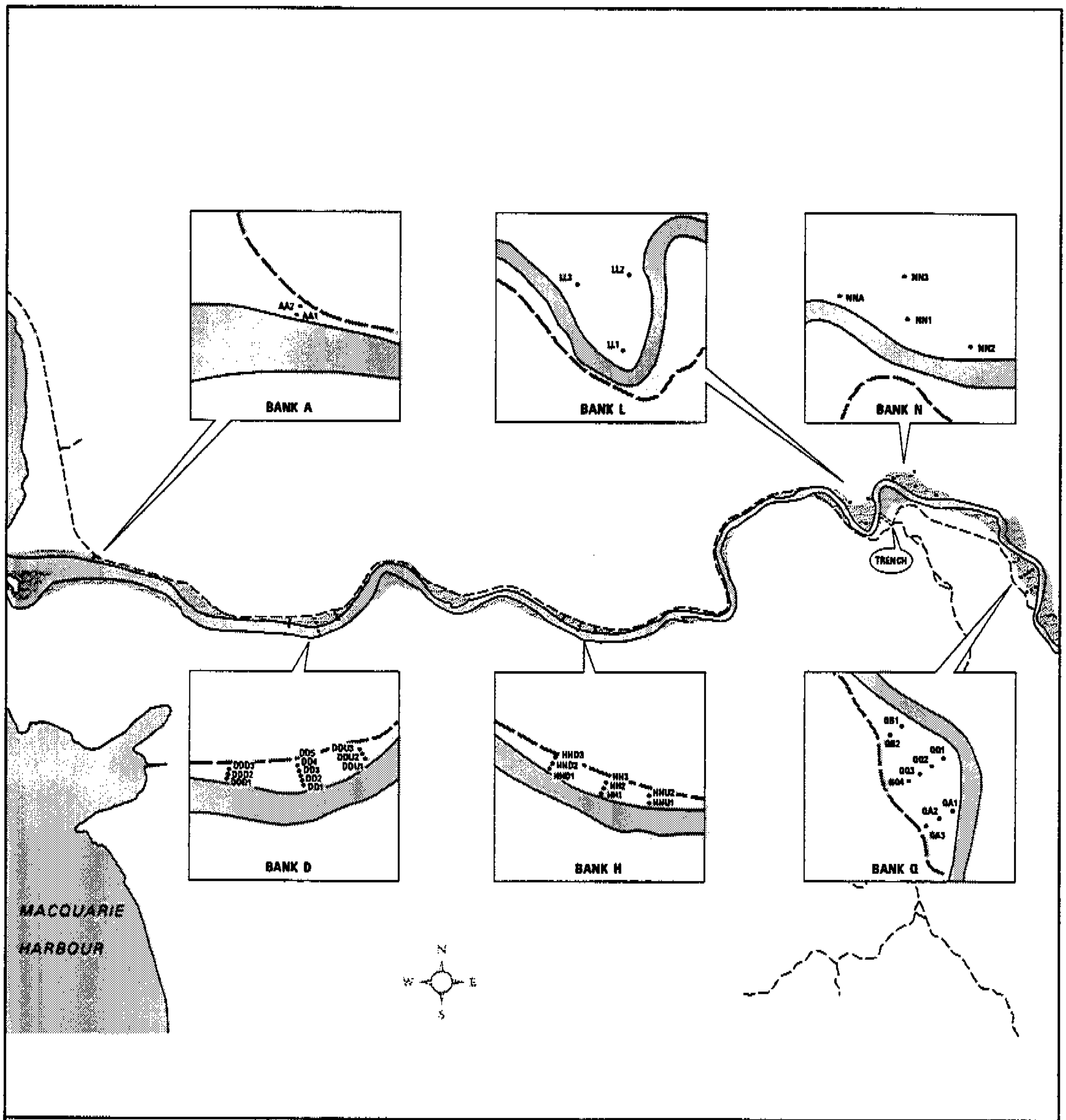


Map 4.2 Locations of auger holes and trench

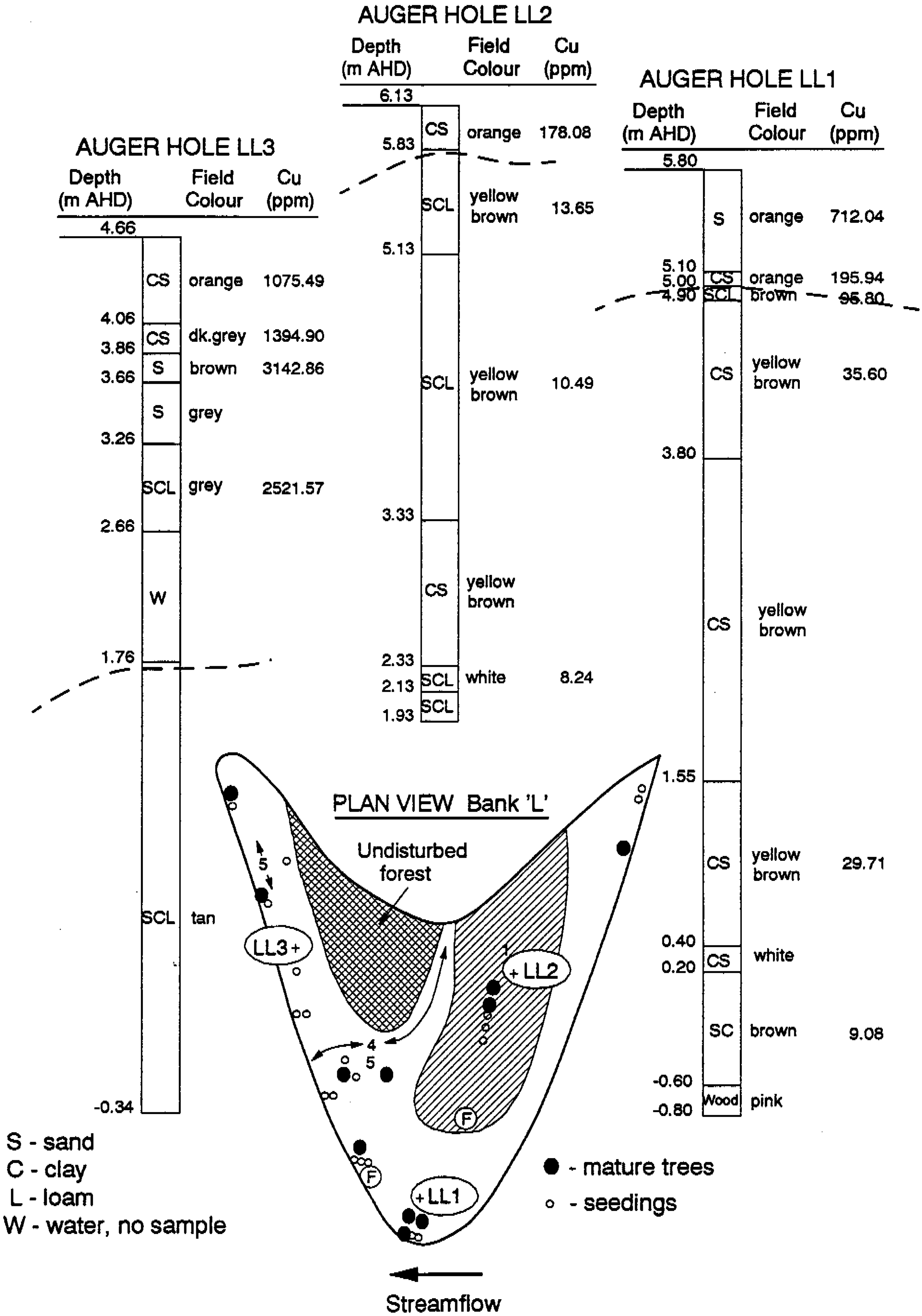


Figure 4.2 Bank L

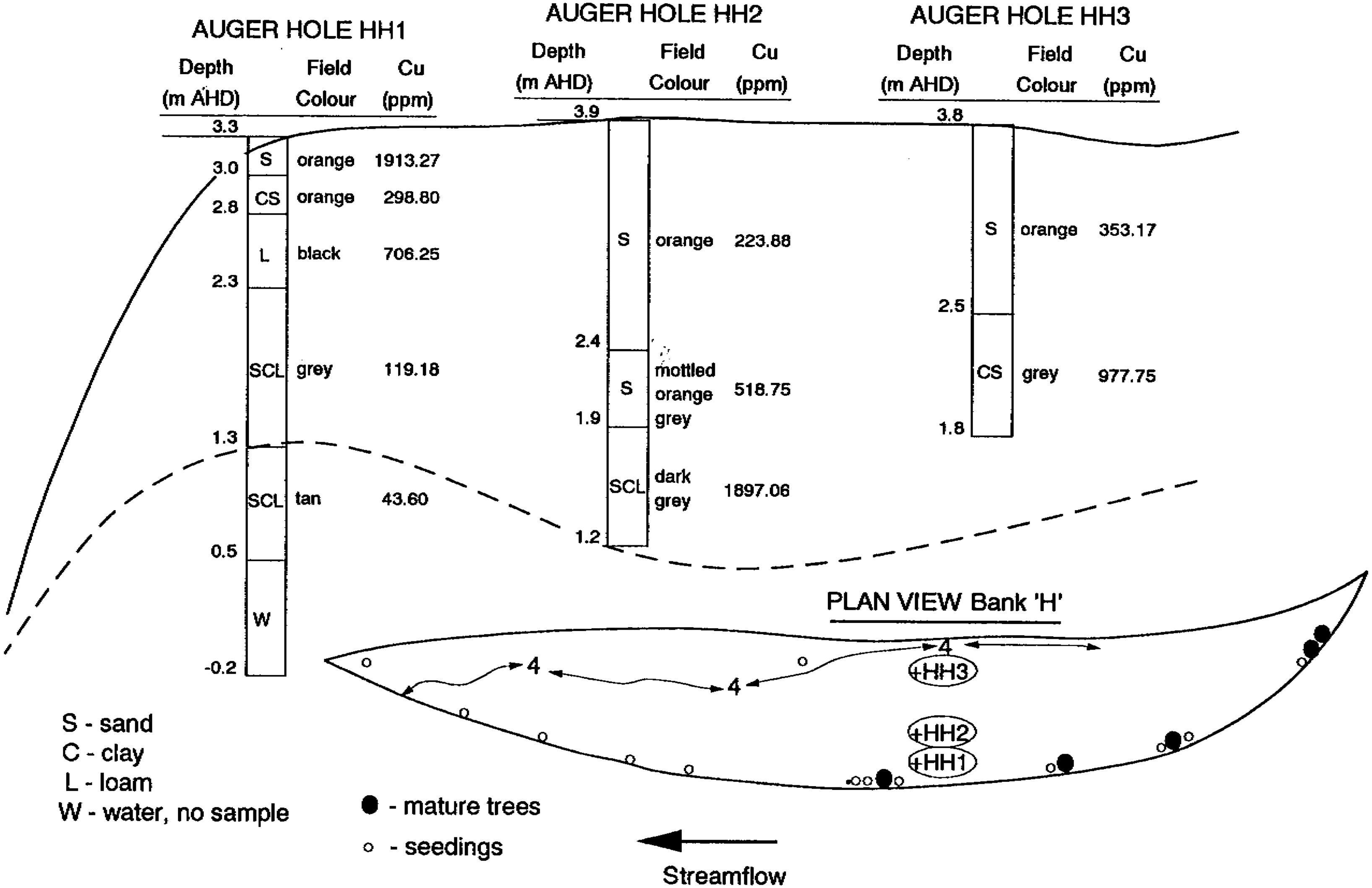


Figure 4.3 Bank H

As anticipated from the surrounding vegetation, the natural bank was very close to the bank surface at auger holes LL1 and LL2, and somewhat deeper (at least 3m) at auger hole LL3. The sands and clayey sands with orange and grey colouration can generally be attributed to mine-derived sediments, although colour alone can be an unreliable basis for identification and the brown sediments were not always natural. The natural bank appears to be predominantly characterised by a tan to yellow-brown sandy clay loam.

Figure 4.3 shows the results for Bank H. Again, the grey and orange colouration was associated with mine-derived sediments, and the tan sandy clay loam appears to be the natural bank. The depths of the stratigraphic changes within the bank support the idea of a levee bank formation as seen in the trench stratigraphy. Samples from the other four banks which were augered have not all been analysed as of yet. Appendix 2 provides the results to date, and indicates with an (*) which analyses are still being conducted.

Figure 4.4 shows a sketch of how the banks are believed to have developed. In the plan view, the banks are believed to have extended in a downstream direction due to deposition of the tailings in the eddy zone below the nose of the bank. In the profile view, tailings deposition has occurred due to successive over-topping of the original levee bank by peak flood events. The surface deposits of mine-derived sediments are generally sands and clayey sands, and many of the fines may have been winnowed out by the action of wind. At depth the stored tailings are often finer, having been carried in suspension by the river and then trapped as the flow receded, and these sediments have presumably been protected by the overtopping sediments.

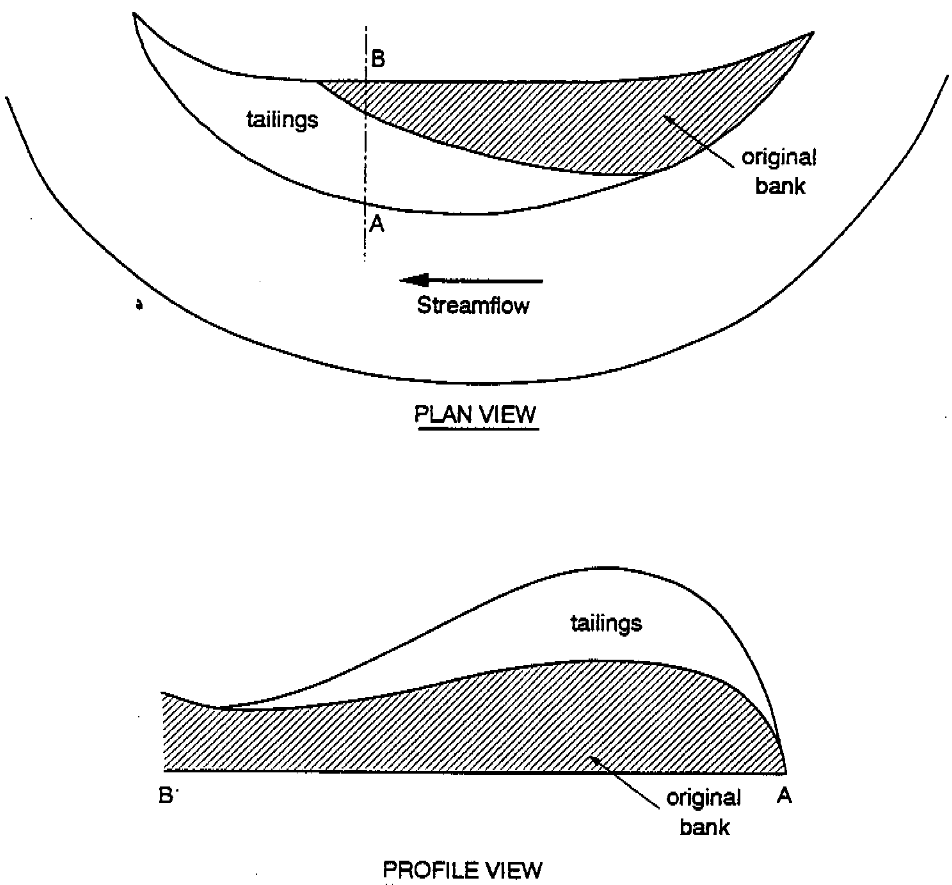


Figure 4.4 Hypothesis of bank formation

Only limited other information is available on the sediment banks. Specific gravity has been analysed for several bank samples with the results listed in table 4.2. The oxidised tailings have a specific gravity of approximately 2.7, whereas the freshly deposited grey tailings have a specific gravity closer to 3.0.

