Appendix 24: Flow Effects

1. Introduction

Flow is a fundamental intrinsic factor affecting aquatic ecosystems. This appendix provides a summary of the various processes that can affect flow as well as the effect that management intervention and potential restoration actions might have on flow regimes. This information has been used in many sections of the main Report and is intended as a resource for the Waikato River Authority to use to evaluate if potential flow effects of mitigations meet Te Ture Whaimana – Vision and Strategy for the Waikato River it may consider in the future.

The flow regimes of streams and rivers can be altered by changes in their catchment land use (e.g., when forestry is replaced by pasture), riparian management, wetland restoration, dams and sand mining. This occurs because of the influences of vegetation type on evaporation and interception losses of incident rainfall and on soil moisture that influences run-off (Duncan and Woods, 2004; Scotter and Kelliher, 2004), water storage within dams and dampening of flood flow velocities by rough riparian vegetation. Estimates of these effects are summarised in Table 1.

Table 1: Predicted effects on flows of land use change, riparian buffers and wetland restoration

Action	Low flow	Estimates annual run-off reduction	Maximum flood flows < 100 km^2 catchments
Pine afforestation of pasture	minus 50%	minus 300-400 mm, 35-45%	minus 30% (5-50%)
Native restoration of pasture	plus 10%	minus 70 mm, 7%	minus 20%
15 m native riparian buffers	minus 3%	minus 30 mm, 3%	minus 10%[1]
5 m riparian buffers	minus 1%	minus 10 mm, 1%	minus 3%
Wetland restoration effect per 1% increase in catchment area as wetland	plus 8%[2]	nil	minus 4%[1]

[1] The actual effects on downstream flooding will be influenced by how reducing the speed of the flood wave affects the phasing of flood waves between major tributaries – in the Waikato the phasing between the main stem and the Waipa is critical for flood effects in Hamilton (water can back up from the Waipa) and lower river. Understanding this will require careful hydraulic modelling at a later stage.
[2] Based on studies in Illinois (Demissie and Khan, 1993) so moderate level of uncertainty.

These effects have implications for sediment and nutrient yields, water quality, flooding, instream habitat and availability of water for irrigation and hydropower generation.

Reduction in riverbed levels due to sand mining may also reduce flood levels and lower groundwater levels (influencing wetlands). The effect of riverbed lowering on ameliorating flood risk along the lower Waikato was reported by Freestone (2003), although it remains the policy of the Environment Waikato Asset Management Group to control riverbed levels through targeted commercial extraction or maintenance dredging. Downstream from about Huntly, falling riverbed levels, in conjunction with land drainage works and pumping, have drawn down the water table in the peaty wetlands adjacent to the river. As these dry out, the peat under the wetlands shrinks and the land surface subsides – a process that displaces ecological boundaries and re-elevates the flood risk on the floodplain. For example, subsidence rates averaging 65–170 millimetres per year from 1967–81 have been reported from Motukaraka Swamp (Freestone, 2003).

Dams also store sediment, and alter downstream water quality and channel morphology (Young et al., 2004). The performance of dams is dealt with in more detail below (see Section 3).

2. Land use and riparian management

2.1 Water yields and low flows

Pasture land use has lower evaporation than native forest or pine forest and hence has greater annual run-off (Fahey et al., 2004). However, because quickflow run-off (i.e., that during rain events) is greater under pasture, subsequent low flows can be lower under pasture than native forest land cover. Changes in annual run-off after whole catchment pine afforestation of grassland in New Zealand range from 30 percent to 81 percent (Fahey et al., 2004), in line with the average 44 percent reduction in streamflow from analysis of many international paired catchment studies of the effects of pine afforestation of grasslands (Farley et al., 2005). Eucalypt plantations had greater run-off reduction effects (average 75 percent) than pines (average 40 percent) in Farley et al.'s (2005) comparison.

Flow effects vary during the typical 27–30 year rotation of pine forest planting, growth, harvest and replanting, with these variations most apparent at small catchment scales (less than 300 hectares) where most of the catchment may be logged over two to three years. However, at medium to large scales (over 5,000 hectares in forest), effects of forestry on water yield are normally averaged out because different parts of the area in planted production forest are typically in different phases of the rotation at any one time (in order to provide a sustainable flow of work and product from the forest).

