E

APPENDIX E

Sediment Assessment – Tonkin & Taylor

REPORT

Tonkin+Taylor

Mangorei HEPS Consent Renewal

Lake Mangamahoe Sediment Assessment

Prepared for
Trustpower Ltd

Prepared by
Tonkin & Taylor Ltd

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Exceptional thinking together

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Executive summary

Trustpower Ltd's (Trustpower) Mangorei (MGR) hydroelectric power scheme (HEPS) requires renewal of its resource consents, which are due to expire on 1 June 2021.

Sedimentation within the lake may reduce lake capacity, affecting the available operating range of Lake Mangamahoe. As such, Trustpower is seeking to understand the implications of the lake tributaries (Mangamahoe Stream and Kent Road Tributary) and the Waiwhakaiho intake and tunnel (diversion from the Waiwhakaiho River) in delivering sediment to Lake Mangamahoe.

Tonkin & Taylor Ltd (T+T) have been engaged to identify catchment scale sediment sources, transport and depositional processes within the wider Lake Mangamahoe catchment (focussing on Mangamahoe Stream, Kent Road Tributary and Waiwhakaiho Stream), and the role of these processes in observed sedimentation patterns within Lake Mangamahoe. Trustpower also requested the development of an indicative sediment budget for Lake Mangamahoe.

An assessment of catchment scale geomorphic processes in the Waiwhakaiho River, Mangamahoe Stream and Kent Road tributary suggests the following:

- Sources of sediment, and consequently sediment loads entering Lake Mangamahoe vary through time. Ongoing and historic land use changes may be increasing sediment loads, with pasture and pine forestry likely to be contributing to any increase in sediment loads. Episodic events such as landslides, bank erosion and infrastructure failures (such as the SH3 culvert blow-out) are unpredictable, are difficult to quantify in an 'annual load', and may contribute large pulses of sediment that may last between several years to several decades.
- Estimated catchment sediment yields and suspended sediment concentration (SSC) monitoring data suggest that Waiwhakaiho River may be the main contributor of sediment to Lake Mangamahoe, through the Waiwhakaiho tunnel, accounting for anywhere between 37% and 80% of the load. However, catchment estimates of sediment yield used in this report (for Mangamahoe Stream and Kent Road Tributary) may be underestimated, and do not take into account episodic events. As such, Mangamahoe Stream and Kent Road Tributary may be responsible for a much larger proportion of Lake Mangamahoe's sediment load than currently predicted.
- Sediment entering Lake Mangamahoe has a variety of origins, with a complex array of catchment scale drivers controlling sediment loads.
- An investigation of changes in bed elevation between 2013 and 2017 suggests the NPDC town water supply pipe across the bed of Lake Mangamahoe is having a considerable effect on sedimentation patterns in the lake, with the greatest accumulations of sediment occurring 'upstream' of the pipe in the southern arm of the lake. Silt depths in the southern arm of the lake are likely to be on average between 3 and 5 m deep.
- The estimated sediment loads from three data sources (Beca (2012), BTW silt monitoring (2019), and SSC monitoring) are different, with the loads calculated from the SSC monitoring lower than the other values derived from the BTW silt monitoring (2019) and Beca (2012) SSC rating curve. Therefore, each will have different implications for water storage volume within Lake Mangamahoe. The lack of detailed lake bathymetry from the 1930's (when the lake was originally formed), and relatively small sediment monitoring dataset make it difficult to determine which is most likely to be correct. In addition, as all the bathymetric surveys to date have occurred in the southern arm, it is impossible to determine the changes in lake bed elevation for the whole lake.

Table E.1: Summary of estimated sediment loads entering Lake Mangamahoe, estimated average sediment depth increases, and estimated average annual volumetric change in the southern arm.

	Beca (2012) updated with NIWA (2020)	Tunnel outlet channel SSC monitoring (2019/2020)* with NIWA (2020)	BTW silt depth monitoring (2019) (Southern arm only)**
Total estimated annual suspended sediment loads (t/yr)	1,575	618	974
Average annual sediment depth change (southern arm only) (m)	0.04	0.02	0.05
Average annual volumetric change (southern arm only) (m^3)	939	368	974

*Extrapolated from a small data set spanning November 2019 to May 2020 and are indicative only.

**Based on estimated overall observed sediment volume from silt depth monitoring for the southern arm undertaken in December 2019. Note that the estimates above have been calculated for the whole 88 year period since the lake's construction.

1 Introduction

Trustpower Ltd's (Trustpower) Mangorei (MGR) hydroelectric power scheme (HEPS) requires renewal of its resource consents, which are due to expire on 1 June 2021.

Trustpower are seeking to understand the role of the lake tributaries (Mangamahoe Stream and Kent Road Tributary) and the Waiwhakaiho intake and tunnel (diversion from the Waiwhakaiho River) in delivering sediment to Lake Mangamahoe. Sedimentation within the lake may reduce lake capacity, affecting Trustpower's generation capacity.

Tonkin & Taylor Ltd (T+T) have been engaged to investigate the following:

1. Indicative sediment budget for Lake Mangamahoe that identifies the approximate proportions of sediment derived from each potential source, including the Waiwhakaiho tunnel and lake tributary streams.
2. An additional review of the effects of the MGR HEPS on downstream river character and behaviour was requested by Trustpower following a community workshop held as part of the reconsenting process. The downstream geomorphic effects review has been included in Appendix B.

A site visit was undertaken by T+T fluvial geomorphologists and a Trustpower hydrologist on 5 February 2019. Several sites within the Waiwhakaiho and Mangamahoe Stream catchments were visited.

1.1 Background

Lake Mangamahoe and the Waiwhakaiho tunnel were both constructed in the 1930's for hydroelectricity generation. An earthen dam was constructed across Mangamahoe Stream, and the valley flooded.

Lake Mangamahoe is used for both hydroelectricity generation and as the town water supply for New Plymouth, managed by New Plymouth District Council (NPDC).

Historically, the flow through the Waiwhakaiho Tunnel was 7 m^3/s. However, Trustpower applied to increase the maximum consented take from the Waiwhakaiho River through the Waiwhakaiho tunnel (to Lake Mangamahoe) to 10 m^3/s in 2013. In order to achieve the maximum take of 10 m^3/s, flow in the Waiwhakaiho River theoretically needs to exceed 17 – 18 m^3/s. However, recent analysis shows that flows higher than 9 m^3/s only occur 0.13% of the time. (T+T 2020).

During the variation to the resource consent condition application process for the increased take, it is understood the issue of sedimentation within Lake Mangamahoe and a potential loss of water supply storage volume was raised. To support an increased take, work was undertaken by Beca (2012) to investigate the potential increase in sediment within Lake Mangamahoe that could be expected from the increased take (10 m^3/s). Beca (2012) developed a sediment rating curve for potential sediment volumes/loads expected to pass through the Waiwhakaiho tunnel into Lake Mangamahoe (Figure 1.1). To do this Beca (2012) analysed 180 suspended sediment samples from the Waiwhakaiho River upstream of the intake over a 15 year period from 1990 – 2005. Of these 180 samples, Beca (2012) excluded 155 samples which fell below 2 g/m^3. Of the remaining samples, only three were in excess of 50 g/m^3. Beca found the 25 samples above 2 g/m^3 to be well correlated to flow within the Waiwhakaiho River (R^2 = 0.78).

Their results suggested that an estimated 1182 tonnes per year of suspended sediment would enter Lake Mangamahoe through the Waiwhakaiho tunnel with the increased maximum take of 10 m^3/s and with the tunnel closed 0.7% of the time. Beca (2012) suggest a further 400 tonnes per year of suspended sediment is entering Lake Mangamahoe from Mangamahoe Stream based on NIWA's Water Resource Explorer NZ (WRENZ) webtool, which is no longer in use[1].

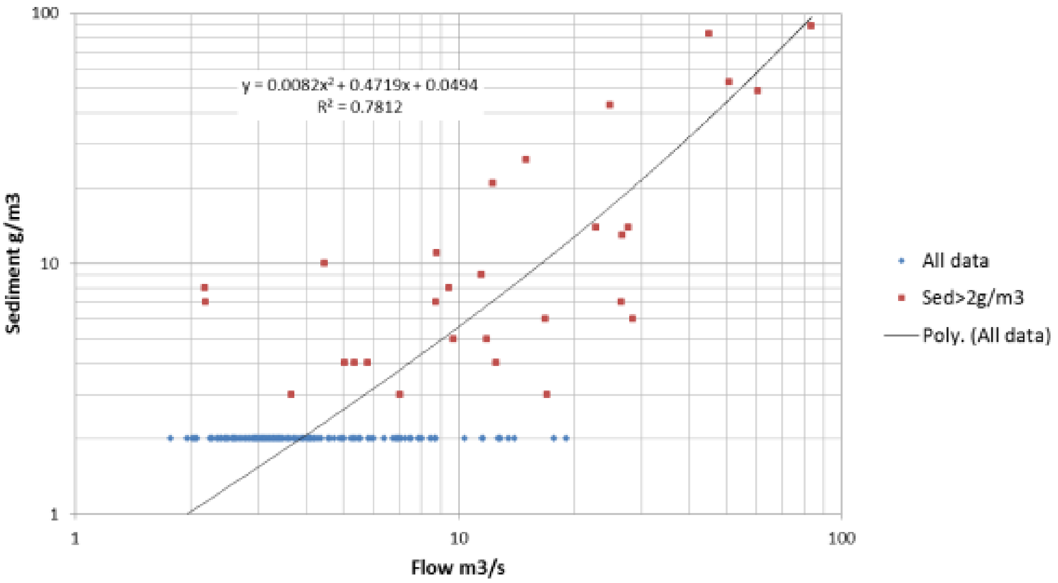
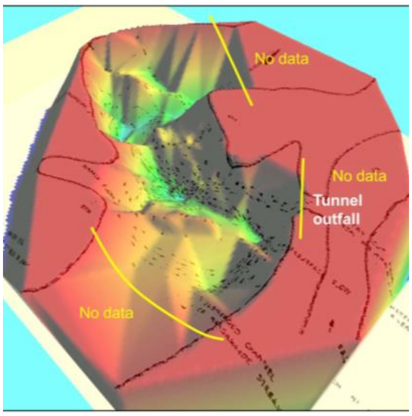


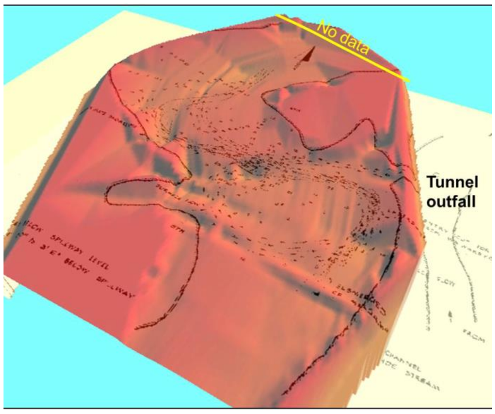
Figure 1.1: Sediment rating curve developed by Beca (2012).

An assessment of changes in lake bed elevation was also undertaken by Beca (2012) which suggests that bed levels in Lake Mangamahoe have increased on average between 4 – 5 m between 1959 and 2011 (Figure 1.2). Beca (2012) also suggest that in some localised areas there may be an increase in elevation of between 7 – 8 m. Beca (2012) do not discuss where these areas are, however casual observation of the 3D elevation surfaces in Figure 1.2 suggest the greatest elevation increases have been in the deepest 'centre' parts of the lake, that would once have been the old Mangamahoe Stream channel. This follows expected depositional processes, where sediment will be more likely to accumulate in the deeper, slower moving parts of the lake.

Evidence of sedimentation in the southern arm of Lake Mangamahoe can also been seen in the earliest historic aerials (1957). This is discussed further in Section 5.2.



3D digitised elevation of the bed of Lake Mangamahoe in 1959 (taken from Beca 2012)



3D image of bed elevation of Lake Mangamahoe in 2011 (taken from Beca 2012)

Figure 1.2: Bathymetric survey of Lake Mangamahoe from 1959 and 2011 undertaken by Beca in 2012.

[1] WRENZ has likely been replaced by more updated tools such as NZ River Maps. As WRENZ is no longer available, the data presented by Beca (2012) is unable to be checked or substantiated. As such, data from the more recent updated tools have been used.

2 Catchment context

The wider catchment context and existing conditions are critical to describing and understanding the source and transport mechanisms of sediment in fluvial systems. While it is recognised that the wider catchment is outside of Trustpower's influence[2], appreciation of the existing conditions helps to provide an understanding of the drivers of sediment dynamics in the Waiwhakaiho River, Mangamahoe Stream and Kent Road Tributary.

2.1 Catchment descriptions

Lake Mangamahoe is an artificial lake 9 km southeast of New Plymouth and has a surface area of 25 ha. The lake is fed by three sources; the Mangamahoe Stream, Kent Road tributary and a diversion from the Waiwhakaiho River via the river intake and tunnel infrastructure (See Figure 2.1 and Table 2.1).

In general, Mangamahoe Stream and Kent Road tributary are similar with respect to catchment conditions, while the Waiwhakaiho River catchment has many catchment characteristics which differ from the other two tributaries, as discussed further in this section. There are several key catchment components that affect sediment source and transfer within a river catchment. These are summarised in Table 2.1, and will be discussed in more detail in the following sections.

Table 2.1: Summary of catchment components that influence sediment source and transfer

Sub-catchment	Waiwhakaiho (to intake)	Mangamahoe (to Lake Mangamahoe)	Kent Road (to Lake Mangamahoe)
Catchment area (km^2)	62	4.5	3
Approx. river length (km)[3]	20	8	7
Average slope	5%	2%	2%
Mean Annual Flood (MAF) (m^3/s)[4]	330 (SH3 gauge)	13.5 (at lake entrance)	8.3 (at lake entrance)
Dominant geology[5]	Debris deposits (85%)	Debris deposits (99%)	Debris deposits (100%)
Dominant soils[6]	Orthic allophanic (40%)	Orthic-allophanic (100%)	Orthic-allophanic (100%)
Dominant landcover[7]	Indigenous forest (55%)	Grassland (98%)	Grassland (97%)

[2] Trustpower holds the title to the bed of Lake Mangamahoe, and small areas around key HEPs infrastructure. Trustpower does not own or manage other land within the wider catchment.
[3] https://shiny.niwa.co.nz/nzrivermaps/
[4] https://niwa.maps.arcgis.com/apps/webappviewer/index.html?id=933e8f24fe9140f99dfb57173087f27d
[5] GNS 250K.
[6] New Zealand Soil Classification
[7] https://www.lawa.org.nz/explore-data/land-cover/

Sub-catchment	Waiwhakaiho (to intake)	Mangamahoe (to Lake Mangamahoe)	Kent Road (to Lake Mangamahoe)
Dominant sediment type	Boulders, cobbles	Lag boulders, fines (sands and silts)	Lag boulders, fines (sands and silts)
Dominant catchment sources of sediment	Landslides Land use	Land use	Land use
Dominant in-stream sources of sediment	Bank erosion In-stream sediment stores	Sediment slugs	Sediment slugs

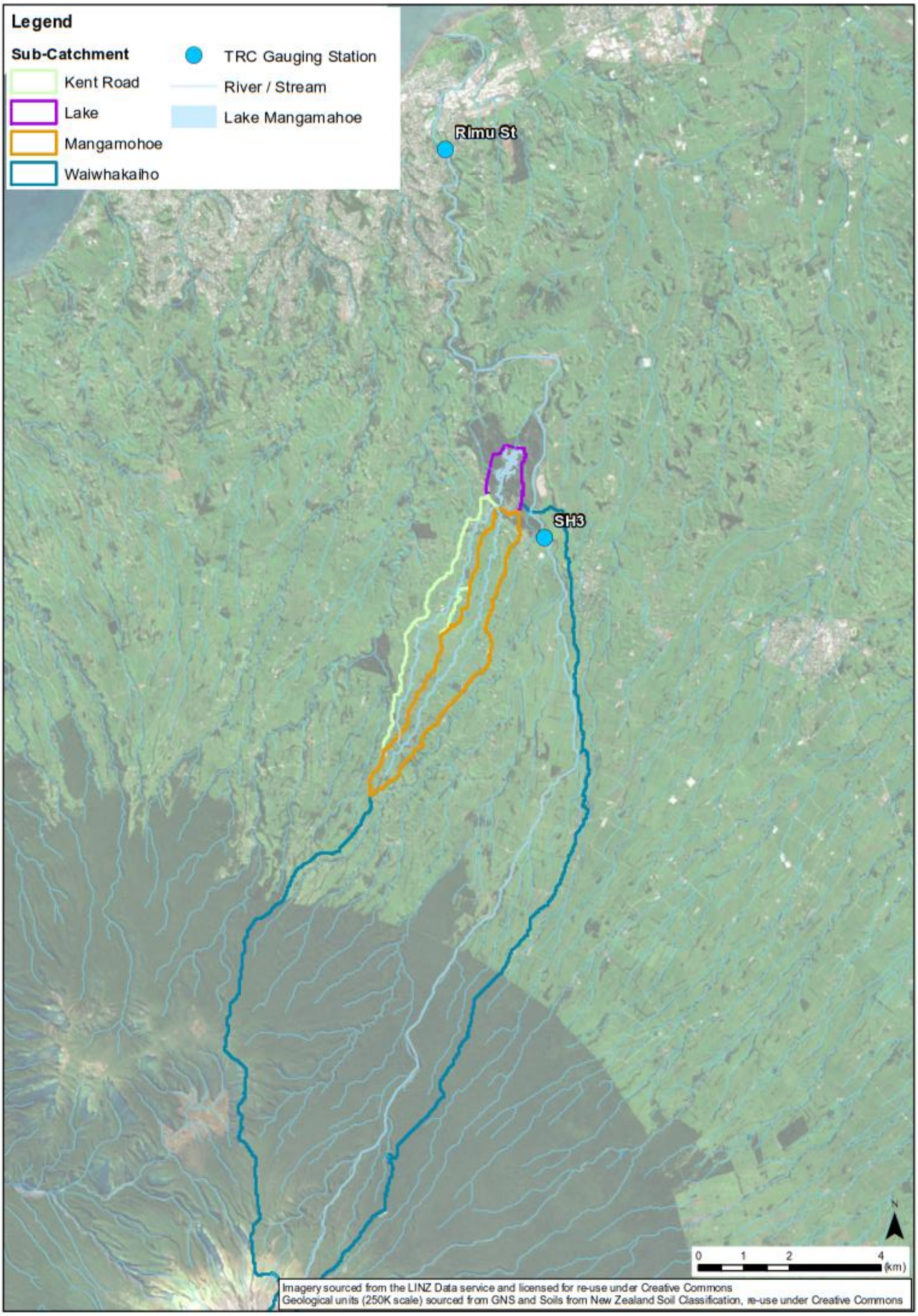


Figure 2.1: Lake Mangamahoe catchment setting with sub-catchments labelled.