Table 4.2 Specific gravity of King River sediment banks

	Sample 1	Sample 2	Sample 3	Average
Bank F oxidised tailings	2.747	2.762	2.739	2.750
Bank M oxidised tailings	2.694	2.701	2.701	2.699
Bank Q oxidised tailings	2.709	2.696	2.716	2.707
Bank Q fresh tailings	3.047	2.995	2.927	2.990

Some sections of the sediment banks show a hard red/brown crusting, a product of sulphide oxidation from the pyrites contained in the tailings. Hince's (1993) thesis shows some interesting microscopic views of oxidised tailings as compared to fresh tailings. In the unoxidised fresh grey tailings (plate 4.10), gold coloured grains were clearly visible at 70x magnification, and were almost certainly pyrite. The oxidised sediment sample (plate 4.11) was coarser, pyritic material was absent, and an orange precipitate could be observed on the grain surfaces.

4.3 King River bed

4.3.1 Pre-mining baseline

There is considerable anecdotal evidence about the water depth and character of the King River channel prior to the commencement of mining.

Local history reports that ocean-going vessels used to come up the King River as far as the port of Teepookana (near Station 15), once the fourth largest port in Tasmania, to collect mine ore delivered by railway from Mount Lyell. The Strahan historian, Harry McDermott, believes that these ships were limited to those with less than a 10' draft. Teepookana was the port site because it was the highest navigable site on the King River (Rae 1993), suggesting that it is the location of a fault or some geological feature which produced a change in river slope and channel character. Other anecdotal evidence concerns the construction of the Quarter Mile Bridge, for which the workers had to sink the pilings down through 18m of unconsolidated sediments (Rae 1988), suggesting that the channel is an old valley infill.

The best documented evidence of the King River channel pre-mining is from the Mount Lyell Mining and Railway Company's 1898 railway survey for the line between Queenstown and Strahan. There were three bridge crossings included in this survey, as shown on map 4.3. The Quarter Mile Bridge and Teepookana Bridges were built, but the Pine Cove crossing was never constructed, an advantage for this study as local scour effects associated with bridges do not need to be taken into account at the Pine Cove crossing. Comparisons with 1994 surveys showed 0.5m of infilling at the Quarter Mile Bridge, and almost 4m of infilling at Teepookana Bridge. The most dramatic infilling can be seen at the Pine Cove crossing (fig 4.5), which has filled in 9m at its deepest point.

The HEC's Survey section is presently digitising the old railway map, both the plan view and the three bridge cross-sections. Overlay of the plan view with the present day 1:25,000 topographic map may give an indication of any growth or migration of sediment banks over the past 100 years. This is thought to be unlikely given the confined nature of the alluvial channel, but such an overlay may verify that the bulk of the river storage has been in the river bed and has had the most influence on channel slope.

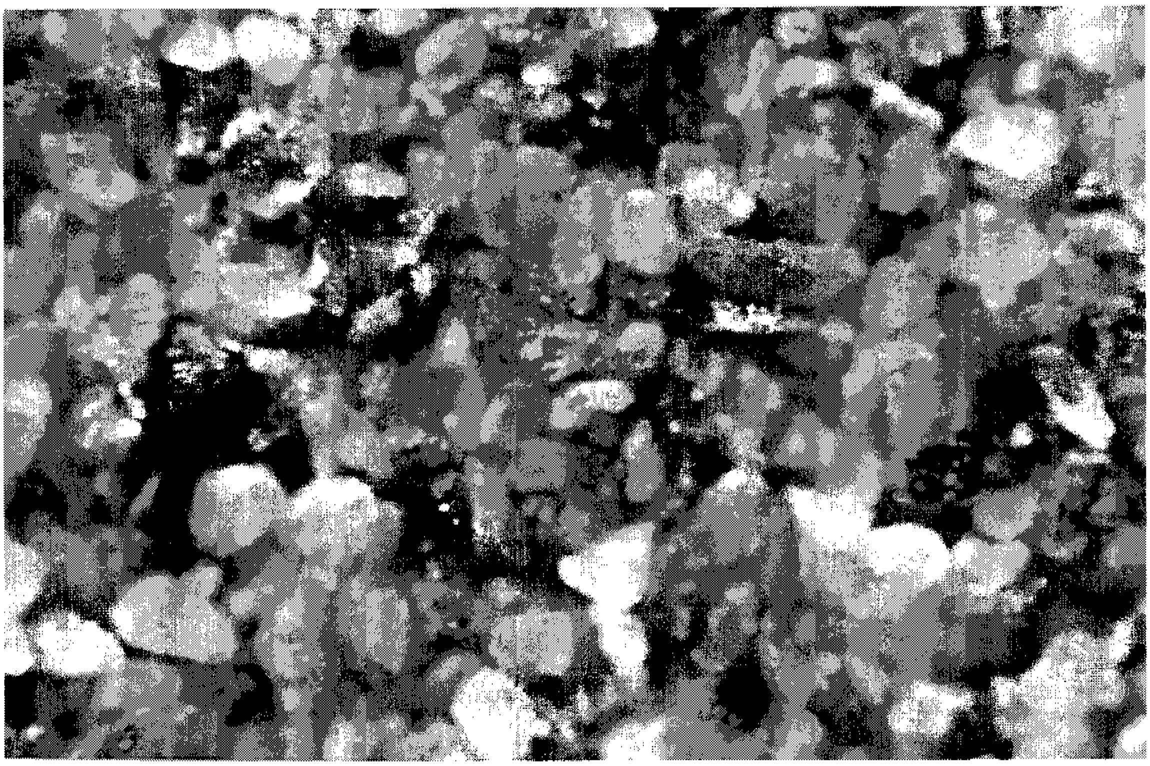


Plate 4.10 Microscopic view of unoxidised tailings

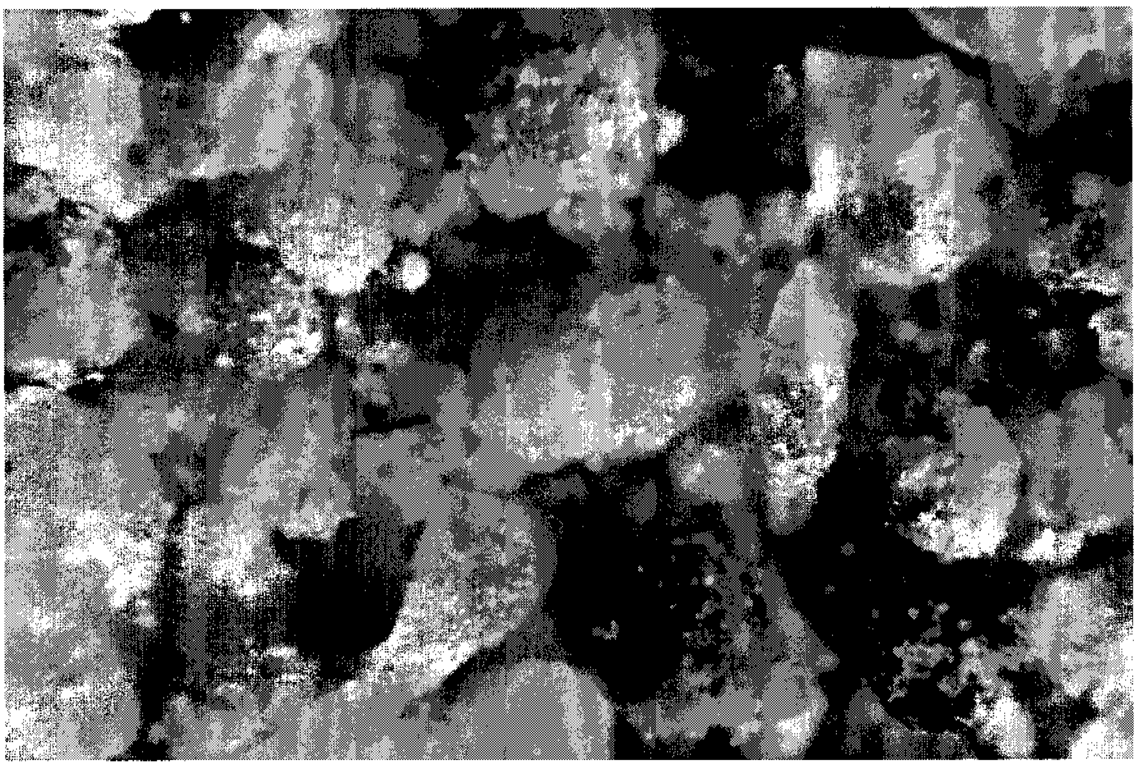


Plate 4.11 Microscopic view of oxidised tailings

4.3.2 HEC drill cores

More recent data on the nature of the King River bottom sediments can be found in the HEC's geological and geophysical investigations in the late 1980s for the King River Power Scheme development. Potential damsites were investigated at Sailor Jack Creek, Four Mile Creek and Cutten Creek, and a number of seismic lines and drill cores were collected. Map 4.4 shows the locations and numbers of those drill cores which were collected within the King River channel and tailings banks. Table 4.3 summarises the results of these drill cores, and typical core material is shown in plates 4.12 and 4.13. Unfortunately little to no tailings were able to be recovered in these cores.

The HEC's drill core data from their dam investigations showed that the King River valley was originally much deeper and has been infilled with gravels. Note that the results shown in table 4.3 are depths below the water surface, so for Drill Hole No 7751 there was 2m of water underlain by 1.5m of tailings underlain by 5.7m of mine slag underlain by 19.7m of gravels, giving a total depth below water level of 28.9m.

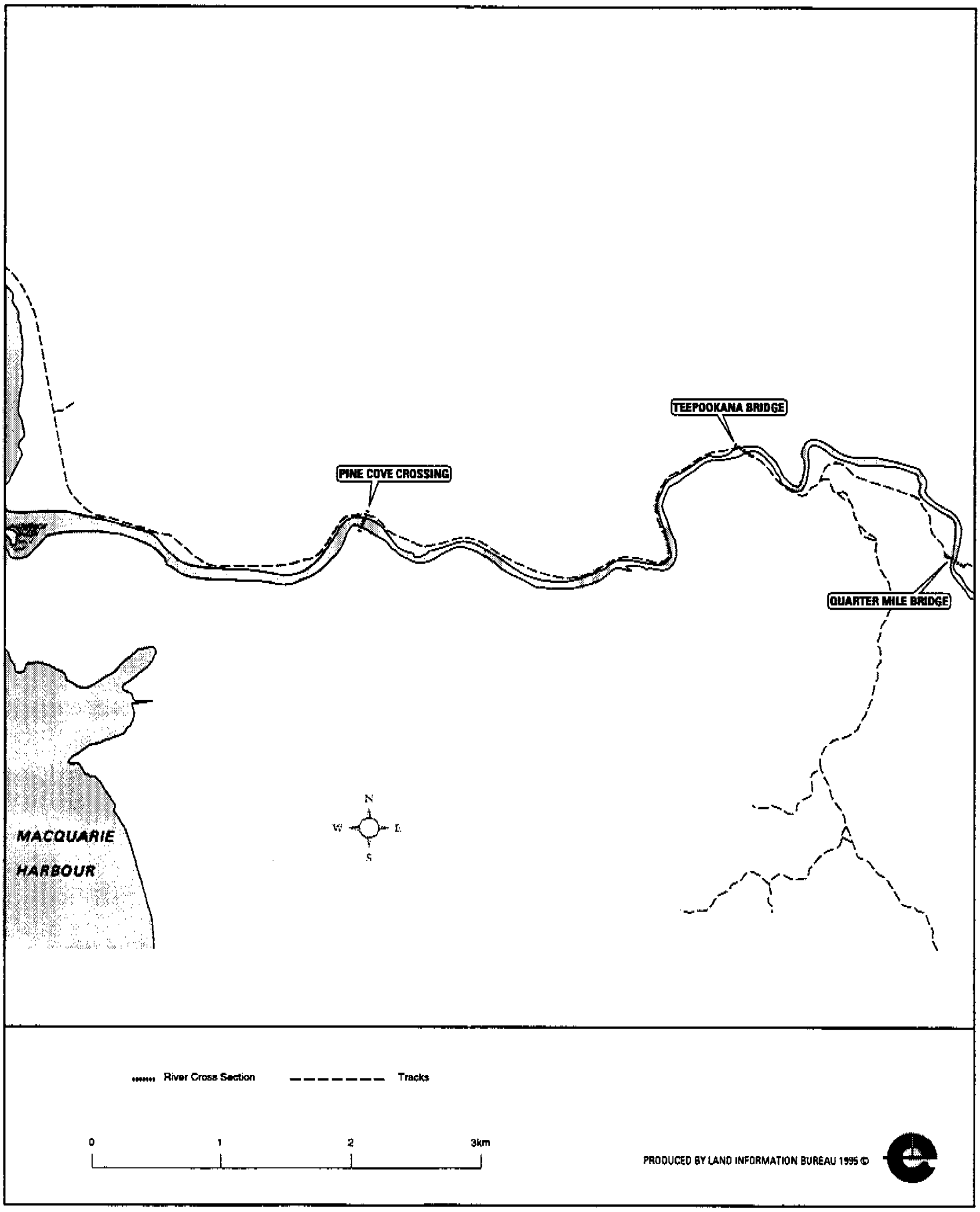
Tailings depths were up to 13.15m at Drill Hole No (DH) 7752 and 13.65m at DH 7754 (500m downstream of Cutten Creek). Slag depths were 5.7m at DH 7751 and 6m at DH 7867. Valley infill was found to be more than 45 m near Cutten Creek, thinning to 23 m at Four Mile Creek which is less than 2 km upstream. This sudden change could possibly represent an old waterfall or fault line. The valley infill was found to consist of gravel, sand and silt, with mine waste admixed in the top layers to a depth of about 9 m.

4.3.3 Surveyed cross-sections

The HEC Survey section surveyed channel cross-sections on the King River in 1988 and 1993, and several of these cross-sections have been re-surveyed during 1994 as part of this study. Map 4.5 shows the locations of channel cross-sections which have been surveyed during 1994 and are being re-surveyed during 1995; these should form a good baseline for future re-surveying to assess changes in channel shape and depth.

Figure 4.6 shows the survey results for those 1994 cross-sections which were able to be compared with the 1988 and 1993 surveys. These show progressive infilling of the river channel, most particularly the central bar, within a few kilometres of the river mouth. Although the centre of the river is filling in, the double channel is still maintained. Unfortunately no cross-sections were taken in 1992 which would enable a comparison of pre- versus post- power station depositional rates. It is interesting to note the infilling of almost 1 metre at Slat 5 (at the river mouth) in the space of a year suggests that the depositional rate behind the delta has increased since the power station has been on line, since 1m/yr could not have been sustained over the 78 years that tailings were deposited.

Stations 18, 19 and Slat 3 suggest a tendency for narrowing of the cross-section, which was also seen with the Pine Cove crossing (fig 4.5). This needs to be evaluated with regard to anticipated changes in channel geometry summarised in the literature. The cross-sections in fig 4.5 are at a point in the river where the width changes rapidly with distance along the river, and there is no guarantee that the more recent cross-sections were at the exact same location as the 1898 survey cross-section.



