clemens & Dunphy 2010). Sediment retention ponds have been considered the most effective tool for mitigating sediment loss from earthwork sites (Auckland Regional Council 1999). A typical SRP consists of an earth-built pond which retains water (Clemens & Dunphy 2010). Water slowly drains out small holes in one or more floating T-bar pipes which are suspended by wire to allow for water retention as 'dead storage'. Figure 1.3 below a typical SRP built to treat runoff from a construction site.

In order to treat water containing fine particulates (e.g. clays), an aluminium flocculant, polyaluminium chloride, is often added to SRPs (at rates determined by an automatic dispenser based on rainfall quantity) to promote fine particles to settle from suspension (Jackson 2008). When flocculant is added, fine particles join and form larger aggregates, known as 'flocs' which settle out of suspension at much faster rates than individual particles (Gregory 2004). Winter (1998) quantified the performance of a SRP and found that it trapped approximately 90% of suspended material. The recommended storage ratio for SRPs ranges from 200-300 m^3 per hectare of contributing catchment, with a maximum catchment size of 5 ha (Clemens & Dunphy 2010).

Figure 1.3: A Sediment Retention Pond used to attenuate sediment in runoff from construction sites. Note the suspended T-bar decant structure attached to a concrete riser allowing 'dead' storage of water. Courtesy of Goodman contracting, Wellington, 2012. Photo: Dylan Clarke, 5/10/2012).

Another form of runoff control tool is Detainment Dams (DDs) which have been designed by hydrologists specifically for control of flood water control and downstream erosion. The Bay of Plenty Regional Council has implemented DDs in the Rotorua catchment since the 1970s to control flood water (i.e. ephemeral streams) leaving pastoral farmland. These DDs were installed to arrest 'headwall gullying' issues downstream and were not designed for nutrient retention, although PP retention may occur. There is no specific control of residence time as water leaves the dam though an unrestricted culvert pipe below the bund (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012). Storage basins behind DDs are generally dry until rainfall produces runoff which fills the dam faster than it can drain.

1.3 Detainment bunds for ephemeral storm water mitigation

1.3.1 Introduction to Detainment Bunds

Detainment bunds (DBs) are a new type of mitigation tool, being trialed in the Rotorua lakes catchment. This trial of various especially constructed DBs is a collaborative project between landowners and the BoPRC to address the large annual P-loads entering lake Rotorua during storm events (Rutherford and Timpany 2008). They are designed to treat ephemeral stream water, particularly for mitigation of sediment and P export in the Lake Rotorua catchment (Figure 1.4). Detainment bunds are essentially a combination of DDs and SRPs (both described above), combining key aspects of each and applying them in an agricultural context. Detainment bunds have been specifically designed for sediment and P retention by intercepting ephemeral stream flow paths before they enter downstream waterbodies, as depicted in Figure 1.5. There may be other co-benefits such as flood control and maximising the efficiency of the downstream mitigation tools mentioned above (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012).

Figure 1.4:A typical detainment bund, designed to temporarily pond ephemeral stream water, Waiteti Stream catchment, Rotorua, March, 2012. This photograph has been taken after a runoff event and the pond is still draining.

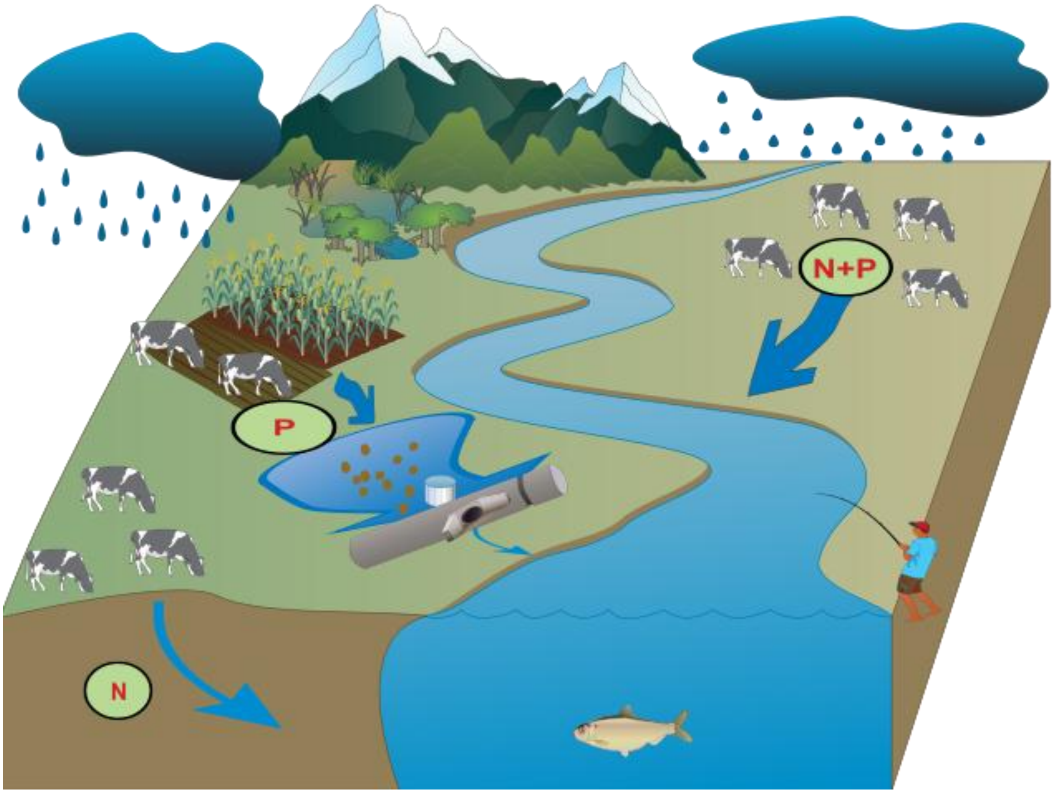

Figure 1.5:Schematic diagram showing the key nutrient pathways including phosphorus in overland flow and nitrogen infiltration through the soil. A detainment bund intercepting runoff water from a cultivated and grazed paddock is shown.

1.3.2 General Detainment Bund design

Detainment bundspond ephemeral stream water behind an earth bund (c. 1.5 m high), with the aim of promoting settling of suspended sediments and associated PP in a ponding area (i.e. onto the pasture). The ponded water drains within several days (c. 3) to ensure pasture quality in the ponding area is maintained. If water ponds for prolonged periods, pasture growth can be temporarily stunted due to supressed photosynthesis from the overlying water. Detainment bunds have been specifically designed to fit into (not disrupt) farm systems. Figure 6 depicts the design of a typical DB. Water is released slowly out a floating decant structure (or drains in the riser). The floating decant structure is similar to SRPs, but has a much larger intake pipe (to avoid blockage) and drains the pond completely empty so there is no ‘dead storage’ like SRPs. No aluminium based flocculant was applied to the ponded water of DBs, unlike many SRPs on earthwork sites. Detainment bunds have a choked outlet riser to control residence time by regulating water storage, unlike the DDs which have an unrestricted outflow pipe.

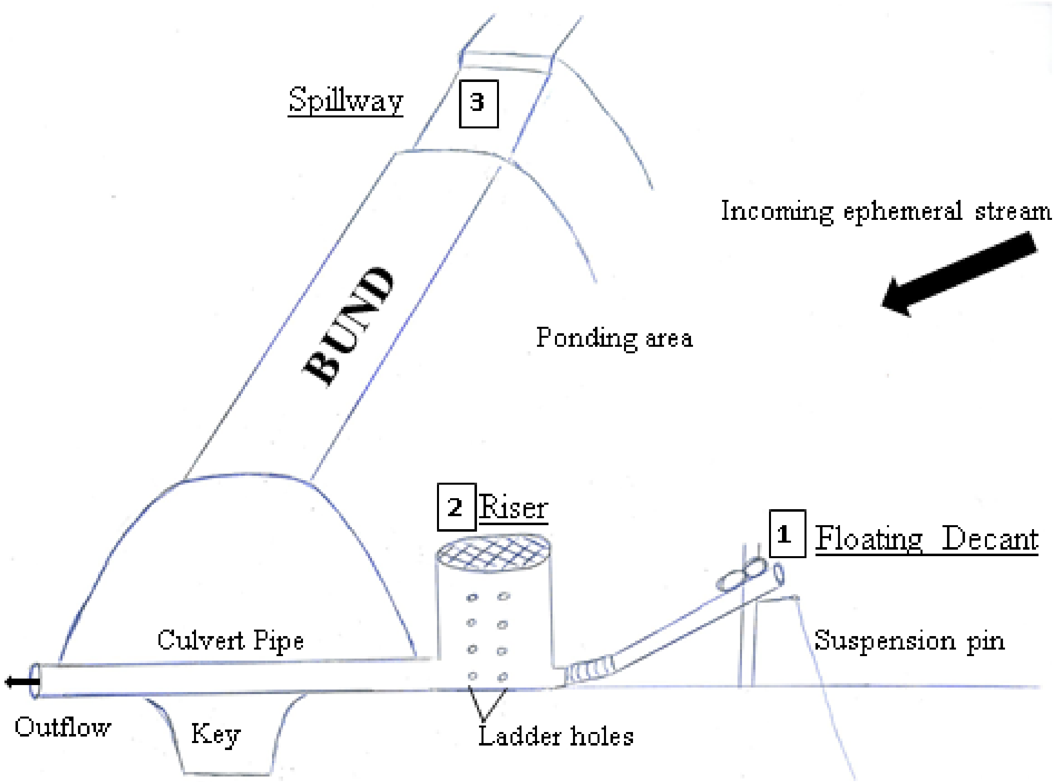

Figure 1.6: Schematic sketch of a functional detainment bund.

Incoming ephemeral stream water is ponded behind an earth bund and water can leave the basin by three outlets, as depicted in Figure 1.6. In theory, the first outflow is via a floating decant (1; Figure 1.6) suspended by a pin which is pulled when water level rises in the basin, this allows the retention of ‘first flush’ water. Sand bags and plugs (in the ladder holes) were also trialed as part of an experimental learning process. The second stage of outflow is via a concrete riser (2; Figure 1.6); water flows into this when the basin fills to storage capacity, as seen in Figure 1.7. The thirdstage of outflow is via an emergency spillway (3; Figure 1.6) which is seldom used but a necessary component. Erosion-proof matting, compact substrate, or stable grass cover are necessary to prevent spillway erosion. Each bund was ‘keyed’ and compacted into the ground during construction for stability when retaining water (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012). The DBs were initially proposed to have a minimum catchment area to storage volume capacity ratioof 100:1 (100 m^3 of water storage per one ha of contributing catchment).

Figure 1.7:A full detainment bund in the upper Waiteti Stream catchment in 2012.Ponded water exits down the top of a concrete riser (outlet #2) when storage capacity has been met.

Detainment bund construction was a joint effort between Bay of Plenty Regional Council (BoPRC) (project director: John Paterson,Sustainable Farming Advisor), independent contractors (funded by BoPRC) and farmers providing machinery and labour *pro bono*. Bund construction is a permitted activityin the Bay of Plenty region as long as the spillway is no higher than 1.5m and storage volume is less than 10,000 m^3 (Rule 46; BoPRC, 2012). Each land owner has signed a memorandum of understanding with BoPRC that outlines a range of commitments to be undertaken by both parties, including the commitment to ensure that water will not be ponded for longer than three days unless arranged otherwise. This assumes the productive potential of the ponding areas, which are “some of the best paddocks of the farm” is retained (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012). SixDBs had been constructed in the Lake Rotorua catchment by the end of 2012.

This MSc study involved monitoring three of these DBs during 2012 in order to assess the potential environmental benefits of these on–farm tools. Sediment deposited across detainment bund ponding areas following seven storm events was analysed and water was sampled from inflows and outflows of the DBs. A range of laboratory analyses were conducted on samples and results were combined with hydrological measurements to provide insight into the efficacy of DBs. The findings of this study will be used as a basis to inform future implementation of DBs on pastoral farmland throughout the Lake Rotorua catchment. In addition to the findings of this study, the level of support and acceptance from the farming community is also an important consideration for the extent of any future DB implementation. If DBs are effective they could fit into the mitigation ‘toolbox’ for interception of overland flow to further minimise the potential environmental impact of pastoral farmland throughout NZ and elsewhere.

1.4 Lake Rotorua

1.4.1 Geology and catchment characteristics

Lake Rotorua is located in the Bay of Plenty region in the north island of New Zealand. The catchment of Lake Rotorua has a rich volcanic history, which dominates the landscapes topography and soil characteristics (Healy 1963). The Mamaku region is characterised by hummocky mounds consisting of ignimbrite which was deposited during the formation of the Rotorua Caldera c. 140,000 years BP (Milner et al. 2003).These unique landscape forms can be seen in Figure 1.8. Much of the Rotorua catchment soil allows rapid infiltration of rainfall into groundwater systems, some of which are renewed on time scales of a century or more (Morgenstern et al. 2005). Porous volcanic soil results in rapid infiltration and minimal runoff via overland flow (Hoare 1980) during moderate rainfall, however, during extreme rainfall events, ephemeral streams form and play a crucial role in the hydrology of the landscape to such a degree that well defined ephemeral stream flow paths can be seen in many areas. An example of such is the upper Waiteti Stream catchment shown in Figure 1.8. Lake Rotorua has several entirely ephemeral catchments (Hoare 1980).

Figure 1.8: The Mamaku landscape in the upper Waiteti Stream catchment, well defined ephemeral stream flow paths have formed. This stream was active on the 09/05/12 after heavy rainfall.

1.4.2 Phosphorus in the catchment of Lake Rotorua

There are both natural and anthropogenic sources of P in the Lake Rotorua catchment. Pumice soils of the region have naturally low nutrient (P) levels(Landcare Research 2011), compared to allophanic soils which are often naturally rich in P, due to their volcanic origin and physical properties. A large part of the naturally occurring P may not be bio-available hence does not directly contribute to plant production. Fertiliser applications are therefore necessary to bring Olsen Pconcentrations up to those that will alleviate P limitation in plants, on both naturally rich P soils and pumice-dominated soils. Lake Rotorua is receiving P from both natural and anthropogenic (originating from agricultural fertiliser) sources (Rutherford & Timpany 2008). However, anthropogenic sources are the main source of P as they are the most readily bio-available.

Storm events contribute significant amounts of particulate phosphorus to Lake Rotorua. Based on analysis by (Rutherford & Timpany 2008)approximately 9.6t of PP enters Lake Rotorua in storm loadsvia permanent streams per year. This estimate does not account for the eight ephemeral sub-catchment contributions (Hamilton et al. 2012), which comprise c. 20% of Rotorua'scatchment (based on an BoPRC assessment), so there may be c. 12t of PP entering Lake Rotorua per year during storm events (J. Paterson, Bay of Plenty Regional Council, *pers. comm.*, 2012).

1.4.3 Lake water quality

Lake Rotorua is a polymictic, eutrophic lake which is sensitive to both N and P inputs (Abell et al. 2011; Burger et al. 2008). Nutrients are derived from both urban and agricultural land use (Rutherford & Timpany 2008). Historic sewage discharge from the city of Rotorua resulted in notable lake deterioration from the 1960s(Rutherford et al. 1989). Subsequent sewage treatment upgrades including state of the art biological treatment and post treatment land disposal have significantly reduced the urban nutrient inputs into Lake Rotorua over the past 20 years (Parliamentary Commissioner for the Environment 2006). Pastoral farm land is a major contributor of nutrients into the lake, especially P, during storm events (Rutherford & Timpany 2008). Although a portion of this PP will be from natural sources, such as stream bank erosion, a significant amount is likely to be anthropogenic associated from pastoral farming activities (e.g. fertiliser application). (McDowell & Sharpley 2001b)found higher concentrations of P in stream bed sediment compared to that in stream bank sediment. This can be related back to the Rotorua area where P-rich river bed sediment may have originated from pastoral farmland, transported by overland flow during rainfall. Excess nutrient input to lake Rotorua has resulted in toxic algal blooms (Rutherford et al. 1989), a burden to society and the environment.

1.4.4 Restoration initiatives

Impaired water quality of Lake Rotorua has initiated significant restoration efforts, initiated through the BoPRC, which funds a Chair of Lakes Management and Restoration at the University of Waikato.

Targets have been set for nutrient loads, in order to reach targets, regional policy (Rule 11) has been implemented to reduce farm intensification in the catchment. The BoPRC has developed the 'Lake Rotorua Phosphorous Mitigation Project Plan' which is linked to the storm water management plan. The latter has been implemented to reduce external loading to the lake by promoting best management practices in the catchment (Parliamentary Commissioner for the Environment 2006). The performance of DBs are being monitored to assess if they are an effective tool suitable for general widespread adoption in the lake Rotorua catchment.

1.4.5 Conclusion

In conclusion, NZ has undergone dramatic land use change over the last century, resulting in over 50% of NZ's land mass becoming occupied by pastoral agriculture. Farming has been beneficialfor the country's economy and rural livelihoods, but has had negative influences especially on the integrity of freshwater ecosystems in lakes and lowland waterways which are in decline throughout the country. Ephemeral stream flow are the main conduit for sediment and associated nutrients from farmland to water bodies across NZ. These ephemeral streams have the potential to transport high concentrations of sediment and nutrients over short periods of time which are a challenge for many mitigation tools available, especially during high flows.

Detainment bunds are a new mitigation tool designed to pond ephemeral stream water in small upper sub-catchment locations to allow sediment and nutrients to settle and reduce storm discharges downstream. This thesis on the performance of trial DBs in the Lake Rotorua catchment to assesses if they are an appropriate tool for reducing P loads into Lake Rotorua during storm events.

1.5 Aim and Objectives

The aim of this project is to quantify the performance of a new type of DB designed to attenuate P and sediment lost from pastoral farms in the Lake Rotorua catchment. This research will determine if DBs are worthwhile mitigation tools to be implemented on farms for meeting P reduction targets specifically for the Lake Rotorua catchment, but also more widely across pastoral farmland.To achieve this aim, the following objectives and hypothesiswere defined (Table 1.1).

Table 1.1 Objectives and hypothesis relating to the assessment of the performance of DBs in the Lake Rotorua catchment.

Objective	Specific objectives	Hypothesis
1. To determine the difference in water quality parameters between inflows and outflows during a ponding event.	A) Compare the water quality characteristics of ephemeral streams entering DBs with water leaving DBs at the same point in time.	Hypothesis 1:Hypothesis 1: The inflowing ephemeral stream water will comprise larger suspended particles compared to the outflow due to the reduction of water velocity in the ponded water.
2. To determine the relationship between ponding time and water quality parameters.	A) Assess how dissolved and total nutrient concentrations vary during ponding time.	Hypothesis 1: Total P concentration of water leaving the bund will decrease over the days of ponding (as sediment settles out) Hypothesis 2: The fraction of TP comprising PP in outflowing water will decrease with ponding time (as sediment settles out) Hypothesis 3: Concentrations of TSS and DRP will be inversely correlated due to adsorption of DRP to soil particles.
	B) Determine the relationship between suspended sediment particle size and ponding time.	Hypothesis: Suspended sediment particle size in ponded water will decrease over time as large particles settle out.
	C) Determine the potential relationship between the composition of suspended solids and ponding time.	Hypothesis 1: TSS concentrations will decrease over ponding time due to sedimentation of suspended particles. Hypothesis 2: Inorganic particles will settle out in the basin before organic particles, which may stay in suspension throughout the ponding period.
3. To determine the quantity and composition of sediment retained by DBs during ponding events.	A) Determine the spatial distribution of sediment deposited in the basins.	Hypothesis 3: Size sorting will promote finest sediment settlement and largest overall mass at low basin elevations, due to longer ponding times.
	B) Investigate if the P concentration of deposited sediment varies with elevation in the basin.	Hypothesis: Phosphorus deposited at low elevations will be enriched with P compared the higher elevations in the ponding basin.
	C) Quantify the concentrations of P and associated elements (e.g. metals that form complexes with P) in deposited sediment.	Hypothesis 1: Sediment deposited in the DB basins after 3 days of ponding will be primarily large particles with low P concentrations Hypothesis 2: Phosphorus will be associated with Fe, Mn and Al.
4. To calculate a mass sediment budget for ponding events.	A) Determine the quantity of P retained sampled per ponding event.	Hypothesis 1: The quantity of P retained per storm event will be directly related to the quantity of sediment deposited and the land use in the contributing catchment
5. To investigate the soil characteristics around an old detainment dam, and a new detainment bund.	A) Compare soil P concentration within and outside new and historic ponding areas.	Hypothesis 1: Soil P concentration will decrease with distance from the bund due to historic sediment settlement. Hypothesis 2: There will be no significant difference in the amount of P within and outside of the new DB ponding area.

Chapter 2: Methods

2.1 Site location

Three detainment bund (DB) structures were constructed by contractors (funded by BoPRC) and farmers (providing machinery and labour *pro bono*) on private dairy farms in the Rotorua district within the Bay of Plenty region, North Island New Zealand (Figure 2.1). Each of the three DBs wereconstructed across ephemeral stream flow paths in the upper reaches of separate sub catchments contributing to Lake Rotorua (Figure 2.1). Two of these structures are located in the upper catchments of permanently flowing streams, the Waiteti (mean discharge is 1391 L/s and the Awahou (mean discharge is 1644 L/s) streams, both of which are major surface inflows to Lake Rotorua (Hoare 1980). The Hauraki catchment is one of nine ephemeral sub-catchments entering Lake Rotorua. At all sites the DBs impound water over highly productive rye-clover pastures.

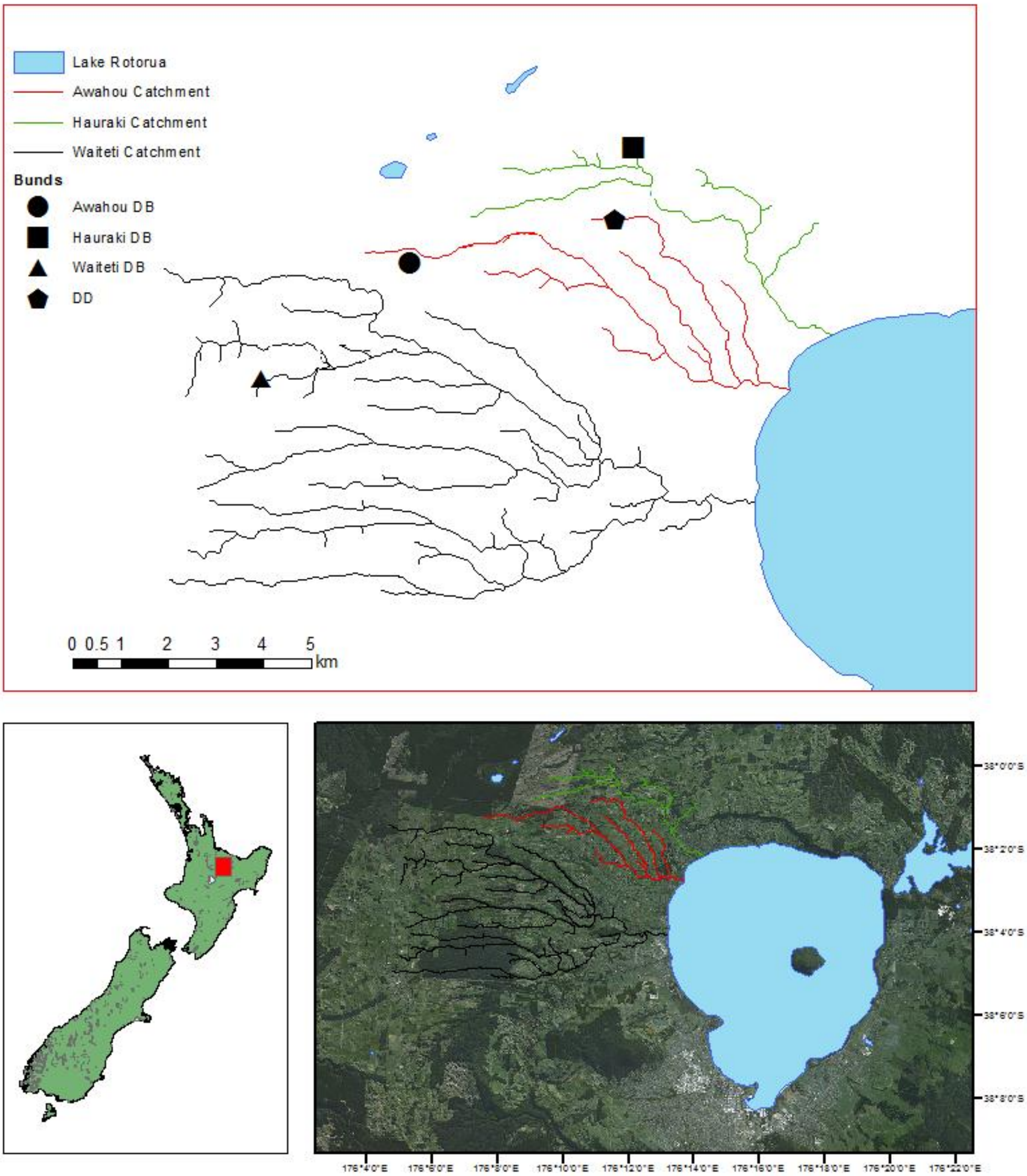

Figure 2.1: Location of sample sites across sub catchments within the Lake Rotorua catchment. The three detainment bunds monitored are labelled based on their sub catchment location. DD refers to a 12 yr old detainment dam where soil samples were taken.

2.1.1 Catchment characteristics

Both Waiteti and Awahou DBs are located in the Mamaku region, so are characterised by similar geologycharacterised by sandy podzol soils. The Awahou

DB is approximately 4 km north-east of the WaitetiDB (Figure 2.1). The Hauraki DB is located in the Kaharoa region, a further 5.4 km to the NE of Awahou DB and has slightly less rainfall and loamy pumice soils (Table 2.1). However, all three sites are located within 10 km of each other so show similar catchment characteristics.

Table 2.1: **Characteristics of each contributing catchment**

	DB location			
	Waiteti	**Hauraki**	**Awahou**	**Ref.**
Annual rainfall	c. 2500 mm	2000- 2400mm	c. 2500 mm	1
Drainage	Rapid	Rapid	Rapid	2
Parent material origin	Tephra	Tephra	Tephra	2
Topsoil clay range	5-8%	5-10%	10-15%	2
Soil classification	TypicOrthicPodzols	Buried-allophanicOrthic Pumice Soils	TypicOrthicPodzols	2
Soil order	Podzol	Pumice	Podzol	2
Dominant texture	Sandy	Loamy	Sandy	2
P topsoil retention	Medium (42%)	Medium (51%)	Medium (42%)	2
Land use in contributing catchment	Pastoral dairy farm	Pastoral dairy farm with summer turnip crop	Pastoral dairy farm with winter forage crop	

Key:

References (Ref.):

1: (Rijkse & Guinto 2010), 2: (Landcare Research 2011).

2.2 Detainment Bund specifications

Each of the three DBs had different storage capacities relative to the size of their contributing catchments, ponding area, and height of the concrete riser (Table 2.2). When expressed as the ratio of storm water storage (m^3) per ha of contributing catchment; Awahou DB had the largest storage capacity to the spillway of 157:1, Hauraki DB had a ratio of 101:1, and Waiteti DB had 67:1. At the time of construction, the desired optimal storage to catchment ratio was considered to be around 100:1 and preferably > 100:1. This was based on anecdotal experiences with historic detainment dam construction in the Bay of Plenty (J. Paterson, Bay of Plenty Regional Council, *Pers. comm.*, 2012; N, Ngapo, *Pers. comm.*, 2012). The storage ratio is different when measuring to the rim of the riser where the storage ratio changes to 39:1, 37:1, and 120:1 at Waiteti, Hauraki, and Awahou DBs respectively. Two ephemeral streams (named 'North' and 'South') enter directly into the Waiteti DB. The Hauraki and Awahou DBs each intercept one main ephemeral stream. The Awahou DB has the deepest ponding area and the Waiteti has the shallowest (i.e. less overlying water per m^2 of pond area when the DB is at capacity) as it is located on a flat valley floor Table 2.2).

Table 2.2 Detainment Bund specifications (for reference to DB design see Figure 1.6 above).

	DB Location		
	Waiteti	**Hauraki**	**Awahou**
Grid reference	-38.0304.23 °S, 176.0550.79 °E	-38.0020.67 °S, 176.1103.93 °E	-38.014697 °S, 176.0754.18 °E
Size of contributing catchment (ha)	69	54	21
Number of incoming ephemeral streams	2	1	1
Height of 1.050 m-diameter concrete man-hole riser (m)	1.5	1	1.8
Height to spillway (m)	1.9	1.54	2.03
DB Volume (m^3): - **i. To Riser rim** - **ii. To spillway (SW)**	i. 2723 ii. 4589	i. 1983 ii. 5469	i. 2527 ii. 3298
Ratio (m^3 of storage per ha of catchment): - **i. To Riser rim** - **ii. To SW**	i. 39:1 ii. 67:1	i. 37:1 ii. 101:1	i. 120:1 ii. 157:1
Choke hole diameter (mm)	135	150	150
Culvert pipe dimensions under DB	2 x 300 mm	1 x 415mm	1 x 300mm
Length of bund (m)	109	85	55
No. of occasions of spillway overflow during sampling period.	4	2	1 (minor)

2.3 Detainment Bund operation

2.3.1 Waiteti DB

Waiteti DB was constructed in September 2011. A floating decant structure was suspended by a pin during the initial filling stage to retain the ‘first flush’ of storm water. This pin was pulled by an attached rope once the pond was full (Figure 2.2). The pivoting decant structure drained water by floating on the receding pond surface (Figure 2.3) until the pond was dry, leaving the decant structure parallel with the ground (Figure 2.4). However, contrary to planned operation, water did not always drain solely from the decant structure. For example, water exited from small holes (ladder holes- labelled in Figure 1.6 above) in the riser from varying levels (Figure 2.5) and also sometimes from the joiner at the base of the decant structure. Ladder holes were subsequently filled with wooden bungs, although they were not a permanent solution. For more detailed information on different outflow cases encountered seeTable 2.1 below. In May 2012 the bund was raised to increase storage capacity. Construction exposed subsoil which washed into the ponded area during rainfall events for the duration of the study period in 2012. Sediment deposited in the basin sourced from the earthwork site had visually different characteristics from agriculturally sourced sediment and these were segregated prior to analysis (see Section 1.5.1.1 for details). Water level was recorded with a pressure sensor housed in a 30 mm diameter PVC pipe attached to the vertical staff gauge and recorded on a data logging device (C. Putt, *pers. comm.*, 2012).Data was adjusted to ground zero by subtracting the average offset of 170mm (the average recorded value when the basin was dry) from the data set.

Figure 2.2: Floating decant suspended by a pin to retain 'first flush' water at Waiteti DB.

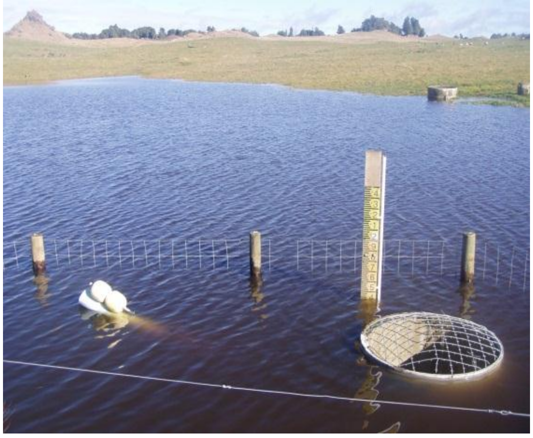

Figure 2.3: Waiteti DB at storage capacity, with water draining from the floating decant structure after heavy rain in March, 2012

Figure 2.4: Floating decant structure after draining ponded water at Waiteti DB, May 2012.

Figure 2.5: Water leaving the Waiteti DB via small holes in the riser, March 2012.

2.3.2 Hauraki DB

The Hauraki detainment bund was constructed in October 2011. Figure 2.6 and Figure 2.7 below show the bund before and during a rainfall event and storm water runoff. Rock was mined from the adjacent hill to build up the bund. Sediment from the rock excavation site was predominantly transported to the downstream side of the bund and did not contribute to sedimentation in the ponding area.

Figure 2.6: Hauraki DB (depicted by the black line), note the dry ponding area to the right, March 2012.

Figure 2.7: Hauraki DB during a storm, with incoming ephemeral stream (background) continuing to fill the detained ponding area.

Initially, the outflow control was a plug and pulley system (Figure 2.8) to allow water to pond for a fixed time before draining; however, it required a person to manually pull the plug once the pond had achieved a desired residence time (i.e. three days) (or earlier depending on rainfall predictions) and proved impractical. A floating decant structure was installed in June 2011 (Figure 2.9). It was suspended by a horizontal release pin which was identical in design to that of the Waiteti DB apart from inclusion of waterproof black flexing material at the hinge of the decant pipe which was used to resolve leaking issues (Figure 2.10). The buoyancy of this decant design meant that water was not decanted properly so the decant structure was removed halfway through a storm in late July 2012, which was the last storm monitored at this site. A water level recording system was constructed to obtain high resolution water level data; this was functional from 18 July 2012. Water level (stage) was recorded with a data logger (Iris 150g) at 5-minute intervals using a counter-weighted float which moved up and down in a vertical box in response to water level changes (Figure 2.10). A wire attached counter-weighted float turned a pulley wheel on an encoder which sent data to the logger (Figure 2.11). These instruments were powered by a 12 V battery, which was charged by a solar panel (Figure 2.11). Data were downloaded to a laptop computer using iLink software (iQuest (NZ) Ltd, Hamilton) (C. Putt, Bay of Plenty Regional Council,*pers. comm.*, 2012). Data was adjusted to ground zero by subtracting the average measured height during dry periods (72mm) from the entire data set.

Figure 2.8: Plug and pulley system, prototype #1, for controlled residence time, March 2012.

Figure 2.9: A floating decant structure suspended by a pin and two waratahs, June 2012.

Figure 2.10: Water level recording system housed in the vertical structure with the blue box on top, powered by a solar panel (top right). Hauraki DB, July 2012.

Figure 2.11: Water level recording system (in the blue box seen in Figure 2.10); as water level rises, pulley wheels turn the encoder (left) and data are logged on the Iris 150g (right). Hauraki DB, July, 2012.

2.3.3 Awahou DB

The Awahou bund is comprised of an existing raised farm access road retro-fitted with a concrete riser (Figure 2.12) to achieve DB storage requirements. Historically, water flowed under this elevated raceway and, although water would pond temporarily, there was no control of residence time. In June 2012 the concrete riser installation allowed water to pond (Figure 2.13) and prevent water conveyance through the pipe until either a sand bag (acting as a plug) was pulled via a rope (Figure 2.14) or water level rose above the riser. The sand bag pluggedthe 150 mm choke at the base of the riser which it covered. Itwas not a complete seal and some water drained from this bund over the days of ponding via infiltration of the sand bag and the ladder holes. The sand bag was generally pulled after three days of ponding (after samples had been taken). Once the sand bag was pulled, all water was drained from the pond within 12 h. The incoming ephemeral stream flowed through the middle of a crop paddock which was less than 300 m upstream of the bund (Figure 2.15). No water level recorder or decant structure was installed at this site and this site was an addition to the original sampling programme.

Figure 2.12: Retrofitted DB at Awahou site. Note: the raceway was already in place and riser was installed in 2012 to increase ponding time.

Figure 2.13: Ponded water at the Awahou DB, July, 2012.

Figure 2.14: The riser at Awahou DB had an outlet at the base, which was plugged by a sand bag that was pulled using an attached rope.

Figure 2.15: Incoming ephemeral stream upstream of the Awahou DB, after flowing through a bare crop paddock.

2.3.4 Water sample collection and analysis

Water samples were analysed for both nutrient and suspended sediment characteristics. Water samples were collected from incoming ephemeral streams and from DB outflows during and after rainfall events which produced ponding behind the bund.

2.3.4.1 Storm Sampling

Samples were taken during storm events and precise timing of sample collection was critical for obtaining samples from ephemeral streams. Weather systems were monitored closely using forecasts produced by Metservice(MetService 2013) and MetVUW(Metvuw.com 2013) to predict the intensity of rainfall events. Despite the close proximity of the three study sites, rainfall intensity could vary markedly between each site. Data measured at BoPRC's 'Oturoa Road' and 'Kaharoa Road' weather stations were closely monitored on the BoPRC live monitoring webpage (Bay of Plenty Regional Council 2012).

Forecasts of rainfall intensity (mm/h) and antecedent soil moisture (%) were used to predict the likelihood of surface runoff which would produce ephemeral stream flow and fill the DB basins. Rainfall intensities of > 10 mm/h had high potential to generate infiltration excess overland flow in the Lake Rotorua catchment, depending on antecedent soil moisture. If soil was saturated, relatively low intensity rainfall also had the potential to runoff (as saturation-excess overland flow), so each study site was closely monitored during these times.

2.3.4.2 Location and timing of samples

DB Inflows

Water samples were taken from inflowing ephemeral stream(s) 20 m upstream of the ponded water (if any) detained behind the bund. Inflow samples were taken as soon as possible, with emphasis on capturing each stage of flow; the start (potential 'first flush' period), the peak discharge and the receding flow at each of the three sites. Due to logistical constraints and the temporal nature of runoff, each of the three stages was not always sampled at each site.

DB outflow

Water samples were taken at various intervalsduring and after each sampled ponding event. Outflow samples were taken from the culvert pipe at the downstream side of each bund. If water velocity was insignificant (i.e. flow rate < c. 0.02 m s^{-1}) samples were taken from the upstream side of the bund next to the riser intake where water was leaving the pond. Both locations (pipe and the riser) were classed as outflow samples. Specific details of sample location and outflow situations during ponding events are outlined in Tables 2.4 - 2.6 in Section 2.6.

2.3.4.3 Water sample field methods and analysis

Collection

At each sample location (ephemeral stream inflow or outflow), water samples for nutrient and suspended sediment analysis were collected from c. 5 cm below the water surface. Sampling involved collecting four separate samples to permit analysis of: dissolved nutrient concentrations, total nutrient concentrations, suspended sediment concentrations, and suspended sediment particle size. Samples for dissolved nutrient analysis were collected using a 50 mL acid washed (10% HCl) syringe and were predominantly filtered in the field through a 0.45 μm glass fibre filter. Approximately 40 mL of sample was collected in a new (assumed sterile) 50 mL polypropylene tube. A number of dissolved nutrient samples were filtered in the laboratory pre analysis (see Tables 2.4 - 2.6). A second 40 mL sample (unfiltered) was collected for total nutrient analysis from the same location. All nutrient samples were immediately placed on ice (< 4 °C) and in the dark for transport to the laboratory where they were frozen until analysis. Two 1 L clean plastic bottles were filled for analysis of suspended sediment characteristics. They were placed on ice and refrigerated on return to the laboratory until analysis within c. 7 days of collection. A small number of these samples were frozen prior to analysis (see Tables 2.4 - 2.6).