2.2 Annual run-off

The average annual run-off of the Waikato River at Mercer is 900 millimetres (or 400 cubic metres per second, based on data in (Environment Waikato, 2008). This varies within sub-catchments in relation to rainfall (c. 1,200 millimetres in lowlands, c. 1,700 millimetres on hills and up to 3,200 millimetres on upper slopes of Ruapehu), vegetation and geology.

2.3 Pine afforestation effects on run-off

At Whatawhata, annual water yield from a pasture catchment (970 millimetres) decreased 29 percent (285 millimetres) by year six after planting (mainly pine) 62 percent of the catchment and averaged 19 percent (158 millimetres) less than the adjacent fully native forest catchment (Quinn et al., 2009); similar changes were observed in year eight after planting (Quinn unpublished data). This indicates a 47 percent (450 millimetres) reduction on pasture water yield would have occurred if the whole catchment was afforested, assuming a linear relationship between area afforested and water yield. Annual flow from pasture at Whatawhata was seven percent (115 millimetres) higher than from native forest.

Somewhat lower responses to pasture afforestation by pines were found at Purukohukohu, in the upper Waikato catchment near Rotorua, where rainfall was similar to Whatawhata but geology differed (pumice soils over impermeable bedrock, compared with yellow-brown earths over greywacke at Whatawhata). Beets and Oliver (2007) compared paired catchments in native forest and in transition from pasture to pine at Purukohukohu and found annual water yield from pasture planted in pine decreased, in proportion to the change in leaf area index, by up to 400 millimetres when leaf area index peaked. They predicted the annual flow from a managed pine site of average-to-high productivity over a 30-year rotation will be 160–260 millimetres lower than from pasture (i.e., 21–35 percent lower than average annual run-off from pasture of 745 millimetres) and 100 millimetres (17 percent) lower than from native forest.

Based on these two Waikato studies, it is estimated that the average effect of complete pine afforestation of pasture over the forest rotation would be to reduce annual water yield by about 300 millimetres. The difference in effects between Whatawhata (c. 450 millimetres at year six) and Purukohukohu (maximum 400 millimetres for mid-late rotation forest; average over 30 year rotation 160–260 millimetres) result in there being a high level of uncertainty around this estimate.

2.4 Riparian forest effects on run-off

Large riparian buffer forests can also influence streamflows. Evaporative losses from buffers are likely to be larger than for full forests because they have more edge, thus allowing greater wind-driven evaporation (Smith, 1992). In a study in Nelson (Moutere, rainfall 1,020 millimetres per year), wide riparian pine plantings (25–35 metre strip enclosing the stream, i.e., similar to 15 metre buffers on each side as proposed for Kyoto compliant carbon forests) that occupied 20 percent of the total catchment area reduced the annual run-off by 68–104 millimetres (i.e., 21–55 percent) when the stands were eight to 10 years old. Native riparian plantings are expected to have lesser effects on flow than these pine plantings, based on comparisons of water yield from the native forest/pine at Whatawhata and Purukohukohu, but the Study team lack direct evidence of how much less. For the purposes of the scoping Study, it is assumed that reduction in water yield relative to pasture of 15 metre native buffers (total width 30 metres, 20 metres and 10 metres) would be one third Smith's (1992) finding for 30 metre wide pine plantings (i.e., mean 86 mm/3 = 30 millimetres or three percent). Similarly the effects of 10 metre and five metre native buffers (20 metre and 10 metre total widths) are estimated to be proportionately lower (i.e., two percent and one percent, respectively).

2.5 Low flows

At Whatawhata (Waipa hill country, annual rainfall 1,650 millimetres, three square kilometre catchments) the annual seven-day low-flow (a commonly used low-flow index) was 11 percent lower in pasture than in an adjacent native forest catchment (Quinn et al., 2009). This suggests a 10 percent increase in baseflow is likely once pasture is restored to native forest, however regrowing native forest is likely to have greater water demand than old growth forest, so there may be little increase in low flow from conversion of pasture to native forest in the first 50–100 years.

