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Opitonui Stream Suspended Sediment Analysis

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Executive Summary

Over recent years, there have been concerns that suspended sediment (SS) from Opitonui Stream has impacted on the water quality and muddied the bed of the Whangapoua Estuary. As a result, since 1991 Environment Waikato have sampled suspended sediment in the Opitonui Stream downstream of the Opitonui and Awaroa stream confluence to monitor the changes in sediment supply resulting from forest harvesting upstream of the Awaroa/Opitonui confluence.

Now that suspended sediment data have been collected, Environment Waikato has commissioned the National Institute of Water and Atmospheric Research (NIWA) to: analyse the data to: assess whether any significant change in suspended loads and concentrations in the Opitonui catchment has occurred since monitoring commenced; determine whether forest harvesting has contributed to the change; and expand any findings to other sub-catchments in the Whangapoua catchment to estimate relative suspended sediment contributions from these streams. NIWA were also requested to provide guidance on the usefulness of “snapshot sampling” for the Whangapoua catchment and advise on an ongoing monitoring approach for Opitonui stream and the Whangapoua catchment.

This study of Opitonui Stream was able to determine significant relationships between event suspended sediment yield and peak discharge, but no clear relationship emerged between sediment yield and forestry activities. This does not necessarily mean that there is no relationship between the two, but there are several factors that ‘cloud’ it. These include:

- Auto-samples have only been collected for a short period of approximately 6 years. Prior to this, depth integrated samples were generally only collected at low flows, giving no indication of storm event yields.

- The auto-sampling programme did not commence in the Opitonui catchment until after a portion of the catchment had been altered by forest harvesting (i.e. there is no good quality, pre-harvesting SSC information for the Opitonui catchment).

- Forestry records (Ernslaw One Limited, 2004), used to determine when harvesting has taken place in the catchment upstream of Opitonui Stream, only indicate the annual harvest record - there is no available record of the exact week/month that harvesting took place (i.e. the length of time between harvesting and storm events can not be very accurately determined).

- Erosion in the catchment – and suspended sediment generation - are expected to be maximised by heavy rain on steep slopes within several years of harvesting. Both the rainfall and harvesting operation tend to be patchy in space and time, thus sediment yields during a given event will tend to vary randomly according to where the rain falls and where the catchment has been harvested. With only one sediment monitoring station near the catchment outlet and with a limited network of rain gauges recording data at a high time resolution, it is difficult to determine which areas of a catchment upstream of the monitoring site have been exposed to the higher intensity rainfall.

Other observations are:

- Snapshot samples were collected on nine occasions between 20 June 2001 and 12 October 2003; the number of sites sampled on each occasion varied from two to 27. At best, these data may only be used to identify gross differences in sediment concentrations during runoff events. This is because of the:
  - small number of samples,
  - unknown variability of rainfall intensity over the catchments,
  - expectation that SSC should vary widely with flow over an event but the lack of information on the phasing of the flow and SSC over each storm event, and
  - lack of any definitive relationship between forestry/landuse and sediment supply.
- To gain some understanding of sediment yields from other catchments adjacent to the Opitonui catchment, a structured sediment-sampling programme would be required for each site of interest. The following programme is recommended:
  - Continuous stream-flow monitoring.
  - A consistent and sustained programme of depth-integrated sampling over a range of flows on both rising and falling stages (resulting in a SSC-Q rating relationship).
  - Occasional “bursts” of auto-sampling during sampling of runoff events, with the purpose of identifying time trends in the event-yield relationship, and also in the hysteresis characteristics of the SSC-Q relation within events.
  - Regular analysis of the particle size of the suspended load sampled by depth-integrated/whole flow samples.
  - Most importantly, to sustain the sampling for an adequate duration for trends to emerge. A decade at least is recommended.
  - For catchments with changing landuse, preferably start monitoring as early as possible (e.g., if possible, start monitoring prior to the start of forestry harvesting in the catchment area upstream of a monitoring site). Alternatively, and if possible, a control catchment in stable landuse should be monitored concurrently.

While these results may question the utility of continuing the sampling program – or repeating it elsewhere - the following points should be considered:

- The monitoring has established the ranges of SSC, event and annual suspended sediment yields for the Opitonui, and these results allow the Opitonui to be compared with other catchments around New Zealand that are subject to forest harvesting. Thus while it may not be possible to quantify the effect of forestry operations on the yield from every storm, it is possible to assess if the operations are having a gross impact on sediment loads.

- In this regard, the available data sets a standard and a range which might be used to monitor and regulate future operations, allowing that the associated monitoring of the Whangapoua Harbour has not shown a declining ecosystem since 1999.

The available data show that the catchment ‘cleans up’ relatively soon (apparently within several months) after moderate to large events, whereas there is a hint (but nothing significant in the formal statistical sense) that extreme events such as the March 1995 event may create an overall increase in sediment yield that may take of the order of a decade to decline.

Snapshot sampling in 2001-2003 suggested that sediment concentrations during storm runoff in other streams flowing into Whangapoua Harbour were not grossly different from those monitored in detail at the Opitonui site.

1. Introduction

Over recent years, there have been concerns that suspended sediment (SS) from Opitonui Stream has impacted on the water quality and muddied the bed of the Whangapoua Estuary. To monitor the changes in sediment supply resulting from forest harvesting in the Opitonui and Awaroa catchments feeding into the Opitonui Stream, Environment Waikato have sampled suspended sediment in the Opitonui Stream downstream of the Opitonui and Awaroa stream confluence since 1991.

Now that suspended sediment data have been collected, Environment Waikato has commissioned the National Institute of Water and Atmospheric Research (NIWA) to analyse the data to:

- Assess whether any significant change in suspended loads and concentrations in the Opitonui catchment has occurred since monitoring commenced.
- Determine whether forest harvesting has contributed to the change.
- Expand any findings to other sub-catchments in the Whangapoua catchment to estimate relative suspended sediment contributions from these streams.

NIWA were also requested to:

- Provide guidance on the usefulness of ‘snapshot’ sampling for the Whangapoua catchment.
- Advise on an ongoing monitoring approach for Opitonui stream and Whangapoua catchment.

The following methodology has been applied:

1. Compute annual suspended sediment yields from 1991 to the present.
2. Compute average monthly yields and thereby identify any seasonal variation in yields.
3. Identify any change in the ‘rating’ relationships between suspended sediment concentration (SSC) and water discharge and between storm event sediment yield and event water discharge.
4. Describe, interpret, and note any change in hysteresis characteristics of the SSC versus water discharge relationship.
5. Relate any time-trends in the above to forest harvesting.

6. If appropriate, extrapolate the results of the suspended-sediment monitoring in the Opitonui to other sites in the Whangapoua catchment to estimate relative suspended sediment contributions from these sites.

2. Literature review

At the outset of this investigation the Environment Waikato offices were visited by NIWA to review reports relating to the Whangapoua harbour, catchment and forestry operations. The findings are summarised below.

2.1. Pre-1991 (before exotic-forest logging commenced)

Donald (1990) summarised the physical features of the Whangapoua catchment prior to exotic forest harvesting commencing, and provided a baseline study of the physical resources (and the present and future demand on the resource).

According to Donald (1990), in the pre-European era the Whangapoua catchment appears to have been well afforested, with soils forming under the podocarp-dicotylous rain forest. However, by 1907, considerable areas had been deforested for settlement and cultivation, and all accessible portions of the remaining bush had been depleted of kauri and other marketable timber. Following this stripping of the forest came gum diggers and gold miners, who used fires to create easier working conditions. Then, after the burning and clearance by gum digging, mining and pastoral activities, regeneration of herbaceous and colonising plants resulted in further cycles of clearing and burning in the area for many years. In places, considerable sheet erosion has resulted in the pre-European topsoil and humus layer being completely removed from the soil profile. Overall, there has been a considerable impact on the vegetation in the area and this has affected the entire resource of soil, water, fauna and flora that exists today.

Most of the present production forest (7560 ha) was established in pines (predominantly *Pinus radiata*) from the early 1960s. The harvest and replanting phase commenced in 1992 and is continuing on a sustainable yield basis (Quinn, 1998). By 1990, only very small pockets of bush remained in their virgin condition (Donald, 1990).

Donald (1990) also noted that changes in the area have included the destruction of habitats (e.g. mature coastal forests), the creation of new habitats (e.g. introduction of new exotic species of trees which have been planted to replace the old forests), or the extension of existing habitats (e.g. grasslands and mudflats). Vegetation cover is summarised in Table 2.1 for the 11,003 hectare Whangapoua Harbour catchment.

Table 2.1: **Vegetation cover for Whangapoua Harbour catchment (Donald, 1990)**

Vegetation type	Area (Ha)	Percentage of catchment
Coastal	392	3.9
Wetland	38	0.4
Scrub associations	660	5.2
Native forest associations	2143	19.2
Exotic forest	5481	50.0
Pasture	2283	20.8

Coker (1988) recommended that harvesting of the steep headwater areas in both the Awaroa and Opitonui catchments should be spread to restrict the increase in runoff after harvesting to one tributary at a time. This would not reduce the impact of harvesting on river levels experienced on the alluvial flats, but should reduce stream erosion, culvert damage, and sediment production within the forest.

2.2. Post 1991 – Catchment monitoring and hydrology studies

2.2.1. NIWA catchment monitoring

The harvest of the first rotation tree crop from Whangapoua Forest by Ernslaw One Ltd commenced in 1992 (Quinn and Wright-Stow, 2004). On 6 October 1992 monitoring commenced at six stream sites, covering the main catchments in the forest area, with the aim of evaluating the effects of harvesting activities. This monitoring included stream water clarity (fortnightly to monthly), temperature (summer) and stream habitat and biota (summer and end of winter). In addition to sites within the plantation forest, information was also collected in the middle reach of the Opitonui (native forest 'control') and on Horongoherehere Stream which is a mainly pasture catchment (Quinn and Wright-Stow, 2004). These control sites were implemented to differentiate between effects of forest management practices and natural factors, such as floods. Other monitoring sites have been added since the monitoring began, to cover additional catchments where harvesting takes place. Appendix A gives further information from Quinn & Wright-Stow (2004) on catchment logging activity (Table A1), and a map showing the location of the monitoring sites (Figure A1).

Some of the findings from Quinn and Wright-Stow (2004), as a result of catchment monitoring, were:

- Water clarity responses to logging have varied between the sites. Some sites saw a decline, others had no decline, and the Owera sites showed a decline for a period during logging but recovered within a couple of years after logging finished. Annual median water clarities at the stream sites below harvested areas were appreciably higher (5-11 times) than the pasture control stream.

- Water temperature measurements tended to be higher after logging compared to the native control stream. The temperature difference tended to decrease over time, with water temperatures returning to levels very similar to native forest 8 years after clear-cut logging in one catchment.

- Channel widths have shown varying responses to logging, apparently depending on the coincidence of severe flooding with logging.

- Sediment particle size measurements ceased in Summer 2000. Quinn & Wright-Stow (2002) noted that between Spring 1992 and Summer 1995, streambed sediment size distributions were relatively stable at sites downstream of harvested catchments, indicating no large changes in sediment supply rates. However, fine sediment became more abundant after the March 1995 storm at three sites downstream of harvesting (sites OW, OWw and A). The locations of these monitored sites are shown in Figure A1, Appendix A, and sediment particle size distributions in shown in Figure B1, Appendix B.

  Catchments OW, OWw and A received particularly heavy rain. Of these sites, OW (where the largest estimated peak storm discharge of c. 45 $m^3/s/km^2$ occurred) had the largest change, with sand covering 60% of the streambed 3 weeks after the storm. The streambed sediments coarsened back towards the pre-storm situation at these three sites between the March storm and Spring 1997, indicating that fines deposited in the storm had been flushed downstream. Harvesting of the area around OWw in 1997 and upstream and adjacent to OW and OP in 1997/98 did not result in any increase in sand and silt cover. However, there was an increase in sand and silt cover at OWw in August 1999 that was probably caused by deposition of fines released when a woody debris dam was removed 200m upstream in June 1999.

- Reduced shading of streams after logging immediately around the monitoring site has been observed to result in increases in the amount of stone surface epilithon (algal and bacterial slimes) due to increased light, temperature and nutrient concentrations. Epilithon biomass has remained well below "nuisance" levels at most sites.

- Stream invertebrate communities integrate the water quality and habitat conditions experienced at a site over time. It was noted that the greatest effects on the communities occurred in response to the combined effects of logging and severe storms. Results also indicated that while clearfell logging impacts on invertebrates are greatest in small streams, recovery may take longer in large streams because of the time taken for riparian trees to regenerate and provide shade.

In overview, what the monitoring has shown is that the impacts of forest harvesting are modulated to a fair degree by the occurrence of storm events. For example, in the Owera catchment harvesting coincided with the intense rainfalls of the March 1995 storm. In consequence, its stream water clarity decreased during harvesting and this effect lasted for a few years after the storm. In contrast, the change in clarity during harvesting in the Awaroa catchment, which received relatively little rainfall during the March 1995 storm, was variable. In some compartments that were being harvested, the effects were very small despite the construction of roads and landings and clear-felling at the time of the storm. This suggested that sediment runoff during less extreme rainfall events may be relatively small (Morrisey et al, 1999).

The Cyclone Fergus storm (29-30 December 1996) caused much less erosion than the March 1995 storm. Experience gained from both of these events has been used to develop new practices to reduce erosion risk posed by woody debris on landing edges (for example, an excavator is now used to pull the material back from the landing edge once harvesting is complete) and to reduce off-site export of woody debris into stream channels (including the use of trash collectors) and damage to culvert fills and crossings (Quinn, 1998). Also, where feasible, the use of cable-hauling from suspension towers has generally prevented disturbance of the soil surface, and low level stream crossings avoid the risk of fill erosion and culvert blockages (Quinn, 1995).

2.2.2. Hydrology of landuse changes in catchment

A literature review by Bepapa (2004) concluded that deforestation increases the frequency and rate of peak flow, increases annual water yield, increases excess overland flow and sediment yield, and increases baseflow during prolonged dry spells.

As part of the Bepapa (2004) study, a comparison was made between the Opitonui catchment (where logging has taken place) and the Tairua catchment (a predominantly native forest catchment with stable landuse). This comparison showed that:

- Opitonui catchment annual water yield tended to increase after logging commenced, while Tairua had a relatively stable water yield.
- Runoff from Opitonui was slightly increased, suggesting a more responsive behaviour to storm events after logging commenced.
- The average peak flow for Opitonui increased after logging, although this may have related to other factors such as changes to annual rainfall patterns and seasonal rainfall distribution.
- There was a large increase in the Opitonui low flows from 1992 to 2002. This was not observed in the Tairua flow duration curves.

2.3. Post 1991 – Whangapoua Harbour monitoring

Prior to the commencement of logging, Thrush et al. (1993) concluded that Whangapoua Harbour was vulnerable to forest harvesting because of the high area of forest and because the harbour had a low proportion of fine sediment habitats. It was thought that the harbour, being 80% inter-tidal, had a low potential for sediment reworking by waves and currents because large areas were vegetated (i.e. eelgrass and mangroves) and large areas experienced low wave energy. Therefore, in the upper arms of the harbour, fine sediment was expected to accumulate in the vegetation, and during floods, coarse material was expected to accumulate at the stream mouths. Further down the harbour, because the harbour is shallow, it was expected that wave and current action would keep the harbour well flushed (tidal prism is approximately 8.5×10^6 m^3). Observations in 1993 indicated that downstream of the Opitonui stream mouth, the harbour bed was unconsolidated gravelly mud, suggesting that there was a high sediment load supplied from the Opitonui. Thrush et al. (1993) concluded that the areas expected to feel the greatest effects of forestry were the sand flats near the forested stream channels. It was recommended that a monitoring program be implemented to assess the effects of forestry.

As a result, in 1992 NIWA (then the Water Quality Monitoring Centre, NIWAR) was commissioned by Ernslaw One Limited to assess the need for a monitoring programme to detect effects of forestry activity on inter-tidal areas of Whangapoua Harbour. A monitoring programme was subsequently developed and implemented by NIWA, focussing on the inter-tidal sediments of the harbour and their biological communities. The monitoring programme was able to track the recovery of the harbour from the effects of March 1995 and other storm events.

As reviewed by Morrisey et al. (1999), the monitoring programme in 1999 included six-monthly sampling of sediments, animal communities and the density of seagrass. The distributions of seagrass and mangroves were also being monitored every 2 years using aerial photographs, and the height of the bed of the harbour was being monitored every other year.

Findings from Morrisey et al. (1999) for the period 1993 to 1999 include:

- Relatively minor changes in the height of the harbour bed, with no consistent pattern of erosion or deposition of sediment at the monitoring sites. There were no overall changes in the position of channels and banks.

- The sediment characteristics at the sampling sites showed no obvious long-term trends, although the effects of individual storm events (e.g. March 1995) were noticeable. Small wind-driven waves were able to rework mud from the sandflats, so any infilling of the harbour by sediment derived from the catchment would require deposition of sand or gravel. However, no clear changes in the amount of sand or gravel in the sediments were observed at the sampling sites.

- Beds of seagrass changed significantly between 1993 and 1997, including complete loss of seagrass from some areas of the harbour. These changes related to the March 1995 rainstorm. However, over a longer time scale (1945 to 1995), the decline after the 1995 storm was not unprecedented.

- The density of seagrass leaves within beds decreased through time at sites where seagrass was not completely eliminated after the 1995 storm. The reason for this was unknown but could have been due to a decrease in water clarity as the 1995 fine sediment was re-suspended and removed.

- Mangroves were spreading or becoming denser in the upper parts of the harbour, particularly the Owera and Mapauriki arms. This could have been a response to deposition of sediment and consequent increase in the height of inter-tidal flats in the *upper* parts of the harbour that had not been surveyed.

- Changes to animal communities living in the sandflats and seagrass beds were dominated by the effects of the March 1995 storm. Many of the sites eventually returned to normal by 1999, but this was not the case at the sites most impacted.

Morrisey et al. (1999) concluded that, between 1993 and 1999, the changes in the seagrass beds and animal communities were largely driven by the 1995 storm. Given that the rainfall for the 1995 storm was most intense in the Owera catchment, where harvesting was taking place, a significant contribution to the total sediment yield in the harbour came from exotic forest during this event (rather than recurring smaller yields in response to small, more frequent events). However, they also stated that "*given that the catchment has been irrevocably altered in the past and the mature, native forest largely removed, other forms of landuse in this area, namely pasture or regenerating native forest are likely to generate more sediment input to the harbour under the same conditions*".

2.4. March 1995 rainstorm studies

The storm of March 1995 was typical of the high intensity rainstorms recorded previously in the Coromandel within the last three decades. Visual inspection of landslide occurrence and of stream flood levels suggested that most of the rain fell to the east of the Opitonui headwaters and was centred over the Owera, Weiti, and Hooker catchments, encompassing an area of approximately 40 km^2 (Marden and Rowan, 1995). Estimates of the peak discharges during the storm at two sites on the Owera Stream ranged from 34 to 69 $m^3s^{-1}km^{-2}$ (Quinn et al, 1995) whereas a peak of 4.0 $m^3s^{-1}km^{-2}$ was recorded at the Opitonui site (Quinn and Kemp, 1998). Although other storm events between 1995 and 1998 also delivered high rainfall, none seem to have been as intense and localised as the March 1995 event and therefore have not produced such high peak discharges (Morrisey et al, 1999). The impact of the March 1995 storm on the Whangapoua Harbour was probably also enhanced by the lack of events of similar intensity during at least the preceding 3 years (Quinn and Kemp, 1998). Rainfall and stream flow data suggest that the March 1995 event had a return period of between 20 and 50 years (Quinn et al, 1995).

For the March 1995 storm event, Marden and Rowan (1995) used stereo-photo interpretation of colour vertical aerial photographs of the storm-damaged area (validated using ground inspections and field measurements) to:

- identify sources of sediment and mechanisms of slope failure,
- quantify eroded area and volume of sediment, and
- identify relationships between physical site factors and slope failure for the March 1995 event.

They found:

- Damage sustained within the worst affected area appeared to be at a level associated with a storm event with a recurrence interval of several decades.
- The most frequent on-site damage was from soil slips and debris avalanches (equally the most frequent type of slope failure). Although debris avalanches accounted for the highest proportion of total sediment volume, soil slips were more numerous and collectively comprised the largest proportion of the total landslide source area. Sites of streambank undercutting and landing-sidecast failure accounted for the least sediment.
- Approximately 42 ha of bare ground (0.6% of the study area) was created as a result of slope failure – 22 ha were identified as source areas (i.e. where scars were left) and 20 ha as depositional areas (i.e. where sediment ended up).
- Debris avalanches generated 71% of the total volume of sediment, soil slips 28%, streambank undercutting 0.6%, and landing sidecast failure 0.5%.
- 99.5% of the total sediment volume was generated by failure on natural slopes and 0.5% was generated by the failure of constructed slopes (e.g. log landings, road cuttings, etc).
- The most sediment was derived from the Department of Conservation estate (51% of the total sediment yield was derived from the 31% of the study area comprising the rugged upper catchment slopes). 38% of the total sediment originated from land administered by Ernslaw One Limited (49% of the study area comprising of exotic forest), while 12% originated from private land holdings (20% of the study area, including pastoral farms on lowland slopes, privately owned blocks of native and exotic forest, and lifestyle blocks).
- The worst affected catchments (Owera and Weiti) collectively generated 66% of the total sediment volume generated during the storm. Minor contributions were derived from the Opitonui (5% of total) and Awaroa (6% of total) catchments. In the Opitonui and Awaroa catchments, most of the sediment volume would likely have been derived from riparian zones of secondary growth and a lesser amount from areas of exotic cutover.
- Sediment production was highest (61%) in areas of native forest and least (c. 1%) on pastoral hill country because the storm and resultant damage were centred over the forested steep and erosion-prone upper catchment slopes while pastoral hill country is confined to more stable slopes in lower catchment areas.
- Areas of secondary growth located on short, steep slopes adjacent to stream channels were a significant source of sediment. Here, the scarcity of large

individual trees for anchorage is considered to have contributed to the high incidence of slope failure.