Nutrient analysis

All nutrient samples were analysed using a LachatQuickChem Flow Injection Analyser (FIA) (FIA+ 8000 Series, Zellweger Analytics, Inc). Unfiltered samples were digested using a combined persulphate digestion method (Ebina et al. 1983) and analysed for total phosphorus (TP) and total nitrogen (TN) on the FIA. The

TP and TN concentrations of some samples (34% of TN and 3% of TP samples) exceeded the upper limit of the calibration range (2 mg P or N L^{-1}) and, consequently, these samples were diluted with MilliQ water (Heal force^{R}, Acorn Scientific Ltd) at a ratio of 1 part sample to 14 parts water, and re-analysed on the FIA. Filtered samples were analysed for concentrations of dissolved nutrients (PO_4, NO_3, NO_2, NH_4) using the FIA with LachatQuickChem methods (10-107-06-2-B (NH_4), 10-107-04-1-A (NO_2 and NO_3), 10-115-01-1-A (PO_4)). Calibration standards ranged from 0.001- 2.0 mg P L^{-1} for P determination and 0.001- 2.0 mg N L^{-1} for N determination.

Suspended sediment analysis

Total suspended solid (TSS) concentrations were determined by filtering water samples through pre-weighed, pre-combusted (500 °C for 1 h)Whatman GF/C filters (nominal pore size = 1.2 µm). Each soiled filter was dried at 105 °C for 24 h and then re-weighed. The inorganic suspended solids (ISS) fraction was determined by combusting the dried filter at 550 °C for 1 hr. The organic suspended solid (OSS) fraction was determined by subtracting the ISS concentration from TSS concentration (as the organic component is ashed during combustion).

Particle size analysis

Particle size distribution of suspended sediment was analysed using laser diffraction (Mastersizer 2000, Malvern Instruments) which quantifies the volume of suspended sediment corresponding to 48 size classes in the range 0.05- 2000 µm. Sample was added into the machine basin until obscuration was in range so the particles could be detected. The exact volumes of sample used differed depending on the sediment concentration of that sample. No dispersant was used to break up aggregated particles in this analysis; this was done in order to represent the true size of material which was suspended in the water. Hence, particle size is a reflection of the suspended material in the water, not necessarily individual particles. This highlighted in the results and discussion chapters.

2.4 Deposited sediment

2.4.1 Sampling approaches: Mats & sediment trays

Two sampling techniques (mats and sediment trays) were trialled and compared to quantify sediment deposition.

Mats

A series of synthetic turf mats (*sensu*)(Owens et al. 2007; Steiger et al. 2003)) were deployed across the ponding area of each basin to sample deposited sediment. The mats (45 cm x 50 cm) were placed on top of a 9-mm thick rubber carpet underlay (50 cm x 55 cm) for stability (Figure 2.16).Each mat was secured down by a wire pin (3 mm diameter, 15 cm length) in each corner. Mats were deployed across the ponding area along a gradient of increasing elevation of 100 mm intervals. A 'dumpy level' was used to determine the mat elevation and a GPS (Garmin GPSmap 62s) was used to record geographical co-ordinates for Hauraki and Waiteti DBs (Appendix 1.4). Each mat was allocated a number and letter reference representing its location in the basin (i.e. 1a, 1b, 1c all at 100 mm elevation relative to the lowest point in the ponding area (see elevation groups in Figures 2.21).

Figure 2.16: A synthetic turf mat used for capturing sediment in the DB ponding basins.

Figure 2.17: Asynthetic turf mat after ponding at Awahou DB. Note this amount of sediment deposit is an extreme example.

Mats were deployed on an event-by-event basis (Figure 2.17). To minimise bias from rain splash effects, mats were lifted as soon as was practical once the pond receded enough to expose them to (Figure 2.18). Once lifted, a standard dishbrush ('Raven' brand) was used to remove sediment adhering to the underside of the mat. Earthworms were occasionally found on and under the mats and these were removed. The mats were folded in half and placed into a clean plastic bag for transit to the laboratory.

Figure 2.18: Sediment mat ready for collection at Hauraki DB after a ponding event in July, 2012. Although this mat looks clean, sediment had been deposited.

Once the mats were harvested and analysed they were cleaned with a high pressure hose so that they were replaced back in the basin ready for the ponding event. However, they were removed during grazing periods to avoid interference from stock see tables 2.4 – 2.6 for details of mat deployment periods at each site.

Sediment trays

During selected storm events plastic trays (33 cm long, 21 cm wide and 2.6 cm deep) were deployed at Hauraki (n=6) and Waiteti DBs (n=6) next to existing mats (Figure 2.19) across a range (100-500 mm) of elevations relative to the lowest point in the ponding area. Larger trays (n=3-4, 35 cm long, 28 cm wide and 3.6 cm deep) were deployed at Awahou DB reflecting the larger mass of sediment deposited at that site (Figure 2.20) compared to the other sites, such as Hauraki DB (Figure 2.18). Water and sediment collected in the trays was tipped into 1 L bottles using a funnel. Any residual sediment was washed off the tray using MilliQ water, and into the bottles. Trays were deployed and collected at the same time as the mats. Trays were subject to invertebrate interference (especially earthworms) as residual water seemed to pose an attractant and trap at some sites. This meant that some samples were discarded. Removing the trays as soon as water receded minimised these effects but immediate removal was not always practical.

Figure 2.19: Sediment tray deployed next to a mat to capture sediment deposited at Hauraki DB, 2012.

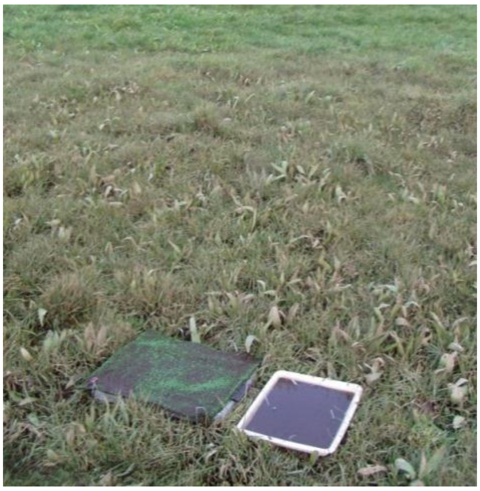

Figure 2.20: Sediment tray full with sediment after a ponding event at Awahou DB, July, 2012.

2.4.1.1 Sediment pooling design

Sediment deposited on the mats at each DB was pooled after each sampling event based on the elevation of the mats above the base level of the bund. Three elevation groups were established: Low (0-200 mm), medium (200-700 mm) and high (>700 mm). Figures 2.21 – 2.23 below show the upper contour of each elevation group at each site. The exact location of these contour lines was estimated based on a combination of GIS data (1 m resolution), elevation measured in the field (represented by the position of mats) and photographs of each ponding area at a range of water levels. Sediment was pooled on a mass-proportional basis to represent overall deposition within each elevation group. These pooled sediment samples were analysed for element content, particle size distribution, and also used as a basis for a sediment and P mass budget as described below.

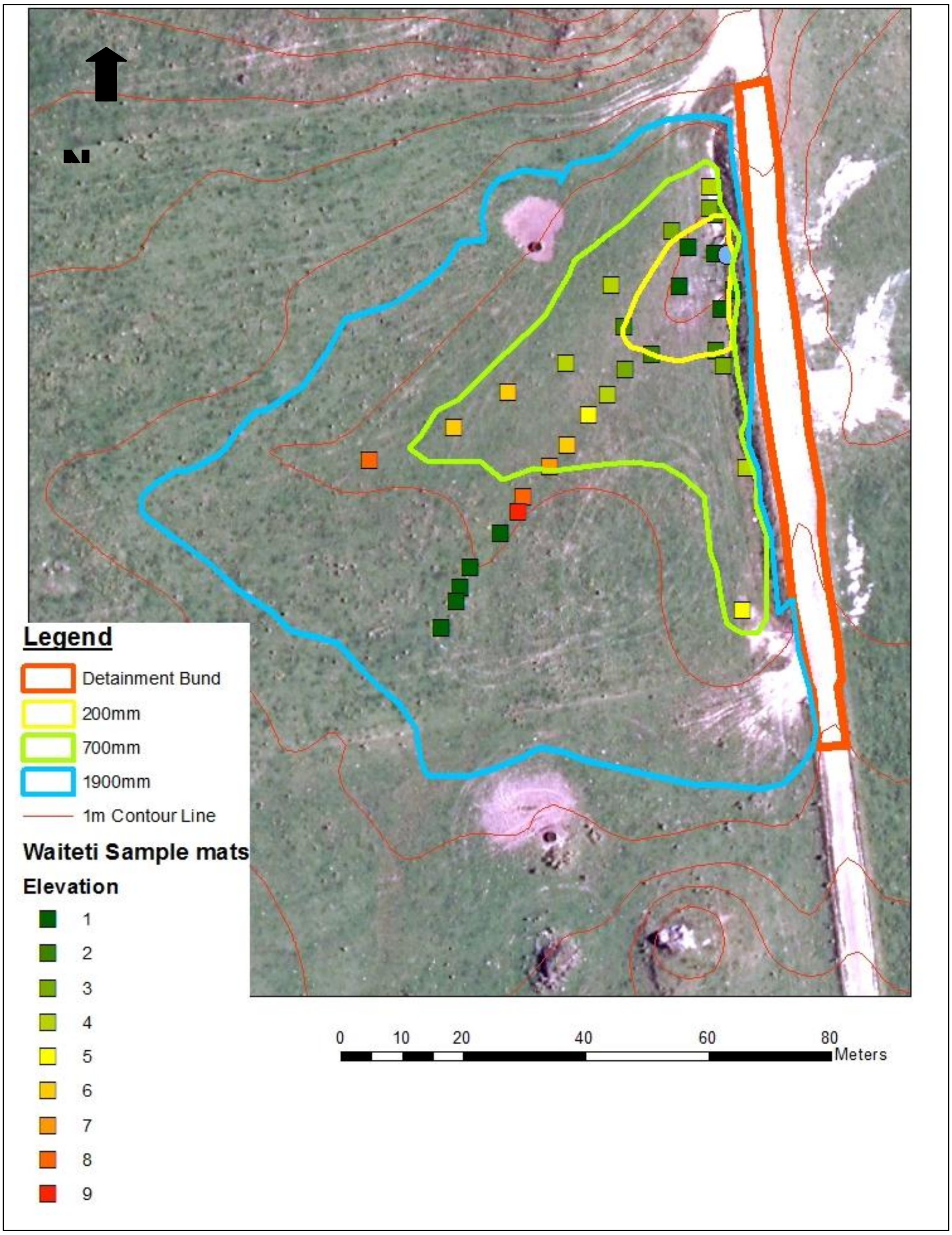

Figure 2.21 Waiteti DB elevation groups;low (yellow), medium (green) and high (blue) used for sediment analysis

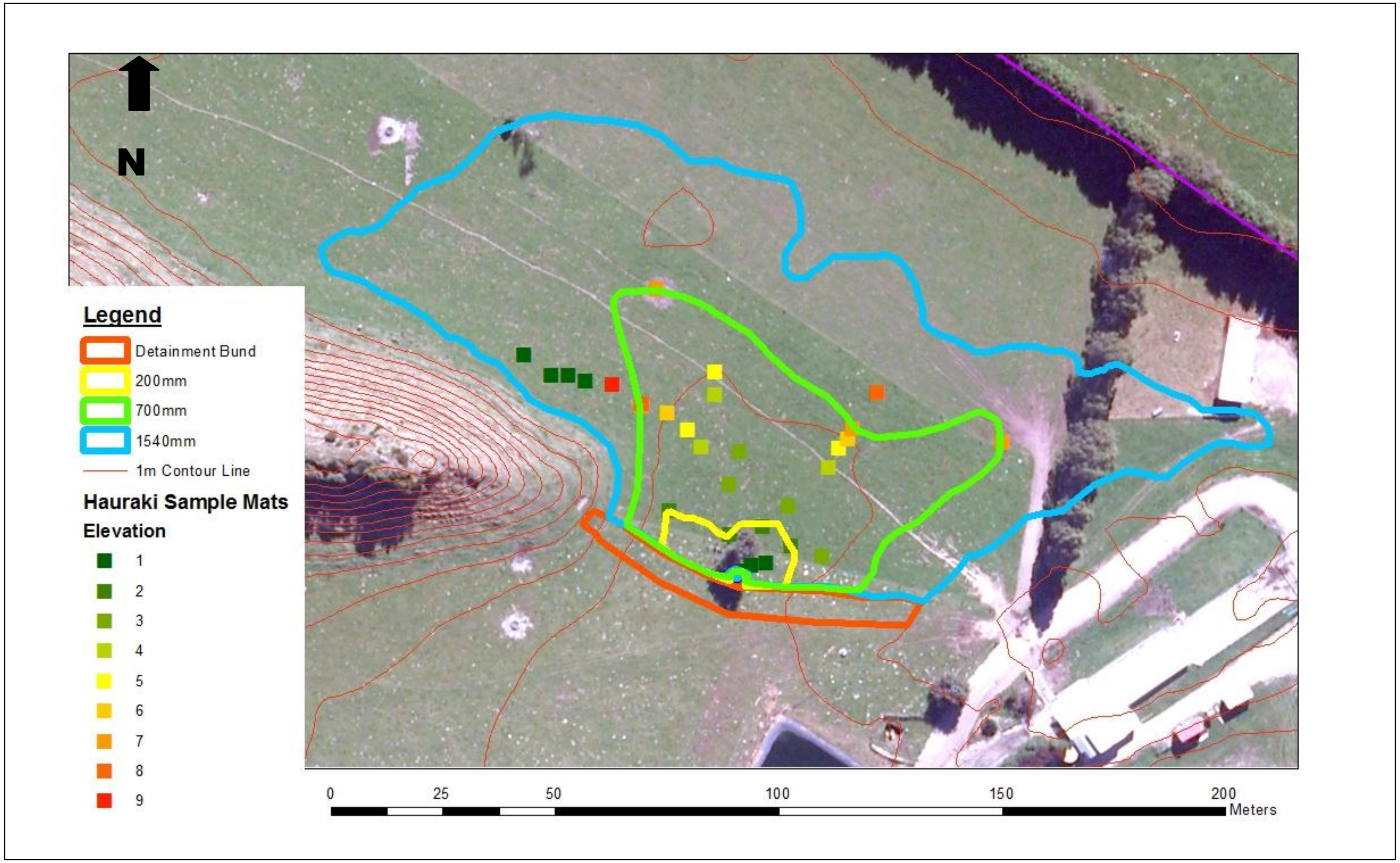

Figure 2.22 Hauraki DB elevation groups;low (yellow), medium (green) and high (blue) used for sediment analysis

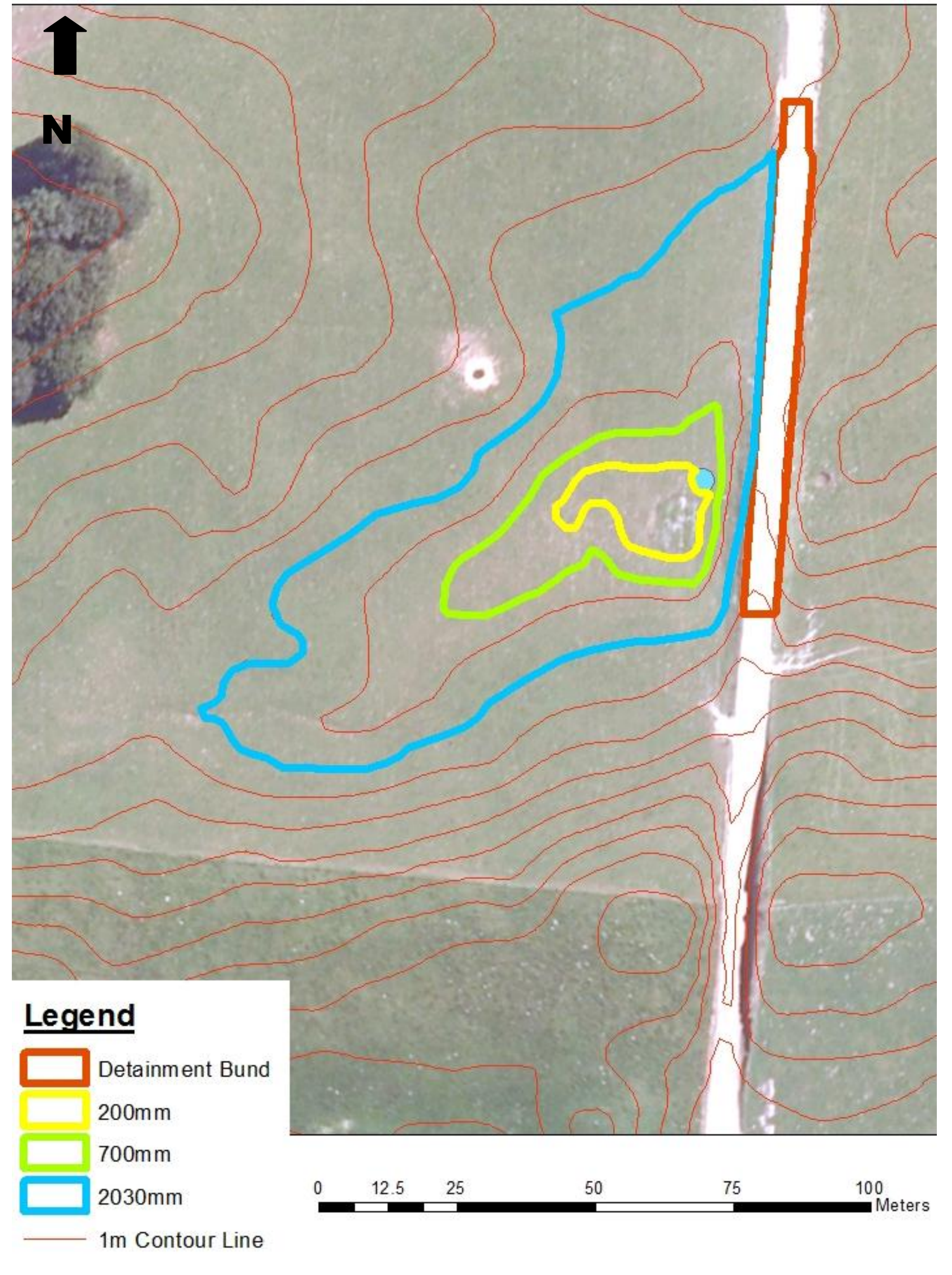

Figure 2.23: Awahou DB elevation groups;low (yellow), medium (green) and high (blue) used for sediment analysis

2.4.1.2 Sediment mass

Mats were dried in an oven (Contherm, series five) at 60 °C for c. 24 h. Sediment was then removed from the mats by shaking the mat vigorously inside a cleanplastic bag whichallowed sediment to fall from the mat inside the bag. Sediment deposited on the trays was oven dried in aluminium trays (1.1 L volume) for 24-48 h at 60 ^{o}C to evaporate all water and dry remaining sediment. Once cool, sediment was weighed (Startorius 2000, precision ± 0.001 g) and stored in a clean, air-tight plastic bag prior to further analysis.

2.4.1.3 Particle size distribution of deposited sediment

Sediment samples collected from mats and trays were analysed for particle size distribution using laser diffraction (Mastersizer 2000, Malvern Instruments) as described above.

Sediment deposited on the mats was analysed using pooled samples, as explained in Section 2.4.1.1 above. Particle size analysis was conducted in triplicate for two samples to quantify analytical precision. This allowed an average standard error (i.e. standard deviation from the mean divided by the square root of the sample size) to be calculated, which was expressed as a percentage (± 11.01%) of the mean and used to quantify analytical error in all other results.

Sediment deposited on the trays was analysed by taking a sub-sample (10-500 mL) of tray water (containing deposited sediments) and placing it into the Mastersizer 2000 after shaking for 10 seconds. This step was carried out before the tray water was oven dried, hence a correction was subsequently applied to sediment mass calculations based on the proportion of the overall sample used for particle size analysis. Standard error was calculated using the same calculation as above, although four samples were analysed in duplicate to derive a standard error (± 6.76%) of the mean to quantify analytical error in all other results.

2.4.1.4 Sediment nutrient analysis:

Sediment collected on mats was analysed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS model ELAN DRC II). Numerous elements (n=24) including phosphorus, aluminium, manganese and iron were detected. Three separate sub-samples of 1 g of dried sediment were analysed from each pooled sediment sample section (Section 2.4.1.1). Bags containing the sediment were first vigorously shaken to homogenise sediments. Sediment was digested with Aqua regia (3:1 v:v of 1:2 conc. HNO_3 and 1:5 conc. HCl solution) based on a modified standard procedure (Martin et al. 1994). Both 10 mL HCl (1:5) and 4 mL HNO_3 (1:2) were added to the sediment in a 50 mL polypropylene centrifuge tube. Tubes were left overnight in a fume hood with the lids loosely capped to allow air flow. The following day they were placed on a hotplate at 80 °C for 1 h. When cool, each sample was diluted with MilliQ water to a final volume of 100 mL in a photometric flask. The sample was then diluted a second time by pipetting a 20 mL sub-sample (after shaking for 10 s) into another photometric flask and filling to 100 mL with MilliQ water. A 12 mL sub-sample was extracted from this flask (after shaking for 10 s) using a 20 mL syringe, and filtered through a 0.45 µm membrane glass fibre filter before placing in a 15 mL polypropylene centrifuge tube and analysed by ICP-MS. Results were multiplied by 500 to account for the dilution. A small number (c. 3%) of pooled sediment samples were < 3 g so did not permit triplicate 1 g sub samples, hence appropriate dilution factors were applied based on the smaller quantity of sediment digested.

At Waiteti DB, localised sediment input from ongoingconstruction and remediation works greatly contributed to deposition on some mats (2D, 3D and 4E) in the northern corner of the basin, adjacent to the bund (Figure 2.21). To analyse the effects of this, a pilot analysis was conducted before sediment was pooled. Sediment from individual mats at Waiteti DB (deposited during an ponding event in July (July #1 & 2)) was analysed by ICP-MS in triplicate for mats across the 200mm elevation group (2A, 2B, 2C, 2D) to quantify spatial variation in deposited sediment across the basin. The location of the mats can be seen in Figure 2.24The P concentration of the sediment derived from the earthwork site (mat 2D) was lower than the other mats (Figure 2.25). Hence, where applicable, two pooled sediment samples were constructed, one including and one excluding sediment derived from the earthworks. This variation across the same elevation supported the need for a mass-proportional based sediment pooling design.

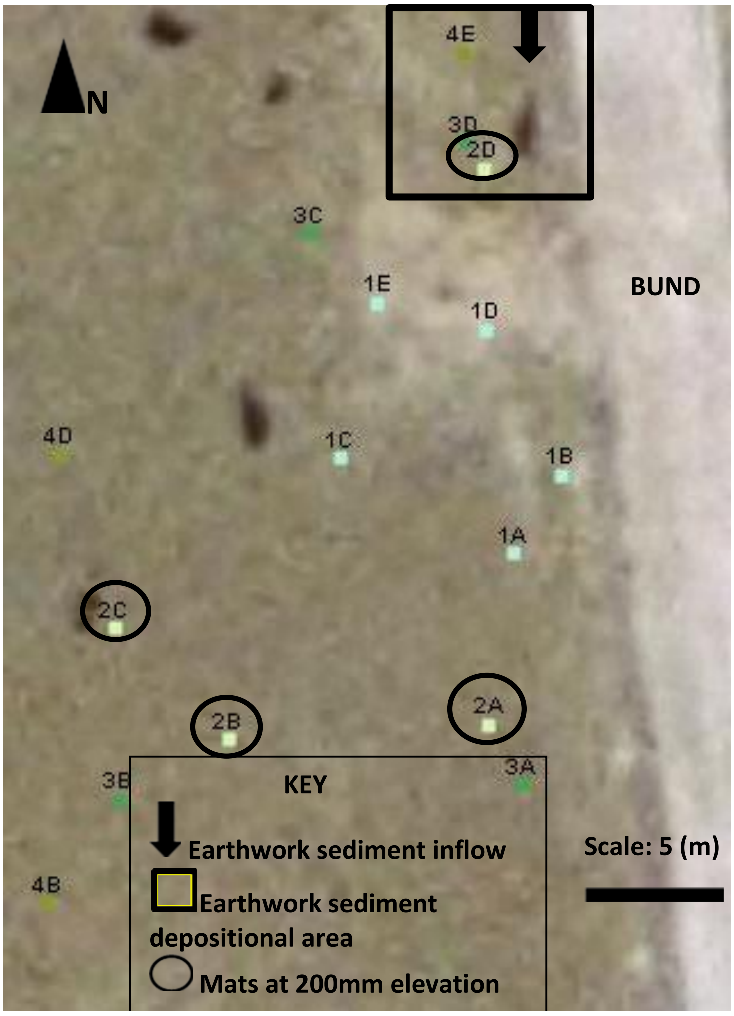

Figure 2.24: Spatial distribution of sediment mats Waiteti DB. Note the location of the sediment input.

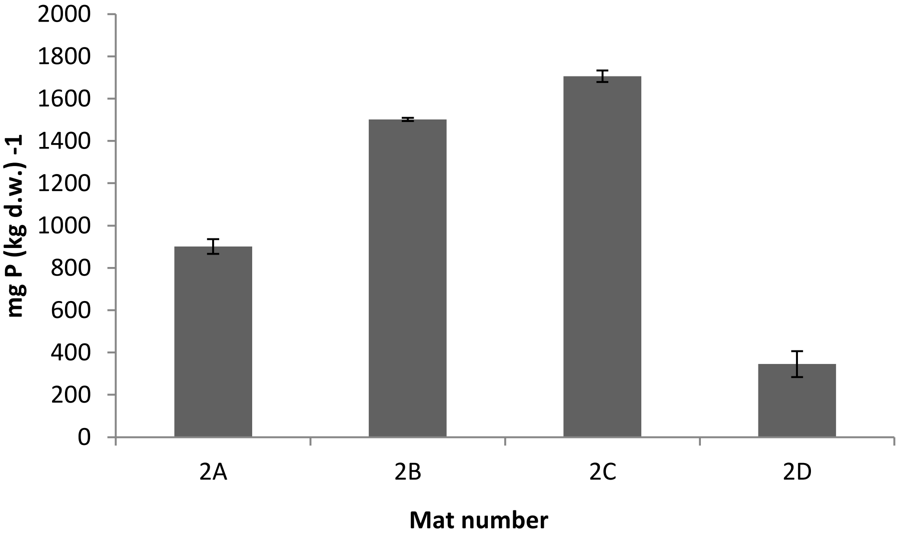

Figure 2.25: Pilot analysis of P concentration of sediment deposited on individual mats across the 200 mm elevation gradient at Waiteti DB during July #1 & 2 events. (Error bars denote standard error of triplicate samples)

This pilot analysis also included ICP-MS analysis of sediment deposited on a mat and adjacent tray (both in triplicate) at Awahou DB (from within the lowest elevation at group at 100 mm) to inform methods used in the sediment collection and processing stages. Sediment remaining on the mats after removal using the standard beating technique (described in Section 2.4.1.2) was vacuumed (using a Black and Decker Dustbuster^{R} Extreme, 7.2 V) and also analysed by ICP-MS (in triplicate) to determine the concentration of elements in residual sediment. Figure 2.26 below displays the P concentration of the sediment collected at each site. This analysis validates the use of the shaking method to remove sediment from the mats, as there was minimal difference in P concentration between the shaken sediment and the residual sediment (vacuumed). Furthermore, the hypothesis that trays would collect finer sediment and hence higher concentrations of P could be rejected because the sediment deposited in the trays had lower concentrations of P compared to the mats. Hence mats subject to shaking were used as the primary sediment collection method in this study and all sediment mass deposition calculations (see below) are based on data collected in this way. Trays were used as a supplementary collection method, there were variable differences between the mass of sediment deposited on trays compared to mats (Figure 2.27) hence data from the two methods were not directly compared in this study. Mats were the predominant form of sediment sampling in this study.

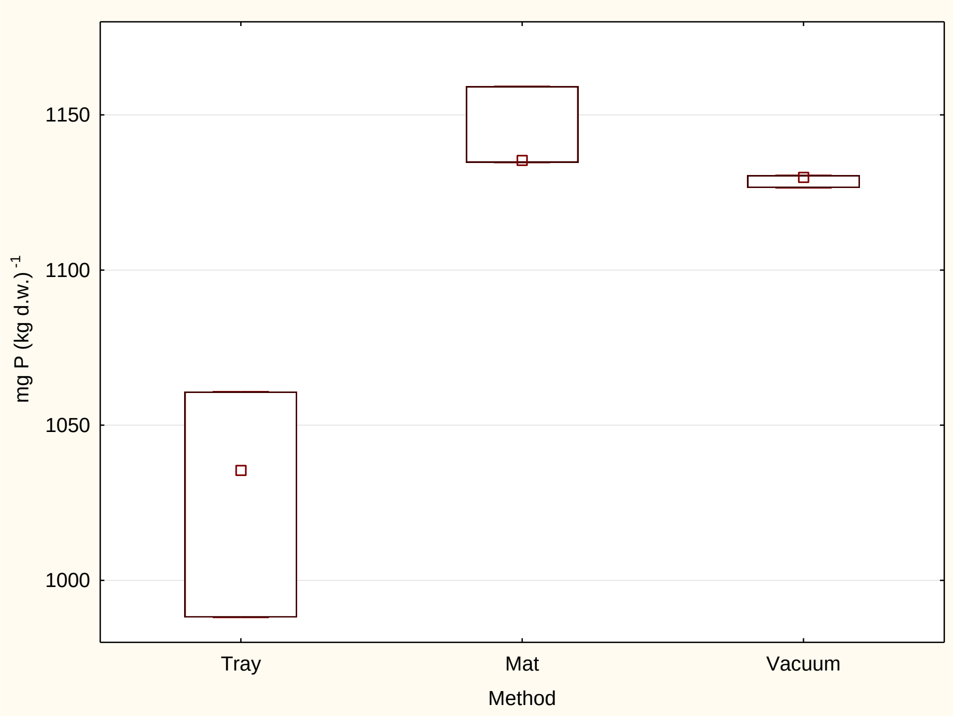

Figure 2.26: Comparison of collection and processing methods used for sediment analysis.

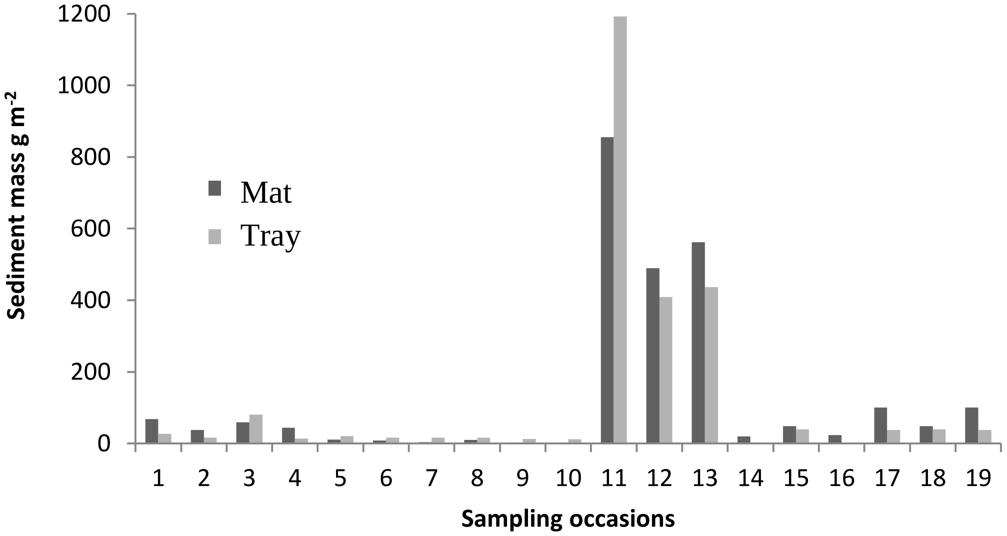

Figure 2.27Comparison of sediment mass (m^2) deposited on mats and trays when they were deployed next to each other, data are from various events and sites.

2.4.1.5 Mass sediment and particulate P Budget

A mass sediment and particulate P budget was calculated to determine the total quantity of sediment and particulate P deposited in the DB basins during each sampled ponding event. Calculations were based on mass-proportional samples for the three elevation groups (defined in section 2.4.1.4 above). The mass of sediment deposited in each elevation group was calculated independently using equation 1 below. The three masses were then summed up to get a total mass for the ponding area. This therefore, accounted for spatial variation in sediment mass and P concentration across the ponding area. Table 2.3 shows the values used as the basis of this exercise. Area was calculated using GIS, and volume was calculated by equation 2 below.

$$Sd = S \times A \qquad (1)$$

Where;

S= Average sediment mass (kg dw m^{-2}) deposited (using the mats within the pooled elevation group)

A= Ponded area m^2 (of the particular elevation group)

$$A = \left(height \times \left(\frac{pond\ area}{3}\right)\right) \qquad (2)$$

Where;

A = Area

'Height' is the height of the water level relative to ground zero in the basin.

'Pond area' is the area which is inundated by water.

Table 2.3:DB metrics of each pooled elevation group, used to derive the mass budget

Bund	Elevation group	Max water level (m) Of each elevation group	Area (m^2)	Volume (m^3)
Waiteti	1	0.2	298	19.9
	2	0.7	1824	425.6
	3	1.9	7248	4590.4
Hauraki	1	0.2	315	21
	2	0.7	3239	755.8
	3	1.54	10663	5473.7
Awahou	1	0.2	302	20.1
	2	0.7	1033	241
	3	2.03	4875	3298.8

Total P deposited (P_d) (kg P (kg dw)$^{-1}$in each separate elevation group for each event was derived using equation 3 below. The P_d values for all elevation groups at each site were combined to obtain mass of$P_d$per storm event.

$$Equation\ 2: Pd = P \times S \times A \qquad (3)$$

Where;

P = average P concentration (kg P (kg dw)$^{-1}$of the sediment deposited (expressed as the mean of the replicate samples analysed for each pool group (as described in section 2.4.1.4 above).

S= Average sediment mass (kg dw m^{-2}) deposited (using the mats within the pool group).

A= Ponded area (m^{2}; of the particular elevation group, see below for method used to derive ponding area of elevation group 3)

Because water level did not always reach the spillway (the upper level of elevation group three) during all events, the ponding area was calculated on an event by event basis to be used as 'A' in equation 2 above. A graph displaying data for stage (y-axis)and pond area (x-axis) graph was plotted, with a polynomial curve fitted through the known areas (the upper line of each pool group), see Figure 2.28 below for an example. The equation from this line was used to calculate the ponding area at any given water level. This method was only used to determine unknown ponding areas within elevation group three because water ponded over pool groups 1 and 2 in during all events.

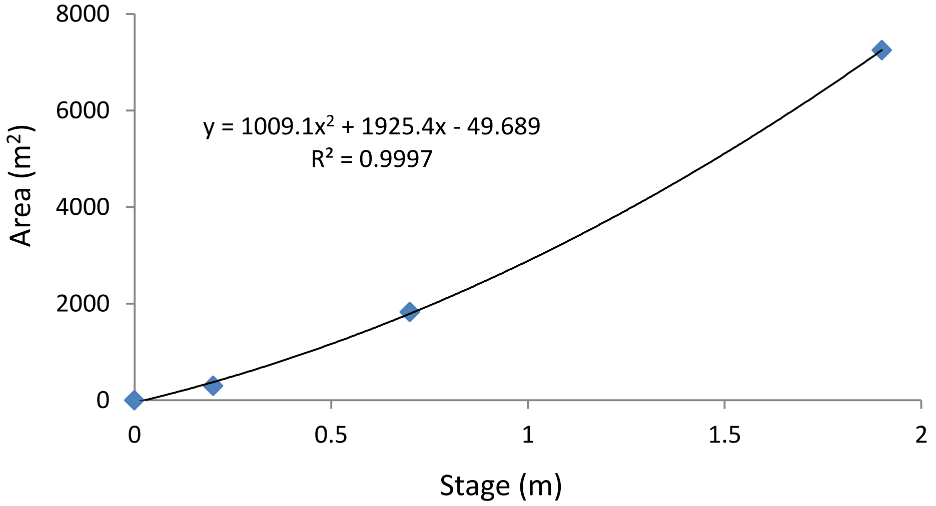

Figure 2.28: Waiteti DB stage - area relationship, used to derive ponding area in basin

At Waiteti DB, remedial work to the bund resulted in sediment inputs to the ponding area which were not representative of the agricultural land use (i.e. from subsoil not top soil as transported by overland flow (as explained in 2.4.1.4 above). The total area subject to earthwork sediment was estimated at 1/5 of the area of each elevation group; this was based on photographic evidence of light coloured sediment which deposited in that northern corner, clearly from the earthwork site. Earthwork sediment input into the Waiteti DB was accounted for using equation 4 below, for May event #2, and July event 1+2.

$$Pdi = \left(P \times S \times \left(\left(\frac{A}{5}\right) \times 4\right)\right) + \left(PI\ \times SI\ \times \left(\left(\frac{A}{5}\right) \times 1\right)\right) \qquad (4)$$

Where;

Pdi = P deposited including earthwork sediment

PI= Average P concentration ((kg P (kg dw)$^{-1}$)of the sediment deposited including the sediment from the earthwork site (calculated using the same mass proportional basis as for ‘P’).

SI= Average sediment mass kg dw^{-1} m^{2} deposited in the basin, including the mats exposed to basis from earthwork sediment (details see 1.4.1.1).

The % reduction in total sediment / PP load was not derived due to a paucity of flow measurements which require fine resolution measurements.

2.5 Sampling details

Detailed records of sample collection are presented in Tables 2.4 – 2.6 below. There were numerous, mostly subtle, within and between site variations in sampling methodology, so the tables have been constructed to give an overview of the storms sampled, sample collection, and details of how water drained from the bund, along with other details. Land management activities in the contributing catchment during ponding events have been included to allow comparisons of land management between sites.

Table 2.4: Summary of sampling at Waiteti DB during 2012. Abbreviations used; In: (incoming ephemeral stream), TSS: (total suspended sediment), PSA: (particle size analysis), DNF: (dissolved nutrients filtered; in the field or in the lab pre analysis), O/R: (over riser), O/S: (over spillway), LH: ((ladder holes; in the concrete riser, includes leaks from plugs that were used to block ladder holes (and the decant structure leak at Waiteti DB only)). * Indicates the main way that water drained from the DB during the ponding period.