Map 4.3 River cross-sections from 1898 Mount Lyell railway survey

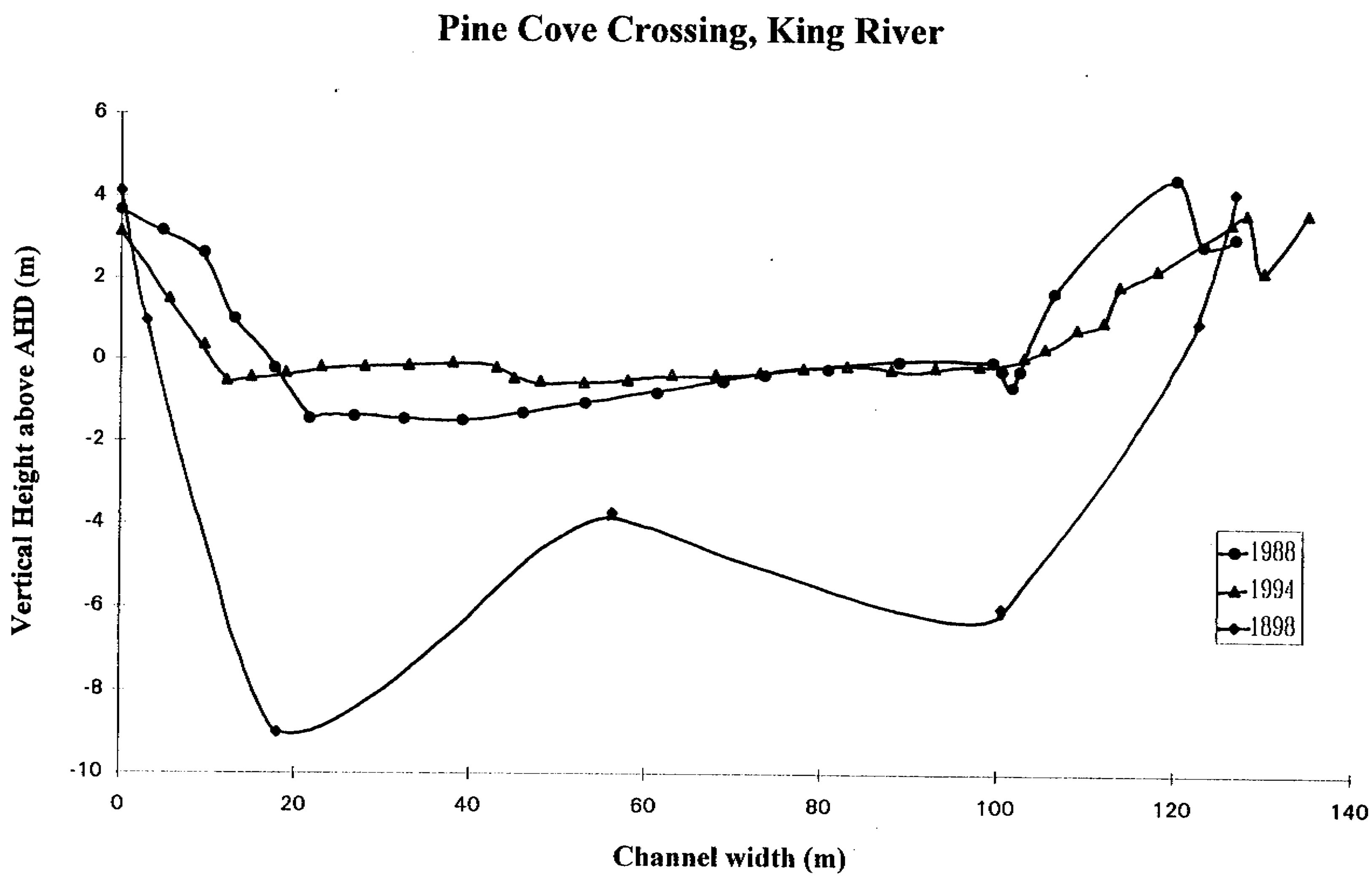


Figure 4.5 Infilling of sediment in the Lower King River 1898–1994

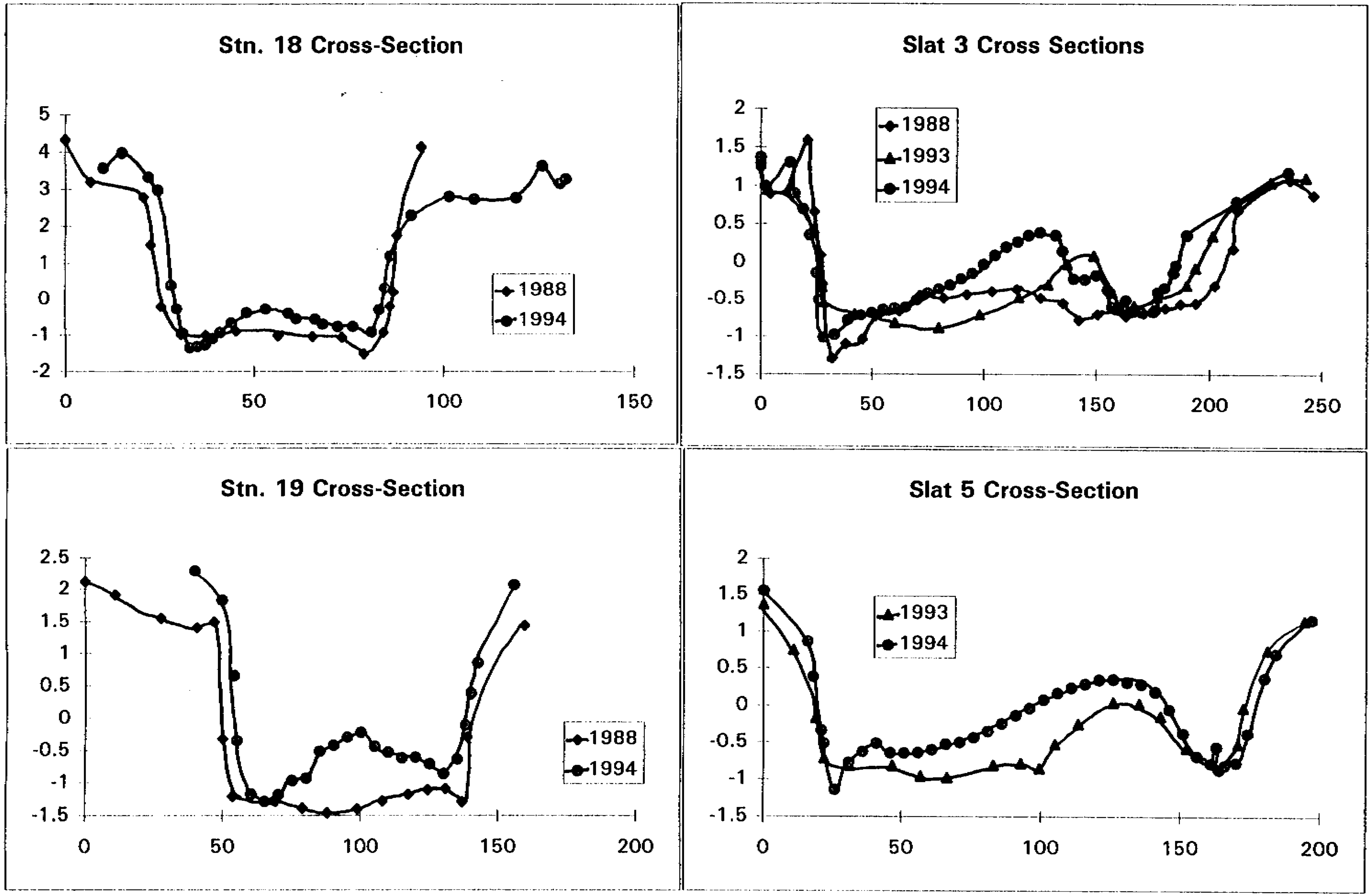
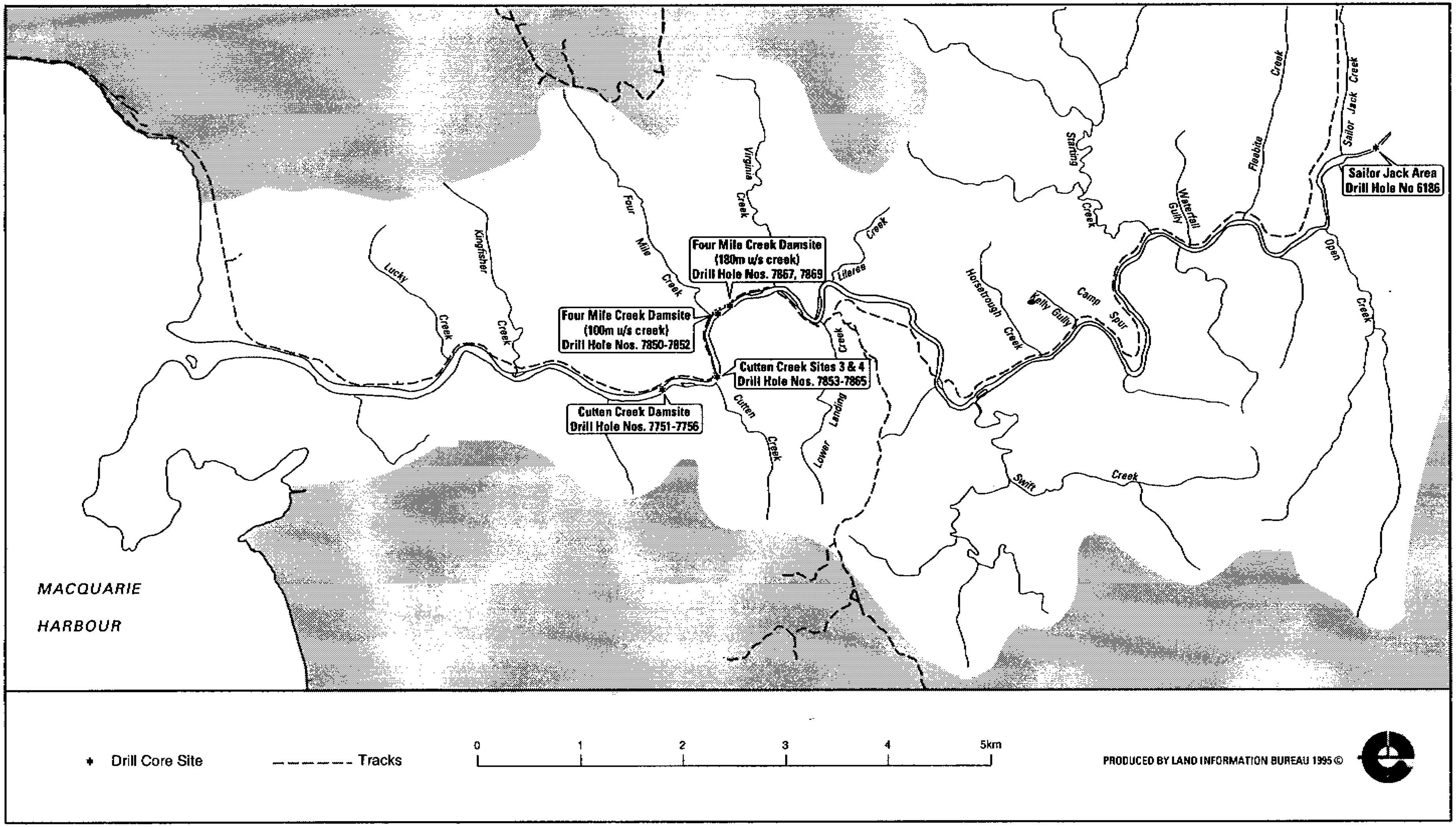
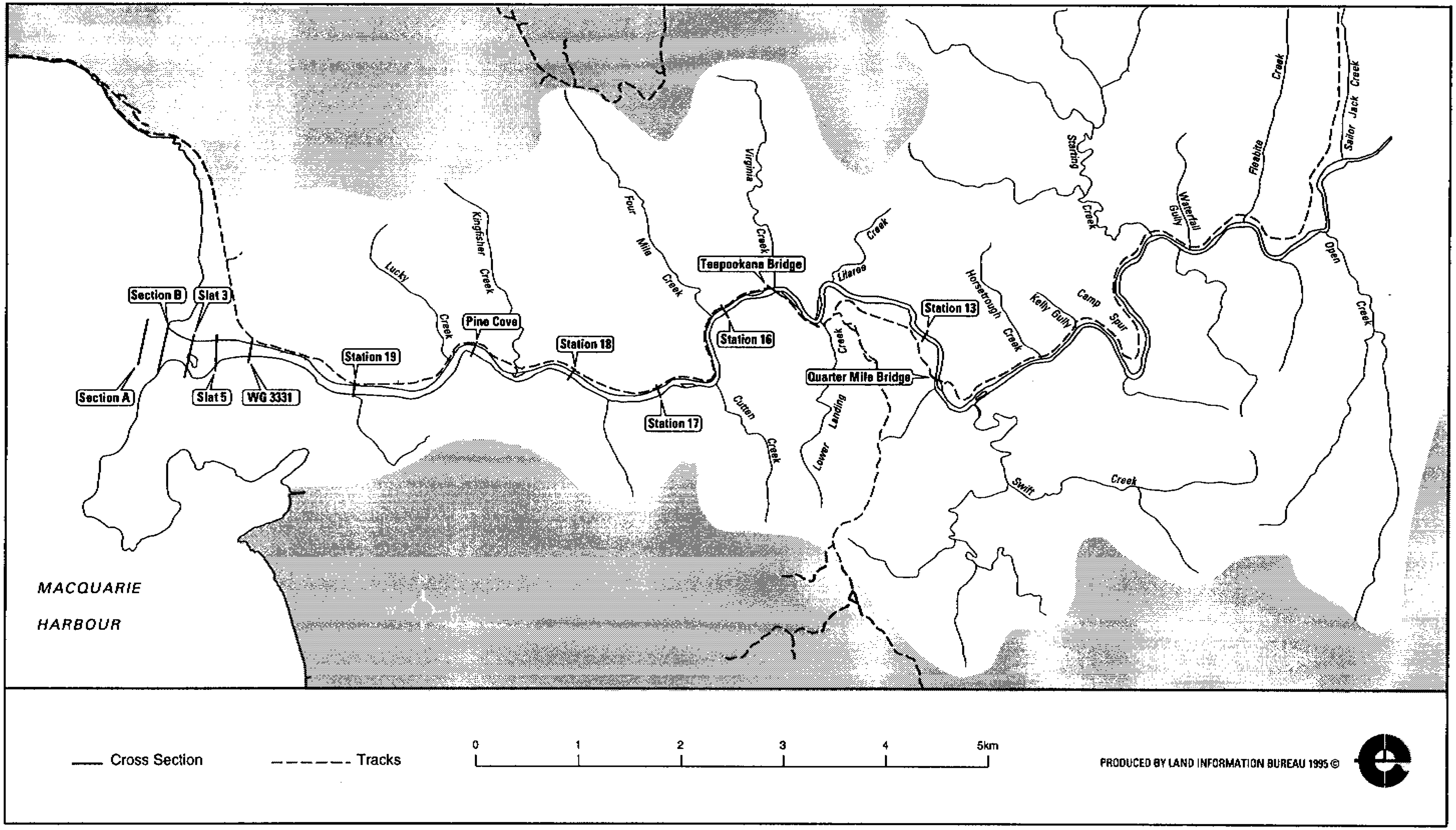