- Sediment production from cutover was 4 times that generated from areas of mature standing exotic forest and contributed 17% of the total sediment volume. Sediment production from cutover increased with increasing time since clear-felling. This trend was probably related to the decline in soil reinforcement as root systems progressively decay over time. For the March 1995 storm, rates of sediment generation from cutover that was clear-felled in three successive years was 212 m^3/ha (1992/93), 129 m^3/ha (1993/94) and 78 m^3/ha (1994/95), showing that the areas logged in 1992/93 were the most vulnerable at the time of the March 1995 storm.
- Sediment production from stands of mature exotic forest, covering one-third of the study area, contributed only 4% of the total sediment volume. Total root biomass and tree root morphology of closely planted pines appear to be the major tree root variables influencing slope stability.
- Sediment production was highest from upper catchment slopes (60%), was significant from mid to upper catchment slopes (39%), and was minimal on low to mid catchment slopes (1%).
- Sediment production was highest from slopes between 26-35º (77%), was moderate from slopes between 21-25º (22%), and was negligible from slopes <20º (c. 0.5%).
- The highest volume of sediment (82%) was generated from unstable upper catchment slopes mapped as Land Use Capability (LUC) units Vie11 and VIIe2.

2.4.1. Impacts on Whangapoua Forest landscape and streams

The effects of the 3-4 March 1995 rainstorm on Whangapoua Forest’s landscape, peak stream flows, stream channels and instream habitat and invertebrate biota are described by Quinn et al. (1995), who estimated that the recurrence interval of the storm was likely to be in the range 20-50 years.

Other observations from Quinn et al. (1995) include:

- Aerial and comparative photo-point surveys showed severe gully erosion in the regenerating native forest in the upper Weiti catchment and both stable pine and recently harvested areas of the Owera catchment. Hillslope slips also occurred in pasture areas of the lower Owera west catchment. Gully erosion and hillslope slips were relatively minor or absent in recently harvested areas of the Awaroa, lower Waingaro and lower Opitonui catchments where rainfall was lower than further south in the forest.

- Woody debris was flushed downstream by the storm flows from ephemeral and perennial channels in the Owera catchments and some of the Awaroa catchments. Large amounts of this wood were deposited on the channel margins amongst riparian trees in the lower floodplain areas of the Owera catchments. These trees appeared to trap and filter out large woody debris in transport in the stream.

- Substantial changes in stream channel morphology were observed at the Owera study sites, where the extreme peak flows occurred. These included infilling of pools by fines, widening of the stream channels, narrowing of the wetted channels, and reduction of woody debris and large sediment particles resulting in lower retentiveness and storage of leaf litter. Lesser effects (but still significant) occurred at the Awaroa site but effects were minimal at the Opitonui site.

- The storm resulted in striking reductions in density of benthic invertebrates and their species richness at the three sites where moderate to severe flood disturbance occurred, but minimal effects on the invertebrate communities were observed at the Opitonui site.

2.4.2. Impacts on the sediments, flora and fauna of Whangapoua Harbour

As a routine monitoring programme for Whangapoua Harbour had been in place since 1993, site visits to Whangapoua Harbour on 9 and 15 March 1995 were able to provide qualitative assessments of changes in sediments, flora and fauna in the harbour immediately following the storm (Morrisey et al., 1995). The findings were that silt appeared to have been distributed throughout the harbour within six days of the storm, with the thickest deposits in the upper parts of the Owera Arm. The silt had not been confined to those parts of the harbour receiving stream inputs from the areas where rainfall was heaviest and most erosion occurred, but had also been deposited in the Mapauriki Arm. In areas of the harbour where wave action and tidal currents are effective, these fine sediments were expected to be re-suspended and transported either elsewhere within the harbour, or flushed outside the harbour. In other areas, the silt was expected to remain for longer and become incorporated into the underlying sediment by the activities of animals living in the sediment. There was very little evidence of woody debris at any of the areas of the harbour visited.

At the time of the next routine monitoring programme fieldtrip in April 1995, deposited silt still remained over eelgrass-beds. These large areas of eelgrass-beds had become partly or completely smothered by silt, particularly in the Owera Arm (Morrisey et al, 1995).

Visual inspections of the sandflats and eelgrass-beds in March 1995 also suggested that there had been an impact on the fauna in the areas most affected by silt (up to 10 cm thick). There were large numbers of dead cockles in and around the eelgrass-beds and a few dead crabs, mantis shrimps and snapping shrimps were also seen on the surface of the silt (Morrisey et al, 1995).

2.5. Other documents relating to forest harvesting

Phillips and Marden (1999) completed a review of vegetation versus slope stability relationships in plantation forests, and assessed the risk of the Ohui Forest to landsliding. Their literature review concluded that:

- The erosion volume increases linearly with area.

- Sediment production from natural slopes is greatly reduced by the presence of a mature forest cover (exotic and indigenous), and that these reductions are attributable to the soil strengthening developed by root systems and to the influence of trees on the hydrology of forested slopes through evapotranspiration.

- From existing data on root growth of new trees, root decay of old trees, rates of regeneration of vegetation on cutovers, and rainfall information, it appears that the period of maximum risk to landsliding from intense or prolonged rainfall is the third year after harvesting.

- There is substantial evidence to suggest that the effectiveness of a forest cover in the prevention of natural slope failure (landsliding) is age-dependent, with the more mature stands giving the better level of protection (i.e. stands c. ≥ 8 years old have a greater canopy closure and a greater mass, depth of penetration, and spread of the root systems).

- Higher planting densities have the potential to reduce risk from rainfall events by providing earlier vegetative cover and root site occupancy.

Quinn (2005) discussed the benefits of riparian buffers on the impacts of logging. Streams that had no riparian buffers (i.e. were clearcut), were found to have wider channels, more bank erosion, higher light input, higher maximum water temperatures, and invertebrate communities with lower diversity and altered composition (more tolerant species). In planted forests, riparian buffers can provide layers of undisturbed litter (and humus and tree roots) that can slowly diffuse runoff from cutover and forest roads, encouraging sediment settling before it reaches the stream. These buffers are likely to be much less effective when runoff is concentrated in gullies, but may help to control hillslope mass movement (by buttressing the base of hillslopes through root reinforcement). Buffers are expected to have limited ability to control sediment input from upslope slip erosion.

O’Loughlin (2005) reviewed the influence of trees on mainly shallow debris slides and debris avalanches, with most emphasis on radiata pine forestry. This review found that forests can deplete soil moisture to considerable depth through evapotranspiration and lower groundwater levels. However, evapotranspiration might only delay soil saturation during large landslide-producing storms (i.e. when usually more than 150 mm of precipitation falls in less than 36 hours, resulting in sufficient water to fill all available soil and vegetation storage). Once the soil is saturated, many slope analyses show that the tree roots are the last line of defence against slope failure. As radiata pines have early rapid growth, and the ability to provide good root reinforcement by age 8 to 10 years, they have some advantages over other crops. However, clear-felling after 25-30 years is not ideal for continued, long term stability on sensitive slopes. On steep harvested sites the period of time 2 to 8 years after harvesting is the most critical for potential slope failure as during this time the original root systems are decaying and the replacement crop of young trees have not yet developed an extensive root system.

Marden (2004) provides an additional comparison between regenerating kanuka and radiata pine. Although the roots of individual kanuka are smaller than radiata pine, the difference in total root mass is more than compensated for by the higher stand densities of kanuka. Therefore, for at least the first 9 years after establishment, dense regenerating kanuka will be less likely to fail than radiata pine.

O’Loughlin (2005) also gave an example from O’Loughlin (unpublished NZ Forest Service Report, 1973) relating to a large storm in 1971 on hill country at Whangapoua. This storm apparently triggered many shallow landslides on non-forested slopes over 32° of steepness but very few on slopes less than 28°. Older, established roads and consolidated, well-vegetated cut and fill slopes were also less susceptible to slope failures, O’Loughlin (2005).

3. Suspended sediment monitoring program

3.1. Catchment summary

The 11,142 ha (111 km^2) Whangapoua catchment has a land cover consisting of approximately 56% plantation forest, 19% indigenous forest, and 16% pasture. There are over 230 km of streams and rivers draining into Whangapoua Harbour (Environment Waikato Document No. 765707).

Like the rest of the Coromandel Region, this area is a sensitive environment predisposed to erosion as a consequence of its weathered soils, steep slopes, and the regular incidence of high intensity rainfall events (Phillips & Marden, 1999). The frequent, high intensity, but highly localised storms (often of tropical origin) commonly cause local flooding of the downstream alluvial farmland (Coker, 1988).

The topography consists of steep hills around the catchment margin; these give way down-catchment to more rolling hills, then to flats, low terraces, and swamps by the harbour. The streams are tidal in their lower reaches.

The northward draining Opitonui, Awaroa, and Owera catchments are covered largely in exotic plantation forest (Ernslaw One Limited estate) on their mid to lower slopes, while indigenous (kauri/hardwood) forest, that has been selectively logged to remove all merchantable timber, occupies the uppermost catchment areas and lies within the Department of Conservation estate.

Hill slopes are greater than 20° over 85% of the catchment, with approximately 66% of this area having slopes >25° (Environment Waikato Document No. 765707).

The hill areas of the catchment are formed mainly in volcanic rocks. These are mainly andesite but some dacite occurs to the south and east (Environment Waikato Document No. 765707).

Volcanic ash formerly covered the entire area (Coker, 1988) but has now mostly been eroded from the hillslopes and tends to be limited to terraces and flat land (Donald, 1990; Environment Waikato Document No. 765707).

The valley basins, flats, terraces and swamps bordering the harbour are alluvium, comprising volcanic sediments eroded from the surrounding hills. Dune sands comprise the land separating the harbour from the sea.

The basement volcanic rocks are relatively stable except where they have been hydrothermally altered. The steep upper slopes have been eroded down to the stable, unaltered volcanic rock, while the mid-slopes, under the forest plantations, are covered by an unstable rock mantle (Coker, 1988). Soils derived from these altered rocks are porous and easily saturated, with an associated decrease in cohesion and the formation of slickenside clay surfaces (Hauraki Catchment Board 1981 unpubl. report – not sighted).

The Whangapoua Forest area covers Class VI and VII land. The soils are clay and yellow-brown earths overlaying weathered greywacke and andesite (NZ Land Use Inventory Worksheet 78). These features necessitate particularly careful forest management to maintain the long-term productivity and stability of the land and to minimise effects of forestry activities on the adjacent stream and harbour ecosystems (Quinn and Wright-Stow, 2004).

Erosion in the Coromandel area is worsened by tectonic influences (e.g., earthquakes), a dynamic climate influenced by tropical cyclones from the northeast, and the relatively recent clearance of vegetation from steep slopes (Phillips & Marden, 1999).

Erosion potential is considered to be severe over 35% of the catchment, moderate for 52%, and slight for 13%. The steeper areas are more susceptible to erosion, sheet erosion and landslides (Environment Waikato Document No. 765707).

Mass movement erosion during storm events is common. This mass movement erosion generates high concentrations of suspended solids, resulting in thick deposits of sediments on floodplains. For example, 54 ha of dairy farmland on the floodplains were covered with up to 60cm of silt after a major storm in 1971 (Coker, 1988).

3.2. Available data

A permanent water level and sediment sampling site is located on the Opitonui Stream downstream of the Opitonui/Awaroa confluence (Site 11310). The catchment area upstream of this site is approximately 29 km^2. Sixty-two depth-integrated sediment samples were collected at this location between July 1991 and July 2001, with most of these samples being collected during periods of low flow. Thirty-nine sets of auto-samples were also collected during freshes in the period July 1999 to August 2004. Unfortunately there were no occasions where concurrent depth-integrated and auto-samples were collected. The flow record commenced on 17 June 1991. The site is operated by Environment Waikato.

Snapshot water sampling is also undertaken during high and low flows at 23 sites throughout the Whangapoua catchment. The hydrology and sediment data used for the analyses in this report are summarised in Table 3.1.

Table 3.1: Data available for sediment analyses.

Site	Site Number	Data	Start of record	End of record
Opitonui recorder site	11310	Rainfall	3 Jul 2001	19 Jan 2005
“	“	Water-level	17 Jun 1991	16 Mar 2005
“	“	Flow	17 Jun 1991	16 Mar 2005
“	“	Depth integrated sediment gaugings (62 samples)	16 Jul 1991	31 Jul 2001
“	“	Sediment autosamples (39 events)	16 Jul 1999	6 Aug 2004
Various (~26 sites)		Snap shot sediment sampling	12 Jul 2002	12 Oct 2003
Castlerock	658610	Rainfall	6 Sep 1990	19 Apr 2005
Otanguru	6854	Rainfall	3 Jul 2001	19 Jan 2005
Pungapunga	8133	Rainfall	3 Jul 2001	19 Jan 2005

4. Analysis

4.1. Inspection of data

The recorded Opitonui stream-flows for 1991 to 2005 are plotted in Figures C1 to C3 in Appendix C. Symbols plotted on these hydrographs show the times at which depth-integrated and auto-samples were collected. Note: Figures C1 to C3 have a logarithmic scale for flows to clarify when samples were collected during flow recessions.

The flow record shows that runoff events occur regularly, often several times per month. However, most depth-integrated samples were made at low flows, with only one gauging made at a flow greater than 7 m^3/s. By comparison, 75% of the auto-samples were collected at flows greater than 7 m^3/s (Figure 4.1).

The maximum, recorded flow at the Opitonui site (Site 11310) was 202.6 m^3/s on 2 July 2000 at 2340 hours. Unfortunately, no auto-sample or depth-integrated gauging data were collected during this event. The largest flow that an auto-sample was collected at was 179.5 m^3/s on 12 October 2003 at 1000 hours. Figures C3 (Appendix

C) and D5 (Appendix D) show the sediment samples that were taken by the auto-sampler during this event.

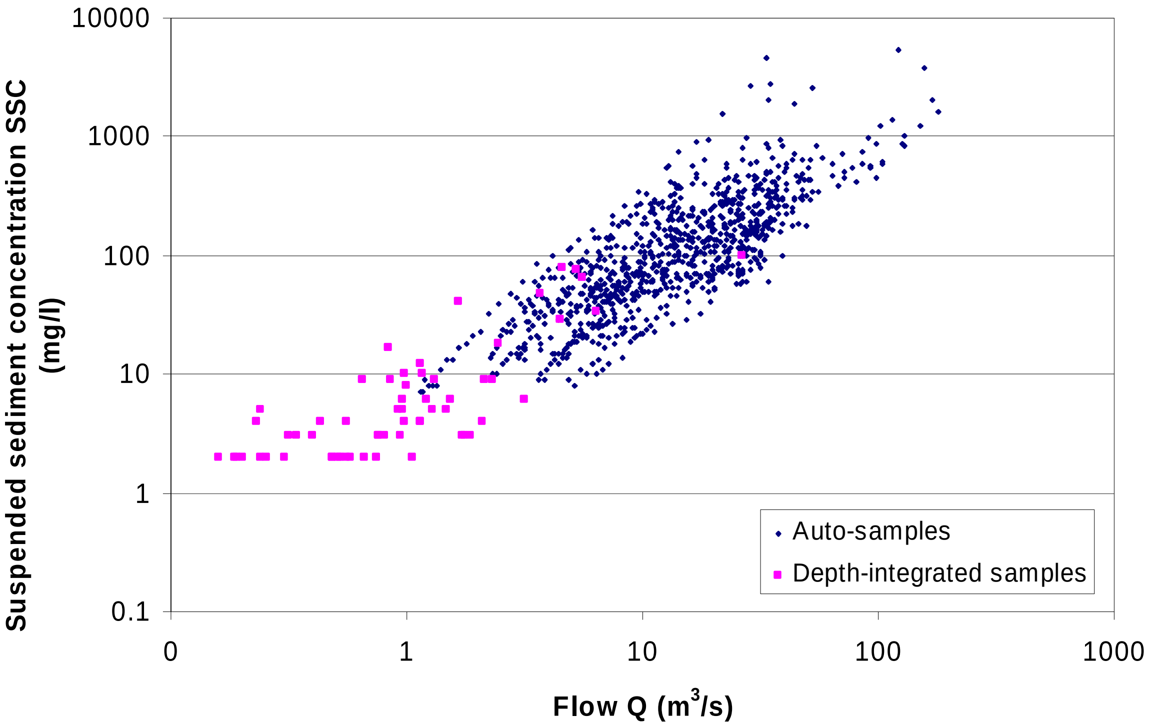

Figure 4.1: **Auto-sample and depth-integrated sediment concentration SSC versus flow Q.**

Details of the suspended sediment concentration (SSC) and water discharge time series during all of the auto-sample events are shown in Figures D1 to D5 (Appendix D). For the purpose of estimating event yields, the SSC time series for each event was extended by inserting nominal values of 2 mg/ℓ at the event start and end. This value was typical of the base flow SSC (Figure 4.1). These synthetic points are shown as red diamonds in Figures D1 to D5 (Appendix D).

4.2. Sediment rating relationship

Both depth-integrated samples and auto-samples were examined to determine whether there was any evidence of trends in sediment concentration between July 1991 and August 2004. Figure 4.1 shows the suspended sediment concentration data plotted against measured flow for all available samples. As noted previously, the depth-integrated samples tend to mainly be measured at lower flows, compared to the auto-samples.

From Figures C1 to C3 in Appendix C we note that most depth-integrated samples were collected prior to the auto-sample program commencing in July 1999 and, as a result, there were no times where both auto-samples and depth-integrated samples were measured simultaneously. However, visual inspection of Figure 4.1 shows that, with regard to suspended sediment concentrations observed at varying flows, there does not appear to be a significant difference between the two data collection methods. We have therefore assumed that there is a 1:1 relationship between auto-sampled and depth-integrated SSC, and have analysed the combined dataset.

The analysis approach proceeded in the following steps:

1. Fit a regression that predicts the concentrations from the flows.
2. Examine the residuals of the regression for evidence of a trend with time.
3. Check for factors that might be aliasing for a time-trend (such as temporal bias in sample collection).

Firstly, a curve was fitted to the combined auto-sample and depth-integrated sample datasets (Figure 4.2). The shape of the scatterplot, including the relationship between data-scatter and flow, indicated that a linear least-squares fit to the log-transformed data would be appropriate. The resulting power-law function is:

$$SSC = 6.627\ Q^{\ 1.05} \tag{4.1}$$

where SSC is the suspended sediment concentration (mg/ℓ), and Q is the water flow rate (m^3/s). The squared correlation coefficient (R^2) for fitting the logarithms is 0.74. This R^2 value was higher than the fit to either individual dataset (i.e. auto-samples or depth-integrated samples).[1]

The differences between the observed and predicted values (i.e. the residuals) showed a wide variation of up to 4500 mg/ℓ (Figure 4.3a). A plot of the residual log-values, [$\log_{10}(SSC_{obs}) - \log_{10}(SSC_{est})$, which equals $\log_{10}(SSC_{obs}/SSC_{est})$] versus time (Figure 4.3b) showed that at the Opitonui recorder site:

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[1] We have used a simple least-squares regression approach for this analysis because the purpose is only to examine the residuals for a time trend. Since we are not using the SSC-Q relationships to estimate yields, it is unnecessary that we use a more sophisticated modelling approach such as LOWESS (Cleveland, 1979) or apply a bias correction factor (e.g. Ferguson, 1986).

- Between July 1991 and July 1999, for flows <7 m^3/s, the expected SSC for a given flow does not appear to change with time. No information is available for trends in SSC for flows higher than 7 m^3/s prior to July 1999.

- Between July 1999 and late 2001 there are generally higher SSC residuals and higher log difference SSC residuals for similar flows, but from 2002 on the residuals fall back to the pre-1999 range (see Figure 4.2)

This pattern suggests a waning sediment supply from 2002 on. This coincides with a reduction in the annual forest harvest in the catchment upstream of the sediment sampling site (Figure 4.3d)[2]. Therefore we conclude that there is some evidence of a correlation between catchment area harvested and conditional sediment concentration at a given flow rate.

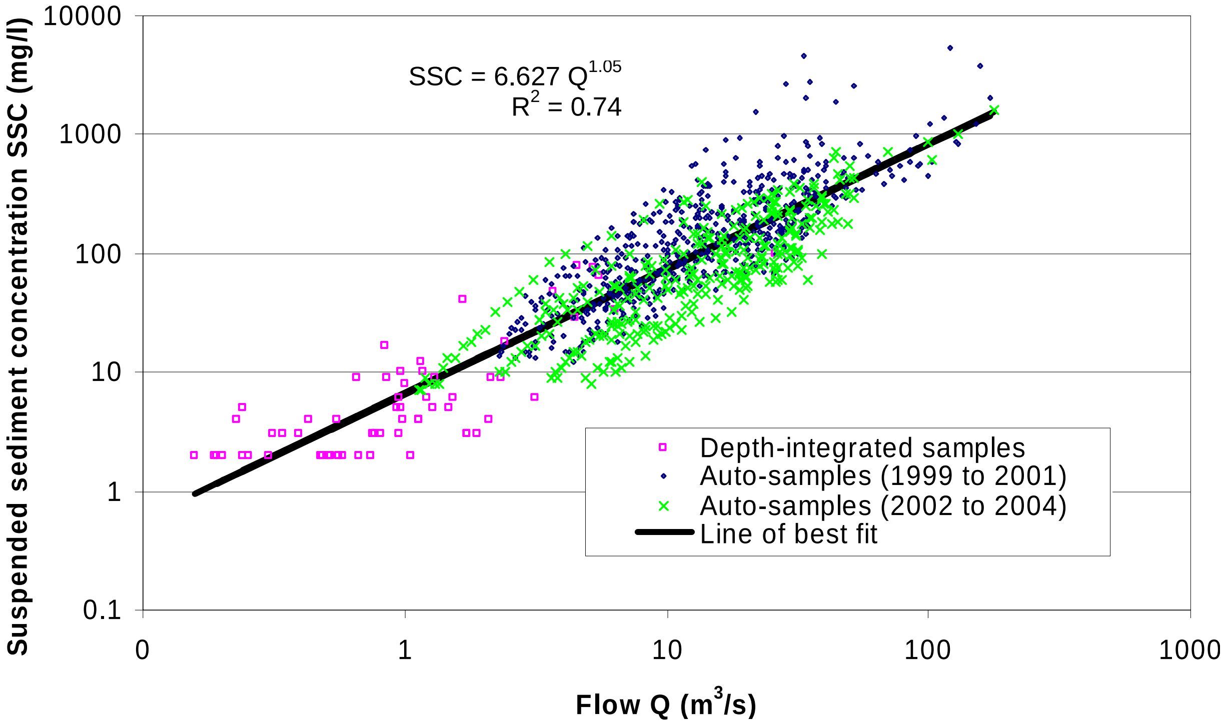

Figure 4.2: **Auto-sample and depth-integrated sediment concentration (SSC) versus flow (Q) with best-fit line for *all* datasets.**

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[2] The percentage of the catchment harvested in a given year is derived from data supplied in Ernslaw One Ltd (2004).