Waiteti									
Storms events sampled	**Ponding period**	**Mats/ trays deployed**	**Outflow situation**	**Dates sampled:**		**Location of outflow samples (pipe or riser)**	**Determinands**	**Sample handling**	**Land use in contributing catchment**
				In (North and South)	**Out**				
March	21 -26	Mats (n=14)	O/R & O/S: 21st/22nd (12pm) *LH: 21- 26th	21st, both	21-26th	Pipe: 21st -26th Riser: 24th	Nutrients TSS, PSA	TSS & PSA- frozen. DNF – lab.	
May #1	9-11	N/A	O/R: 9th *LH	9th, both	9-11th	Pipe: 9th -10th Riser: 10th -11th	Nutrients TSS, PSA	TSS – frozen. PSA - not frozen. DNF – field.	Bund construction works
May #2	17 -20	Mats (n=32) 16 submerged	*LH	N/A	17-20th	Riser: 17th -20th	Nutrients TSS, PSA	TSS & PSA- frozen. DNF – field.	
July #1	16 -21	Mats (n=28) 6 lifted before July2	O/R: 16th *LH	16th both	16-21st	Riser: 16th -21st	Nutrients TSS, PSA	TSS & PSA- not frozen. DNF – field.	
July #2	22 -25	Mats (n=22) Trays (n=6) Submerged since 16th	O/R: 23rd , O/S: 23rd *LH * Spillway incised	22nd, North only 23rd& 24th both	22-25	Riser:22nd -23rd Pipe:24th -25th	Nutrients TSS, PSA	TSS & PSA- not frozen. DNF – field.	
July #3	30 July-6Aug	N/A	Out unrestricted pipe	N/A	30th, 31st, 2nd, 6th.	Pipe: 30th, 31st Riser: 2nd, 06th	Nutrients (30th-31st) TSS, PSA	TSS & PSA -not frozen. DNF- field.	
Sept #1	c. 3 -5	Trays (n=6)	Out unrestricted pipe	N/A		N/A	N/A	N/A	
Sept #2	c. 9 –11	Trays (n=6)	Out unrestricted pipe	N/A		N/A	N/A	N/A	

Table 2.5: Summary of sampling at Hauraki DB during 2012, abbreviations given in caption to 2.4

Hauraki									
Storms Events sampled	**Ponding period**	**Mats/ trays deployed**	**Outflow situation**	**Dates sampled:**		**Location of outflow samples Pipe or Riser**	**Determinands**	**Sample handling**	**Land use in contributing catchment**
				In	**out**				
March	22 – 24	Mats (N=14)	O/R: 22nd (1am) *LH: 22- 24th	22nd	22nd -26th	Pipe: 22nd -23rd Riser: 24th	Nutrients, TSS, PSA	TSS & PSA - frozen. DNF - Lab	Summer crop in adjacent paddock, re –sown in grass
May #1	9 -12	N/A	O/R: 9th *LH: 9th – 12th	9th	9th -12th	Pipe: 9th -11th Riser: 12th	Nutrients, TSS, PSA	TSS & PSA – not frozen. DNF - field	Grass established in crop paddock
May #2	No ponding	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
July #1	16 -18	Mats (N=27) Trays (N=6)	*LH: 16- 18th	N/A	16th -18th	Pipe: 16th Riser: 17th, 18th	Nutrients: TSS, PSA	TSS & PSA -not frozen. DNF - lab	Cows grazing upstream
July #2	23 – 26	N/A	O/R: 23rd *LH: 23rd – 26th	23rd, 24th	23rd -26th	Pipe:23th -26th	Nutrients: TSS, PSA	TSS & PSA -not frozen. DNF - lab	Cows grazing in adjacent paddock
July #3	30 July- 01 August	Mats (N=32) Trays (N=6)	O/S: 30th Decant structure removed	N/A		N/A	N/A	N/A	

Table 2.6: Summary of sampling at Awahou DB during 2012, generic abbreviations given in caption to Table 2.4, specific to this table; SL: Sandbag leak.

Awahou									
Storms Events sampled	**Ponding period**	**Mats/ trays deployed**	**Outflow situation**	**Dates sampled:**		**Location of outflow samples Pipe or Riser**	**Determinands**	**Sample handling**	**Significant activities in catchment**
				In	**Out**				
July #1	Unknown	N/A	O/R: 16th *Out base of riser	16th	16th	pipe: 16th	TSS, PSA	TSS & PSA -not frozen.	Winter crop (Charamolia) in upstream paddock, grazed by cows
July #2	23 -24	N/A	*SL	23rd, 24th	23rd- 25th	Pipe:23rd- 24th PP: 25th	Nutrients TSS, PSA	TSS & PSA -not frozen. DNF - Lab	Cows grazing the last of the crop
July #3	30 -31	Mats (N:14) Trays (N:3)	O/R: 30th O/S: 30th *SL		30th- 31st	Pipe: 30t, 31st PP: 01st Aug	Nutrients, TSS, PSA	TSS & PSA -not frozen. DNF - lab	
August	12-14	N/A	*SL	12th	12th	Pipe: 12th PP: 14th	Nutrients, TSS	TSS -not frozen. DNF - lab	Grass sown in crop paddock
Sept #1	3-5	N/A	*SL	3rd	3rd- 4th	Pipe: 3rd – 4th PP: 5th	Nutrients, TSS, PSA	TSS & PSA -not frozen. DNF - lab	Cows grazing in nearby paddock.
Sept #2	9 –12	Mats: (N: 11) Trays (N=4)	*SL		9th – 12th	Pipe: 9th – 11th PP: 12th	Nutrients (9th only), TSS, PSA	TSS & PSA -not frozen. DNF - lab	Grazing rotation- in bund paddock on the 8th, during ponding grazing in adjacent paddocks. Grass germinating in upstream crop paddock.

2.6 Soil characteristics of new and historic ponding areas

2.6.1 Location:

On 29 June 2012 soil samples were collected in and around the ponding area of two bund structures in the. One structure was the Hauraki DB (described in Section 2.3.2) and the second structure was a detainment dam (DD) (described in section 1.2.5.3 above) which is located in the Awahou catchment, but is in close proximity to the Hauraki DB. The old DD was constructed c. 12 years prior to sample collection. Locations of both sites are depicted in figure 2.29.Sampling targeted the areas inside and outside the ponding areas of both basins.

2.6.2 Soil sampling and analysis

2.6.2.1 Location of sample transects

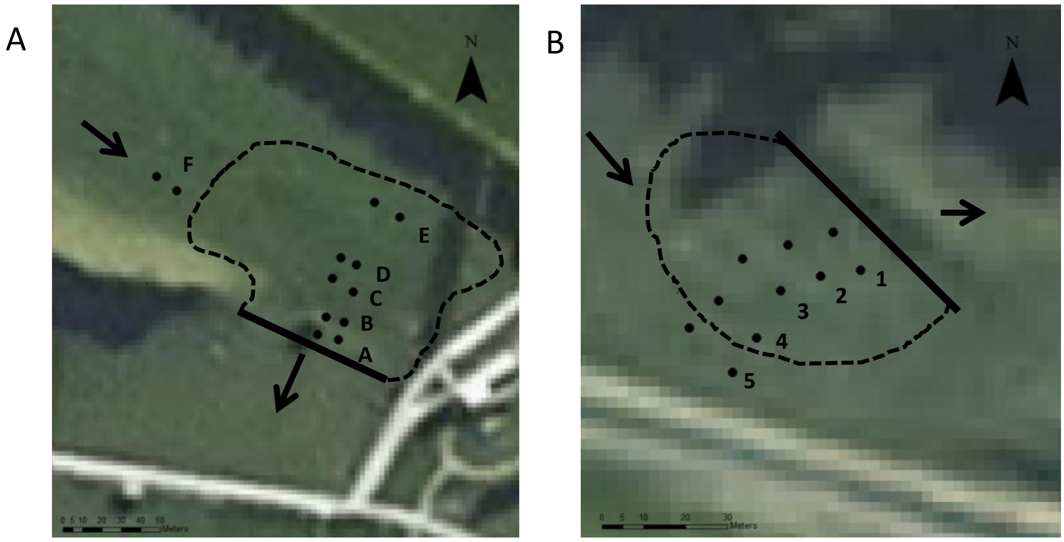

Figure 2.29:location of sample transects in the ponding are of the New c. 1 yr DB (Hauraki) (A) and the old c. 12 yr DD (B). Solid black line represents the bund. Dashed line represents the approximated ponding area. Arrows represent water flow in and out of ponding area. Dots represent the start and end of each sample transect which ran parallel to each bund, varying distances from the bund (distance calculated from the middle of each transect to the middle of each bund. Distance of transects from the bund in Figure 2.28 A are, A; 2m, B; 11m, C; 29m, D; 42m, E; 74m, F; 116m. Distance in Figure 2.28 B are, 1; 5m, 2; 15m, 3; 25m, 4; 35m, 5, 45m.

2.6.2.2 Soil phosphorus and pH

Samples were collected by deploying a 12 m tape parallel to each bund and taking soil cores (plugs) using a standard 7.5 cm long soil sampler at 1 m intervals (11 cores along each transect). Soil plugs were placed into a 10 L bucket, grass and earth worms removed and then plugs were mixed thoroughly by hand (using non-powdered latex gloves). Each combined sample was then placed in a pre-labelled plastic soil sample bag. The above steps were repeated at each transect. This sampling protocol is standard soil sampling practice (D. Guinto, *pers. comm.*, 2012). Transect location was based on approximate elevation. At the Hauraki DB, transects were located in the basin in relation to existing sediment mats marking elevation gradients. At the old Detainment Dam, transects were spaced at 10 m intervals across the ponding area and beyond. The distance from each bund was calculated measuring from the middle of each transect and from the middle of each bund.The locations of the transects are slightly different across each basin due slightly different basin profiles. Transect location was recorded with a GPS (Garmin GPSmap 62s).Pooled soil samples from each transect were analysed by a commercial laboratory (Hill Laboratories, Hamilton) to determine soil pH and concentrations of Olsen P(mg L^{-1}) and total phosphorus (TP)(mg kg^{-1}). Olsen P was derived on a volume basis using a bicarbonate extraction at a pH 8.5 over a period of 30 minutes. Total phosphorus (mg kg^{-1}) includes unavailable inorganic and organic forms of P and is extracted by hot concentrated acid.

Bulk density

Soil samples for bulk density determination were collected using a modified PVC pipe (10 cm long and 5.2 cm in diameter with a tapered end (D. Guinto, *pers. comm.*, 2012). The pipe was inserted into the soil with a hammer and extracted with the aid of a spade. The collected soil was then placed into a plastic zip-lock® bag. Samples were collected from the middle of each transect at the new Hauraki DB, and from the transects at lowest and highest elevation at the old Awahou DD. Samples were oven dried at 105 ^{o}C for 24 h. Bulk density (BD (dry weight of soilper unit volumeof soil; g^{-1}:cm^{-3}) was calculated by the following formula: BD= oven dry weight (g) /volume of cylinder (cm ^{3}).

2.6.2.3 Particle size analysis

Sub-samples were taken from the pooled soil sample from each transect and analysed to determine particle size distribution. A c. 1 g sub-sample was analysed for particle size distribution using the procedure described in section 2.4.1.3. above.

2.7 Data analysis

Data was collated into a master spread sheet and analysed on an exploratory basis initially. A master spread sheet was created to allow cross comparisons between water quality parameters (Appendix 1.1). Statistica software (version 11) was used to analyse data. Firstly, data was checked for normality. A Pearson's pair-wise correlation (at the $p<0.05$ significance level) was conducted to assess the significance of trends between variables as outlined in the results chapter. A one way ANOVA was performed to assess if there was a difference in P concentration between define elevation groups, if there was a post hock Tukey HSD test was performed to determine which variables were significantly different.

Sedimentation rates were determined by applying a natural logarithm to normalised TSS data which were applied a time zero, details are provided in the Results 3.2.3 section. Sediment data collected using the Astorturf mats was combined to derive mass deposition estimates across the ponding area of each DB, details are provided in section 2.4.1.5. Particle size data was condensed into broad size categories based on an approximate Wentworth scale shown in Table 2.7 below (Wentworth 1922). The median particle size was also used for simple analysis.

Table 2.7: Size classes of suspended sediments based on an approximate Wentworth scale.

	Very fine clay	Fine clay	Medium-coarse clay	Silt	Very fine - fine sand	Medium - sand	Coarse - sand
Size range (µm)	0.05-0.24	0.24-0.98	0.98-3.9	3.9- 53	53- 210	210-500	500-2000

Chapter 3: Results

The performance of DBs was evaluated with a large data set as follows. Results are presented in the order of; what went in (ephemeral streams), what went out (during the ponding period), and what was left behind in the basin (sediment and associated P) for a range of ponding events in 2012. Results from a soil test comparing P levels in an historic ponding basin (12 yr) compared to a new ponding basin (1 yr) are presented in the final section.

3.1 Hydrological characteristics of rainfall events

Sampling was undertaken from March to September 2012, during this period 1,555 mm of rain fell in the upper Waiteti catchment draining to Lake Rotorua. Ephemeral streams were intercepted by DB during nine major rainfall events; these events are labelled in Figure 3.1 and Figure 3.2. The names associated with each ponding event will be referred to throughout the following chapters. For full details about samples taken and duration of events, see section 2.5 'sampling details', tables 2.4-2.6).

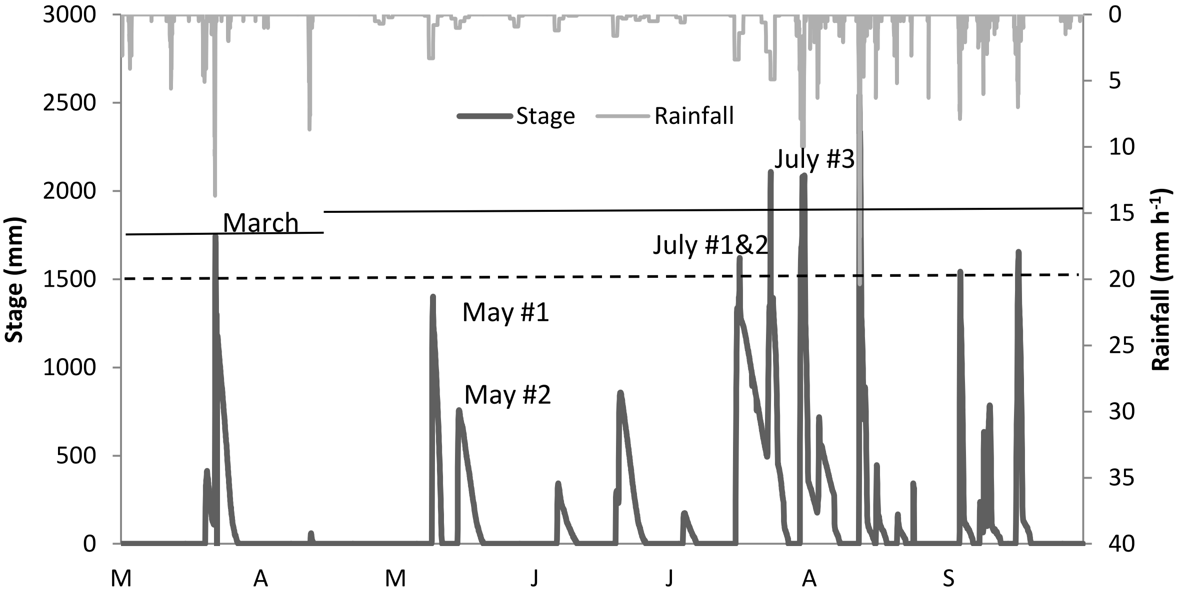

Figure 3.1: Water level (stage) at Waiteti DB and rainfall (measured at Oturoa Road climate station) from March – September 2012 (the start of each month is indicated with a letter). Sampled ponding events are labelled next to the corresponding stage peaks. Stage data have been adjusted for baseline drift; see Methods, section 2.3.1. The solid horizontal line represents the spillway height (the bund was raised in April, hence the step in spillway height in that month), the dashed line represents the height of the concrete riser.

Stage rose rapidly in response to large rainfall events. Small rainfall events in late summer did not produce ponding behind the detainment bund (e.g. the beginning of March), however, an intense rainfall event in late March (62 mm over 72 h) produced ponding which breached the bund. The Waiteti bund was raised to 1.9 m in April to resolve overtopping, although ponding events in July and August still breached the spillway (Figure 3.1). In winter months, even relatively small rainfall events produced rises in stage and not all events were sampled. In July a rainfall event of 117 mm over a 72 h period resulted in a rapid rise in stage up to the Waiteti DB spillway level of 1.9 m and water did not completely drain from the basin before a second event re-filled the basin. Hence, this event is named 'July #1&2'. There were several large events from August to September and samples were taken from the Awahou DB during these ponding periods. From July – September there were seven rainfall events which produced significant ponding at Waiteti DB (Figure 3.1).

Stage at Hauraki DB (Figure **3.2**) shows similar patterns to the Waiteti DB reflecting the geographical proximity of the two sites. However, there was one event (May #2) which produced ponding at Waiteti DB, but not at Hauraki DB, due to localised rainfall variations on the Mamaku plateau (Figure **3.2**). Rainfall data from another BoPRC climate station (Penny Road, Kaharoa) was matched up with Hauraki DB stage but the correlation between these variables was weak, so rainfall data from the Oturoa Road station was used for further analysis at all three sites.

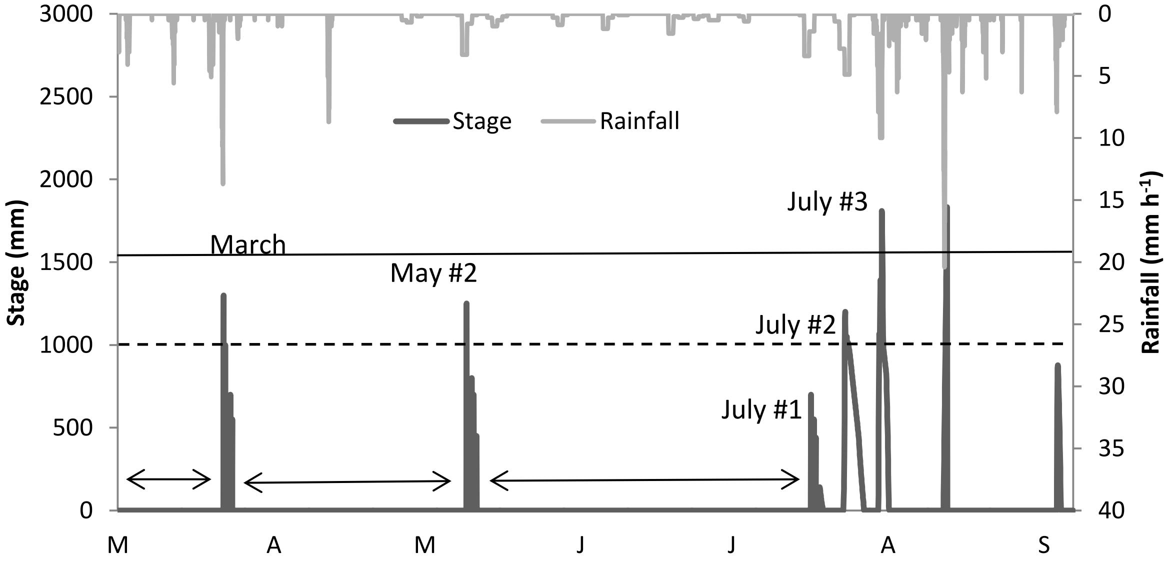

Figure 3.2: Stage (water level) at Hauraki DB and rainfall (measured at Oturoa Road climate station) from March – September 2012 (the start of each month is indicated with a letter). Sampled ponding events are labelled next to the corresponding stage peak. An electronic water logger was functional from 18/07/2012, stage data before this date was collected by visual observation, the arrows indicate when no stage data was recorded between sampled events prior to 18 July. Stage data have been adjusted for slight drift in recording. For more details see Methods 2.32. The solid horizontal line at 1,540 mm indicates the spillway height, the dashed line represents the height of the concrete riser.

Water completely drained from the Hauraki DB following all three July ponding events (Figure 3.2), unlike Waiteti DB (Figure 3.1). In August, stage was less responsive to rainfall at Hauraki DB compared to Waiteti DB. The spillway was breached during the July #3 event which resulted in the highest stage across all sampled events.

Soil moisture increased rapidly in response to rainfall events, and reached field capacity (i.e. was saturated) following rainfall > c. 10 mm/h.Figure 3.3 displays the rainfall and corresponding soil moisture of the particularly wet summer in 2011/2012 which preceded the sampling period.

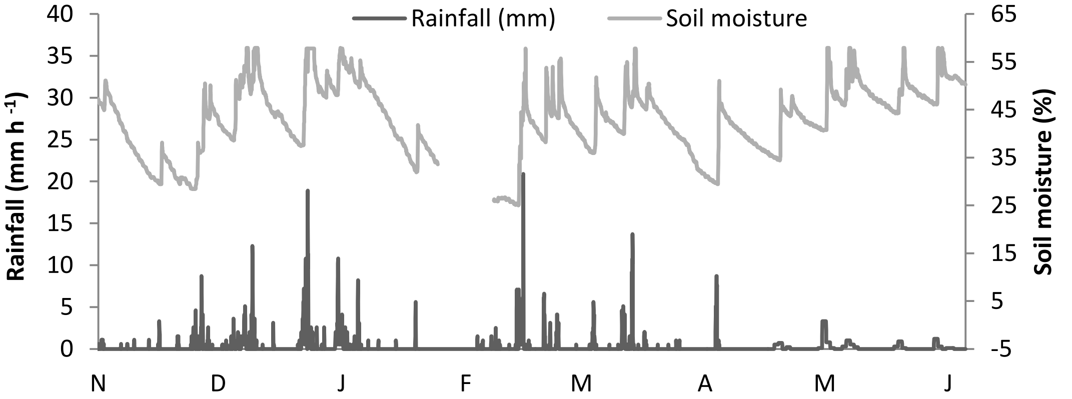

Figure 3.3: Rainfall and soil moisture (hourly frequency) at Oturoa Road climate station (near Waiteti DB) from 09/11/2011 – 09/06/2012, Monthly time periods are indicated by the first letter of each month, on the ninth day of each month. Soil is saturated at 58% moisture at this station.

Low intensity rainfall events (i.e. < 5mm h $^{-1}$) did not affect soil moisture content to the same extent as larger events. Rapid recharge of soil moisture is followed by gradual decrease over following weeks until the next significant rainfall event. The rate of soil moisture decrease after an event is faster in summer months (e.g. January) compared to winter (e.g. June) (Figure 3.3).

Table 3.1: Characteristics of sampled rainfall events which produced ponding in the detainment bunds. Event intensity was derived as total rainfall (mm) / duration of rainfall (h). Rainfall duration was derived by excluding rainfall <0.05 mm h.

Sampled event	**Rainfall event characteristics**			
	Total rainfall (mm h^{-1})	**Duration (h)**	**Max rainfall intensity (mm h $^{-1}$)**	**Average event intensity (mm h^{-1})**
March	62	70.6	13.7	0.88
May #1	103	96	3.3	1.07
May #2	48	97	0.8	0.49
July #1	118	72	3.4	1.63
July #2	201	97	4.9	2.07
July #1 &2	319	169	4.9	1.89
July #3	152	46	7.3	3.30
September #1	52	26	7.9	2
September #2	32.5	37.0	3.5	0.88

There were differences in the intensity of sampled rainfall events. The most intense rainfall event (3.30 mm h^{-1}), when averaged over the rainfall period, was July #3, and the least intense event (0.49 mm h^{-1}) was May #2 (Table 3.1). The rainfall total from July #1 & 2 combined was by far the largest quantity of rainfall (319 mm h^{-1}), although the storm intensity was low in relation to rainfall (1.89 mm h^{-1}) because rain fell over two extended periods (72 and 97 mm h^{-1}, respectively (see Table 3.1)). September #2 was a particularly short and intense rainfall event (Table 3.1).

3.2 Water quality

3.2.1 Ephemeral stream suspended sediment and nutrient concentrations

Ephemeral streams were sampled before they were ponded behind each detainment bund. Figures 3.4 – 3.8 summarise the concentrations of suspended sediments and nutrients in ephemeral streams entering each site during each measured flow event. These samples reflected 'snapshots' of highly dynamic flow conditions. There were spatial (between-site) and temporal (between-storm) variations in the concentrations of suspended sediments and nutrients in the ephemeral streams that flowed into the three detainment bunds.

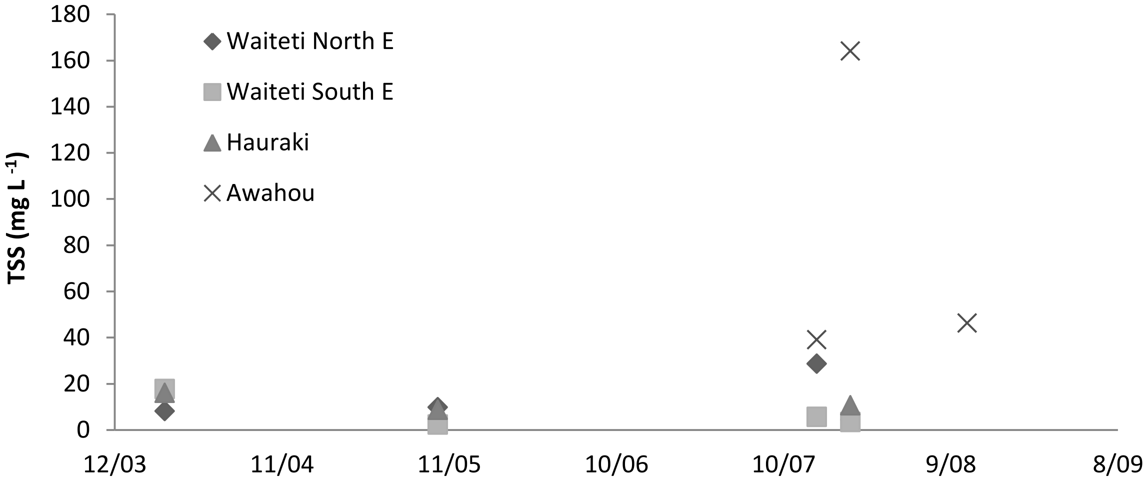

Figure 3.4: Total suspended sediment (TSS) concentrations in ephemeral streams entering DBs during events throughout the study period in 2012. Two ephemeral streams entered Waiteti DB; these are named 'North E' and 'South E'.

Total suspended sediment concentrations varied throughout the sample period. The Awahou ephemeral stream inflow consistently had the highest TSS concentration, with a maximum of 164 mg L $^{-1}$ recorded in July #2. This event occurred following grazing and complete removal of vegetation in a winter forage crop in the contributing catchment, exposing bare soil. At Waiteti DB in July #1 the TSS concentrations of the two inflowing ephemeral streams varied from 5.5 mg L $^{-1}$ in the 'South' ephemeral to 28.5 mg L $^{-1}$ in the 'North' ephemeral, however, concentrations were similar during the other events (Figure 3.4). The Hauraki ephemeral stream inflow had low TSS concentrations in relation to the other sites (maximum 16 mg L $^{-1}$). Figure 3.5shows the variation of TP concentrations of ephemeral streams between sites.

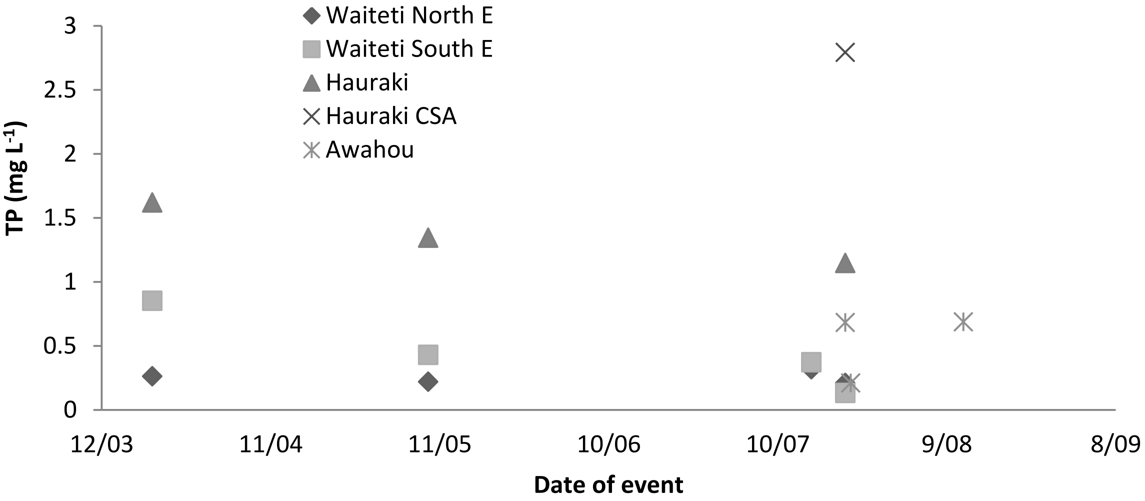

Figure 3.5: Total phosphorus (TP) concentrations of ephemeral streams entering DBs during events throughout the study period in 2012. Two ephemeral streams entered Waiteti DB; these are named 'North E' and 'South E'), 'Hauraki CSA' (critical source area) is a small ephemeral stream leaving an adjacent paddock where cows were grazing during rainfall.

The highest TP concentrations were measured in ephemeral streams entering Hauraki DB. Total phosphorus concentrations were highest in March at Hauraki and Waiteti DBs compared to subsequent events. Figure 3.6 displays the dissolved and particulate forms of P in these ephemeral streams.

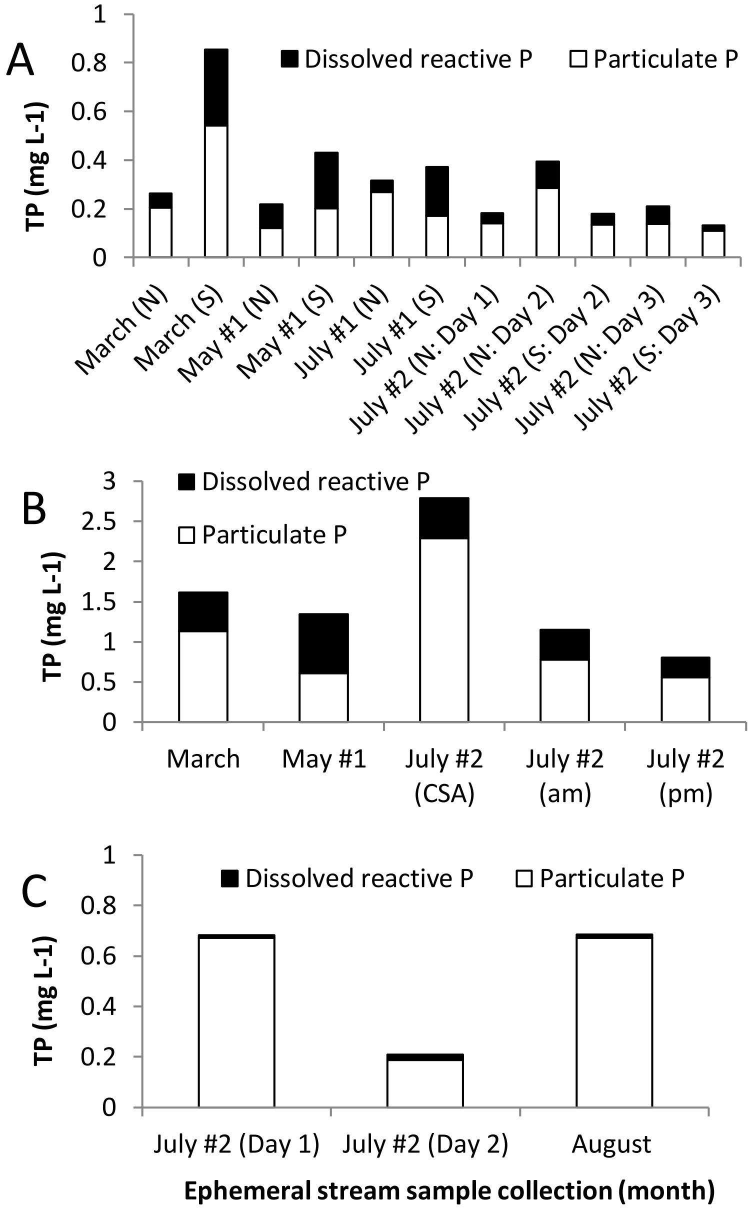

Figure 3.6:Dissolved and particulate concentrations of phosphorus in ephemeral stream water entering DBs during events throughout the study period in 2012. Sites displayed are, A; Waiteti DB, B; Hauraki DB, C; Awahou DB. The 'North' and 'South' ephemeral streams entering Waiteti DB are labelled 'N' and 'S'. At Hauraki DB 'CSA' (critical source area) is a small ephemeral stream leaving an adjacent paddock on which cows were grazing during rainfall.

At Waiteti DB the 'South' ephemeral had a higher proportion of DRP in TP concentrations compared to the adjacent 'North' ephemeral stream in most events (Figure 3.6A). Waiteti and Hauraki had higher proportions of DRP compared to Awahou where almost all of the TP was in particulate form (>95%) (Figure 3.6A-C). There were variations in the proportion of DRP between events at the same location. For example, the proportion of DRP in TP was 30% at Hauraki in March

(TP = 1.6 mg L^{-1}) over 50% in May (TP = 1.34 mg L^{-1}) and average over the three ephemerals in July #2 was <20% DRP (TP= 1.58 mg L^{-1}) (Figure 3.6B).

The highest TN concentration measured over the entire study period was 7.06 mg L^{-1} corresponding to a small ephemeral stream draining from a paddock where cows were grazing during heavy rainfall (Hauraki CSA) in July #2 (Figure 3.7). There was more variation in TN between events at the same site (Figure 3.7) compared to TP (Figure 3.5). This variation is explored in more detail in Figure 3.8 which displays the dissolved and particulate fractions of N in each of the sampled ephemeral streams.

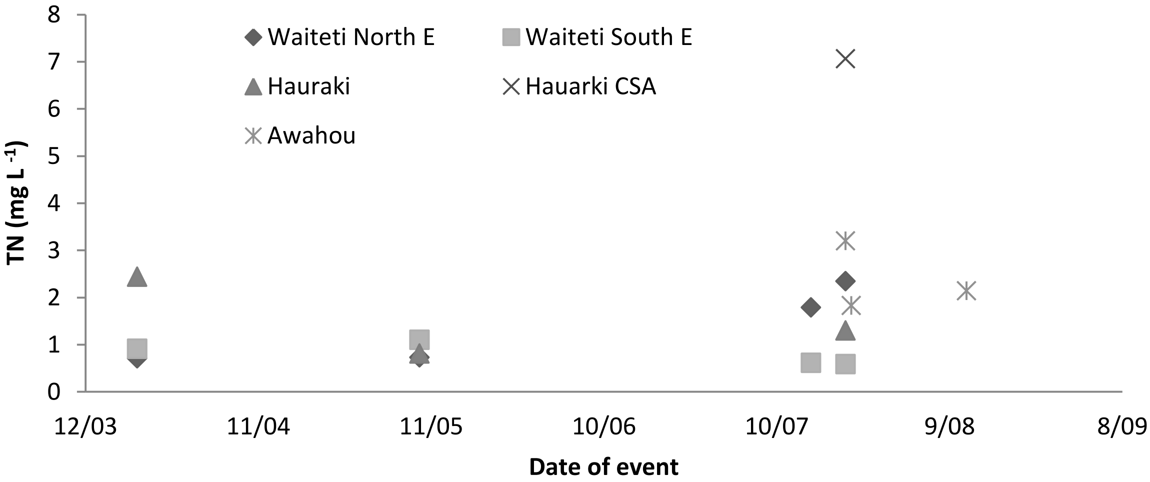

Figure 3.7: Total nitrogen (TN) concentrations of ephemeral streams entering DBs during events throughout the study period in 2012. Sites displayed are, A; Waiteti DB, B; Hauraki DB, C; Awahou DB. Two ephemeral streams named 'North E' and 'South E' entered Waiteti DB. 'Hauraki CSA' (critical source area) represents a sample from a small ephemeral stream leaving an adjacent paddock on which cows were grazing during rainfall.

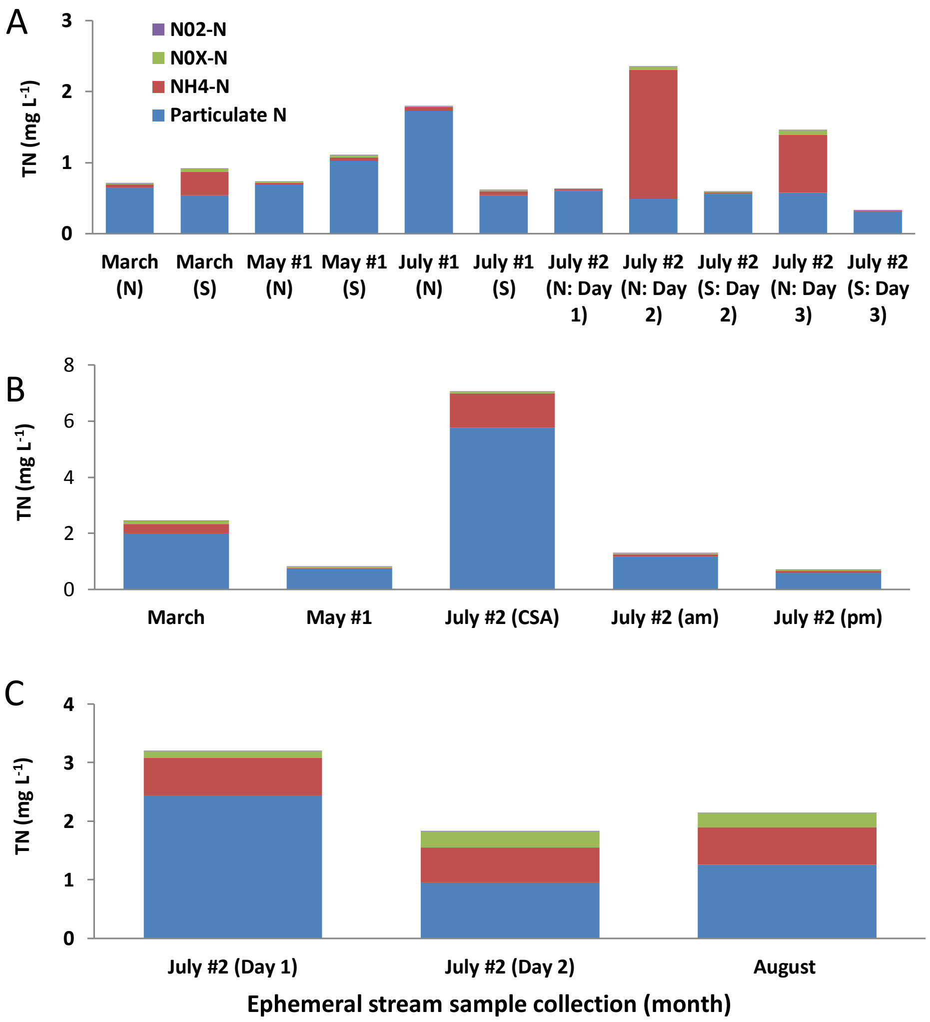

Figure 3.8:Dissolved and particulate concentrations of nitrogen in ephemeral stream water entering DBs during events throughout the study period in 2012. The North and South ephemeral streams entering Waiteti DB are labelled 'N' and 'S'. At Hauraki DB the CSA (critical source area) is a small ephemeral stream leaving an adjacent paddock on which cows were grazing during rainfall.

