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Waikato River suspended sediment: loads, sources & sinks

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Information to inform economic modelling for the Healthy Rivers Wai Ora Project

May 2015

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Executive summary

This report reviews and presents information on the suspended sediment loads, the importance of river bank erosion, and the role of hydro-reservoir sediment trapping within the Waikato and Waipa River systems. This is one component of a suite of technical studies that have been commissioned through the Healthy Rivers/Wai Ora Technical Leaders Group (TLG).

This report found that:

- NZEEM suspended sediment load estimates appear reasonable. However they assume that floodplain/bank deposition and bank erosion are in balance so they do not explicitly consider the contribution from river bank erosion.
- The SedNetNZ bank erosion equation and previous field-based studies suggest that river banks are potentially an important component of the Waipa River's sediment budget.
- Bank erosion is probably also important in the tributaries of the Waikato River.
- The SedNetNZ bank erosion equation is subject to several sources of uncertainty - its use outside of the full SedNet model (where all major catchment sources and sinks are accounted for) is unlikely to provide a useful indication of the relative contribution of sediment derived from bank erosion to the total suspended sediment load.
- There is very limited data available on the net contribution of bank erosion to the sediment budgets of New Zealand catchments. Limited field-based work within the Waipa catchment found that river banks contributed ~60% of the catchment sediment yield. This level of contribution is comparable to estimates from other NZ catchments. A Bay of Plenty (BoP) study indicated that bank erosion could contribute an even higher proportion (>90%) of sediment in parts of the Waikato system with a similar geological history. However, the BoP study did not differentiate sediment derived from bank erosion from other subsurface sources, therefore the more conservative figure of 60% is still a fair estimate for these areas.
- Bank erosion of the main stem of the Waikato River is probably negligible and is unlikely to contribute significantly to the catchment sediment yield.
- Sediment trapping efficiencies of the Waikato River hydro-reservoirs determined by three approaches (Churchill, Brune and Chen methods) were compared. As a result of close agreement between results from the Churchill method with estimates derived from other methods, and the fact that it explicitly accounts for the effect of sediment trapping of upstream reservoirs, I recommend that the trapping efficiencies determined by the Churchill method be utilised in this project.

1 Introduction

1.1 Preamble

The Waikato Regional Council (WRC) and the Waikato and Waipa River iwi are partners in Healthy Rivers: Plan for Change/Wai Ora: He Rautaki Whakapaipai. This aim of this plan is to develop changes to the regional plan to help restore and protect the health of the Waikato and Waipa Rivers. The plan aims to reduce inputs of sediment, bacteria and nutrients (primarily nitrogen and phosphorus) to water bodies (including groundwater) in the Waikato and Waipa River catchments.

Water clarity has been identified as a key water quality attribute of interest for the Waikato region. Water clarity is affected by a number of factors including suspended sediment, suspended organic material and coloured dissolved organic matter. Fine suspended sediment in particular, however, has the greatest impact on water clarity in most river systems.

This report reviews and presents information on the suspended sediment loads, the importance of river bank erosion, and the role of hydro-reservoir sediment trapping within the Waikato and Waipa River systems. It provides information to support modelling of sediment and clarity within the Waikato catchment. This is one component of a suite of technical studies that have been commissioned through the Healthy Rivers/Wai Ora Technical Leaders Group (TLG). These studies will provide information regarding the state of the Waikato River catchment, sources of contaminants, accumulation and movement of contaminants through the catchment, and economic modelling of the costs of meeting water quality goals and targets.

1.2 Suspended sediment in rivers

Fine sediment is widely recognised as an important diffuse pollutant. Sediment is sometimes referred to as the ‘universal’ pollutant because it is invariably mobilised when vegetation or land are disturbed (Campbell et al. 2004). Elevated sediment mass concentrations in rivers can adversely affect ecosystem health by the process of infilling and shoaling, and smothering downstream biota. However, the light-attenuating effects of suspended sediment causing reduced visual range and light penetration, are probably of more ecological significance (Ryan 1991; Davies-Colley et al. 2014).

While suspended sediment is the main driver of increased light attenuation, coloured dissolved organic matter (CDOM, leached from decaying plant material in soils) also affects light penetration in water. The greater the attenuation of light by suspended sediment and CDOM, the lower the water clarity. While elevated suspended sediment and CDOM have the greatest effect during flood events, they are also important during baseflow conditions.

1.3 Catchment sediment sources and sinks

Erosion from catchments is the ultimate source of sediment transported by rivers. In New Zealand catchments the main processes that contribute sediment to rivers are sheetwash and rill erosion (commonly referred to as *hillslope erosion*), mass movement (e.g., landslides, mud flows), and stream bank erosion. Although large amounts of sediment eroded by these processes may be delivered to streams, it does not always get transported to the outlet of a catchment. Sediment may be intercepted by a number of catchment storages (e.g., floodplain/in-channel and reservoir deposition). The inputs of sediment from erosion, loss to catchment storage and output and the catchment outlet is often describe in terms of a ‘sediment budget’. This concept was simply illustrated in the following equation of Prosser et al. (2001b):

$$Y_x = T_x + I_x - D_x$$

where Y_x is sediment yield from river reach x (a river reach can be considered to be a section of river between tributaries), T_x is the sediment input from upstream tributaries to the reach, I_x is the sediment input along the reach, and D_x is deposition or storage within the reach.