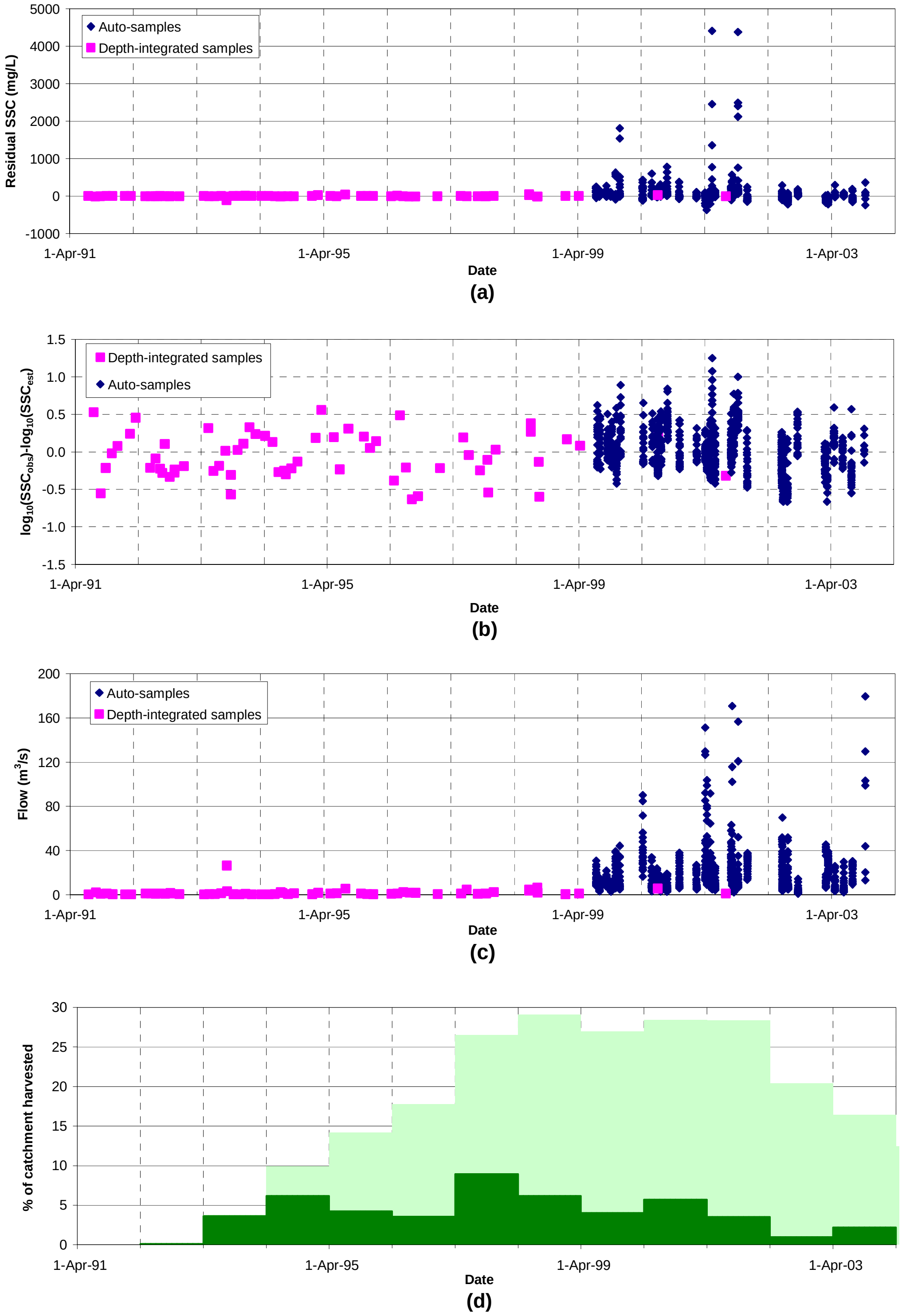

Figure 4.3: SSC, flow and upstream forest harvesting data for the Opitonui catchment at the permanent water-level and sediment sampling site for January 1991 to January 2005: a) Residual SSC (mg/ℓ) from regression line in Figure 4.2. b) Log difference SSC of residuals from regression line in Figure 4.2. c) Flow (m^3/s). d) % of upstream catchment harvested each year – annual % (dark green) and 5 year ‘rolling’ accumulated % total for previous 5 years (light green).

4.3. Hysteresis relationships between suspended sediment concentration and water discharge

Information about sediment sources during flood events can be obtained by plotting flow (Q) versus suspended sediment concentration (SSC) over the duration of storm events. Williams (1989) gives examples of this, and Appendix E shows the hysteresis relationships for all auto-sampled events recorded at Opitonui between July 1999 and August 2004.

In streams it is quite common for the maximum SSC during an event to precede the time of the maximum flow. This can be caused by several factors relating to the supply of water and sediment including that:

- readily entrainable sediments from sources either in or close to the channel are relatively exhausted, or

- sediment load sourced from outside the channel mainly arrives with the surface runoff, and this becomes increasingly diluted with baseflow through an event.

For example, a positive hysteresis loop with a large fall in SSC between rising and falling stages points to rapid exhaustion, while sustained or erratically high values of SSC on falling stages point to continuing supplies at erosion sites through the event. Changes in these characteristics over time may be expected as a result of erosion mitigation measures or other activities in the catchment (e.g. forest harvesting).

The hysteresis plots in Appendix E show some variation over time, although the events generally had a positive hysteresis loop. A summary of the hysteresis loop behaviour is:

- for most events maximum SSC occurs around the time of the peak flow or within the half hour prior to the peak flow

- from July 1999 to February 2001, SSC values were approximately twice as high on the rising limb of hydrographs compared to the falling limb

- from 2 April to 5 May 2001 SSC was approximately the same on the rising and falling limbs of events, and the overall SSC for a given flow tended to be lower than during the previous period

- the 12 May 2001 and 9 October 2001 events had the largest recorded SSC values; and the 9 October event showed a complex hysteresis behaviour.

- the smaller events between May and October 2001, and between October 2001 and June 2002, had SSC values on falling stages that were either the same as or lower than those on rising stages.

- the events from June 2002 to August 2004 generally had low SSC relative to the flow, and falling limbs had a mixture of lower or the same SSC as the rising limbs.

Overall, there is a suggestion that the relative amplitude of the clockwise hysteresis loops was greater in the period up to February 2001, and it was typically less through to about December 2001, and then increased again. This suggests greater sediment availability through 2001.

4.4. Event sediment yields

For each of the individual events that were well sampled by the auto-sampler, suspended sediment yields were computed by summing the product of suspended sediment concentration (SSC) and flow (Q) over the duration of each event. A number of characteristics of the event runoff, such as peak discharge, total quickflow runoff, total runoff, time to peak, etc, were also determined (Table 4.1).

Thirty-two events in total were analysed over the sampling period from July 1999 to August 2004. As the sampler is only activated above a threshold stage, and is then set to a sampling interval of 30 minutes, the beginning and end of each event is not sampled. It was therefore necessary to add “synthetic” values of 2 mg/l to the start and end of each SSC record. This nominal value was based on inspection of depth-integrated sample concentrations during base flow conditions (Figure 4.1).

A multiple-regression analysis was undertaken to derive a predictive relation for event sediment yield. The independent variables included peak flow, total runoff, and quickflow runoff. The best predictor of event yield was found to be flow peak (Q_p).

No improvement arose by adding additional variables into the regression model. The derived prediction equation is shown in Figures 4.4 and 4.5, and is given below:

$$Event\ yield = 0.585\, Q_p^{1.539} \tag{4.2}$$

where

Event yield = sediment load during an event (t)

Q_p = peak flow during the event (m^3/s)

and $R^2 = 0.84$.

Predictions from Equation 4.2 compare quite well with the measured loads in Figure 4.4, particularly for larger magnitude events.

Table 4.1: Events sediment yields and runoff characteristics

Date (yyyymmdd)	Qpeak (m^3/s)	Quickflow runoff (mm)	Total runoff (mm)	Event sediment yield (t)	% event yield on rising stage	Max conc (mg/ℓ)	Ave. conc on rising stage (mg/ℓ)	Ave. conc on falling stage (mg/ℓ)	Event duration (hrs)	Time to peak flow (hrs)	Time to peak conc (hrs)
19990716	30.6	16	26	138	44	445	254	93	17	4	4
19990803	15.3	8	12	46	62	250	172	55	14	4	3
19990913	22.3	24	33	103	26	388	169	55	32	3	2
19991008	11.8	8	12	26	48	184	101	33	22	5	5
19991128	44.6	14	21	398	42	2061	624	175	15	2	2
20000408	90.4	77	85	843	54	965	409	84	36	8	8
20000530	34.1	7	12	139	31	834	288	313	5	2	2
20000629	24.2	9	16	86	50	371	225	102	10	3	3
20000720	16.9	5	10	51	40	432	195	98	12	3	3
20000826	19.2	4	8	111	42	913	584	322	5	2	1
20001105	37.9	15	26	221	42	652	369	191	8	2	2
20010212	27.9	10	19	99	76	299	196	121	8	5	2
20010402	153.2	67	79	1170	52	1209	231	165	26	11	11
20010412	103.8	47	60	580	25	590	223	211	14	3	3
20010502	95.8	41	48	327	44	587	212	54	30	7	6
20010504	30.0	26	38	83	33	169	59	42	25	7	8
20010512	33.5	10	17	532	25	4451	2005	329	15	1	1
20010530	25.4	9	16	64	42	338	193	65	13	2	2
20010904	172.0	38	53	1331	44	1991	339	333	13	5	5
20010915	23.5	4	7	67	41	548	386	262	4	1	1
20011009	186.2	24	30	2690	45	5170	3331	1283	5	1	1
20011201	37.8	32	49	234	33	501	226	105	18	4	3
20020620	68.5	54	90	759	74	709	264	181	25	16	16
20020628	20.4	14	23	40	79	141	88	20	15	6	2
20020723	54.8	18	24	101	61	371	212	45	10	2	2
20020919	14.2	5	7	25	32	267	65	54	17	4	5
20030311	39.1	32	56	162	35	304	149	59	21	4	4
20030609	29.9	7	11	59	34	320	186	114	7	1	2
20030729	31.5	60	78	261	42	381	286	58	36	4	2
20031012	179.5	59	71	1301	22	1569	477	211	14	2	2
20040618	41.1	16	29	104	47	265	111	77	12	5	5
20040805	25.2	4	9	47	38	279	214	136	5	1	1

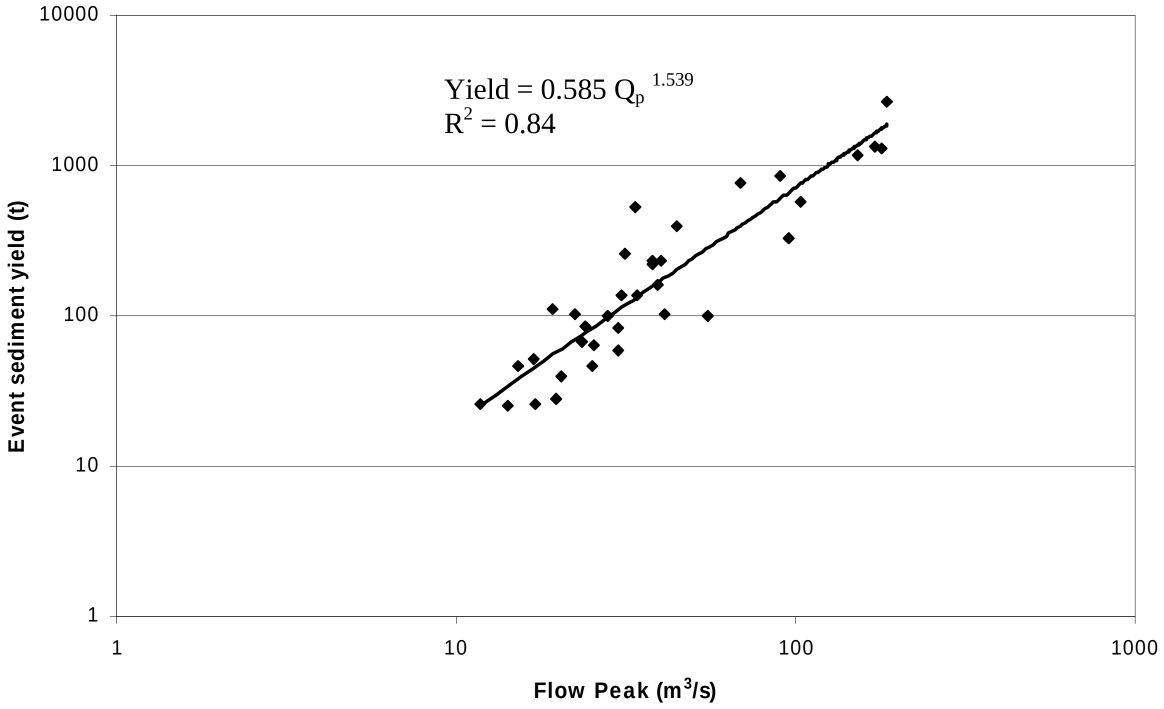

Figure 4.4: **Relationship between flow peak (Q_p, m^3/s) and event sediment yield (t) for thirty-two storm events between July 1999 and August 2004.**

When time (days since the beginning of the first event) was also included in the regression analysis it did not make a significant contribution to the regression model. This may well reflect the short period (6 years) for which the auto-samples were available, with any time trend masked by the natural variability. It should also be noted that, by the time auto-sampling commenced in July 1999, forestry activities in the catchment upstream of the monitoring site had been active for over 6 years. Up to 22.3% of the Opitonui catchment (upstream of Site OP, see Figure A1, Appendix A) and 40.7% of the Awaroa catchment (upstream of Site A, see Figure A1, Appendix A) had been clear-felled between February 1993 and September 1999 (Quinn & Wright-Stow, 2004).

To use equation 4.2 to predict event sediment yield it is necessary to apply a correction factor for the log-transformation of the data. This is because, when log-values are used, a regression fit tends towards the conditional geometric mean SSY for a given peak flow, rather than the desired conditional average mean. Using the method of Ferguson (1986), we determined the log-bias correction factor to be 1.14, thus the event yield predictive model becomes:

$$Event\ yield = 0.667\ Q_p^{1.539} \qquad (4.3)$$

Figure 4.5 shows a comparison between the measured event yield and the predicted event yields using Equation 4.2 and 4.3.

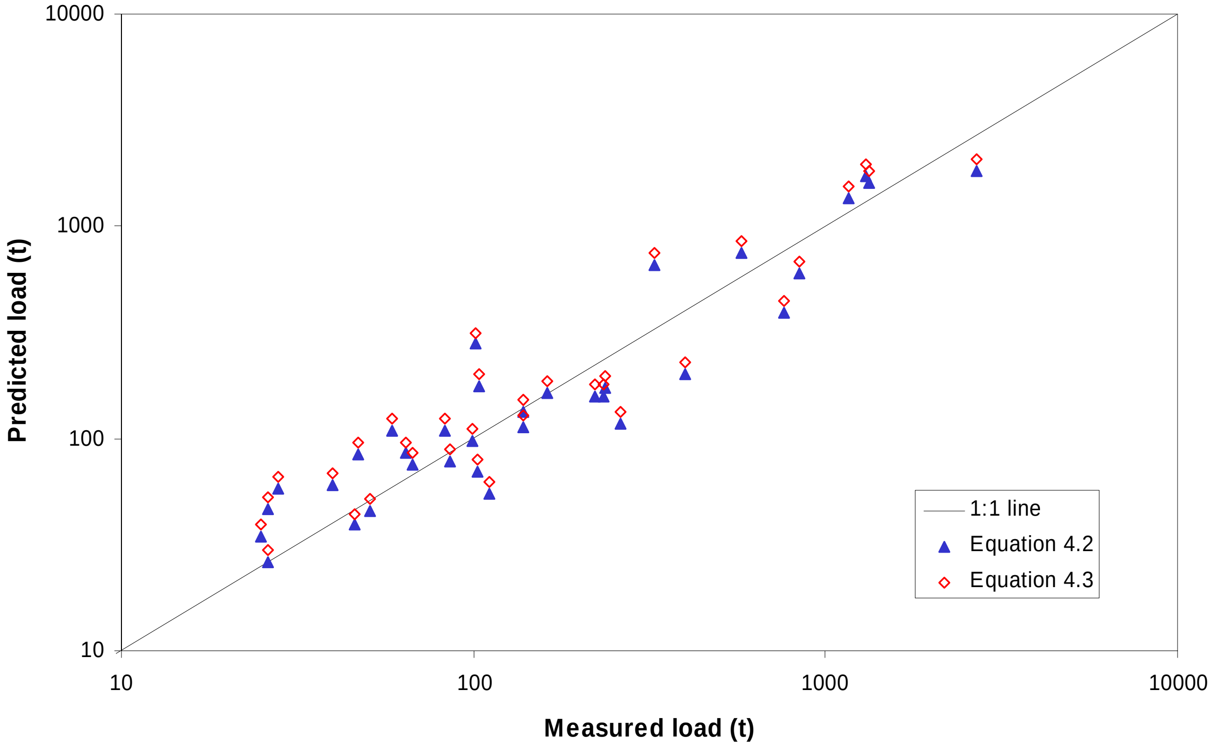

Figure 4.5: **Comparison of predicted and measured sediment loads during events monitored by auto-sampler (using Equation 4.2 and 4.3 for predictions).**

We revisited the possibility of time dependence on event sediment yields by examining the ratio of measured auto-sample sediment yield to predicted sediment yield (using Equation 4.3) over time. Figure 4.6 appears to show measured event sediment yield decreasing over time relative to the predicted event yield. In effect, this suggests that the value of the coefficient 0.667 in Equation 4.3 reduced with time. A linear regression analysis on observed versus predicted yield indicated a reduction rate of approximately 7-10% per year of the observation period. Such a trend might be expected as the catchment recovered from the ‘shock’ of the March 1995 storm (focussed over the Awaroa catchment), and the April 1995 storm (Opitonui catchment). However, there is significant scatter in the data and a t-test showed that the slope of the trend is not significantly different from zero at the 5% level – even when the obvious outlier (e.g. 3.6 on 13 May 2001, Figure 4.6) is removed from the analysis. Therefore we cannot reject the possibility that there is no trend, and on that basis we have used Equation 4.3 to estimate event yields during un-sampled events, both over the period 1999 to 2005 and between 1991 and 1999 before the auto-sampler was installed

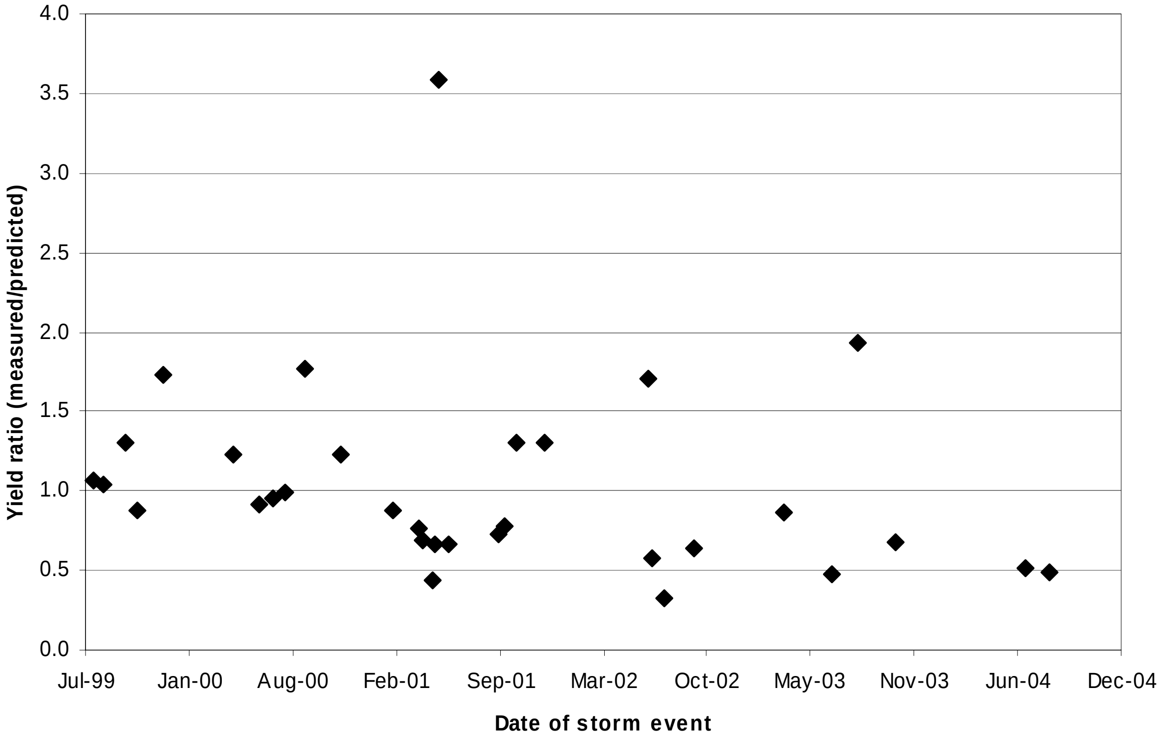

Figure 4.6: **Comparison over time of the ratio of auto-sample calculated load and load predicted using Equation 4.3 (for thirty-two storm events between July 1999 and August 2004).**

4.5. Long-term variability in event and annual sediment yields

For the period 1999 to 2005, monthly and annual loads were computed directly from the auto-sampler records, with yields for missed events estimated via Equation 4.3. For the period up until the auto-sampling commenced in July 1999, yields were estimated from the stream-flow record using Equation 4.3.

When using Equation 4.3, events were defined in terms of discrete quickflow events. The start and end of quickflow events were determined using a quickflow-separation slope of 350 l $s^{-2}km^{-2}$. This was set by inspection of typical runoff events. Events with less than 2 mm of quickflow runoff were ignored.

Most of the gaps in the Opitonui record of peak flows were able to be patched using flow records from Mahikarau at E309 Road (Site 11605). This site lies immediately south of the Opitonui catchment, shares a common divide, and has a similar catchment area (20.5 km^2 compared with 29 km^2 for the Opitonui). A relationship was developed between Mahikarau and Opitonui flow peaks (Figure 4.7), and this was used to scale the Mahikarau flow peaks to fill the Opitonui record gaps.