2.1.1 Geology and soils

Sediment supply and transfer within all three sub-catchments is profoundly influenced by geology, and consequently surface soils. At the headwaters of the Waiwhakaiho River, on the north-eastern flanks of Mount Taranaki, the river flows through recent (Holocene) volcanic material dominated by multiple beds of unconsolidated deposits, mostly of gravel and sands. However, cobbles and boulders are also present. These deposits erode easily, with sand to clay sized particles being transported the furthest downstream as suspended sediment.

On the ring plain, the river flows through Holocene lahar flow deposits made of gravel and sands, with occasional deposits of large boulders, before flowing through Late Pleistocene lahar deposits (debris deposits in Figure 2.2). Downstream of the Waiwhakaiho tunnel intake, the Waiwhakaiho River passes through Holocene river deposits of reworked volcanic material (boulders, gravels and sands).

The Mangamahoe and Kent Road catchments consist of mid-Pleistocene debris avalanche deposits (lahar deposits; Figure 2.2), which are predominately debris cobbles overlain by sand and ash.

Generally, the lahar deposits are likely to be unconsolidated and will contribute fine gravels to clays (mostly silt and clays) into the fluvial system. This is because these deposit types are highly erodible. However, the older lahar deposits (such as in the Mangamahoe and Kent Road catchments) are likely to have a higher content of clay due to weathering processes. The higher clay content makes these deposits less erodible.

The surface geology throughout all catchments shows that ash and sand contained within debris deposits is prevalent, which will be forming most of the suspended sediment load.

Detailed regional soil maps do not yet exist for the Taranaki area, however the soil orders have been mapped. Most of the catchments are identified as Allophanic Soils which have a low erosion rate unless exposed or on steep slopes. The Allophanic soils mostly comprise fines and in exposed banks will likely erode into waterways as sands, silts and clays.

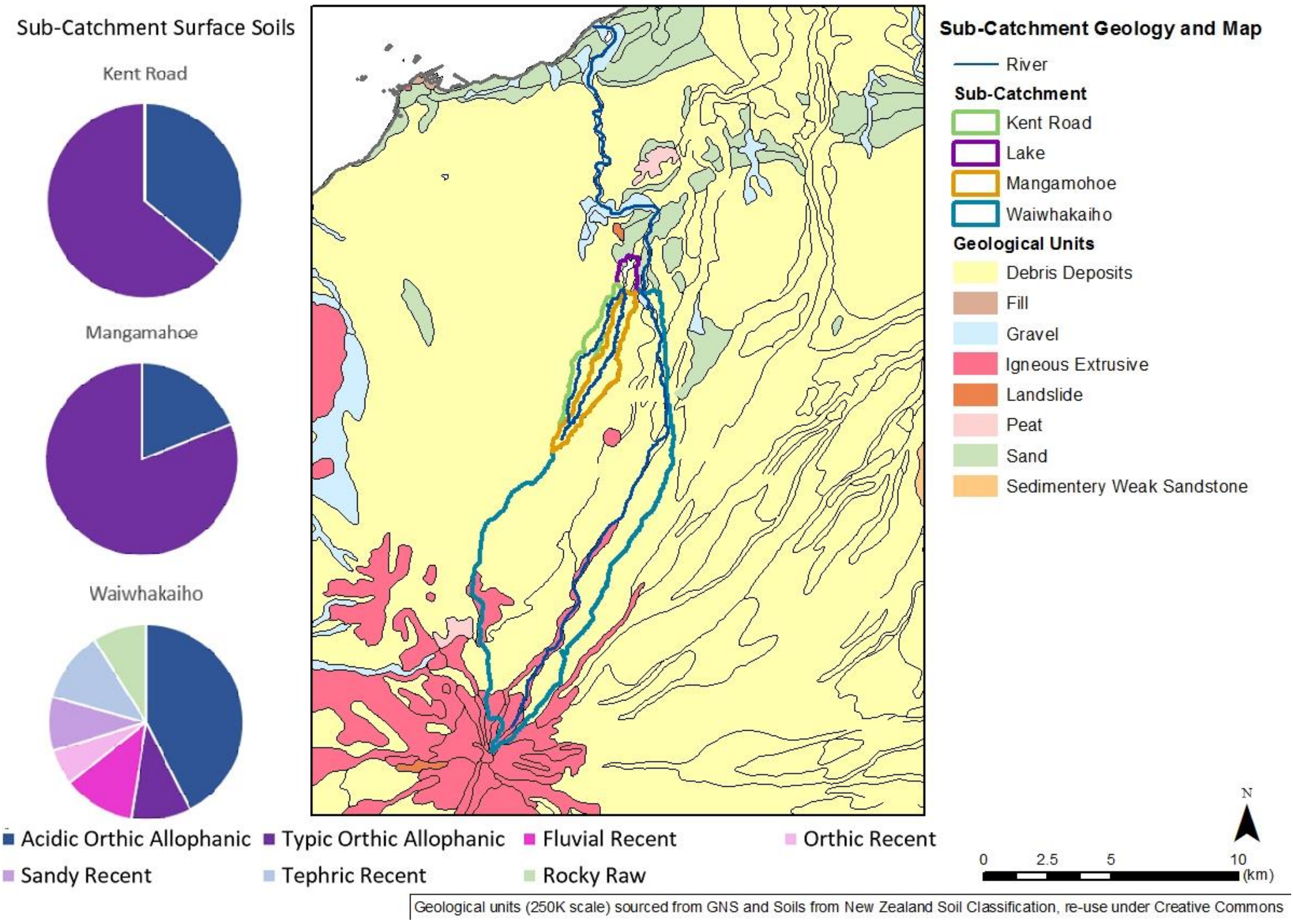


Figure 2.2: Geology and soils map of the Waiwhakaiho catchment. Source: GNS 250K and New Zealand Soil Classification.

2.1.2 Catchment land-cover

Land-cover is well known to greatly affect soil erosion, as well as surface run-off. The headwaters of the Waiwhakaiho River are predominantly in indigenous forest in the Egmont National Park. In the lower reaches of the Waiwhakaiho River (from the ring plain almost to the coast), pastureland (e.g. grassland/cropland) is prevalent (42%).

Pastureland is the dominant land-cover in the Mangamahoe Stream and the Kent Road tributary sub-catchments (~ 97%) (Table 2.2).

There are several blocks of pine surrounding Lake Mangamahoe which have been present since at least the 1960’s and possibly earlier.

Table 2.2: Land cover in the Waiwhakaiho River catchment in 2012. Source: Landcare Research.

Land cover	Area as % of Mangamahoe catchment	Area as % of Kent Road tributary catchment	Area as % of Waiwhakaiho sub-catchment
Indigenous forest	1	3	55
Exotic forest	1	0	1
Shrubland	0	0	0
Grassland/Cropland	98	97	42
Bare earth	0	0	2
Urban area	0	0	0

2.2 Stream descriptions

2.2.1 Waiwhakaiho River

The Waiwhakaiho River catchment is approximately 145 km^2, and the river is approximately 39 km long from the headwaters (at 1,600 m above sea level) to the coast.

The 20 km reach from the headwaters to the Waiwhkaiho intake is the study area for this report, which has an approximate catchment area of 62 km^2.

This 20 km reach has an approximate gradient of 5%. However, the grade is not uniform, with the first 10 km from the headwaters being approx. 12%, compared to a channel grade of 2% in the lower 10 km of the Waiwhakaiho River upstream of the intake (Figure 2.3).The steeper sections of the Waiwhakaiho River will be better at transporting sediment than the less steep sections.

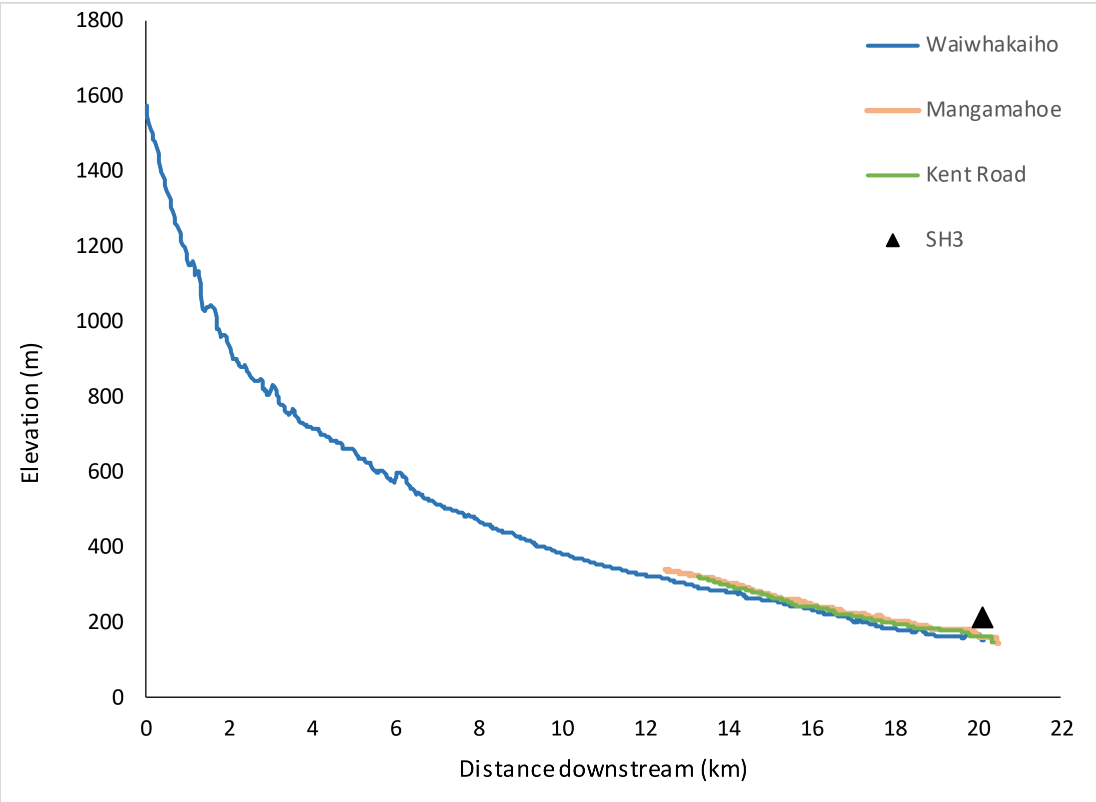


Figure 2.3: Long profile of Waiwhakaiho River up to the intake tunnel, Mangamahoe Stream and Kent Road tributary. DEM sourced from University of Otago National School of Surveying.

The mean annual flood (MAF) at the approach to the Waiwhakaiho intake structure is about 330 m^3/s. For the purposes of this report, we assume MAF to be bankfull discharge and the flow capable of undertaking the most geomorphic work, and therefore transport the most sediment (Rutherford *et al.* 2000).

Analysis of the largest 60 flows within the Waiwhakaiho River between 1980-2019 suggest that there are 'clusters' of larger events, with some years experiencing several large floods (Figure 2.4). These event clusters are likely to increase the amount of sediment transported by the Waiwhakaiho River in certain years, and is discussed in more detail in Section A1. In addition, flood events in the Waiwhakaiho River display a 'flashy' nature, with flows rising and falling rapidly, discussed further in Section 3.2.

The Waiwhakaiho River is an incised wandering, mixed bed river characterised by bed and bank material comprised of large boulders, cobbles, coarse gravels and fine sediment. The true left bank near the intake structure is bedrock (conglomerate), and on the true right, there are erodible banks of cobbles held in a loose sand matrix. Evidence of scroll bars on the true right bank floodplain (opposite the intake structure), suggests the river is laterally active, and the thalweg has migrated towards the true left bank (where it now sits, near the intake structure).

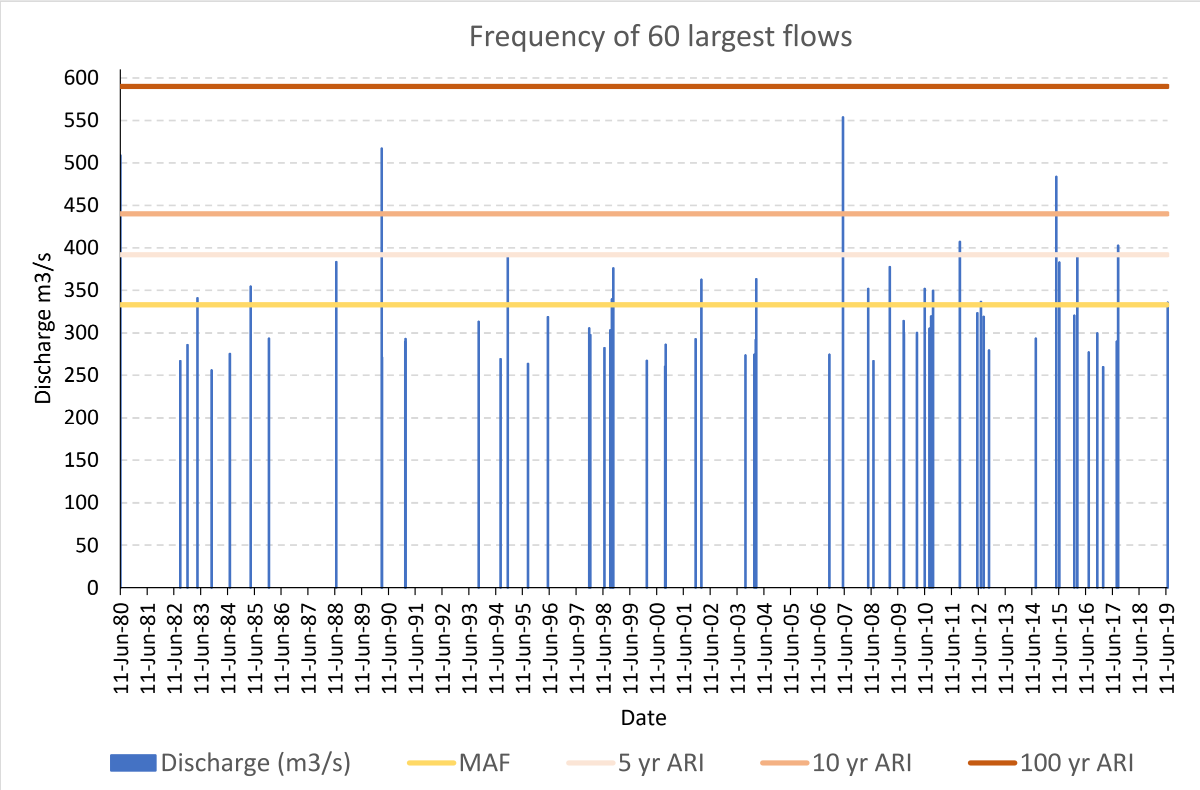


Figure 2.4: The 60 largest flows recorded for the Waiwhakaiho River (SH3) between 1980 and 2019, with mean annual flood (MAF), 5, 10 and 100 year ARI flow thresholds (using EV1) shown.

Near the headwaters, the average active channel width is 10 m, which widens near the tunnel intake to an average active channel width of approximately 40 m. With a decrease in slope and the active channel widening, the reach near the Waiwhakaiho intake is likely to be a 'storage reach' where sediment is deposited and temporarily stored within the channel. This is supported by the occurrence of in-stream geomorphic units such as lateral bars, point bars and islands (which are all 'stores' of sediment) in areas where the channel is wider. These units temporarily store sediment in the channel, which is available to be reworked and transported downstream during subsequent flood events.

A terrace on the true right floodplain near the intake structure, suggests the Waiwhakaiho River has undergone substantial incision in the past. This could be attributed to a long-term reduction in sediment supply, or an increase in sediment transport capacity. It could also be a remnant of volcanism, such as localised uplift or river incision through lahar deposits/debris flows.