In New Zealand, recent human-induced catchment disturbance has probably resulted in increased rates of catchment erosion, deposition and sediment yield (Page and Trustrum 1997; Glade 2003). Although our knowledge is sparse, prior to human settlement erosion rates were probably relatively low. There is evidence to indicate that the large scale clearance of indigenous vegetation and establishment of agricultural-based land uses resulted in a relatively rapid pulse of sediment to rivers, much of which may be still be in catchment sediment stores (Richardson et al. 2013a; Richardson et al. 2013b). In recent years erosion rates have probably declined in many catchments but remain elevated above pre-settlement levels. There may, however, be some legacy effects of this historical disturbance that may result in the release of sediment from catchment sediment stores in the future. A good example of this is the finding that headwater streams in pastoral catchments are often narrower than in equivalent forested catchments (e.g., Davies-Colley 1997; Trimble 1997). Davies-Colley (1997) argues that headwater pastoral streams have become narrower due to the input of sediment from recent catchment disturbance. This sediment became readily stored in channels due to the high light conditions which promotes the growth of pasture grasses on exposed in-channel bars, as well as on stream banks. A number of studies (e.g., Trimble 1997; Collier et al. 2001; Parkyn et al. 2005) have suggested that this stored sediment could be released (over a number of decades) if these channels are revegetated in tree species (as is often done during riparian rehabilitation efforts) due to the shading effect of a riparian tree canopy inhibiting the growth of groundcover vegetation.

It is therefore important to understand in as much detail as possible the sources and sinks of sediment within catchments. Such information will assist catchment managers to efficiently target rehabilitation efforts as well as provide critical information for catchment models to better simulate the processes occurring within catchments.

1.4 Scope

The scope of this report is to:

- Review the bank erosion estimates for the Waipa River generated by the SedNetNZ bank erosion equation.
- Assess the applicability of the SedNetNZ bank erosion equation to the rest of the Waikato River catchment.
- Provide estimates of the contribution of bank erosion by each Healthy Rivers Wai Ora (HRWO) sub-catchment.

- Review the NZEEM generated sediment load estimates for the Waikato and Waipa Rivers.
- Provide estimates of Waikato River hydro-reservoir suspended sediment trapping efficiencies.

2 Waikato River sediment loads and the contribution of river bank erosion

2.1 SedNetNZ river bank erosion predictions for the Waipa River

There is a dearth of information on river bank erosion rates within New Zealand catchments. The SedNetNZ bank erosion equation determines bank erosion as a function of the mean annual flood level. Data for this relationship (R^2 =0.4) was obtained from 26 river reaches throughout New Zealand, including the Mangaotama Stream that lies within the Waipa River catchment. All but five of the 26 sites had a mean annual flood discharge of over 100 m^3 s^{-1}, therefore smaller streams were poorly represented. This under-representation of small streams is likely due to the difficulty in detecting (with precision) the small scale changes likely to occur in smaller channels using the widely used remote sensing techniques. The under-representation of small streams is significant because most (90%) of the reaches in the Waipa River have a mean annual flood discharge < 100 m^3 s^{-1}. Therefore, the relationship has been largely applied to reaches where there is least knowledge of rates of bank erosion. Further information is required regarding bank erosion rates in smaller channels to improve confidence in predicted bank erosion rates for these streams.

The use of the mean annual flood as a predictor of bank migration rates is also worthy of comment. Although little comparative work exists, during a global review of river bank migration data, Rutherfurd (2000) found that the best hydrological predictor of bank erosion was *bankfull discharge*. The importance of bankfull discharge is likely due to it being the most effective flow for transporting sediment, meander and channel bend development, and for doing work that determines the average morphological characteristics of rivers (Mulvihill et al. 2009). Although what may be considered 'bankfull discharge' will vary from catchment to catchment, Leopold (1994) argues it lies between the 1 and 2.5 year flood level, while Rosgen (1994) states that it is often the 1.5 year flood level. Indeed, bankfull discharge (defined as an event with a 1.58 year return period) was used as a predictor of bank erosion in the original version of the SedNet model (e.g., Prosser et al. 2001a; Wilkinson et al. 2004). The effect of using bankfull discharge as opposed to mean annual flood on the bank erosion predictions is not possible to know without some sort of sensitivity analysis.

Although the SedNetNZ bank erosion equation provides information regarding the areal extent of bank erosion, to provide a volumetric estimate of bank erosion-derived sediment, river bank height information is also required. The description of the application of the SedNetNZ bank erosion equation to the Waipa River (Palmer et al. 2013), is somewhat unclear. However, it appears that a relationship between bank height and mean discharge, that was developed from over 200 field measurements, was poor, hence a more generalised relationship (i.e., $2+2\log_{10}$(mean discharge) was used. Although bank heights predicted by this equation appear reasonable, no reason was given as to why a logarithmic relationship was considered appropriate. Using this relationship does result in negative bank heights for stream reaches where mean discharge is less than 0.1 m^3 sec^{-1} (for the Waipa River this was the case for over 30% of river reaches). To correct for this, Palmer et al. (2013) assigned a default bank height value of 0.5 m where negative bank heights were predicted. Other attempts to develop a relationship that allows predictions of bank height at the catchment scale have included a power law relationship between bank height and contributing area (which can be considered a surrogate for mean discharge) (e.g., Dougall et al. 2006).