An additional gap in the Opitonui record of peak flows (from 1 September to 18 October 2000) was able to be patched using flow records from Waiwawa at Rangihau Road (Site 11807). This site lies further south from the Opitonui catchment, and has a larger catchment area (120 km^2 compared with 29 km^2 for the Opitonui). A fairly crude relationship was developed between Waiwawa and Opitonui flow peaks (Figure 4.8), and this was used to scale the Waiwawa flow peaks to fill the Opitonui record gap. As there were no significantly large flood events during this short gap in the record, the low correlation was not considered significant to the overall results.

Figures 4.9 and 4.10 show the Opitonui recorder site event yields and peak flows, respectively (note that the date scale lists event dates; it is not a linear time scale). From these plots it appears that there were several large flow events for which no or inadequate auto-samples were collected.

Monthly sediment loads for the period September 1991 through to February 2005 are plotted in Figure 4.11, and annual sediment yields for 1992 to 2004 are plotted in Figure 4.12. These figures can be compared to the Opitonui Stream flow record (Figure 4.14). Figure 4.13 shows the average monthly sediment loads.

Figures 4.11 to 4.13 highlight the month-by-month and annual variability in yields. We note that, because of the approach used to estimate yields before auto-sampling commenced in July 1999, the 1992-1999 variability is solely a response to storm/runoff events and does not contain any landuse influence.

Over the 1992-2004 period, the average annual sediment yield was 3340 t/yr (115 $t/km^2/yr$), the annual yield ranged from 290 to 8077 t (10-279 t/km^2), while the standard deviation of the annual yield was 2530 t/yr (87 $t/km^2/yr$).

The largest annual yield of 8077 t occurred in 2001 in association with several large runoff events. The second largest was 6758 t in 1995 mainly during the large March event. The 2001 yield was measured directly by the auto-sampler and so is more reliable than the 1995 yield, which was estimated off Equation 4.3. The lowest annual yields occurred during the 1992-94 period of relatively benign flows, when the peak flow was less than 50 m^3/s.

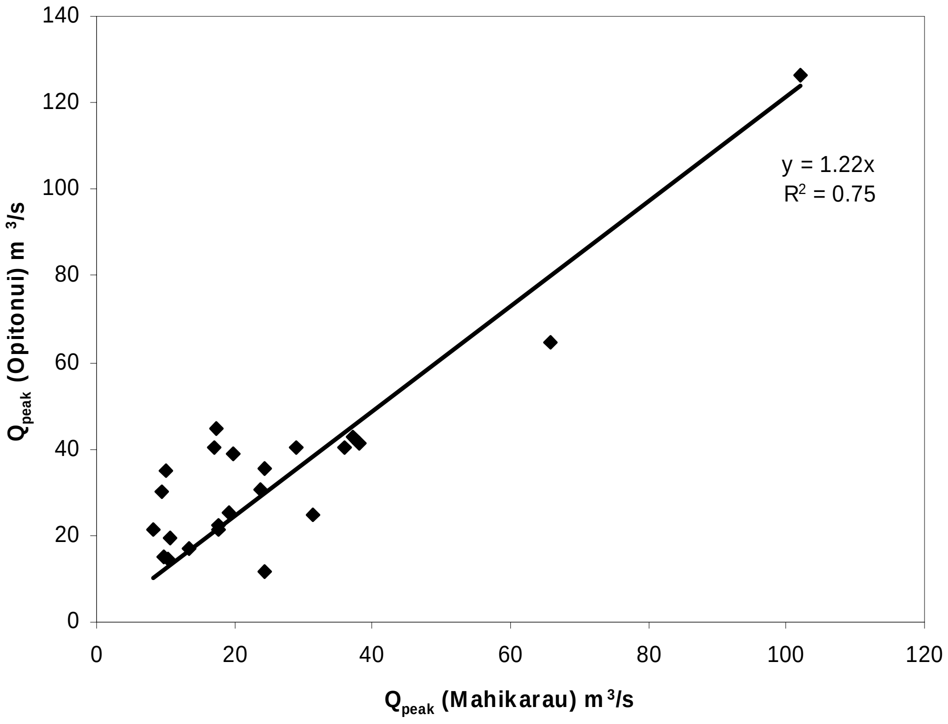

Figure 4.7: Relationship between peak discharges for the same events at the Opitonui and Mahikarau sites.

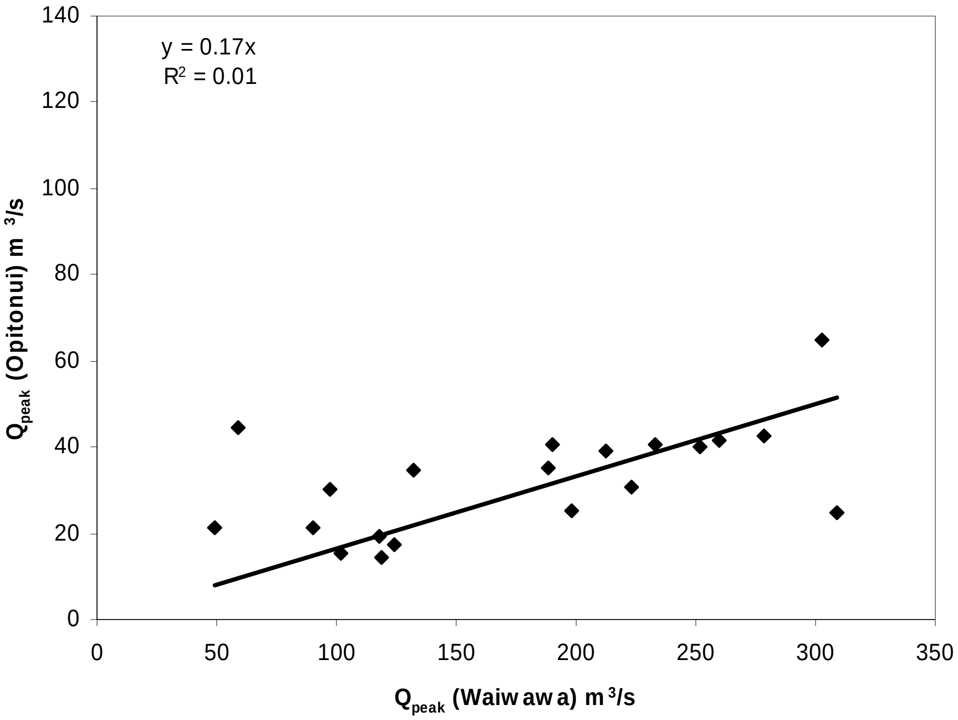

Figure 4.8: Relationship between peak discharges for the same events at the Opitonui and Waiwawa sites.

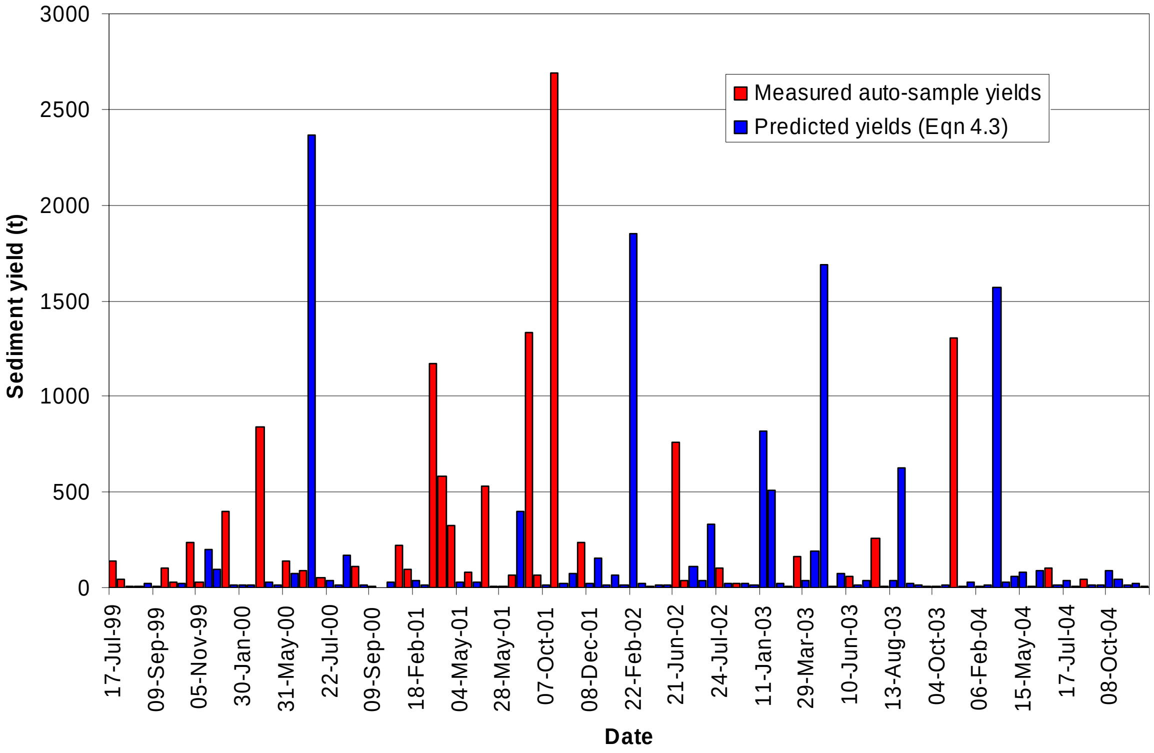

Figure 4.9: Measured auto-sample yields (red) and predicted yields (Equation 4.3, blue) for events between July 1999 and February 2005.

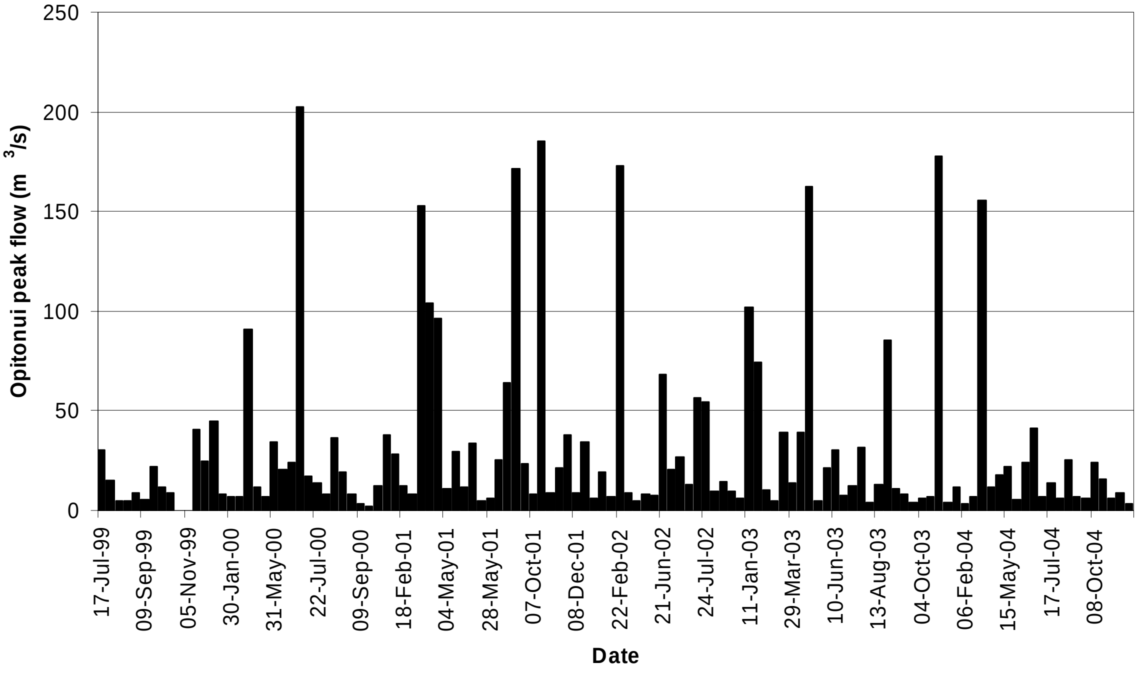

Figure 4.10: Opitonui recorder site peak flow for events between July 1999 and February 2005.

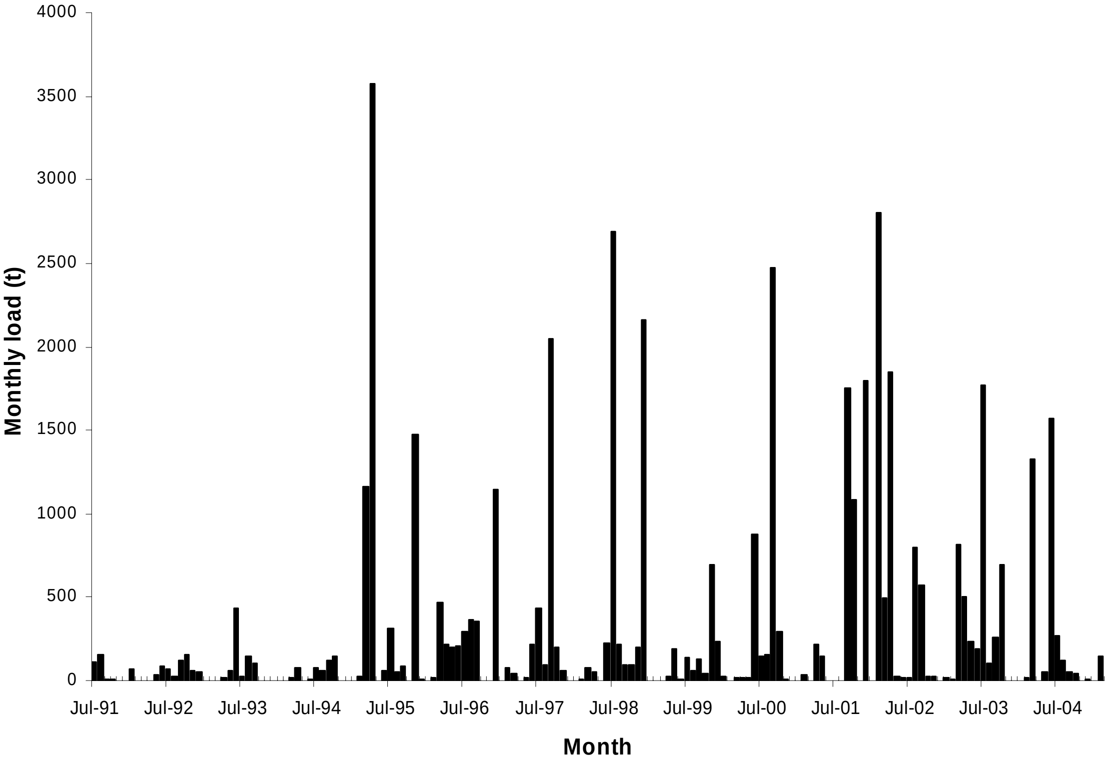

Figure 4.11: **Monthly sediment loads for Opitonui Stream (July 1991 to February 2005).**

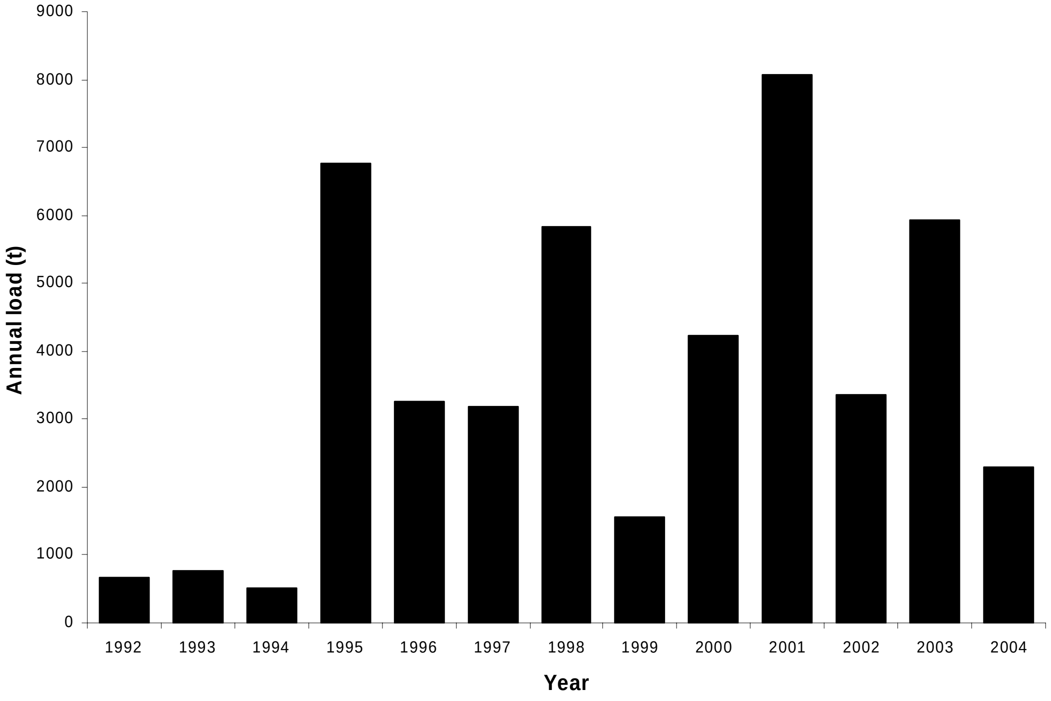

Figure 4.12: **Annual sediment loads for Opitonui Stream (1992 to 2004).**

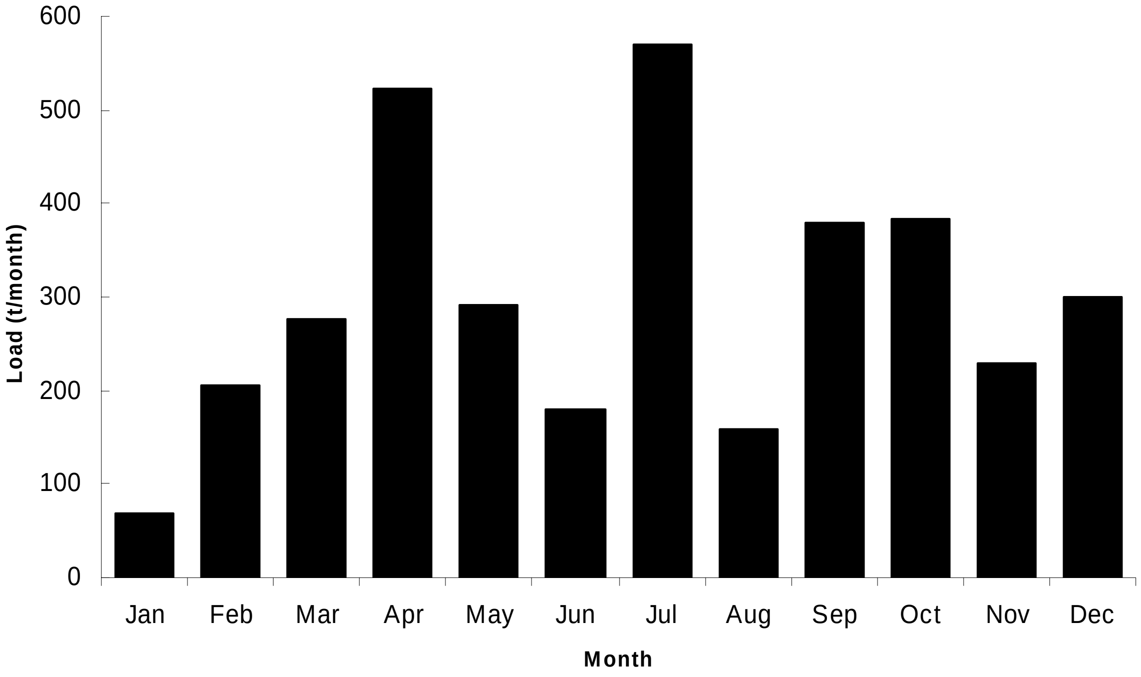

Figure 4.13: **Average monthly sediment loads for Opitonui Stream (1992 to 2004).**

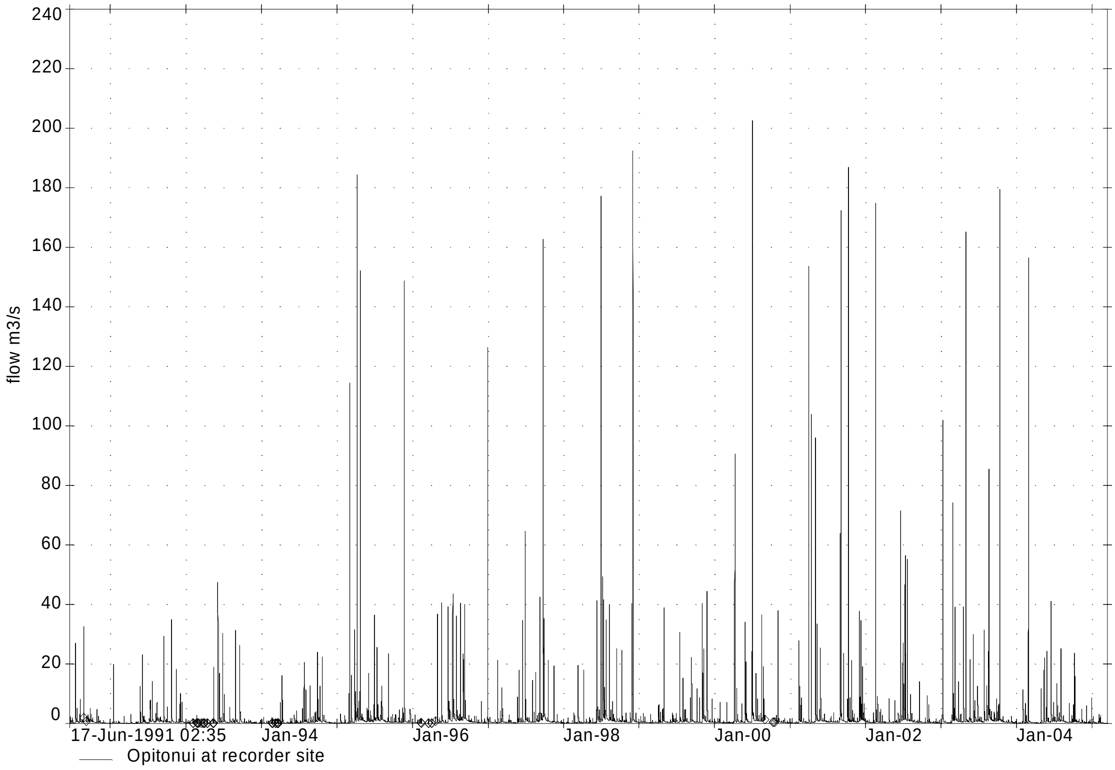

Figure 4.14: **Recorded Opitonui Stream flow from July 1991 to March 2005.**

Correlation of the annual sediment yields with annual average values of the Southern Oscillation Index (SOI) and the Inter-decadal Pacific Oscillation (IPO) index[3] showed no significant correlation with the SOI but an inverse correlation with the IPO (at a 7% significance level) – that is, sediment yields tend to be greater when the IPO is small.