2.2.2 Mangamahoe Stream and Kent Road tributary

In comparison to the Waiwhakaiho River, the Mangamahoe Stream and Kent Road tributary stream are both relatively small. The Mangamahoe Stream catchment is approximately 4.5 km^2 with a stream length of 8 km to Lake Mangamahoe, and an average slope of 2%. Kent Road Tributary has a catchment size of 3 km^2, stream length of 7 km and slope of 2%. Both streams originate on the ring plain at about 380 m above sea level, and both are relatively lower discharge streams (mean annual flood is 13.5 m^3/s in Mangamahoe Stream and 8.3 m^3/s in Kent Road tributary (NIWA 2019).

Both the Mangamahoe Stream and the Kent Road tributary are characterised as deeply incised, single thread streams. Channel widths range from about 1 – 3 m. As the streams are incised, they are essentially confined to a narrow valley, reducing the possibility for substantial in-stream sediment storage. While these streams are characterised by modest flows, the confinement of all flows to a narrow valley setting increases the sediment transport capacity during larger events.

While both streams appear to be ‘meandering’, lateral migration through bank erosion is unlikely to occur, as this process is often difficult in incised streams. However, when it does occur, bank erosion will produce large volumes of sediment. Erosion of the bed is more likely to occur but is often controlled by coarse surface armouring of large boulders from the lahar deposits, which the stream is unlikely to be able to mobilise.

Near the headwaters, these streams have a fine sediment bed. However, downstream of SH3 and entering into Lake Mangamahoe, these streams contain large boulders (approximately 1 m in diameter) from lahar deposits. Evidence of excessive fine sediment deposited in the pools between the boulders was observed during the site visit.

Historic photographs suggest that the Mangamahoe Stream has previously been subjected to large pulses of fine grained sediment. Figure 2.5 shows substantial deposits of fine grained sediment behind a weir in the Mangamahoe Stream. Lambert (2015) suggests the photo is from the draining of Lake Mangamahoe in 1950, which would explain the large volume of fine grained material. The weir still exists today, and is located downstream of Lake Mangamahoe, and is no longer subject to substantial stream flows. It is therefore likely this portion of Mangamahoe Stream (downstream of Lake Mangamahoe) may still have large stores of fine-grained sediment.

Figure 2.5: Historic photo of Mangamahoe Stream likely taken in the 1950's following the draining of Lake Mangamahoe. Source: Trustpower Ltd and Lambert 2015.

3 Sediment regime

There are a few critical elements in assessing a sediment regime in a system. One is the type of sediment in the system, how each type is transported (bed load versus in suspension), and how the different sediment types interact with each other (Section 3.1).

As only the suspended sediment in the Waiwhakaiho River is able to pass through the intake structure and into Lake Mangamahoe (due to the debris screens, location of the intake in relation to the flow current, and intake position in relation to bed level), it is the suspended sediment type that is of particular interest for this report.

The suspended sediment faction in the Waiwhakaiho River, Mangamahoe Stream and Kent Road Tributary originates almost entirely from the underlying geology and surface soils (Section 2.1.1 and discussed further in Section 3.1). Land-cover, river behaviour and flow dynamics (amongst other factors) all influence the volume and concentration of fine-grained sediment held in suspension (discussed further in Section 3.2 and Section 3.3). Other than routine and infrequent clearing of the weir pool by the intake structure[8], Trustpower's operational and maintenance activities have no effect on suspended sediment in the Waiwhakaiho River.

To understand suspended sediment dynamics in the Waiwhakaiho River and how this relates to sediment entrainment into Lake Mangamahoe, continuous suspended sediment concentration (SSC) monitoring was undertaken in the tunnel outlet channel since November 2019, and at the Waiwhakaiho intake structure since January 2020 (refer to T+T, 2019 for the sampling methodology and sensor locations). Section 3.2 describes the results of the monitoring to date (up until May 2020).

The suspended sediment load that is able to pass through the Waiwhakaiho intake and into Lake Mangamahoe is discussed in Section 3.3. This analysis is based on different data sources, including the SSC monitoring.

3.1 Sediment type

The sediment present in the Waiwhakaiho River is predominantly rounded grey boulders (> 0.3 m diameter), and large cobbles (between 0.06 m and 0.3 m diameter) with some fine sediment (e.g. sands and silts) (Table 3.1). There are some large boulders that are approximately 1 m in diameter, which are likely sourced from lahar deposits (Section 2.1.1). There are several of these large boulders immediately downstream of the weir, with one resting on the weir apron, suggesting they are transported during high flows. Anecdotal evidence suggests these boulders are mobilised frequently during annual flood events.

Table 3.1: Summary of sediment types for the three study watercourses.

Watercourse	Large sediment type and diameter	Large sediment mobility	Armour layer present	Armour layer removable	Dominant mobile sediment type
Waiwhakaiho River	Boulders (1 m)	Mobile	Yes	Yes	Boulders and cobbles, with some fines
Mangamahoe Stream	Boulders (1 m)	Immobile (lag)	Yes	No	Fines
Kent Road Tributary	Boulders (1 m)	Immobile (lag)	Yes	No	Fines

[8] Chris England pers. comm. 5 February 2019.

In the Waiwhakaiho River, fine sediment was observed on geomorphic units (e.g. at the downstream end of a gravel bar) and in the banks of the river during the site visit (Figure 3.1). Layers of fine sediment are also likely to be present under the surface armour layer on some gravel bars (shown in Figure 3.1). These fines are likely to be protected from entrainment, until higher flow events mobilise the surface armour layer, exposing the fine sediment for entrainment and transport. The armour layer was observed to be partially imbricated on the bar immediately upstream of the intake structure. Imbrication of surface gravels is where the individual gravel or boulders overlap and interlock in the direction of flow, providing greater protection to the bar surface from erosive forces. This kind of armouring suggests that some sediment stores in the Waiwhakaiho River are less likely to be reworked, with larger flows required to mobilise and entrain the sediment. This would suggest that suspended sediment concentrations may not necessarily be directly or proportionally linked to river discharge.

There was no observed sediment deposition (coarse or fine) near the tunnel outlet, or in most of the outlet channel (it was just bedrock). However, 40 m downstream of the tunnel outlet structure there were angular boulders that were different in appearance from the sediment observed in the Waiwhakaiho River. Angular boulders are indicative of minimal fluvial reworking, suggesting the boulders in the outlet channel are colluvial in nature and have come directly from the adjoining hillslopes. Due to the size of these boulders, they would also not fit through the screens on the Waiwhakaiho River side of the intake structure.

Downstream of the tunnel outlet structure (approximately 80 m), the channel widens (from approximately 3 m to 10 m wide), and velocities are low enough to encourage sediment deposition. A submerged bench attached to the bank, and an in-stream bar in the centre of the channel were observed at this location during the site visit. Both areas of sediment deposition contained reddish yellow sediment, which was noted to be different in appearance to the sediment observed in the Waiwhakaiho River (Figure 3.1). It suggests there may be other sources of sediment contributing to the outlet channel, such as the local lake catchment hillslopes.

As mentioned in Section 2.2 and summarised in Table 3.1 near Lake Mangamahoe, both the Kent Road tributary and Mangamahoe Stream have large boulders in the channel (approximately 1 m diameter), but the observed fine sediment deposition in the spaces between boulders suggests the fines are the most active portion (Figure 3.1). There did not appear to be an active cobble layer. Downstream coarsening of sediment in this manner is unexpected and is most likely attributable to the surrounding geology (lahar deposits, Figure 2.2). Given the relatively low discharge regimes of both Mangamahoe Stream and Kent Road tributary, it is unlikely that these boulders are able to be transported as bedload (TRC 2011) and therefore supports the theory these are lahar remnants (lag boulders). These lag boulders are considered an 'armour layer', but they are unlikely to be removed in the current hydrological regime, and unlikely to expose any fine-grained sediment underneath.

	
Evidence of coarse sediment in the Waiwhakaiho River at the Waiwhakaiho tunnel intake. Note the deposition of fine gravel and sands at the edge of the gravel bar.	*Large boulders downstream of the weir on the Waiwhakaiho River. Banks of boulders and gravels held in a loose sand matrix.*
	
Boulders and gravels in the Waiwhakaiho tunnel outlet channel which was angular in comparison to the rounded boulders in the Waiwhakaiho River.	*Underwater fine sediment and some pebbles deposited at the end of the Waiwhakaiho tunnel outlet channel, near Lake Mangamahoe. The sediment was red/yellow in colour.*
	
Evidence of fine sediment deposited near the headwaters in Mangamahoe Stream.	*Evidence of fine sediment bed in a low velocity pool near the headwaters in Mangamahoe Stream.*

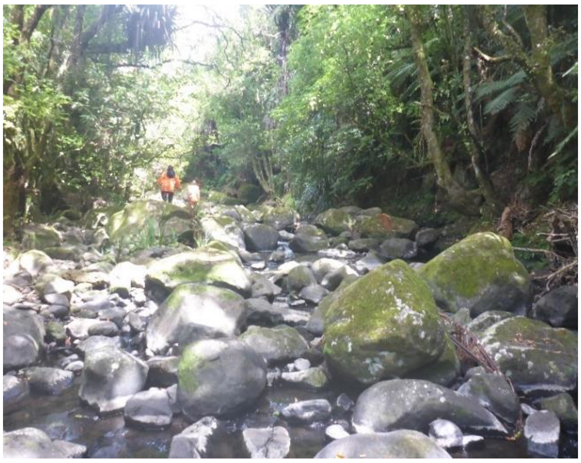
	
Evidence of large boulders (approximately 1 m in diameter) in the Mangamahoe Stream near Lake Mangamahoe. Fine sediment is deposited in the pools between boulders.	*Evidence of thick fine sediment deposition in the Kent Road tributary.*

Figure 3.1: Site photographs showing differences in sediment size and type in the Waiwhakaiho River, Waiwhakaiho tunnel outlet channel, Kent Road tributary and Mangamahoe Stream.

3.2 Suspended sediment monitoring

Suspended sediment concentration (SSC) was measured in the Waiwhakaiho tunnel outlet channel to determine the concentration of suspended sediment actually entering Lake Mangamahoe from the Waiwhakaiho tunnel (refer to T+T 2019 for the methodology). The monitoring began on 16 October 2019. To enable a comparison of SSC in the Waiwhakaiho River with the SSC entering Lake Mangamahoe through the Waiwhakaiho tunnel, another SSC sensor was installed on the intake structure. Due to operational constraints, this sensor was installed and operational several weeks later on 17 January 2020.

To develop an understanding of how SSC relates to both the Waiwhakaiho River discharge and the water flow passing through the tunnel, the SSC data was matched to TRC flow records at the Waiwhakaiho SH3 gauge (Figure 2.1) and the tunnel flow data provided by Trustpower.

SSC at the tunnel outlet is typically below 50 mg/l (Figure 3.2). However, there are 21 events where SSC at the tunnel outlet exceeds 100 mg/l, and only four of these events correspond to river flows greater than 85 m^3/s as measured at the Waiwhakaiho River SH3 gauge.

There were spikes in SSC when flow in the Waiwhakaiho River was low in February and March 2020. This suggests that the SSC measurement in the tunnel outlet channel may be affected by something other than flow. These anomalies have mostly been removed for further analyses.

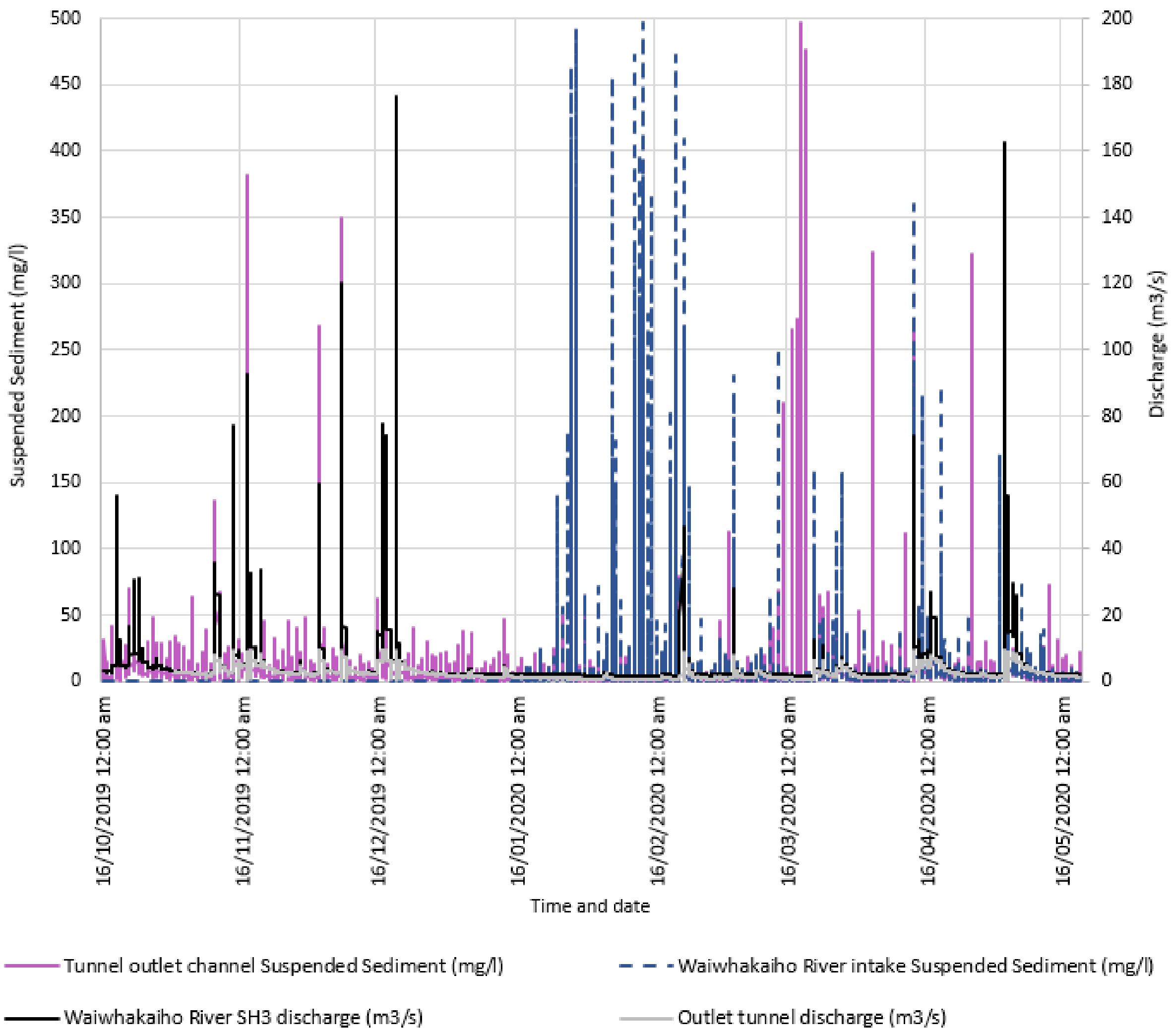


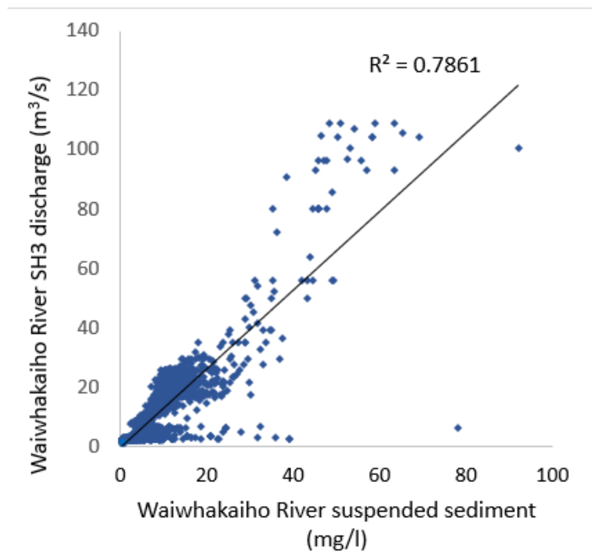
Figure 3.2: Suspended sediment (mg/l) at the Tunnel Outlet and the Waiwhakaiho River Intake, as well as Waiwhakaiho River SH3 discharge (m^3/s) over time (October 2019 to May 2020).

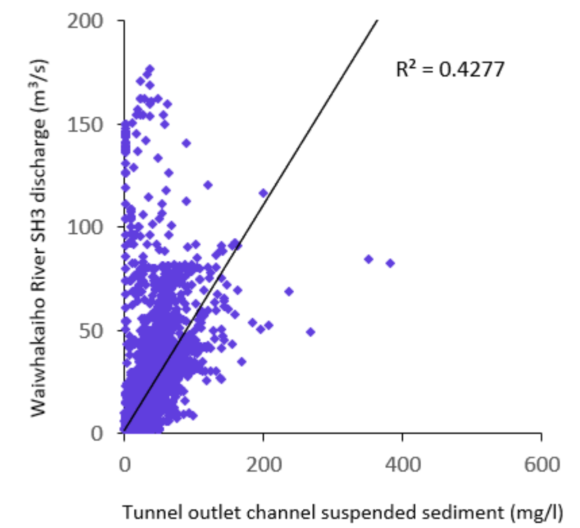
There is a strong correlation between SSC and flow in the Waiwhakaiho River when data anomalies were removed[9] (Figure 3.3A). There appears to be a moderate correlation between flow in the Waiwhakaiho River and SSC in the tunnel outlet channel entering Lake Mangamahoe (Figure 3.3B).

The correlation between SSC in the Waiwhakaiho River and SSC in the tunnel outlet channel also appears to be moderate (Figure 3.3C). This correlation appears to be driven by the instances when SSC has been high in the Waiwhakaiho River, and not in the tunnel outlet channel. Almost all of these occurred when flow was low in the Waiwhakaiho River, and discharge through the tunnel was low.