Figure 4.6 Surveyed channel cross-sections



Map 4.4 Locations of HEC drill cores (within river bed and banks) 1986–88



Map 4.5 Locations of survey cross-sections

Table 4.3 HEC geology/geophysics drill core results

Drill Hole No.	Date	Grid Ref.	Bank	Level (m AHD)	Depth below Water Surface (m) Water	Tailings	Slag	Sm.Gravels & Sand	Gravels	Underlying Rock	Gravel Description
Sailor Jack Area (370m upstream of Sailor Jack Creek)											
6186	4/87	758 292	left	17.17							
Cutten Creek Damsite (500m downstream of Cutten Creek)											
7751	2/86	689 269	-	0.20	2	3.5	9.2		28.9		well-rounded to sub-rounded pebbles of quartzitic sandstone and minor poryphory, 25 mm ave, 50 mm max
7752	3/86	690 269	-	0.70	3.45	16.55			28.85		well rounded grey quartzite and sandstone, 20-30 mm ave, 100 mm max
7753	3/86	689 269	-	0.53	1.8	6.65			13.75	tuff over sandstone	rounded to well rounded grey to pink quartzite clasts, ave 50 mm, max 100 mm
7754	4/86	690 269	-	0.34	2	15.65		32.7	45.3	sandstone	well rounded to angular clasts mainly grey sandstone and tuff, max 150 mm, ave 50 mm; boulders of quartzite & tuff to 700mm
7755	5/86	690 269	left	0.86		2.15				tuff	
7756	5/86	690 269	left	3.69		1.5				tuff	
Cutten Crk Sites 3 & 4 (150m upstream of Cutten Creek)											
7853	2/88	695 272	-	0.39	1.4	?			24.7	SiS	flattish rounded pebbles of quartzite to 80 mm
7854	2/88	695 272	-	0.79	1.3	?			23.22	SiS & silty SS	
7855	2/88	695 272	-	0.79	1.63	?			13.25	silty SS	
7856	2/88	694 270	-	0.54	1.8	?			29.7	feldspathic quartzite or silicified tuff	mainly rounded sandstone
7857	2/88	695 270	-	0.54	3	?			22.77	SS	subrounded to well rounded pebbles of mainly quartzite to 50 mm (Camb & Ord)
7858	2/88	695 270	-	0.69	1.95	?			15.55	feldspathic SS	rounded pebbles of fresh to slightly weathered sandstone & siltstone (Camb & Ord)
7859	2/88	695 270	-	0.49	0.85	?			23.4	SiS	
7860	2/88	695 270	-	1.09	0.85	?			15.85	quartzite and quartzitic SS	mainly rounded sandstone & quartzite (Camb & Ord) to 200 mm
7861	2/88	694 270	right	0.56					27.84	quartzitic SS	
7862	3/88	695 272	-	0.49	1.3	?			20.96	calcareous SiS	subrounded to well rounded fresh sandstone (Camb & Ord) to 50 mm
7863	3/88	695 272	-	0.39	1.35	?			9.3	feldspathic SS	
7864	3/88	695 272	-	0.49	1.25	2.4?			19.75	SS	
7865	3/88	694 272	right	5.29					1.9	SiS	
Four Mile Crk Damsite (100m upstream of Four Mile Creek)											
7850	1/88	696 277	-	0.59	1.1	2.6			21.4	silty sandstone over quartzite	pebbles to 30 mm rounded to angular quartzite and quartzitic sandstone
7851	1/88	696 277	-	0.74	1.23	2.35		19	19.23	sandy SiS over SS	well rounded to subangular quartzite and quartzitic sandstone
7852	1/88	696 277	-	0.69	0.47	3.35		19	24	quartzitic SS	well rounded to angular pebbles to 50 mm across of quartzite conflomerate (Cambrian)
Four Mile Crk Damsite (180m upstream of Four Mile Creek)											
7867	4/88	696 277	-	0.30	2.1	3	9		22.85	SS	mainly rounded to subrounded quartzite and sandstone to 30 mm across
7869	5/88	697 278	right	0.73	1.35	3.35	4.05		14.4	SS	rounded to well rounded clasts of quartzite and conglomerate 50 mm max

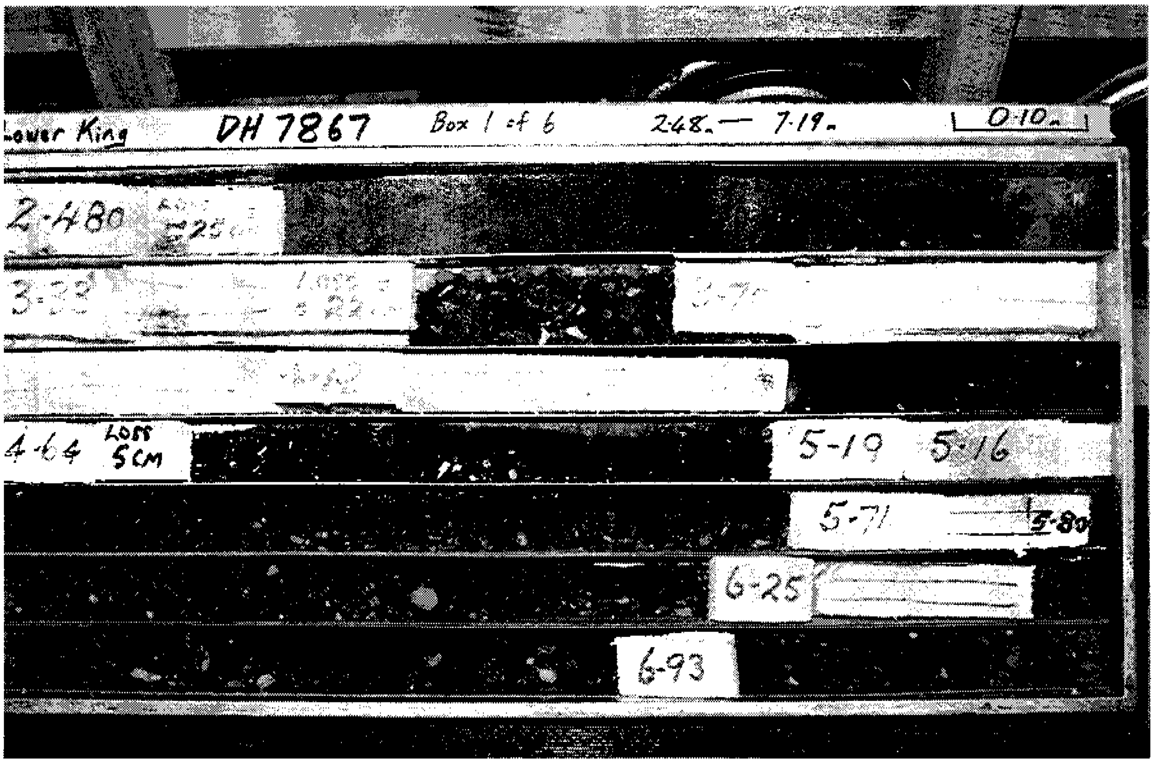


Plate 4.12 HEC drill core 7867 (2.48–7.19m)

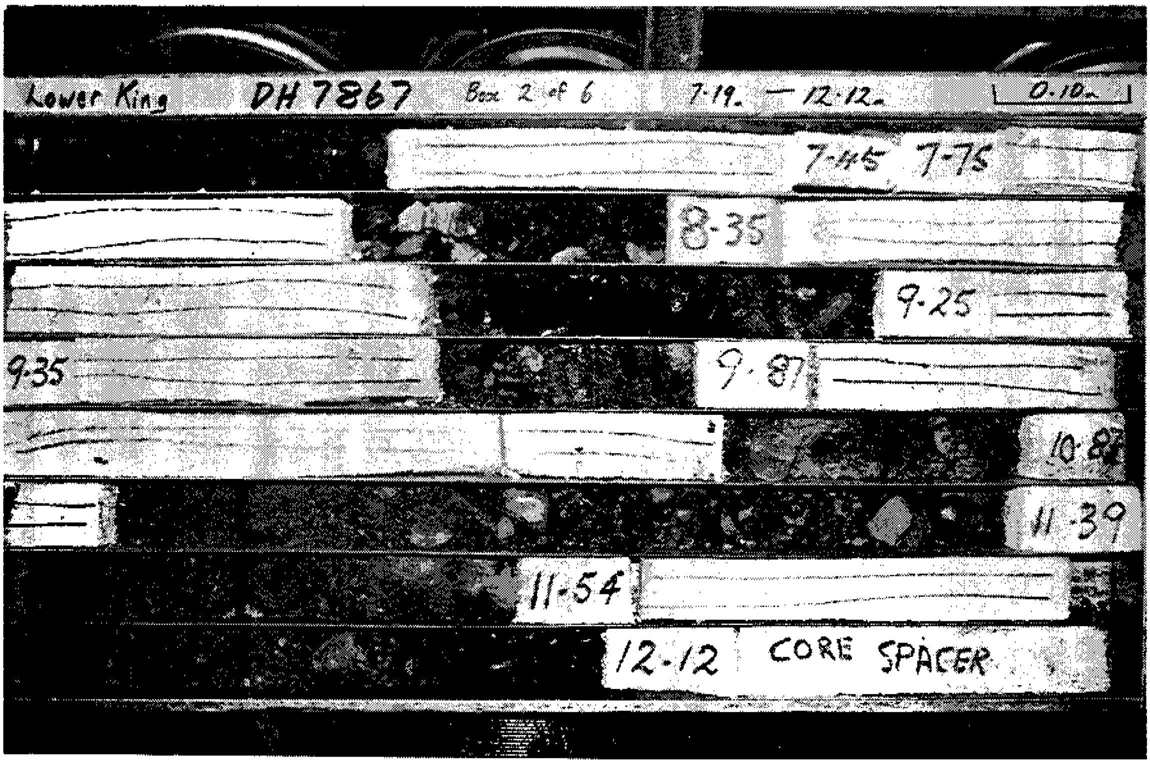


Plate 4.13 HEC drill core 7867 (7.19–12.12m)

4.3.4 Bottom sediment sampling

Some description of the present day river bottom was provided in section 3 as it related to river bottom friction. Much of the upper sections of the King River (between Stations 4 and 9) appear to be natural river gravels, cobbles, boulders and bed rock. The middle section (between Stations 10 and 16) appears to consist of alternating regions of hard pan, gravel bars and spots of soft tailings accumulation. From Station 17 down to the mouth, the bottom appears on the surface to consist almost entirely of mining wastes, with some local exceptions where fine gravel has been deposited. Fine gravels can be found on top of the fine tailings as shown in plate 4.14.

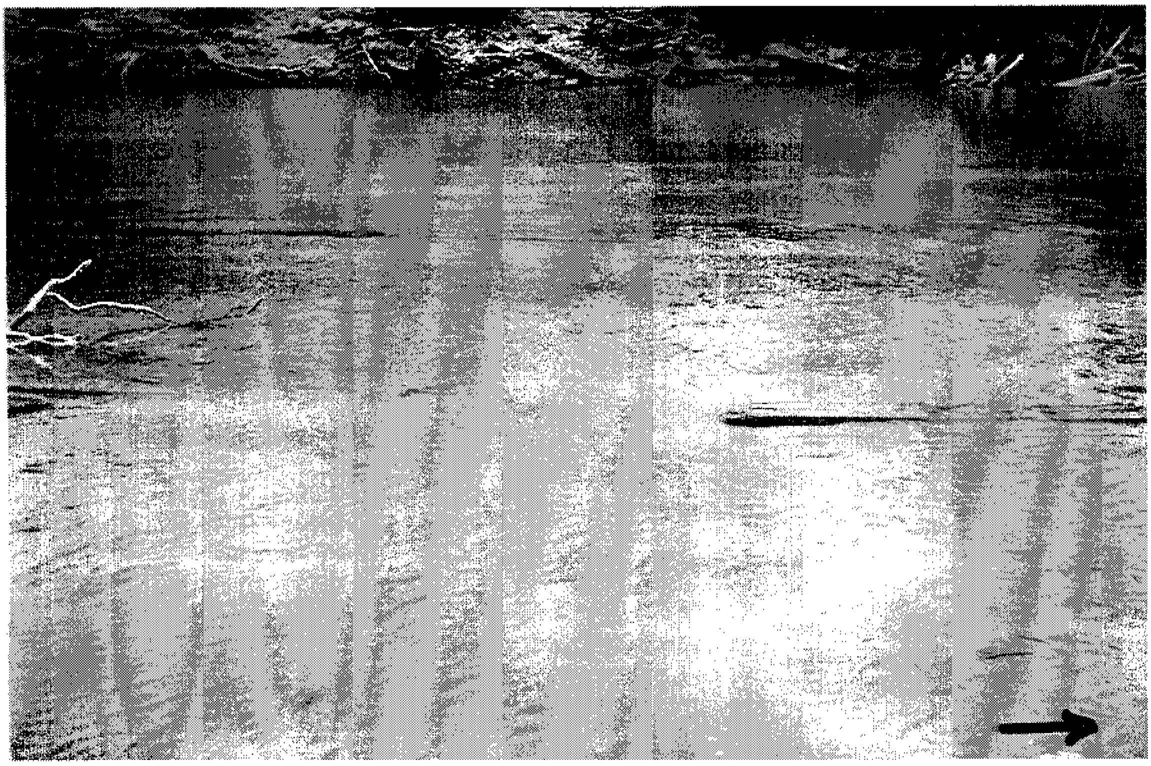


Plate 4.14 Fine gravels on top of tailings

An initial investigation of bottom sediment size found that median grain sizes varied from fine to very coarse sand, approximately 0.16 mm near the mouth of the King River to 1.2 mm in the upstream sections (Station 6). In general, particle size appeared to decrease as one moved downstream, presumably due to a decreasing of the channel gradient, but there was some significant variability to this trend as shown in fig 4.7. These samples were obtained by dragging a heavy cylinder along the bottom, so could have been cutting through dune structures, gravel bars or other local features. Dragging a heavy cylinder would also have created a local turbulence which would have affected the sediment sizes which were retained in the cylinder.

The 'hard pan' in the middle reaches of the river has been analysed and found to be geothite, or iron hydroxides, perhaps precipitating from the underlying mine wastes. The Strahan Forestry Commission, working near Teepookana Bridge during late January 1994, punched through the hard pan near Station 15 with an excavator and was able to reach down 6m and continuously bring up a coarse gravel/mine slag mixture.

During February 1994, there was a period of one week in which the power station was off, causing settling/deposition of tailings upstream at Sailor Jack, and enabling the King River bottom between Sailor Jack and the river mouth to be observed. An investigation of the King

River bottom sediments was conducted during this time. Dune structures were evident at Station 14 and between Teepookana Bridge and the river mouth, approximately 2–2.5m long and 0.20–0.25m high. Samples of bottom sediments were collected from the stations shown on map 4.6 using a wedge-shaped sampler to 40 cm and an auger below that.

Results are shown in table 4.4, and help explain the local variabilities which would have influenced the particle sizes shown in fig 4.7. There were no significant trends in particle size coarsening or fining with distance downstream. There was finer material deposited on the inside bends, for example at sampling sites 14a, 16, 18b and 19a. In the straighter reaches of the river there was a tendency for the sediments to coarsen with depth, such as at sites 17, 18 and 20. The sections with a double channel had finer material on the edges (in the channels) and coarser material in the centre. Armouring was observed in some of the gravel bars, but the particle size distributions from the bottom sediment samples do not show this effect occurring in the sandy bottom sediments.

4.3.5 Storage estimate

From the piecemeal data available on river infill, one can project that the mine wastes (tailings and slag) have filled in the equivalent of 5m of river bottom for much of the river's length. This 5m figure is based on the measured rise in river level (roughly an average of 5m across the 'Pine Cove' Mount Lyell Railway Crossing), the fact that mine wastes have intermixed with natural river gravels up to 9m depth (as found in the HEC's drill cores), and the more than 6m of mine slag found by the Forestry Commission above Teepookana.

Using this 5m figure uniformly up to Station 9, one can project as has been done in table 4.5 that approximately 4.5 million m^3 or 7.3 million tonnes of mining wastes are stored in the King River bottom.

It may be more realistic for the depths of mining wastes to gradually increase towards the river mouth, as is also projected on table 4.5. This version gives a total tonnage of 10 million. These figures assume a specific weight of deposit of the bottom sediments of 1.60, which will be tested using the same technique as for the bank sediments during June 1995. The figure will be an approximation only, as the specific weight of deposit is likely to change with depth, with changing percentages of different sized materials, and with percentage of water trapped with the sediments.

Given the uncertainties in the composition and depths of the river bottom sediments, a coring program is proposed with cores to be collected at the sites shown on map 4.7. These are to be collected using a sonic drill which has a bottom trap to enable recovery of unconsolidated materials.

4.4 King River delta

According to the Strahan historian Harry McDermott, the King River had a natural delta before any mining activities began, probably due to glacial activity in the upper King River catchment. A delta at the King River mouth is very evident on a 1930 British Admiralty chart of Macquarie Harbour. This natural delta has been described as a sequence of small islands like the fingers of a hand, with deep channels in between (McDermott, pers comm). The Gordon River, the other major freshwater input to Macquarie Harbour, has a natural sand bar at its mouth.