Particulate N was the predominant form of N at Waiteti and Hauraki (Figure 3.8 A and B) , however, the Waiteti 'North' ephemeral stream sample taken in July was an exception with dominance of N by NH_4-N (Figure 3.8A). On average, the fraction of N that was is DN form was highest for ephemeral stream water at Awahou (Figure 3.8). The opposite trend occurred for P, where the relative P fraction that was PP was highest at Awahou (Figure 3.8). The Awahou site had the highest NO_X-N concentration but NH_4-N was the predominant dissolved form of N in all ephemeral streams sampled across the study period in 2012.

3.2.2 Changes in outflow water quality over ponding time

The following section summarises the key trends in SS and nutrient concentrations for water leaving the DBs during ponding periods. Included in this section is information on sedimentation rates and sizes of suspended particles.

3.2.3 Sedimentation rates

Five ponding events were selected for detailed analysis of changes in TSS concentrations over time, to give insight into sedimentation rates in water ponded by detainment bunds. Events were selected based on the number of samples taken (at least four) and the time that the ephemeral inflow and rain stopped. A 'time 0' was applied to each data set so that different events could be compared. 'Time 0' corresponded to when water ceased to enter the bund (i.e. from rainfall or ephemeral flow), or in the case of the Awahou Sept#2 and Hauraki July #2 events, it was based on the maximum TSS value (i.e. as a start point). Three ponding events at Hauraki DB were analysed to explore differences between events. Only one ponding event at Waiteti DB was analysed due to interference from input of sediment derived from earthworks which were not representative of agriculturally derived sediment inputs to the DB. The full data set is given in Appendix 1.1.

Total suspended soilds data from each event were normalised by dividing by TSS concentrations at time zero. Data were then natural-log transformed to represent the natural exponential decay of sediment settlement. These data are presented in Figure 3.9.

All relationships were significant at $p<0.05$, which suggests that the slopes of the regression lines are significantly different from zero, so the null hypothesis that TSS concentration does not change over ponding time can be rejected. Some events did not show exponential decay (Hauraki May, Hauraki July #2 and Awahou September) however, all data was natural-log transformed to represent the theoretical exponential decay of suspended sediments in a standing body of water, in the assumed absence of any substantial gains (e.g. rainfall) or losses (outflows).

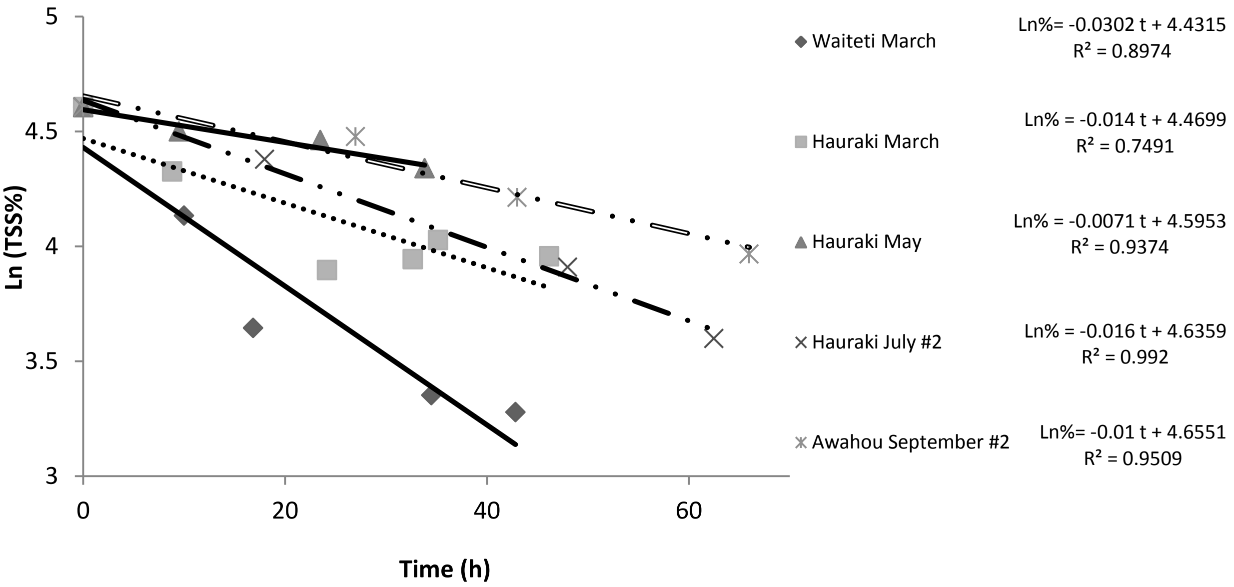

Figure 3.9 Total suspended sediment (TSS) concentrations of water leaving Waiteti and Hauraki detainment bunds during March 2012. TSS data are expressed as the natural logarithm (Ln) of the proportion (%) of TSS concentration relative to the starting concentration at time zero.

The March event at Waiteti had the fastest settling rate (0.030 ln units h^{-1}) (relative rate of decrease), when there was a 73.4% reduction in TSS over a 43-h ponding period (Figure 3.9). The May event at Hauraki had the slowest settling rate (0.0071 ln units h^{-1}), when there was a 23.3% reduction in TSS over a 34 h ponding period (Figure 3.9), the rainfall event which produced this ponding was the least intense of all events (Table 3.1). The September event at Awahou had 47% reduction in TSS over 66 h; the second-fastest settling rate observed.

The standard error of the slope of each regression line was compared between events to determine whether the rates of change were statistically significantly different between events. The sedimentation slope at Waiteti DB in March is the only statistically different slope, as the standard error for the slope of the line lies outside the range of the other slopes.

The median particle size of each water sample collected for each event was averaged to derive a mean particle size. Water leaving the Awahou DB in

September had the largest particle size (1,310 µm) followed by Waiteti (1,048 µm) in March, although Waiteti March had a higher proportion of inorganic suspended solids at time 0. The smallest particle size observed out of all of the events was (701 µm) at Hauraki DB in May. Hauraki March and July #2 had similar sized particles, 978 µm and 972 µm respectively.

3.2.4 Particle size distribution of suspended sediments

Large variations in particle size distribution occurred over each ponding event (Appendix 1.2). Data presented in this section are displayed for qualitative assessment purposes.

Inflow vs. outflow

Sediment suspended in water entering and exiting the detainment bunds was analysed to determine particle size characteristics. There were differences in the size distribution between inflow and outflow samples during the same time period. Examples from each site are displayed in Figures 3.10 – 3.11.

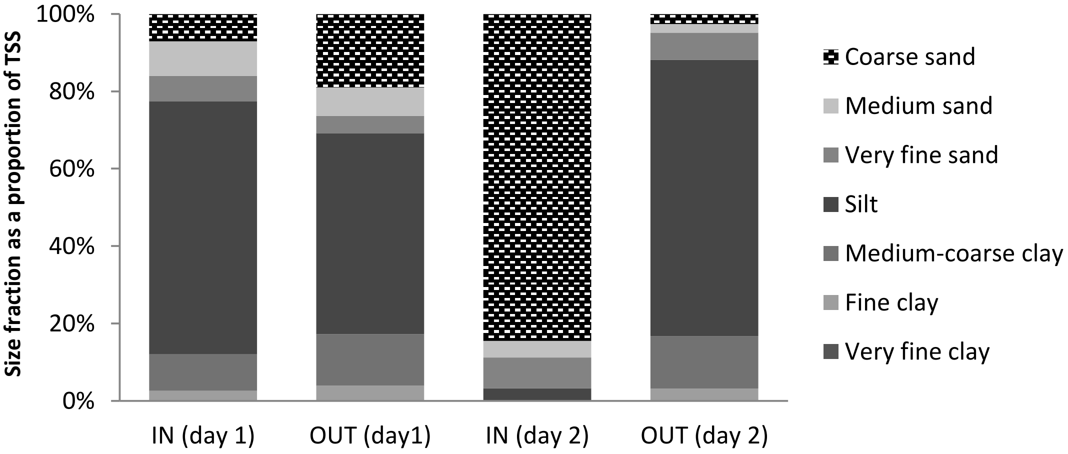

Figure 3.10: Size distribution of suspended sediment in water entering (IN) and water leaving (OUT) Awahou DB on 23 (day 1) and 24 July (day 2). Size fractions are basd on a Wentworth scale; see methods section 2.7. Particle size data include aggregates.

Water entering the Awahou basin on day 2 comprised a higher percentage of coarse sand sized particles compared to the inflow on day 1 which mainly comprised of silt-sized particles. The TSS concentration of the inflow on day 1 was 164 mg L^{-1}, and the outflow was 268 mg L^{-1}. On day two, the TSS concentration of the inflow was 19 mg L^{-1} and the outflow was 37 mg L^{-1}. The outflow on day two contained the smallest proportion of sand-sized suspended sediment and the largest fraction of silt-sized particles amongst the four samples. Outflow samples at Waiteti and Hauraki DBs also comprised of smaller-sized particles compared to the inflows (Figure 3.11). There was little difference in the size class of the two ephemeral streams at Waiteti, but there was 15% less coarse-sand sized particles in the outflow compared to the inflow (Figure 3.11A).

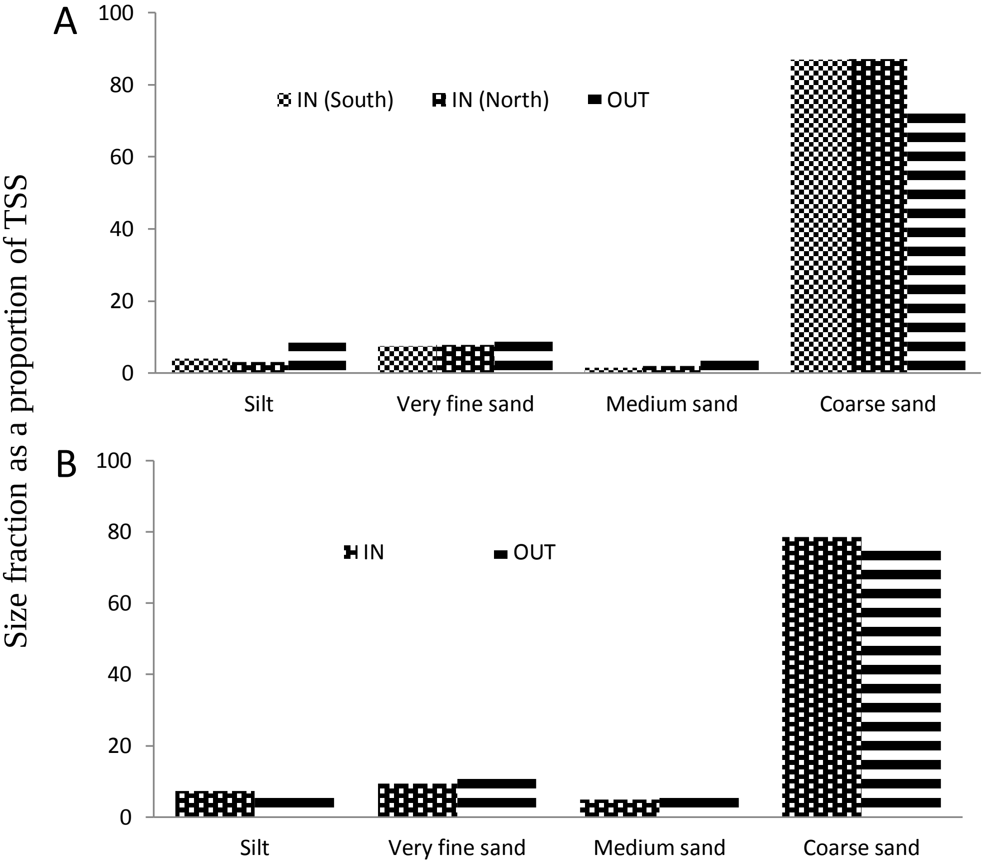

Figure 3.11:Size distribution of suspended sediment in water entering (IN) and water leaving (OUT) detainment bunds (DBs). Events displayed are; A; Waiteti DB on 21 March (two different ephemeral streams), B; Hauraki detainment bund, 23 July (event July #2). Size fractions are basd on a Wentworth scale; see methods, section 2.7 (no particles below 'silt-sized' were detected). Particle size data include aggregates.

Variation in particle size distribution over time

Particle size distribution of suspended sediments was examined for outflow samples taken during the course of ponding events, using the same five events presented in section 3.2.3. All samples represented in Figure 3.12 were dominated by coarse sand-sized particles. Hauraki DB in March (Figure 3.12B) had the largest overall fraction of fine particles throughout the ponding period, with fewer coarse sand-sized particles and more medium-sand and silt-sized particles compared to the initial ponding period at time zero. During ponding at Waiteti in March, Hauraki in May and Hauraki in July there was a spike in the proportion of samples during the ponding period relative to time zero and the final sample (Figure 3.12A, C and D). After 27 hours ponding, outflow water at Awahou DB (September #2) was stronglydominated by coarse sand-sized particles. Thus there was an increase in particle size through time, especially compared with time 0 when smaller-sized fractions occupied a higher proportion of TSS (Figure 3.12E).

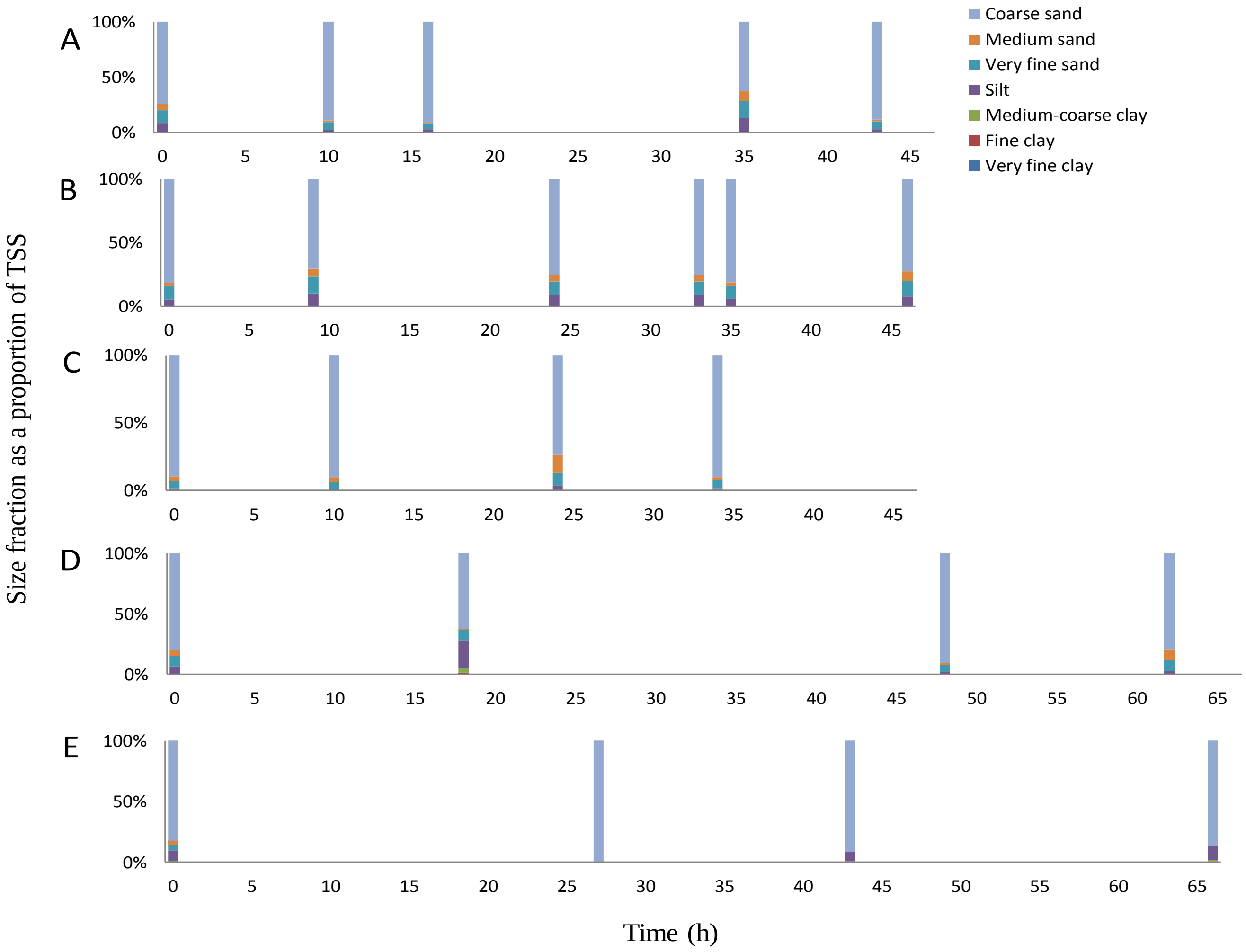

Figure 3.12: Particle size distribution of suspended sediments in outflow water from detainment bunds during ponding events. Events displayed are, A; Waiteti in March, B; Hauraki in March, C Hauraki in May #2, D; Hauraki in July #2, E; Awahou in September #2. Samples have been allocated a time 0 (as described in section 3.2.3). Size classes are based on the Wentworth scale, outlined in Methods section 2.7. Particle size data include aggregates.

The organic fraction of TSS in water leaving DBs during the same five events shown in Figure 3.12 is shown inFigure 3.13. In most cases the proportion of the organic fraction comprising SS in water leaving the DBs increased with ponding time in these events. The only significant relationship ($p < 0.05$) between the percentage of organic suspended sediment and ponding time was at Waiteti in March, (VSS= $1.148 \times t + 25.9$), Pearson's correlation (r) = 0.99, $p < 0.05$) (Figure 3.13).

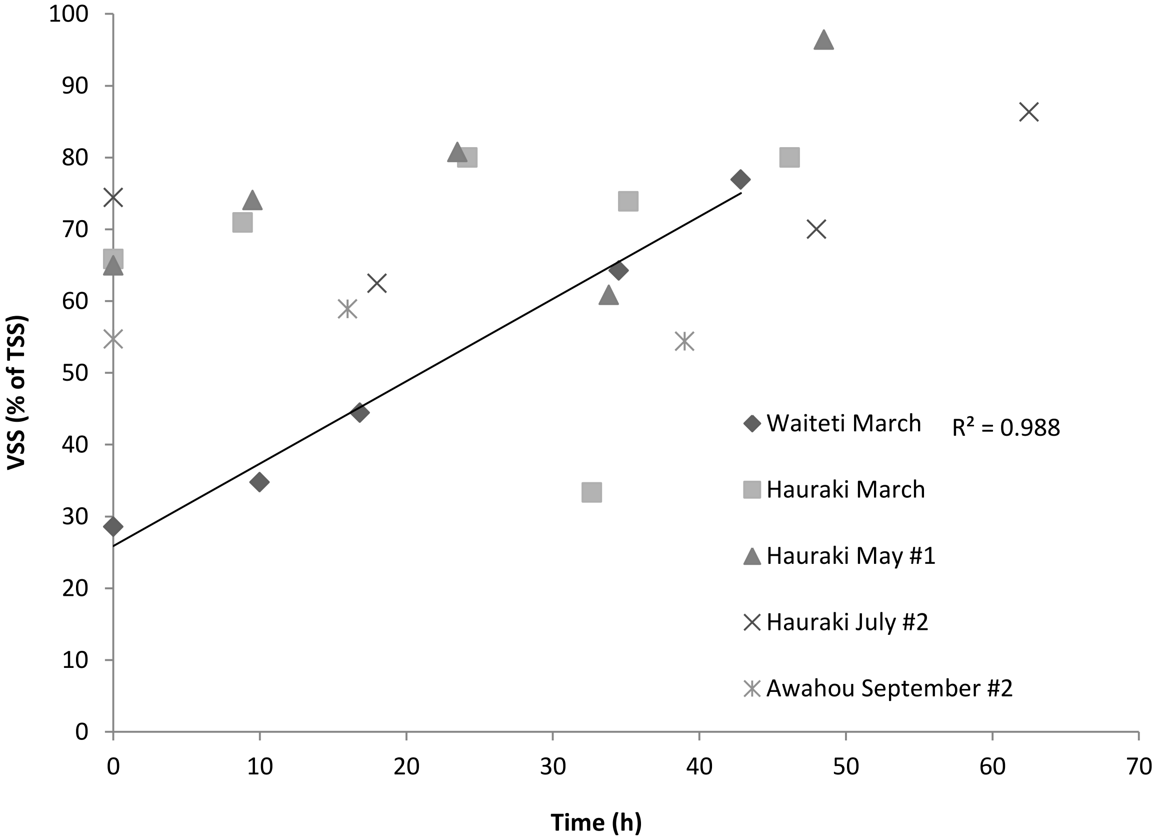

Figure 3.13 Percentage volatile (organic) suspended sediment (VSS) in water leaving DBs during selected ponding events. A significant relationship was observed for data collected during a ponding event at Waiteti detainment bund in March.

There is was correlation between particle size and PP across the three sites (Figure 3.14). The majority of particles are in the coarse sand sized range.

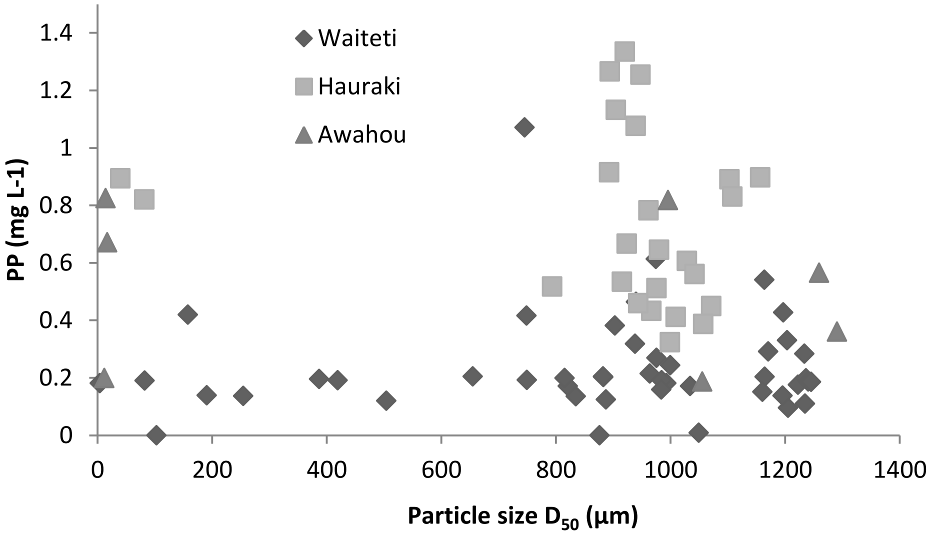

Figure 3.14Particle size of suspended sediments (median) and particulate phosphorus (PP) in all water samples collected during the sampling period (March-September 2012) at each of the three sample sites.

3.2.5 Nutrient concentrations

This section displays nutrient data collected throughout the ponding periods at Hauraki and Waiteti DBs in March, Hauraki DD in July and Awahou DB in July #3 and September #2 to provide examples of how nutrient concentrations changed during ponding time.

Outflows over time

At Hauraki DB in July (event July #2), there were decreases in both PP (40%) and dissolved reactive P (32%) over first 48-h ponding period, although TP increased by 19% over thelast 15 h of the ponding period, even though TSS continued to decrease (Figure 3.15C). Over 37 h of ponding at Hauraki DB in March PP decreased by 31% (1.3 to 0.9 mg L^{-1}), however, the DRP concentration increased by 35% (0.46 to 0.62 mg L^{-1}) (Figure 3.15B). There was no relationship between TP and ponding time at Waiteti DB in March (Figure 3.15A). Both PP and TSS concentrations decreased in the first 17 h, but TP concentrations were then quite variable through the remainder of the 105-h ponding period. Ducks were present in the pond prior to collection of the last three samples. They appeared to have stirred up the water prior to sampling at the 105-h time period (note very high TSS concentration at 105 h; Figure 3.15A). Data collected in other events (see Appendix 1.1 for all nutrient data collected in ponding events) showed similarly variable trends (as seen in Figure 3.15) in TP over ponding time.

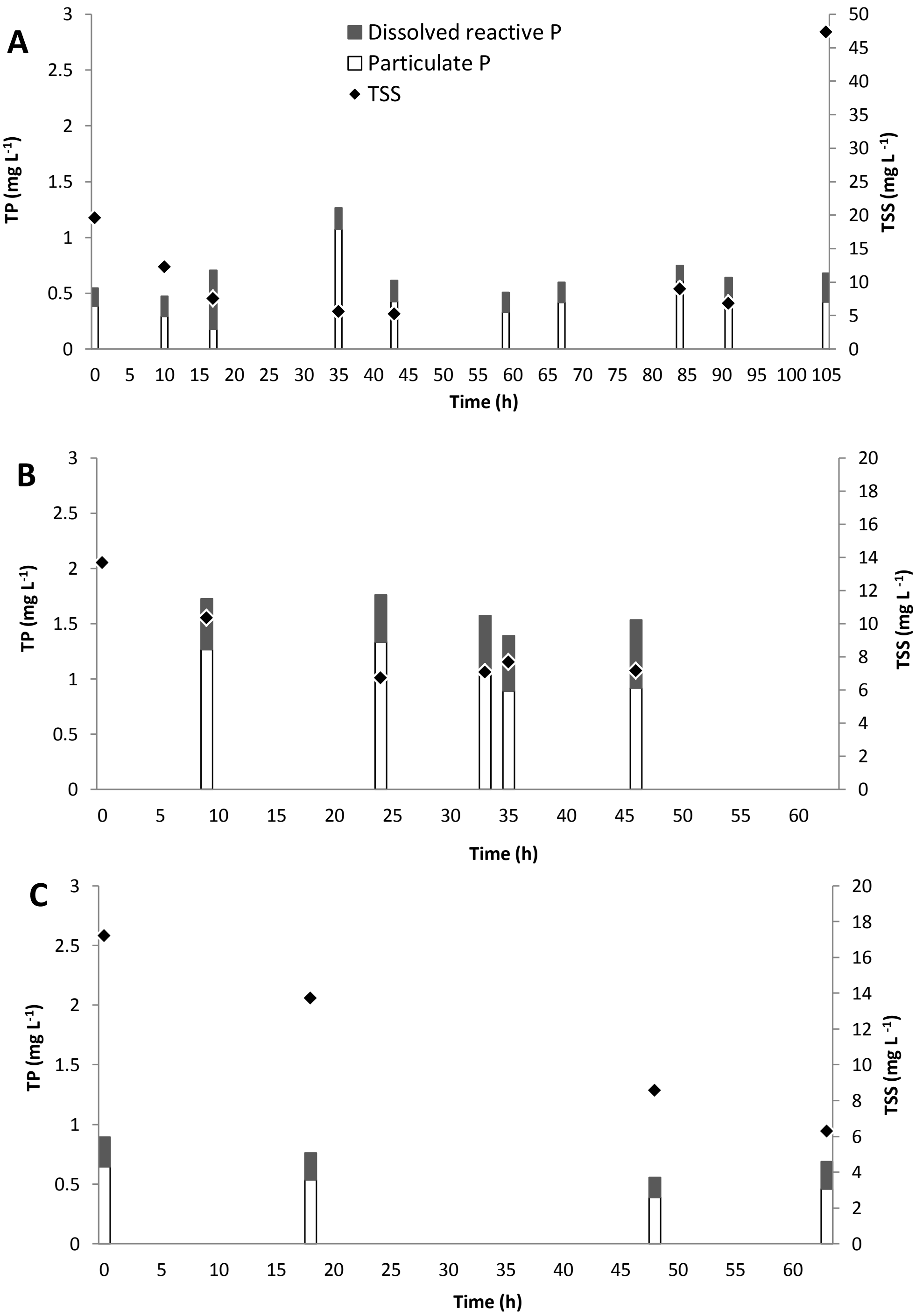

Figure 3.15: Particulate phosphorus (P) , dissolved reactive P and total suspended sediment (TSS) concentrations of water leaving detainment bunds throughout ponding periods at A; Waiteti DB in March, B; Hauraki DB in March, C; Hauraki DB in July #2. Samples for TSS determination were not obtained during two sampling periods at Waiteti DB in March and no P data were obtained for time zero at Hauraki March.

There was a 40% reduction in TN (mainly PN) within the first 48 h ponding at Hauraki in July #2, there was also a reduction in TSS (63%) over this time period (Figure 3.16C). Both particulate and dissolved nitrogen concentrations were highly variable and TSS concentrations showed no relationship with TN throughout the ponding periods at Waiteti and Hauraki in March (Figure 3.16A and Figure 3.16B). There was a larger fraction of total N in dissolved inorganic form at Hauraki DB in March (Figure 3.16B) compared to Waiteti in March (Figure 3.16C). The last sample at Waiteti (105 h) comprised over 75% in dissolved inorganic form when ducks were present immediately prior to sample collection. Data from other ponding events showed similarly variable trends (Appendix 1.1).

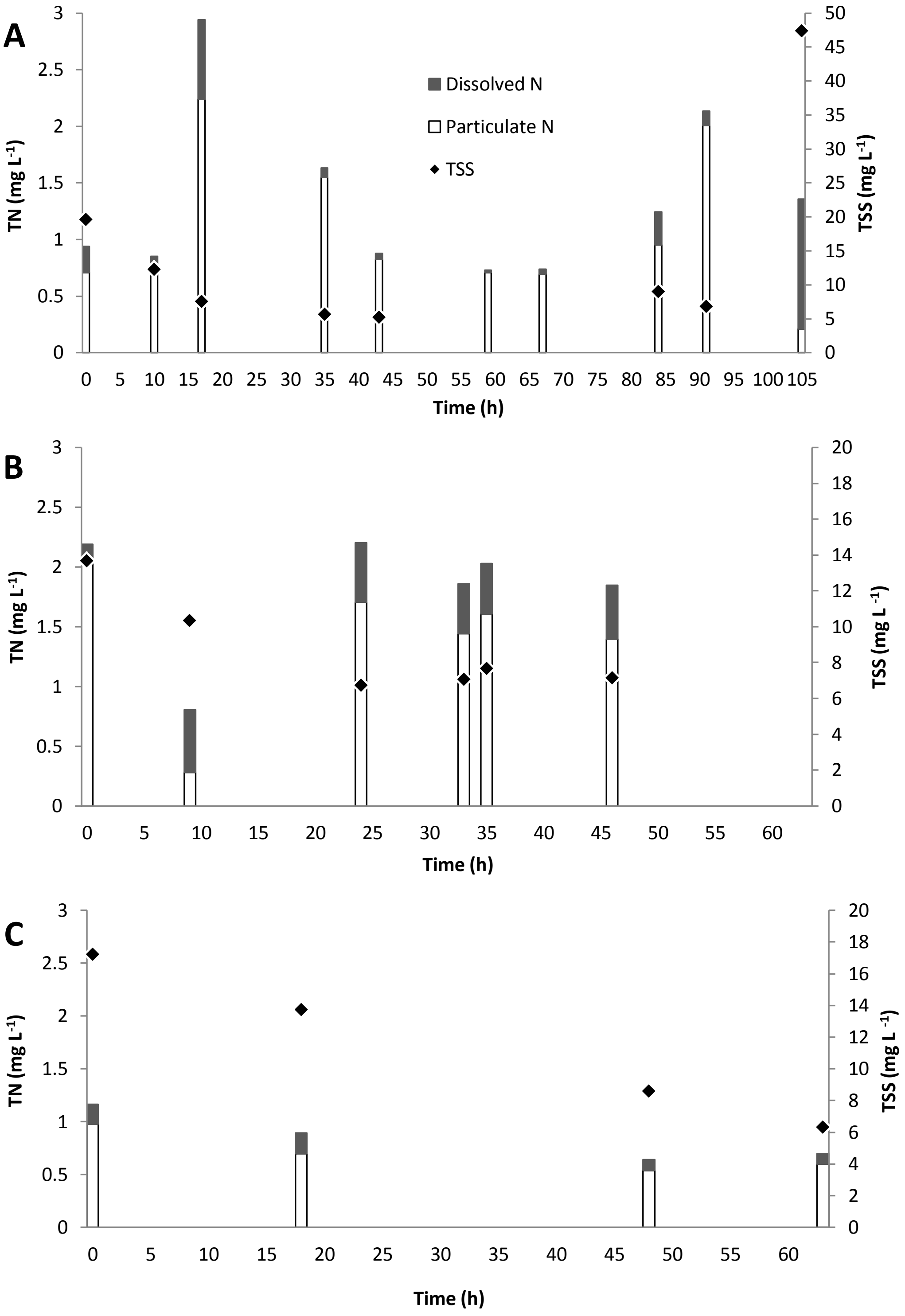

Figure 3.16: Total nitrogen (particulate and dissolved) and total suspended solids concentrations of water leaving detainment bunds throughout ponding periods at A; Waiteti DB in March, B; Hauraki DB in March, C; Hauraki DB in July #2. Samples for TSS determination were not obtained during two sampling periods at Waiteti DB in March.

The largest reductions in nutrients and TSS concentrations over the shortest ponding period (20 h) across all sampled sites were observed at Awahou DB. Total suspended solids reduced by 37% and 58% over 20 h in July #3 and September #1 (Table 3.2). Particulate P reduced by 28% in July #3, and 36% in September #1. Almost all of the TP comprised PP in the July #3 (average of 98.0%) and September #1 (average of 99. 6%) events, which had the lowest DRP concentration measured over the entire study period. Dissolved reactive P increased by 14% (but only 0.001 mg L^{-1}) in September #1, and decreased by 17% in July #3 (Table 3.2). In September #2 PN decreased by 43%, but there was little variation in dissolved inorganic nitrogen (-1%) over the 20 h ponding period (Table 3.2).

Table 3.2: Nutrients (total phosphorus (TP), particulate P (PP), dissolved reactive P (DRP), total nitrogen (TN), particulate N (PN), dissolved inorganic N (DN)) and total suspended solid (TSS) concentrations (mg L^{-1}) of water leaving the Awahou DB during a 20 h ponding event in July (July #3) and September (September #1), Time zero represents the time the first sample was collected. The % change over the 20 h is represented with a – for decrease and + for increase.

	July #3			September #1		
			% change			% change
Time (h)	0	20		0	20	
TSS	125	78.75	-37.0	184	78	-57.6
TP	0.585	0.424	-27.6	0.571	0.368	-35.6
PP	0.574	0.415	-27.8	0.566	0.361	-36.2
DRP	0.011	0.009	-17.0	0.006	0.007	(+) 14.0
TN	2.513	1.808	-28.1	4.762	3.590	-24.6
PN	1.957	1.431	-26.9	2.705	1.555	-42.5
DN	0.556	0.377	-32.2	2.058	2.034	-1.1

Inflows vs outflows

Figure 3.17A-D displays the TP and TSS concentration of water entering and leaving detainment bunds at a range of sites over three different events. The outflow at Waiteti DB had TP concentrations that were intermediate between the TP concentrations of the two ephemeral streams entering the DB (Figure 3.17A). The water level was above the concrete riser during most sampling events displayed in Figure 3.17; these events are Waiteti in March (A) (45cm above), Hauraki in March (B) (30cm above), and Hauraki in July #2 (C)(10cm above).Water level was below the riser at Awahou (Figure 3.17D). At Hauraki in March there was little change in TP between the inflow and outflow, although

TSS concentrations were lower (Figure 3.17B). The outflow TSS and TP concentrations were higher than the inflow concentrations at Hauraki in July #2 and Awahou in September #2, samples were taken after the peak ephemeral flow in these cases (Figure 3.17C and D). The highest TSS concentration recorded over the entire study period was 268 mg L^{-1} at Awahou in July #2, in this event DRP concentration was 40% lower in the outflow compared to the inflow (Figure 3.17D).

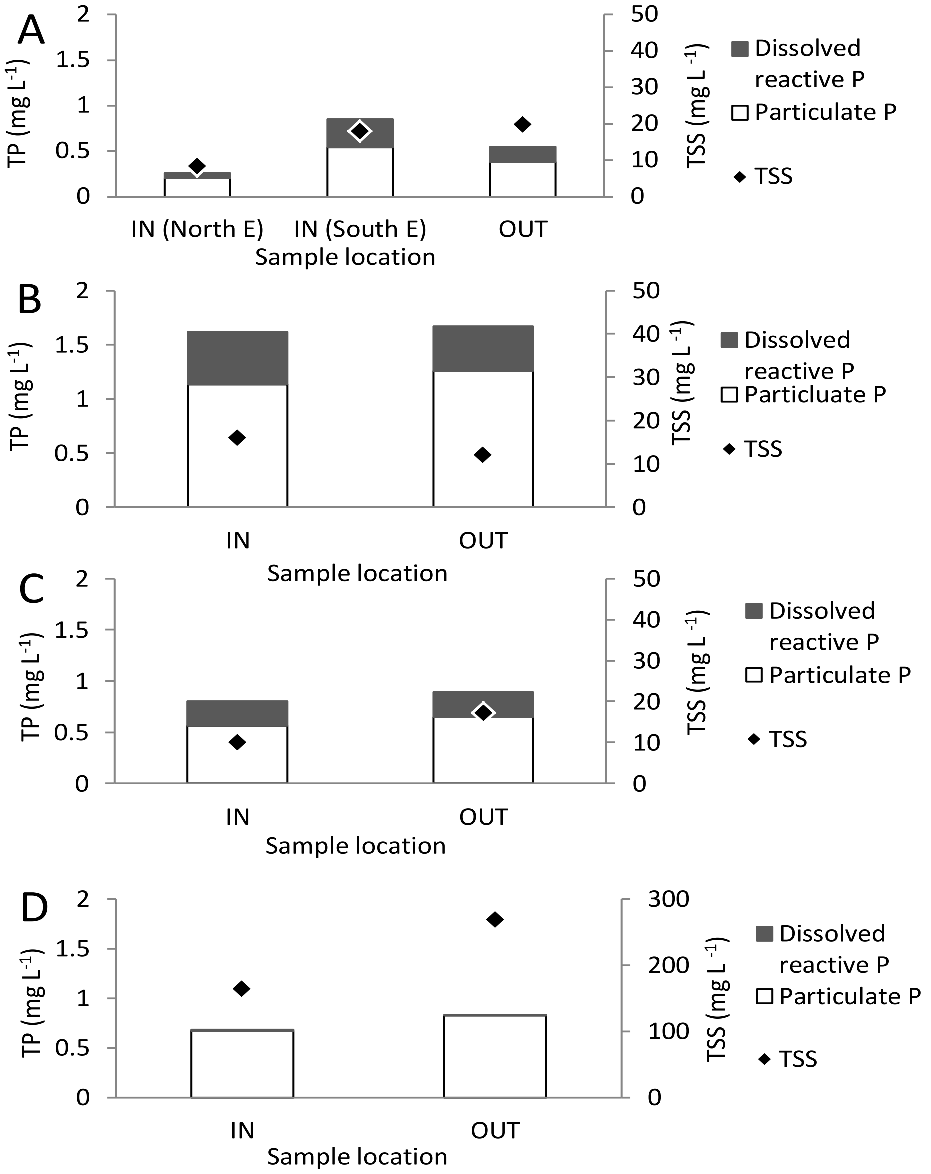

Figure 3.17: Total phosphorus (TP) and suspended sediment (TSS) concentrations of water entering (IN) and leaving (OUT) at three detainment bunds (DBs) during various events, A; Waiteti DB at 11.40 pm on 21 March, B; Hauraki DB at 1 am on 22 March, C; Hauraki DB at 6 pm on 23 July (July #2), D; Awahou DB at 5 pm on 23 July (July #2). Water was leaving over the riser in A – C, but not at Awahou (D). Note that Waiteti DB had two inflows (North E and South E) (Figure 3.17A). Note the different TSS range in D.