To convert the volumetric estimates of bank erosion to estimates of sediment mass, Palmer et al. (2013) assumed a bulk density of 1.0 t/m^3. Although there will always be a degree of subjectivity when generalising the characteristic of sediment through a catchment the size of the Waipa River, the estimate of Palmer is on the low side, especially given the high proportions of sand and silt measured within suspended sediment samples collected from the Waipa river catchment (see Figure 15 in Palmer et al. (2013)). In comparison, the Australian version of the SedNet model assumed a bulk density of 1.5 1 t/m^3, Hicks and Hill (2010) estimated the sediment accumulated with hydro-reservoirs at 1.6 t/m^3, and De Rose (1999) measured the bulk density of river bank sediments within the Mangaotama Stream to be ~1.2 t/m^3.

As previously noted by De Rose and Basher (2011), no universal empirical bank erosion model exists that can be applied across a wide range of scales and environments to provide reliable sediment estimates. Although the bank erosion equation used in SedNetNZ may be regarded as a “best attempt” method for estimating the contribution of bank erosion in NZ catchments, bank erosion estimates within the Waikato River catchment derived from this equation are likely to be highly uncertain.

2.2 NZEEM sediment load predictions within the Waikato catchment

Landcare Research used the NZEEM model to estimate sediment loads by HRWO sub-catchment. The reliability of NZEEM estimates was assessed by comparing them with sediment load estimates derived from the work of Hoyle et al. (2011). Hoyle et al. (2011) used sediment rating curves developed from flow and suspended sediment data to calculate mean annual sediment loads and specific yields.

The relationship (power law) between the loads determined by the two methods are illustrated in Figure 2-1 (R^2= 0.8, SE = 0.38, P < 0.01). Although, there are only nine data points, the good fit and significance level of the relationships provides confidence that the NZEEM model provides reasonable estimates of catchment suspended sediment load.

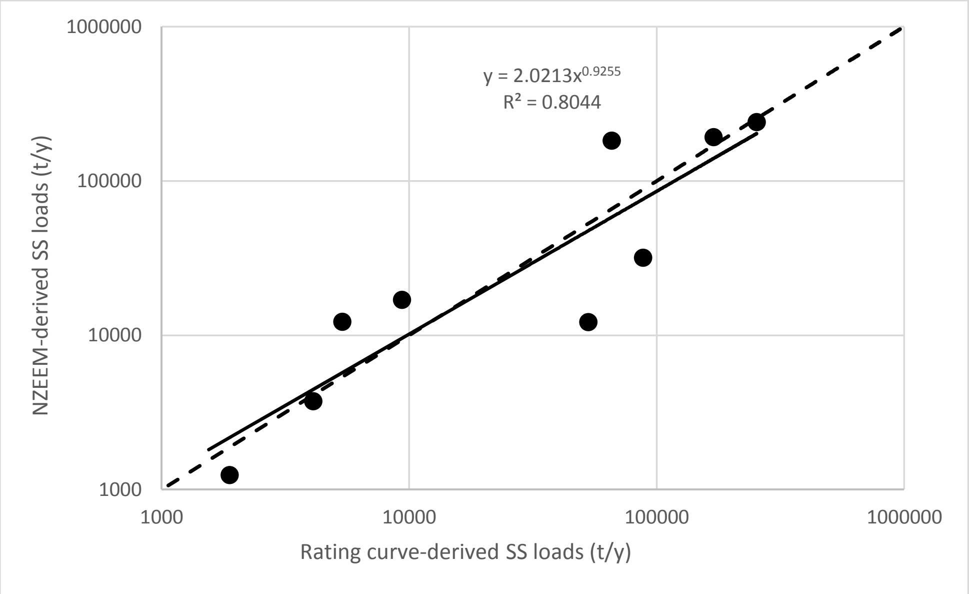

Figure 2-1: Power law relationship between catchment suspended sediment (SS) loads determined by NZEEM and those determined by the sediment rating curve method. (Source: Hoyle et al. 2011) for HRWO catchments. Dashed line indicates 1:1 line.

2.3 NZEEM sediment load predictions and (non)-inclusion of bank erosion derived sediment

The NZEEM model predicts an average annual sediment load of 205 kt/y for entire Waipa catchment and 192 k/y for the catchment above the SH23 Bridge at Whatawhata. This is similar to the load determined by Hoyle et al. (2011) for the Waipa at SH23 Bridge Whatawhata monitoring site (the most downstream Waipa River monitoring site - 168 kt/y ± 58 kt/y). The Hoyle et al. (2011) estimate was determined using a 38 year (1972 – 2011) flow record and suspended sediment data collected over 20 years (1990 -2010). Although the load estimates of the two methods are comparable, it should be noted that the NZEEM model does not explicitly account for sediment derived from bank erosion (or lost to floodplain deposition).The SedNetNZ bank erosion equation estimates (albeit with a high level of uncertainty) that 650 kt/y of sediment is derived from bank erosion. This is three times greater than the catchment sediment yield estimated by NZEEM. Clearly, not all the sediment eroded from river banks will contribute to the net sediment load at the mouth of the Waipa River, as potential exists for sediment storage along the way (e.g., floodplain accretion and channel deposition).

Another consideration is that not all material eroded from banks will contribute to the suspended sediment load of a river (i.e., the particle size of some bank-derived sediment is such that it is generally transported as bed load). While limited data exists regarding the proportion of bank material that contributes to the suspended sediment loads of rivers, previous work (e.g., Dietrich and Dunne 1978) suggests that 50% is a reasonable estimate. This figure has been used as a default value in most Australian applications of the SedNet model (e.g., McKergow et al. 2005; Hughes and Croke 2011). The SedNetNZ bank erosion equation therefore only gives an estimate of the *gross* contribution of bank erosion derived sediment. Running the full SedNet model (where all major catchment sources and sinks are accounted for and factors such as the contribution of bank erosion to the suspended sediment load are included), is likely to provide a better indication of the *net* contribution of bank erosion derived sediment.