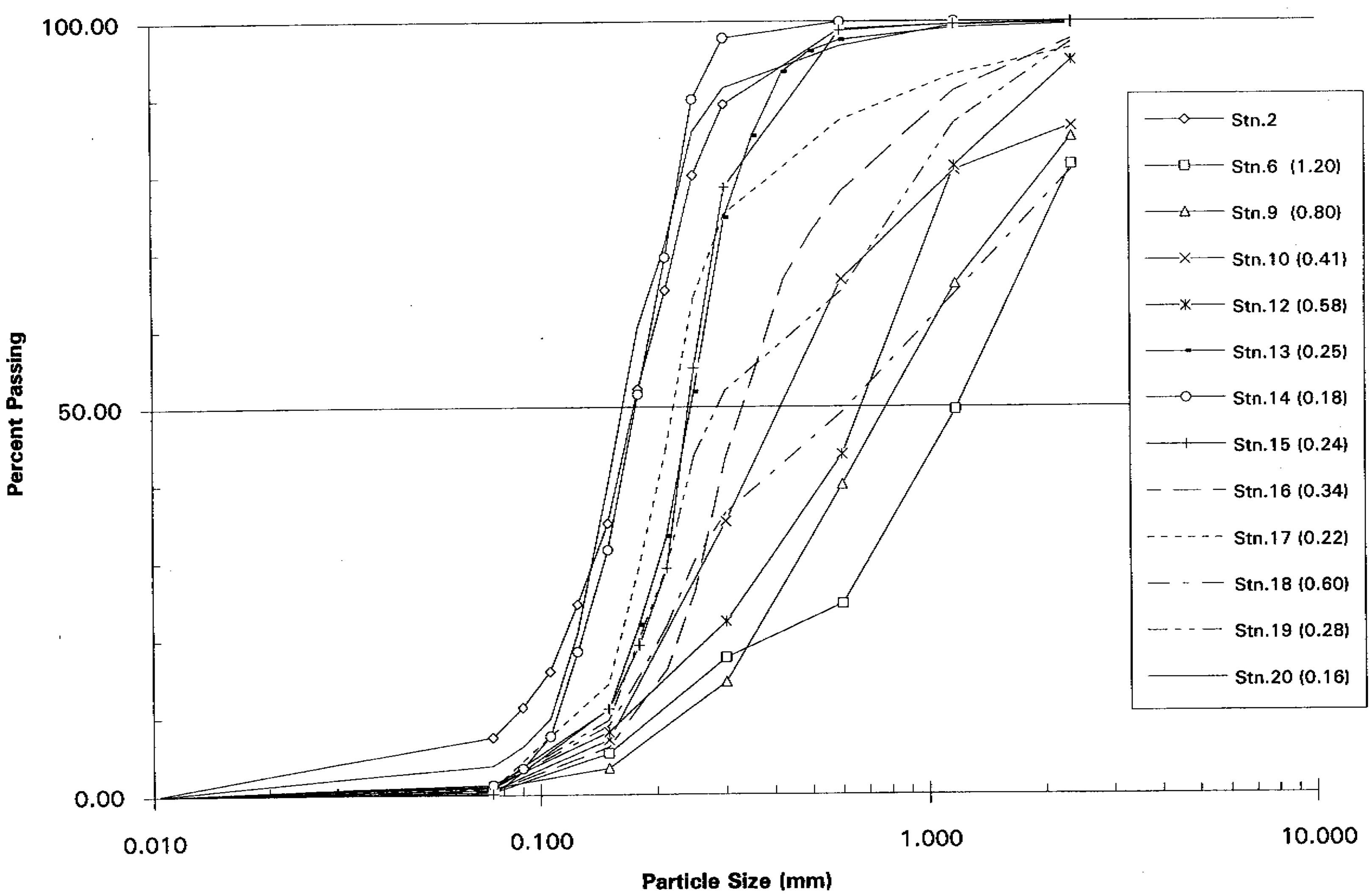
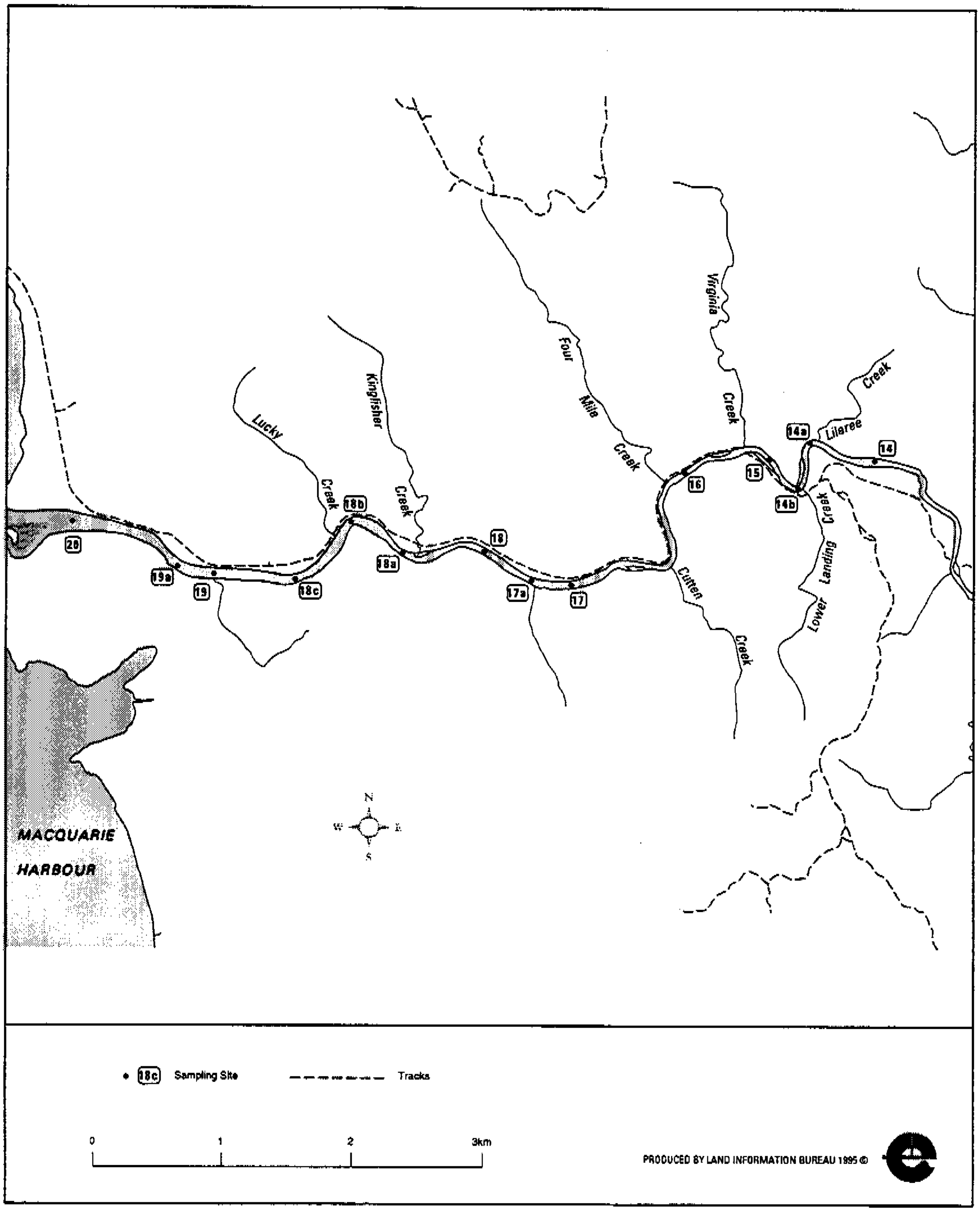
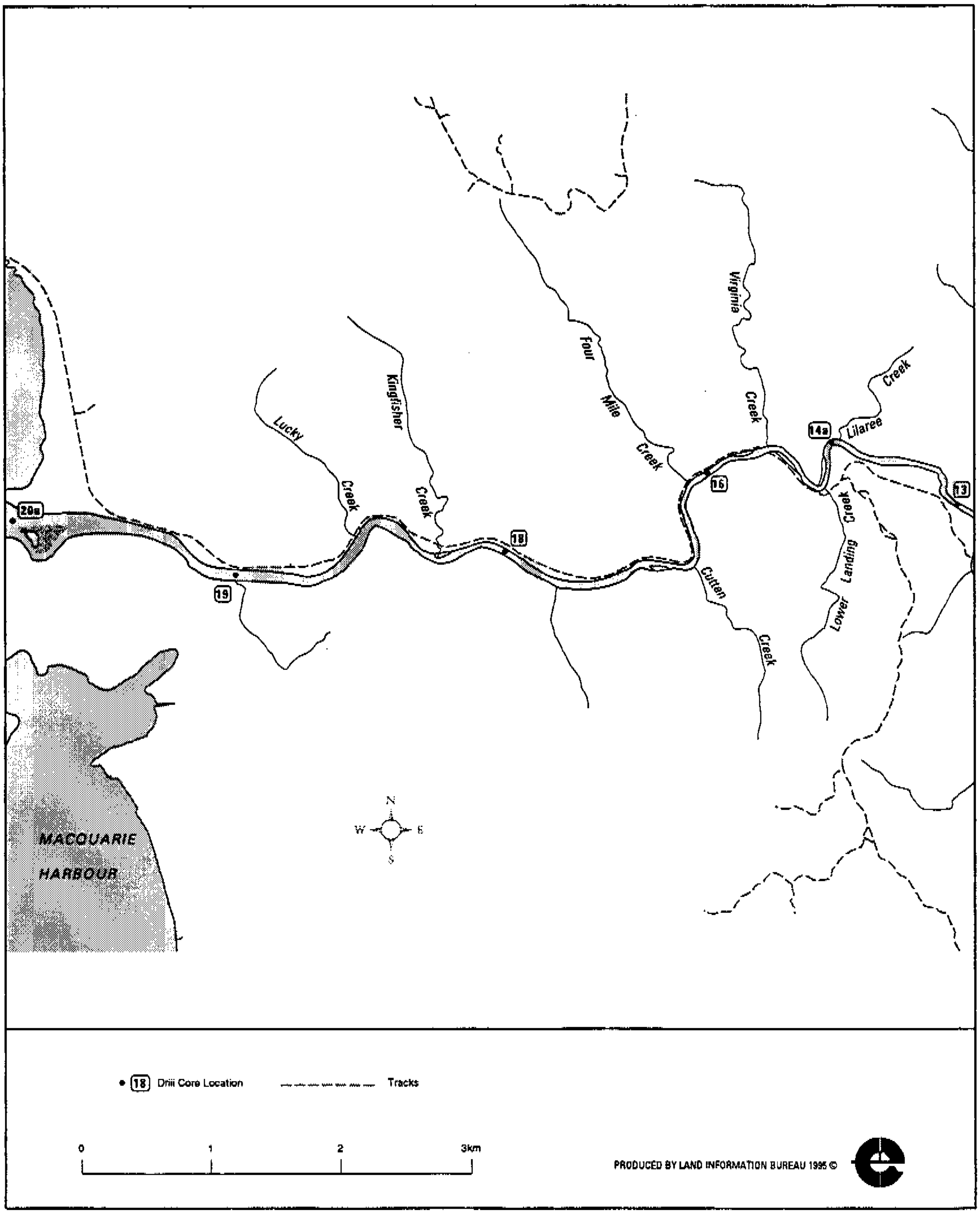


Figure 4.7 King River bottom sediments



Map 4.6 Locations of bottom sediment samples



Map 4.7 Locations of drill cores to be collected July 1995

Table 4.4 King River bottom sediments

Stn. No.	Grid Ref.	Sediment Bank	Distance to Bank	Water Depth	Tailings Depth	Median Particle Size (mm) at Depth 0.0-0.1m	0.15-0.25m	0.4-0.45m	Material Description
14	710278	N-u/s side							Hardpan right across, light gravel coating to 0.10m
14a	706279	M-u/s side							Sandy dunes 2m long x 0.25m high; particle size 0.44mm on back, 1.04mm on crest
14b	704276	L-nose	4m off RB	0.50	1.60	0.220	0.198	0.193	Silt on top of gritty material
			8m off RB	1.00	1.80				Silt on top of gritty material
15	702278	K-centre							Hardpan right across, light gravel coating to 0.10m
16	695277	J-u/s side	5m off LB	1.50	1.00	0.220	0.205	0.190	Tailings only in main channel, hardpan rest of x-section.
17	688268	H-u/s side	10m off RB	0.50	0.40	0.270	0.230	0.540	Silt on top of mine slag
			20m off RB	0.90	0.30	0.340	0.360	0.500	Silt on top of mine slag
17a	684268	H-centre	10m off RB	?	0.50	0.140			Silt on top of hardpan
			25m off RB	?	0.60	0.260			Silt on top of hardpan
18	682270	G-u/s side	30m off RB	0.80	0.50				Silt over coarser more compacted sediments
			Centre			0.240	0.510	1.100	Essentially a gravel bar
			5m off LB	1.20	0.10				Silt over predominantly slag
18a	674271	F-centre	5m off RB	0.15	0.80				Silt over coarser more compacted sediments
			12m off RB	0.60	0.85	0.400	0.920	0.980	Silt over coarser more compacted sediments;
									dunes 2m long x 0.20m high; fine grey dusting over darker fine
									river gravels on back, coarser river gravels on face
			25m off RB	1.20	1.10				Silt over coarser more compacted sediments
18b	671273	E-u/s side	Centre	0.55	>1.8				Silt increasingly compacted
									dunes 3-4m long x 0.30m high
		E-centre	5m off LB	0.70	>4.0				Very soft silt to unknown depth; ran out of auger length!
			10m off LB	1.60	>1.3	0.166	0.245	0.219	Silt to unknown depth; water too deep to auger
		E-d/s side	15m off LB	1.30	0.30				Silt overlying gritty sediments
18c	666268	D-u/s side	Centre						X-section gravelly in centre, channel either side;
									dunes in centre 2.5m long x 0.25m high
		D-centre	30m off RB	1.20	>1.3	0.240	0.660	0.300	Silt becoming increasingly compacted
19	659268	C-u/s side	10m off LB	0.60	0.60	1.020	0.860	1.000	Silt over coarser more compacted sediments
			Centre	0.50	>1.3	0.310	0.330	0.300	Silt over coarser more compacted sediments
			15m off RB	0.90	0.60	0.180	0.210	0.198	Silt over >0.5m fine gravels & slag
19a	656270	C-d/s side	0m off RB	0.00	0.60				Silt over fine gravels & slag
			10m off RB	0.70	>1.8	0.193			Silt becoming increasingly compacted
			15m off RB	1.50	>0.8				Silt becoming increasingly compacted
20	648273	A-u/s side	20m off RB	0.75	0.65	0.170	0.160	0.170	Silt over >0.25m fine gravels & slag
			Centre	0.60	0.40	0.200	0.410	0.800	Silt over >0.25m fine gravels & slag
			30m off LB	0.60	0.40	0.190	0.190	0.320	Silt over >0.20m fine gravels & slag
			3m off both banks						Narrow deeper channel with extremely fine soft silt

Table 4.5 Initial estimate of mining wastes in King River bed

Reach above stn no	Horiz'l dist (m)	Av. channel width (m)	Est. depth of mine waste (m)	Total vol (m^3)	Est. depth of mine waste (m)	Total vol (m^3)
			Version 1		Version 2	
4	0					
5	800					
6	1200	40			0.5	24000
7	500	40			0.5	10000
8	400	40			0.5	8000
9	400	40			1	16000
10	2400	40	5	480000	2.5	240000
11	550	40	5	110000	2.5	55000
12	1100	50	5	275000	5	275000
13	500	50	5	125000	5	125000
14	600	50	5	150000	5	150000
15	1000	50	5	250000	5	250000
16	900	50	5	225000	5	225000
17	1400	50	5	350000	5	350000
18	800	60	5	240000	7.5	360000
19	2600	80	5	1040000	7.5	1560000
20	1100	100	5	550000	10	1100000
mouth	500	300	5	750000	10	1500000
				4545000 m^3		**6248000 m^3**
				x 1.60		**x 1.60**
				= 7.3 million tonnes		**= 10 million tonnes**

Figure 4.8 shows the growth of the delta from aerial plates from 1953, 1974 and 1984 (EGI 1991). The EGI report on the geochemistry of the delta estimated the surface area to have grown from 110 hectares to 170 hectares within that timeframe. The most recent estimate of the surface area is 250 hectares (Mt Lyell 1990).