While SSC in the Waiwhakaiho River and SSC in the tunnel outlet channel appears to be reasonably well correlated from the continuous monitoring data (Section 3.2 and Figure 3.3), no flows at or above MAF occurred throughout the monitoring period.

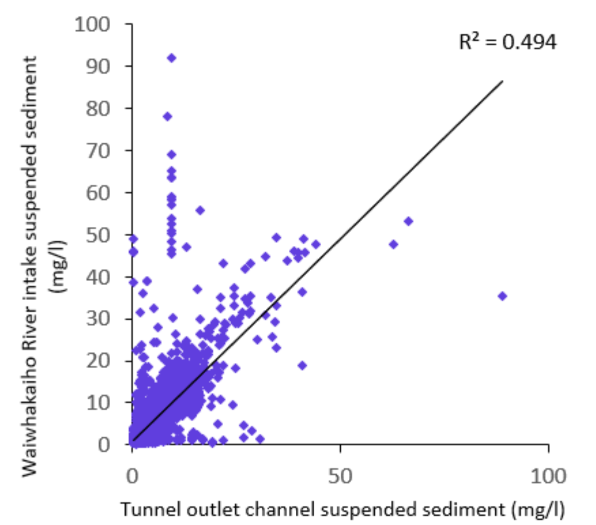
[9] Data anomalies suggested SSC was elevated in the Waiwhakaiho River when flows in the Waiwhakaiho were very low (<5 m^3/s). These anomalies could have been caused by debris sitting against the sensor, or increased turbidity associated with fish movement.





A -Waiwhakaiho suspended sediment concentration (mg/l) compared to Waiwhakaiho River SH3 discharge (m^3/s) (with all results below 5 m^3/s removed from the analysis).

B - Tunnel outlet channel suspended sediment concentration (mg/l) compared to Waiwhakaiho River SH3 discharge (m^3/s) (with all results below 5 m^3/s removed from the analysis).



C - Tunnel outlet channel suspended sediment (mg/l) compared to Waiwhakaiho River Intake suspended sediment (mg/l) (with all results below 5 m^3/s removed from the analysis).

Figure 3.3: Relationships between SSC (mg/l) and Waiwhakaiho River SH3 discharge (m^3/s) (Graphs A and B) and relationship between SSC in the tunnel outlet channel and the Waiwhakaiho River (Graph C). Values below 5 m^3/s have been removed from the analysis.

3.3 Suspended sediment loads

Estimates of the suspended sediment load for the three contributing catchments from NIWA (2017) are presented in Table 3.2. These estimates do not include sediment contributed to the systems through bed and bank erosion. In reality, sediment movement throughout a catchment is not uniform over time (Brierley and Fryirs 2013) and is greatly affected by episodic events. As mentioned in Section 1.1, Beca (2012) present the sediment load entering Lake Mangamahoe from Mangamahoe Stream as 400 tonnes/yr based on WRENZ[1] (Table 3.2). It is unclear whether this value includes the Kent Road tributary, and as such, this value has not been used in any further calculations, and the values from the publicly available NIWA River Maps used instead.

As these values are generally for terrestrially derived sediment (e.g. from run-off), they do not include the proportion of the Waiwhakaiho River sediment load captured by the Waiwhakaiho intake, which consequently enters Lake Mangamahoe.

To understand the suspended sediment loads entering Lake Mangamahoe from all sources, the amount of sediment passing through the tunnel needs to be accounted for. Table 3.2 provides the Beca (2012) estimate, and the estimate derived from the SSC monitoring data (Section 3.2)

Table 3.2: Estimated annual suspended sediment loads for the three study watercourses from several different data sources.

River	**Annual suspended sediment load (tonnes per year)**		
	Data taken from Beca (2012)	Data taken from NIWA (2017) and Sediment monitoring (2019/2020)	Updating Beca (2012) with data from NIWA (2017)
Mangamahoe Stream above SH3	*400**	243	243
Kent Road Tributary above SH3	*Unknown*	150	150
Waiwhakaiho tunnel (entering Lake Mangamahoe)	*1,182*	225**	1,182
TOTAL load entering Lake Mangamahoe per year	***1,582****	**618**	**1,575**

*Due to uncertainties in this data, these values are not used in further calculations.

**Based on continuous suspended sediment monitoring conducted over summer/autumn 2019/2020. Refer to Section 3.2.

Between 1994 and 2007 there was apparently a period of accelerated erosion in surrounding catchments. In particular, large storms in the second half of 1998 caused large scale erosion and vegetation damage on Mount Taranaki, leaving slopes and river banks vulnerable to higher erosion rates during following storms (TRC 2011). During subsequent high flow events, larger volumes of sediment were available to be transported downstream. This would suggest that any sediment monitoring undertaken between 1994 and 2007 (as used by Beca 2012) may in fact show elevated suspended sediment concentrations and should be recognised in the context of longer term patterns of sediment loads.

From their sediment rating curve, Beca estimated that the Waiwhakaiho tunnel was contributing 75% of the suspended sediment into Lake Mangamahoe (1,182 t/yr) based on a diversion capacity of both 7 m^3/s (no tunnel closure at river flows above 85 m^3/s) and 10 m^3/s (tunnel closed at river flow >85 m^3/s). While the annual load derived from the suspended sediment monitoring is likely to be underestimated (due to a small data set), the preliminary results suggest the load from the tunnel may be as low as 37% of the overall load entering Lake Mangamahoe.

A comparison of the SSC data analysed by Beca (2012) and that collected and analysed for this report (Figure 3.4) was undertaken. The results suggest that both the small sample size used by Beca in 2012, and possibly elevated sediment levels in the river due to headwater landslides, may have skewed the rating curve, and consequently be over-estimating the annual sediment load entering

Lake Mangamahoe. For example, based on the rating curves in Figure 3.4, a flow of 80 m^3/s would equate to an estimated 90 mg/l of sediment based of the Beca (2012) rating curve, and 40 mg/l based on the rating curve developed as part of this report.

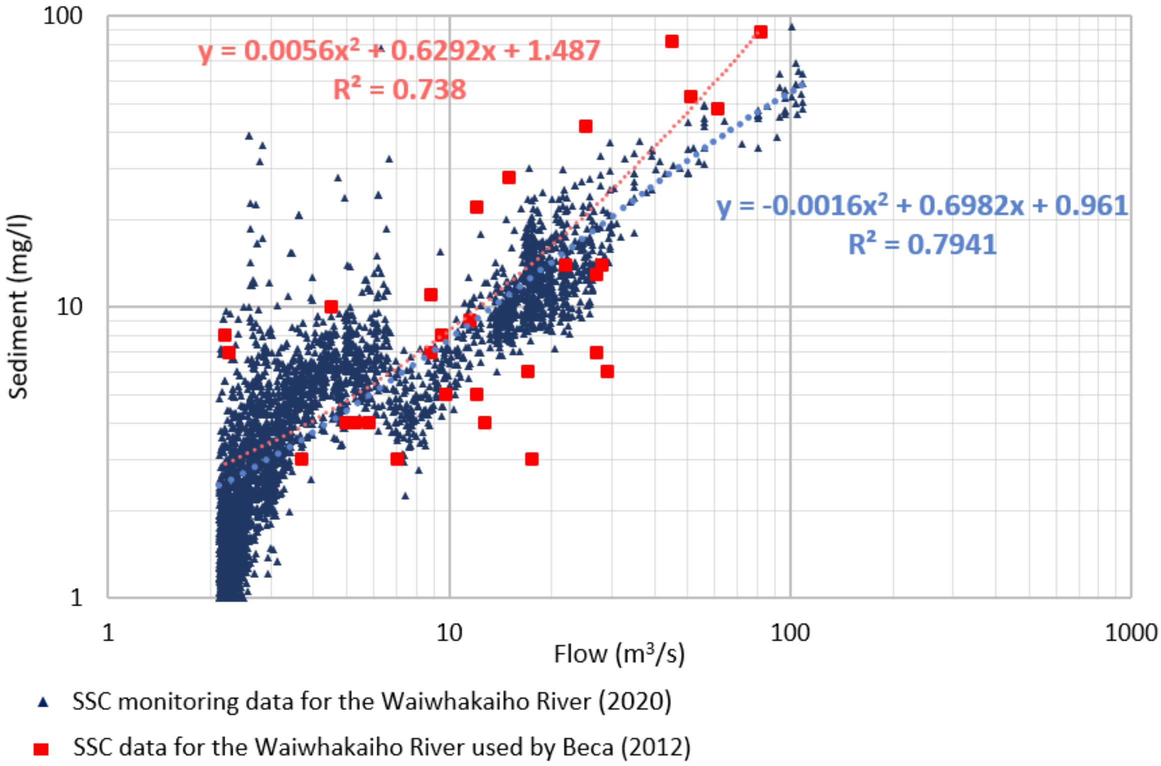


Figure 3.4: Comparison of SSC data analysed by Beca (2012) but collected between 1990 and 2005, and the SSC data collected and analysed as part of this report (January to May 2020).

The SSC continuous monitoring undertaken as part of this report is over a seven month period covering summer and autumn only, and as such flows have been reasonably low and the potential for elevated SSC low also. Despite this, some attempt has been made to determine daily and annual sediment loads likely to be entering Lake Mangamahoe through the Waiwhakaiho intake[10] (Table 3.3). These calculated loads are likely to be underestimated because the short period of monitoring coincided with the generally drier months of the year.

[10] The weighted-discharge method was used to determine sediment loads Qs=Qw Cs k, where Qs=suspended-sediment discharge, in tonnes per day; Qw=water discharge cubic meters per second; Cs=mean concentration of suspended sediment milligrams/litre; and k a coefficient based on the number of seconds in a day (86400) divided by a million (mg/litre). From Gray and Simões (2008).

Table 3.3: Indicative daily and annual sediment loads using continuous SSC monitoring data collected over between November 2019 and May 2020.

Data used	Time period	# of days	Total sediment load (tonnes)		
			Total load for monitoring period (tonnes)	Indicative daily load* (tonnes per day)	Indicative annual load** (tonnes per year)
Tunnel SSC x Tunnel Flow	1/11/2019-20/05/2020	204	125	0.6	225
Waiwhakaiho SSC x Waiwhakaiho River Flow	17/01/2020-20/05/2020	125	131	1.0	383

*Daily loads are indicative only as they have been extrapolated from a small data set spanning summer/autumn only.

**Annual loads have been extrapolated from indicative daily loads (assuming a similar daily load for the balance of the year) and are therefore affected by the same assumptions.

4 Sediment sources

Assessing the potential sediment sources into Lake Mangamahoe requires an acknowledgment of the variable catchment sources of sediment and significant inter-annual variability which wouldn't be accounted for in Table 3.2. It also requires an understanding of potential instream sources of sediment in the Waiwhakaiho River, Mangamahoe Stream and Kent Road tributary.

These catchment-scale sediment sources are outside of Trustpower's control, and are unrelated to the operation of the Mangorei HEPS. However, they are a key component in understanding suspended sediment dynamics.

This section discusses catchment sources of sediment, including landslides and changes in land use, as well as in-stream sediment sources such as bank erosion and geomorphic units.

4.1 Catchment sources

The Waiwhakaiho River originates on the slopes of Mt Taranaki. Google Earth imagery from 2001 shows an increase in landsliding activity prior to this date, which resulted in mass aggradation of the stream channels (tributaries to the Waiwhakaiho River) (Appendix A). TRC (2011) noted an increase in landslides on the slopes of Mt Taranaki between 1994 and 2007. TRC (2011) also noted that the recovery timeframe for these streams was up to 15 years. This means that for a period of 15 years after a landslide in the headwaters, the Waiwhakaiho River may experience elevated SSC during high flow conditions. A more detailed discussion of the effects of landslides can be found in Appendix A.

Land-cover is well known to also play a large role in sediment yields. The majority of land-use change occurred during European colonisation of the Taranaki region. However, between 1996 and 2012, there was also a 38% increase in grassland and cropland (LAWA 2019), suggesting the land use within the area is still evolving. The major land-cover in both the Waiwhakaiho and Mangamahoe-Kent Road catchments is pasture. Research suggests that sediment yields are between 50-80% less under indigenous forest than under pasture for small catchments. This suggests that catchments with a high coverage of pasture (such as Mangamahoe Stream and Kent Road tributary) will have elevated sediment yields, and these will be even higher if the pasture extends to the stream edge. A more detailed discussion of the effects of land-cover can be found in Appendix A.

While there isn't much pine forest in the wider catchment, the local Lake Mangamahoe catchment is predominantly in commercial pine forest. Harvesting of pine forests also leads to large areas of exposed soil, which has been linked to an increase in sediment yield of between 50-75% (Basher 2013; Gibbs 2006; Gibbs and Woodward 2017). These elevated sediment yields can persist for up to seven years post harvesting. The forestry around Lake Mangamahoe was harvested between 1982 and 1987, and again between 2005 and 2016. There appears to be a corresponding sediment plume in Lake Mangamahoe in 1987 (Figure Appendix A.3, and there is a possibility that this plume is linked to the harvesting of the pine forest. A more detailed discussion of the effects of pine forestry harvesting can be found in Appendix A.

4.2 In-stream sources

In-stream sediment sources incorporate any source of sediment within a stream channel that can be entrained through fluvial processes. This report focusses on bank erosion, and the remobilisation of sediment stores (such as bars).

Estimating the amount of sediment contributed to a system from bank erosion is notoriously difficult. Ongoing research suggests that bank erosion can contribute anywhere between 0% and 90% of a catchment's sediment load (Hughes 2017), with bank erosion mechanisms directly linked to bank material and morphology, which can vary widely even at a reach scale. Estimating the contribution of sediment from in-stream sediment stores is equally difficult. Bed load entrainment is difficult to predict and has been suggested to be possibly related to hydrostatic pressure between surface flows and sub-surface flows as much as surface flows (Neverman *et al.* 2018). This interaction becomes even more complex if the surface armour layer is imbricated (as discussed in Section 3.1). Nevertheless, once entrained, flow velocities and discharge will dictate what size particles are able to be transported when during the flood hydrograph.

There is a high likelihood that once the coarse armour layer is removed, fine sediments underneath are 'released'.

Notwithstanding, during low flow conditions geomorphic units are generally not exposed to flows, and as such, suspended sediment entrainment from in-channel units will be limited.

During the site visit there was ongoing work to repair a culvert underneath SH3 on the Kent Road tributary. It is understood that the culvert blew out in August 2017 following a large flood event[11]. A sediment slug of fine-grained sediment was observed in the middle of the channel, downstream of the culvert[12]. The sediment slug appeared to extend from the culvert to the confluence with Lake Mangamahoe (approximately 150 m) and was in excess of 0.5 m deep in places. The channel had aggraded almost to the top of the bank. It is likely the sediment slug provided an initial pulse of sediment into Lake Mangamahoe in 2017 and continued to supply sediment during most flow events.

A more detailed discussion of the role in-stream sediment sources play in SSC in the Waiwhakaiho River, Mangamahoe Stream and Kent Road Tributary can be found in Appendix A.

[11] https://www.stuff.co.nz/taranaki-daily-news/news/108999205/repair-work-at-damaged-mangamahoe-culvert-under-sh3-to-cost-900k

[12] Sediment slugs are thick deposits of sediment resulting from an oversupply of sediment in the system, reducing the ability to for the stream to carry that sediment, which results in aggradation.

5 Sedimentation in Lake Mangamahoe

All lakes can be considered 'sediment sinks', meaning they generally do not have sufficient flow velocities to flush out sediment that enters them. There are some exceptions to this rule, however as Lake Mangamahoe is effectively a 'closed system' with controlled outflows, it can be considered a sediment sink. When turbid water from each of the tributaries reach the slower flowing water in Lake Mangamahoe, the sediment begins to be deposited in the area where the tributary enters the lake (Figure 5.1). This process starts with the coarser sediment depositing first (closest to the confluence with the tributary), followed by the finer sediment as the water moves further into the slower water of Lake Mangamahoe.

Approximately 85% of the inflows into Lake Mangamahoe come from the Waiwhakaiho River diversion, with preliminary results from the suspended sediment monitoring suggesting that 37% of the annual sediment load comes through the diversion into Lake Mangamahoe. The remaining inflows (15%) and sediment are mostly attributed to Mangamahoe Stream and Kent Road Tributary.