3.3 Deposited sediment characteristics

3.3.1 Spatial distribution of sediment deposited

Larger masses of sediment were generally deposited on the Astorturf mats at low elevations compared to high elevations in DBs. For example, during a ponding event at Hauraki in July #3 the majority of sediment was deposited on individual mats deployed at the 100- 400 mm elevations (elevation relative to the lowest point in the DB) (Figure 3.18).

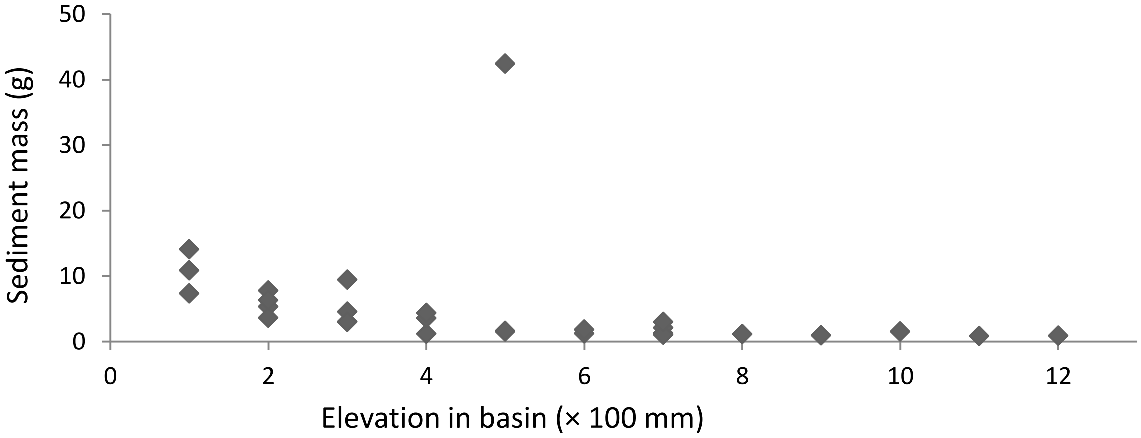

Figure 3.18: Sediment mass deposited on individual mats at Hauraki DB after a ponding event in July (July #3). The outlier at elevation 500 mm was likely influenced by localised sediment input from a stock track.

Mats within the low-elevation group (at 100 and 200mm above the lowest point in the DB) often had larger average areal sediment deposition rates than mats in medium and high elevations(Figure 3.19). Large standard deviations from the average (especially at low elevations) represents the difference in sediment deposition across the elevtions. There is no detectable trend insediment deposited at Awahou DB in July #3 does not show this trend, and has a large standard deviation representing variation in sediment mass deposited on the mats within this elevation (Figure 3.19).

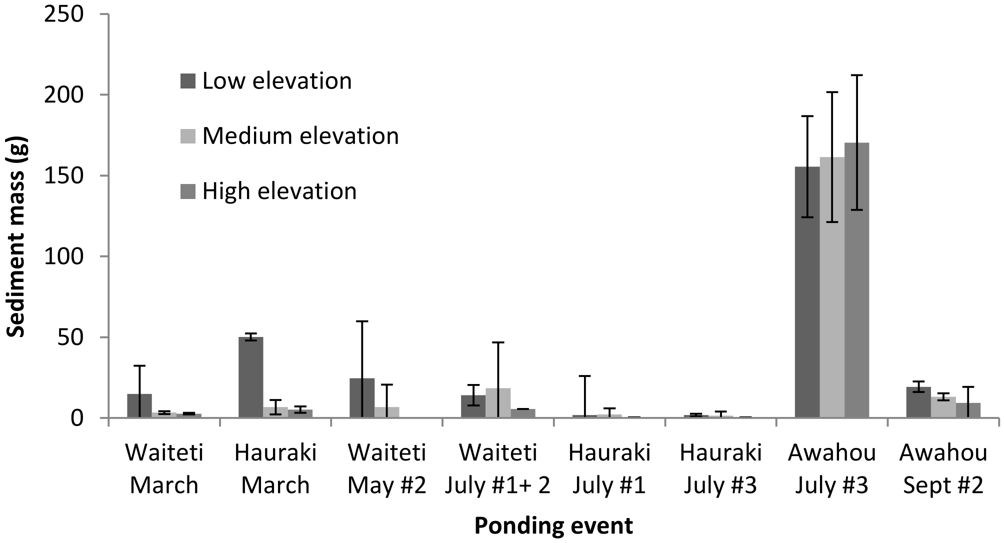

Figure 3.19: Average sediment mass deposited on Astorturf mats in the detainment bund ponding areas during various ponding events. Data have been averaged based on elevation in the ponding area (see Methods section 2.4.1.1 for the elevation ranges). Error bars represent standard deviation from the mean mass deposited on mats within each elevation group.

To further explore the spatial distribution of sediment deposition at Awahou DB in July, sediment collected on three trays at different elevations in the basin (100, 600, 900mm) was analysed (Figure 3.20). Trays and sediment mats were examples of two different sampling techniques and results are therefore not directly comparable (Methods 2.4.1.4) although they can be used to explore the relative spatial variation across the basin. There was larger areal sediment deposition and largest median particles size on the tray at the 900mm elevation compared to the lower elevations (Figure 3.20). The tray at 900mm was closest to the ephemeral inflow and the tray at 100 mm was nearest to the bund (Figure 3.20). The trend of increasing sediment mass with increasing elevation at Awahou July #3 (Figure 3.20) is the opposite to the trend observed during most other sampled events across all sites (Figure 3.19).

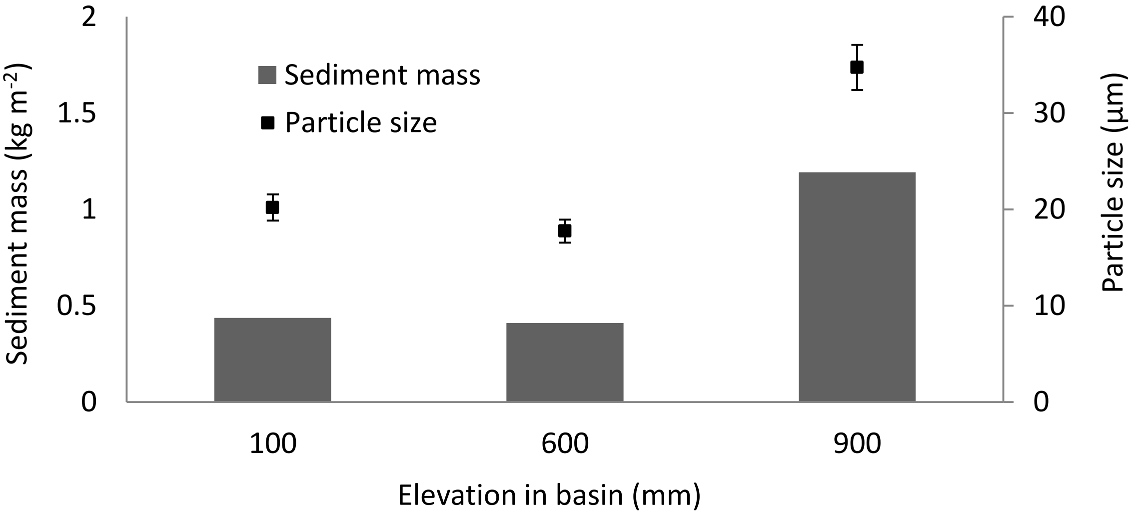

Figure 3.20: Sediment mass and particle size of sediment deposited on three individual trays at Awahou DB in July#3) across a range of elevations. Distance from the bund increases with elevation (the tray at 100 mm was closest to the bund and tray at 900 mm closest to the ephemeral inflow). Error bars represent measurement error (% error based on the measurement error described in Methods 2.4.1.3).

Sediments deposited on the mats were pooled, based on elevation in the ponding area (on a mass-proportional basis) (see Methods section 2.4.1.1). Samples were analysed for P and particle size. There is a general trend of smaller-sized particles in the low elevations, with higher elevations characterised by coarse sand-sized fractions relative to the lower elevations at each site (Figure 3.21). The only events for which this trend was not observed were Waiteti May #2 and Awahou July #3 (Figure 3.21 C and G). Sediment deposited at the high elevations at Hauraki July #2 (E) and Waiteti July #1+ 2 (D) had lower TP concentrations and larger particles (i.e. coarse-sand and medium-sand sizes) compared to the lower elevations (Figure 3.21E), although, this trend was not observed for most of the other storms sampled (Figure 3.21). Total phosphorus concentration of the pooled sediment deposited on the mats was not significantly related ($P > 0.05$) to particle size for any of the sites.

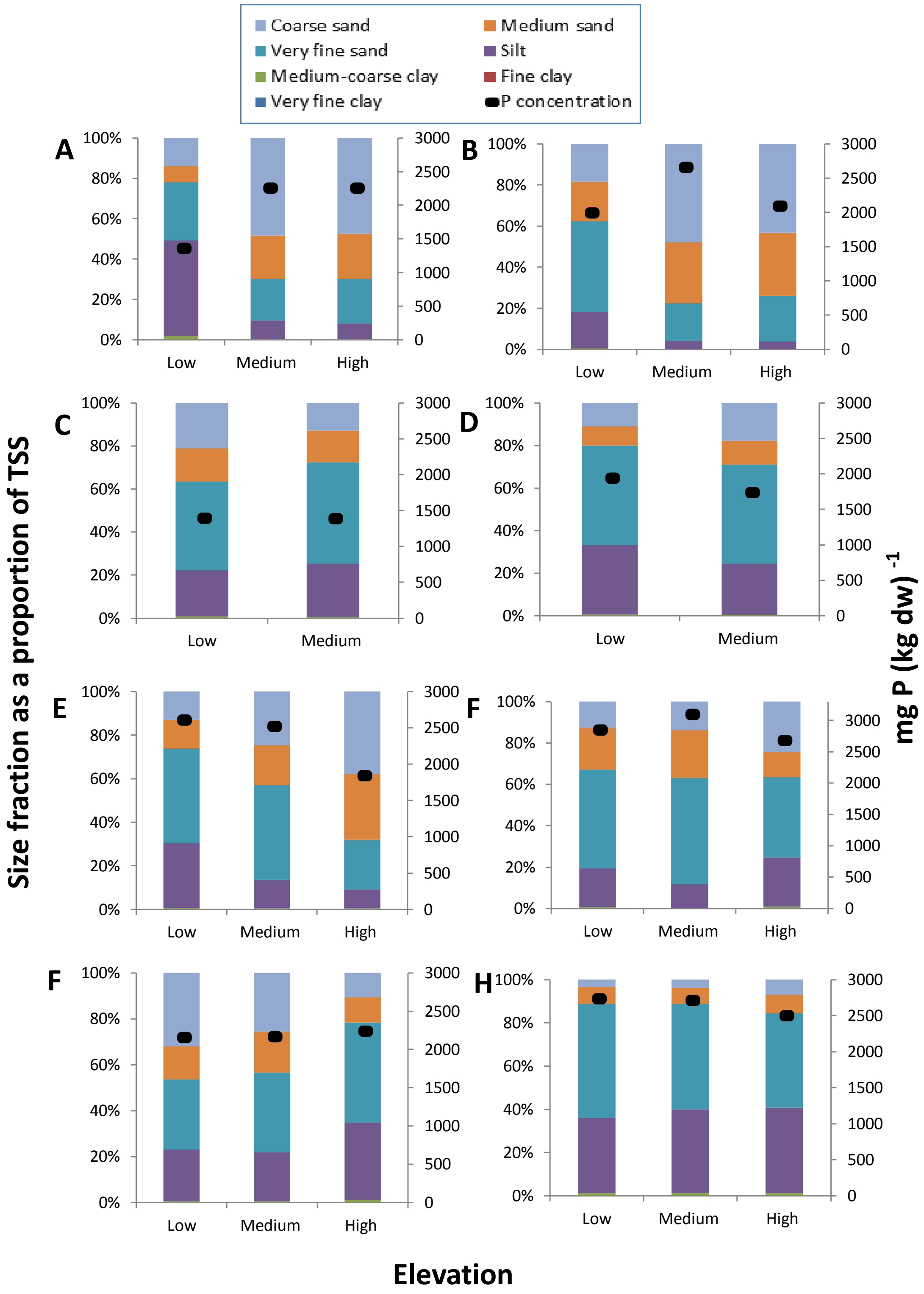

Figure 3.21: Particle size distribution (and total P concentration) of sediments deposited on mats over the study period. Sediments deposited on the mats were pooled based on elevation in the ponding area (see Methods section 2.4.1.1). Events are displayed in chronological order, A: Waiteti March, B: Hauraki March, C: Waiteti May #2, D: Waiteti July 1+2, E: Hauraki July #2, F: Hauraki July #3, G: Awahou July #3, H: Awahou September #2.

To further explore the relationship between each elevation (low, medium high) and TP concentration of the deposited sediment a one-way ANOVA was performed for each site. This revealed that there was a significant difference between TP and elevation at Waiteti DB (d.f=18, F=5.16, P=0.017), and Hauraki DB (d.f=24, F=25.67, P<0.001), but the relationship was not significant at Awahou (d.f=15, F=0.14, P=0.87) (Figure 3.22C). A post-hoc Tukey HSD analysis was performed for sites where there was a difference. At Waiteti the average TP concentration deposited at the 'high' elevation was significantly higher than that deposited at the 'low' elevation (Figure 3.22A). At Hauraki the TP concentration at the 'high' elevation was significantly lower than both the 'low' and 'medium' elevations (Figure 3.22B).

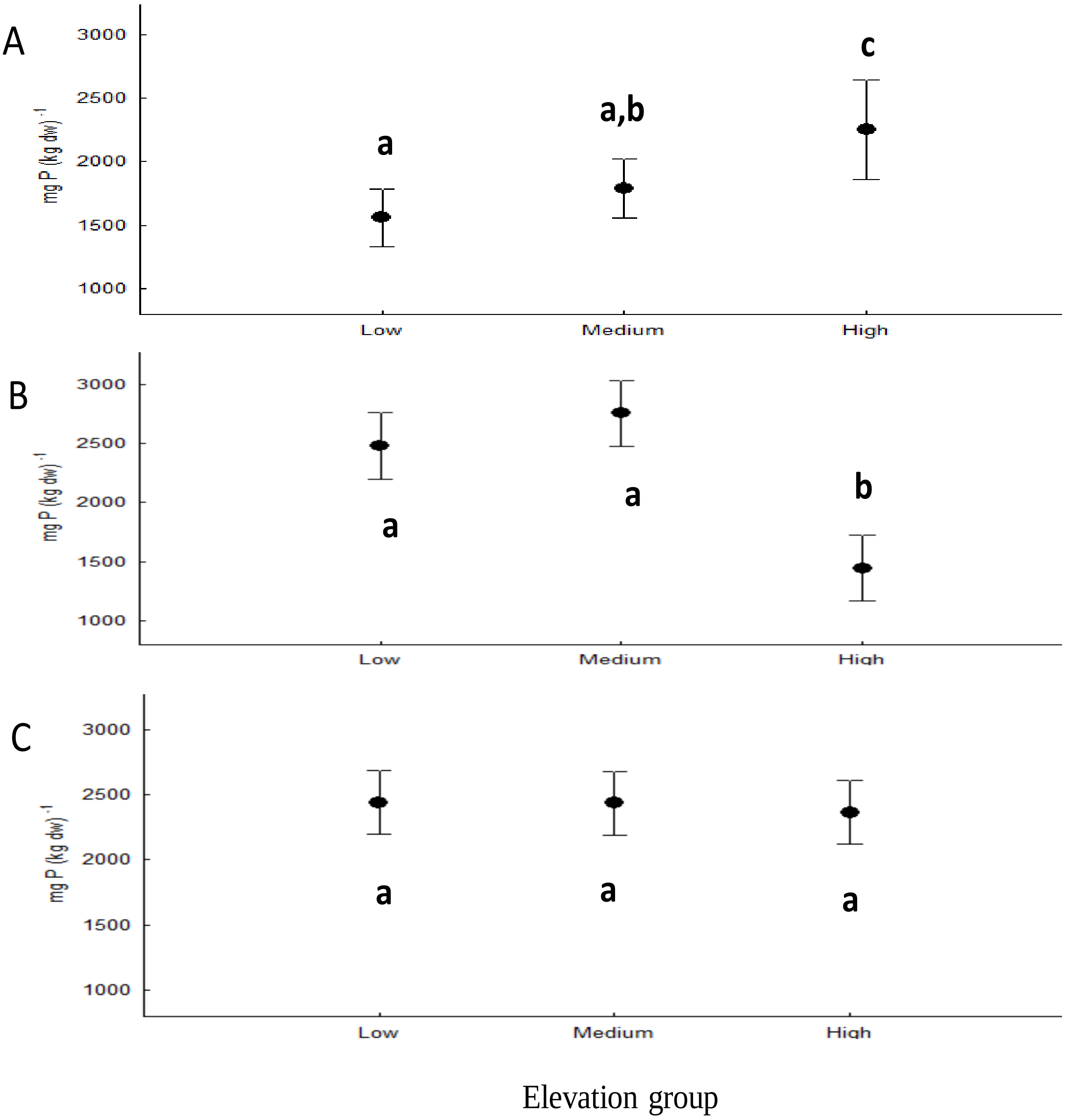

Figure 3.22: Average total phosphorus concentration of sediment deposited at each detainment bund over all sampled events, split up into in three elevation groups, low (0-200 mm), medium (200-700 mm) and high elevation (>700 mm) (explained in more detail in methods section 2.4.1.1). Figure A; Waiteti DB, B; Hauraki DB, C; Awahou DB. Black dots represent the average TP concentration (mg P (kg dw)$^{-1}$), whiskers represent the 95% confidence intervals. Measurement error has been calculated as % standard error derived from triplicate samples, averaged for each site; Waiteti 2.27%, Hauraki 2.28%, Awahou 2.21% (expressed as a % error). The letters in each figure a, b, c represent statistically significant differences between elevations ($p<0.05$).

3.3.2 Relationships between phosphorus and selected metal cation concentrations

Sediments deposited on mats in the detainment bunds throughout the study period were analysed for elemental composition with the specific objective to investigate if there were relationships between P and metal cations that are known to form complexes with P. Out of all the metals, Mn formed the strongest correlation with P in the deposited sediment (Awahou (r^2=0.92) and Hauraki (r^2=0.81) (Figure 3.24). There was also a correlation Fe with P in sediment deposited at Hauraki DB (r^2=0.73) (Figure 3.24) but not between Al and P at Hauraki or Waiteti (Figure 3.25).

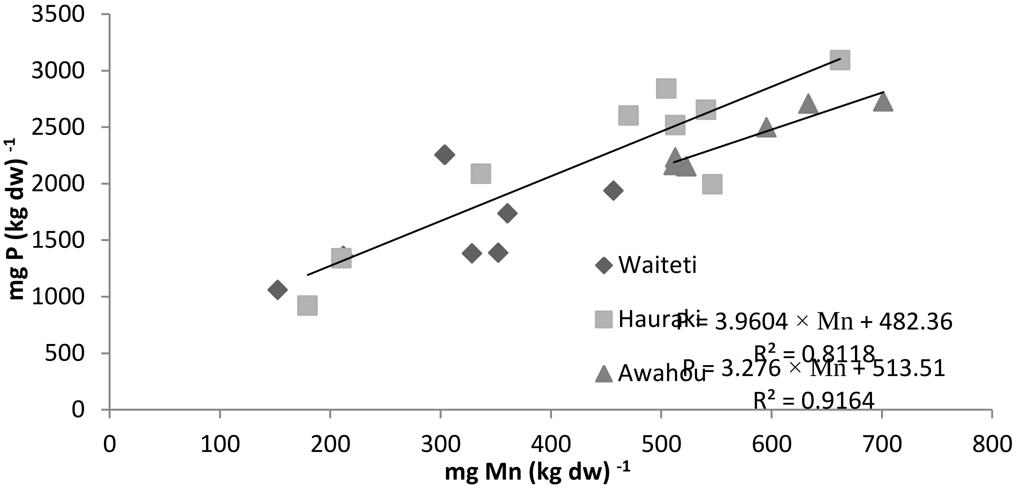

Figure 3.23:Plot of phosphorus versus manganese in sediments deposited on mats in detainment bund basins during sampled storm events.

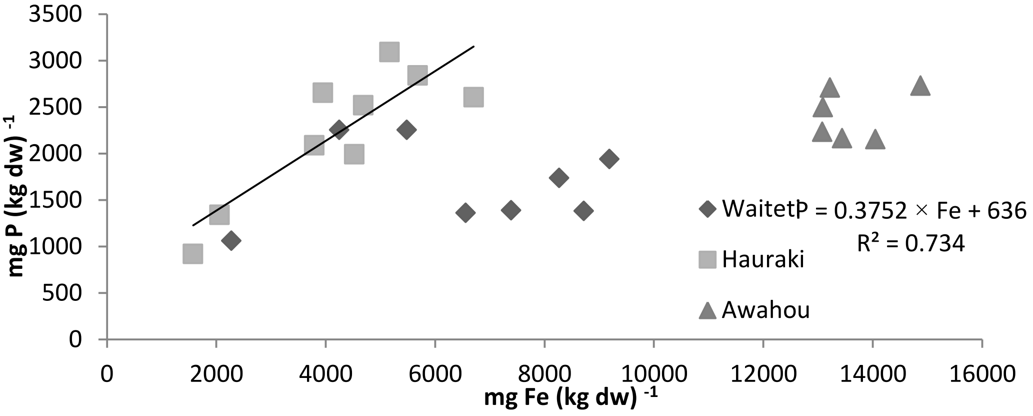

Figure 3.24: Phosphorus versus iron in sediments deposited on mats in detainment bund basins during sampled storm events.

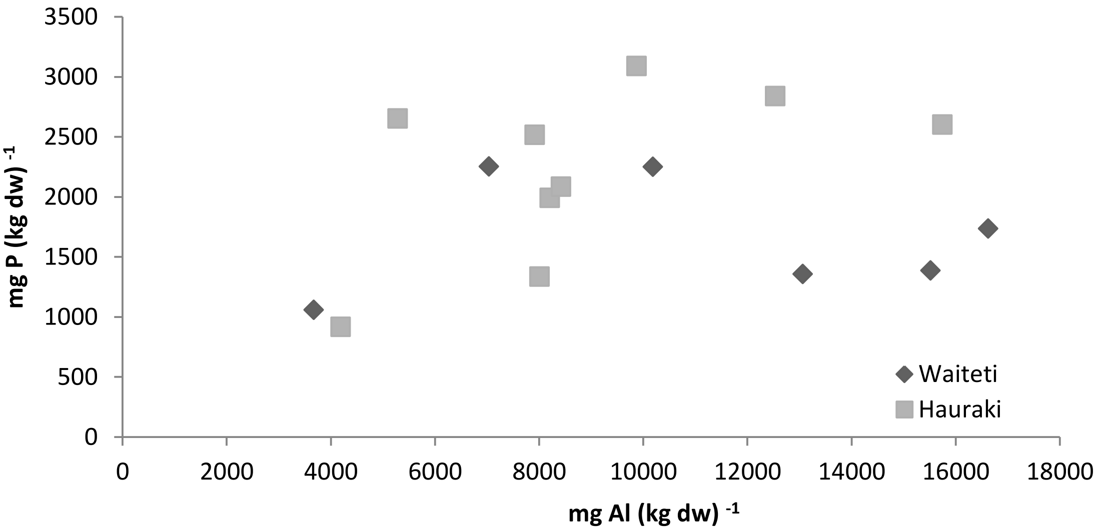

Figure 3.25: Phosphorus versus aluminium in sediments deposited on mats in detainment bund basins during sampled storm events. Note: Al concentrations for some sediments exceeded the ICPMS detection limit of 30,000 mg Al (kg dw)$^{-1}$.

Table 3.3 displays the results of Pearson's pair-wise correlation analysis to examine relationships between both metals and P, and, metals and metals. There are statistically significant relationships between P and metals (Mn and Fe) in sediment deposited at Hauraki and Awahou (Table 3.3). There are also correlations between the metals themselves, for example, Fe–Mn, Fe–Al and Mn–Al, However, correlations of P–Mn (r = 0.901) and P–Fe (r = 0.857) are stronger than Fe–Mn (r = 0.773). The strongest association of all was Fe–Al at Waiteti, followed by P–Mn at Awahou. Out of all the elements Mn formed the closest relationship with P (Table 3.3).

Table 3.3: Pearson's case wise correlation between mass of metals in sediments deposited on mats throughout a range of ponding events in 2012, significant at $p < 0.05$ (*) and $p < .001$ (**). Data are averages of three replicate samples.

	Waiteti (n=8)	Hauraki (n=9)	Awahou (n=6)
P vsMn	0.548	0.901**	0.957**
P vs Fe	0.100	0.857*	0.278
P vs Al	0.012	0.546	N/A
Fe vsMn	0.797*	0.773*	0.53
Fe vs Al	0.995**	0.829*	N/A
Mnvs Al	0.707*	0.356	N/A

3.3.3 Sediment and P mass deposition estimates

Estimates were derived of the total quantity of sediment and P retained during each sampled event using data collected using mats. The estimates presented in Figure 3.26 and Figure 3.27 exclude the input from sediment derived from an earthwork site at Waiteti DB. The latter result is included in a separate calculation in Table 3.4. Sediment and P estimates were derived by multiplying the average sediment mass (kg m^2) and P concentration (kg P m^2) deposited in each event by the total ponded area (m^2). Full details of the method for derivation of the estimates are given in section 2.4.1.5 in Methods. The quantity of sediment deposited in the detainment bund basins was highly variable between sites and also between events (Figure 3.26).

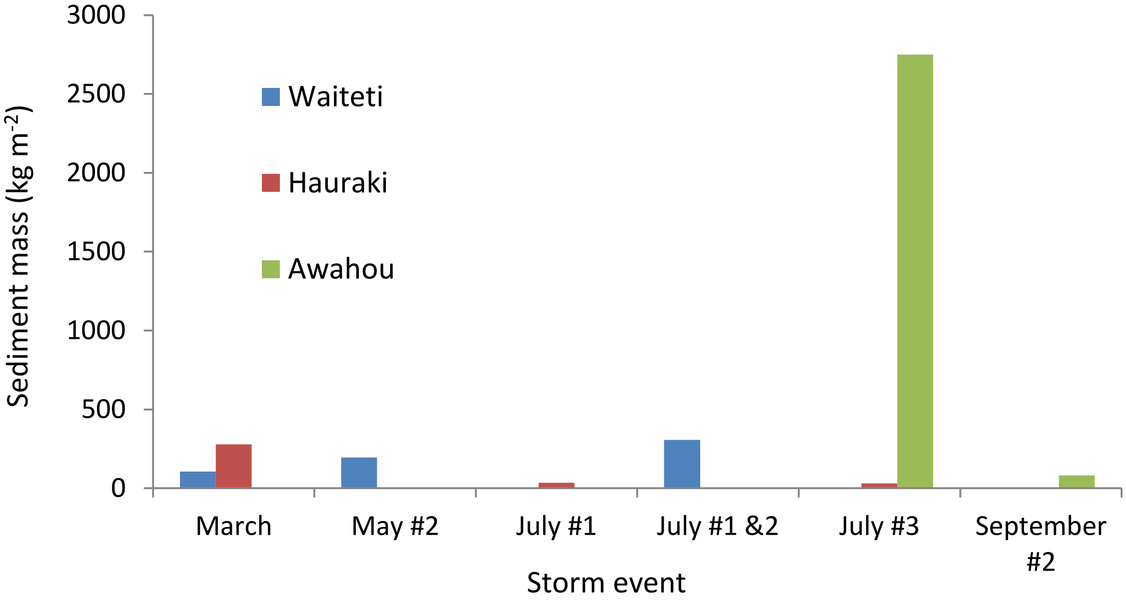

Figure 3.26: Total mass of sediment retained in each DB during each sampled storm event (excluding quarry sediment at Waiteti May #2 and July #1&2 to represent only agriculturally-sourced inputs).

It was estimated that 2,749 kg of sediment was deposited in the Awahou DB basin after three days of ponding after a rainfall event in July (July #3) (Figure 3.26). A much smaller mass (82 kg) was deposited during the second sampled ponding event at Awahou (Sept #2) (Figure 3.26). At Hauraki DB, the largest quantity of sediment (278 kg) was deposited in March, around eight times larger than the mass deposited in following events at this site. At Waiteti DB, the largest quantity of sediment (306 kg) was deposited during an extended ponding period of nine days in July (July# 1&2), although 195 kg was deposited in a ponding event over a three-day ponding period (Figure 3.26).

The largest quantity of P (6.08 kg) was deposited at Awahou DB after a rainfall event in July (July #3). The second largest retention of P was at Hauraki DB in March, when 0.62 kg was deposited (Figure 3.27). In both cases, there was a forage crop paddock in the contributing catchment.

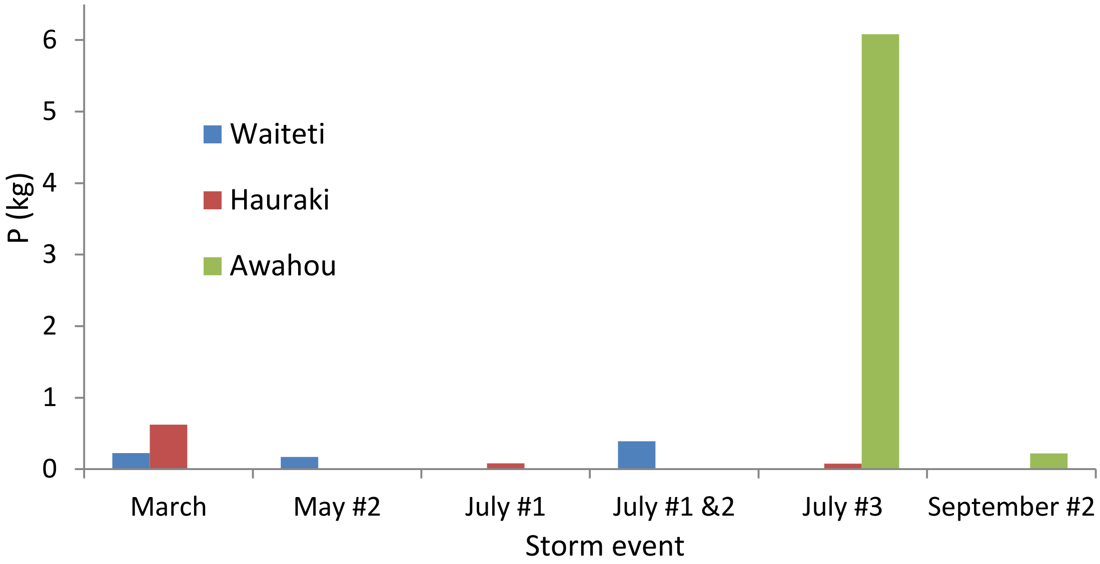

Figure 3.27:Total mass of particulate P retained in each DB during each sampled storm event, excluding sediment inputs from an adjacent earth works site to represent agriculturally-sourced inputs.

There were similar proportions of sediment and P deposited at Hauraki and Awahou between sampled events Figures 3.26 and 3.27. However, at Waiteti the ponding event in May produced more sediment than the March event, but there was less P deposited in May compared with March. In May and July there was sediment input from an adjacent earthworks site at Waiteti DB. This input was estimated using another equation which incorporated a localised average of sediment and P from within the specific area in which the input was deposited (see Methods 2.4.1.5). Masses of sediment and P derived from this calculation are displayed in Table 3.4.

Table 3.4: Estimates of sediment and phosphorus mass with or without the earthworks (EW) sediment input to Waiteti DB.

Event	Sediment (kg)	P (kg)
May #2 without EW	100	0.165
May #2 with EW	195.4	0.170
July #1&2 without EW	264.9	0.382
July #1&2 with EW	306.7	0.389

The earthworks site adds a considerable amount to the calculated deposited sediment in the DB at Waiteti. However, P concentration varies very little between the two calculations, a reflection of the different P concentrations (Table 3.4). The pooled sediment sample which excluded sediment from the earthworks site had higher P concentrations, for example, in the May #2 event the pooled sample for the ‘medium’ elevation group had P concentrations of 144.5 mg P (kg dw) $^{-1}$ including the earthwork-derived sediment and a concentration of 1380.9 mg P (kg dw) $^{-1}$excluding this sediment.

The mass of phosphorus deposited during each storm event was normalised by converting data to units of kg P deposited per day of ponding (Table 3.5). Caution needs to be taken when making comparisons between the two sites due to the different catchment sizes, storage capacities and land use in the contributing catchment (e.g. the winter forage crop at Awahou).

Table 3.5: Mass of phosphorus (kg) in dried sediment retained per day of ponding in each DB. The number of days water was ponded is represented in brackets (this was used to derive the average P deposition per day. Storage ratio is expressed as the volume of water storage (m^3) (up to the rim of the riser), per ha of contributing catchment.

Sampled event	**Waiteti**	**Hauraki**	**Awahou DB**
Catchment size (ha)	**69**	**54**	**21**
Storage ratio (m^3 : ha)	**39:1**	**37:1**	**120:1**
		kg P day $^{-1}$	
March	0.045 (5)	0.208 (3)	
May #2	0.043 (4)		
July #1		0.028 (3)	
July #1 &2	0.039 (10)		
July #3		0.026 (3)	1.521 (3)
September #2			0.073 (4)

The Awahou DB retained the largest quantity of P per day (1.5kg) over a three-day ponding period. This bund has the smallest catchment (21 ha) and the largest storage ratio of water (120m^3per ha of catchment area (Table 3.5). This DB also had the highest TSS concentrations measured across all sites. Hauraki DB retained the second largest quantity of P per day (0.2 kg), which was much more than the quantity deposited across all events at both Hauraki and WaitetiDBs. Waiteti DB has largest contributing catchment (69 ha) and had consistently low quantities of P deposited per day of ponding. It also had the longest ponding period (10 days), when P was deposited at a similar rate (0.04 kg d^{-1}) compared to the shorter ponding events (4 and 5 days) at that site.

3.3.4 Concentration of sediment deposited in DBs in context of downstream water bodies

The average P concentration of sediment retained by each detainment bund is placed in the context of other known sediment concentrations in the Lake Rotorua catchment in (Figure 3.28) and this is discussed further in the discussion.

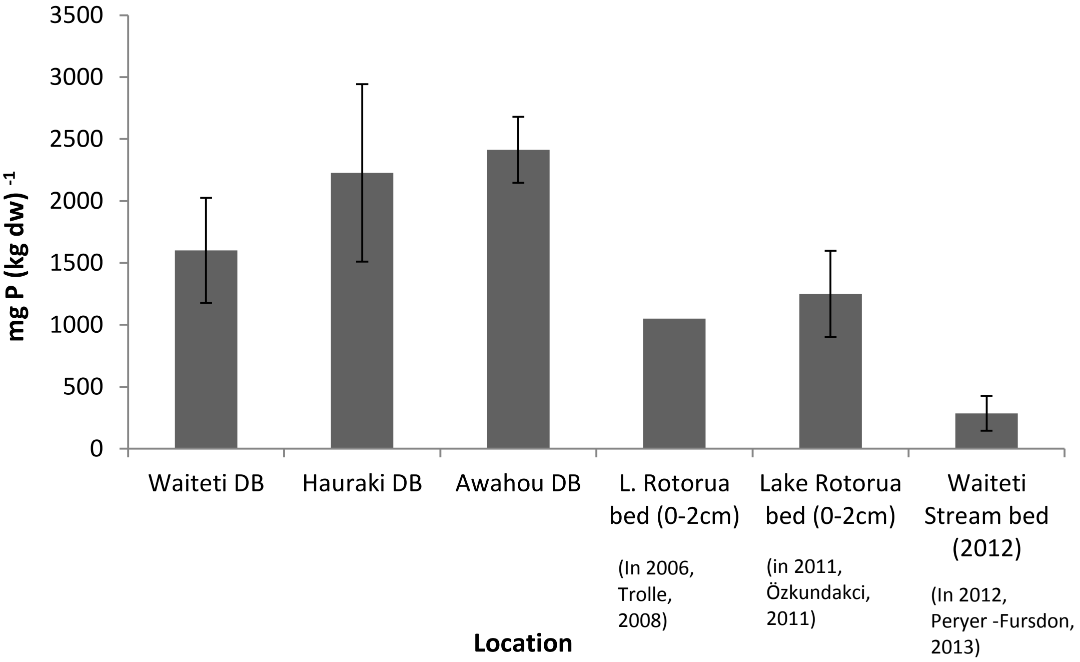

Figure 3.28: Average P concentration of sediment retained at detainment bund (DB) site (excluding earthwork sediment at Waiteti) in comparison to lake and river bed P concentrations (error bars expressed as standard deviation from the mean). Other studies are cited in the figure, along with the year samples were taken.

The TP concentration of sediment retained in the DBs is significantly higher than data from other studies relating to benthic sediment in Lake Rotorua or the bed sediments of the Waiteti Stream.

3.4 DB Forensic investigation

An investigation into the soil characteristics (bulk density, pH, particle size, Olsen P and TP) of the ponding areas of a new detainment bund (c. 1 year) and an old detainment dam (c. 12 years) revealed distinct differences between the two sites.

The bulk density of the soil at both sites was around 0.7 g cm^{-3}, and ranged from 0.70 - 0.78 g cm $^{-3}$ at the new detainment bund, and from 0.748- 0.712 g cm $^{-3}$ at the old detainment dam (from transects closet to furthest from bund).