The fact that not all sediment eroded from river banks contributes to the net sediment load is acknowledged by Palmer et al. (2013). They state, however, that there is insufficient data to quantify how much sediment is lost to storage. The developers of the NZEEM model (Dymond et al. 2010) argue that there is balance between floodplain deposition and bank erosion. This argument is sound in the context of long-term catchment evolution. However, in the context of determining the contribution of river bank erosion (and floodplain deposition) over the short- to medium-term, such as during a period when a catchment is probably still responding to historic catchment disturbance, this assumption is probably less pertinent.

2.4 The contribution of river bank erosion to catchment sediment loads

River bank erosion can be an important source of sediment with some international studies estimating that up to 90% of a catchment's sediment yield is derived from channel sources (Caitcheon et al. 2012; Kronvang et al. 2013; Olley et al. 2013). River bank erosion has also been identified as an important process in New Zealand (Basher et al. 2012), although there has been very little quantitative research carried out to date (Basher 2013). River bank erosion has anecdotally been identified as an important source of sediment within the Waikato River catchment, although there have been few attempts to quantify it (Hicks and Hill 2010; NIWA 2010). The Waipa River catchment may be a particular "hot spot" for bank derived sediment due the legacy effects of a large landslip at Tunawaea in 1991. The large amount of sediment contributed by the Tunawaea slip has resulted in localised bed aggradation and this has exacerbated river bank and terrace erosion during flood events (Hoyle 2013).

The dearth of bank erosion studies probably reflects the long duration (i.e., multiple years to decades) required for the results of bank erosion studies to be meaningful. Furthermore, determining the proportional contribution of river bank erosion to the sediment load of a catchment can be difficult. It may require long-term monitoring of flow and suspended sediment monitoring at a site in combination with field measurements of bank erosion, or the use of a sediment 'fingerprinting' approach such as sediment radionuclide tracing (Collins and Walling 2004). Most previous NZ studies have focussed on the effects of individual storm events (e.g., De Rose and Basher 2011) and have not attempted to determine the contribution of bank erosion to the total sediment budget.

Studies that have estimated the contribution of bank erosion within NZ catchments show that it can be a significant component of catchment sediment budget (Table 2-1).

Table 2-1: Estimates from New Zealand catchments of the proportional contribution of bank erosion to catchment sediment yield.

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, Manawatu	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, BoP	Hughes and Hoyle (2014)

De Rose and Basher (2011) analysed sequences of remotely sensed images to determined river bank migration rates on the main stem of the Waipaoa River (East Cape). The authors estimated that ~1% of the catchment sediment load was derived from bank erosion. Mass wasting within the catchment contributes huge volumes of sediment to the river system, which completely overshadows the small contribution from bank erosion. The large-scale mass wasting is the result of a combination of high rainfall rates, steep terrain, highly erodible underlying lithology and historical land use. The authors suggested that, as tributary channels were not considered in their study, bank erosion may be underestimated. Due to the unique susceptibility of the Waipaoa catchment to mass wasting, the findings of this study are probably not pertinent to the Waikato River catchment.
Hughes and Hoyle (2014) used sediment radionuclide concentrations to determine the relative contribution of hillslope and river bank sources to sediment loads in the Kopurererua Stream, which drains into the Tauranga Harbour. This study estimated that river bank sources contribute over 90% of the sediment deposited at the mouth of the stream. Within-catchment field reconnaissance provided qualitative support of the importance of river bank erosion. This study was, however, unable to differentiate river bank sources from other subsurface sources (e.g., mass wasting and urban development), therefore it is likely to have overestimated the importance of river banks as sediment sources. Importantly, however, the Kopurererua catchment is primarily underlain by tephra and ignimbrite from eruptions from the Taupo Volcanic Zone. The stream channels are deeply incised, eroding non-cohesive alluvial pumice banks - as such, they are likely to be comparable to channels within tributaries of the upper Waikato River catchment.

De Rose (1999) used fallout radionuclide measurements of channel sediments, and analysis of aerial photographs to construct a catchment sediment budget for the Mangaotama Stream, a tributary of the Waipa River. This study suggested that while mass movement was once the major sediment source, it has become less important and bank sources now make up ~60% of the annual sediment yield. Both the radionuclide and aerial photograph analysis methods used in this study have multiple sources of uncertainty. This field data based study is the only attempt to quantify the contribution of bank erosion within the Waikato River catchment known. Its findings are corroborated, to some extent, by the work of Hughes et al. (2012), which inferred the dominance of near-channel sources from 12 years of monitoring within the Mangaotama catchment.

McDowell and Wilcock (2007) used a composite sediment fingerprinting approach to determine the relative contribution of various erosion sources to the Waiokura Stream in Taranaki. The Waiokura catchment is characterised by low hillslope gradients and fertile, free draining volcanic ash soils so is comparable to parts of the Waikato River catchment. This study found seasonal variations in the contribution of different sources, with bank erosion contributing between 23% and 100% river suspended sediment during winter/spring, and between 0% and 17% during summer/autumn.

McDowell et al. (2013) used a sediment fingerprinting approach (based on geochemistry) to determine the relative contribution of various erosion sources within the Waituna Lagoon catchment, Southland. The Waituna catchment is gently undulating to flat and is underlain by a thin layer of poorly sorted Quaternary clay-bound gravels. Stream channels in the catchment have undergone significant modification and straightening in order to improve drainage for agricultural activities. McDowell et al. (2013) analysed suspended sediment at two stream sites and found that river banks contributed 64% of the sampled sediment at one and 94% at the other.