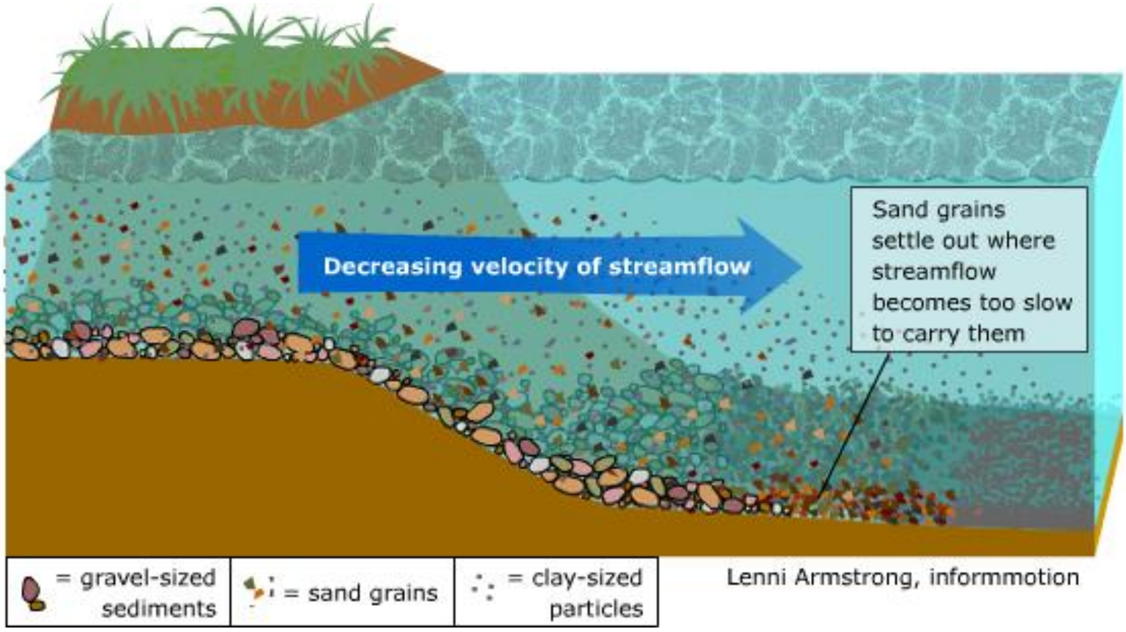


Figure 5.1: Schematic demonstrating the settlement of sediment when a stream enters a lake. Source: Exploring Earth Visualizations website.

5.1 Historic aerial imagery analysis

An assessment into historical aerials of Lake Mangamahoe (sourced from Retrolense and TRC) shows evidence of sediment deposition in the southern arm of Lake Mangamahoe since 1957, the year the earliest historic aerial photograph was available.

The build-up of sediment in the southern arm of Lake Mangamahoe is clearly visible in historic and current aerial photography, and the development of the sediment lobes is able to be tracked through time. There appears to be differences in the size and shape of the sediment deposition in Lake Mangamahoe over time, and the effect of the NPDC water supply pipe is evident (Figure 5.2 and Figure 5.4). The differences are likely due to differences in sediment loads from source rivers during individual events, as well as reworking of deposits through flows entering the lake and other lake processes (such as wind and wave action).

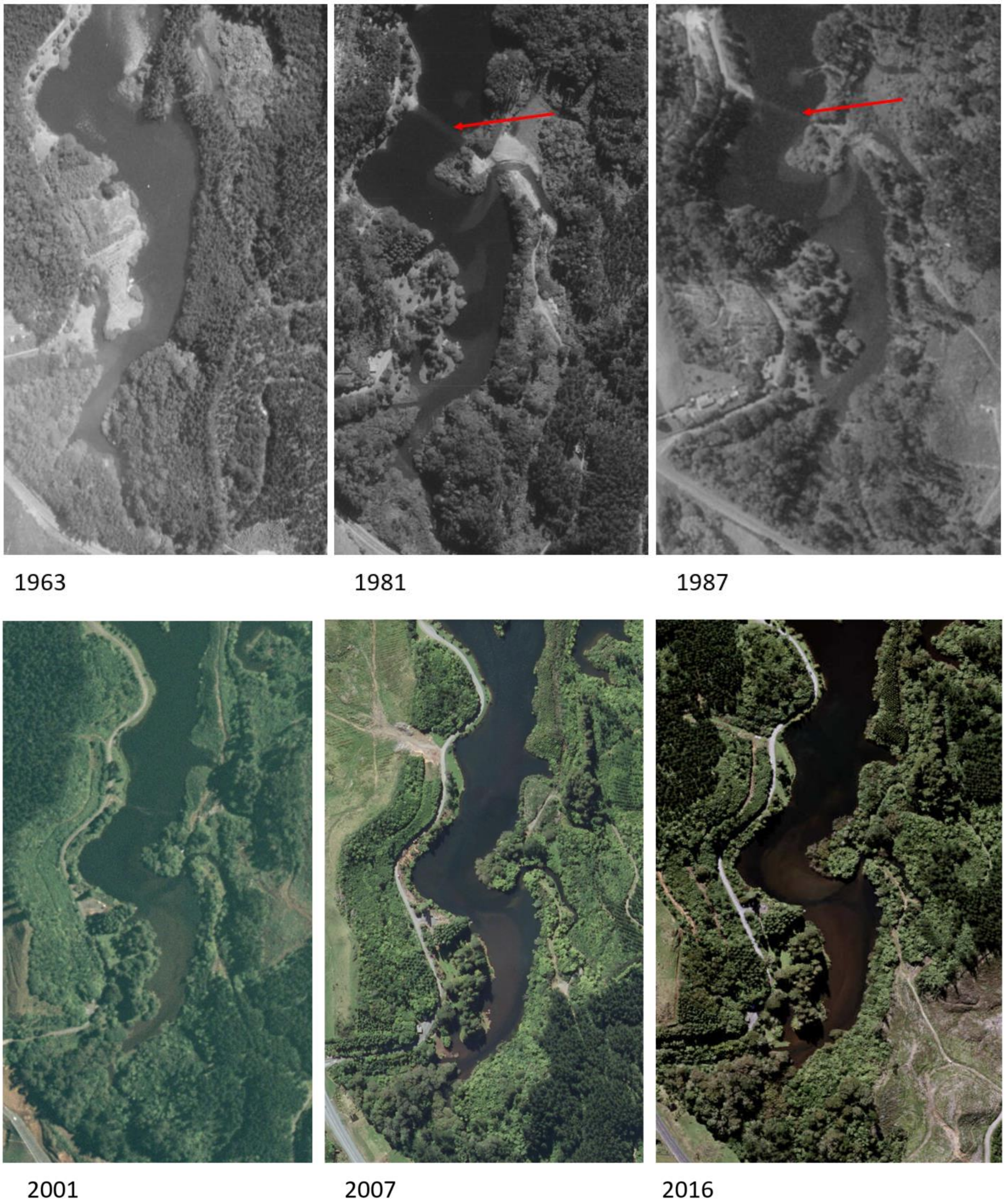


Figure 5.2: Historic aerial photographs of the southern arm of Lake Mangamahoe. Note the water pipeline is clearly visible in the 1981 and 1987 images (red arrows). Source: Taranaki Regional Council (1963, 1981 and 1987) and New Plymouth District Council (2001, 2007 and 2016).

In the 1963 image there is evidence of a sediment plume originating from Mangamahoe Stream (Figure 5.2), but not from the tunnel outlet channel. Closer inspection of the tunnel outlet channel suggests that the channel used to discharge into the lake further to the north of its current location (Figure 5.3). In addition, the tunnel outlet channel appears to be 'choked' with sediment, with the channel visibly wider and shallower than today. The tunnel outlet channel was in this same northerly position in 1970 but had shifted to its current location (discharging in a south-westerly direction) by 1979.

Incidentally, the change in the location of the tunnel outlet channel coincides with the construction of a pipe crossing across Lake Mangamahoe (Figure 5.3). The construction of the NPDC water supply pipe across Lake Mangamahoe is likely to have altered the sediment dynamics in the lake, increasing sediment deposition in the southern arm of Lake Mangamahoe.

In 1981 and 1987 the areas of sedimentation become more visible, with the visibly larger area of deposition located at the southern end of lake, near the mouths of Mangamahoe Stream and Kent Road tributary (Figure 5.2). Small plumes are also evident at the mouth of the tunnel outlet channel in 1981 and 1987 (Figure 5.2), as well as in 1979 (Figure 5.3).

By 2001 the areas of sedimentation appear to be well established. The depositional bar on the western shore of the lake is the largest depositional area and does not appear to change size between 2001 and 2016. The bar at the mouth of the tunnel outlet channel appears to get larger, most notably between 2007 and 2016, and the location of the channel through these deposits moves further to the west.

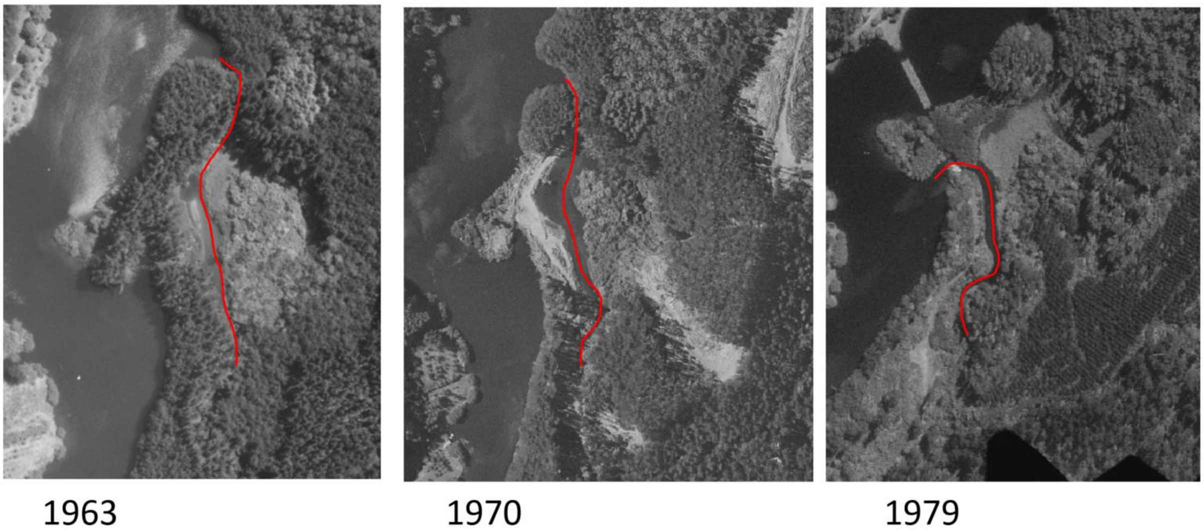


Figure 5.3: Historic aerial analysis of the changes in the location of the tunnel outlet channel between 1963 and 1979. Note the pipe crossing the bed of Lake Mangamahoe in the 1979 aerial. Source Retrolense.

5.2 Observed morphology and processes

The morphology of the fine-grained sediment build-up in the lake suggests sediment has entered the lake from Mangamahoe/Kent Road tributaries as well as the tunnel outlet channel.

As stated in Section 1.1, the tunnel outlet channel has a consented maximum discharge of 10 m^3/s. However, Trustpower can only access a practical maximum discharge of around 9 m^3/s or higher some 0.13% of the time, with the tunnel closed 0.8% of the time (the proportion of time on average that the river discharge is greater than 85 m^3/s). This means for more than 99% of the time flows through the tunnel outlet are less than 9 m^3/s.

In contrast, the mean flow for the Kent Road tributary and Mangamahoe Stream is approximately 0.2 m^3/s and 0.3 m^3/s respectively, with the mean annual flood (MAF) likely to be short durations of around 8 and 14 m^3/s respectively.

This would suggest that flows from the tunnel outlet channel form the dominant discharge into Lake Mangamahoe more frequently, but during large events (MAF or greater), flows from Mangamahoe Stream and Kent Road tributary will be the dominant flows (with potentially no flow in the tunnel outlet channel at the same time).

While lake hydrodynamics are often influenced by factors other than stream inflows, preliminary assessments would suggest that the dominant ‘bar forming’ flows could be associated with Mangamahoe Stream and Kent Road tributary. The evidence for this is that the sediment lobes/bars appear to be moving from Mangamahoe/Kent Road tributaries towards the Waiwhakaiho outlet tunnel, and the thalweg/channel associated with flows from Mangamahoe Stream and the Kent Road Tributary is maintained as a deep channel throughout (Figure 5.4).

If the majority of sediment, and the dominant ‘bar forming flows’ were coming from the tunnel outlet channel, it is very likely that sediment lobes/bars would have formed further to the north of the tunnel outlet channel, and the Mangamahoe/Kent Road channel would have been lost through sediment infill. That said, a sediment lobe/bar is still evident at the tunnel outlet channel, so the tunnel outlet channel is still a contributor of sediment to Lake Mangamahoe.

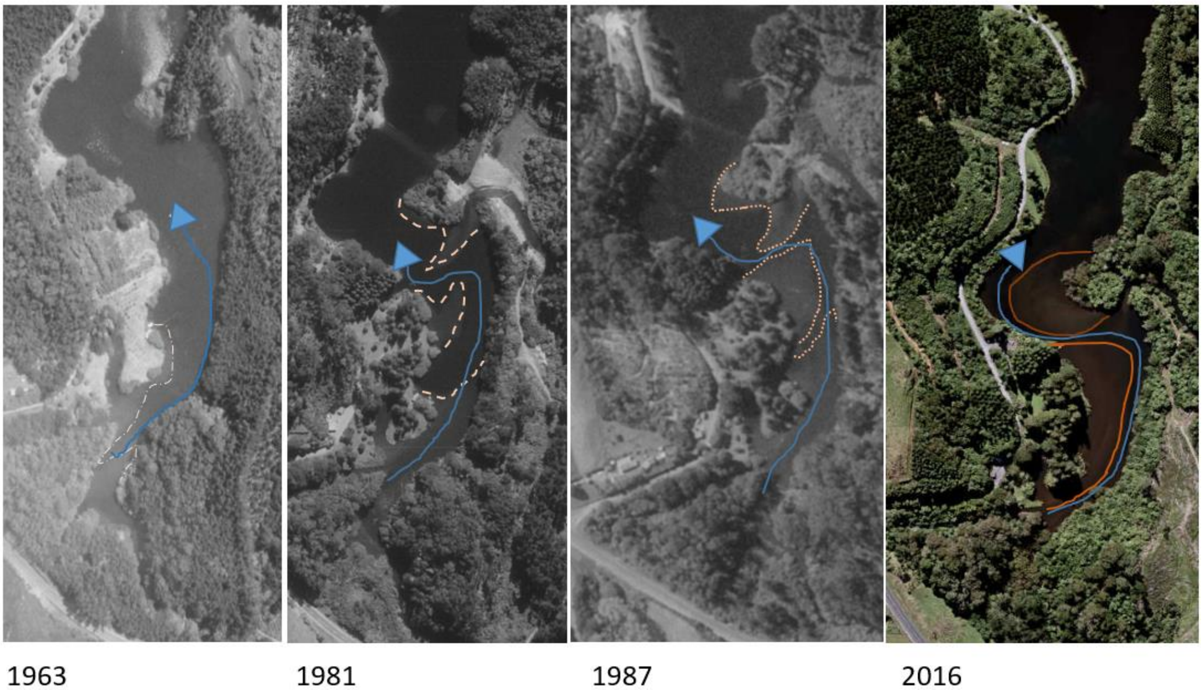


Figure 5.4: Sediment lobe/bar evolution through time (as denoted by the beige/orange lines) and the position of the Mangamahoe/Kent Road channel (as denoted by the blue line) through the southern arm of Lake Mangamahoe between 1963 and 2016.

5.3 Bathymetric surveys

Bathymetric surveys were undertaken in May 2013 and March 2017 and a comparative analysis of these surveys (Figure 5.5) show several areas in the southern arm have an elevation increase of greater than 0.8 m between 2013 and March 2017. It should be noted that this comparative survey does not capture any increase in sedimentation as a result of the SH3 culvert blow out, as the survey pre-dated the culvert blow-out (Section 4.2).

The analysis clearly shows the impact of the NPDC town water supply pipe in impounding sediment within the southern arm (Figure 5.5).

There are several caveats to note with the DEM of Difference (DoD). Firstly, there is a gap (missing data) in the March 2017 DEM in the location of the point bar formation of sediment build up, therefore the change in elevation in this spot cannot be quantified in the DoD (refer to Figure 5.5). Secondly, it is unknown how the DEM’s are processed and there is a possibility that the survey is detecting macrophyte growth under the surface of the water. Therefore, the indicated change in bed elevation in the DoD may be accounting for the change in macrophyte height rather than exclusively on the sediment accumulation.

An additional survey of the lake bed in the southern arm was undertaken in December 2019, which measured the depth of unconsolidated sediment on the lake bed in a 10 m grid across the southern arm of the lake (Figure 5.6). The top of silt was determined by lowering a staff with a plate on the bottom. A 4.5 m probe was then pushed through the silt until a hard layer was encountered and the depth recorded[13]. A large proportion of the lake was too deep to survey, and this may correlate with the deepest areas of silt deposition. Nevertheless, the results suggest that the southern extents of the southern arm near the Mangamahoe Stream/Kent Road tributary confluence, and the sediment lobe/bar near the tunnel outlet channel have the greatest amounts of deposited sediment (between 4.5 and 5 m deep). This generally fits with the observed morphology of the sediment lobes/bars described in Section 5.2, and the sediment depths described by Beca (2012) in Section 1.1.

BTW Company (2020) expect the total silt volume in the southern arm to be in excess of 85,750 m^3 based on the silt depth monitoring.