Since the operation of the King River power station, observational evidence suggests that significant volumes of sediment are being deposited behind the delta in the river, and sediment may be eroding off the front of the delta. The increased depositional rate suggested by the Slat 5 cross-section supports this. There are several sand bars and a large sand island not far upstream from the mouth of the King River which during this study appear to have become more enlarged.

Volumes of sediments in the delta and Macquarie Harbour have been estimated by comparison of the 1930 British Admiralty Chart with a 1993 HEC bathymetric survey, some profiles for which are shown in fig 4.9 (courtesy of Macquarie Harbour Environmental Study). Based on these bathymetric surveys, an estimated 100 million cubic metres of sediments have been deposited on the delta since 1930. Samples to estimate the specific weight of deposit will be collected during June 1995, and the results will be compared with the literature on deltaic sediment deposits.

4.5 Sediment budget

It is interesting to note from the discussion above how small a percentage of the total mine wastes are actually deposited in the river system. Of the 97 million tonnes of tailings and 1.4 million tonnes of slag discharged into the river system over the life of the mine, an estimated 3.4 million tonnes are in the sediment banks and no more than 10 million tonnes are in the river bed, 13.6% of the total. A large percentage of the tailings discharged reside in the delta and the harbour floor. The Macquarie Harbour Environmental Study has good evidence of at least 20 cm of sediments accumulated over a large area of the harbour as far south as Coal Head (Koehnken, pers comm).

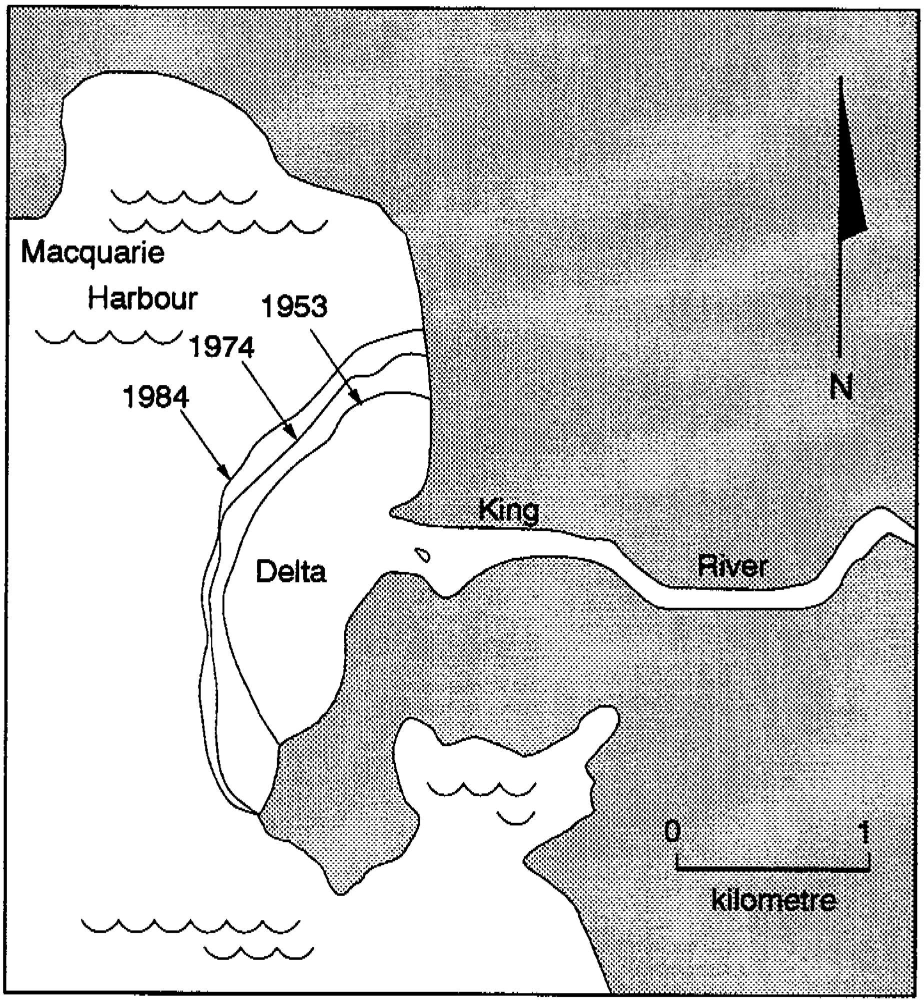


Figure 4.8 Delta outline as seen from aerial photographs

The sedimentation patterns within the Queen and King Rivers show different characteristics in distinct reaches as shown on map 4.8. Within the river system, little to no sediments are in storage in the Queen and King1 Reaches, and only minor bank sediment deposits are in Reach King2. More than 80% of the estimated total bank sediments are stored upstream of Teepookana Bridge in Reach King3, while more than 80% of the estimated total bottom sediments are in storage below Teepookana Bridge in Reach King4.

It is interesting to look at the availability of mine tailings over particular size fractions and compare the total discharged with the estimated total river storage of 13.5 million tonnes. This has been done in fig 4.10.

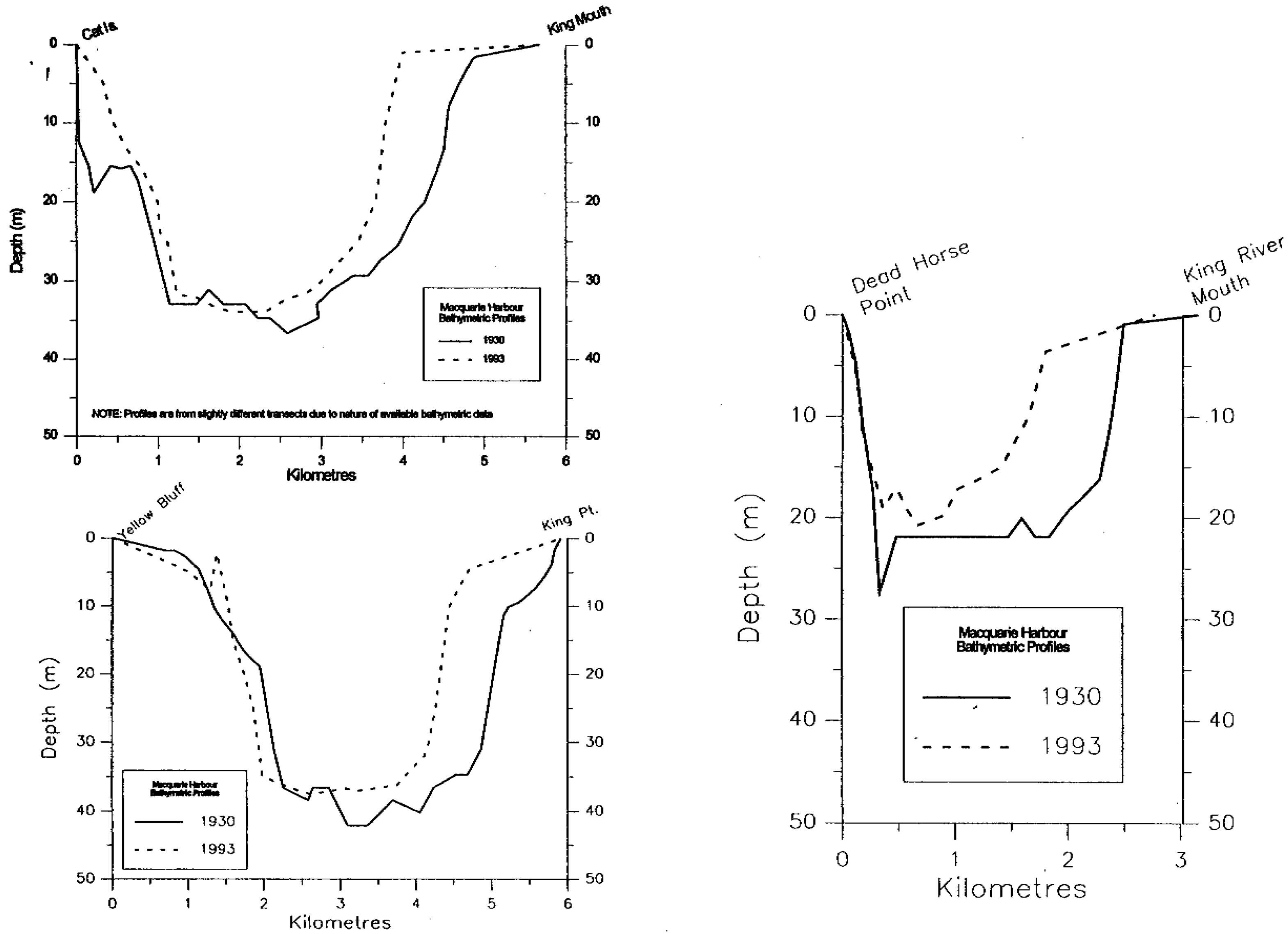


Figure 4.9 Delta profiles

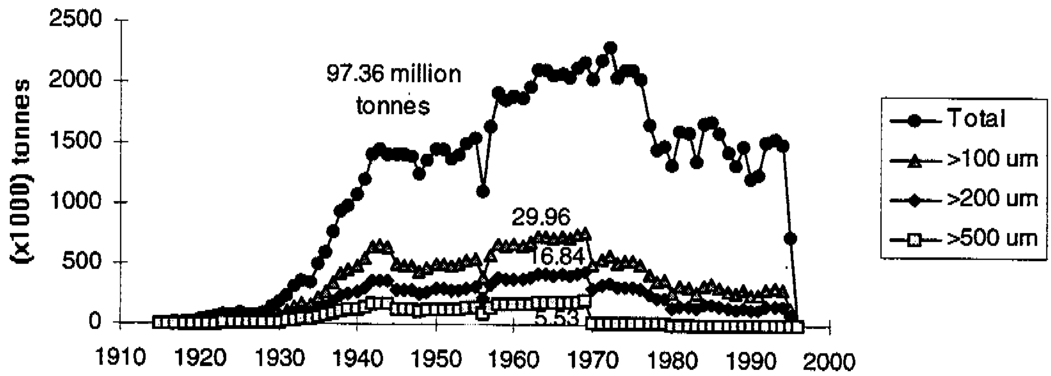


Figure 4.10 Tailings deposition in King River

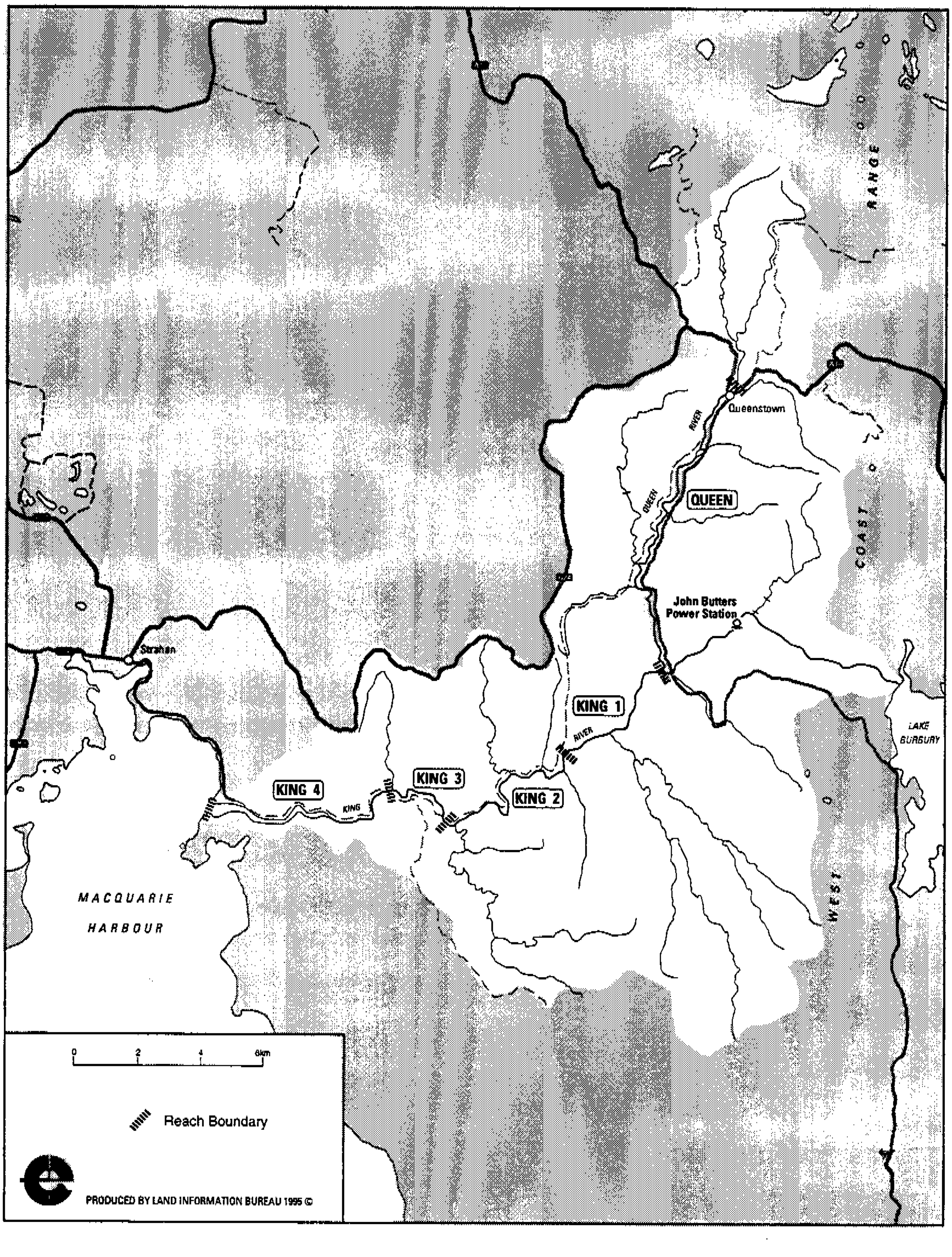
If the fraction of mine tailings greater than 100 µm (0.1 mm) remains in the river system, there should be almost 30 million tonnes in storage. The fraction greater than 200 µm (0.2 mm) gives a total tonnage of 16.84 million tonnes. This is not to say that only coarser than 0.2 mm will be found stored in the King River. In the sediment banks in particular, the sediments have been stranded due to events overtopping the banks, so they do not reflect the sediment carrying capacity of the river. It is highly likely, and consistent with present day observations, that many of the fines deposited in the sediment banks have been winnowed out by wind action. The bank sediments in Reach King4 were inundated more regularly than those in Reach King3, particularly before the power station came on line, so the deposited sediments were not protected from fluvial action and were subsequently resuspended and moved along.

The size of the material in the river bed should be a more accurate reflection of the river's capacity to transport it. Most of the mine tailings pass right through the river system as washload, with only the coarsest fraction being deposited and travelling as bed load. There would have been less and less deposition as bed load as the milling process improved and tailings became generally finer, as suggested by fig 4.10.