A study within the Pohangina sub-catchment of the Manawatu River estimated that over the period from 1953 to 2000, river bank erosion accounted for ~28% of the catchment sediment yield (Rosser et al. 2008). It should be noted, however, that the terrain within the Pohangina River catchment is particularly susceptible to mass movement (Wright 2005).

2.5 Bank erosion of the main stem of the Waikato River

A literature review by Hicks and Hill (2010) suggests that bank erosion rates on the main stem of the Waikato River are very low. One report (McConchie 2001) suggested that, despite river banks being made of relatively soft material, bank erosion and bank migration rates were very low when compared to other New Zealand Rivers. This finding is supported by a recent survey that found that only 5% of the main stem is actively eroding (Beca 2013). Previous work suggests that near-bank flow velocities generally remain below the threshold required to entrain bank material, therefore erosion by fluvial scour is likely to be minimal. The most prevalent mechanism of erosion appears to be by localised mass failure, such as bank slumping. The Hicks and Hill (2010) review also stated that the occurrence of bank instability along the Waikato River main stem is largely a function of its geomorphic setting, with no evidence that human-induced bed degradation or other hydro-dam effects have increased bank erosion.

For the purpose of this project I will therefore assume that the river banks of the main stem of the Waikato River contribute no sediment to the river system.

2.6 Summary and recommendations regarding sediment load and bank erosion predictions

- NZEEM estimates of suspended sediment loads appear reasonable.
- The NZEEM model does not explicitly include the contribution of sediment from river bank erosion.
- The SedNetNZ river bank erosion equation and previous field-based studies suggest that river banks are potentially an important component of the Waipa River’s sediment budget. Using current data and knowledge, there is no way of knowing how much sediment is lost to catchment storage (e.g., floodplain deposition, bank accretion). However, assuming bank erosion is balanced by floodplain deposition is probably not justified in the timescale of post-settlement disturbance. This implies that NZEEM may have over-predicted the contribution of sediment from hillslope sources.
- Bank erosion is probably also important in the tributaries of the Waikato River.
- The SedNetNZ bank erosion equation has a number sources of major uncertainty and its use outside of the full SedNet model (where all major catchment sources and sinks are accounted for) is unlikely to provide useful indications of the relative contribution of sediment derived from bank erosion.
- There is very limited data available on the net contribution of bank erosion to the sediment budgets of New Zealand catchments. Previous field-based work within the Waipa catchment found that river banks contributed ~60% of the catchment yield. This level of contribution is comparable to estimates from other NZ catchments. Work from a Bay of Plenty (BoP) catchment underlain by Taupo Volcanic Zone derived sediment indicates that bank erosion could contribute an even higher proportion (>90%) of sediment in parts of the Waikato system with a similar geological history. However, the BoP study did not differentiate sediment derived from bank erosion from other

subsurface sources, therefore the more conservative figure of 60% is still a fair estimate for these areas.

- Bank erosion of the main stem of the Waikato River is probably negligible and is unlikely to contribute significantly to the catchment sediment yield.
- The proportional contribution of bank erosion-derived sediment from HRWO sub-catchments that include both Waikato River main stem (0% contribution) and tributary channels (60% contribution) need to be adjusted to account for the different contribution levels of the two channel types. This was achieved by:
  - Using stream channels greater than 1st order streams from the River Environment Classification (REC) network, I determined the proportion of all river channels (within each HRWO sub-catchment) that are *tributary* channels (i.e., not main stem Waikato River).
  - The proportion of tributary channels within each HRWO sub-catchment was then multiplied by 60% (the proportion contribution of bank erosion from tributary channels) (Table 2-2).

Table 2-2: The estimated contribution of bank erosion from HRWO sub-catchments that include reaches of main stem Waikato River. Locations and extents of each HRWO sub-catchment are presented in Figure A-1 of Appendix A.

HRWO sub-catchment	Length of tributary channels (km)	Total length of channels within sub-catchment (km)	Proportion of tributary channels within each sub-catchment (%)	Net proportion of sediment from bank erosion (%)
Waikato at Port Waikato	191.9	223.5	86	52
Waikato at Tuakau Br	134.8	144.0	94	56
Waikato at Mercer Br	333.7	359.0	93	56
Waikato at Rangiriri	42.2	58.8	72	43
Waikato at Huntly-Tainui Br	122.8	143.7	85	51
Waikato at Horotiu Br	31.7	46.4	68	41
Waikato at Bridge St Br	30.9	40.1	77	46
Waikato at Narrows	78.0	99.1	79	47
Waikato at Karapiro	373.9	428.4	87	52
Waikato at Waipapa	498.0	520.9	96	57
Waikato at Whakamaru	305.7	334.5	91	55
Waikato at Ohakuri	362.6	400.8	90	54
Waikato at Ohaaki	175.0	213.6	82	49

In conclusion, the NZEEM sediment load estimates for the Waikato River appear to be sound. For the purpose of this study, I recommend that 60% of the NZEEM derived loads should be considered to be derived from river bank erosion on the Waikato River tributaries. Bank erosion along the main stem of the Waikato River is assumed to contribute no sediment to the NZEEM-derived estimates for those reaches. Where a HRWO sub-catchment includes both Waikato River main stem and tributary channels, the contribution of bank erosion to the sub-catchment's sediment yield has been adjusted based according to the proportion of tributary channels within the sub-catchment. See Table B-1 for NZEEM loads and proportion contribution from bank erosion for all HRWO sub-catchments.