[13] Methodology given by C. Smith from BTW company, 28/01/2020

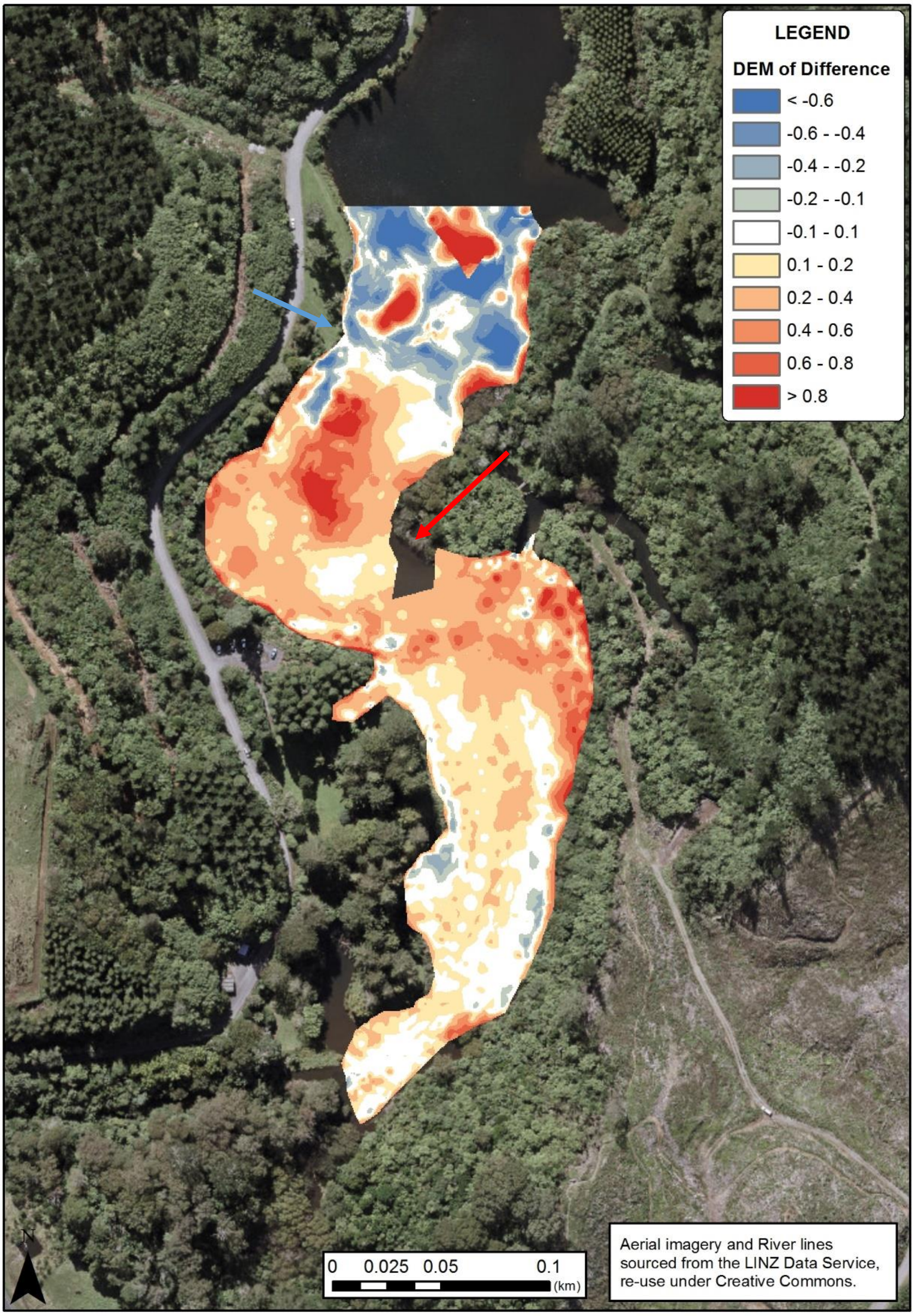


Figure 5.5: DEM of Difference between 2013 and 2017 in Lake Mangamahoe, where shades of blue show a decrease in elevation and shades of red indicate an increase in elevations. The area of missing data is indicated by the red arrow, and the location of the water pipeline indicated by the blue arrow.

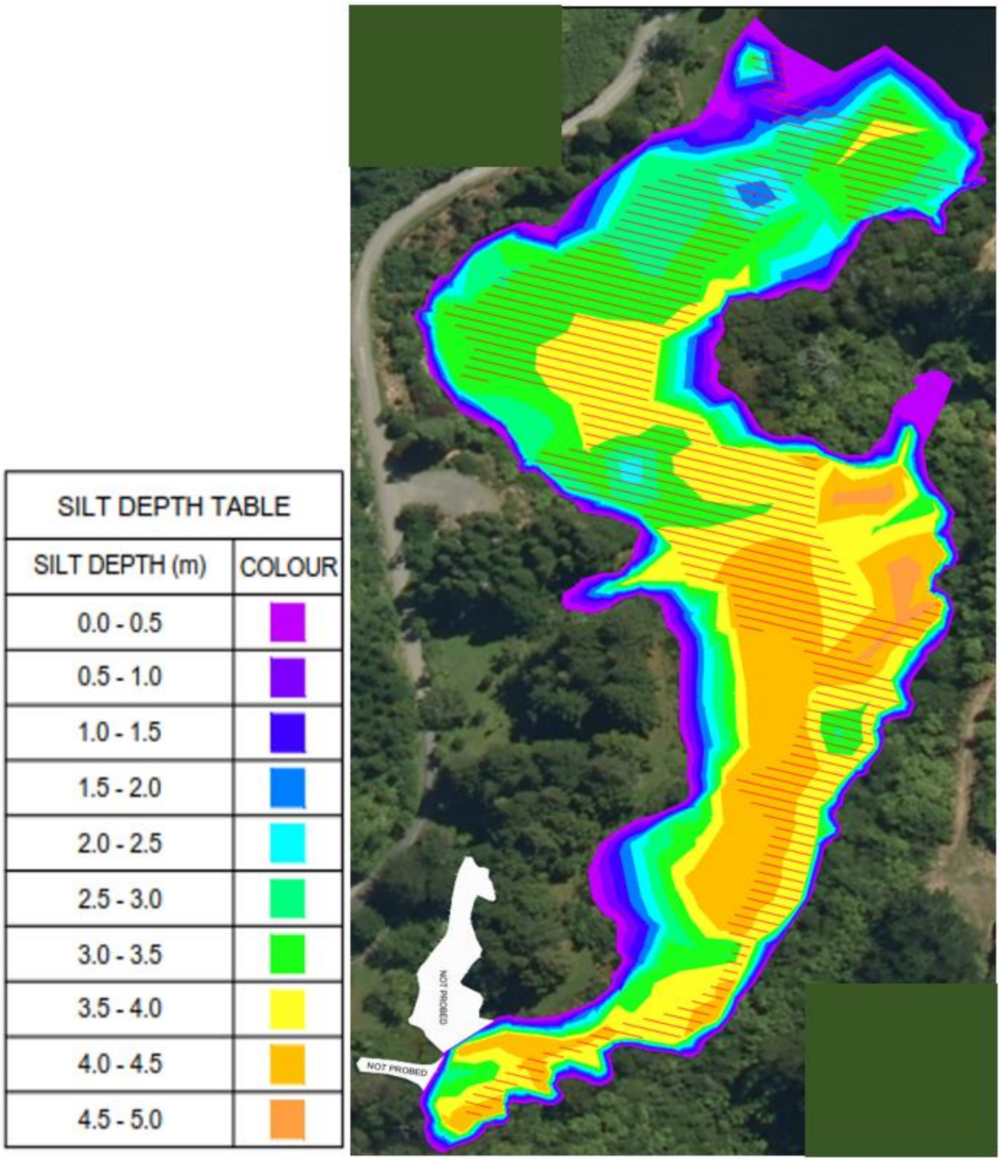


Figure 5.6: The depth of silt measured in the southern arm of Lake Mangamahoe in December 2019. Red hatched area was not surveyed (modified from BTW 2020).

5.4 Annual sediment infill rate

All of the suspended sediment load of both the Mangamahoe and Kent Road sub-catchments is captured and stored within Lake Mangamahoe. The annual suspended sediment yield values from NIWA (2017) have been used for Mangamahoe Stream and Kent Road tributary where no data currently exists (Table 5.1).

To determine the annual suspended sediment loads entering Lake Mangamahoe through the tunnel outlet channel, both the values from Beca (2012) and the extrapolated results from the SSC monitoring have been presented (Table 5.1).

As an additional check, the total overall observed volume of silt determined through the silt depth monitoring (Section 5.3) has been used to determine the possible annual suspended sediment loads[14] (Table 5.1).

Table 5.1: Estimated annual suspended sediment loads based on four different data sources

Source	Estimated annual suspended sediment load (t/yr)		
	Beca (2012) updated with NIWA (2017)	**Tunnel outlet channel SSC monitoring (2019/2020)* with NIWA (2017)**	**BTW silt depth monitoring (2019) (Southern arm only)****
Mangamahoe Stream	243	243	N/A
Kent Road Tributary	150	150	N/A
Waiwhakaiho tunnel (entering Lake Mangamahoe)	1,182	225	N/A
Total estimated annual suspended sediment loads (t/yr)	**1,575**	**618**	**974**

*Extrapolated from a small data set spanning November 2019 to February 2020 and are indicative only.

**Based on estimated overall observed sediment volume from silt depth monitoring for the southern arm undertaken in December 2019. Note this value has been calculated for the whole 88-year period since the lake's formation.

The annual suspended sediment loads presented in Table 5.1 have then been used to determine potential overall sediment depths. As the NPDC water supply pipe appears to have such a significant effect on sediment dynamics within Lake Mangamahoe (as discussed in Section 5.2), sediment depths have been calculated differently for pre and post water supply pipe construction.

For the pre-water supply pipe scenario, we have assumed that sediment would have had the ability to be deposited across the whole lakebed (24 ha) between 1930 and 1970. The post-water supply pipe scenario assumes that sediment is only able to be deposited within the southern arm (2.13 ha) between 1970 and 2019. The resulting two values have then been aggregated to provide an estimated overall sediment depth for the southern arm.

Beca (2012) and BTW (2019) both suggest that the average depth of sediment in the southern arm is 4 to 5 m (refer to Sections 1.1 and 5.3 respectively).

Based on the suspended sediment load for the tunnel outlet channel from Beca (2012) and sediment loads from NIWA (2017), the overall depth of sediment of 3.9 m is similar to those previously recorded by Beca (2012) and BTW (2019), if a little on the shallow side (Table 5.2).

The average depth of sediment based on the suspended sediment monitoring appears to be an under-estimation at 1.5 m. This is possibly due to the SSC data being collected over a short time period over the drier months of the year and may change if a larger data set is analysed.

It should also be noted that as Lake Mangamahoe is a drowned river valley, there are likely to be very deep areas of the lake (refer to Figure 1.2) which are most likely to fill with sediment first. It is also likely that some sediment held in suspension, especially during flood scenarios, will pass over the NPDC water supply pipe and be deposited in the larger lake area.

[14] Assuming that one cubic meter of sediment is equal to a tonne. There is a range of possible densities for in-situ sediment, so there is some uncertainty with using this simplistic conversion.

Table 5.2: Indicative overall sediment depths based on the different annual suspended sediment loads, and adjusted for pre and post water pipeline conditions.

Rough assessment of sediment depths (m)	Based on Beca (2012)	Based on SS Monitoring (2019/2020)	Based on BTW silt monitoring (2019) (Southern arm only)
Whole lake 1931-1970	0.2	0.1	N/A
Southern arm only 1970-2019	3.6	1.4	N/A
Total overall sediment depths 1931-2019 (m)	**3.9**	**1.5**	**4.0**
Average annual sediment depth change (southern arm only) (m)	0.04	0.02	0.05
Average annual volumetric change (southern arm only) (m^3)	937	367	974
Estimated annual sediment volume entering Lake Mangamhoe[14] (based on sediment loads per Table 5.1)	1,575	618	974

When the overall sediment depth data presented in Table 5.2 above is broken down into an average annual sediment depth for the 88 year period since lake formation and then converted to an overall volumetric change over the lake area.

The annual volumetric change based on the silt depth survey (BTW 2019) (974 m^3) is aligned with the annual volumetric change based on the Beca (2012) values (937 m^3). Both are higher than the annual volumetric change based on the SSC monitoring data (367 m^3).

These volumetric changes imply a progressive loss of potential water storage capacity in Lake Mangamahoe. However, the effects of deposited sediment are concentrated to the southern arm only, and generally result in small annual volumetric change. As such, low impact sediment removal could be considered as an appropriate sediment management tool in Lake Mangamahoe if necessary in the future.

6 Summary

Trustpower's MGR HEPS requires renewal of its resource consents, which are due to expire on 1 June 2021.

To assist in the resource consent renewal process, Trustpower are seeking to understand the relative contributions of sediment to Lake Mangamahoe from the contributing catchments, as well as the development of an indicative sediment budget for Lake Mangamahoe.

Sediment loads in the Waiwhakaiho River, Mangamahoe Stream and Kent Road tributary are influenced by a range of factors including geology, surface soils, landcover, valley confinement, channel slope, discharge, flood dynamics, sediment type, in-stream sediment stores, as well as episodic events such as landslides, bank erosion, pine forest harvesting and infrastructure failures (e.g. road culvert blowout following a flood).

This assessment demonstrated that Mangamahoe Stream and Kent Road tributary have similar geomorphic conditions and processes, while the Waiwhakaiho River is substantially different. This suggests that the sediment dynamics in the Waiwhakaiho River are also going to be different to those in the Mangamahoe/Kent Road streams.

Estimated catchment sediment yields and suspended sediment concentration (SSC) monitoring data suggest that Waiwhakaiho River may be the main contributor of sediment to Lake Mangamahoe through the Waiwhakaiho tunnel, accounting for between 37% (SSC monitoring data) and 85% (Beca 2012) of the total load. The catchment estimates of sediment yield for Mangamahoe Steam and Kent Road tributary may be underestimated. As such, Mangamahoe Stream and Kent Road tributary may be responsible for a much larger proportion of Lake Mangamahoe's sediment load than currently predicted.

The complexities of suspended sediment dynamics arise from a range of driving factors, including catchment scale factors. For example, the potential percentage of sediment yield derived from bank erosion can be anywhere between 0-100%, depending on bank material and morphology. The composition of its riverbanks means the Waiwhakaiho River is likely to be more vulnerable to fluvial erosion, and bank erosion is likely to contribute fine-grained sediment in events as frequent as the mean annual flood (MAF) and smaller. However, bank erosion is considered to contribute less in the Mangamahoe Stream and Kent Road Tributary due to the consolidated nature of the banks and the incised nature of the streams, meaning lateral migration of the channel is limited.

Landslides and forest harvesting also appear to play a role in episodic increases in sediment yield. There is evidence of landslides in the upper Waiwhakaiho catchment contributing sediment directly to the Waiwhakaiho River. This would likely have resulted in elevated sediment yields over a 15 year period between 1990 and 2005. Kent Road Tributary and Mangamahoe Stream are less likely to experience landslides.

In addition, sediment plumes were observed in Lake Mangamahoe during and shortly after periods of harvesting in the forest around Lake Mangamahoe. Sediment would have been contributed directly to the lake from the local lake catchment, and not from any of the three tributaries discussed in this report. Research suggests pine harvesting can result in up to 50% increases in sediment yield for up to seven years.

Lastly, landcover is well known to greatly affect soil erosion, as well as surface run-off, with sediment yields between 50 and 80% less for catchments under indigenous forest than under pasture. There are substantial areas of pasture in all three sub catchments (97% in Mangamahoe and Kent Road catchments), and the coverage of cropland/pasture has increased 38% in the wider Waiwhakaiho Catchment since 1996. These changes in landcover may also have contributed to elevated sediment levels post 1996.

In the Kent Road tributary, a fine-grained sediment slug was observed during the site visit on 5 February 2019. The sediment slug was from the SH3 culvert that blew out in August 2017. This sediment slug had been moved through the site and into Lake Mangamahoe by February 2020 and may account for a large volume of sediment.

While flows from the tunnel outlet channel are more frequently the dominant discharge into Lake Mangamahoe, during large events (MAF or greater), flows from Mangamahoe Stream and Kent Road tributary will be the dominant flows (with potentially no flow in the tunnel outlet channel at the same time). In addition, preliminary assessments would suggest that the dominant 'bar forming' flows could be associated with Mangamahoe Stream and Kent Road tributary, as the sediment lobes/bars appear to be 'growing' from Mangamahoe/Kent Road tributaries towards the Waiwhakaiho outlet tunnel, and the thalweg/channel associated with flows from Mangamahoe Stream and the Kent Road Tributary is maintained as a deep channel.

An investigation of changes in bed elevation between 2013 and 2017 suggests the NPDC water supply pipe is having a considerable effect on sedimentation in Lake Mangamahoe, with the greatest accumulations of sediment occurring 'upstream' of the pipe in the southern arm of the Lake. A silt depth assessment undertaken in December 2019 suggests that silt depths in the southern arm of the lake are, on average, between 3 and 5 m deep.

The estimated sediment loads from three data sources Beca (2012), BTW silt monitoring (2019), and the current SSC monitoring are different, with the loads calculated from the SSC monitoring lower than the values derived from the BTW silt monitoring (2019) and Beca (2012) SS rating curve. Therefore, each will have different implications on potential loss of water storage volume within Lake Mangamahoe. The lack of detailed lake bathymetry from the 1930's, and relatively small sediment monitoring dataset make it difficult to determine which is most likely to be correct. In addition, as all the bathymetric surveys to date have occurred in the southern arm, it is impossible to determine the changes in lakebed elevation for the whole lake.

Table 6.1 provides a summary of the range of estimated sediment loads entering Lake Mangamahoe from the difference data sources, and then the estimated average annual sediment depth change based on those sediment loads, and the consequent annual losses in storage volume in the southern arm only.