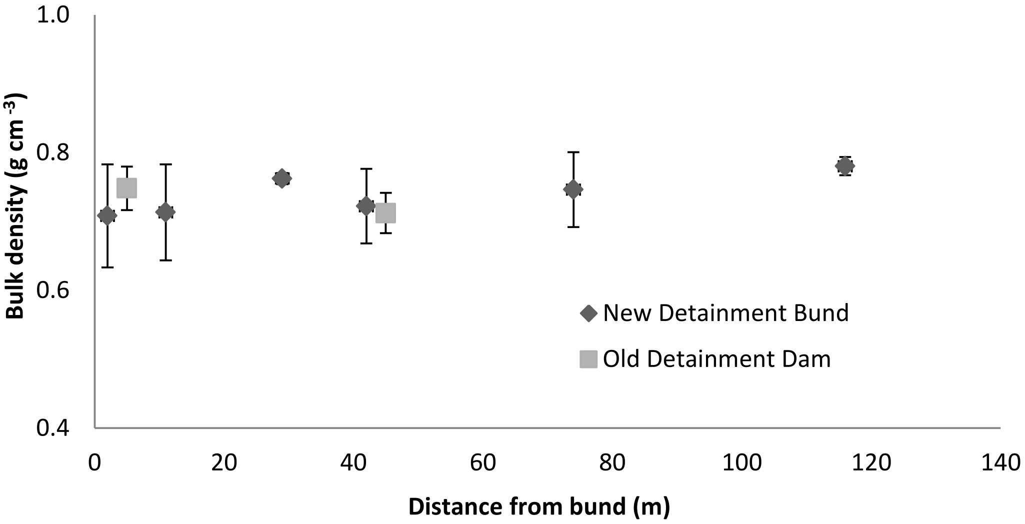

Figure 3.29: Average bulk density of soil transects within the ponding area of a new detainment bund and an old detainment dam. Standard error is based on three samples at each transect.

The particle size characteristics of soils varied with distance from the bund at both sites at both sites. Overall, particles were larger at the new detainment bund, especially within 45 m of the bund (Figure 3.30).

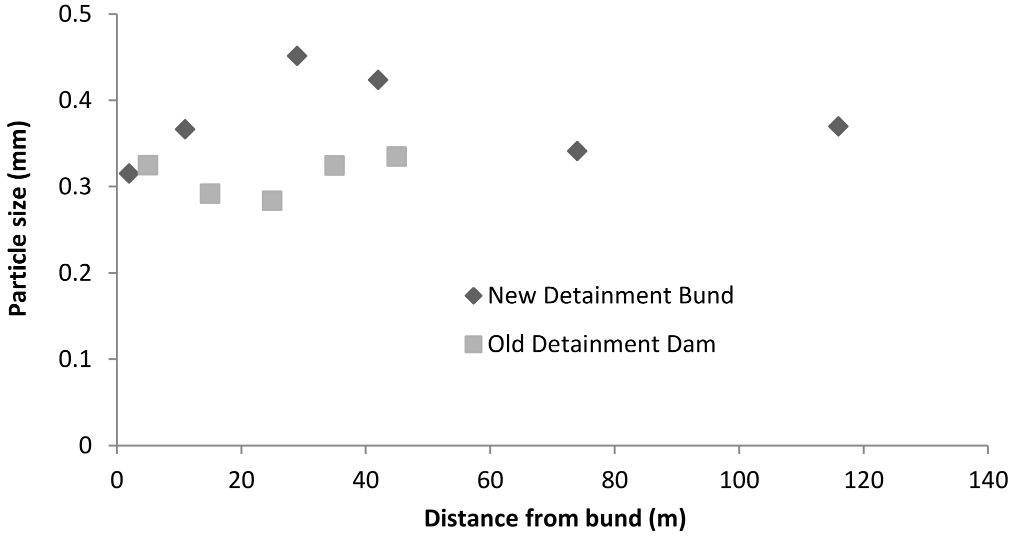

Figure 3.30: Median particle size of pooled transect soil samples.

Olsen P concentration ranged from 72 to 100 mg L^{-1}across the ponding area of the new DB (Figure 3.31). The relationship between Olsen P and distance from the bund is not significant (Pearson’s r=-0.69, $p>0.05$).

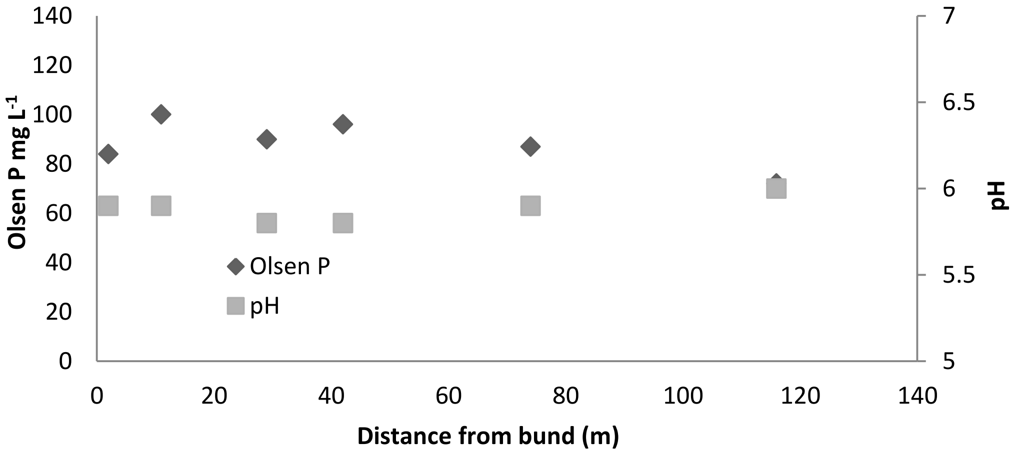

Figure 3.31: Soil Olsen P (plant available P) and pH across the ponding area of the new detainment bund. Elevation increases with distance from the bund. The transect at 74 m is on the upper edge of the ponding area and the transect at 116 m is outside of the ponding area.

There is a strong ($r^2 = 0.89$) negative correlation between distance from the bund and Olsen P level at the old DD, which is statistically significant ($p<0.05$) (Figure 3.33). Olsen P increased by 10 mg L^{-1} at the 35 m transect, before decreasing to the lowest value (41 mg L^{-1}) at the 45 m transect furthest from the bund, outside the approximated ponding area. There was a slight decrease in pH from the 15 m transect (pH = 6) to the 25 m transect (pH = 5.8) although the overall change in pH was small (5.8 – 6.1). This range in pH is similar to the range observed at the new detainment bund site of 5.8 – 6 (Figure 3.29)

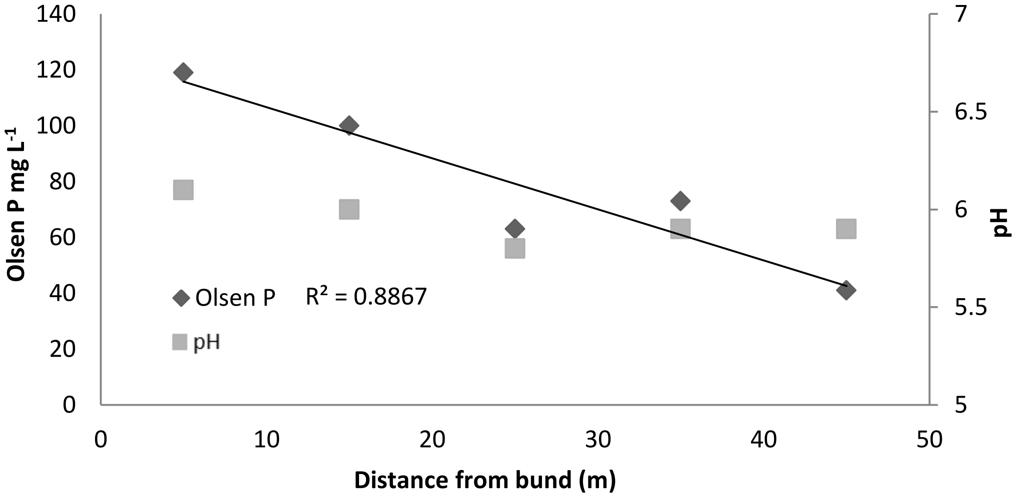

Figure 3.32: Soil Olsen P (plant available P) and pH across the ponding area of an old detainment dam. Elevation increases with distance from the bund, the last transect (at 45 m) is outside the upper limit of the approximated ponding area.

There is a significant negative relationship between TPand distance from the bund at the old DD basin (Pearson's r=-0.9, p<0.05) , but not at the new DB (p>0.05) (Figure 3.33), these trends are similar to that observed for Olsen P across the two ponding areas (Figure 3.31 and Figure 3.32).

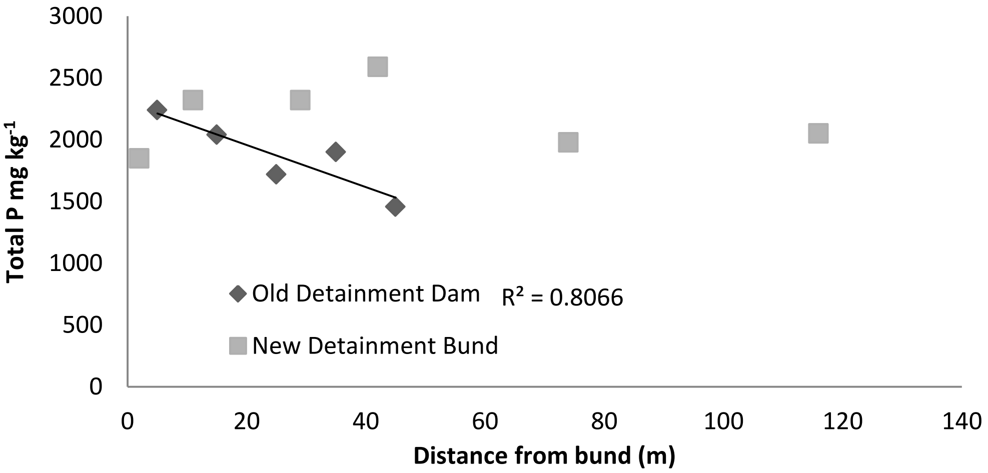

Figure 3.33: Total phosphorus (TP) concentration of soil across the ponding area of a new and an old detainment dam basin. Transects at 74 m and 116 m at new detainment bund, and at 45 m at old detainment dam are outside or on the upper edge of the ponding area.

There are differences in TP concentrations of soil between the two sites. The old DD had the highest Olsen P and the largest range 41 - 119 mg L^{-1}, and the new DB had the highest TP concentration of 2590 mg kg $^{-1}$. There is sufficient evidence to accept the null hypothesis that there is no difference between Olsen P and TP across the ponding area at the new DB site and reject this hypothesis for the old DD ponding area.

Chapter 4: Discussion

This chapter examines the attenuation performance of three DBs during several ponding events. Key infomation from this research is summarized to give insights and reflections to guide effective future use of DBs on pastoral farmland.

4.1 Ephemeral streams

Ephemeral streams are an important hydrological pathway in the Lake Rotorua catchment during heavy rainfall events which produce surface runoff, despite the highly permeable soils (Landcare Research 2011). It is likely that surface runoff was generated as saturation-excess overland flow during large storm events (McDowell & Srinivasan 2009). Although infiltration excess overland flow would have also played a role in generating runoff especially during intense rainfall events in summer periods.

The large range in P concentrations and forms measured in ephemeral streams in this study supports Hart et al. (2004), in a review of research conducted on the diffuse losses of P via surface flow world-wide, that no general statement can be made about the predominant form of P transported by surface runoff (i.e. ephemeral streams) due to the dynamic nature of P runoff and event-specific influences. The differences in concentrations which then lead to the differences in attenuation of sediment and P in the DBs highlight the highly dynamic nature of ephemeral streams and how they are directly connected to land activities in the contributing catchment.

Nutrient concentrations measured in the ephemeral water over the study period were elevated compared to the median concentrations in low-elevation rivers of New Zealand which had recorded levels of TN= 1.03 mg L^{-1} and TP= 0.06 mg L^{-1}between 1999–2002 (Peryer-Fursdon 2013). The low-elevation river concentrations are lower than the average concentration across all sampled ephemeral streams in this study (TN = 1.475 mg L^{-1} and TP = 0.619 mg L^{-1}), and much lower than the maximum concentrations measured (TN = 7.06 mg L^{-1} and TP = 1.618 mg L^{-1}) during my study. Storm flows have the capacity to transport a disproportionately large amount of P to lake Rotorua over a short period of time

(Rutherford & Timpany 2008). Hence, prioritised mitigation efforts focusing on this disproportionate loss (i.e. using DBs to retain this storm water) can potentially result in large benefits to lake water quality.

4.1.1 Biogeochemical processes in DBs: Suspended sediment and associated nutrients

Particle entrainment

Water flows (inertial forces) play an influential role in the suspension of particles. The relative importance of inertial and viscous forces is expressed by the dimensionless Reynolds number (Hsü 2004). Sediments in an ephemeral stream will have a larger Reynolds number compared to in the ponded water in the DB, indicating the importance of inertial forces in the ephemeral streams. As hypothesised, there was a higher percentage of larger-sized particles in the inflowing ephemeral stream water compared with the outflow at the DBs, and this will be directly due to the inertial forces acting upon the particles in suspension (Hsü 2004). Particle entrainment in unidirectional flow is a function of flow velocity and particle size; and these factors will determine if there is transport or deposition of sediments (Hjulstrom 1935). Ephemeral streams have the capacity to transport sediments as they have high flow velocities. Once water is retained in a DB, however, velocity is much reduced (low Reynolds number) and hence sediment falls out of suspension. A clear example of this was seen at Awahou DB after a ponding event in July #3 (Figure 4.1). The ephemeral flow path in the foreground of Figure 4.1 was visually ‘clean’, compared with the ponding area. It was estimated that 2,749 kg sediment was deposited during this sediment deposition event. Large-sized sediment settled out of suspension soon upon entering the bund (Tray #3 had largest particle sizes (>50% larger) and the largest sediment mass (3 x larger) compared with the other two trays at lower elevation and greater distances from the ephemeral stream inflow.

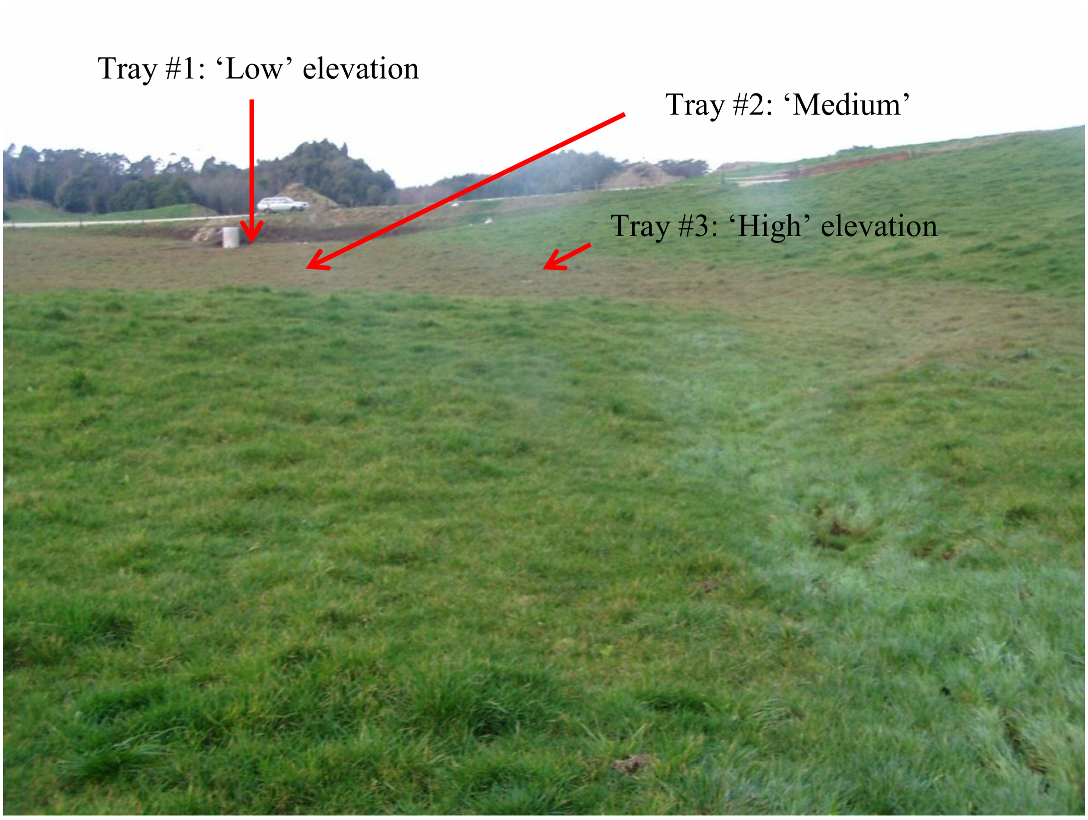

Figure 4.1:Awahou DB after a ponding event in July (July #3). Approximate location of trays are depicted by the red arrow. Elevations of the trays were 100 mm (Tray 1), 600 mm (Tray 2) and 900 mm (Tray 3) relative to ground 0 in the basin at the low elevation. Note the distinct evidence of sediment settling in the basin and the water level line on the bund wall.

Sedimentation rates

Particles are removed from a standing body of water via sedimentation at a rate that can be described by exponential decay, with large particles settling out first and smaller particles settling out at slower rates (Hsü 2004). This was observed at the Hauraki and Waiteti DBs during a ponding event in March, where the greatest sedimentation losses occurred on the first day of ponding, and particles were removed increasingly more slowly on following days. The fastest settling rate observed across all events was at Waiteti DB during March (73% of TSS over 43 h). This rate could have been due to the high inorganic fraction of sediments suspended in the water at time zero (>70%). In this ponding event there was a significant increase in the % of organic material that was suspended over the ponding period, as hypothesised. Inorganic particles settle out faster than organic particles as they are denser and hence the lighter organics stay in suspension for longer periods. The sedimentation of particles through a standing medium of water is defined by Stokes Law which incorporates the diameter and density of the particle, the viscosity of the fluid medium and gravitational forces (Hsu, 2004).

Large particles settle out faster than smaller particles due to the differences in diameter and this may be the reason why the slowest settling velocity was observed at Hauraki DB in May as this event had the smallest median particle size. Suspended sediment measured during this event also had a high percentage of organic matter (65- 96% of SS respectively).

Winter (1998) found higher attenuation performance of sediment retention ponds treating earthwork sites in summer compared to winter (96% and 87% of TSS load retained, respectively). He associated this with the higher concentrations of SS in summer (due to less water volume) which aided the natural flocculation process, resulting in larger particles with higher rates of sedimentation. A similar process may have influenced the large (58%) reduction in TSS concentration over a 20-h ponding period at Awahou DB in September, because TSS concentrations were high (184 – 78 mg L^{-1}). The natural flocculation process in these conditions would be greater enhanced, resulting in rapid sedimentation. The hypothesis that TSS concentrations of ponded water decrease during ponding in the DBs was accepted.

Within-bund nutrient dynamics

The rate at which particulate nutrients (PP and PN) are deposited out of a body of water depends on the rate of sedimentation of the particles carrying these nutrients. It was expected that there would be a negative relationship between PP concentration and the size of particles suspended in the water because fine particles have a capacity to hold more P (i.e. higher surface area to volume ratio) and stay suspended for long periods (Stone & Mudroch 1989). The lack of relationship between median particle size (of suspended material) and PP in the water samples, and even water samples with large sand-sized material suspended also had high PP (PP ~ 0.2 – 0.8 mg L^{-1}) could explain why the PP (and PN) concentrations of outflow water did decrease throughout the ponding events (as hypothesised), as the PP was generally invariant with particle size. This is contrary to other studies such as McDowell (2006) who found less than expected P attenuation in a sediment trap draining deer wallow areas in Southland due to fine particles with attached P remaining in suspension during residence (McDowell 2006, as cited in McDowell & Nash, 2012). If P was predominantly bound to small particles suspended in the water ponded by the DBs, we may have observed smaller reductions in PP concentrations.

The reduction of PP and PN in DBs was often related to the rate of sedimentation. For example, the largest rate of decrease in PP and PN was observed at Awahou DB where TSS concentrations were highest. By comparison at Hauraki DB, where similar reductions in particulate nutrient concentrations occurred but there was over twice the ponding period (40 h compared to 20 h), TSS concentrations were much lower than at Awahou. This trend may not have been observed if the majority of PP was bound to small particles. In some cases, such as Waiteti DB in March, there was no trend between TSS and PP or PN. Reasons for this are unclear.

As hypothesised, TSS and DRP were inversely correlated. Dissolved P adsorbs onto, and desorbs from, sediment depending on the equilibrium phosphorus concentration (EPC). This is the P concentration of solution where no net sorption or desorption occurs (McDowell et al. 2001a; McDowell & Sharpley 2001b; Steenhuis et al. 1995). As TSS concentrations increases, DRP often decreases (McDowell et al. 2003; Sharpley et al. 1981; Steenhuis et al. 1995). This was observed at Awahou DB (downstream from a winter forage crop) where ponded water comprised the highest TSS concentrations (maximum 268 mg L^{-1} in July #2) and the lowest DRP concentrations out of all the sites (minimum 0.39% of TP average in Sept #1). In this case, DRP will have adsorbed onto the soil particles in transit. Sharpley et al. (1981) noted the importance of P sorption during transport in runoff, and that soil can be seen as a sink instead of a source of P in some cases. However, if SS is P-rich relative to the surrounding water, net desorption can occur (McDowell et al. 2001a). This is likely the reason why DRP increased at Hauraki DB in March over the ponding period. As High TP and SS concentrations in this ponding event, appeared to be sourced largely from a summer turnip crop paddock in the upper catchment, it is possible that SS contained high levels of P-enriched soil.

Although the process of phosphate adsorption can occur quickly while P is in transit (Sharpley et al. 1981), ponding water behind a DB may increase the opportunity for further adsorption of P due to the extended residence time before reaching a downstream water body. An example of this was the difference in DRP concentration of the ephemeral stream entering and leaving the Awahou DB on 23 July (0.010 mg L^{-1} and 0.006 mg L^{-1}, respectively). This reduction in DRP may not have occurred if the water was not ponded, and the DRP retained on particles was more likely to have sedimented out in the DB than to have been transported in dissolved form to the lake.

When DBs retain the ‘first flush’ water which can have high concentrations of DRP relative to the peak flow, subsequent inflow of SS may act as a P sink and hence result in net adsorption onto the particles which may subsequently fall out of suspension. The extent of adsorption will depend on the P sorption capacity of the sediment (McDowell et al. 2004). This highlights the potential benefit of elevating the decant structure on the DB during initial runoff stages to prevent any drainage of ‘first flush’ water through the DB.

Inflows vs outflows

As hypothesised, the ephemeral streams comprised a larger percentage of coarse sand–sized particles, compared with the outflow samples which had more fine sand and silt–sized particles. At Awahou DB in July (#2) both the inflow and outflow samples comprised of small-sized particles, however on the second day there was a notable difference with the ephemeral stream water comprised >80% coarse sand–sized particles, compared to <5% sand and >50% silt sized particles in the outflow. There are two possible explanations for this. Firstly, the difference between the inflows on the two days could be due to selective entrainment of fine particles during the initial stages of flow (i.e. first flush on the first day), which will have left the large particles to be entrained on the second day (McDowell et al. 2004). Secondly, the inertia forces (as described above) may have entrained the sediment in suspension in the ephemeral flow, but not in the ponded water (i.e. the outflow), which could have contributed to the consistently smaller particles in the outflow samples. No conclusive result could be drawn when comparing the nutrient and TSS concentrations of the inflows and outflows at the same time period as samples were often taken after the peak of discharge of the ephemeral stream. Ephemeral streams are highly dynamic and require high frequency sampling to detect changes over the flow duration.

4.2 Characteristics of attenuated sediments

4.2.1 Spatial distribution of attenuated sediment

The mass of sediment deposited in the DB basins varied between the three elevation groups. Most sediment was deposited at the low elevations compared with the high elevations, although there was large variations in mass deposited on individual mats within pooled elevations (hence the mass proportional sediment pooling design described in Methods 2.4.1.1). This was likely because water resided over areas of low elevation for longer periods, allowing more time for particles to settle out. It was hypothesised that the sediment deposited at the high elevations would have comprised larger particles and less P relative to the low elevations. There were generally larger proportions of large sand-sized particles in the ‘high’ elevation compared with the others, although P concentrations were more variable. This could have reflected the fact that even large sand-sized particles were associated with PP (as discussed above).

An unexpected trend occurred at Waiteti where larger and more P-rich sediments were deposited at ‘high’ elevations compared with the ‘low’ elevations which were P-poor (as an average across events). This is likely due to the input of sediment from the earthworks site which had greater influence on the mats at ‘low’ compared to ‘high’ elevations which were generally further away from the earthwork input zone in the paddock (Figure 2.24; see Methods 2.4.1.3). The mats at the ‘high’ elevation may have represented sediments derived solely from agricultural land, which had higher in P concentration compared to the earthworks subsoil (1380 and 144 mg P (kg dw)$^{-1}$, respectively). Hence, this case is not necessarily representative of a typical DB. There was no difference in P concentration across the elevations in the studied DBs.

4.2.2 Event-specific deposition

A large rainfall event coincided with the timing of a winter forage crop in its most vulnerable state (i.e. grazed to bare soil) to produce what was the ‘perfect storm’ for large-scale sediment and P loss (Awahou July #3). Multiple factors combined to produce these conditions and ultimately resulted in this bund and event having the largest attenuation of sediment (2,749 kg) and P (6.08 kg) throughout the study period. The crop paddock had been grazed bare within days prior to the rainfall event. This bare soil would have been exposed to direct rainfall impact and prone to surface transport. Antecedent soil moisture was high due to a rainfall event one week prior (July #1) and grazing during these conditions would have increased the potential for soil erosion through treading damage to the soil profile (Elliott et al. 2002; Nguyen et al. 1998). Sloping topography will have increased overland flow velocity and hence increased the ability of overland flow to transport sediment. An ephemeral stream flowed through the middle of the crop paddock; this acted as a ‘transport highway’ connecting up-side ephemerals flowing down nearby slopes, hence this was a critical source area (CSA) (McDowell et al. 2004; McDowell & Srinivasan 2009). This CSA conforms with the 80 / 20 rule of Gburek and Sharpley (1998) as the crop paddock occupied <20% of the 69 ha catchment but will have certainly contributed >80% of the sediment and nutrient load.

Obviously, the size of a rainfall and runoff event can influence the total nutrient and sediment load of ephemeral stream and hence drive the quantity of deposited material in a DB. The much smaller quantity of sediment and P retained at Awahou DB in September (#2) compared to July (#3) is likely directly due to the volume of runoff (2224 m^3 in July, 161 m^3 in September). The previous event in September (Sept #1) was a short intense event and produced extremely high TSS concentrations (268 mg L^{-1}), but no mats were deployed. This indicates that even after one month after grazing of a winter forage crop, large sediment losses can still occur during extreme rainfall events. Pionke et al. (2000) note that large proportions of annual P export can occur during several large events a year and this is likely the case at the Awahou DB.

The size of the rainfall event does not always directly correlate with the mass of sediment and P exported. The smallest rainfall and runoff event (sampled with mats at Hauraki DB) resulted in the largest amount of sediment (278 kg) and P (0.62 kg) retained at the Hauraki DB across all sampled events. Other events had considerably lower P (0.07-0.08 kg) and sediment (30-35 kg) retained even though the rainfall events were larger, and the P concentration of the sediment retained was similar. The main reason for this large difference in retention is due to the land use in the catchment. There was a freshly tilled paddock which had been recently sown in grass following a turnip crop adjacent to the bund. Although the main ephemeral flow path did not go through this area, there was a side ephemeral 300 m upstream, which did flow though this paddock. This could explain why the TSS (16 mg L^{-1}), TP (1.6 mg L^{-1}) and PP concentrations in the main ephemeral inflow in March were the highest measured across the entire sampling period at Hauraki. Grass fully established in this adjacent paddock before the next event, so this further supports the theory that the tilled paddock contributed to this larger sediment (and P) loss, even though the size of the rainfall event was small.

4.2.3 Composition of attenuated sediment in the context of Lake Rotorua water quality

The average P concentration of sediment deposited in the DB basins (2080 mg P(kg dw)$^{-1}$) was 45% higher than the average P concentration in the top 2 cm layer of benthic sediments of Lake Rotorua (1250 mg P mg P (kg dw)$^{-1}$) measured in a recent (2011) survey (D. Özkundakci, *pers. comm.*, 2012). This highlights the importance of retaining this P-enriched sediment at source. Even if this P was not bioavailable in the short term, it could potentially become bioavailable under anoxic conditions in the lake (discussed further below; (Reynolds & Davies 2001; Trolle et al. 2008).

The average P concentration of sediment deposited at Waiteti DB (1601 mg P (kg dw)$^{-1}$) is 5.6 times higher than the Waiteti Stream bed sediments (average of 285 mg P (kg dw)$^{-1}$). (Harding et al. 2004). Furthermore, Peryer-Fursdon (2013) found that the sediment deposited in the Waiteti DB would be expected to desorb P if transported into the Waiteti stream as the EPC of the DB sediment was 0.140 mg L^{-1}, which was greater than the DRP concentration of Waiteti Stream (0.042 mg L^{-1} average from 2002-2009). This difference suggests that the DB sediments would release P whilst concentrations of P remained below the EPC. Peryer-Fursdon's (2013) findings suggested that the Waiteti Stream bed sediments are likely to be a sink for P at typical DRP concentrations due to net absorption of DRP from the water. These stream bed sediments may have originated mostly from erosion of stream banks, rather than transport of sediments sourced some distance from the main channel in overland flow, as captured by the Waiteti DB. There is sufficient evidence to reject the hypothesis that P deposited in the DB basins would contain low P concentrations. It is important to retain these agriculturally sourced p- rich sediments in the upper catchments before they enter downstream water bodies such as the Waiteti Stream and Lake Rotorua.

It was hypothesised that there would be an association between P in the deposited sediment and metals cations that are known to form associations with P, such as Fe, Mn and Al, this hypothesis was accepted. Phosphorus bound to Mn and Fe is potentially ‘redox sensitive’, as it is readily desorbed into solution if exposed to anoxic conditions (Davison 1993; Reynolds & Davies 2001). Manganese formed the closest relationship with P (at Hauraki and Awahou DBs) although there were also significant correlations between P and Fe. However, there were also correlations between the metals, for example, Mn and Fe in Hauraki sediments. This co-variation suggests that the correlation observed between P and Mn, and P and Fe may in fact be due to the association between Mn and Fe, as also found by Davidson (993). The Al concentrations of Awahou sediment were too high for detection on the ICP-MS. Phosphorus bound to Al is largely refractory within the typical pH range of the water column of Lake Rotorua because Al binds strongly to P, hence the use of Al compounds for binding P for lake restoration (Özkundakci 2010).

The associations discussed above can indicate correlation, not causation. To explore this in more detail, Harding et al. (2004) conducted a sequential phosphorus extraction analysis of sediments retained at the Waiteti DB in May (May #2) and July (July #1&2). Results showed that 23% of P was bound to Fe and Mn. This highlights that caution is needed when using correlation analysis in this way to infer P speciation characteristics, as there was no significant relationship between P and either Fe or Mn at Waiteti using the ICP-MS data. If this sediment reached the lake, P bound to the Fe and Mn could become bioavailable when exposed to anoxic conditions (Reynolds & Davies 2001), such as during lake stratification periods (Vant 1987). This highlights the importance of intercepting SS from ephemeral streams before they reach the lake where additions of P can potentially contribute to eutrophication (Müller et al. 2010).

The quantity of P retained by DBs can be placed in the context of the cost of removing/inactivating P once it is in the lake, as part of lake restoration that involves a technique such as sediment capping. Phosphorus costs c. \$3.30 kg $^{-1}$ to buy in bulk form (V. Fulton, *pers. comm.*, 2012). To remove 1 kg of P from the lake via in lake restoration methods, it costs around \$1000 depending on the form of P and the method used (D. Hamilton, *pers. comm.*,2012). There was a range in P concentrations retained at each DB (average over all sampled ponding events; 0.026, 0.261 and 3.145 kg P atWaiteti, Hauraki and Awahou DBs respectively). Assuming that the hydrological characteristics were similar to the 2012 year, there should be at least seven ponding events per year. It will take c. five ponding events (of 0.2 kg P deposition) to retain 1 kg of P at the Hauraki DB. Over a 20-year period there would be at least c. 28 kg P retained. This would amount to a saving of \$28,000 in reduced lake restoration costs by having the Hauraki DB in the catchment. The there is a large range in P retention between Waiteti DB and Awhaou, this is relative to land use at the time of the runoff events (e.g. a winter forage crop or good pasture cover). The retention of 6.08 kg P in a single ponding event at Awahou amounts to \$6080 saving in reduced lake restoration costs within just 3 days, although this was an exceptional case. These savings highlight the value of focusing land management efforts on storm water treatment in upper catchments where large losses in nutrient and sediment can occur over short periods of time.

4.3 Insights into the future soil characteristics in DB basins

The aim of this investigation was to compare the soil characteristics around a detainment dam (DD) that was built for storm water erosion management in 2000, and a new (1-yr) detainment bund (DB) built by the Rotorua P-Project to test P-mitigation properties. There was no significant difference in bulk density (average 0.73 g cm $^{-3}$) and pH (average 5.9) across the ponding areas or between the sites. These values were similar to those observed by Larned et al. (2004) in survey of top soils on dairy farms across the Bay of Plenty region (average bulk destiny 0.85 g cm $^{-3}$, average pH 5.8). There were similar pH levels between the two sites (DB; 5.94 and DD; 5.98) and this increased the robustness of the comparisons of

Olsen P between the two sites because Olsen P levels can be higher in low-pH conditions and vice-versa (Curtin & Syers 2001).

As hypothesised, there were no differences in soil P levels in and around the ponding area of the new DB. In contrast, and as hypothesised, there was a significant trend of decreasing soil P levels (Olsen P and TP) with increasing distance from the bund (and elevation in the ponding area) at the 12-year old DD. This difference suggests that the historic ponding of water in the DD basin has had an influence on the P concentrations in the soil. There was no clear trend in particle size of soil across the basins. This could be because sediment which is deposited on the grass in the ponding area becomes part of the soil profile, where soil organisms incorporate these new particles into the soil matrix (J. Paterson, Bay of Plenty Regional Council, *pers. comm*., 2012). Insights from data collected on sediment mats during a range of ponding events at various DBs in this study can help to explain the spatial variation observed in soil P levels across the 12-year old DD basin. For example, it is likely that the majority of sediment was deposited at the low elevations (deepest part of the ponding area, i.e. near the bund) due to longer residence times and hence more sediment (and PP) deposition. In addition, the sediment deposited nearer the bund may have been comprised of finer particles (which have the potential to hold more P) due to the longer ponding time compared to the high elevations furthest from the bund.

This finding can give insights into how we can expect soil P levels within the DB basins to change in the future. It is likely that after a number of years of ponding at a DB, where water residence time is regulated for longer periods (i.e. due to a restricted outflow), there may be large differences between P levels inside compared to outside the ponding areas. This raises the question of whether DBs become a P source rather than a P sink. Olsen P levels were 119 mg L^{-1} near the bund compared to 41 mg L^{-1} outside the DD ponding area. Soils with elevated Olsen P levels have a higher capacity to release P into solution (McDowell et al. 2001b). Menneer et al. (2004) found more DRP lost from agricultural soils in the United Kingdom with Olsen P levels > 70 mg L^{-1}. This suggests that the soil in the DD basin may be a eventually be a P source and be released P into solution once an equilibrium is reached (although the soil types will be different between countries).

Phosphorus can be released from soils at a range of Olsen P levels, even at those levels recommended for optimum plant growth (Sharpley et al. 2000). However the amount of P is released will depend on various factors including; the Olsen P concentration of the soil, the surface area of soil which is inundated by water (i.e. the ponding area), the duration in which soil is inundated by overlying water, the DRP concentration of the overlying water (McDowell & Sharpley 2001a), and the oxygen concentration of the water (Reynolds & Davies 2001). Essentially, there may be a net desorption of P from soil in a ponding area if the DRP concentration of the overlying water is less than the EPC of the soil. However, there is a potential for phosphate which has desorbed from the soil to be adsorbed onto SS if the TSS concentrations in the ponded water are high, and subsequently this PP may fall out of suspension. Thus the DB could be a net P- sink as described in section 4.1.1 above(Sharpley et al. 1981). In contrast, TP concentrations could increase after ponding if DRP was released from the soil and the TSS (and PP) concentrations were low (McDowell et al. 2004).

There are therefore many factors which could influence whether DB basins become a source or a sink in the long term. This soil comparison highlights the importance of strategically managing DB basins to reduce the likelihood of P release from the soils. For example, basins could be treated as ‘special management blocks’ with customised fertiliser plans (P will likely not need to be added in the long term) and specific grazing plans (i.e. fencing off the ponding are from stock during wet periods). Other options include planting high P- demanding crops to remove excess P from the soil.

The on-going P-Project collaborative plans to develop a good management practice (GMP) guide to help farmers operate their new DB’s for best results that contribute towards improved environmental sustainability of their farms. This GMP guide is intended to be based on the findings of this thesis coupled with a review of the farmers’ own anecdotal experiences during their first year of operating their new DBs. The following summary, Lessons Learnt (section 4.4) is intended to contribute to the proposed DB GMP Guide.

4.4 Lessons learnt for improved implementation and operation

This section gives an overview and reflections on the key lessons learned during the implementation and study of DBs in the Rotorua catchment. This was an experimental project and many of the methods used were trailed for the first time in this context. This section has been split up into two sections, design criteria for the implementation of DBs based on lessons learnt, and integration of DBs with other mitigations.

4.4.1 Design criteria for the use of DBs in agricultural landscapes

1. *Define the contributing catchment*

The size of contributing catchment needs to be carefully determined before DB structures are proposed and constructed. In this case the sub-catchments were scoped for possible sites by BoPRC staff using geospatial information systems (GIS) including the light detection and ranging tool (LIDAR) with a 1-m contour capability. On-going catchment scoping at BoPRC is using ArcHydro which is an advanced Arc tool. Ground truthing the catchment boundary during overland flow is essential if flow paths are uncertain. The Waiteti DB had a larger than expected contributing catchment due to complex topography in the upper catchment.

2. *Adequate storage capacity*

Adequate storage of storm water runoff in DBs is integral to optimising the treatment performance. Observations from this study revealed several key insights into the design of these structures. Firstly, DBs were initially designed to a nominal storage ratio of 100m^3:1 ha^1 (100 m^3 per ha of contributing catchment) (J. Paterson, Bay of Plenty Regional Council, *pers. comm*., 2012). Storage was based on the height of the spillway, not accounting for losses over the riser. This study revealed that water which left the DB over the riser (Figure 4.2) had high nutrient and sediment concentrations relative to the outflow over following days. This was likely because of the short residence time (c. <1 day) of the water had been detained behind the bund. At Waiteti and Hauraki DBs large volumes of water left the DB over the riser during most ponding events (Figures 3.1 and 3.2). This water is essentially ‘untreated by pass’ (although there will have been sedimentation of large particles, as discussed in section 4.1.1). Water leaving the riser is a wasted opportunity of treatment, although possibly tolerable for extreme events with long return time. If the DBs outlet riser is frequently overtopped the DB is undersized and its storage capacity needs to be increased.