Afforestation of 62 percent of a pasture catchment at Whatawhata (58 percent pines and four percent natives) reduced the seven-day low-flow by 33 percent (Quinn et al., 2009). Scaling this to 100 percent afforestation, assuming that flow reduction is proportional to area afforested, indicates that complete afforestation would result in a low-flow reduction of 55 percent (Quinn et al., 2009). This is greater than the 20 percent reduction in the seven-day mean low-flow in Berwick forest in east Otago (Smith, 1987). In smaller catchments, pine afforestation near Rotorua (Dons, 1987) and Nelson (Duncan, 1995) extended the duration of periods of zero flow.

In contrast to riparian forests, riparian and other wetlands store water and enhance base/low flows (Mitsch, 1992). Hence, as well as reducing contaminant concentrations and loads (Tanner et al., 2005), restoration of wetlands on drainage systems can modify flood and baseflows.

Lowland agricultural areas of the Waikato have been drained extensively using under-field (mole-pipe) systems linked to open drains that typically lower the water table and bypass wetlands. Upland Waikato agricultural areas commonly have valley bottom wetlands at the head of stream channels, and riparian wetlands occur where springs emerge. However these wetlands are commonly drained by digging a central channel that lowers the water table to provide more grazing land. Thus there is scope to restore the hydrological functions of wetlands in pasture by creation of artificial wetlands on tile drains and infilling/damming channels cut through wetlands and restoring wetland vegetation by planting and livestock exclusion.

The relationships between wetland management and flow regimes have not been systematically addressed in the New Zealand context, so the estimates on wetland effects on flows in the predictions table are based on a study in the United States of America (Demissie and Khan, 1993). Some local evidence indicates that these predictions may be quite conservative for effects on low-flow enhancement in lowland Waikato catchments: low-flow yield during the current Waikato drought (mid-march 2010) was more than 200 percent higher from a 10 hectare catchment with a large wetland (2.3 percent of catchment area) at its outlet than from the larger total catchment that has low wetland cover (Dr R.J. Wilcock, NIWA, pers. comm.). This catchment, Toenepi near Morrinsville, has similar characteristics to many lowland Waikato streams. This compares with 18 percent increase (eight percent multiplied by 2.3) predicted based on Demissie and Khan (1993). Specific studies on low-flow enhancement of wetlands are needed to better understand their effects in the Waikato.

2.6 Land use and mitigation effects on flood peaks

2.6.1 Afforestation of pasture

Afforestation of pasture is expected to reduce flood flow peaks (by increasing interception and infiltration of rainfall into soil), with benefits for flood hazard management throughout the catchment, particularly in lowland areas. Afforestation of pasture with pines and gorse reduced flood flows by 80 percent in a small catchment study in Nelson (Duncan and Woods, 2004) and pine afforestation reduced storm flows by about 50 percent in a small Rotorua catchment (Dons, 1987). There was an indication of reduced peak flows in the first eight years after the 62 percent area afforestation at Whatawhata when the median ratio of annual maximum was 20 percent lower than in the seven years before the changes. This suggests complete afforestation may reduce storm flows by about 30 percent.

Concerns about the hydrological effects of recent conversion of pine forest to pasture in the upper Waikato catchment led to Environment Waikato commissioning, in 2007, a modelling series of studies on potential effects on flooding throughout the downstream catchment of the potential pine-pasture land-use change of 12 percent of the total land area of the Taupoo to Karaapiro catchment. Findings are summarised on the Environment Waikato website[1]. Although the Environment Waikato coordinated study addresses deforestation (pine to pasture land-use change), it is useful for evaluating the level of benefit that would accrue if afforestation of pastures was adopted as a restoration action. Key predictions are summarised in Table 2.