Table 6.1: Summary of estimated sediment loads entering Lake Mangamahoe, average sediment depth increases for the whole lake, and estimated average annual volumetric change in the southern arm

	Beca (2012) updated with NIWA (2017)	Tunnel outlet channel SSC monitoring (2019/2020)* with NIWA (2017)	BTW silt depth monitoring (2019) (Southern arm only)**
Total estimated annual suspended sediment loads (t/yr)	1,575	618	974
Average annual sediment depth change (southern arm only) (m)	0.04	0.02	0.05
Average annual volumetric change (southern arm only) (m^3)	937	367	974

*Extrapolated from a small data set spanning November 2019 to May 2020 and are indicative only.

**Based on estimated overall observed sediment volume from silt depth monitoring for the southern arm undertaken in December 2019. Note this value has been calculated for the whole 88-year period since the lake's formation.

7 Applicability

This report has been prepared for the exclusive use of our client Trustpower Ltd, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

We understand and agree that our client will submit this report as part of an application for resource consent and that Taranaki Regional Council as the consenting authority will use this report for the purpose of assessing that application.

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
Selene Conn	David Leong
Senior Fluvial Geomorphologist	Project Director

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Appendix A: Catchment scale sediment sources

A1 Catchment sediment sources

A1.1 Landslides

In the headwaters of the Waiwhakaiho River, and one of the tributaries (Kokowai Stream) there is evidence of multiple landslide scarps (Figure Appendix A.1). From the Google Earth images available, these landslides occurred before 2001. The landslides contribute sediment directly into the river including coarse boulders carried as bedload and fine sediment carried in suspension. Fine sediment on or near the surface is likely to be flushed downstream during or immediately after the event, due to the high transport capacity and steep slopes of the reach. However, a portion of the fine-grained sediment is likely to be protected by coarse surface armouring on geomorphic units, and mobilised under different magnitude events over a number of successive years. Coarse boulders are transported through the system sporadically, usually at large discharges (Brierley and Fryirs 2005).

This process supports the evidence provided by TRC, which showed an increase in landslides in the upper catchments of rivers on Mt Taranaki between 1994 and 2007. Evidence from the Stony River (which originates on the western slopes of Mt Taranaki) suggests that the recovery timeframes from a large-scale landsliding event is approximately 15 years (TRC 2011). Recovery is usually determined as occurring when there is evidence of a switch from an aggradational environment to a degradational environment (usually through vegetation colonisation), with subsequent incision of the channel, often leaving terraces behind.

Figure Appendix A.1: Example of confined river at the headwaters of the Kokowai Stream, which is a tributary into the Waiwhakaiho River. Note the evidence of landsliding, directly contributing sediment into the river system.

Increased landsliding on the slopes of Mt Taranaki is likely to increase the overall sediment yield from the modelled values for some catchments, potentially over a number of years. Therefore, climatic changes resulting in an increase in the frequency and intensity of storm events may result in an increase in suspended sediment yields in the Waiwhakaiho River, but potentially not in streams that originate on the ring plain, such as Mangamahoe Stream and Kent Road tributary.

TRC (2011) also suggest that the large pulses of sediment associated with large-scale landsliding can cause channel blockages that result in flow diversion into adjacent catchments. This process, called landslide-induced avulsion, occurred in the 1950s when the upper Oanui Stream was diverted into the Waiaua River.

Avulsion can occur in any catchment, but the effects of this on smaller streams originating on the ring plain (such as Mangamahoe Stream) can be more pronounced than if it occurred in a larger river such as the Waiwhakaiho. Nevertheless, an avulsion is likely to have an impact on suspended sediment concentrations and will increase annual sediment yields in the receiving stream for as long as the diversion is active.

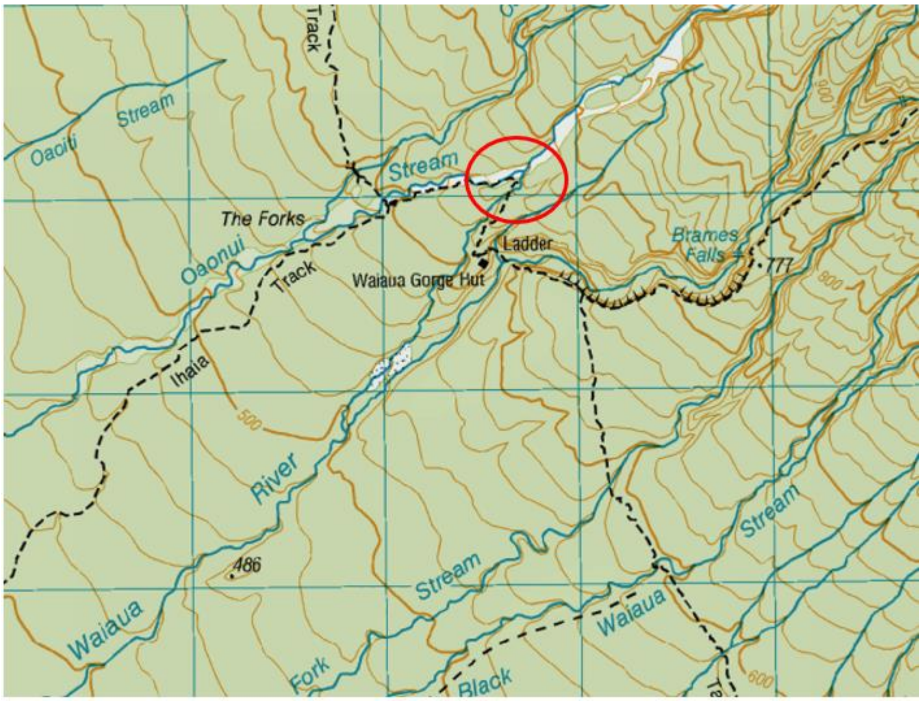


Figure Appendix A.2: Topographic map showing the location of the the Oanui/Waiaua avulsion from the 1950's.

A1.2 Changes in land-cover

Over the course of the last several hundred years, the land cover in the Taranaki region has moved from indigenous forest to an agricultural landscape dominated by pasture. Between 1996 and 2012, there was also a 38% increase in grassland and cropland (LAWA 2019), suggesting the land use within the area is still evolving (Appendix A Table 1).

Appendix A Table 1: Land cover change (ha and %) in the Waiwhakaiho River Catchment between 1996 and 2012 (LAWA, 2020).

Land cover	Area change (ha)	Area change (%)
Indigenous forest	6	<1%
Exotic forest	-37	-7%
Indigenous scrub/shrubland	1	48%
Exotic shrub/shrubland	-2	-4%
Tussock grassland	0	<1%
Exotic grassland	-73	-1%
Other herbaceous vegetation	-1	-6%
Cropping/horticulture	15	38%
Natural bare/lightly-vegetated surfaces	0	<1%
Artificial bare surfaces	-5	-13%
Urban area	96	21%
Water bodies	0	<1%

Both the Mangamahoe Stream and Kent Road tributary sub-catchments are comprised of ~ 97% grassland/pastureland, and the Waiwhakaiho catchment up to the tunnel intake structure has 42% grassland/pastureland (Table 2.2). Basher (2013) suggests that small (<1 – 10 km^2) forested catchments can have a sediment yield up to 95% less than pasture catchments. This is supported by much of the literature which suggests sediment yields are between 50 – 80% less than pasture under forest in small catchments, regardless of forest type. In larger catchments, vegetation may be a secondary influence, but still affect sediment yields (Basher 2013). This suggests that catchments with a high coverage of pasture (such as Mangamahoe Stream and Kent Road tributary) will have elevated sediment yields, and these will be even higher if the pasture extends to the stream edge.

Bare soil has even less protection against erosion and sediment run-off than pasture. Some construction activities create large areas of bare soil. It is now best practice to ensure suitable erosion and sediment control measures are in place. However, this has not always been so, and application of these measures can be sporadic. There is evidence of construction activities on aerial images that have exposed a large area of soil by the Mangamahoe Stream and Kent Road tributary in 2001. Depending on the effectiveness of erosion and sediment control measures, this may have contributed sediment to Lake Mangamahoe during that time.

Harvesting of pine forests also leads to large areas of exposed soil, which has been linked to an increase in sediment yield (Basher 2013; Gibbs 2006; Gibbs and Woodward 2017). The degree to which sediment yields change appears to be vary spatially, with sediment yield increases of 54/75% in the Whangapoua Harbour in the Coromandel (Gibbs 2006), and 50% below the Maitai Dam in Nelson (Gibbs and Woodward 2017). In addition, Phillips (2005) provides a summary of several New Zealand studies that have investigated the change in sediment yield during the various stages of plantation forestry (Appendix A Table 2). These results suggest geology plays a critical role in the volume of sediment yield change, but that yield is likely to be elevated during the harvesting and post harvesting phases.

It is generally well accepted that this increased sediment yield can persist up to seven years post harvesting. Lake Mangamahoe is surrounded by pine forest, and these blocks were harvested between 1982 and 1987, and again between 2005 and 2016 (Appendix A Table 2). There appears to be a corresponding sediment plume in Lake Mangamahoe in 1987 (Figure 5.2). There is a possibility that this plume is linked to the harvesting of the pine forest.

As mentioned earlier, TRC (2011) noted an increase in high intensity rainfall events between 1994 and 2007 with particularly intense storm events in 1998 and 2007. Based on aerial image analysis, the size and shape of the sediment deposition in the lake is larger and extends further into the lake from 2007 onwards. While actual sediment effects from forestry activities will be difficult to retrospectively determine, the timing of the intense storm events corresponds with periods of pine forest harvesting, which may have contributed large pulses of sediment directly into Lake Mangamahoe.

Appendix A Table 2: Changes in sediment yield from two New Zealand catchments in different geology (modified from Phillips 2005).

Catchment	Geology	Pre-harvesting sediment yield (t/yr)	Construction phase sediment yield (t/yr)	Logging phase sediment yield (t/yr)	Post harvesting sediment yield (t/yr)	Reference
Greenhill	Granite	32.9	7.5*	81.5	60	Hewitt 2000 and 2001b in Phillips 2005
Pakuratahi	Mudstone	44	45	179	348	Fahey et al 2003 in Phillips 2005

*Authors acknowledge the value is likely to be low due to low rainfall during the construction phase.

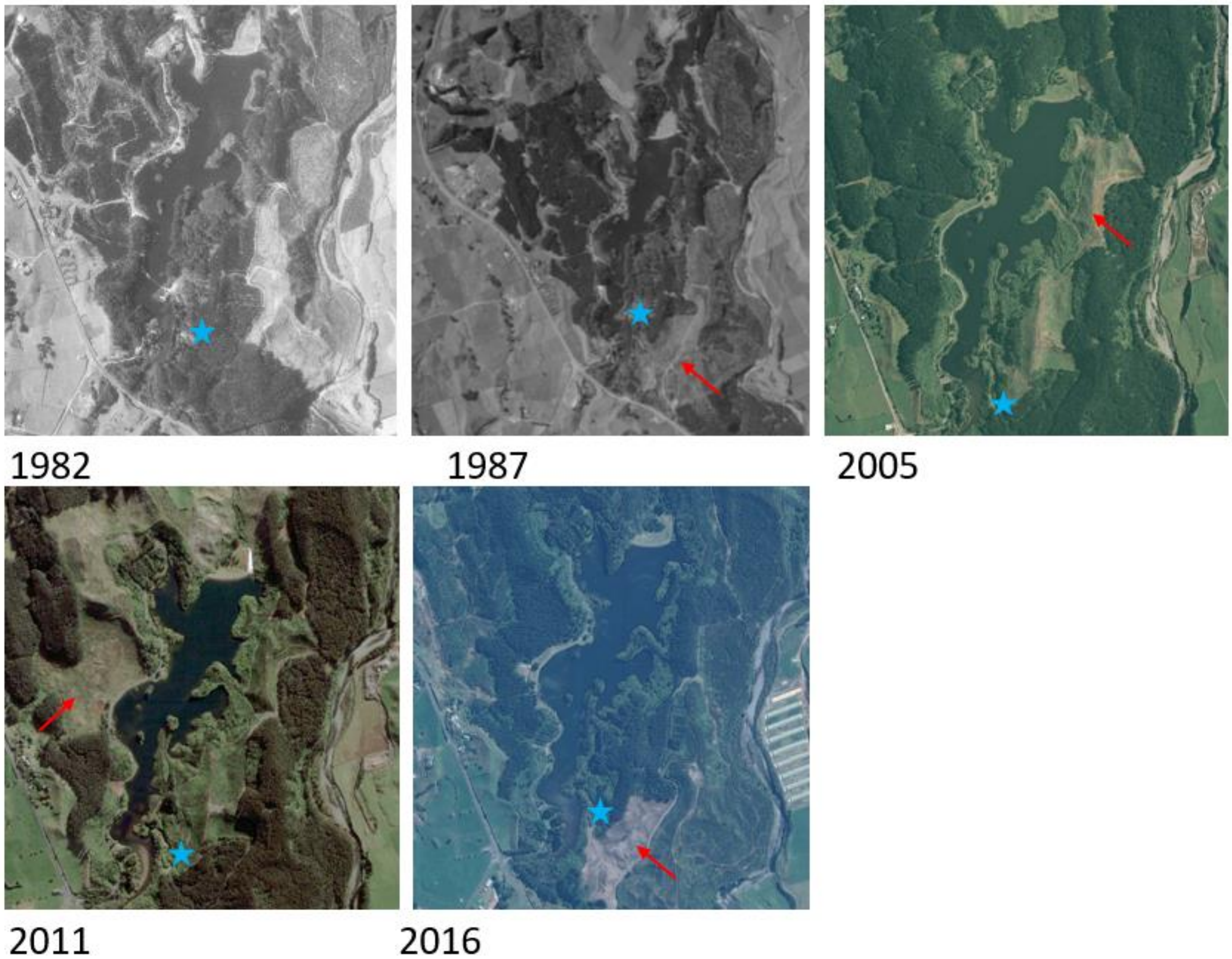


Figure Appendix A.3: Photographs of pine harvesting (red arrows) between 2001 and 2016 at Lake Mangamahoe. The blue star shows the tunnel outlet channel. The Waiwhakaiho River runs along the edge of the right side of each image. Source: Google Earth.

A2 In-stream sediment sources

A2.1 Bank erosion

Estimating the amount of sediment contributed to a system from bank erosion is notoriously difficult, and the focus of much on-going research. Six studies assessing bank erosion rates in different catchments throughout New Zealand were reviewed in Hughes (2017). The results suggest that anywhere between 0-100% of the sediment load within a catchment could come from bank erosion Appendix A Table 3.

In addition, bank erosion is generally not constant though time, with large flood events often resulting in increased erosion rates. In the Waiwhakaiho River, bank erosion is likely to be more common than in the Mangamahoe or Kent Road streams, based on geology and the ability (or inability) for the streams to move laterally.

This again highlights the complex nature of sediment yields within dynamic fluvial environments.

Appendix A Table 3: Estimates the proportional contribution of bank erosion to catchment sediment yield from six catchments in New Zealand. Table sourced from Hughes, 2017.

Proportion of bank erosion to catchment sediment yield (%)	Location	Study
~60%	Mangaotama Stream, Waikato	De Rose (1999)
0 – 100%	Waiokura catchment, Taranaki	McDowell and Wilcock (2007)
28%	Pohangina River, Manawatū	Rosser et al. (2008)
~1%	Waipaoa River, East Coast	De Rose and Basher (2011)
64% and 94% (2 sites)	Waituna Catchment, Southland	McDowell et al. (2013)
>90%	Kopurererua Stream, Bay of Plenty	Hughes and Hoyle (2014)

A2.2 Sediment stores

In the Waiwhakaiho River, there are in-channel geomorphic units that have a coarse surface armour layer protecting underlying fine sediment. These geomorphic units act as both sediment storage and a source of sediment.

Bed load entrainment is difficult to predict and has been suggested to be possibly related to hydrostatic pressure between surface flows and sub-surface flows as much as surface flows (Neverman *et al.* 2018). This interaction becomes even more complex if the surface armour layer is imbricated (as discussed in Section 3.1). Nevertheless, once entrained, flow velocities and discharge will dictate what size particles as able to be transported when during the flood hydrograph. It can be assumed that removal of the coarse armour layer is not consistent in time or space. Therefore, the entrainment of fine-grained sediment from in-channel geomorphic units is also not consistent or easy to predict.

A simplistic assumption would be that suspended sediment entrainment mimics changes in flood flows, with SSC increasing on the rising limb of the flood hydrograph, maximum SSC occurring at the peak of the hydrograph, and reducing again as flow reduces on the falling limb of the flood hydrograph. However, based on the continuous suspended monitoring results (Section 3.2) SSC doesn't match the flow hydrograph, with the maximum concentration often occurring well after that flood peak has occurred. This kind of SSC dynamic could be suggestive of fine-grained sediment stores being 'released' as the coarse armour layer is removed, but could equally suggest terrestrial derived fine-grained sediment entering the system through run-off.

Notwithstanding, during low flow conditions geomorphic units are generally not exposed to flows, and as such, suspended sediment entrainment from in-channel units will be limited.

Due to the local geology (lahar flow deposits that are composed of boulders, poorly consolidated gravels and sand (Figure 2.2)), suspended sediment entrainment can occur from the bed and banks during any flow conditions, as long as the surface is exposed to flows. This mechanism of fine-grained sediment entrainment is applicable to the Waiwhakaiho River, as well as Mangamahoe Stream and Kent Road tributary.

During the site visit there was ongoing work to repair a culvert underneath SH3 on the Kent Road tributary. It is believed that the culvert blew out in August 2017 following a large flood event. A sediment slug of fine-grained sediment was observed in the middle of the channel, downstream of the culvert. Sediment slugs are thick deposits of sediment resulting from an oversupply of sediment in the system, reducing the ability to for the stream to carry that sediment, which results in aggradation.