Retrospective checks of catchment areas and storage volumes of the Waiteti and Hauraki DBs using ArcHydro (T. Merz*pers. comm*. 2013) revealed storage ratios (to the rim) of just 39 m^3: 1 ha^1 and 37 m^3: 1 ha^1 respectively. These storage ratios are far below what is deemed necessary if water is to be retained below the riser for a significant treatment period. In contrast, the Awhaou DB had a storage capacity of 120 m^3: 1 ha^1 to the rim of the riser, and water only went down this riser two times over six sampled events during a three month period. Based on these observations a storage capacity of 120 m^3: 1 ha^1 to the rim of the riser is a more suitable minimal nominal guideline.J. Paterson. *pers. comm.*(2012) believes “The larger storage capacity the better” and a future nominal storage to catchment ratio may be in the order of 150:1 to the rim of the riser.

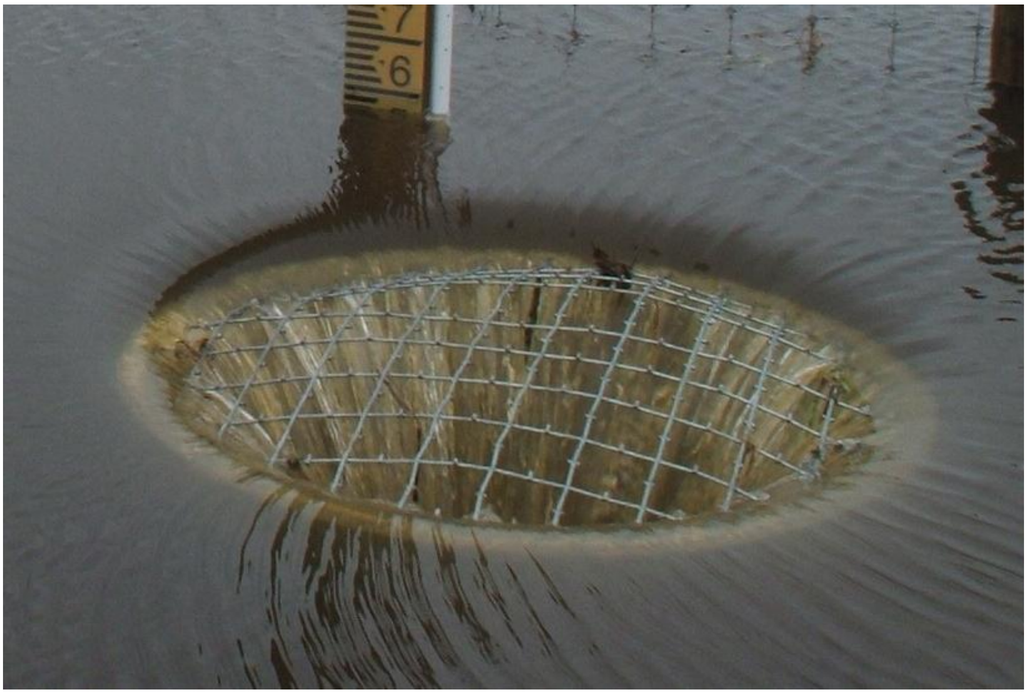

Figure 4.2: Water leaving the Waiteti DB over the riser in 2012. Note this water will have had a short residence time in the DB. Large volumes of water left via this riser in most storm events.

3. Optimal outflow

Control of the flow rate at which water exits the DB is key to ponding water for sufficient time to allow reasonable levels of sedimentation. Several outflow situations were trialed in this study. These ranged from a sand bag plug, a wooden bung, a floating decant and the ladder fitting holes in the precast concrete risers. The predominant way in which water drained from the DBs was via the small ladder fitting holes in the side of the riser. Phosphorus-enriched sediment was retained using all of the above outflow methods. However, the optimal outflow situation is a floating decant structure which drains the pond by decanting surface water. Surface water is likely to have less SS (and PP) than water lower in the pond profile (based on the physics of sedimentation in a standing body of water; see section 4.1.1).

The floating decant structure design used in this study needs further development. It is of vital importance that specific design criteria are developed to ensure that the flow rate of each specific decant matches the volume of the DB and the time necessary to drain it. The decant structures worked well with a bending pipe and a float although the size and placement of the float will ultimately determine the rate of drainage (Figure 4.3). There will be further trials of decant design options in the future (J. Paterson, Bay of Plenty Regional Council, *pers. comm.* 2013).


Float positioning is key to decant flow rate

Figure 4.3: Floating decant structure used at Waiteti DB. Further trials are needed to optimise the decant design.

In addition, it is advised that an emergency plug is installed on the riser to allow manual drainage of the pond if necessary (a prototype design is shown in Figure 2.8). Elevation of the decant structure to retain the first flush water worked well (Figure 4.3). It is advised that DBs are monitored during rainfall events to ensure water is draining sufficiently. Agricultural debris can pose a risk of clogging up outflow intakes. An open ended 200 mm diameter pipe (as used in this study, see Figure 4.3) should suffice for the decant and >40 mm grating on the riser is advised. An example of agricultural debris caught on a grill with 20 mm diameter grating is shown in Figure 4.4.

Figure 4.4 Agricultural debris deposited on a grate (20 mm spaces) on top of the riser at Hauraki DB after a ponding event in May, 2012. The debris is a potential hazard for outflow structures.

4. Optimal ponding time

The DBs were built following the signing of individual agreements (Memorandum of Understanding) with the land owners that contained agreed limits to time that their highly productive pasture would be under water (J. Paterson, Bay of Plenty Regional Council, *pers. comm*,. 2012). The ponding time necessary for a desired level of attenuation of sediment and associated P will depend on the load which the ephemeral water carries. The load will vary between sites, and between events. Given the productive pasture on which future structures will be implemented, compromise between ideal ponding time (to allow maximum sedimentation) and practical ponding time (the ponding duration land owners are willing to inundate their pasture for) will continue to be a necessity.

Land owners involved in this study had tolerated three days of pasture inundation, with no observed reduction in pastoral production. If in the future it is decided that, ponding may need to be extend beyond the 3 day period to achieve desired efficiencies, palatable, water-tolerant plant species may be an option. DBs have been specifically designed to be incorporated into the farm grazing system with no or minimal impact on production and this collaborative pre-requisite will remain as an important factor in future DB design criteria and on-going modifications (J. Paterson. *pers. comm.* 2012).

5. Special management areas

The DB ponding areas can be treated as special management areas. It is likely that in the long term, Olsen P levels within the ponding area will increase due to sediment and P attenuation, as observed for the 12-yr DD in this study. If this is the case, there will be no need for addition of P fertilisers in the deeper sections of the DB ponding area. However, there may be a need for addition of readily leeched nutrients such as nitrogen and sulphur (A. Roberts, Ravensdown, *Pers. comm.*, 2012). During saturated soil conditions it will be beneficial to keep stock out of the ponding area to avoid soil disturbance and pugging damage.

4.4.2 Integration of DBs with other mitigations

There is a range of mitigation tools available for attenuating nutrient and sediment from overland flow, each with strengths and weaknesses (McDowell & Nash 2012). To achieve an overall goal of improved water quality a range tools from the ‘mitigation toolbox’ can be integrated and used collectively each with their specific function and place in the landscape (McKergow et al. 2007). The cost effectiveness and attenuation performance of mitigation tools can be optimised by strategic placement in a catchment (McDowell & Nash 2012). For example, this study has shown that DBs are capable of slowing down storm flow and retaining PP, however they are less effective at retaining dissolved nutrients such as DRP and dissolved inorganic nitrogen. Wetlands can be effective at attenuating DRP and DN (Tanner et al. 2005; Tanner &Sukias 2011) but are less effective at dealing with large volumes of water during extreme rainfall events (Tanner 2003). By implementing the two in a catchment together they could complement eachother and improve overall attenuation. This is just one example of where DBs could be potentially used to complement other mitigation tools.

DBs could play an increasingly important role in regulating catchment hydrology if there is a higher frequency of extreme rainfall events as projected by NIWA due to a changing climate. A 1-in100 yr event could become a 1-in-50 yr event by 2100 (Niwa 2008). Prioritised implementation of DBs in headwater catchments could retain water on the landscape for longer periods of time and reduce flood peaks downstream. Detainment bunds need to be easy to implement, low maintenance and cost effective to enable their implementation at a catchment scale. Detainment bunds can reduce flooding downstream. There has already been active involvement and funding for the construction of DBs for flood control to reduce risks to a local State Highway (SH36).Two sub-catchments of Lake Rotorua have now been totally GIS-scoped by BoPRC in collaboration with NZ Transport Agency (NZTA) for nutrient and sediment mitigation as well as the co-benefit of flooding prevention, the Hauraki (three DBs installed) and the Waimihia (39 DBs proposed) (J. Paterson, Bay of Plenty Regional council, *pers. comm.* 2013).

4.5 Future research

The main limitation of this study was the lack of data to quantify discharge of inflows and outflows. This prevented calculation of inflow and outflow nutrient and sediment loads. Therefore a full mass balance could not be undertaken to quantify attenuation performance. Future research should involve the collection of water quality samples and flow measurements at high temporal resolution from inflowing ephemeral stream (throughout the entire flow period) and the outflow during the ponding period. Automatic water samplers and *in situ* current speed and stage meters could be deployed in future studies.

The use of aluminium flocculant to remove fine particles from suspension is a potential option. This is common practice in sediment retention ponds treating runoff from earthwork sites around NZ, although careful consideration would need to be made to ensure farm production is not impaired in any way. McDowell

(2007) implemented ‘P- socks’ (which included altered steel melter slag) along a 200 m stretch of stream in the Lake Rerewhakaaitu catchment and found that overall there was a reduction of DRP load by 30%. There is a possibility of adding some form of P- sorbing material onto the outflow pipe of DBs, to attenuate the DRP which leaves throughout the ponding period. If the outflow discharge is low, these could be a valuable addition to DB design.

A dissolved oxygen meter could be placed in the DB basin during the ponding period to better assess the potential for P desorption from underlying soils. There is a possibility of periods of anoxia which can enhance P desorption.

A study on the succession of flora in a newly constructed basin could be conducted and successive surveys could be done over time to detect any changes in pasture species. Alternative grass species that can tolerate wet soil conditions could be trailed, along with tests of their productive potential. This may allow water to be ponded for longer periods than three days as originally proposed, and may result in further attenuation of sediment and particulate nutrients.

Conclusions

The attenuation performance of three DBs in three sub catchments of the lake Rotorua catchment were monitored from March – September 2012. During this period, there were eight rainfall events which, despite the free draining soils of the region, produced surface runoff and subsequent ephemeral stream flow which was retained by the DBs. Samples were taken throughout the duration of ponding events to analyse changes in water quality parameters over time.

There were significant reductions in TSS concentrations throughout the ponding events. Sedimentation rates varied between events due to the composition of suspended material. The fastest settling rate (73% reduction in TSS over 43 h) occurred when ponded water comprised a large percentage inorganic material. Organic material stayed in suspension for longer periods than inorganic sediments, and events with slow settling rates were comprised of a high percentage of organic SS. Particulate nutrient concentrations generally decreased in a similar trend to TSS; the largest reductions (i.e. 36% of PP and 42% of PN over 20 h at Awahou DB) were observed when initial TSS concentration was high (>100 mg L^{-1}). Similar reductions were observed at other sites with lower TSS concentrations but generally it took over twice the ponding time to reach the same reductions. The amount of PP retention in DBs is dependent on the size of the particles that the PP is bound to, the ponding time, and the catchment characteristics.

The sediment retained by the three DBs in this study was enriched with P (average 2080 mg P $(kg\ dw)^{-1}$) relative to the benthic sediments of Lake Rotorua and the alluvium of the Waiteti Stream. Phosphorus in the deposited sediments was associated with metal cations such as Fe and Mn; this indicates that such PP which is present in redox–sensitive forms is potentially bioavailable in Lake Rotorua during periods of lake stratification which lead to anoxia in the hypolimnion. The observed relative enrichment of sediments with P indicates the important role that DBs can play in the Lake Rotorua catchment to reduce P loads to the lake and minimise nutrient pollution which can contribute to eutrophication.

The quantity of P retained was generally directly proportional to the quantity of sediment deposited which was highly dependent on land use in the contributing catchment and event characteristics. The largest sediment and P retention (2749 kg and 6.08 kg respectively) of all events occurred when a large rainfall and runoff event occurred in July, coincided with the recent complete removal of vegetation in an upstream paddock sown with a winter forage crop. The setting of the Hauraki DB was the most representative of a typical dairy farm and the average deposition per sampled event was 0.261 kg P^{-1}. Using this figure it was estimated that over a 20 year period 28 kg of P could be retained (given the same hydrological and catchment characteristics as 2012). This equates to a saving of c. $28,000 if the P was to be removed by in-lake restoration methods.

Detainment bunds did not attenuate dissolved nutrients (Dissolved reactive P (DRP) and Dissolved inorganic Nitrogen) during ponding in most cases; however, DRP was inversely correlated with TSS when the TSS concentrations were high. In some ponding events DRP increased, this was likely due to net desorption from suspended sediments. There were cases where DRP increased, likely due to net desorption from SS. An investigation of the soil P concentrations around the ponding area of an old (12 y) detainment dam built for flood control revealed a significant decrease in Olsen P with distance from the dam wall, indicating that historic ponding had deposited sediment enriched with P in the ponding area (Olsen P ranged from 119 mg L $^{-1}$ inside to 41 mg L $^{-1}$ outside of the ponding area). There is a potential for DB ponding areas to be a P source at certain times if DRP is desorbed from P enriched soils to overlying water, however, in the long term the investigation indicated that they are likely to be a P sink and there may be no need for addition of P fertiliser in the ponding area.

This study has highlighted the importance of designing DBs with adequate storage ratios for the size of contributing catchments. Storage ratios should be based on rim of the riser (not the spillway height) to maximise water retention in the bund and make the most of the water treatment potential. Water that left DBs over the risers was high in total nutrients and TSS compared to outflow over the following days that drained from the DB. This result is a reflection of short residence time. A storage ratio of at least of 120 m^3 of water storage per 1 ha of contributing catchment (to the concrete riser) is recommended for DBs in the lake Rotorua catchment. It is of vital importance that the floating decants used to drain DBs are designed specifically for the volume of each DB to allow ponded water to drain from the DB within the desired time of ponding. Land owners have tolerated three days of ponding and they did not report negative impact on pastoral production in the DB ponding areas.

Detainment bunds can play a pivotal role in moderating the hydrological pathways at the catchment scale by prioritising headwater catchments and slowing down water flow to reduce the loss of nutrients and sediment from pastoral farmland during intense rainfall and runoff events. The level of DB implementation within pastoral landscapes will depend on the willingness of landowners to incorporate them into farm systems. A win-win situation is possible where water quality is improved and pastoral production within the ponding areas is maintained.

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Appendix 1

1.1: Nutrient samples

Detainment Bund	Location of sample	Notes	Date of sample	Time sample taken	TimePassed	Assigned 'time 0'	Rainfall since last sample	TSS	VSS	ISS	ISS	TP Concentration	Particulate P	TN	Particulate N	Dissolved N	NH_4-N	PO_4-P (DRP)	NOX-N	NO_2-N
					(h)		(mm)	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(%)	(UD)	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L -1)	(mg L^{-1})	(mg L^{-1})
Waiteti	North E		21/03/2012	11.40pm	0		0	8.148148148	5.185185185	2.962962963	63.63636	0.26220322	0.2041744	0.710019	0.646112127	0.063906873	0.044263	0.058029	0.018482	0.001161
Waiteti	South E		21/03/2012	11.40pm	0		0	17.71428571	4.285714286	13.42857143	24.19355	0.8527119	0.5414543	0.917583	0.537929162	0.379653838	0.330891	0.311258	0.046528	0.002235
Waiteti	Pipe		21/03/2012	11.40pm	0	0	0	19.6	5.6	14	28.57143	0.5485428	0.3816567	0.937175	0.70711129	0.23006321	0.176579	0.166886	0.051668	0.001817
Waiteti	Pipe		22/03/2012	9.40 am	10	10	2	12.23404255	4.255319149	7.978723404	34.78261	0.4728929	0.29146444	0.851396	0.688510794	0.162884706	0.126454	0.181428	0.034559	0.001871
Waiteti	Pipe		22/03/2012	4.30 pm	16.83333333	16.83333333	0	7.5	3.333333333	4.166666667	44.44444	0.7064345	0.1763401	2.942921	2.240766616	0.702153884	0.463671	0.530094	0.232105	0.006377
Waiteti	Pipe		23/03/2012	10.10am	34.5	34.5	0	5.6	3.6	2	64.28571	1.2664321	1.07181732	1.632408	1.549136644	0.083271356	0.053824	0.194615	0.02749	0.001958
Waiteti	Pipe		23/03/2012	6.30pm	42.83333333	42.83333333	0	5.2	4	1.2	76.92308	0.6150896	0.42804994	0.876812	0.825365241	0.051446259	0.032689	0.18704	0.017013	0.001744
Waiteti	Riser		24/03/2012	10.30am	58.83333333	58.83333333	0					0.507108	0.33101018	0.729081	0.706467083	0.022613917	0.015915	0.176098	0.005413	0.001287
Waiteti	Riser		24/03/2012	6.20pm	66.66666667	66.66666667	0					0.5993946	0.41665686	0.738083	0.696668397	0.041414103	0.033375	0.182738	0.006587	0.001452
Waiteti	Pipe	Ducks	25/03/2012	11.30 am	83.83333333	83.83333333	0	8.941176471	7.294117647	1.647058824	81.57895	0.7481832	0.6137953	1.245344	0.951507624	0.293835876	0.264944	0.134388	0.027103	0.001789
Waiteti	Pipe	Ducks	25/03/2012	6.40pm	90.83333333	90.83333333	0	6.8	6	0.8	88.23529	0.6408294	0.46393666	2.133845	2.006635518	0.127208982	0.115987	0.176893	0.009563	0.00166
Waiteti	Pipe	Ducks	26/03/2012	8.45am	105.0833333	105.0833333	0	47.33333333	22	25.33333333	46.47887	0.6813225	0.4198643	1.356539	0.210955177	1.145583323	1.137087	0.261458	0.006704	0.001792
Hauraki	Ephemeral		22/03/2012	1am	0		0	16.04278075	9.625668449	6.417112299	60	1.618314	1.1326416	2.440955	1.993040311	0.447914189	0.338637	0.485672	0.104674	0.004604
Hauraki	Pipe		22/03/2012	1am	0		0	12	7.333333333	4.666666667	61.11111	1.6707353	1.2554367	5.447985	5.070843321	0.377141679	0.308097	0.415299	0.064582	0.004463
Hauraki	Pipe		22/03/2012	8.50 am	7.833333333	0	2	13.66666667	9	4.666666667	65.85366			2.190501	2.054271219	0.136229781	0.090205	0.182364	0.044234	0.001791
Hauraki	Pipe		22/03/2012	5.40pm	16.66666667	8.833333333	0	10.33333333	7.333333333	3	70.96774	1.7262956	1.2656398	0.8048	0.281250639	0.523548861	0.377143	0.460656	0.139577	0.006829
Hauraki	Pipe		23/03/2012	9am	32	24.16666667	0	6.726457399	5.381165919	1.34529148	80	1.7601968	1.3348448	2.204268	1.706933785	0.497334215	0.387765	0.425352	0.102534	0.007035
Hauraki	Pipe		23/03/2012	5.30pm	40.5	32.66666667	0	7.058823529	2.352941176	4.705882353	33.33333	1.5746819	1.0768519	1.859034	1.440625462	0.418408538	0.331776	0.49783	0.079972	0.006661
Hauraki	Pipe		23/03/2012	8pm	31	35.16666667	0	7.666666667	5.666666667	2	73.91304	1.3916782	0.8910426	2.030592	1.606135219	0.424456781	0.336866	0.500636	0.080423	0.007167
Hauraki	Riser		24/03/2012	9.30 am	56.5	46.16666667	0	7.142857143	5.714285714	1.428571429	80	1.5323054	0.9150036	1.847915	1.396339983	0.451574517	0.44132	0.617302	0.008074	0.002181
Waiteti	North E		9/05/2012	9am	0		0	9.777777778	4	5.777777778	40.90909	0.21916753	0.12046457	0.733317	0.683718178	0.049598822	0.03465	0.098703	0.013042	0.001906
Waiteti	South E		9/05/2012	9am	0		0	2.244	1.5	0.744	66.84492	0.4295747	0.20297606	1.105026	1.024945381	0.080080619	0.05133	0.226599	0.026156	0.002594
Waiteti	Pipe		9/05/2012	9am	0		0	3.360666667	1.5	1.860666667	44.634	0.4119963	0.24341422	0.981123	0.86115282	0.11997018	0.072363	0.168582	0.045268	0.002339
Waiteti	Pipe		9/05/2012	6.15pm	9.25		8.6	3.378	1.4	1.978	41.44464	0.3853148	0.21476872	1.206161	1.1073507	0.0988098	0.046323	0.170546	0.049957	0.002529
Waiteti	Pipe		10/05/2012	9.30am	24.5		12	3.334	1.2	2.134	35.9928	0.3463912	0.18169784	0.962591	0.903854034	0.058736466	0.028075	0.164693	0.028512	0.00215
Waiteti	Riser		10/05/2012	5.30pm	32.5		0	3.363	0.9	2.463	26.76182	0.3435661	0.19136378	0.885813	0.842443031	0.043369969	0.017928	0.152202	0.022428	0.003015
Waiteti	Riser		11/05/2012	9.30am	48.5			3.420333333	1.6	1.820333333	46.77907	0.5529374	0.31863988	2.044359	1.755961896	0.288397104	0.252241	0.234298	0.032016	0.00414
Waiteti	Riser		16/05/2012	12noon	0		0	3.362666667	1.7	1.662666667	50.55511	0.29538245	0.19597245	1.321062	1.271983582	0.049078418	0.039012	0.09941	0.007628	0.002438
Waiteti	Riser		17/05/2012	8.30am	20.5		4.2	22.5	14	8.5	62.22222	0.29538245	0.20473189	1.160624	1.03844223	0.12218127	0.108021	0.090651	0.010638	0.003521
Waiteti	Riser		18/05/2012	8.30 am	44.5		0	25.625	16.25	9.375	63.41463	0.29538245	0.19031613	1.531274	1.332074596	0.199198904	0.190613	0.105066	0.006067	0.002519
Waiteti	Riser		19/05/2012	1.11pm	73.18333333		0	23.75	16.875	6.875	71.05263	0.29538245	0.19283005	1.5138	1.303125803	0.210674197	0.202885	0.102552	0.004947	0.002842
Waiteti	Riser		20/05/2012	2pm	98		0	25.625	18.75	6.875	73.17073	0.29538245	0.20516397	1.50321	1.334408574	0.168801426	0.157482	0.090218	0.007854	0.003465
Hauraki	Ephemeral		9/05/2012	8am	0		0	8.666666667	5	3.666666667	57.69231	1.3439654	0.6064518	0.813801	0.747344627	0.066456373	0.016757	0.737514	0.047291	0.002408
Hauraki	Pipe		9/05/2012	8am	0		0	7.333333333	4	3.333333333	54.54545	1.238495	0.5127654	0.713196	0.63810593	0.07509007	0.022024	0.72573	0.050094	0.002971
Hauraki	Pipe		9/05/2012	5.30pm	9.5		20.4	7.666666667	3.666666667	4	47.82609	1.1961185	0.4326801	0.793151	0.651305802	0.141844698	0.052913	0.763438	0.085677	0.003255
Hauraki	Pipe		10/05/2012	8.30am	24.5	0	13	6.666666667	4.333333333	2.333333333	65	1.0495272	0.3237976	0.906993	0.780841579	0.126151421	0.055276	0.72573	0.067354	0.003522
Hauraki	Pipe		10/05/2012	6pm	34	9.5	0	6	4.444444444	1.555555556	74.07407	1.1298856	0.412012	0.708431	0.637091547	0.071338953	0.012751	0.717874	0.055274	0.003314
Hauraki	Pipe		11/05/2012	8am	48	23.5	0	5.777777778	4.666666667	1.111111111	80.76923	1.1845042	0.5180874	0.668718	0.652700179	0.016017821	0.00746	0.666417	0.006637	0.001921
Hauraki	Pipe		11/05/2012	6.20pm	58.33333333	33.83333333	0	5.111111111	3.111111111	2	60.86957	1.1728899	0.4503027	0.735435	0.707976958	0.027458042	0.017441	0.722587	0.00828	0.001737
Hauraki	Riser		12/05/2012	9am	73	48.5	0	9.333333333	9	0.333333333	96.42857	1.4290323	0.6671651	1.464027	1.268919102	0.195107898	0.189894	0.761867	0.003463	0.001751

Detainment Bund	Location of sample	Notes	Date of sample	Time sample taken	TimePassed	Assigned 'time 0'	Rainfall since last sample	TSS	VSS	ISS	ISS	TP Concentration	Particulate P	TN	Particulate N	Dissolved N	NH$_4$-N	PO$_4$-P (DRP)	NOX-N	NO$_2$-N
					(h)		(mm)	(mg L $^{-1}$)	(mg L $^{-1}$)	(mg L $^{-1}$)	(%)	(UD)	(mg L $^{-1}$)	(mg L $^{-1}$)	(mg L $^{-1}$)	(mg L $^{-1}$)	(mg L $^{-1}$)	(mg L -1)	(mg L $^{-1}$)	(mg L $^{-1}$)
Waiteti	North E		16/07/2012	5pm	0		0	28.57142857	18.57142857	10	65	0.3165707	0.2697959	1.792317	1.729271789	0.063045211	0.053034	0.046775	0.006925	0.003086
Waiteti	South E		16/07/2012	5pm	0		0	5.555555556	3.555555556	2	64	0.3708754	0.17177276	0.616298	0.536903403	0.079394097	0.058853	0.199103	0.018456	0.002085
Waiteti	Riser		16/07/2012	5pm	0		0	18.57142857	9.428571429	9.142857143	50.76923	0.30395192	0.17127176	0.91017	0.83471341	0.07545659	0.064016	0.13268	0.008764	0.002677
Waiteti	Riser		17/07/2012	10.30 am	17.5		24.6	12.63157895	8.157894737	4.473684211	64.58333	0.30018512	0.19775056	0.949883	0.860852843	0.089029657	0.070723	0.102435	0.016444	0.001862
Waiteti	Riser		17/07/2012	6.35pm	25.58333333		0	10	6.857142857	3.142857143	68.57143	0.29001476	0.182081	0.813272	0.768071404	0.045200096	0.030617	0.107934	0.012172	0.002411
Waiteti	Riser		18/07/2012	1.40pm	44.66666667		0	10	6.857142857	3.142857143	68.57143	0.29199233	0.18672961	0.795269	0.751422033	0.043846467	0.033309	0.105263	0.007885	0.002652
Waiteti	Riser		19/07/2012	5.15pm	72.25		0	8	5.714285714	2.285714286	71.42857	0.29230623	0.19124647	0.997008	0.943960967	0.053047033	0.04635	0.10106	0.0045	0.002197
Waiteti	Riser		20/07/2012	6.25pm	97.41666667		0	6.222222222	4.444444444	1.777777778	71.42857	0.2861224	0.19629672	0.760322	0.708693059	0.051628441	0.046965	0.089826	0.002609	0.002054
Waiteti	Riser		21/07/2012	5.55pm	120.9166667		0	5.555555556	4	1.555555556	72	0.23624369	0.15144585	0.853514	0.794688758	0.058824742	0.053906	0.084798	0.00264	0.002278
Waiteti	North E		22/07/2012	7.35 pm	0		0	43.91304348	14.34782609	29.56521739	32.67327	0.18225289	0.13920969	0.626888	0.60377264	0.02311486	0.019731	0.043043	0.001824	0.00156
Waiteti			22/07/2012	7.35 pm	0		0	5.777777778	4	1.777777778	69.23077	0.07784975	0.00931383	0.644891	0.597466197	0.047424303	0.037615	0.068536	0.007961	0.001849
Waiteti	South E		23/07/2012	4pm	20.41666667		75.1	14.82758621	10.34482759	4.482758621	69.76744	0.18021254	0.1360695	0.591411	0.564233636	0.027177364	0.019349	0.044143	0.006877	0.000952
Waiteti	North E		23/07/2012	4pm	20.41666667		75.1	15.6	7.2	8.4	46.15385	0.3925345	0.28444362	2.348822	0.490540383	1.858281117	1.811561	0.108091	0.043597	0.003123
Waiteti	OVER FLOW		23/07/2012	4pm	20.41666667		75.1	18.4	10	8.4	54.34783	0.28577711	0.18550295	1.733543	0.471893862	1.261648638	1.224831	0.100274	0.033553	0.003264
Waiteti	MHR		23/07/2012	4pm	20.41666667		75.1	30	12.4	17.6	41.33333	0.24810911	0.15906903	1.278702	0.305979617	0.972722383	0.937856	0.08904	0.032046	0.002821
Waiteti	South E		24/07/2012	12noon	40.41666667		86.2	3.428571429	2.571428571	0.857142857	75	0.13096163	0.10999379	0.326555	0.312999723	0.013555377	0.0092	0.020968	0.002654	0.001702
Waiteti	North E		24/07/2012	12noon	40.41666667		86.2	4.285714286	3.142857143	1.142857143	73.33333	0.21028416	0.13648472	1.457673	0.572826851	0.884846149	0.819319	0.073799	0.061332	0.004196
Waiteti	Pipe		24/07/2012	12noon	40.41666667		86.2	4.285714286	2.857142857	1.428571429	66.66667	0.15977765	0.09540541	0.996479	0.248584362	0.747894138	0.699034	0.064372	0.046226	0.002635
Waiteti	Pipe		25/07/2012	830am	60.91666667		2	3.142857143	2.857142857	0.285714286	90.90909	0.15877317	0.124210522	0.802152	0.619406457	0.182745543	0.166142	0.034563	0.014748	0.001856
Waiteti	Pipe		30/07/2012	12noon	0		0	24.23076923	13.07692308	11.15384615	53.96825	0.23938269	0.19916765	0.944058	0.83659683	0.10746117	0.086683	0.040215	0.019739	0.00104
Waiteti	Pipe		31/07/2012	11am	23		58.7	27	14.5	12.5	53.7037	0.16803322	0.138184172	0.734906	0.623833518	0.111071982	0.0777	0.029849	0.032001	0.001371
Waiteti	Riser		2/08/2012	5pm	77		0	9.428571429	5.428571429	4	57.57576		0		0	0				
Waiteti	Riser		6/08/2012	2.50pm	170.8333333		0	13.33333333	9.666666667	3.666666667	72.5		0		0	0				
Hauraki	Pipe		16/07/2012	6.20pm	0		0	7.428571429	6.285714286	1.142857143	84.61538	1.1637868	0.8307858	1.812438	1.065962756	0.746475244	0.08423	0.333001	0.658854	0.003391
Hauraki	Riser		17/07/2012	7.45am	25.41666667		0	6.857142857	5.714285714	1.142857143	83.33333	1.247912	0.8945704	1.292999	1.134281286	0.158717214	0.090626	0.353342	0.064483	0.003608
Hauraki	Riser		17/07/2012	5.20pm	23		0	6	5.333333333	0.666666667	88.88889	1.1860737	0.8208083	1.260699	1.133604576	0.127094424	0.073077	0.365265	0.050337	0.00368
Hauraki	Riser		18/07/2012	11.30am	41.16666667		0	7.555555556	5.111111111	2.444444444	67.64706	1.260468	0.8980082	1.093907	1.036444409	0.057462091	0.030631	0.36246	0.023853	0.002978
Hauraki	CSA	Hauraki CSA'	23/07/2012	9am			0					2.7933156	2.2876533	7.06296	5.773662127	1.289297873	1.223947	0.505662	0.05907	0.006281
Hauraki	Ephemeral		23/07/2012	9am	0		0	10.57142857	9.428571429	1.142857143	89.18919	1.1462084	0.7823458	1.299353	1.163422264	0.135930236	0.083832	0.363863	0.049045	0.003053
Hauraki	Ephemeral		23/07/2012	6pm	9		45.6	10	6.285714286	3.714285714	62.85714	0.8043713	0.5613833	0.702606	0.58924792	0.11335808	0.061414	0.242988	0.049335	0.002609
Hauraki	Pipe		23/07/2012	6pm	9	0	45.6	17.2	12.8	4.4	74.4186	0.8954023	0.6463355	1.163801	0.978713098	0.185087402	0.139843	0.249067	0.042868	0.002376
Hauraki	Pipe		24/07/2012	12noon	27	18	27.1	13.71428571	8.571428571	5.142857143	62.5	0.7601114	0.5344246	0.891108	0.697173226	0.193934774	0.1288	0.225687	0.062836	0.002299
Hauraki	Pipe		25/07/2012	6pm	57	48	0	8.571428571	6	2.571428571	70	0.557332	0.38796762	0.640125	0.538817382	0.101307618	0.071483	0.169364	0.027983	0.001842
Hauraki	Pipe		26/07/2012	830am	71.5	62.5	0	6.285714286	5.428571429	0.857142857	86.36364	0.6869727	0.46001169	0.696782	0.597313447	0.099468053	0.067433	0.226961	0.029745	0.002289
Awahou	E		16/07/2012	5pm	0		0	39	20.5	18.5	52.5641		0		0	0				
Awahou	Pipe		16/07/2012	5pm	0		0	134.2857143	65.71428571	68.57142857	48.93617		0		0	0				
Awahou	Ephemeral		23/07/2012	5pm	0		0	164	80	84	48.78049	0.6819503	0.671506794	3.203435	2.438340727	0.765093773	0.64226	0.010444	0.118665	0.004169
Awahou	Pipe		23/07/2012	5pm	0		0	268	126	142	47.01493	0.8319945	0.82524971	2.408655	1.809068929	0.599586071	0.503505	0.006745	0.093265	0.002816
Awahou	Ephemeral		24/07/2012	1pm	20		86.3	19.14285714	9.428571429	9.714285714	49.25373	0.20874605	0.18676919	1.83203	0.952368563	0.879660937	0.598443	0.021977	0.271557	0.009661
Awahou	Pipe		24/07/2012	1pm	20		86.3	37	19	18	51.35135	0.2170644	0.198919522	1.156917	0.662576429	0.494340571	0.388872	0.018145	0.102084	0.003385
Awahou	Pipe		30/07/2012	5pm	0		0	125	59	66	47.2	0.5849552	0.574179698	2.512967	1.957398393	0.555568107	0.432689	0.010776	0.119792	0.003087
Awahou	Pipe		31/07/2012	1pm	20		39.8	78.75	41.25	37.5	52.38095	0.4236106	0.41466809	1.807673	1.430801478	0.376871022	0.297917	0.008943	0.075844	0.003109
Awahou	Ephemeral		12/08/2012	4pm	0		0	46.15384615	23.84615385	22.30769231	51.66667	0.6860364	0.670566194	2.144964	1.254114142	0.890849858	0.642703	0.01547	0.23989	0.008257
Awahou	Pipe		12/08/2012	4pm	0		0	106.25	51.25	55	48.23529	0.6141559	0.597652298	2.482785	1.829160726	0.653624274	0.55706	0.016504	0.093545	0.003019
Awahou	Ephemeral		3/09/2012	6pm	0		0						#VALUE!		0	0				
Awahou	Pipe		3/09/2012	6pm	0		0	184	80	104	43.47826	0.5714655	0.565686304	4.762283	2.704561622	2.057720878	0.492883	0.005779	1.557894	0.006944
Awahou	Pipe		4/09/2012	2pm	20		6.2	78	36	42	46.15385	0.3677444	0.361158594	3.58997	1.555476552	2.034492948	0.48735	0.006586	1.539528	0.007615
Awahou	Pipe		9/09/2012	2pm	0		0	108	62	46	57.40741	0.8351415	0.81898626	6.41697	4.426119613	1.990850387	1.326741	0.016155	0.64978	0.014329
Awahou	Pipe		10/09/2012	5pm	27	0	16	95	52	43	54.73684		0		0	0				
Awahou	Pipe		11/09/2012	9am	43	16	0	73	43	30	58.90411		0		0	0				
Awahou	Pipe		12/09/2012	8am	66	39	0	57	31	26	54.38596		0		0	0				