Table 2: Changes in flood peaks predicted by Environment Waikato Technical panel for a 12 percent change from pine forest to pasture land use in the upper Waikato River catchment[1]

Landscape scale	Small flood (5 yr rainstorm)	Medium flood (20 yr rainstorm)	Large flood (100 yr rainstorm)	Extreme flood (500 yr rainstorm)
Local flooding within upper Waikato 10–100 km^2 catchment area, 0–80% upstream land-use conversion	Significant increase (5–50%) for streams where most of catchment has land-use change	Significant increase (5–50%) for streams where most of catchment has land-use change	Very significant increase (more than 50%) for streams where most of catchment has land-use change	Very significant increase (more than double) for streams where most of catchment has land-use change
Upper Waikato Taupoo–Karaapiro inflow 4,405 km^2 area, 542 km^2 land-use conversion (12%)	Little or no change	Little or no change	From 2–9% increase in peak flow rate (average 4%) 3–5% increase in 72-h flow rate (average 2%)	From 3–16% increase in peak flow rate (average 7%) 2–9% increase in 72-h flow rate (average 4%)
Waikato River at Hamilton 8,230 km^2 area	Little or no change	Little or no change	40–110 mm water level increase 6–21 m^3/s peak flow increase	280–530 mm water level increase 70–140 m^3/s peak flow increase

[1] http://www.ew.govt.nz/Projects/landusechangeupperwaikato/

The overall conclusions from the Study, as agreed by the Technical Expert panel, are that the effect on flood flows and water levels from land-use change in approximately 12 percent of the upper Waikato catchment are likely to have:

- Significant to very significant increases in peak flow rate for local flooding in small catchments where full conversion is expected.

[1] http://www.ew.govt.nz/Projects/landusechangeupperwaikato/

- At Hamilton, insignificant impacts during small to medium floods, increases of up to 40–110 millimetres in peak water level for large floods, and increases of 280–530 millimetres for extreme floods.

- From Ngaaruawaahia to Rangiriri, insignificant impacts during small to medium floods, increases in the peak flood water level of 20–40 millimetres during large floods, and increases of 170–270 millimetres in extreme floods.

Afforestation of pasture is likely to produce reductions on peak flows of similar magnitude to these predicted increases in response to deforestation.

2.6.2 Riparian forest and wetland restoration/revegetation

Riparian forests and wetlands are also expected to attenuate the peak flow of run-off into the stream channel in small rainfall events (Smith, 1992). Furthermore, well-developed riparian vegetation, and particularly forests, has greater hydraulic roughness than short grass and hence retards the progress of flood flows that spill out into the riparian area (Coon, 1998). This may cause increased local flooding of the riparian area and adjacent land, but typically reduces the peak flow in downstream reaches (Anderson et al., 2006). Anderson et al., (2006) predict that three-metre high riparian vegetation in their 50 kilometre long model channel would reduced the downstream flood peak by 10 percent for two-year annual return period floods, and 13 percent and 50-year annual return period floods, respectively. Factors expected to influence these effects are the likelihood of overbank flow events (less in deeply incised channels), the width of the riparian area and floodplain, the extent of wetlands and the roughness (size/density in relation to the flow depth) of the riparian vegetation (Sholtes, 2009).

Demissie and Khan (1993) found four percent reduction in peak flows in relation to rainfall for every additional one percent of catchment area as wetland in their United States study of 30 watersheds, and the Study team have used this relationship for estimating benefits of wetland restoration in this scoping Study.

3. Dams and flows

3.1 Introduction

Dams affect the river flow regimes and, in some cases, provide opportunities to manage floods and low flows. Dams can reduce flooding, through storm flow storage (e.g., management of the Waikato hydro dams assist with flood control), and have variable effects on low flows depending on their design, location and operating regimes. Farm dams typically reduce low flows, particularly headwater dams that capture flows of headwater ephemeral streams. Dams can also reduce sediment loads, enhancing water clarity by reducing downstream suspended solids, but can also increase algal phytoplankton biomass (reduces water clarity) by increasing residence time of water in the river (Pridmore and McBride, 1984). Dams also influence downstream channel morphology, particularly by reducing peak flows and sediment supply (e.g., Young et al., 2004; McKerchar et al., 2005). The Waikato hydro dams produce daily fluctuations in lake and river water levels that affect the edge/littoral habitat available for macrophyte growth and habitat for macroinvertebrates and fish. This hydropeaking issue is discussed in more detail in the Appendix 23: Hydro dams.

3.2 Farm dam rules

The Waikato Regional Plan has a permitted activity rule allowing (with conditions) creation of farm dams in the bed of ephemeral rivers or streams, where the catchment area is less than one square kilometre (100 hectares), and the maximum water depth of the pond is less than three metres, and/or the dam retains not more than 20,000 cubic metres of water. Larger dams require resource consents.