The specific sediment yields (i.e., yield per square km) fall within the range measured from exotic forest catchments undergoing harvesting operation elsewhere in New Zealand. For example, Fahey et al. (2004) report yields during harvesting or immediately post-harvesting of 160 t/km^2/yr in the Motueka-Golden Downs area in Nelson, 218 t/km^2/yr in the Marlborough Sounds, 25-139 t/km^2/yr from Maimai on the South Island West Coast, and 89-150 t/km^2/yr from the Napier area. The variability shown by these catchments reflects several factors including: climate; catchment steepness and rock-type; harvesting methods; proportion of catchment under harvest; and the coincidence of (or lack of) harvesting operations with extreme runoff events.

4.6. Comparison with Phillips et al. (2005) study

Phillips et al. (2005) have recently reported on the results of a 30-month period of monitoring suspended sediment loads from a 36 ha block in the adjacent Waitekuri Catchment (Compartment 49 mainly). Their study catchment, originally under exotic forest, was clear-felled between October 2000 and March 2001. Suspended sediment concentration was monitored from October 2000 until March 2003 using a turbidity sensor calibrated against sediment concentrations measured from auto-samples. They also collected data on rainfall intensity and stream discharge. Nine of the events captured by Phillips et al. (2005) at Compartment 49 were also captured by the Opitonui auto-sampler. The specific suspended sediment yields during these events from the two sites are compared in Figure 4.15. The specific (per unit catchment area) yields are very similar except for the event of 9 October 2001, when the Opitonui yield was grossly larger. We expect that the difference during that event would reflect greater rainfall intensities in the Opitonui catchment, although we have not examined this in detail. If anything, we might have expected that the Compartment 49 specific sediment yields would be larger on average than those from the Opitonui for the same event, since Compartment 49 was clear-felled whereas the larger Opitonui catchment

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[3] The SOI indexes the El Nino – Southern Oscillation (ENSO). When the SOI is in its positive (La Nina) phase, New Zealand tends to experience weaker westerly winds generally, and the Coromandel area tends to experience more storms associated with depressions of tropical origin. During the negative (El Nino) phase, the westerly airflow tends to be stronger and more persistent, thus the Coromandel might be expected to experience less stormy weather.

The IPO is a Pacific-wide multi-decadal oceanic-atmospheric signal that essentially modulates the ENSO climate teleconnections.

was not. However, the relative yields during each event will be sensitive to the rainfall distribution. A detailed examination of the event rainfall records and a comparative plot of event specific sediment yield against event rainfall from the two datasets would be worthwhile but is beyond the brief of the current study.

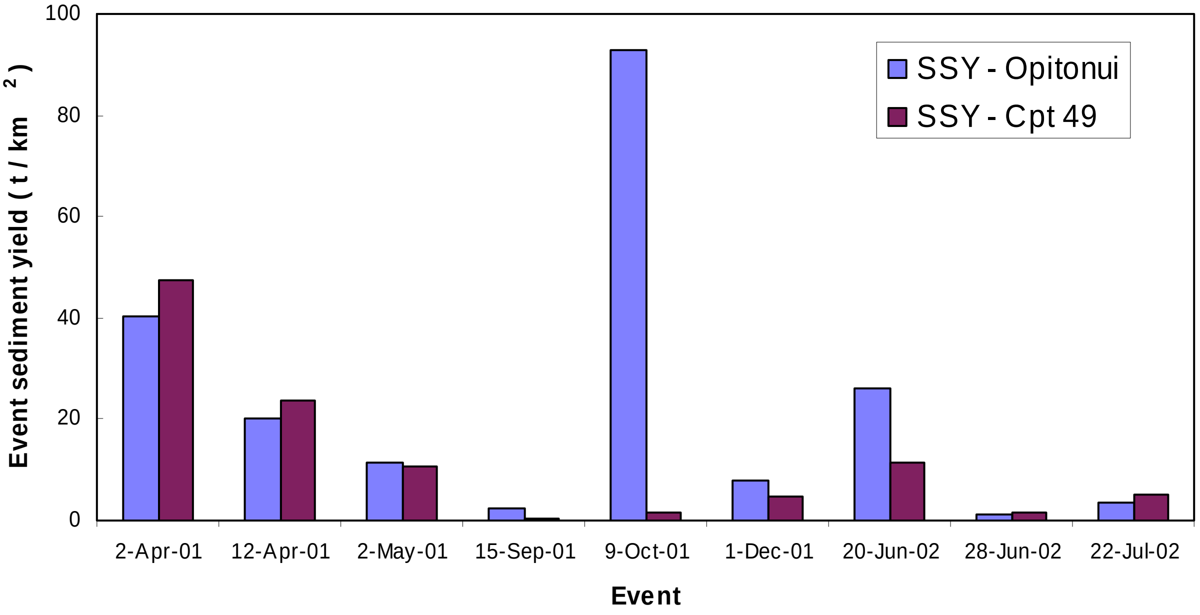

Figure 4.15: Comparison of specific sediment yields during the same events from the Opitonui Stream and Compartment 49 in the Waitekuri Catchment (from Phillips et al., 2005).

5. Conclusions on monitoring at Opitonui Site

This study of Opitonui Stream was able to determine significant relationships between event suspended sediment yield and peak discharge, but no clear relationship emerged between sediment yield and forestry activities. This does not necessarily mean that there is no relationship between the two, but there are several factors that ‘cloud’ it. These include:

- Auto-samples have only been collected for a short period of approximately 6 years. Prior to this, depth integrated samples were generally only collected at low flows, giving no indication of storm event yields.

- The auto-sampling programme did not commence in the Opitonui catchment until after part of the catchment had been altered by forest harvesting (i.e., there is no good-quality, pre-harvesting SSC information for the Opitonui catchment).

- Forestry records (Ernslaw One Limited, 2004), used to determine when harvesting took place in the catchment upstream of the Opitonui sampling site, only indicate the annual harvest record - there is no available record of the exact week/month that harvesting took place (i.e., the length of time between harvesting and storm events cannot be very accurately determined).

- Erosion in the catchment – and suspended sediment generation - are expected to be maximised by heavy rain on steep slopes within several years of harvesting. Both the rainfall and harvesting operation tend to be patchy in space and time, thus sediment yields during a given event will tend to vary randomly according to where the rain falls and where the catchment has been harvested. With only one sediment monitoring station near the catchment outlet and with a limited network of rain gauges recording data at a high time resolution, it is difficult to determine which areas of a catchment upstream of the monitoring site have been exposed to the higher intensity rainfall.

While these results may question the utility of continuing the sampling program – or repeating it elsewhere - the following points should be considered:

- The monitoring has established the ranges of SSC, event and annual suspended sediment yields for the Opitonui, and these results allow the Opitonui to be compared with other catchments around New Zealand that are subject to forest harvesting. Thus while it may not be possible to quantify the effect of forestry operations of the yield from every storm, it is possible to assess if the operations are having a gross impact on sediment loads.

- In this regard, the available data sets a standard and a range which might be used to monitor and regulate future operations, allowing that the associated monitoring of the Whangapoua Harbour has not shown a declining ecosystem since 1999.

- The available data show that the catchment ‘cleans up’ relatively soon (apparently within several months) after moderate to large events, whereas there is a hint (but nothing significant in the formal statistical sense) that extreme events such as the March 1995 event may create an overall increase in sediment yields that may take something like a decade to decline.

6. Discussion on utility of snapshot sampling

Snapshot samples were collected by Environment Waikato from sites within the greater Whangapoua Harbour catchment on nine occasions between 20 June 2001 and 12 October 2003, six of these during runoff events. These provided “synoptic” data on suspended sediment concentration and estimated discharge at each sampling site, although in reality the sampling spanned periods ranging from a few hours to over a day. The number of sites sampled on each occasion varied from two to 27. We briefly examine these data and discuss the utility of the snapshot sampling approach.

Without time-series information on sediment concentration and water discharge at these sampling sites, it is impossible to extract sediment yield data from this snapshot dataset. At best, an attempt can be made to compare sediment concentrations. Even so, various factors combine to make it impossible to identify anything less than gross differences in concentration that might be linked to landuse differences and activities such as forest harvesting. These factors include:

- the small number of samples,
- unknown variability of rainfall intensity over the catchments,
- the sampling error associated with point samples
- the expectation that SSC should vary widely with flow over an event but the lack of information on the phasing of the flow and SSC over each storm event, and
- the lack of any definitive relationship between forestry/landuse and sediment supply.

These factors confuse interpretations made directly from synoptic maps of sediment concentrations. An approach that partly addresses the sampling issues is to compare the results from different streams on a normalised sediment rating plot, where water discharge is normalised by dividing by catchment area. Figure 6.1 shows such a plot, where we overlay the snapshot data on the data from the Opitonui sediment monitoring site. The latter data capture the distribution of the Opitonui in SSC – Q space, thus other sites whose points plot outside this space may reasonably be inferred to be different from the Opitonui. By this approach it is possible to identify any likely gross differences between the sampled stream and the Opitonui. The approach assumes that catchment area is an appropriate scaling factor. We have lumped snapshot sampling points by their major catchment (i.e., by the stream through which they flow into Whangapoua Harbour or to the coast).

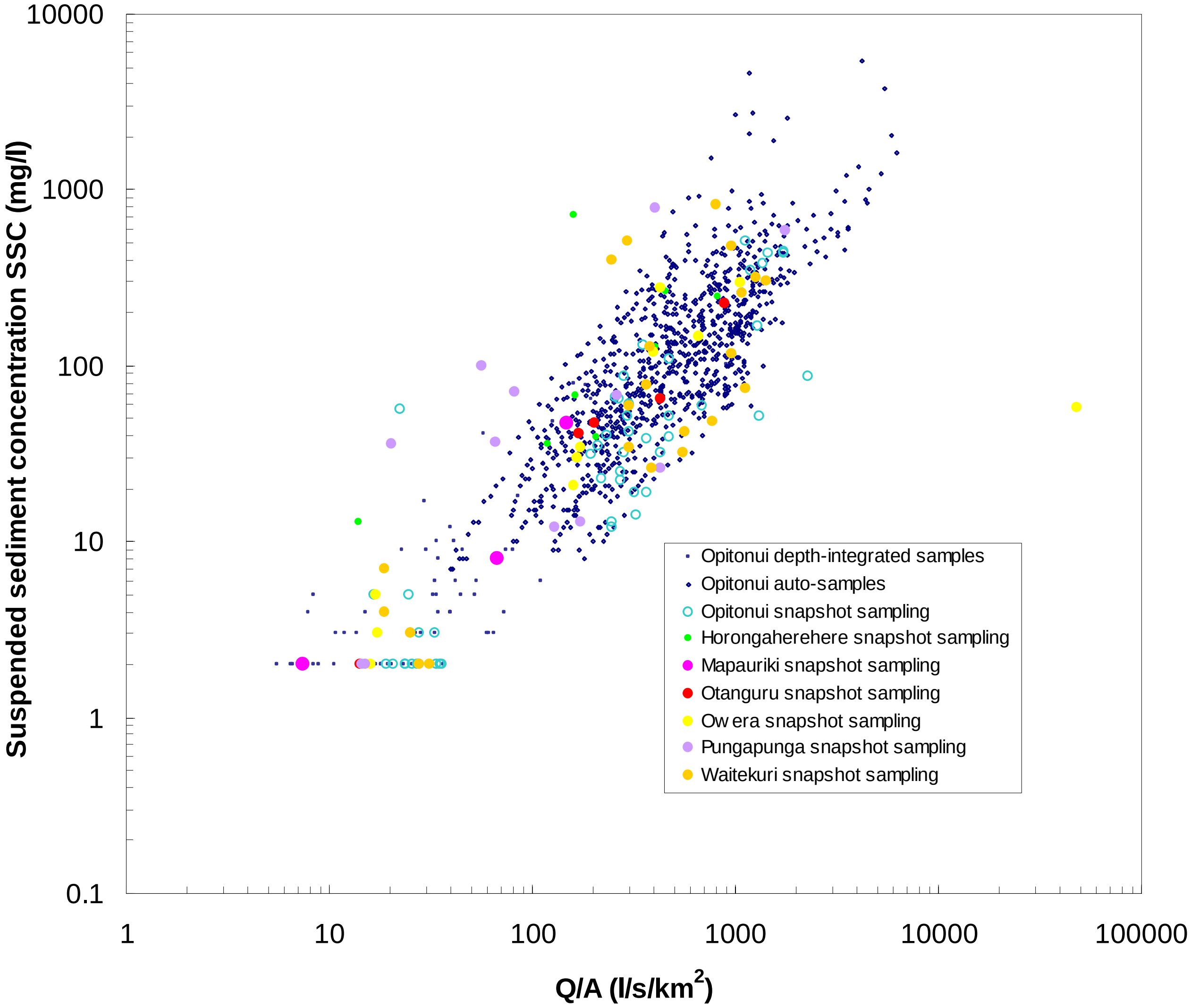

Figure 6.1: **Normalised discharge (Q/A) vs SSC relation for the Opitonui sampling site and the snapshot sampling sites.**

Figure 6.1 shows that almost all of the snapshot sampling points plot within the space occupied by the Opitonui monitoring dataset. Only points from the Pungapunga River, and possibly the Horongaherehere Stream, appear to lie above the Opitonui distribution. Both of these exceptions lie at the northeast corner of the Whangapoua Basin, and their different behaviour may reflect differences in geology. A similar pattern arises if discharges are normalised by dividing by catchment area to the power of 0.8 (which is a common scaling factor for event peak discharge).

We conclude that, apart from the northeast corner, the snapshot sampling suggests that sediment concentrations during storm runoff from the rest of the Whangapoua basin are not grossly different from those monitored in detail at the Opitonui site. It follows that the Opitonui results may reasonably applied to the other tributaries.

More generally, we comment that if the motivation for snapshot sampling through storm events is to gain a relatively inexpensive indication that some tributaries are yielding grossly more sediment per unit area than others (perhaps because of landuse activities), then this approach is useful providing (i) there is a reference station (such at the Opitonui) where the joint distribution of SSC and Q is well defined, and (ii) the discharge can be normalised. On this basis, the approach may be used as a pointer to catchments where more detailed monitoring may be warranted.

7. Recommendations

Generally, snapshot sampling may be useful as a reconnaissance technique to identify gross differences in suspended sediment supply, providing there is a nearby reference station that the snapshot data can be compared to. Beyond that, if accurate sediment yields are required for a catchment, it will be necessary to undertake detailed monitoring.

For the catchments adjacent to the Opitonui, for accurate determination of sediment yield we would recommend the following programme:

- Continuous stream-flow monitoring.

- A consistent and sustained programme of depth-integrated sampling over a range of flows on both rising and falling stages (resulting in a SSC-Q rating relationship).

- Occasional “bursts” of auto-sampling during sampling of runoff events, with the purpose of identifying time trends in the event-yield relationship, and also in the hysteresis characteristics of the SSC-Q relation within events.

- Regular analysis of the particle size of the suspended load sampled by depth-integrated/whole flow samples.

- Most importantly, to sustain the sampling for an adequate duration for trends to emerge. A decade at least is recommended.

- For catchments with changing landuse, preferably start monitoring as early as possible (e.g., if possible, start monitoring prior to the start of forestry harvesting in the catchment area upstream of a monitoring site). Alternatively, and if possible, a control catchment in stable landuse should be monitored concurrently.

8. Acknowledgements

We would like to acknowledge assistance received from: Yannina Whitely and Lisa Yuan from Ernslaw One Limited for providing information on forestry activities undertaken by Ernslaw One Limited; Reece Hill, Grant Blackie, Ross Jones and Ian Blair from Environment Waikato for providing hydrological data and general background information (including local knowledge and previous reports); and John Quinn from NIWA Hamilton for providing background information and electronic copies of his previous reports.

9. Glossary

Soil slip:	The movement of soil and or subsoil to expose a slip surface which is approximately parallel to the original slope surface. Depth of failure is normally less than 1m but can occur at depths of up to 2 m where surficial cover-beds are thick. Displaced debris from soil slips is most often deposited as colluvium on slopes below the point of failure but may enter directly into watercourses (Marden and Rowan, 1995).
Streambank erosion:	The removal of material from the bank of a permanent stream or watercourse by the action of flowing water. This normally involves collapse of blocks of material by undercutting of the bank (Marden and Rowan, 1995).
Debris avalanche:	A slope failure where the soil mass moves out or down and out along a more or less planar or gently undulatory surface. Failures are typically shallow (<5 m) and occur where shallow and pervious regolith overlies impervious bedrock. Failure occurs when the regolith becomes saturated, often coinciding with major storm event during which rainfall intensities exceed 25 mm/hr (Marden and Rowan, 1995).
Landing sidecast failure:	Failures occur mostly around the perimeter of landings and involve sidecast soil and tree stumps cleared from the site during landing construction. Other failures associated with landings only involve woody debris and occur when piles of decaying slash from clearfell operations destabilise. Both types of failure commonly occur during periods of

heavy rainfall when rotting woody debris and sidecast materials become saturated and subsidence occurs (Marden and Rowan, 1995).

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Appendix A

Whangapoua Forest catchment monitoring locations and timeline of forest harvesting (Quinn & Wright-Stow, 2004)

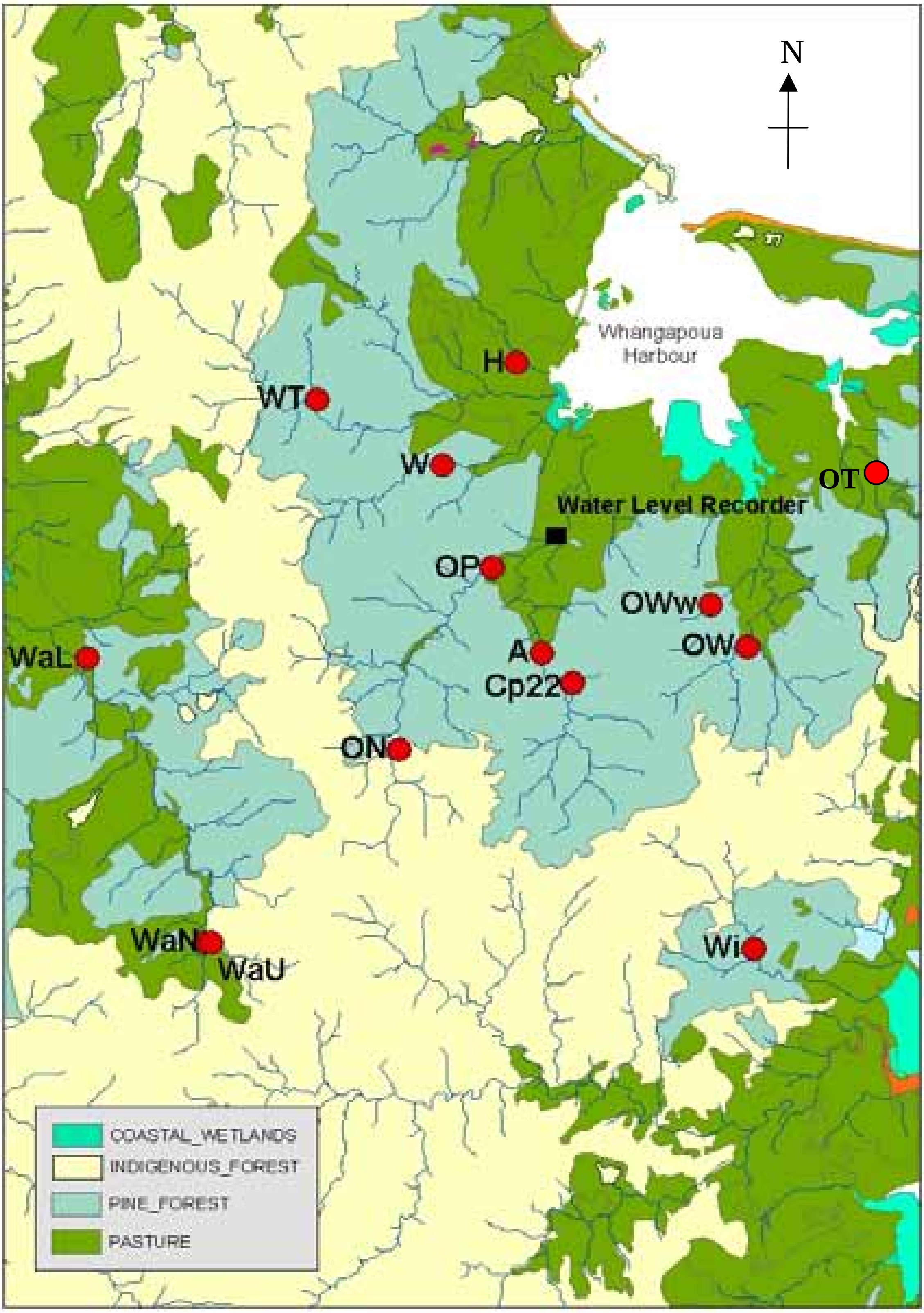


Figure A1: **Location of stream sampling sites in and around Whangapoua Forest plus position of the water level recorder (Quinn and Wright-Stow, 2004).**

Table A1: Location and codes of sampling sites and summary of upstream harvesting.