1.2: Particle size of SS

Detainment Bund	Location of sample	Date of sample	Time sample taken	Time Passed (h)	New "Time 0"	Summary statistics (particles in µm)										Size class %									
						Standard Deviation	Mean	d (0.1)	d (0.5)	d (0.9)	D [4, 3] - Volume weighted mean	Kurtosis	Span	Mode	Skew	Very fine clay	Fine clay	Medium course clay	Silt	Very fine sand	Med sand	Coarse sand	Med sand	Coarse sand
Waiteti	North E	21/03/2012	11.40pm	0.0		456.55	-0.867	187.966	1164.682	1587.973	1091.469	0.275	1.202	1260.543	1091.469	0	0	0	3.045747	7.862244	1.974462	87.11755	1.974462	87.11755
Waiteti	South E	21/03/2012	11.40pm	0.0		462.546	-0.878	169.507	1164.087	1588.574	1087.698	0.265	1.219	1263.245	1087.697	0	0	0	4.015608	7.515922	1.522305	86.94617	1.522305	86.94617
Waiteti	Pipe	21/03/2012	11.40pm	0.0	0	523.838	-0.08	66.141	903.078	1536.041	857.567	-0.938	1.628	1123.595	857.567	0	0	0	8.474179	11.37217	6.005641	74.14801	6.005641	74.14801
Waiteti	Pipe	22/03/2012	9.40 am	10.0	10	435.457	-0.898	235.733	1170.572	1588.79	1111.192	0.572	1.156	1254.939	1111.192	0	0	0	2.452673	6.774074	1.635408	89.13785	1.635408	89.13785
Waiteti	Pipe	22/03/2012	4.30 pm	16.8	16.83333	411.885	-1.159	750.636	1222.334	1598.472	1165.694	1.438	0.694	1297.528	1165.694	0	0	0	2.698254	5.147998	0.81148	91.34227	0.81148	91.34227
Waiteti	Pipe	23/03/2012	10.10am	34.5	34.5	541.154	0.228	41.759	745.328	1474.649	730.915	-1.059	1.922	1110.36	730.915	0	0	0.054342	12.75216	15.38738	9.008364	62.79775	9.008364	62.79775
Waiteti	Pipe	23/03/2012	6.30pm	42.8	42.83333	440.428	-1.042	212.609	1197.04	1578.058	1122.51	0.714	1.141	1274.136	1122.51	0	0	0	2.881101	7.02463	1.803611	88.29066	1.803611	88.29066
Waiteti	Riser	24/03/2012	10.30am	58.8	58.83333	459.685	-0.946	201.118	1203.569	1618.715	1126.168	0.43	1.178	1308.219	1126.168	0	0	0	3.154994	7.167693	1.978905	87.69841	1.978905	87.69841
Waiteti	Riser	24/03/2012	6.20pm	66.7	66.66667	528.486	0.231	47.161	748.72	1472.544	744.131	-0.993	1.904	1101.659	744.131	0	0	0.138237	10.86361	13.40947	11.78718	63.80151	11.78718	63.80151
Waiteti	Pipe	25/03/2012	11.30 am	83.8	83.83333	496.882	-0.198	145.323	974.313	1572.058	937.187	-0.73	1.464	1150.183	937.187	0	0	0	4.247147	9.440473	6.142138	80.17024	6.142138	80.17024
Waiteti	Pipe	25/03/2012	6.40pm	90.8	90.83333	489.147	-0.097	160.452	939.882	1551.29	914.06	-0.761	1.48	1125.601	914.059	0	0	0	3.085406	9.931351	8.079278	78.90397	8.079278	78.90397
Waiteti	Pipe	26/03/2012	8.45am	105.1	105.0833	355.941	1.562	20.743	157.839	837.795	315.562	2.131	5.176	541.246	315.562	0	0.4	1.250816	22.6428	31.46934	20.41461	23.82641	20.41461	23.82641
Hauraki	Ephemeral	22/03/2012	1am	0.0		518.086	-0.08	75.111	904.444	1537.183	864.415	-0.901	1.617	1122.014	864.415	0	0	0	7.584382	11.17677	6.286314	74.95253	6.286314	74.95253
Hauraki	Pipe	22/03/2012	1am	0.0		510.161	-0.184	84.848	947.622	1556.585	905.58	-0.787	1.553	1132.782	905.58	0	0	0	7.321333	9.337801	4.819849	78.52102	4.819849	78.52102
Hauraki	Pipe	22/03/2012	8.50 am	7.8	0	500.621	-0.687	107.377	1114.97	1554.065	1010.187	-0.441	1.298	1226.578	1010.187	0	0	0	5.397674	10.71897	2.625069	81.25829	2.625069	81.25829
Hauraki	Pipe	22/03/2012	5.40pm	16.7	8.833333	547.158	-0.04	51.93	894.212	1544.185	833.643	-1.092	1.669	1160.589	833.643	0	0	0	10.18959	13.40069	6.055531	70.35419	6.055531	70.35419
Hauraki	Pipe	23/03/2012	9am	32.0	24.16667	526.053	-0.124	60.896	920.269	1545.967	870.51	-0.923	1.614	1133.034	870.51	0	0	0	8.967606	10.87086	4.952903	75.20863	4.952903	75.20863
Hauraki	Pipe	23/03/2012	5.30pm	40.5	32.66667	529.62	-0.151	68.634	939.47	1557.736	882.639	-0.945	1.585	1151.384	882.639	0	0	0	8.015912	11.84503	4.881236	75.25782	4.881236	75.25782
Hauraki	Pipe	23/03/2012	8pm	31.0	35.16667	510.399	-0.605	98.724	1103.109	1582.362	1006.195	-0.531	1.345	1242.196	1006.195	0	0	0	6.215296	9.915868	2.703422	81.16541	2.703422	81.16541
Hauraki	Riser	24/03/2012	9.30 am	56.5	46.16667	527.061	-0.038	69.318	893.162	1536.358	848.306	-0.986	1.643	1137.762	848.306	0	0	0	7.915	11.99882	7.660956	72.42523	7.660956	72.42523
Waiteti	North E	9/05/2012	9am	0.0		403.341	0.792	87.829	503.986	1136.334	566.306	0.188	2.08	656.87	566.306	0	0	0.226986	5.077431	16.90369	27.39697	50.39492	27.39697	50.39492
Waiteti	South E	9/05/2012	9am	0.0		464.768	0.028	177.38	883.202	1499.047	879.973	-0.635	1.496	1029.01	879.973	0	0	0	2.540044	9.364544	8.926327	79.16909	8.926327	79.16909
Waiteti	Pipe	9/05/2012	9am	0.0		458.94	-0.229	222.005	999.576	1576.381	985.429	-0.412	1.355	1126.85	985.429	0	0	0	2.723119	6.847395	4.043	86.38649	4.043	86.38649
Waiteti	Pipe	9/05/2012	6.15pm	9.2		460.912	-0.139	207.125	963.781	1552.453	952.362	-0.521	1.396	1100.513	952.362	0	0	0	2.175669	7.946187	5.688693	84.18945	5.688693	84.18945
Waiteti	Pipe	10/05/2012	9.30am	24.5		431.077	-0.134	467.948	993.198	1563.812	996.827	-0.295	1.103	1092.137	996.827	0	0	0	1.246533	5.819399	3.77769	89.15638	3.77769	89.15638
Waiteti	Riser	10/05/2012	5.30pm	32.5		448.325	-0.153	265.041	984.768	1563.688	978.683	-0.423	1.319	1105.502	978.683	0	0	0	1.809498	6.494553	5.211374	86.48458	5.211374	86.48458
Waiteti	Riser	11/05/2012	9.30am	48.5		455.304	-0.061	234.803	938.387	1537.36	935.647	-0.526	1.388	1078.048	935.647	0	0	0	2.486311	6.641007	7.39967	83.47301	7.39967	83.47301
Waiteti	Riser	16/05/2012	12noon	0.0												0	0	0	0	0	0	0	0	0
Waiteti	Riser	17/05/2012	8.30am	20.5		566.644	0.031	62.968	882.611	1552.702	809.984	-1.235	1.688	1196.066	809.984	0	0	0	7.924882	20.26995	5.585727	66.21944	5.585727	66.21944
Waiteti	Riser	18/05/2012	8.30 am	44.5		233.333	3.894	25.289	82.595	297.431	152.8	17.604	3.295	85.547	152.8	0	0	0.355741	30.49428	53.56853	9.533659	6.047787	9.533659	6.047787
Waiteti	Riser	19/05/2012	1.11pm	73.2		579.816	0.263	43.33	749.474	1512.443	713.639	-1.269	1.96	1193.362	713.639	0	0	0.045861	13.01742	22.84469	6.399426	57.69261	6.399426	57.69261
Waiteti	Riser	20/05/2012	2pm	98.0		572.729	0.387	45.365	654.96	1486.823	674.354	-1.191	2.201	1185.887	674.354	0	0	0.048078	12.29563	25.68762	7.892206	54.07647	7.892206	54.07647
Hauraki	Ephemeral	9/05/2012	8am	0.0		395.876	-0.297	586.114	1028.587	1524.166	1025.984	0.157	0.912	1094.888	1025.984	0	0	0	1.177155	4.826142	1.784425	92.21228	1.784425	92.21228
Hauraki	Pipe	9/05/2012	8am	0.0		450.109	-0.139	240.735	975.405	1557.113	969.277	-0.45	1.35	1096.589	969.277	0	0	0	1.592499	7.290417	5.181514	85.93557	5.181514	85.93557
Hauraki	Pipe	9/05/2012	5.30pm	9.5		455.167	-0.099	243.926	966.582	1556.307	958.878	-0.547	1.358	1108.037	958.878	0	0	0	1.418137	7.213304	7.114665	84.25389	7.114665	84.25389
Hauraki	Pipe	10/05/2012	8.30am	24.5	0	429.705	-0.137	482.551	998.955	1568.878	1003.134	-0.282	1.087	1099.194	1003.134	0	0	0	1.436791	5.229515	3.827685	89.50601	3.827685	89.50601
Hauraki	Pipe	10/05/2012	6pm	34.0	9.5	427.392	-0.134	506.654	1009.239	1579.622	1015.015	-0.277	1.063	1115.185	1015.015	0	0	0	1.172408	5.05159	3.550831	90.22517	3.550831	90.22517
Hauraki	Pipe	11/05/2012	8am	48.0	23.5	460.287	0.211	156.762	793.529	1437.824	808.451	-0.601	1.614	953.792	808.451	0	0	0	3.592085	9.346272	13.32667	73.73498	13.32667	73.73498
Hauraki	Pipe	11/05/2012	6.20pm	58.3	33.83333	422.551	-0.463	530.684	1071.105	1565.573	1048.932	0.084	0.966	1160.746	1048.932	0	0	0	1.553882	6.05772	2.067274	90.32112	2.067274	90.32112
Hauraki	Riser	12/05/2012	9am	73.0	48.5	462.658	-0.05	202.945	923.67	1528.93	917.927	-0.579	1.436	1069.211	917.927	0	0	0	2.900151	7.413345	7.82797	81.85853	7.82797	81.85853

						Summary statistics (particles in µm)										Size class %								
Detainment Bund	Location of sample	Date of sample	Time sample taken	Time Passed (h)	New "Time 0"	Standard Deviation	Mean	d (0.1)	d (0.5)	d (0.9)	D [4, 3] - Volume weighted mean	Kurtosis	Span	Mode	Skew	Very fine clay	Fine clay	Medium course clay	Silt	Very fine sand	Med sand	Coarse sand	Med sand	Coarse sand
Waiteti	North E	16/07/2012	5pm	0.0		484.784	-0.209	174.835	975.79	1573.182	950.231	-0.593	1.433	1142.698	950.231	0	0	0.209882	5.446558	5.851313	6.048882	82.44337	6.048882	82.44337
Waiteti	South E	16/07/2012	5pm	0.0		475.534	0.194	178.7	820.96	1489.488	834.342	-0.748	1.597	1057.201	834.342	0	0	0	2.790878	8.982996	15.17941	73.04672	15.17941	73.04672
Waiteti	Riser	16/07/2012	5pm	0.0		478.811	-0.323	204.545	1034.172	1606.556	1002.519	-0.475	1.356	1184.717	1002.519	0	0	0	4.258563	5.974083	4.678797	85.08856	4.678797	85.08856
Waiteti	Riser	17/07/2012	10.30 am	17.5		463.181	-1.008	225.138	1236.512	1642.672	1153.834	0.531	1.146	1342.873	1153.834	0	0	0	3.584844	5.844615	2.835057	87.73548	2.835057	87.73548
Waiteti	Riser	17/07/2012	6.35pm	25.6		0.905	0.398	3.346	4.396	5.727	4.473	-0.24	0.542	4.504	4.473	0	0	28.5472	71.4528	0	0	0	0	0
Waiteti	Riser	18/07/2012	1.40pm	44.7		426.943	-1.134	295.164	1240.335	1614.201	1171.025	1.091	1.063	1322.664	1171.025	0	0	0	2.189578	5.527595	2.550627	89.7322	2.550627	89.7322
Waiteti	Riser	19/07/2012	5.15pm	72.2		445.998	0.983	51.336	419.04	1207.465	530.576	0.294	2.759	510.323	530.575	0	0	0.55814	9.706727	18.62819	28.34606	42.76088	28.34606	42.76088
Waiteti	Riser	20/07/2012	6.25pm	97.4		275.994	0.563	68.937	387.112	801.266	415.351	-0.249	1.892	498.28	415.351	0	0	0.479442	7.163474	19.02227	38.33109	35.00373	38.33109	35.00373
Waiteti	Riser	21/07/2012	5.55pm	120.9		497.567	-0.752	146.072	1160.734	1594.239	1056.091	-0.321	1.248	1288.633	1056.091	0	0	0	3.274049	11.03033	3.31809	82.37753	3.31809	82.37753
Waiteti	North E	22/07/2012	7.35 pm	0.0		622.229	0.37	1.088	190.992	1442.377	597.939	-1.549	7.546	1250.586	597.939	0.017	9.19	7.248243	22.35727	12.14916	3.125347	45.91283	3.125347	45.91283
Waiteti		22/07/2012	7.35 pm	0.0		508.788	-0.351	151.144	1049.289	1621.326	991.925	-0.705	1.401	1224.882	991.925	0	0	0	3.187304	10.82615	4.549852	81.4367	4.549852	81.4367
Waiteti	South E	23/07/2012	4pm	20.4		492.495	0.131	137.313	834.825	1500.536	831.414	-0.845	1.633	1080.075	831.414	0	0	0.118737	2.778703	12.59546	12.19101	72.31609	12.19101	72.31609
Waiteti	North E	23/07/2012	4pm	20.4		436.416	-1.001	298.695	1233.566	1637.456	1168.2	0.771	1.085	1329.478	1168.2	0	0	0	2.025405	5.508031	2.871423	89.59514	2.871423	89.59514
Waiteti	OVER FLOW	23/07/2012	4pm	20.4		391.03	-1.22	831.206	1245.738	1609.506	1200.776	2.006	0.625	1324.791	1200.776	0	0	0	2.652912	3.583019	0.519797	93.24427	0.519797	93.24427
Waiteti	MHR	23/07/2012	4pm	20.4		469.778	-0.218	208.092	984.067	1573.85	967.875	-0.462	1.388	1130.772	967.875	0	0	0.422711	4.405947	5.234374	4.997709	84.93926	4.997709	84.93926
Waiteti	South E	24/07/2012	12noon	40.4		407.027	-0.977	752.011	1235.005	1635.998	1187.57	1.059	0.716	1320.532	1187.57	0	0	0	0.834734	5.13313	2.171352	91.86078	2.171352	91.86078
Waiteti	North E	24/07/2012	12noon	40.4		481.23	1.15	40.154	254.245	1246.306	467.675	0.277	4.744	1123.781	467.675	0	1.04	1.293948	10.88401	31.95705	20.33668	34.48956	20.33668	34.48956
Waiteti	Pipe	24/07/2012	12noon	40.4		420.55	-0.926	665.943	1205.344	1615.972	1152.289	0.772	0.788	1294.113	1152.289	0	0	0	1.071997	6.207996	2.173864	90.54614	2.173864	90.54614
Waiteti	Pipe	25/07/2012	830am	60.9		454.701	0.056	251.89	887.466	1512.669	898.62	-0.543	1.421	1044.728	898.62	0	0	0	2.639901	6.568799	9.540185	81.25112	9.540185	81.25112
Waiteti	Pipe	30/07/2012	12noon	0.0		505.774	0.069	32.458	815.563	1489.683	809.382	-0.8	1.787	1064.05	809.382	0	0.44	1.236369	9.876667	5.831811	10.30338	72.31669	10.30338	72.31669
Waiteti	Pipe	31/07/2012	11am	23.0		428.649	-0.989	671.199	1195.731	1609.063	1141.05	0.956	0.784	1282.946	1141.05	0	0	0.301036	3.704999	4.032956	1.194336	90.76667	1.194336	90.76667
Waiteti	Riser	2/08/2012	5pm	77.0		467.01	0.07	191.082	876.32	1512.052	881.453	-0.657	1.507	1058.32	881.453	0	0	0	2.617703	8.169249	10.62995	78.5831	10.62995	78.5831
Waiteti	Riser	6/08/2012	2.50pm	170.8		351.041	2.526	11.337	103.272	701.283	238.059	6.156	6.681	90.812	238.059	0	2.72	2.633889	18.94378	48.91622	13.49116	13.29328	13.49116	13.29328
Hauraki	Pipe	16/07/2012	6.20pm	0.0		542.342	-0.534	84.479	1107.888	1563.538	967.139	-0.923	1.335	1260.709	967.139	0	0	0	6.786067	13.80075	4.014229	75.39895	4.014229	75.39895
Hauraki	Riser	17/07/2012	7.45am	25.4		75.759	2.014	10.139	39.863	178.098	68.57	3.968	4.213	36.393	68.57	0	0.97	1.896933	58.38643	31.47198	7.273342	0	7.273342	0
Hauraki	Riser	17/07/2012	5.20pm	23.0		592.62	0.897	14.131	81.72	1408.237	463.755	-0.914	17.06	1301.924	463.755	0	0.86	1.428411	38.34265	23.19058	3.59041	32.58368	3.59041	32.58368
Hauraki	Riser	18/07/2012	11.30am	41.2		520.219	-0.694	126.906	1156.907	1561.765	1015.994	-0.688	1.24	1286.017	1015.994	0	0	0	4.128419	12.53982	5.662271	77.66949	5.662271	77.66949
Hauraki	Ephemeral	23/07/2012	9am	0.0		524.937	-0.157	107.982	961.632	1580.71	909.049	-0.934	1.531	1190.489	909.049	0	0	0.15251	4.803785	12.70187	6.215329	76.1265	6.215329	76.1265
Hauraki	Ephemeral	23/07/2012	6pm	9.0		475.918	-0.332	197.317	1041.914	1610.944	1011.054	-0.458	1.357	1188.937	1011.054	0	0	0.05276	2.740629	7.75764	3.701301	85.74767	3.701301	85.74767
Hauraki	Pipe	23/07/2012	6pm	9.0	0	509.966	-0.235	115.683	980.178	1582.906	936.153	-0.749	1.497	1171.947	936.153	0	0	0.485825	5.991571	8.787786	4.81334	79.92148	4.81334	79.92148
Hauraki	Pipe	24/07/2012	12noon	27.0	18	588.828	-0.085	8.486	915.545	1458.717	745.233	-1.458	1.584	1174.213	745.233	0	1.33	3.713947	23.1094	8.668727	0.649657	62.52795	0.649657	62.52795
Hauraki	Pipe	25/07/2012	6pm	57.0	48	425.733	-0.441	530.989	1057.41	1561.499	1037.658	0.072	0.975	1154.695	1037.658	0	0	0	2.072654	6.04736	1.395878	90.48411	1.395878	90.48411
Hauraki	Pipe	26/07/2012	830am	71.5	62.5	481.973	-0.091	181.627	943.695	1550.518	921.4	-0.729	1.451	1125.319	921.4	0	0	0	2.718254	8.91351	8.78599	79.58225	8.78599	79.58225
Awahou	E	16/07/2012	5pm	0.0		589.889	-0.062	16.537	922.083	1576.464	822.043	-1.277	1.692	1228.47	822.043	0	0.65	1.34161	15.93906	10.65359	4.671919	66.7407	4.671919	66.7407
Awahou	Pipe	16/07/2012	5pm	0.0		614.237	0.315	6.687	684.063	1506.439	653.39	-1.339	2.192	1209.978	653.39	0	1.51	4.3135	30.80345	5.83735	3.589711	53.94546	3.589711	53.94546
Awahou	Ephemeral	23/07/2012	5pm	0.0		182.181	2.241	3.214	17.272	419.992	95.89	3.904	24.13	16.173	95.89	0	2.65	9.444876	65.41902	6.538856	8.928996	7.015156	8.928996	7.015156
Awahou	Pipe	23/07/2012	5pm	0.0		394.971	2.007	2.181	14.355	840.643	219.621	3.349	58.409	12.016	219.621	0	3.99	13.25814	52.00035	4.437518	7.380809	18.92889	7.380809	18.92889
Awahou	Ephemeral	24/07/2012	1pm	20.0		486.925	-0.373	187.371	1055.822	1619.14	1013.554	-0.512	1.356	1205.953	1013.554	0	0	0.047005	3.238676	7.928053	4.335413	84.45085	4.335413	84.45085
Awahou	Pipe	24/07/2012	1pm	20.0		146.624	6.176	2.385	12.026	72.237	47.612	46.562	5.808	13.322	47.612	0	3.26	13.54711	71.37765	7.027027	2.247171	2.539795	2.247171	2.539795
Awahou	PIPE	30/07/2012	5pm	0.0		223.264	1.145	3.711	24.313	535.704	171.029	0.03	21.881	480.96	171.029	0	2.12	8.435075	45.70771	10.79595	20.61832	12.32128	20.61832	12.32128
Awahou	PIPE	31/07/2012	1pm	20.0		126.732	2.996	2.161	11.3	170.406	57.341	8.258	14.89	11.534	57.341	0	3.82	13.83255	65.14016	8.150291	6.342176	2.712641	6.342176	2.712641
Awahou	Pipe	3/09/2012	6pm	0.0			1200.679	695.218	1259.68	1733.683	1200.679		0.824	1439.036	-0.995	0	0	0.715405	7.291201	0	0.011126	91.98227	0.011126	91.98227
Awahou	Pipe	4/09/2012	2pm	20.0			1246.337	851.655	1290.665	1699.19	1246.337		0.657	1388.478	-1.23	0	0	0.31086	5.42842	0	0	94.26072	0	94.26072
Awahou	Pipe	9/09/2012	2pm	0.0			954.647	71.825	996.049	1590.621	954.647		1.525	1170.138	-0.316	0	0.35	0.857298	8.37089	4.42317	3.612008	82.38376	3.612008	82.38376
Awahou	Pipe	10/09/2012	5pm	27.0	0		1352.024	1029.003	1345.247	1667.585	1352.024		0.475	1402.567	0.119	0	0	0	0	0	0	100	0	100
Awahou	Pipe	11/09/2012	9am	43.0	16		1224.095	850.506	1301.045	1649.057	1224.095		0.614	1366.201	-1.529	0	0	0.579051	8.243262	0	0	91.17769	0	91.17769
Awahou	Pipe	12/09/2012	8am	66.0	39		1166.164	19.15	1283.331	1641.808	1166.164		1.264	1366.323	-1.31	0	0.59	1.349579	11.09588	0.155161	0	86.80679	0	86.80679

1.3: Deposited sediment characteristics

Elevation (mm)	Location	Storm Event	Average concentrtions of sediment from ICPMS															
			Al mg P (kg dw) $^{-1}$				P mg P (kg dw) $^{-1}$				Fe mg P (kg dw) $^{-1}$				Mn mg P (kg dw) $^{-1}$			
			Mean Al conc	Std Error	Al Std error	Adv	Mean P conc	Std Error	P Std error	Adv	Mean Fe conc	Std Error	Fe Std error	Adv	Mean Mn conc	Std Error	Mn Std error	Adv
			(mg Al/kg)	(mg Al/kg)	(% of mean)	(% Al)	(mg P/kg)	(mg P/kg)	(% of mean)	(% P)	(mg Fe /Kg)	(mg Fe/kg)	(% of mean)	(% Fe)	(mg Mn /Kg)	(mg Mn/kg)	(% of mean)	(% Mn)
100	Waiteti	March	13062.12733	222.782502	1.705561	1.306213	1358.8295	30.360454	2.234309	0.135883	6562.02345	146.450511	2.231789	0.656202	211.9045024	5.10757933	2.410321	0.02119
200	Waiteti	March	10188.92433	56.6053269	0.555557	1.018892	2252.47283	58.501772	2.597224	0.225247	5484.09169	113.366724	2.067192	0.548409	303.6268194	7.63027423	2.513044	0.030363
300	Waiteti	March	7039.481833	72.9142542	1.03579	0.703948	2252.95533	103.28946	4.584621	0.225296	4247.7579	19.815218	0.466487	0.424776	304.1996194	8.07957011	2.656009	0.03042
100	Hauraki	March	8207.930667	257.101707	3.132357	0.820793	1991.48867	62.418986	3.134288	0.199149	4521.61113	137.05496	3.031109	0.452161	546.3795743	4.23017551	0.774219	0.054638
200	Hauraki	March	5287.266833	285.89825	5.407298	0.528727	2653.80717	118.05035	4.448339	0.265381	3952.21823	288.464082	7.298789	0.395222	540.7501362	29.0500923	5.372184	0.054075
300	Hauraki	March	8421.712667	334.883793	3.976433	0.842171	2086.23233	49.454376	2.370511	0.208623	3790.57392	137.319048	3.622645	0.379057	336.6582051	15.5971555	4.632935	0.033666
100	Waiteti	May #2	15521.534	349.65082	2.252682	1.552153	1387.56483	39.415992	2.840659	0.138756	7388.58465	200.565533	2.714533	0.738858	352.4154858	10.2968549	2.921794	0.035242
200	Waiteti	May #2	12240.939	302.045027	2.467499	1.224094	144.455833	2.8150871	1.948753	0.014446	6336.24389	118.191511	1.865325	0.633624	277.2913193	5.42533142	1.956546	0.027729
200	Waiteti	May #2	15922.29308	NA	NA	NA	1380.89533	15.660482	1.134082	0.13809	8719.10254	200.519249	2.299769	0.87191	328.5085044	4.49316745	1.367748	0.032851
100	Waiteti	July #1 + 2	Al > 30000	NA	NA	NA	1204.22124	42.745939	3.549675	0.120422	9598.36774	125.729505	1.309905	0.959837	368.5184173	7.79789229	2.116012	0.036852
200	Waiteti	July #1 + 2	Al > 30000	NA	NA	NA	378.7032	25.415971	6.711317	0.03787	7738.68311	42.70859	0.551884	0.773868	272.4568069	2.12924616	0.781499	0.027246
300	Waiteti	July #1 (only)	3671.811882	87.4335711	2.381211	0.367181	1058.5005	52.81043	4.989174	0.10585	2277.20983	63.393852	2.783839	0.227721	152.4457466	7.83637185	5.140433	0.015245
100	Waiteti	July #1 + 2	Al > 30000	NA	#VALUE!	#VALUE!	1937.41765	47.68338	2.461182	0.193742	9187.28643	196.863704	2.142784	0.918729	456.7841488	7.00012208	1.532479	0.045678
200	Waiteti	July #1 + 2	16623.1748	220.029259	1.32363	1.662317	1735.79999	15.226482	0.877203	0.17358	8270.6689	23.4891488	0.284005	0.827067	360.8983063	2.7231472	0.754547	0.03609
100	Hauraki	July #2	15746.31186	123.756708	0.785941	1.574631	2602.40243	22.600802	0.868459	0.26024	6703.183	32.4700246	0.484397	0.670318	470.5972132	5.55202793	1.179783	0.04706
200	Hauraki	July #2	7919.708048	172.258964	2.175067	0.791971	2517.06416	69.193932	2.748994	0.251706	4685.92623	72.1422689	1.539552	0.468593	512.7176876	13.7945057	2.690468	0.051272
300	Hauraki	July #2	4189.77912	80.746626	1.927229	0.418978	1837.07952	26.285401	1.430825	0.183708	3150.04123	35.9462335	1.141135	0.315004	358.9429961	13.1589206	3.66602	0.035894
100	Hauraki	July #3	12535.99586	73.2499857	0.584317	1.2536	2839.21117	38.676709	1.362234	0.283921	5683.56088	38.5237311	0.67781	0.568356	504.6081595	5.40107739	1.070351	0.050461
200	Hauraki	July #3	9872.398667	245.606189	2.487807	0.98724	3091.63433	76.43191	2.472217	0.309163	5164.82959	108.680351	2.104239	0.516483	662.1326072	16.2679034	2.456895	0.066213
300	Hauraki	July #3	8009.359783	260.828294	3.256544	0.800936	2675.51233	43.970756	1.643452	0.267551	4120.28579	110.642489	2.685311	0.412029	420.2594392	2.78702184	0.663167	0.042026
100	Awahou	July #3	Al > 30000	NA	NA	NA	2150.69233	28.178566	1.310209	0.215069	14048.6134	197.01787	1.402401	1.404861	523.0071989	7.38636044	1.412287	0.052301
200	Awahou	July #3	Al > 30000	NA	NA	NA	2164.00983	36.114728	1.66888	0.216401	13443.6579	204.330821	1.519905	1.344366	511.5044128	8.51328359	1.664362	0.05115
300	Awahou	July #3	Al > 30000	NA	NA	NA	2231.472	21.492357	0.963147	0.223147	13076.9055	14.895648	0.113908	1.307691	512.8502501	1.78475589	0.348007	0.051285
100	Awahou	Sept #2	Al > 30000	NA	NA	NA	2726.51183	99.211354	3.638765	0.272651	14875.9342	569.591176	3.828944	1.487593	701.3654799	36.8218116	5.250018	0.070137
200	Awahou	Sept #2	Al > 30000	NA	NA	NA	2706.00233	96.525108	3.567074	0.2706	13220.7051	212.721615	1.609004	1.322071	633.6430378	11.9037655	1.878623	0.063364
300	Awahou	Sept #2	Al > 30000	NA	NA	NA	2496.27933	37.474576	1.501217	0.249628	13088.5278	516.693093	3.947679	1.308853	595.6161836	14.7352735	2.473955	0.059562
100	Hauraki	July #2	9617.4435	150.129496	1.561013	0.961744	1494.47137	35.233057	2.35756	0.149447	7762.1443	95.9793879	1.236506	0.776214	340.0395593	5.68897282	1.673033	0.034004
200	Waiteti	July #1 + 2	11595.91533	85.7647309	0.739612	1.159592	901.13319	8.2256876	0.912816	0.090113	10189.4953	178.445477	1.751269	1.01895	244.9732719	3.04002292	1.240961	0.024497
200	Waiteti	July #1 + 2	10423.32617	114.068736	1.09436	1.042333	1501.57637	27.034536	1.80041	0.150158	10053.6218	149.726778	1.489282	1.005362	406.5521026	8.59598703	2.114363	0.040655
200	Waiteti	July #1 + 2	10011.14183	170.037263	1.69848	1.001114	1706.13326	60.952032	3.572525	0.170613	9714.71829	173.252858	1.783406	0.971472	492.1805986	19.5387785	3.969839	0.049218
200	Waiteti	July #1 + 2	Al > 30000	NA	NA	NA	345.296073	0.349064	0.101091	0.03453	9221.45095	67.9104401	0.73644	0.922145	175.9310415	1.04868174	0.596075	0.017593
200	Awahou	July #3	Al > 30000	NA	NA	NA	1143.0697	8.0835873	0.707182	0.114307	15771.6326	201.453276	1.277314	1.577163	348.4090741	5.2494203	1.506683	0.034841
200	Awahou	July #3	Al > 30000	NA	NA	NA	1028.07894	21.332423	2.074979	0.102808	13731.5184	246.846116	1.797661	1.373152	307.4356636	7.01959235	2.283272	0.030744
200	Awahou	July #3	Al > 30000	NA	NA	NA	1128.98805	1.2691767	0.112417	0.112899	15252.9668	209.086286	1.370791	1.525297	329.5547154	1.6510294	0.500988	0.032955

Elevation (mm)	Location	Storm Event	Particle size distribution (SUMMARY STATISTICS)										Size class % (of suspensed sediment)						
			Standard deviation	mean	d (0.1)	d (0.5) (Mean)	d (0.9)	D [4, 3] - Volume weighted mean	Kurtosis	Span	Mode	Skew	Very fine clay	Fine clay	Medium-coarse clay	Silt	Very fine sand	Medium sand	Coarse sand
100	Waiteti	March	358.464	206.907	12.306	53.421	732.434	206.907	5.787	13.48	36.453	2.495	0	0.465878	1.398812	47.21716	28.5738	7.798038	13.86733
200	Waiteti	March	487.558	588.813	54.632	474.933	1320.58	588.813	-0.414	2.666	978.858	0.738	0	0	0.337035	9.383743	20.68987	21.14104	48.44832
300	Waiteti	March	486.506	586.101	64.62	455.912	1322.771	586.101	-0.376	2.76	1006.618	0.776	0	0	0.305671	7.99668	21.99303	22.37699	47.32763
100	Hauraki	March	352.92	288.507	35.313	140.746	795.89	288.507	4.164	5.404	107.589	2.071	0	0	0.365788	17.87095	44.15559	19.33264	18.27503
200	Hauraki	March	448.169	590.975	114.538	471.518	1268.973	590.975	0.009	2.448	814.68	0.889	0	0	0	4.011497	18.55601	29.71385	47.71865
300	Hauraki	March	446.361	556.74	105.848	415.86	1244.621	556.74	0.215	2.738	837.521	1.008	0	0	0	3.889471	22.14471	30.7139	43.25191
100	Waiteti	May #2	404.134	312.763	26.359	130.937	960.313	312.763	2.785	7.133	105.919	1.862	0	0	0.716731	21.68515	40.95202	15.61764	20.91536
200	Waiteti	May #2	39.113	26.725	3.844	18.297	48.928	26.725	48.824	2.464	22.541	6.121							
200	Waiteti	May #2	326.569	231.09	25.619	106.106	647.252	231.09	6.818	5.859	98.336	2.585	0	0	0.632379	24.73378	46.98732	14.63357	12.91625
100	Waiteti	July #1 + 2	334.802	185.665	11.02	53.789	620.948	185.665	7.502	11.339	45.919	2.775							
200	Waiteti	July #1 + 2	77.651	46.77	5.292	24.107	94.828	46.77	24.15	3.714	25.478	4.417							
300	Waiteti	July #1 (only)	472.391	550.013	74.797	395.409	1274.996	550.013	-0.116	3.035	966.621	0.911							
100	Waiteti	July #1 + 2	303.844	191.217	22.733	78.692	548.146	191.217	8.875	6.677	70.941	2.922	0	0	0.753463	32.41252	46.81254	9.063794	10.85426
200	Waiteti	July #1 + 2	393.758	276.776	28.015	105.233	914.141	276.776	3.717	8.421	88.427	2.107	0	0	0.520298	24.17976	46.35175	11.15388	17.7761
100	Hauraki	July #2	333.544	224.918	23.036	92.78	656.221	224.918	6.69	6.825	77.282	2.585	0	0	0.593119	29.74275	43.56073	13.17279	12.90919
200	Hauraki	July #2	416.051	358.244	42.909	168.033	1026.871	358.245	2.026	5.856	122.928	1.665	0	0	0.34673	13.18317	43.48359	18.50616	24.48035
300	Hauraki	July #2	432.55	494.993	59.211	355.556	1158.093	494.993	0.639	3.091	366.643	1.144	0	0	0.378821	8.831803	22.72805	30.2479	37.81343
100	Hauraki	July #3	306.534	241.429	27.875	132.705	603.812	241.429	7.344	4.34	130.285	2.589	0	0	0.64698	18.84008	47.78781	20.07001	12.56227
200	Hauraki	July #3	313.508	266.266	46.736	155.975	650.105	266.266	6.749	3.868	144.889	2.507	0	0	0.345664	11.50286	51.35012	23.16369	13.63767
300	Hauraki	July #3	441.148	339.058	21.149	122.67	1072.608	339.058	1.719	8.571	95.531	1.636	0	0	0.983834	23.67199	38.86406	12.01113	24.27541
100	Awahou	July #3	473.091	413.962	23.903	172.697	1176.338	413.962	0.535	6.673	1010.604	1.251	0	0	0.615573	22.42531	30.57108	14.3625	31.93027
200	Awahou	July #3	424.046	355.719	25.782	160.132	1032.674	355.719	1.775	6.288	108.353	1.588	0	0	0.564728	21.17348	34.79512	17.96478	25.41346
300	Awahou	July #3	299.971	191.529	17.877	80.411	528.628	191.529	9.033	6.352	76.908	2.917	0	0.182453	0.84676	33.65379	43.36323	11.05372	10.53965
100	Awahou	Sept #2	178.481	119.28	16.723	72.76	225.049	119.28	30.08	2.863	81.59	4.846	0	0.190407	1.049319	34.80565	52.29826	7.886345	3.352614
200	Awahou	Sept #2	168.7627	116.1613	15.293	70.345	232.265	116.1613	33.371	2.947667	78.001	4.928333	0	0.166434	1.302198	38.42977	48.32209	7.656468	3.674597
300	Awahou	Sept #2	252.244	149.012	15.946	66.466	340.529	149.012	15.08567	4.894667	65.84433	3.648333	0	0.232455	1.036551	39.33261	43.54225	8.378834	7.038472

1.4: Location of sediment mats

	Elevation	New Tag ref	Co- ordinates	
			Latitude	Longitude
Waiteti	1	1A	-38.0511	176.0974
Waiteti	1	1B	-38.0511	176.0974
Waiteti	1	1C	-38.0511	176.0973
Waiteti	1	1D	-38.0511	176.0973
Waiteti	1	1E	-38.051	176.0973
Waiteti	2	2A	-38.0512	176.0973
Waiteti	2	2B	-38.0512	176.0972
Waiteti	2	2C	-38.0512	176.0972
Waiteti	2	2D	-38.051	176.0973
Waiteti	3	3A	-38.0512	176.0974
Waiteti	3	3B	-38.0512	176.0972
Waiteti	3	3C	-38.051	176.0973
Waiteti	3	3D	-38.051	176.0973
Waiteti	4	4A	-38.0514	176.0974
Waiteti	4	4B	-38.0513	176.0971
Waiteti	4	4C	-38.0512	176.0971
Waiteti	4	4D	-38.0511	176.0971
Waiteti	4	4E	-38.051	176.0973
Waiteti	5	5A	-38.0516	176.0974
Waiteti	5	5B	-38.0513	176.0971
Waiteti	6	6A	-38.0513	176.0971
Waiteti	6	6B	-38.0513	176.097
Waiteti	6	6C	-38.0513	176.0969
Waiteti	7	7A	-38.0514	176.097
Waiteti	8	8A	-38.0514	176.097
Waiteti	8	8B	-38.0514	176.0967
Waiteti	9	9A	-38.0514	176.097
Waiteti	10	10A	-38.0515	176.097
Waiteti	11	11A	-38.0515	176.0969
Waiteti	12	12A	-38.0516	176.0969
Waiteti	13	13A	-38.0516	176.0969
Waiteti	14	14A	-38.0516	176.0969

	Elevation	New Tag ref	Co-ordinates	
			Latitude	Longitude
Hauraki	1	1A	-38.0058	176.18432
Hauraki	1	1B	-38.0058	176.18433
Hauraki	1	1C	-38.0058	176.18437
Hauraki	2	2A	-38.0057	176.18412
Hauraki	2	2B	-38.0057	176.18428
Hauraki	2	2C	-38.0057	176.18436
Hauraki	2	2D	-38.0057	176.18443
Hauraki	3	3A	-38.0056	176.18427
Hauraki	3	3B	-38.0056	176.18429
Hauraki	3	3C	-38.0057	176.18442
Hauraki	3	3D	-38.0058	176.18452
Hauraki	4	4A	-38.0055	176.1842
Hauraki	4	4B	-38.0054	176.18423
Hauraki	4	4C	-38.0056	176.18452
Hauraki	5	5A	-38.0055	176.18416
Hauraki	5	5B	-38.0054	176.18422
Hauraki	5	5C	-38.0055	176.18455
Hauraki	6	6A	-38.0055	176.18411
Hauraki	6	6B	-38.0055	176.18457
Hauraki	7	7A	-38.0055	176.18404
Hauraki	7	7B	-38.0052	176.18407
Hauraki	7	7C	-38.0055	176.18458
Hauraki	7	7D	-38.0055	176.18496
Hauraki	8	8A	-38.0055	176.18404
Hauraki	9	9A	-38.0054	176.18396
Hauraki	10	10A	-38.0054	176.1839
Hauraki	11	11A	-38.0054	176.18385
Hauraki	12	12A	-38.0054	176.18381
Hauraki	12	12B	-38.0054	176.18374