3 Sediment trapping by hydro-reservoirs on the Waikato River

In simple terms, rivers transport sediment to downstream waterbodies either in *suspension* (generally fine sediment) or as *bed load* (generally coarse sediment). It is reasonable to assume that the Waikato River hydro-reservoirs trap all bed load sediment (Hicks and Hill 2010). The issue of trapping of *suspended* sediment by the hydro-reservoirs along the main stem of the Waikato River was addressed by Hicks et al. (2001). Two commonly used approaches (Churchill 1948; Brune 1953) were used to calculate the sediment trapping efficiencies of the eight major hydro reservoirs (Table 3-1). The Brune and Churchill curves are empirical relationships developed after measuring trapping efficiencies of North American reservoirs (Lewis et al. 2013).

- The Brune curve was developed from the ratio of reservoir capacity to mean annual inflow. It is easily applied and requires little input data (Lewis et al. 2013).
- The Churchill curve was developed from relationships between the percentage of incoming silt passing through a reservoir and the Sedimentation Index (period of retention/mean velocity) of a reservoir. The Period of Retention is determined from: reservoir volume/average inflow rate (Hicks et al. 2001).

The Churchill index produces two trapping efficiency curves, one that that describes trapping efficiencies for “local silt” that is derived from upstream tributaries and one for ‘‘discharged silt”’ that have passed through upstream reservoirs. This accounts for:

- preferential settling of coarser suspended sediment in upstream reservoirs, and
- small likelihood that finer sediment will be deposited in any downstream reservoir (Hicks et al. 2001).

Close agreement of trapping efficiency estimates for Lake Ohakuri with an independent method for estimating trapping efficiency favoured the use of the Churchill (discharged silt) method by Hicks et al. (2001).

Another method for calculating reservoir trapping efficiency is presented in Chen (1975). Unlike, the Brune and Churchill methods, which are empirically derived relationships, the Chen method is centred upon a theoretical analysis of particle settling. Based on the assumption that reservoir inflow is laminar (i.e., non-turbulent), Chen determines trapping efficiency (*TE*) by:

$$TE = \frac{wA}{Q}$$

where w is settling velocity (m yr^{-1}) of different particle sizes, A is the surface area (m^2) of the reservoir, and Q is the mean annual inflow ($\text{m}^3\ \text{yr}^{-1}$). Using a particle size diameter of 10 µm (<10 µm sediment particles (fine silt, clay and colloids) can be considered to be the most ‘optically active’ fraction (Davies-Colley and Smith 2001)), trapping efficiencies for each of the Waikato reservoirs were calculated (Table 3-1).

Table 3-1: Waikato River hydro-reservoir sediment trapping efficiencies. Churchill and Brune method estimates are from Hicks et al. (2001).

Reservoir	Sediment trapping efficiency (%)			
	Churchill method (local silt)	Churchill method (discharged silt)	Brune method	Chen method (laminar flow)
Lake Aratiatia	24	0	0	7
Lake Ohakuri	88	66	68	57
Lake Atiamuri	70	34	20	22
Lake Whakamaru	80	50	53	41
Lake Maraetai	85	60	53	32
Lake Waipapa	58	18	6	12
Lake Arapuni	84	58	58	48
Lake Karapiro	76	45	48	45

Table 3-1 shows that there is reasonable agreement between trapping efficiencies estimated using the Churchill (discharged silt), Brune and Chen methods. Comparing the Chen method with the discharged silt estimates of the Churchill method shows that while the Chen method consistently resulted in lower trapping efficiencies, there is a good relationship between the data from the two methods (Figure 3-1).