Stream/River Catchment (ha)	Site code	Grid reference NZMS 260	Catchment activities	Cumulative % clearfell
Plantation forest				
Owera West (66)	OWw	T11:457875	Feb 93-Oct 95, 78% clearfell	78
			Oct 96-Oct 97, 22% clearfell	100
Owera (328)	OW	T11:463868	June 92-Oct 95, 15 landings, 51% clearfell	51
			Oct 95-Oct 96, 21% clearfell	72
			Oct 96-Oct 97, 1.4% clearfell	73.4
			Oct 97-Oct 98, 4.9% clearfell	78.3
Awaroa (857)	A	T11:430867	Oct 93-95, 1.2 km roading, 20 landings, 8.4 % clearfell mostly between sites A2 and A	8.4
			Oct 95-Oct 96, 5 landings, 12.8% clearfell mostly between sites A3 and A	21.2
			Oct 96-Oct 97, 5 landings, 0.35 km roading, 5.6% clearfell mostly upstream of A3	26.8
			Oct 97-Oct 98, 17 landings, 8.1%, 4.3 km road upgrade and 2.1 km new roads.	34.9
			Oct 98-Sep 99, 5 new landings, 5.8% clearfell, 1.1 km of new roading	40.7
			Oct 99-July 2000, 11.5% clearfell, 4 new landings	52.2
			Aug 00-Aug 01, 5.8% clearfell, 10 skids, 0.9 km new roading, 1.7 km road upgrade	58
			Sept 01-Aug 02, 9.2% clearfell, 6 skids, 0.15 km new roading	67.2
			Oct 02-Sept 03, 3.4% clearfell, 1 landing, 0.1 km new track	70.6
Opitonui (1671)	OP	T11:422881	Oct 94-Oct 95, 0.8 km roading	0
			Oct 95-Oct 96, 17 landings, 1 km new road, 4.6 km road upgrade, 0.4% clearfell	0.4
			Oct 96-Oct 97, 26 landings, 1.25 km roading, 2.4 km road upgrade 7.2% clearfell	7.6
			Oct 97-Oct 98, 7.9% clearfell, 5 landings and 1 km new roads.	15.5
			Oct 98-Sep 99, 5 new landings, 6.8% clearfell, 1.8 km of new roading	22.3
			Oct 99-July 2000, 4.2% clearfell, 2 new landings	26.5
			Aug 00-Aug 01, 3% clearfell, 5 skids, 1.0 km new roading	29.5
			Sept 01-Aug 02, 2.6% clearfell, 0.9 km new roading	32.1

Table A1 ***(continued)***

Stream/River Catchment (ha)	Site code	Grid reference NZMS 260	Catchment activities	Cumulative % clearfell
Waingaro (441)	W	T11 414898	Oct 95-Oct 96, 2 landings, 0.1% clearfell	0.1
			Oct 96-Oct 97, 1 landing, 0.35 km roading,	0.1
			Oct 97-Oct 98, 4 landings and 1 km new roads.	0.1
			Oct 98-Sep 99, 2 new landings, 1 km roading upgrade	0.1
			Oct 99-July 00, 7.5% clearfell, 7 new landings, 0.5 km new road, 1 km road upgrade	7.6
			Aug 00-Aug 01, 5.5% clearfell, 2 skids, 0.5 km new roading	13.1
			Sept 01-Aug 02, 9.2% clearfell, 1 skid, 0.1 km new Roading	22.3
			Oct 02-Sept 03, 0.1% clearfell	22.4
			Oct 03-Sept 04, 7.7% clearfell, 1.2 km new road, 9 landings	30.1
Compartment 22 (46)	Cp22	T11 435862	spring 1995, 100% clearfell	100
Waitekuri Trib. (101.2)	WT	T10 394909	Oct 00-Aug 01, 6 skids, 1.5 km road upgrade	0
			Sept 01-Aug 02, 27.9% clearfell, 7 skids	27.9
			Oct 02-Sept 03, 52.8% clearfell	80.7
Waiau Lower (2354)	WaL	T11 357866	Oct 03-Sept 04, 3.4 % clearfell, 7 landings, 0.9 km roading	3.4
Waiau Upper (265)	WaU	T11 376819		0
Weiti (495)	Wi	T11 464818	Oct 02-Sept 03, 11 landings, 1.05 km new road, 0.2 km new track	0
			Oct 03-Sept 04, 14.6 % clearfell, 5 landings, 2.5 km roading	14.6
Reference sites				
Opitonui (469)	ON	T11 407851	Reference native forest	0
Horongoherehere (148)	H	T10 426915	Pasture reference comparison	0
Waiau Native (218)	WaN	T11 377819	Reference native forest – Coromandel Harbour side	0

Appendix B

Whangapoua catchment sediment particle-size distributions (Quinn & Wright-Stow, 2002)

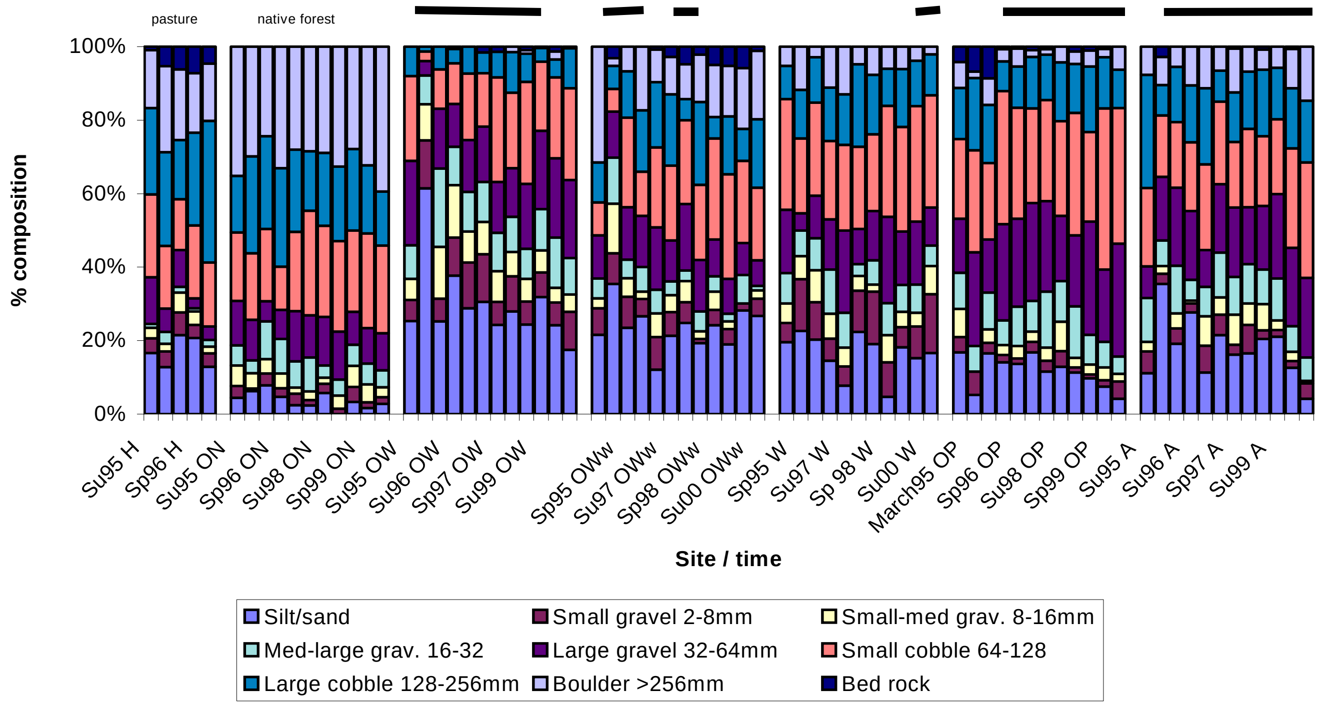


Figure B1: **Stream sediment particle size distributions measured at regular cross-sections at the Whangapoua forest study sites in summer (Su) and spring (Sp) from summer 1995 – summer 2000 when measurements were halted. Arrows show timing of storm prior to March 1995 sampling at four sites where a storm on 3-4 March caused minimal (at OP) to severe (at OW) impacts. The solid lines represent the periods of forest harvest in the monitoring sites' catchments.**

Appendix C

Opitonui recorder site flows and times of suspended sediment data collection

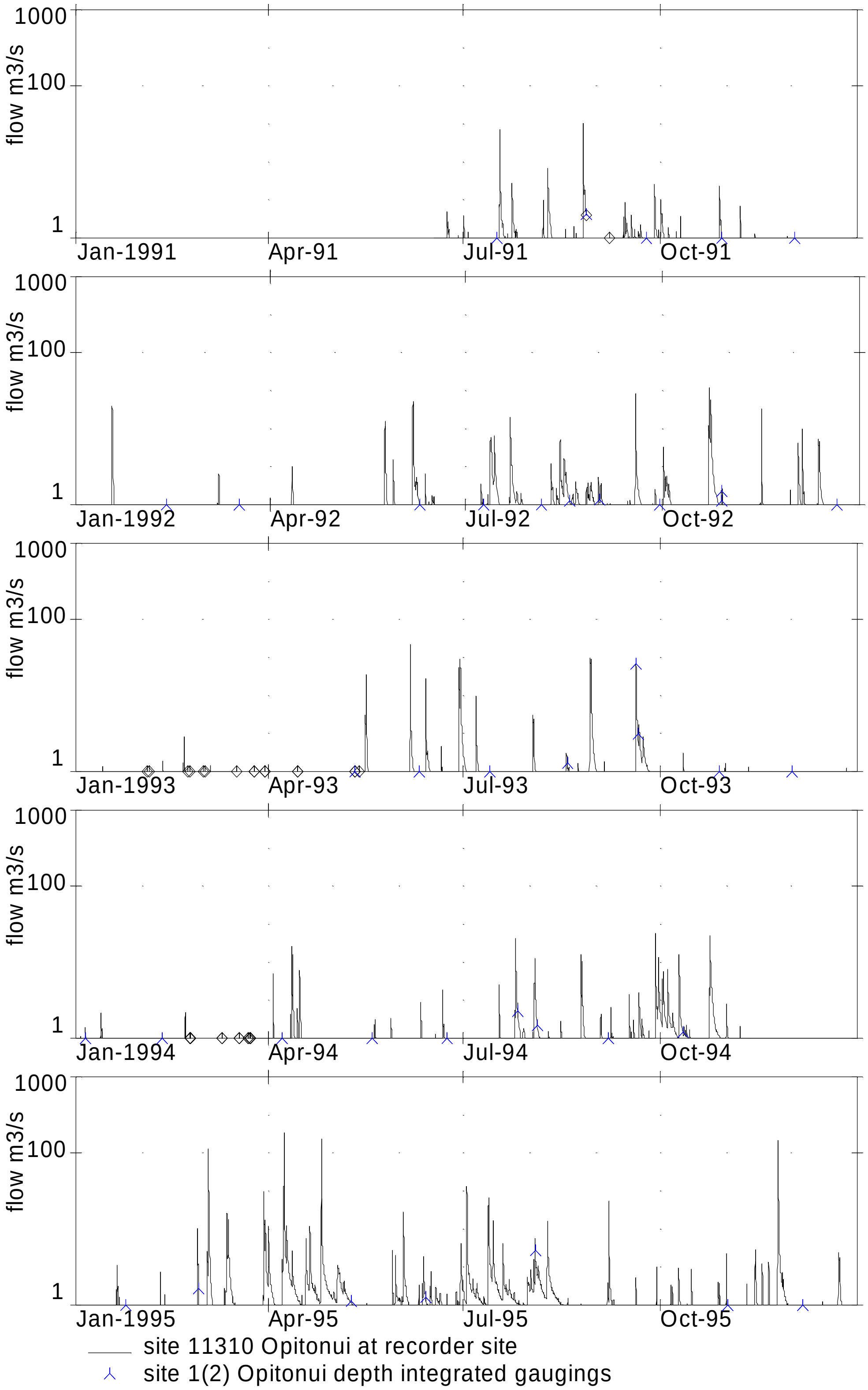


Figure C1: **Flows (m^3/s) and the times of suspended sediment gaugings for 17 June 1991 to 31 December 1995. Times of depth-integrated samples (blue crosses) are marked. *Note: logarithmic vertical scale.***

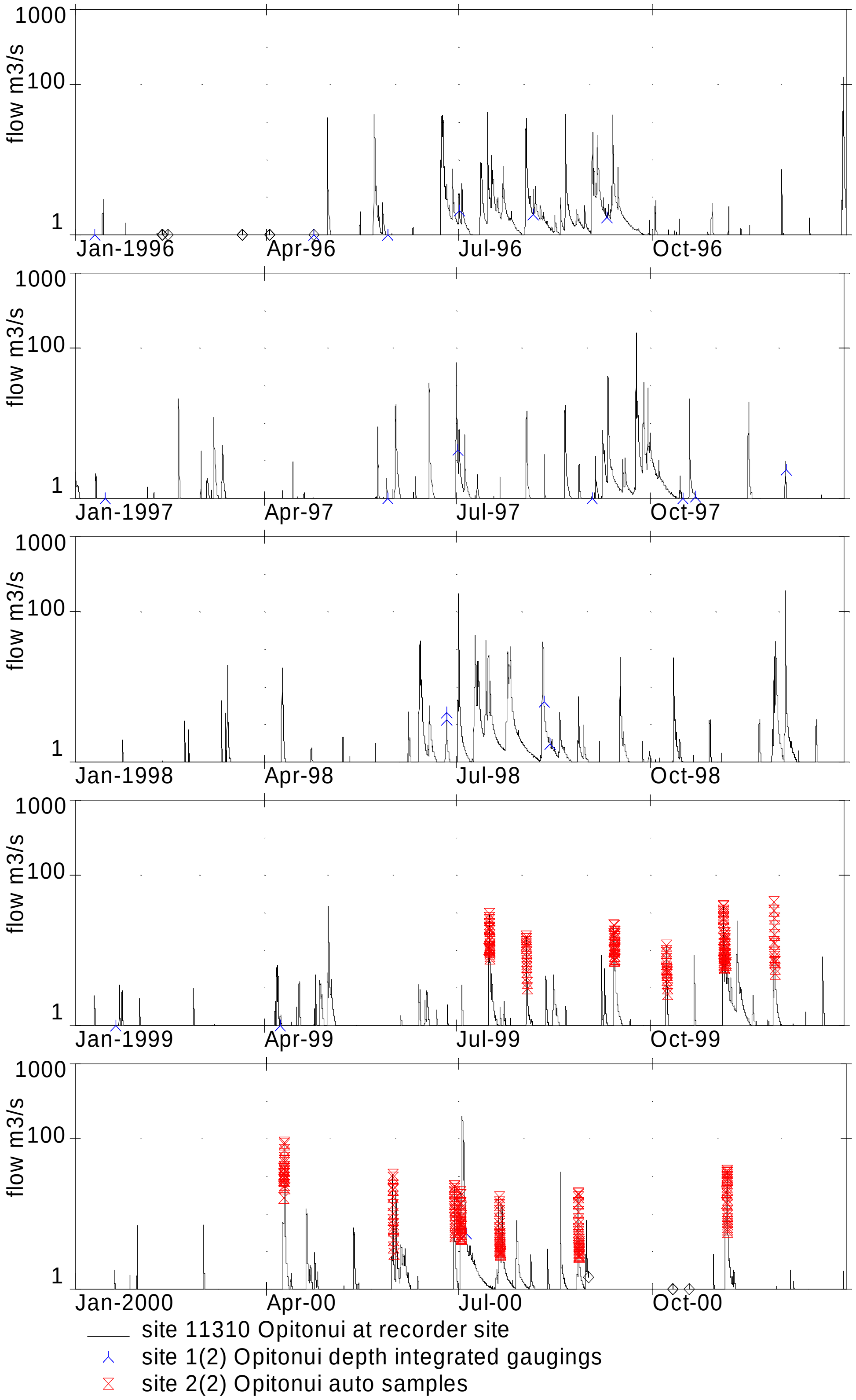


Figure C2: **Flows (m^3/s) and the times of suspended sediment gaugings for 1 January 1996 to 31 December-2000. Times of depth-integrated samples (blue crosses) and auto-samples (red crosses) are marked.** ***Note: logarithmic vertical scale.***

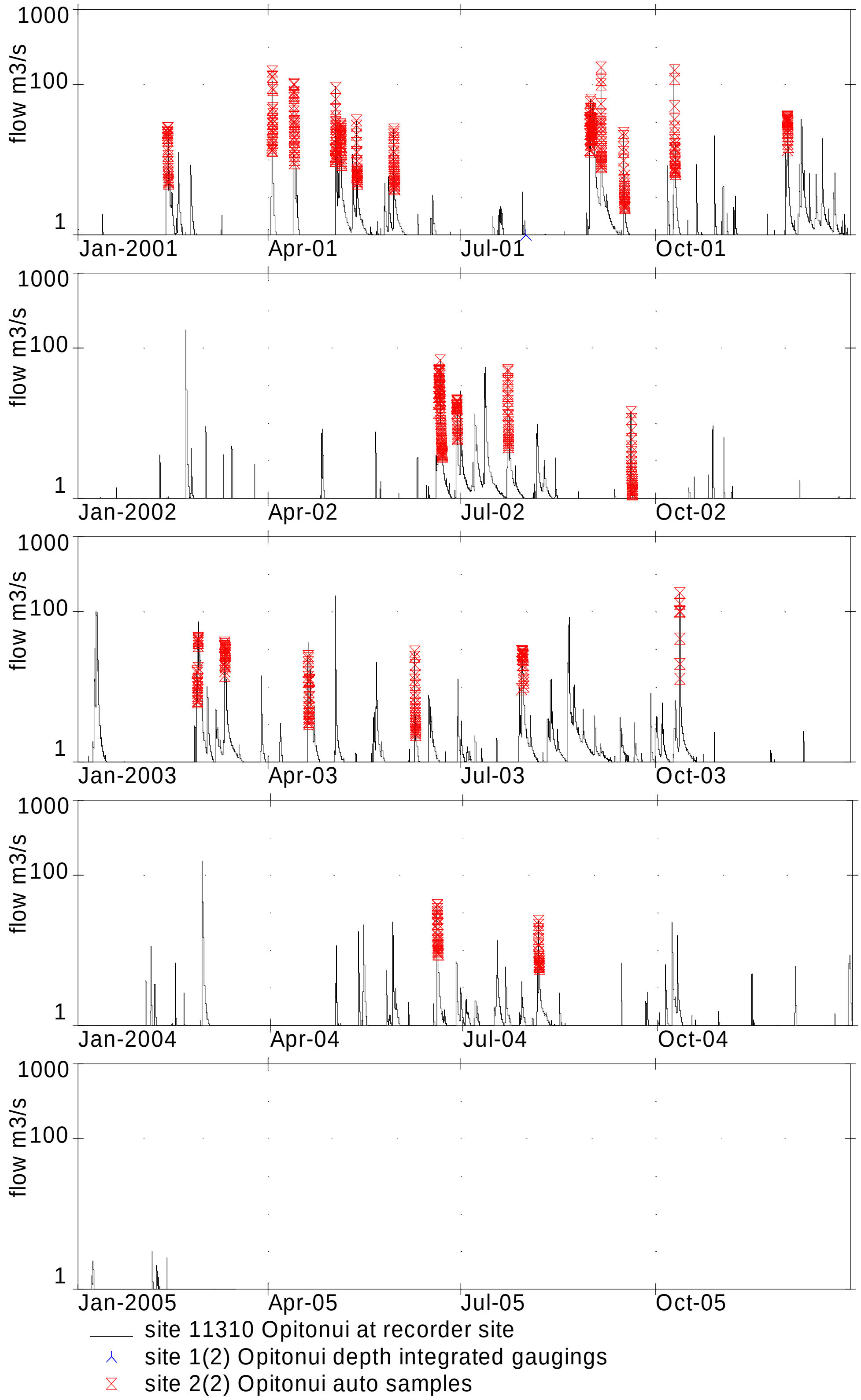


Figure C3: **Flows (m^3/s) and the times of suspended sediment gaugings for 1 January 2001 to 16 March 2005. Times of depth-integrated samples (blue crosses) and auto-samples (red crosses) are marked.** ***Note: logarithmic vertical scale.***

Appendix D

Opitonui Stream flows and auto-sample concentrations for individual storm events

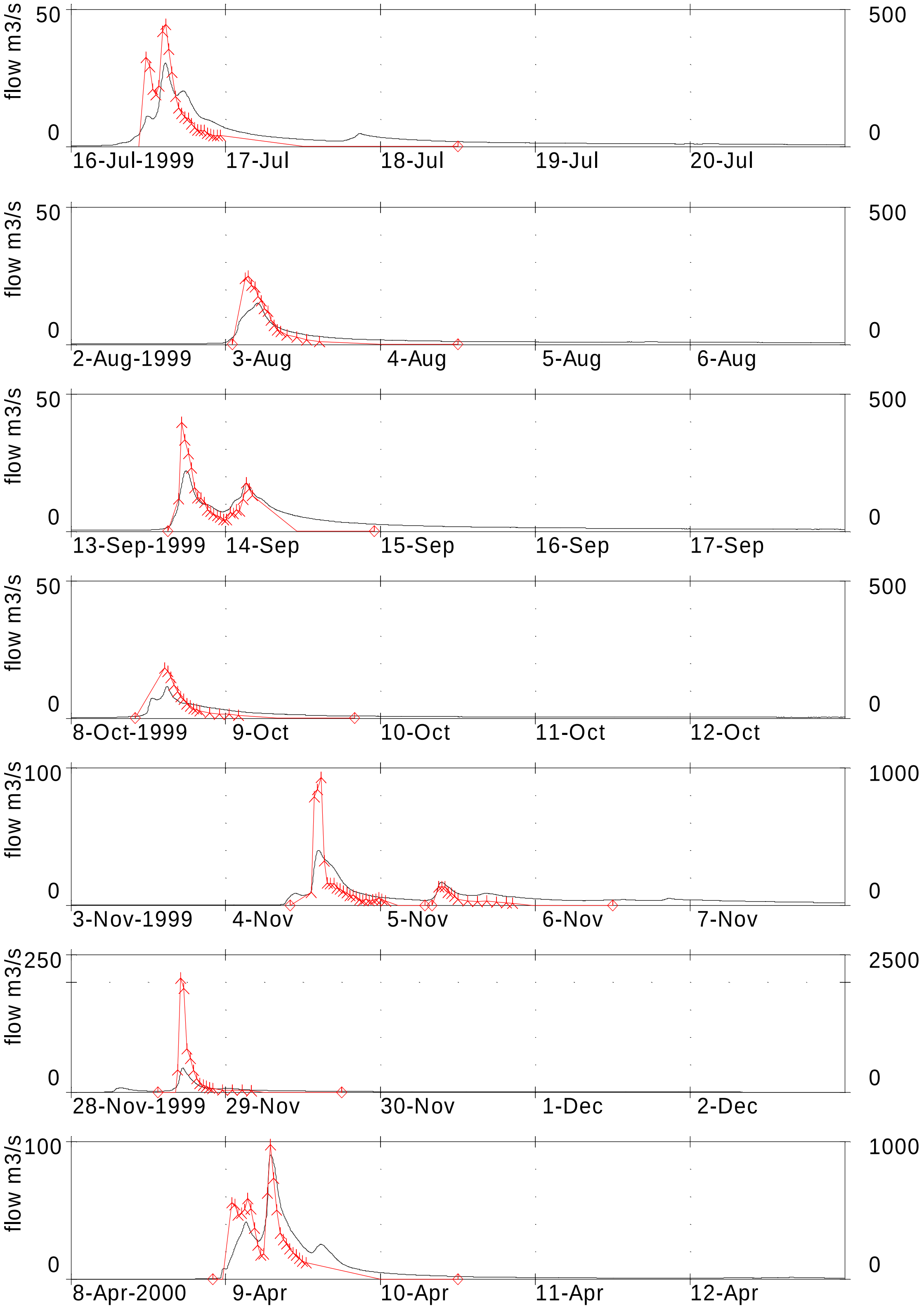


Figure D1: **Flows (black line, m^3/s, left axis) and suspended sediment concentrations (red line, mg/l, right axis) from auto-samples for storm events between July 1999 and April 2000. Times of auto-samples (red crosses) are marked.**