The tendency for some sampling stations in the King River bed to have a coarser particle size with depth may reflect the higher sediment carrying capacity of the river prior to the power station coming on line. Since the power station came on line, the flows have not been large enough to flush through the coarser tailings which were likely to have been transported under previous large floods. However, the power station will have increased the frequency of flows which are capable of carrying sediments of a relatively finer grain size, and as these are no longer being replenished by the mine they should clear through the system reasonably quickly. Fining up sequences could also be associated with sediment deposition due to events; without knowing more about the sediment characteristics at depths greater than have been sampled to date, it is difficult to interpret more fully.

4.6 Summary

This section described the storages of mine wastes in the river system. Little to no sediments are stored in the Queen River or in the steep section of the King River just below the confluence with the Queen. An estimated 3.44 million tonnes are stored in the sediment banks in the last 8 km of the King River above its mouth, and 80% of these are within a 3 km reach between Teepookana and Quarter Mile Bridges (5–8 km above the river mouth). Copper levels have proven to be an effective tracer to differentiate mine-derived sediments from the original sediment banks. A levee configuration of the original banks is hypothesised, with growth of the banks occurring due to successively overtopping flow levels from the peak flow events (prior to the power station's operations).



Map 4.8 Study reach names

A maximum of 10 million tonnes of mine wastes are estimated to be stored in the river bottom, 80% of which are between Teepookana Bridge and the river mouth, causing a rise in bed elevation of as much as 9m at the Pine Cove railway crossing (about 2 km above the river mouth). The river bed itself is an old valley infill with gravels as deep as 45m below sea level, and the mine wastes in the top 9–10m are a mixture of tailings, slag and fine river gravels. The vast majority of sediments, about 100 million m^3, are stored in the delta and harbour.

A major aim of this study is to predict future transport of sediments within the King River. Now that the mine has closed and there is no longer the steady external supply of sediments to the river system, the river will have an excess sediment carrying capacity and may start scouring out the sediments stored in the river banks and bed. Results from this section have shown the types of material in storage in the river system which will be available to be transported if those deposits erode or scour now that the mine has closed. The next section looks at the stability of the sediment banks in the river system and their potential to supply sediments to the river system.

5 Bank stability

5.1 Erosion processes

5.1.1 Pre-mine closure

Erosion processes have always been very evident on the King River sediment banks, even while the mine was discharging its tailings. Plates 5.1 to 5.4 show some of the erosion processes evident on the King River sediment banks prior to the mine closing. Typical erosion processes include rilling, tunnelling, undercutting, bank slump and collapse, rainfall and wind erosion. Rilling was most often seen in the most recently deposited fresh grey tailings. Tunnelling was often seen mid-way up the banks, and appeared to be due to water infiltrating down to a resistant layer and then running off out of the bank face. Undercutting appeared to be a later stage of the tunnelling phenomenon, and was most often seen under more resistant crusty layers on the bank face. Bank slump and collapse were seen in many forms, and could results from severe undercutting, collapsed tree stumps pulling out sections of the bank, the weight of fresh grey tailings on the bank face after a major storm event, or tension cracks developing in the thick wedges of fresh tailings behind local promontories. Most of these processes were seen on the larger sediment banks in reach King3, although the bank slump and collapse were also seen in reach King4.

Rainfall and wind erosion were evident on the bank surfaces rather than the bank faces. The bank surfaces are generally extremely exposed due to the lack of vegetative cover. Wind erosion was evident from the occurrence of surface ripples on some of the bank surfaces, and the relatively coarser nature of the surface sands suggesting a winnowing out of the fines by wind action. One or two of the large sediment banks showed evidence of formation of dunes and migration back away from the river towards the adjacent forest.

Liquefaction of the fresh grey tailings and sediment-rich run-off were evident due to draw-down effects as the water level rapidly dropped with the turning off of the power station, as shown in plate 5.5. Because the banks were constantly replenished with fresh grey tailings, erosion was generally restricted to the recently deposited material, and the old oxidised tailings were protected by the cover of fine, wet, relatively cohesive material.

A survey of bank erosion features was conducted during July 1994, and the results are being drawn up on a map to provide a baseline for changes post-mine closure.

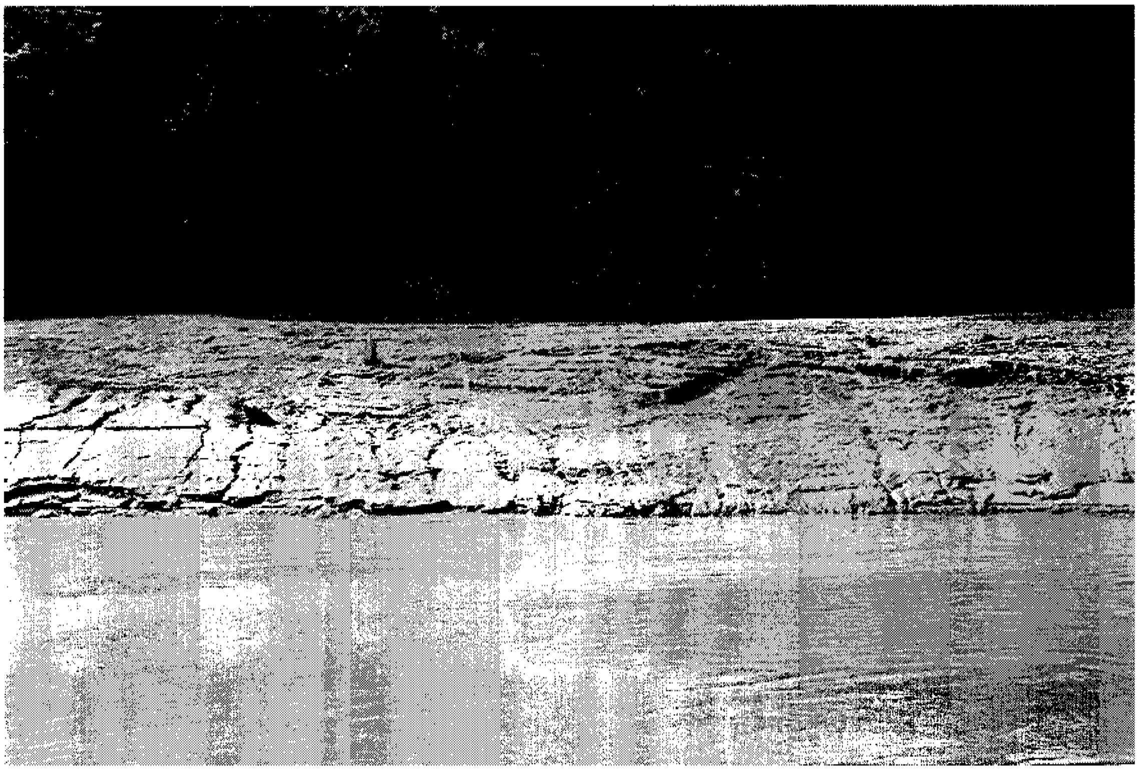


Plate 5.1 Rilling

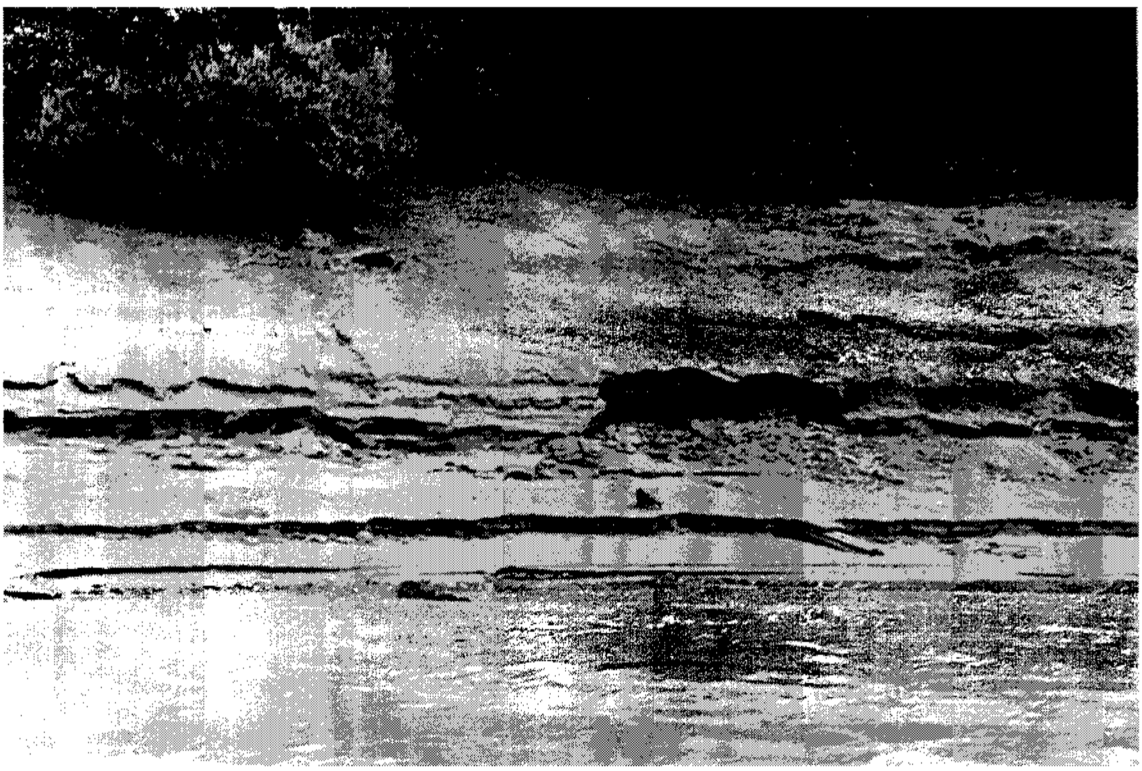


Plate 5.2 Tunnel erosion

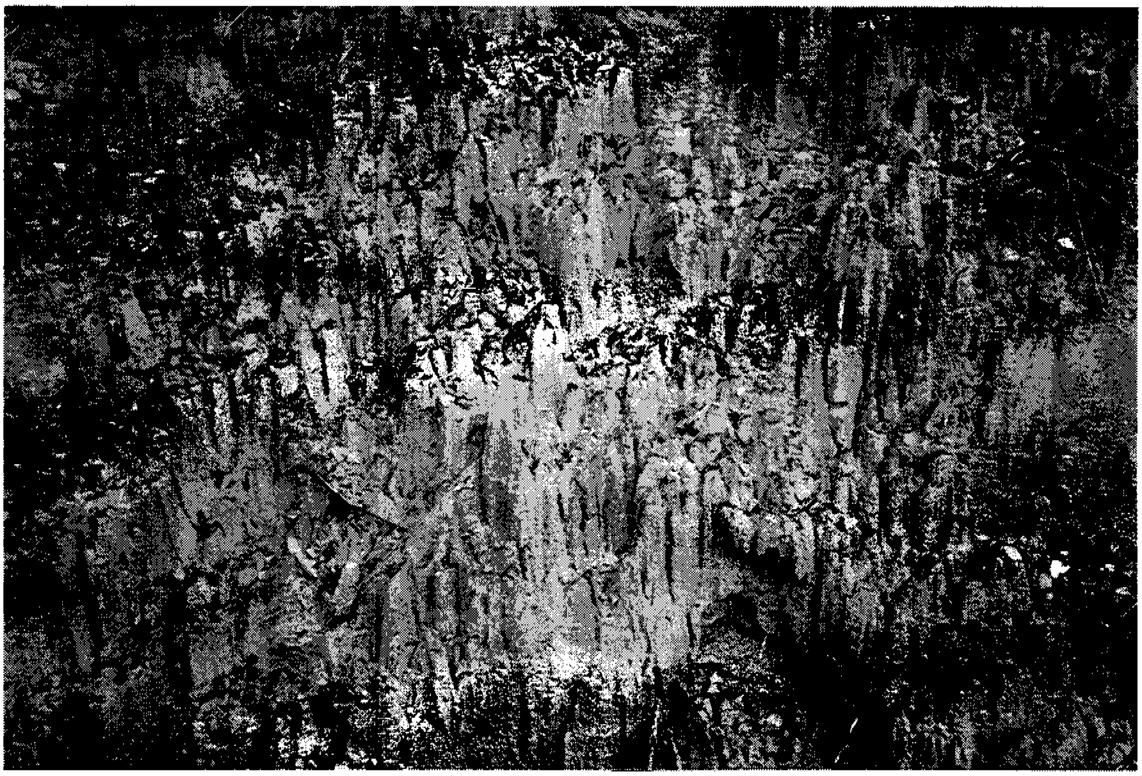


Plate 5.3 Rainsplash erosion

Plate 5.4 Bank collapse

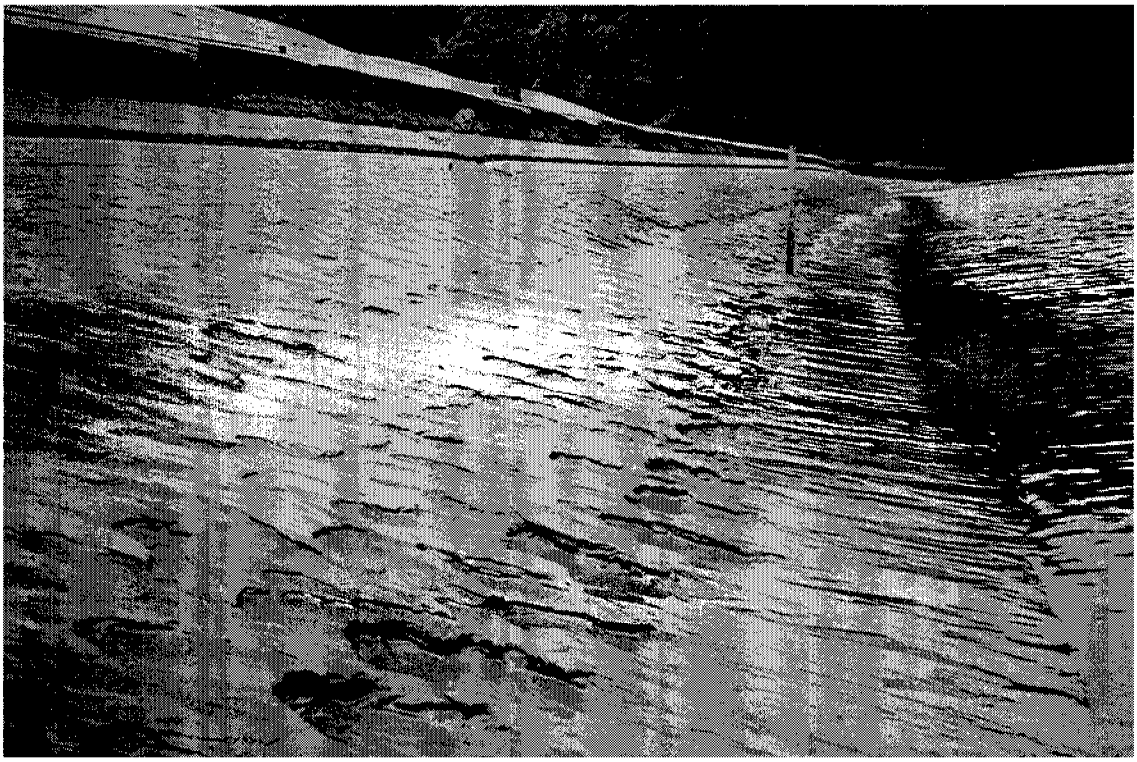


Plate 5.5 Power station draw-down effects

Table 5.1 provides a brief summary of surface and erosional characteristics associated with individual banks. Refer to map 4.1 for the locations of these banks. Note that not all of the banks have been listed, but only those most prominent. As can be seen, some banks were more exposed to wind processes than others, and the relative locations of the banks within the river system had a strong influence on what types of erosion were evident.