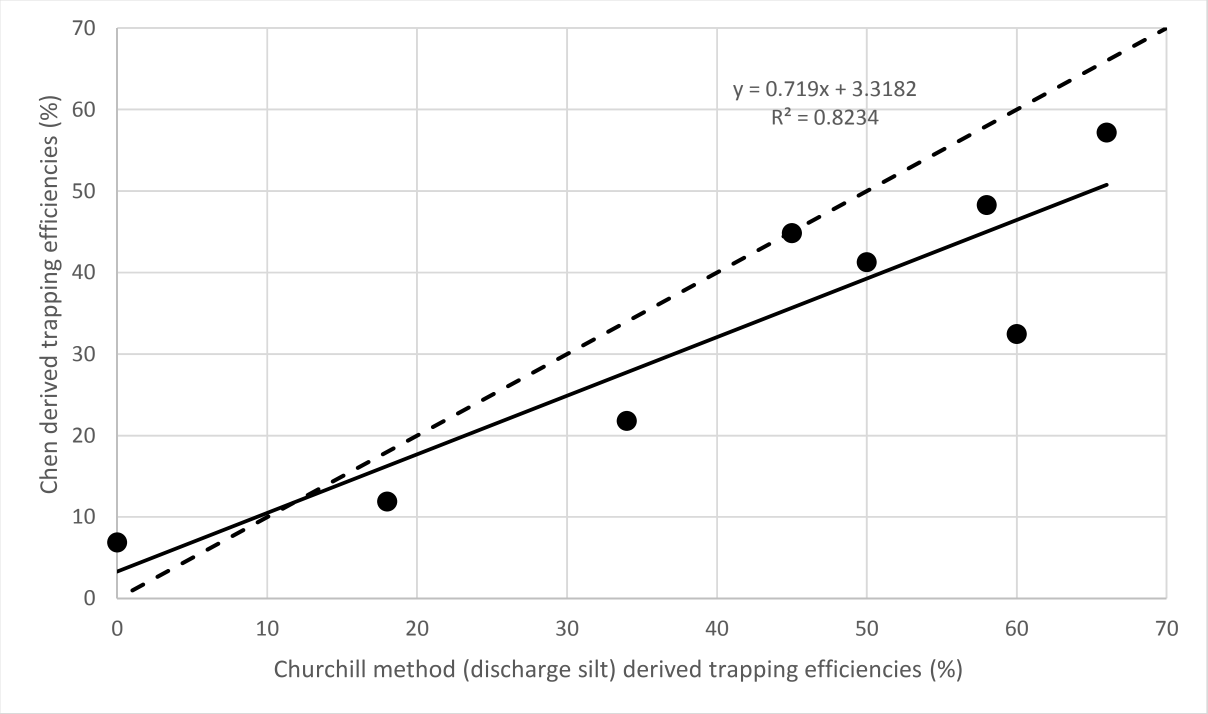

Figure 3-1: Plot of trapping efficiencies determined by the Chen and Churchill (discharged silt) methods. The dashed line is the 1:1 line.

Due to close agreement between results from the Churchill method with estimates derived from other methods, and the fact that it explicitly accounts for the effect of sediment trapping of upstream reservoirs, I recommend that the trapping efficiencies determined by the Churchill method be utilised in this project.

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Appendix A Healthy River Wai Ora (HRWO) sub-catchments

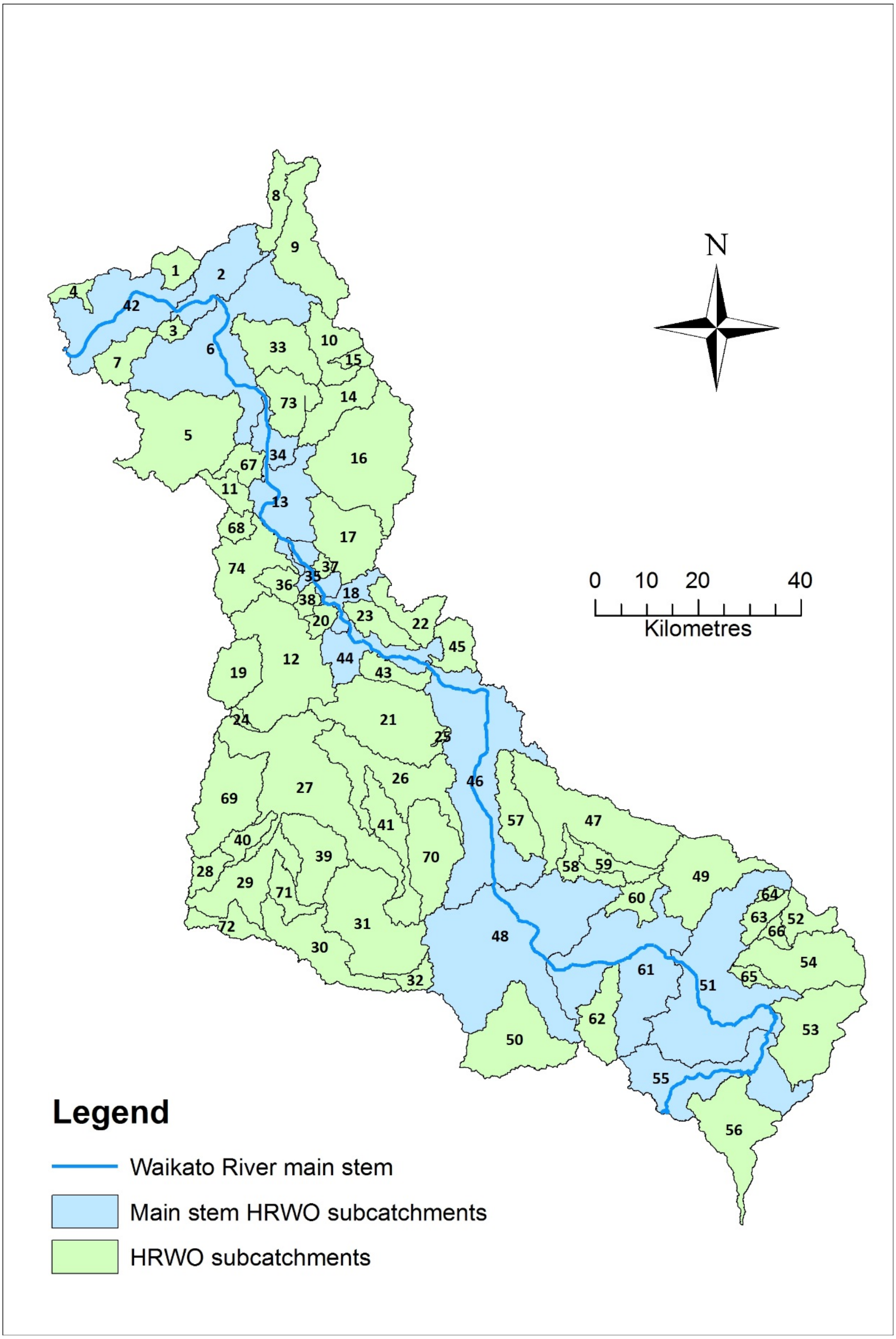

Figure A-1: Healthy Water Wai Ora sub-catchment locations. Sub-catchment ID numbers refer to Map ID numbers in Table B-1 of Appendix B.