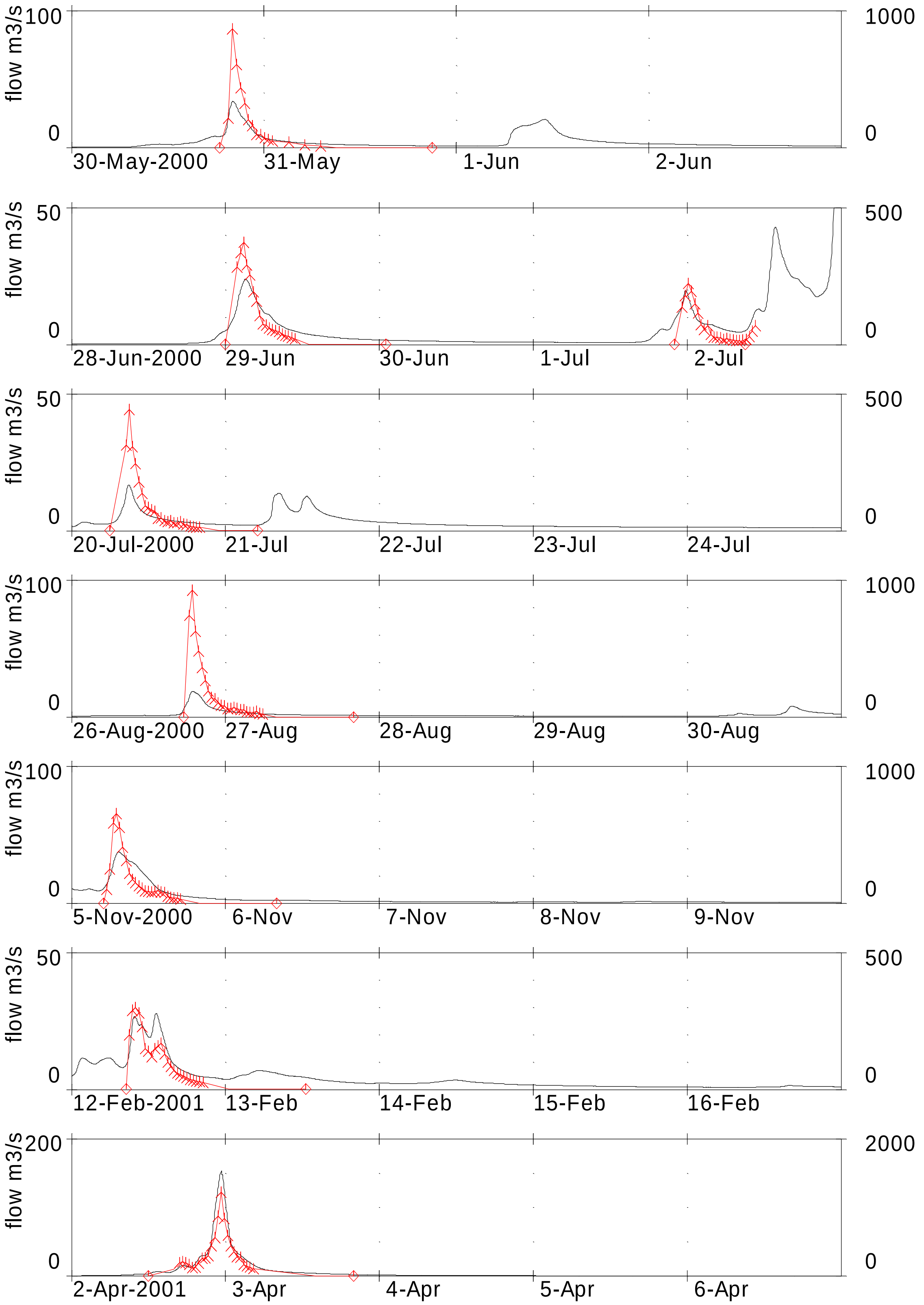


Figure D2: Flows (black line, m^3/s, left axis) and suspended sediment concentrations (red line, mg/l, right axis) from auto-samples for storm events between May 2000 and April 2001. Times of auto-samples (red crosses) are marked.

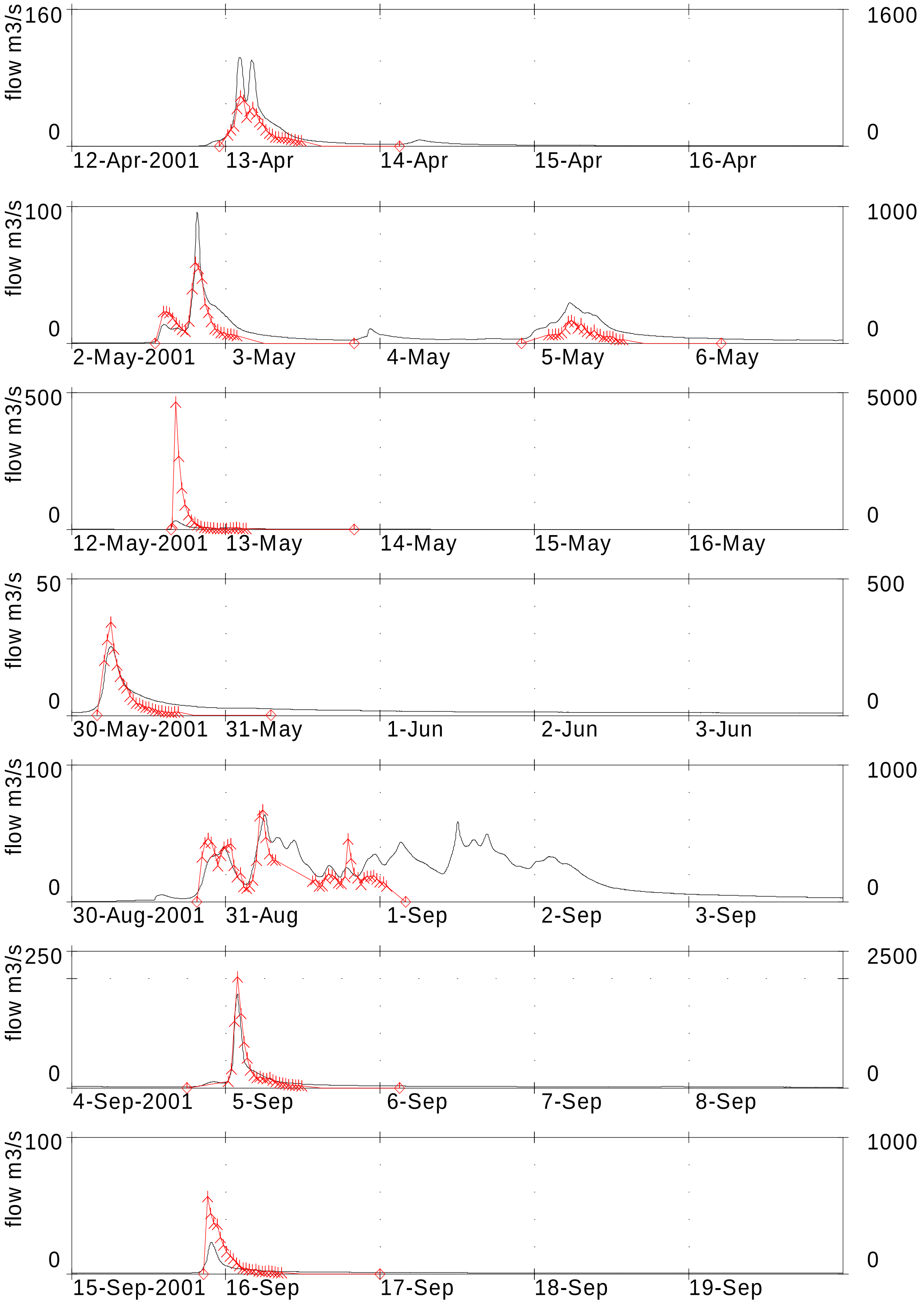


Figure D3: **Flows (black line, m^3/s, left axis) and suspended sediment concentrations (red line, mg/l, right axis) from auto-samples for storm events between April 2001 and September 2001. Times of auto-samples (red crosses) are marked.**

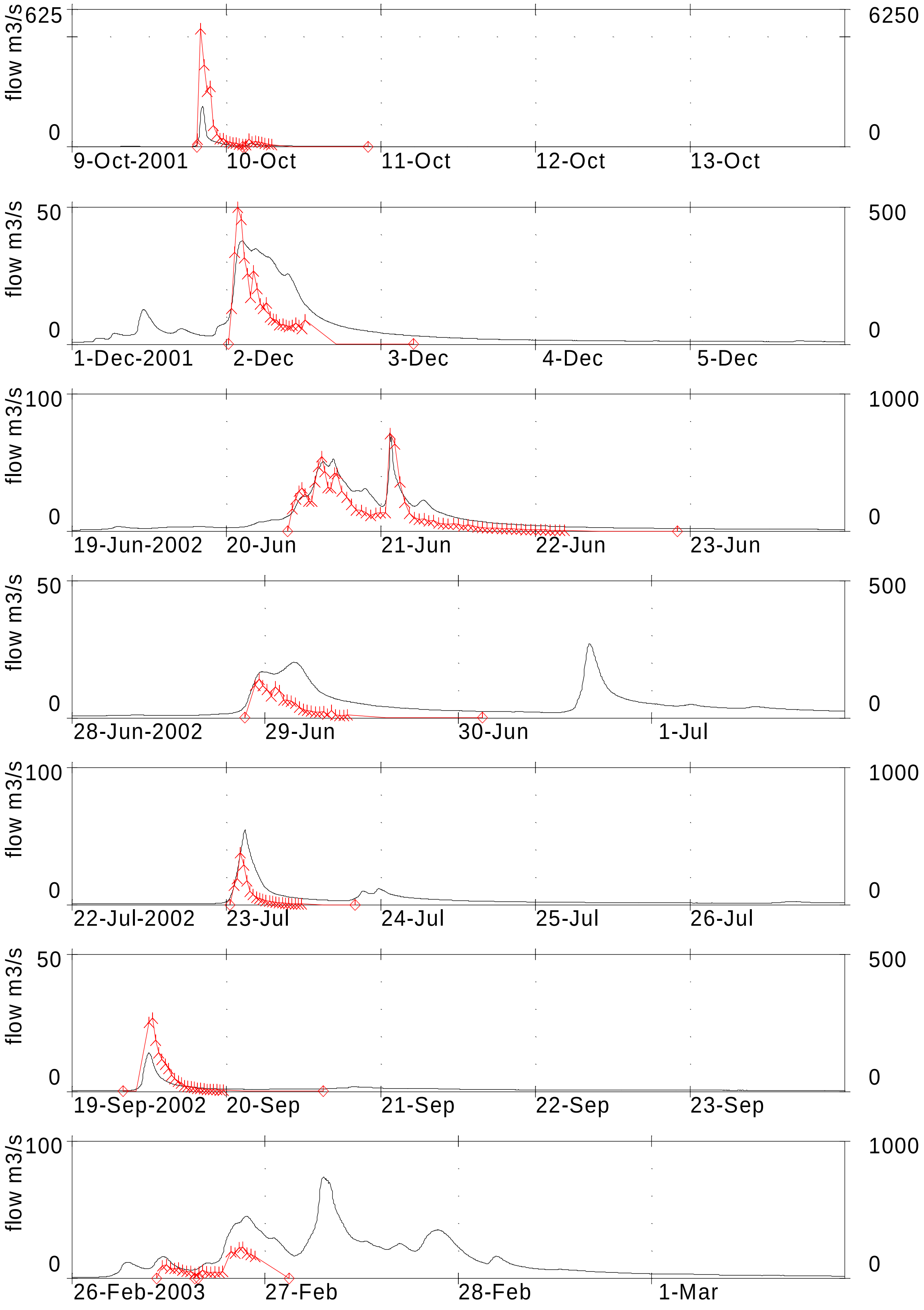


Figure D4: **Flows (black line, m^3/s, left axis) and suspended sediment concentrations (red line, mg/l, right axis) from auto-samples for storm events between October 2001 and February 2003. Times of auto-samples (red crosses) are marked.**

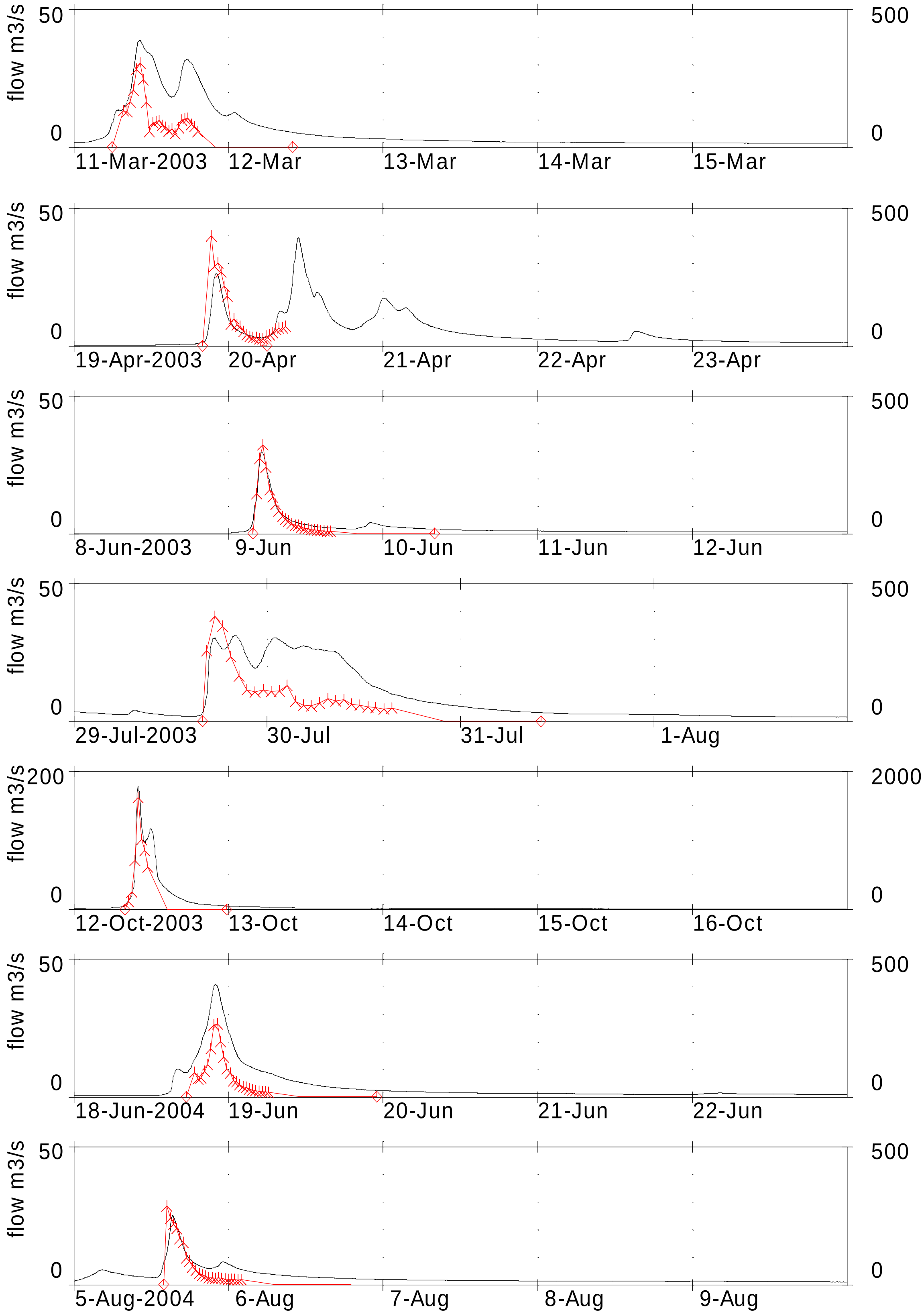
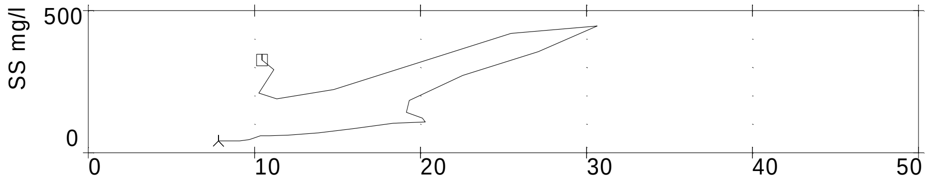


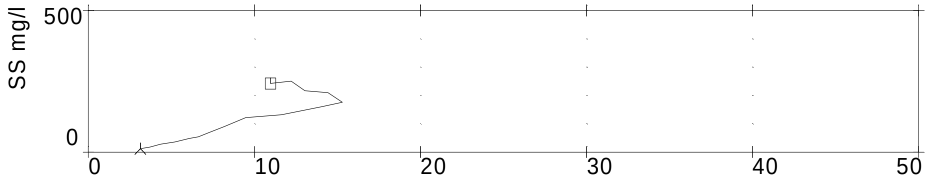
Figure D5: Flows (black line, m^3/s, left axis) and suspended sediment concentrations (red line, mg/l, right axis) from auto-samples for storm events between March 2003 and August 2004. Times of auto-samples (red crosses) are marked.

Appendix E

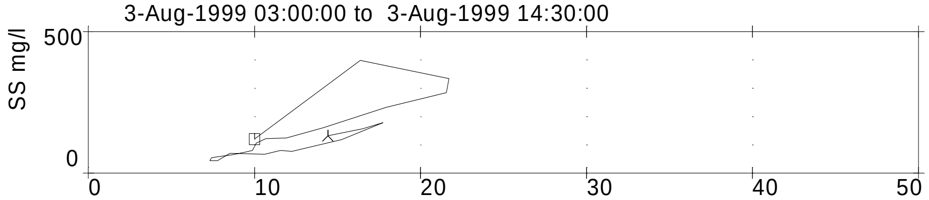
Hysteresis plots of Opitonui Stream flows and auto-sample concentrations for individual storm events



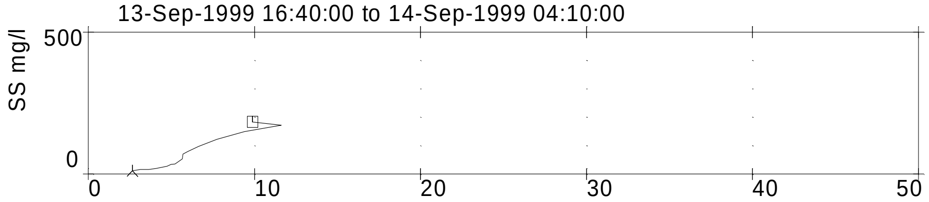
◇ Opitonui auto samples SS mg/l vs flow m3/s
16-Jul-1999 11:40:00 to 16-Jul-1999 23:10:00



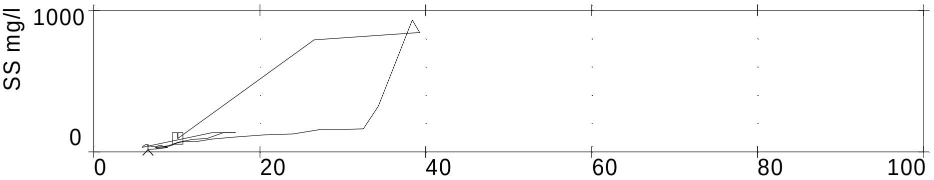
◇ Opitonui auto samples SS mg/l vs flow m3/s
3-Aug-1999 03:00:00 to 3-Aug-1999 14:30:00



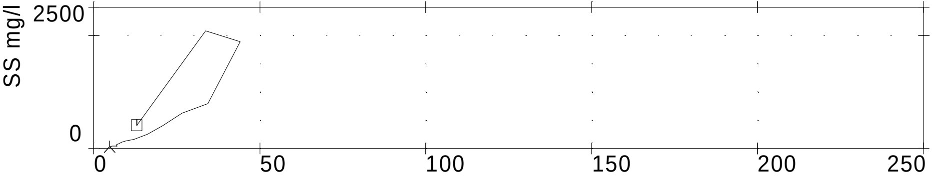
◇ Opitonui auto samples SS mg/l vs flow m3/s
13-Sep-1999 16:40:00 to 14-Sep-1999 04:10:00



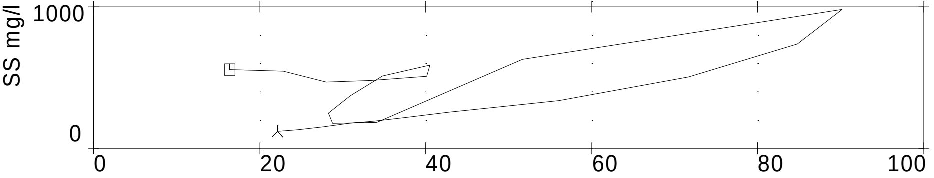
◇ Opitonui auto samples SS mg/l vs flow m3/s
8-Oct-1999 14:30:00 to 9-Oct-1999 02:00:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
4-Nov-1999 13:15:00 to 5-Nov-1999 20:30:00

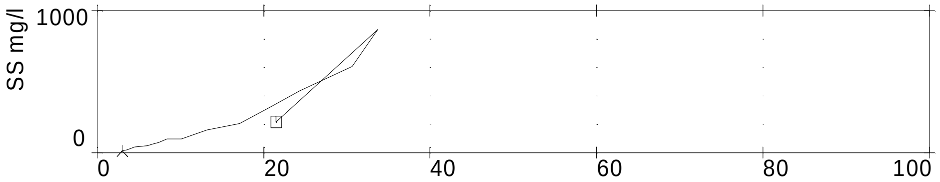


◇ Opitonui auto samples SS mg/l vs flow m3/s
28-Nov-1999 16:30:00 to 29-Nov-1999 04:00:00