3.3 Waikato Catchment Study area dam numbers

There are 246 dams in the Waikato River catchment Study area listed in NIWA's database (McKerchar et al., 2005) developed during 2004–05 (Figure 1). This includes records provided by Environment Waikato and the territorial local authorities, and so appears not to include the numerous small dams created under Environment Waikato's permitted activity rule – this accounts for only eight farm stock water dams being listed as 'permitted activity' dams that do not need to be notified. Average hydraulic residence time (HRT) was calculated for each of the 120 dams for which volume estimates are available, by dividing the volume by the mean inflow, calculated from the upstream catchment area and the average specific discharge of 28 litres per second per square kilometre (Environment Waikato, 2008). Only three dams had 'high' HRT (after McKerchar et al., 2005; more than 100 days). Twenty-three had 'medium' HRT (six to 100 days), corresponding to interception of one to 25 percent of run-off, and the majority (91) had 'low' HRT with little effect on flow regimes. Median HRT was greatest for silt detention dams and least in recreational/aesthetic and tailings/mining dams (Table 3). The Waikato hydro dams have HRTs between 1.5 days (Aratiatia) and 10.5 days (Ohakurii). Rural and urban water supply dams had the greatest range of HRT; this was greatest for the WaterCare dams in the Hunua Ranges. Rural and urban water supply dams had the greatest range of HRT; this was greatest in the Watercare dams in the Hunua Ranges that provide water supply to Auckland. A farm dam built within the permitted activity rule (i.e., 20,000 cubic metres volume, mean depth two metres, 50 hectare catchment with 1,000 millimetres of run-off) would occupy c. two percent of the catchment and have an HRT of 15 days.