Appendix B NZEEM loads and contribution of river bank erosion by HRWO sub-catchment

Table B-1: NZEEM loads by sub-catchment and proportion of load that is derived from river bank erosion.

HRWO sub-catchment	Map ID	NZREACH ID	Area (ha)	NZEEM sediment load estimate (t/y)	Estimate of proportion of sediment derived from river bank erosion
Whakapipi	1	3006346	4648	1245	0.6
Waikato at Tuakau Br	2	3007421	15178	7212	0.56
Ohaeroa	3	3007733	2033	523	0.6
Awaroa (Waiuku)	4	3007434	2506	594	0.6
Whangape	5	3010847	31767	59030	0.6
Waikato at Mercer Br	6	3006806	45168	53989	0.56
Opuatia	7	3008985	7067	14986	0.6
Mangatawhiri	8	3005110	6808	3722	0.6
Mangatangi	9	3006132	19452	12016	0.6
Whangamarino at Jefferies Rd Br	10	3008369	9701	5322	0.6
Awaroa (Rotowaro) at Sansons Br	11	3013581	4561	6758	0.6
Waipa at SH23 Br Whatawhata	12	3017829	31506	13806	0.6
Waikato at Huntly-Tainui Br	13	3013160	17322	7593	0.51
Matahuru	14	3010952	10637	12242	0.6
Waerenga	15	3009556	1959	2440	0.6
Mangawara	16	3013137	35884	13840	0.6
Komakorau	17	3014466	16399	1519	0.6
Waikato at Bridge St Br	18	3017901	5072	1143	0.46
Kaniwhaniwha	19	3019566	10259	12380	0.6
Mangakotukutuku	20	3018237	2708	427	0.6
Mangapiko	21	3022010	28069	11783	0.6
Mangaonua	22	3017726	8096	5242	0.6
Mangaone	23	3018213	6760	1673	0.6
Mangauika	24	3023179	978	87	0.6
Mangaohoi	25	3023476	431	18	0.6
Puniu at Bartons Corner Rd Br	26	3023180	22785	7703	0.6
Waipa at Pirongia-Ngutunui Rd Br	27	3022669	43607	17245	0.6
Waitomo at Tumutumu Rd	28	3028966	4318	4957	0.6
Mangapu	29	3027166	16170	15715	0.6
Mangaokewa	30	3031564	17419	16976	0.6
Waipa at Otewa	31	3029370	28665	11387	0.6
Waipa at Mangaokewa Rd	32	3036214	3221	813	0.6
Whangamarino at Island Block Rd	33	3007681	14365	2945	0.6
Waikato at Rangiriri	34	3010604	6853	4006	0.43
Waikato at Horotiu Br	35	3015830	5405	367	0.41
Ohote	36	3017348	4041	582	0.6
Kirikiriroa	37	3016924	1233	85	0.6
Waitawhiriwhiri	38	3017487	2223	26	0.6

HRWO sub-catchment	Map ID	NZREACH ID	Area (ha)	NZEEM sediment load estimate (t/y)	Estimate of proportion of sediment derived from river bank erosion
Waipa at Otorohanga	39	3027129	13889	5156	0.6
Waitomo at SH31 Otorohanga	40	3026779	4393	3096	0.6
Mangatutu	41	3024473	12269	3743	0.6
Waikato at Port Waikato	42	3009006	28148	9769	0.52
Mangawhero	43	3020102	5347	2000	0.6
Waikato at Narrows	44	3018977	12987	3919	0.47
Karapiro	45	3020352	6741	5595	0.6
Waikato at Karapiro	46	3020656	53969	17458	0.52
Pokaiwhenua	47	3023849	32701	8558	0.6
Waikato at Waipapa	48	3030247	69392	23066	0.57
Tahunaatara	49	3032435	20816	8310	0.6
Mangakino	50	3036710	22186	10127	0.6
Waikato at Ohakuri	51	3035123	53139	29767	0.54
Waiotapu at Campbell	52	3034280	6079	1681	0.6
Torepatutahi	53	3038300	21721	4607	0.6
Waiotapu at Homestead	54	3037105	20478	4075	0.6
Waikato at Ohaaki	55	3039804	29009	12672	0.49
Pueto	56	3042044	20029	10348	0.6
Little Waipa	57	3023862	10649	2878	0.6
Mangamingi	58	3027230	5175	1536	0.6
Whakauru	59	3027821	5302	1827	0.6
Mangaharakeke	60	3032678	5415	933	0.6
Waikato at Whakamaru	61	3035301	44665	16880	0.55
Waipapa	62	3035556	10049	5209	0.6
Otamakokore	63	3031549	4573	1925	0.6
Whirinaki	64	3031392	1080	492	0.6
Mangakara	65	3037027	2235	1759	0.6
Kawaunui	66	3034452	2134	893	0.6
Awaroa (Rotowaro) at Harris/Te Ohaki Br	67	3012631	4730	1099	0.6
Firewood	68	3015451	3372	4014	0.6
Moakurarua	69	3023962	20630	30122	0.6
Puniu at Wharepapa	70	3025988	16853	6908	0.6
Mangarapa	71	3028468	5443	14768	0.6
Mangarama	72	3031371	5528	15389	0.6
Waikare	73	3010071	10418	3147	0.6
Waipa at Wainaro Rd Br	74	3015066	15484	8851	0.6