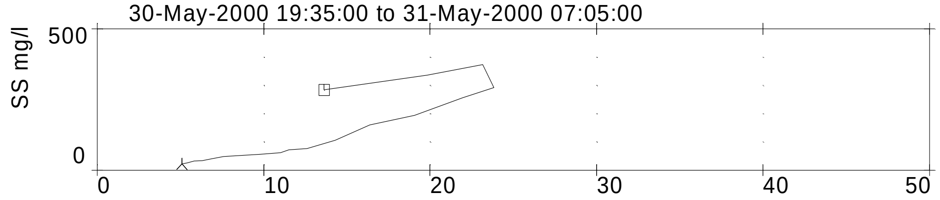


◇ Opitonui auto samples SS mg/l vs flow m3/s
9-Apr-2000 00:55:00 to 9-Apr-2000 12:25:00

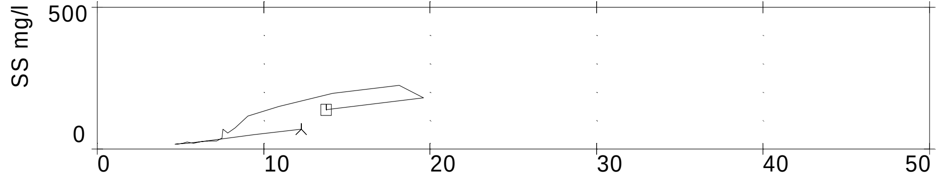
Figure E1: **Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between July 1999 and April 2000 (□ = start of event, ⅄ = end of event). Note various x and y axis ranges.**



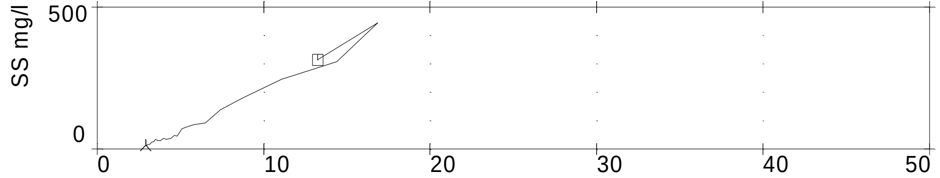
◇ Opitonui auto samples SS mg/l vs flow m3/s
30-May-2000 19:35:00 to 31-May-2000 07:05:00



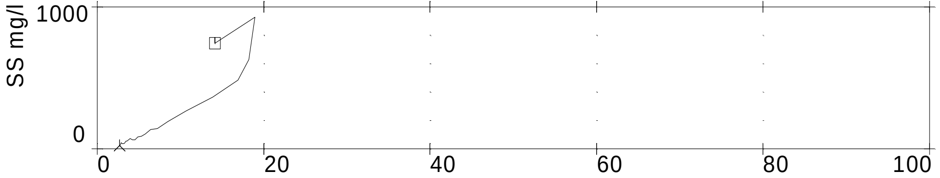
◇ Opitonui auto samples SS mg/l vs flow m3/s
29-Jun-2000 01:50:00 to 29-Jun-2000 10:50:00



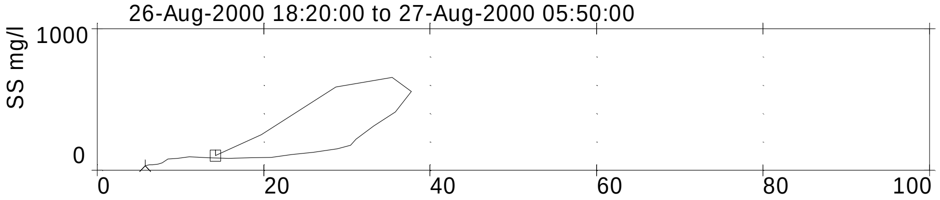
◇ Opitonui auto samples SS mg/l vs flow m3/s
1-Jul-2000 23:10:00 to 2-Jul-2000 10:40:00



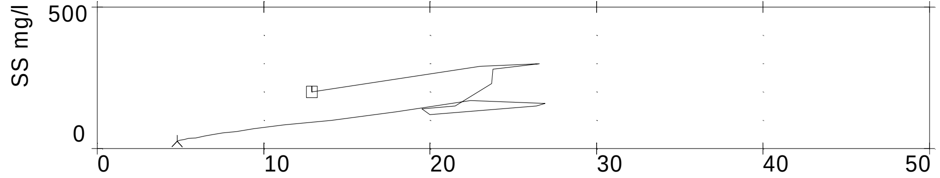
◇ Opitonui auto samples SS mg/l vs flow m3/s
20-Jul-2000 08:30:00 to 20-Jul-2000 20:00:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
26-Aug-2000 18:20:00 to 27-Aug-2000 05:50:00

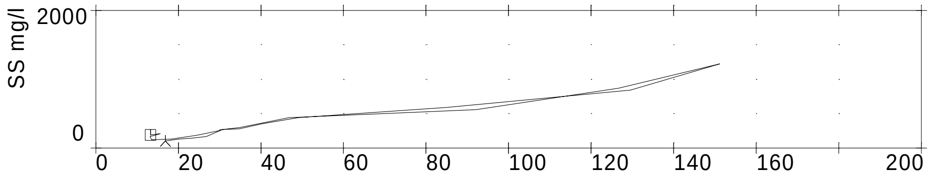


◇ Opitonui auto samples SS mg/l vs flow m3/s
5-Nov-2000 05:30:00 to 5-Nov-2000 17:00:00

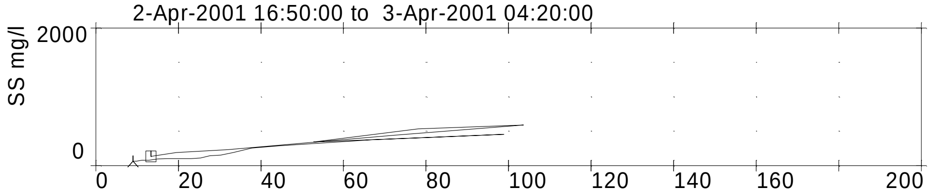


◇ Opitonui auto samples SS mg/l vs flow m3/s
12-Feb-2001 09:00:00 to 12-Feb-2001 20:30:00

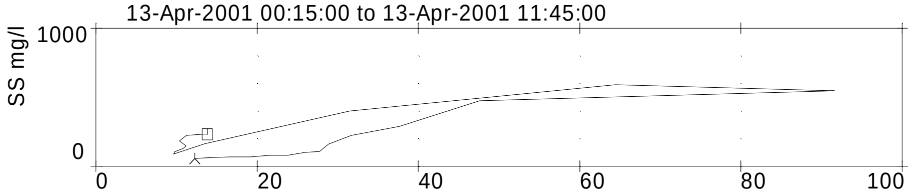
Figure E2: **Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between May 2000 and February 2001 (□ = start of event, ⅄ = end of event). Note various x and y axis ranges.**



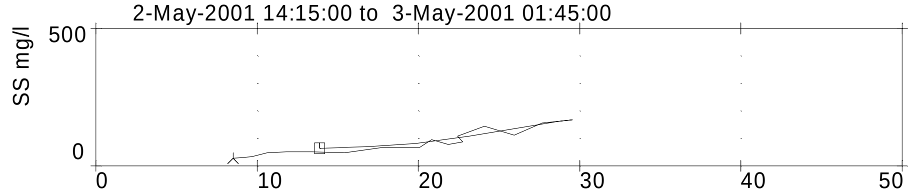
◇ Opitonui auto samples SS mg/l vs flow m3/s
2-Apr-2001 16:50:00 to 3-Apr-2001 04:20:00



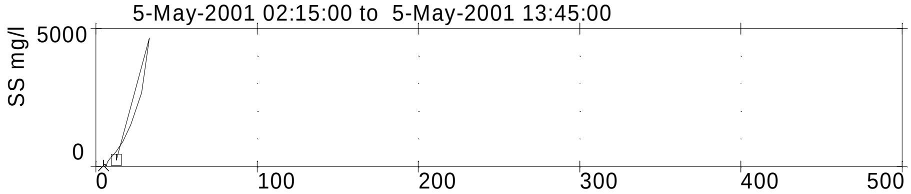
◇ Opitonui auto samples SS mg/l vs flow m3/s
13-Apr-2001 00:15:00 to 13-Apr-2001 11:45:00



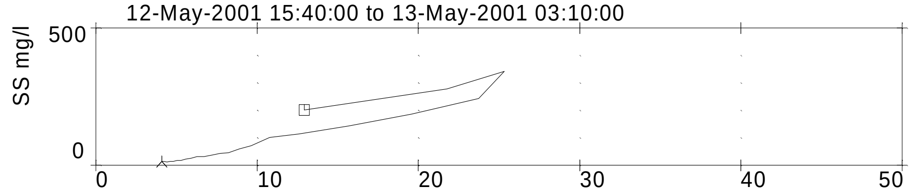
◇ Opitonui auto samples SS mg/l vs flow m3/s
2-May-2001 14:15:00 to 3-May-2001 01:45:00



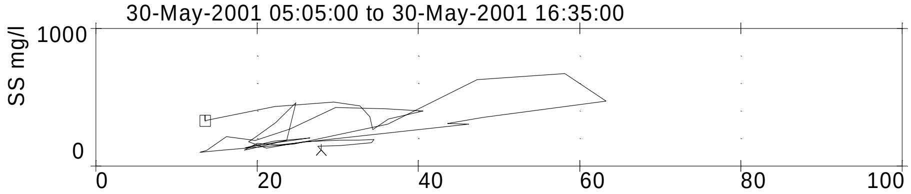
◇ Opitonui auto samples SS mg/l vs flow m3/s
5-May-2001 02:15:00 to 5-May-2001 13:45:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
12-May-2001 15:40:00 to 13-May-2001 03:10:00

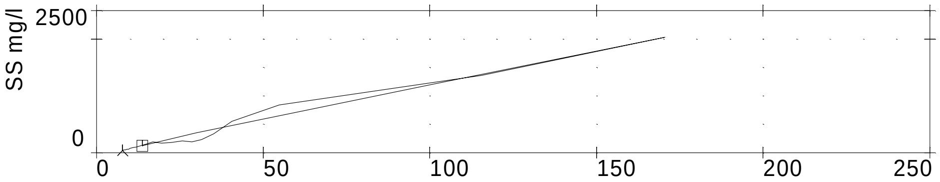


◇ Opitonui auto samples SS mg/l vs flow m3/s
30-May-2001 05:05:00 to 30-May-2001 16:35:00

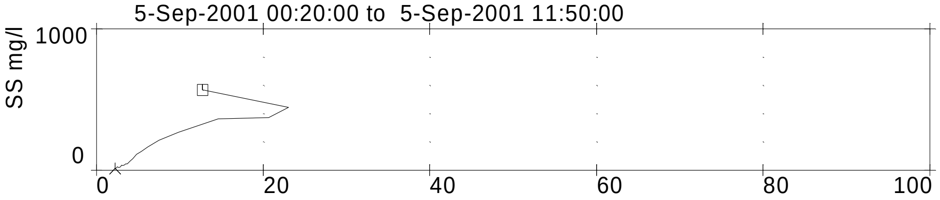


◇ Opitonui auto samples SS mg/l vs flow m3/s
30-Aug-2001 20:15:00 to 1-Sep-2001 01:00:00

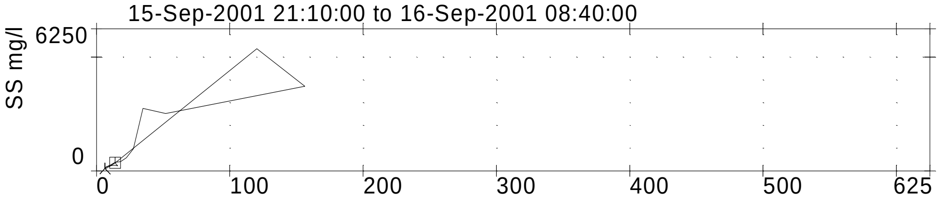
Figure E3: **Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between April 2001 and August 2001 (□ = start of event, ⅄ = end of event). Note various x and y axis ranges.**



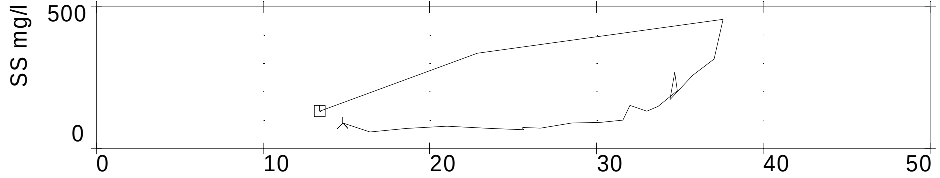
◇ Opitonui auto samples SS mg/l vs flow m3/s
5-Sep-2001 00:20:00 to 5-Sep-2001 11:50:00



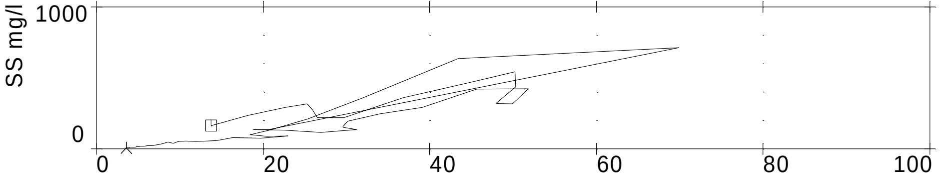
◇ Opitonui auto samples SS mg/l vs flow m3/s
15-Sep-2001 21:10:00 to 16-Sep-2001 08:40:00



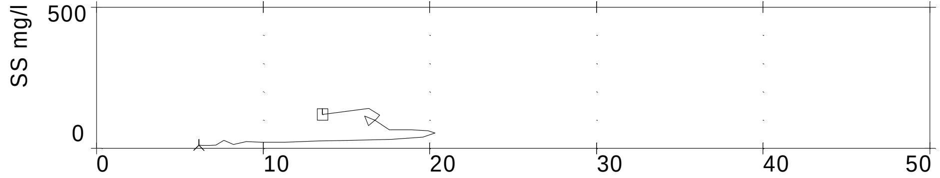
◇ Opitonui auto samples SS mg/l vs flow m3/s
9-Oct-2001 19:30:00 to 10-Oct-2001 07:00:00



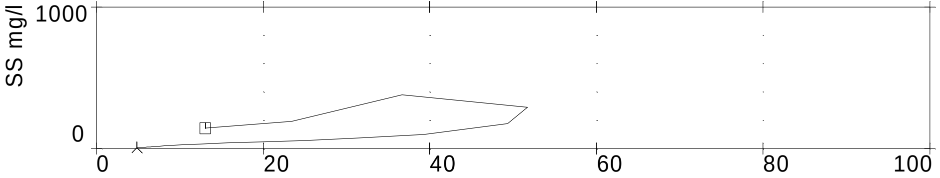
◇ Opitonui auto samples SS mg/l vs flow m3/s
2-Dec-2001 00:45:00 to 2-Dec-2001 12:15:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
20-Jun-2002 10:15:00 to 22-Jun-2002 04:30:00

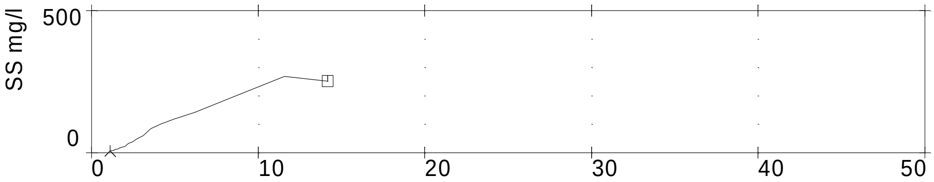


◇ Opitonui auto samples SS mg/l vs flow m3/s
28-Jun-2002 22:45:00 to 29-Jun-2002 10:15:00

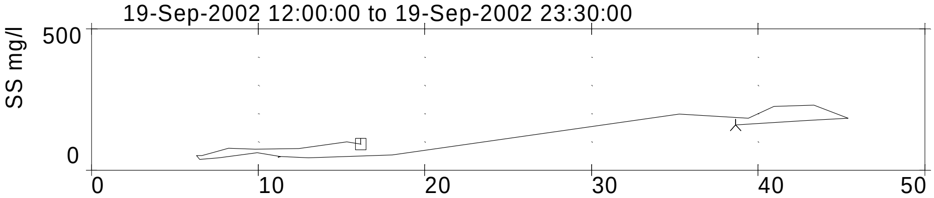


◇ Opitonui auto samples SS mg/l vs flow m3/s
23-Jul-2002 01:10:00 to 23-Jul-2002 11:40:00

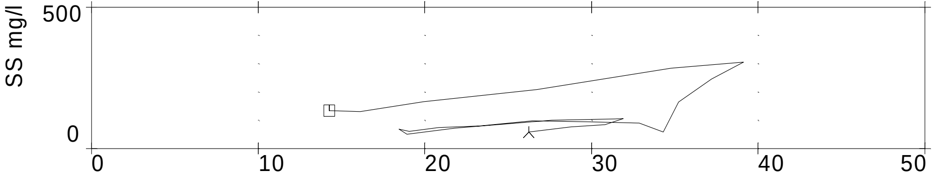
Figure E4: **Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between September 2001 and July 2002 (□ = start of event, ⅄ = end of event). Note various x and y axis ranges.**



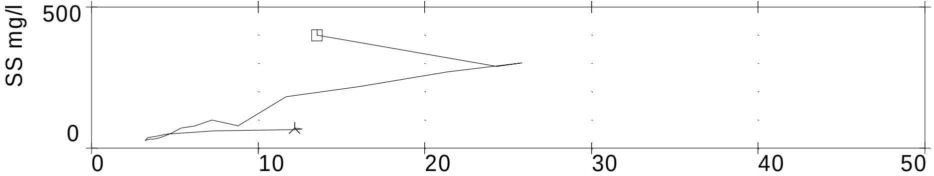
◇ Opitonui auto samples SS mg/l vs flow m3/s
19-Sep-2002 12:00:00 to 19-Sep-2002 23:30:00



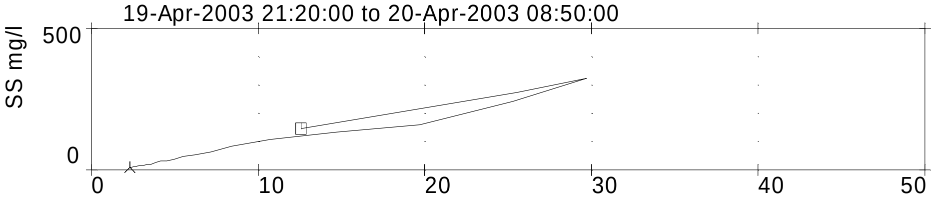
◇ Opitonui auto samples SS mg/l vs flow m3/s
26-Feb-2003 11:15:00 to 26-Feb-2003 22:45:00



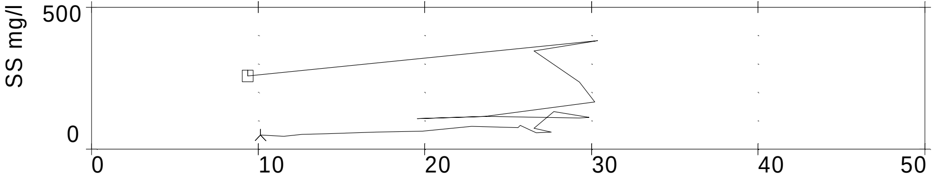
◇ Opitonui auto samples SS mg/l vs flow m3/s
11-Mar-2003 07:45:00 to 11-Mar-2003 19:15:00



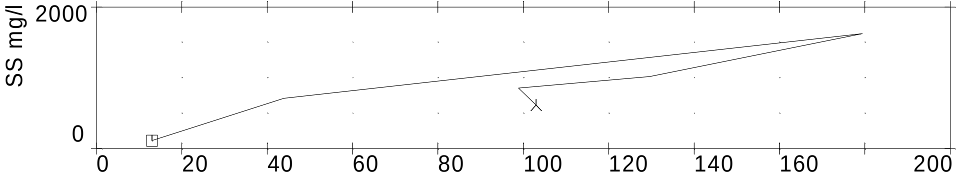
◇ Opitonui auto samples SS mg/l vs flow m3/s
19-Apr-2003 21:20:00 to 20-Apr-2003 08:50:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
9-Jun-2003 04:20:00 to 9-Jun-2003 15:50:00

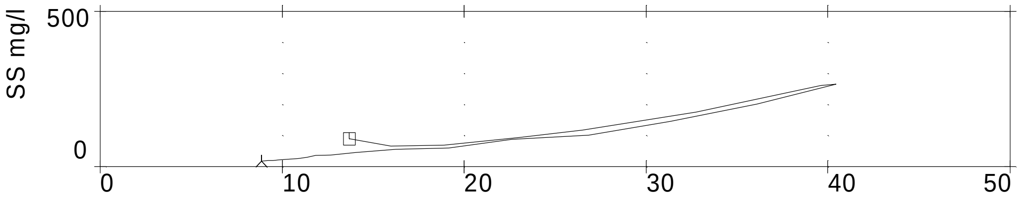


◇ Opitonui auto samples SS mg/l vs flow m3/s
29-Jul-2003 16:30:00 to 30-Jul-2003 15:30:00

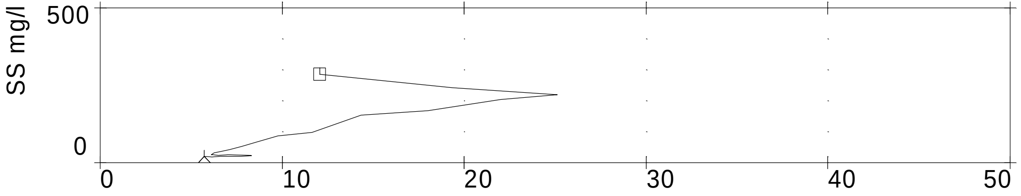


◇ Opitonui auto samples SS mg/l vs flow m3/s
12-Oct-2003 08:30:00 to 12-Oct-2003 11:30:00

Figure E5: Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between September 2002 and October 2003 (□ = start of event, ⅄ = end of event). Note various x and y axis ranges.



◇ Opitonui auto samples SS mg/l vs flow m3/s
18-Jun-2004 18:45:00 to 19-Jun-2004 06:15:00



◇ Opitonui auto samples SS mg/l vs flow m3/s
5-Aug-2004 14:28:00 to 6-Aug-2004 01:58:00

Figure E6: **Flow (m^3/s) versus auto-sample suspended sediment concentrations (mg/l) for storm events between July 2004 and August 2004 (□ = start of event, ⅄ = end of event).**