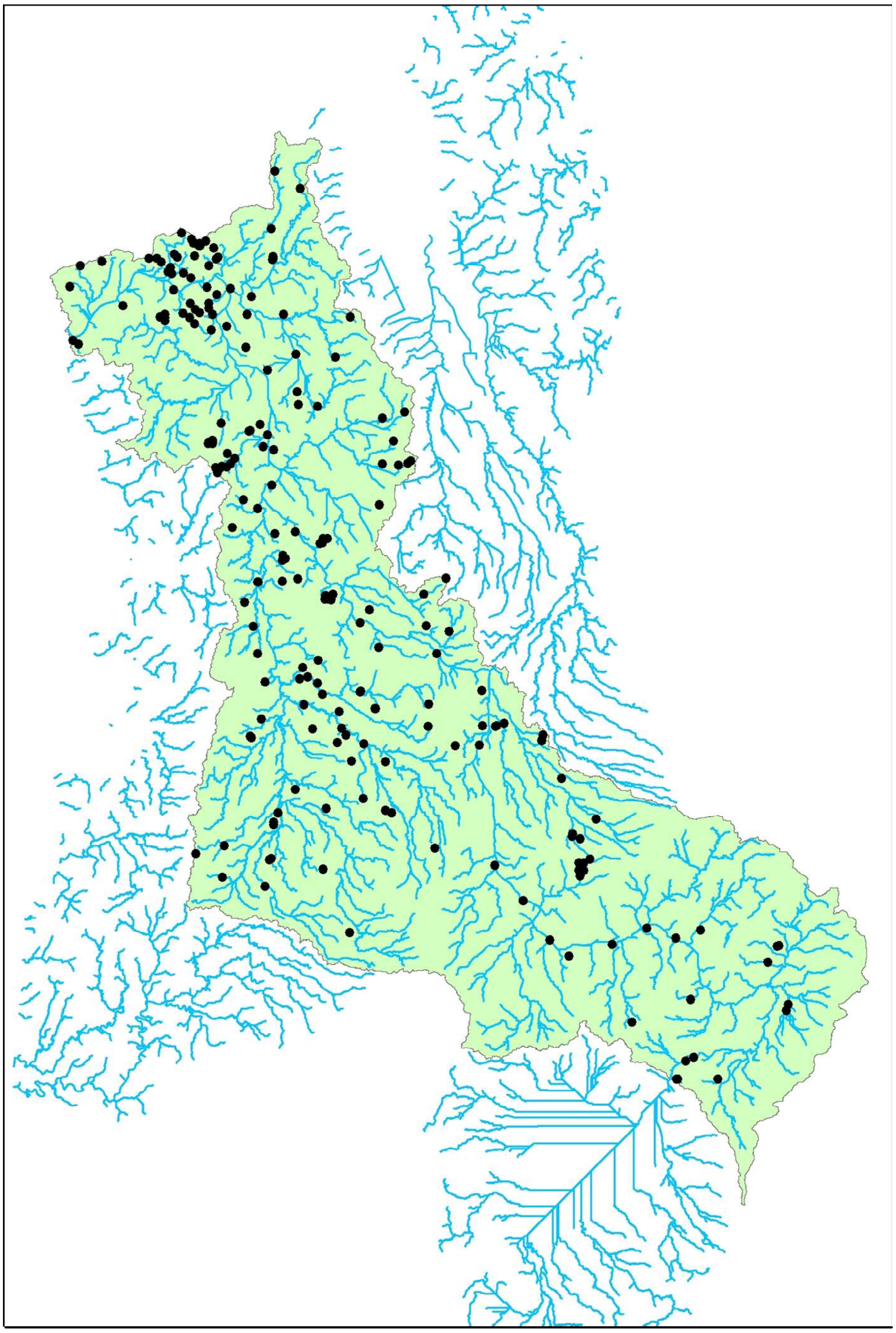

Figure 1: Location of dams listed in the NIWA database within the Waikato River catchment area (shaded in green) overlain on the River Environment Classification (REC) stream network showing third to seventh order streams.

Table 3: Summary of dams within the Waikato River catchment Study area in the NIWA database (McKerchar et al., 2005) types ordered by median hydraulic residence time (HRT)

Dam type		HRT (days) median, range, n for which HRT calculated	Volume stored by type in dams for which estimates are available (Million m^3)
Silt detention	17	16, 7–27, n=17	0.1
Farm stock water	8	8.4, 0.6–10.5, n = 8	0.06
Flood control	62	6, 0.1–64, n=13	>1.5[1]
Waikato hydro dams	11	5, 1.5–10.5, n=8	570
Irrigation	45	3.5, 0.1–208, n = 45	0.8
Water supply (urban and rural)	18	0.9, 0.02–416, n=18	56
Recreational/aesthetic	70	0.7, 0.05–3.8, n=21	>0.26[2]
Tailings/mining	2	0.9, n=1	negligible

[1]Volumes available for only 20 percent of dams of this type, so actual storage may be c. five times higher.
[2]Volumes available for only 37 percent of dams of this type, so actual storage may be c. three times higher.

The eight Waikato River hydro dams have the vast majority of the total storage within the catchment totalling 570 million cubic metres, equivalent to 16.5 days of the average Waikato flow at Mercer (400 cubic metres per second) (Table 3). The next largest store of 56 million cubic metres is in the water supply dams, while other dam types have estimated storages if less than 1.5 million cubic metres.

3.4 Farm dams

3.4.1 Farm dam numbers

The actual number of farm dams in the Study area is undoubtedly underestimated in the NIWA database (Table 3). Some large areas of the Waikato are probably unsuitable for creation of small dams due to problems with sealing them in areas of peat and pumice soils. However, Fish and Game NZ staff spoken to considered that most hill-land farms have at least one or two dams for waterfowl or aesthetic purposes (pers. comm. Ben Wilson, Fish and Game NZ, Hamilton). A scan of 60 one square kilometre areas of hill farm around the Waikato catchment on Google Maps satellite images located 32 dams, confirming that these are under-represented in the NIWA database. Farm dam creation was subsidised by Acclimatisation Societies in the 1970–80s (Ben Wilson, Fish and Game NZ, pers. comm.). Currently, Fish and Game NZ is active in wetland restoration (particularly to enhance waterfowl) in the eastern part of Whangamarino wetland, where 25 ponds have been developed recently.