The sediment slug appeared to extend from the culvert to the confluence with Lake Mangamahoe (approximately 150 m), and was in excess of 0.5 m deep in places (Figure Appendix A.4) The channel had aggraded almost to the top of the bank. It is likely the sediment slug provided an initial pulse of sediment into Lake Mangamahoe in 2017 and continued to supply sediment supply during most flow events.

Interestingly, the sediment slug had largely been mobilised into Lake Mangamahoe and was no longer evident by February 2020. Suggesting these slugs are mobilised during most flow events and are quickly moved through the system[15].

	
Sediment slug downstream of the culvert blowout in Kent Road tributary. Here the sediment is unconsolidated and around 0.5 metre deep.	*Fine sediment deposition downstream of the culvert blowout in Kent Road tributary.*
	
Fine grained sediment deposited behind a piece of the SH3 culvert.	*Evidence of channel aggradation, almost to the top of the bank (red dashed lines).*

Figure Appendix A.4: Site photographs of instream fine sediment build up in Kent Road tributary near Lake Mangamahoe.

[15] R. Goldsmith, pers. comm. May 2020.

Appendix B: Downstream geomorphic assessment

Trustpower requested T+T to investigate community concerns of a perceived change in the Waiwhakaiho River downstream of the Mangorei Powerstation tailrace. This section (Appendix B) outlines the results of the downstream geomorphic investigation.

B1.1 Aerial analysis

Historic aerial imagery for the downstream reaches of the Waiwhakaiho River is inconsistent and patchy. The earliest historic aerial imagery available on Retrolense was from 1950, but unfortunately these images only covered a small area of the river. As such, an analysis of historic changes in the active channel area was only able to be carried out on a 14.5 km section of the Waiwhakaiho River, near Rimu Street.

Overall, the analysis suggests there is a slow contraction (narrowing) of the channel (Appendix B Table 1 and Figure Appendix B.1). Channel contraction is also usually accompanied by a reduction in channel depth (refer to Section B1.2)

There was a slight increase in channel width between 2000 and 2019. This could have been due to a large flood in the Waiwhakaiho River on 30 April 2008, which may have 'reset' the channel width.

Appendix B Table 1: Changes in active channel area based on an analysis of historic aerial imagery for a 14.5 km reach of the Waiwhakaiho River.

	Channel area (m^2)
2019	80,853
2000	74,022
1970	91,950
1950	95,394

The contraction of the channel has resulted in a loss of geomorphic diversity in the channel, most notably in the active/exposed gravel surfaces. This can be seen in Figure Appendix B.2 near Rimu Street (orange arrow) where the channel changed from a wide bifurcated channel with an active and exposed gravel bed in 1950, to a bifurcated channel with dense vegetation (and no exposed gravel bed) in 1970, to a narrow single thread channel with exposed bedrock in 2000.

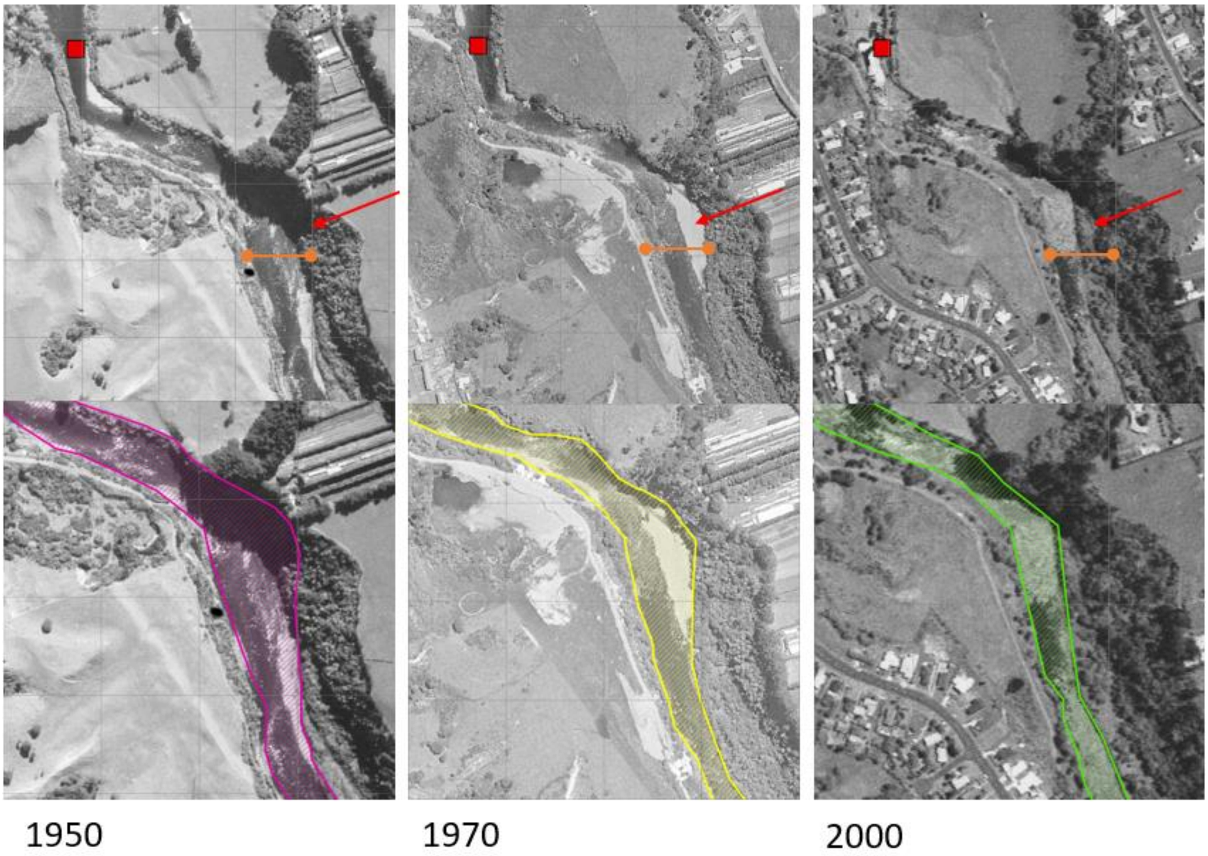


Figure Appendix B.1: Example of changes in channel width between 1950, 1970 and 2000. The red square is the approximate location of the Rimu Street flow gauge.

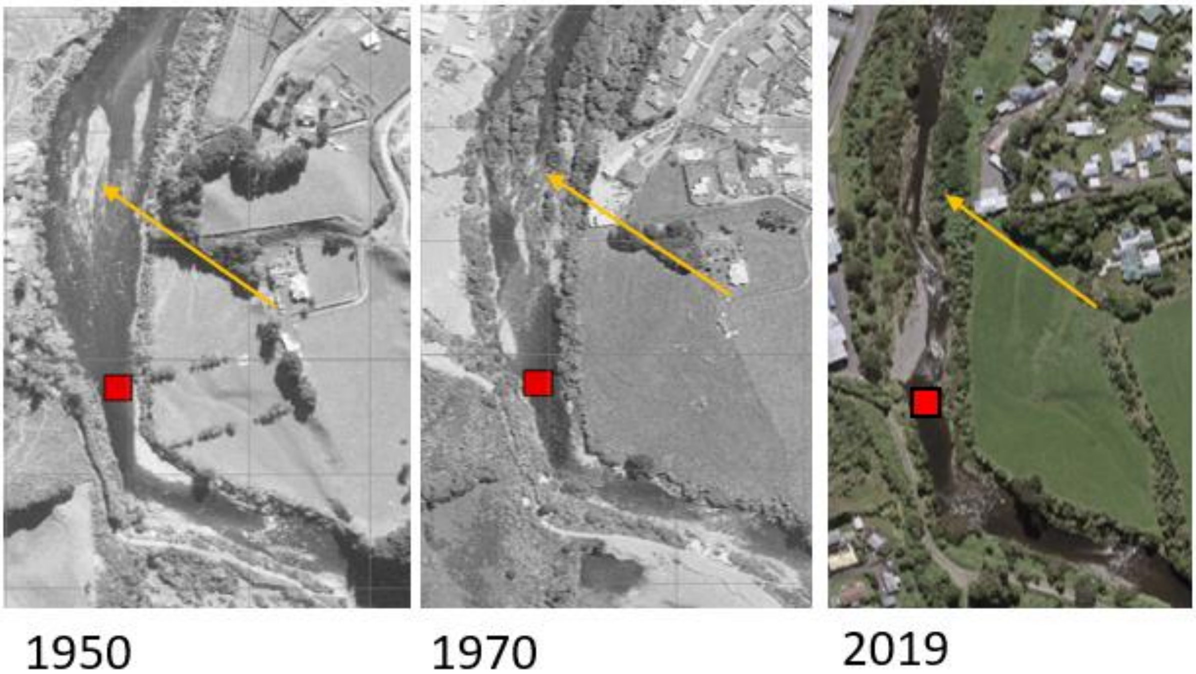
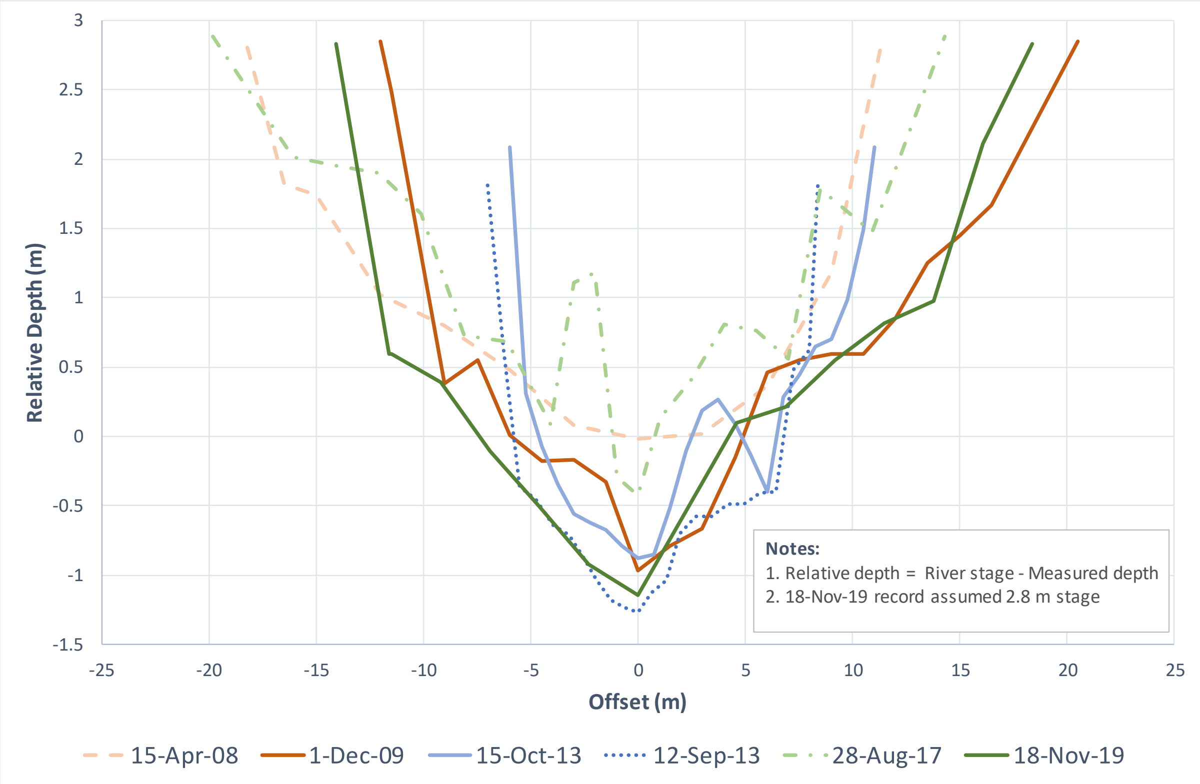


Figure Appendix B.2: Example of changes in channel morphology in the Waiwhakaiho River downstream of the Rimu Street flow gauge.

B1.2 Cross-section analysis

TRC regularly measure the Waiwhakaiho River channel cross-sections near the Devon Road bridge. Cross-section measurements began in 2008 and have been undertaken sporadically six times since then.

The cross-section measurements are undertaken using an acoustic river survey system (ADCP (m9)) which can be prone to errors during periods of high turbidity. Nevertheless, there does appear to be a slow increase in channel depth. The channel appears to have scoured following the 30 April 2008 flood (note the differences between 15 April 2008 and 1 December 2009). Since the 2008 flood, the channel appears to have continued to degrade. The bed levels appear to be elevated in August 2017, however, this may be due to survey error as opposed to actual bed level change.



B1.3 Changes in flow

The MGR HEPS operates by diverting up to a maximum of 10 m^3/s of flow (mean of 3.56 m^3/s) from the Waiwhakaiho River (diversion point is 900 m downstream from the Waiwhakaiho at SH3 gauging station) into Lake Mangamahoe. All of the flow from the Mangamahoe Stream catchment (including Kent Road tributary) is captured by Lake Mangamahoe. The scheme has consents to use up to 864,000 m^3/day of the water stored in Lake Mangamahoe to generate power. Water is diverted from the northern end of Lake Mangamahoe through the intake gates, through tunnel No. 2 and the penstock into the powerhouse. The mean discharge from the powerhouse to the tailrace, and then into the Waiwhakaiho River at the 'Meetings of the Waters' is 3.82 m^3/s (T+T 2020).

It is generally well accepted that most geomorphic 'work' occurs during bank-full events, when the maximum volume of water is confined between banks. Geomorphic work refers to erosion and deposition of sediments from the effects of flow. Bank-full is often consider analogous to the Mean Annual Flood (MAF), or a 2 Year ARI flood event (Rutherfurd *et al*. 2000). The MAF discharge for the Waiwhakaiho River at SH3 is 330 m^3/s and at Rimu Street is 353 m^3/s.

A substantial change in the frequency of bankfull events may result in a change in river character and behaviour.

The reduction in flow in the Waiwhakaiho River at the mean diversion flow equates to 1% of the MAF discharge for the Waiwhakaiho River at SH3, while the maximum take equates to 3% of MAF at SH3. As such, the Waiwhakaiho intake diversion is considered to have a negligible effect on river character and behaviour (namely sediment processes such as erosion and deposition) between the intake and tailrace.

The mean tailrace discharge equates to approximately 1% of the MAF discharge for the Waiwhakaiho River at Rimu Street. As such, the tailrace discharge is considered to have a negligible effect on river character and behaviour (namely sediment processes such as erosion and deposition) downstream of the tailrace.

The combined MAF discharge for Mangamahoe Stream and Kent Road Tributary is approximately 6% of the MAF discharge for the Waiwhakaiho River at Rimu Street. This discharge is captured entirely by Lake Mangamahoe, and represents a small reduction in discharge in the Waiwhakaiho River downstream of the tailrace. This reduction in discharge may have some minor effects on river behaviour, such as a small reduction in the frequency of sediment mobilisation and flushing.

B1.4 Changes in sediment loads

A small percentage (between 2% and 12% depending on the source, refer to Section 3.3) of suspended sediment from the Waiwhakaiho River is removed from the system and stored within Lake Mangamahoe via the diversion. No bedload (e.g. gravels and boulders) are captured or removed by the diversion. During modest floods, much less a MAF or greater flood event, it is likely that the Waiwhakaiho Weir would operate as ‘run of river’ in regards to sediment transport, with the majority (if not all) bed load able to pass over the weir. As such, the weir is considered to have a negligible effect on bedload.

It is estimated that 100% of the sediment load from the Mangamahoe Stream and Kent Road Tributary is captured and stored within Lake Mangamahoe. This could be up to 393 tonnes per year of suspended sediment, and all bedload (undetermined but unlikely to be substantial relative to the suspended load). The suspended sediment load equates to around 4% of the total suspended load estimated for the Waiwhakaiho River immediately above the tailrace, and 3% of the total suspended load estimated for the Waiwhakaiho River at Rimu Street.

The suspended sediment loads used may be underestimated, and therefore the reduction in sediment load due to Lake Mangamahoe may be greater than this (refer to Section 3.3).

As such, the effect of Lake Mangamahoe on sediment loads may affect the amount of fine-gained and suspended sediment in the Waiwhakaiho River downstream of the tailrace. However, reductions in bedload are expected to be minimal. Therefore, it is unlikely that changes in sediment loads attributed to Lake Mangamahoe are driving any changes in river character and behaviour in the Waiwhakaiho River.

B1.5 Summary

The Waiwhakaiho River channel downstream of the MGR HEPS appears to be displaying a slow incision (narrowing and deepening) trend. The changes in channel-forming discharge and sediment loads associated with the MGR HEPS are considered to be negligible. As such, any changes in river character and behaviour are unlikely to be due to the MGR HEPS.

It is more likely that the changes are attributable to long-term geomorphic trends. Evidence of past incision has been identified in the Waiwhakaiho River, and is described in Section 2.2.1:

> *A terrace on the true right floodplain near the intake structure, suggests the Waiwhakaiho River has undergone substantial incision in the past. This could be attributed to a long-term reduction in sediment supply, or an increase in sediment transport capacity. It could also be a remnant of volcanism, such as localised uplift or river incision through lahar deposits/debris flows.*

Based on this evidence, there are likely to be underlying natural processes contributing to incision and channel narrowing trends in the lower Waiwhakaiho River.