3.4.2 Farm dams as a water quality management tool

NIWA has included ponds on headwater/ephemeral streams as a mitigation tool for control of sediment and nutrients in NPLAS (Nitrogen and Phosphorus Load Assessment System). Pond performance was simulated by Rob Collins using BUCSHELL (a specialised computer programme). Time series of sediment loads were generated for four soil drainage types and three rainfall records. The loads were passed through ponds of various sizes (pond volume in cubic metres as a percentage of catchment area in square metres), assuming a single settling velocity of 0.000001 metres per second, corresponding to a fine sediment (coarse clay). The model assumes that there is no infiltration through the base of the pond. The depth was 1.5 metres, with vertical sides. A preliminary set of simulations showed that there was little effect of slope in terms of percentage removal of sediment, so slope was not included as a factor thereafter.

The results are shown in the Figure 2 and 3 below. As the rainfall increases, the pond performance deteriorates, as there are higher hydraulic loadings. As the soil drainage gets worse, the performance also deteriorates, for similar reasons. Also, as the pond size increases, the performance improves. Note that these results are for fine sediment only.

The performance decreases exponentially ($1-E = \exp(aS)$) where S is the size and E is the efficiency (Figure 3). This will be useful for interpolation of results for different pond sizes.

Nitrogen and phosphorus removal efficiency are estimated to be c. 50 percent of that for fine sediment, due to dissolved fractions and particulate fractions associated with very fine sediment.

Colin Stace (soil conservationist, Environment Bay of Plenty) commented that it is hard to get more than 0.3 percent storage in detention ponds in steeper areas. This is expected to increase in flatter areas.

Dams on perennial streams can have negative effects on some aspects of downstream water quality by increasing water temperature and reducing dissolved oxygen (Maxted et al., 2005). These can be avoided by locating dams off-channel and in ephemeral channels.

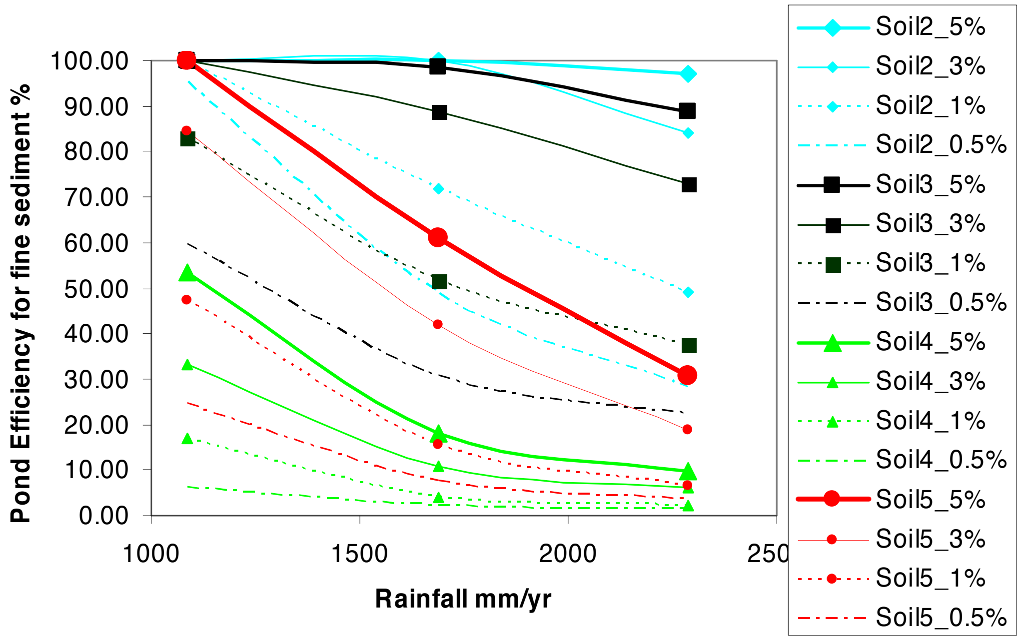

Figure 2: Simulation results for pond performance for fine sediment removal as a function of pond size (percentage of catchment area drained) and catchment soils. Soil 2=very well drained; 3 = well drained; 4 = poorly drained; 5 = average drainage.

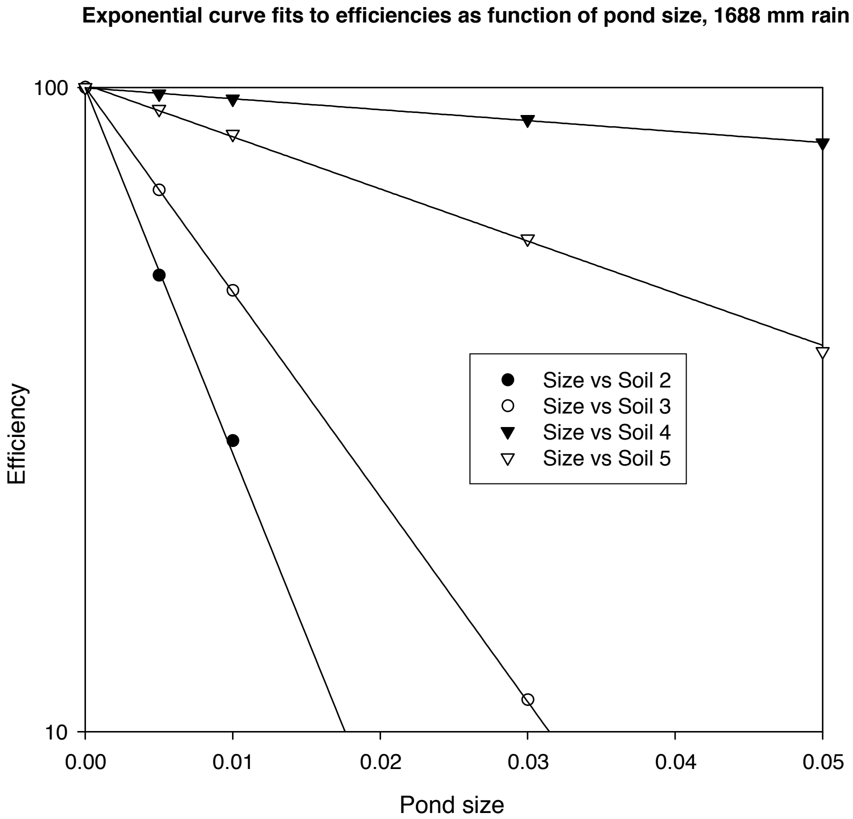

Figure 3: Fine sediment removal efficiency curves for a typical Waikato hill rainfall in relation to pond size and soil type.

This analysis suggests that there is scope for additional small dam development in ephemeral headwater areas for the purpose of controlling flood flows and trapping sediment and nutrients. Such dams could be designed to enhance benefits for fish (particularly tuna (freshwater eels); see Appendix 5: Tuna), waterfowl and aesthetics (e.g., by incorporating requirements for tuna access in the outlet design and slope of the downstream batter of the dam). These dams could also provide stock water by supplying troughs rather than by direct livestock access.

4. Sand mining

Sand and gravel extraction from the bed of the lower Waikato began in the 1940s, largely to service the construction industry. The overall rate of extraction increased up until the mid 1970s, with over one million cubic metres extracted in 1974. Between 1953 and 2006, the extraction rate averaged 350,000 cubic metres per year, which was more than three times the average rate of bed-material entrapment in the hydro lakes. Most extraction has occurred in the Mercer area but over time the focus has shifted downstream. The historical extraction has created a long hole in the riverbed, lowering average bed levels by up to two metres in the Mercer-Puni area, and the extraction volumes between Rangiriri and the coast show a good overall match with surveyed riverbed volume changes. As discussed in Section 1, the lowered riverbed has reduced flooding in this area but it has also lowered the water table in the adjacent wetlands such as Whangamarino and Motukaraka, which in turn has led to subsidence of the wetland peat deposits.

Current sand extraction is confined to the Puni-Tuakau area and is approximately 160–180,000 cubic metres per year. This accords with the strategy of the Lower Waikato and Waipa Control Scheme’s Asset Management Plan (Environment Waikato, 1997), which sets a sustainable average extraction rate of 180,000 cubic metres per year based on best estimates of the bed-material load entering the extraction reach. This management plan includes maintaining a target water-level profile at a reference discharge, thus the hole created by the current mining is expected to infill about as fast as it is dug-out.

Sand mining is being managed by Environment Waikato through resource consents. It is recommended that the Waikato River Authority keeps a watching brief on the issue.

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