5.1.2 Post-mine closure

Erosion features evident in the sediment bank post-mine closure are similar to those pre-mine closure, but somewhat exacerbated due to the lack of protective cover from the fresh grey tailings. The river seems to have quickly cleared much of the fresh grey tailings, exposing more of the orange/red, sandy oxidised tailings to the forces of erosion. Relative to pre-mine closure, erosion is more visible on the river banks because it is not regularly covered up as it was before. There is also considerable 're-adjustment' going on in the banks, because as the more cohesive fresh tailings dry and fall down off the banks, they pull old bank material down with them exposing fresh surfaces.

A survey of bank erosion features post-mine closure was conducted during July 1995, to enable comparison with the pre-mine closure survey and to provide a baseline for future surveys.

5.2 Monitoring of sediment banks

Erosion pins and scour chains have been used to monitor changes in bank form, as well as visual and photographic surveys. Erosion pins have been established on varying scales to measure erosional processes. Star pickets along the bank profile have been hammered into the banks to measure changes in large scale bank form (plate 5.6). On a smaller scale, grids of 6" nails have been monitored to assess rainsplash and wind erosion effects, and the degree of expansion/ contraction in the banks (plate 5.7). Scour chains have been placed next to the erosion pins show how dynamic scour and deposition processes on the river banks have been (plate 5.8).

Table 5.1 Summary of major sediment bank features

Sed. Bank	Bank Description	Erosional Features	Surface Features	Overtopping Flow (m3/s)
A	Flat, narrow	Featureless	Fine grained	200
C	Flat, wide	Featureless	Medium grained	264
D	Flat, wide	Minor undercutting & collapse	Fine grained, "soft"	217
F	Flat, wide	Some minor collapse	Extremely crusty, some pebbles	350
H	Slightly higher, very wide	Regular bank collapse on faces	Fine to medium grained	545
L	Prominent point bar, high	Major collapse d/s of nose	Some mature veg'n, coarse sand d'stream	561
M	Prominent point bar, high, narrow	Stable undercutting u/s, depos'n d/s	D/s end very exposed to wind, coarse grained	606
N	Long straight, high, wide	Rilling	Very exposed to wind, no veg'n, coarse grained	580
O	Narrow, high	Minor collapse	Very sheltered, fine grained, surrounding veg'n	503
Q	Very large, wide, long	Occasional very minor collapse	U/s vegetated, d/s end exposed to wind, some dunes	593
R	Very large, wide, long	Tension cracks in fresh tailings	Exposed to wind, coarse grained	585

The erosion pins will only show the net change over the period of time between measurements, and so the processes of scour and deposition may have been far more extreme in the intervening period than is reflected in the erosion pin measurements. The scour chains were inserted to provide some indication of this. The scour chain shown in plate 5.8 is inserted inside the metal tube with the cone end of the chain at the bottom, and the two pins stop the chain from sliding out when the tube is stood erect. The tube and chain are hammered vertically into the bank, and about half a metre of chain left exposed lying horizontally on the bank surface. The depth of burial of the horizontal section of chain after a certain time interval indicates the maximum depth of scour that had occurred during that time interval.

Locations of erosion pins, 6" nails and scour chains are shown on map 5.1. The majority of them are in reach King3, where the majority of the bank sediment storages are located. Locations in King3 were selected to try to represent a range of bank positions relative to the flow, eg straight bank sections (Bank N), the upstream and downstream side of a tight point bar (Bank Ma and Mb), etc.

Table 5.2 shows the results from measurements of the erosion pins since they were established in February 1994. All pins were numbered so that '1' was in the water, and '5' the highest up on the bank. An 'X' on table 5.2 indicates the pin was lost or fallen over so no reading was possible; a '+' sign indicates deposition and a '-' indicates scour.

Banks N, Mb and H showed very little change. The pins on these banks are located on relatively straight sections of river. The largest changes were at banks R and Q, where all but the highest erosion pins showed active scour and deposition. Bank R was the most dramatic, where thick wedges of fresh tailings would deposit in the eddy zone downstream of Quarter Mile Bridge. Erosion pin R3, which originally had 1m exposed, got totally buried after five months, but was re-exposed again as thick slices of fresh tailings broke off and gradually worked their way back to R3. Bank Mb, located downstream of a point bar, also showed fairly large scour and deposition at the middle and lower pins. Banks F, D and C showed active scour and deposition at the lowest erosion pins only.

The results showed that the processes of scour and deposition were at times quite dynamic. At location Q2 there was a maximum scour of 32 cm between July and November 1994, even though the adjacent erosion pin showed a net change over that time of only 3 cm scour.

Figure 5.1 graphically illustrates the processes of scour and deposition measured in the banks. AHD heights of the erosion pins have not yet been obtained. Once these are available, the changing profiles of the sediment banks over time will be plotted.

The measurements for the 6" nails still need to be collated and interpreted. Briefly, the grid patterns did not greatly change at any of the banks, and the greatest changes seemed to be on those banks most susceptible to wind activity. Ripples due to wind action were very evident on exposed banks (eg Banks R, Q and N), and the surface bank material was noticeably coarser presumably due to the wind winnowing out most of the fines. The 6" nails were always very clean on these banks with the coarser wind-blown surface sediments (see plate 5.7). Banks on which the erosion pins were more protected (eg Banks O, H) showed no such surface ripples, and the 6" nails were often dirty with finer material clinging to the sides, presumably from rainsplash effects.

The banks in reach King4 are somewhat of a curiosity, because of inconsistencies in their surface features. No 6" nails were able to be established on Bank F because of the extensive hard crusting on this bank. However, Banks H, D and C upstream and downstream of Bank F posed no such problem. The Bank D 6" nails were regularly coated with soft fine material which looked very much like the pins were inundated (plate 5.9). The Bank C 6" nails were cleaner and the surface material sandier. Banks D and C showed occasional sections of crusting, but nothing so complete as Bank F. Also curious was the occurrence of pebbles in the Bank F crust, almost as if they had been transported as bed load when the bank was inundated.

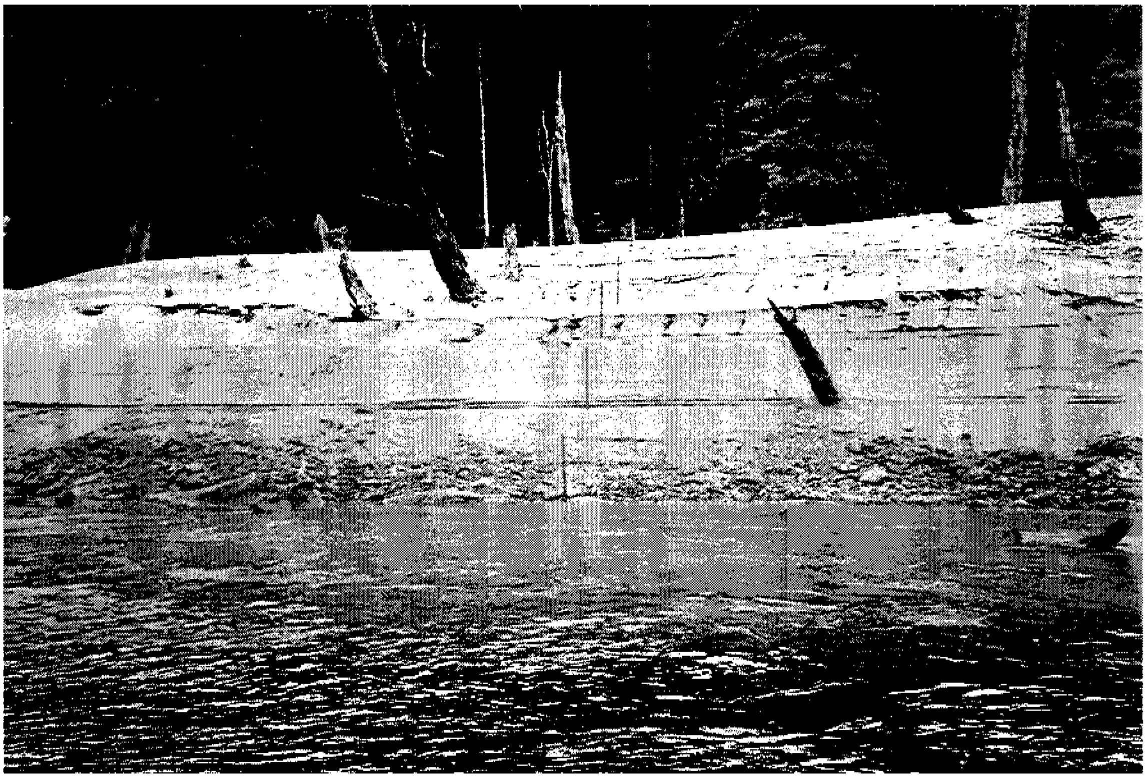


Plate 5.6 Erosion pins

Plate 5.7 6" nails

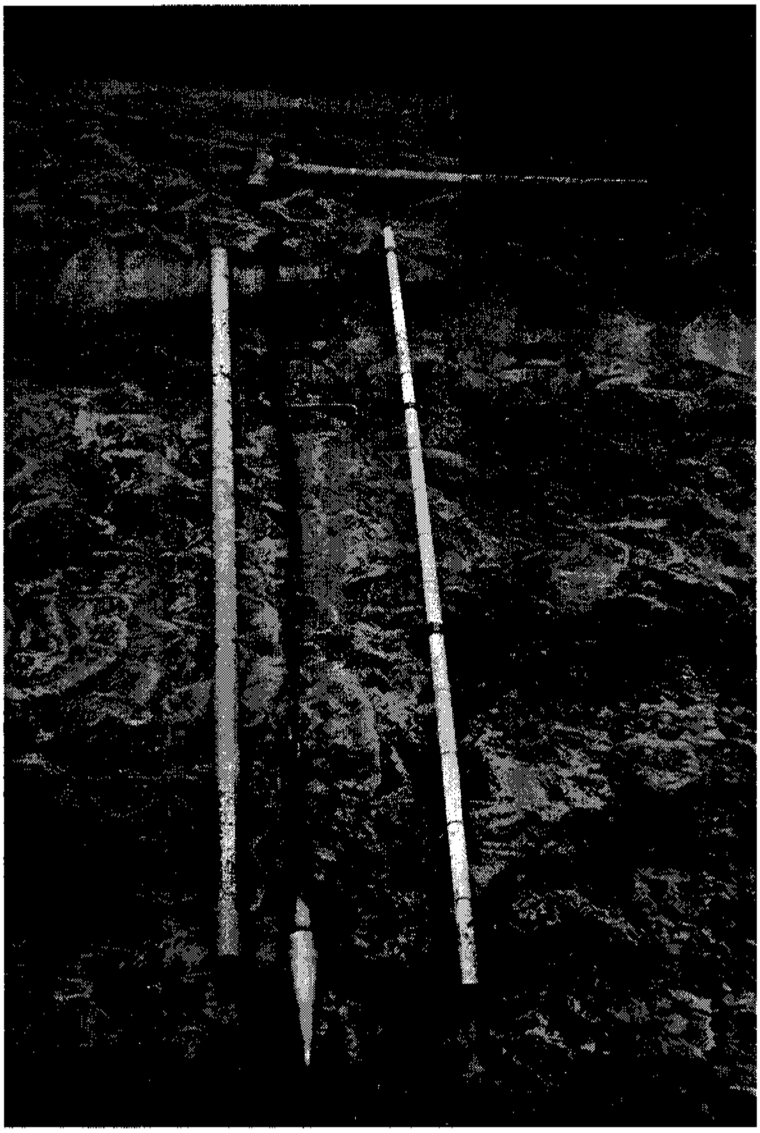
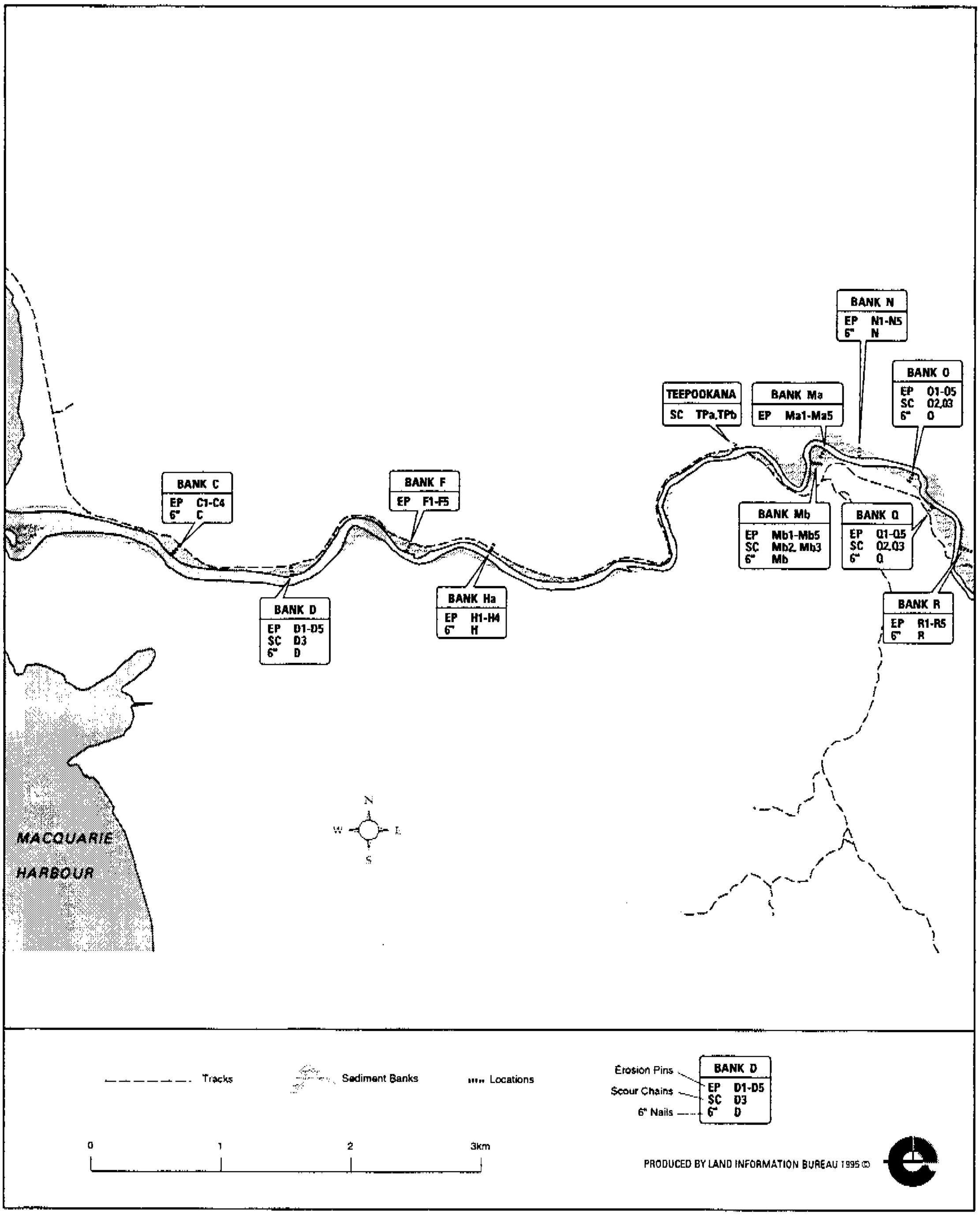


Plate 5.8 Scour chains

Plate 5.9 Bank D 6" nails



Map 5.1 Locations of erosion pins, scour chains and 6" nails

Table 5.2 Erosion pin and scour chain results

	DATE	3/06/94 112 days	12/07/94 39 days	21/11/94 132 days		8/02/95 79 days		12/04/95 63 days	
LABEL	LOCATION	erosion pin	erosion pin	erosion pin	scour chain	erosion pin	scour chain	erosion pin	scour chain
R1		+0.50	-0.23	-0.29		-0.05		X	
R2	Reach 3	+0.39	-0.14	+0.05		-0.44		+0.14	
R3	below RR	+0.40	+0.87	-0.29		-0.92		+0.27	
R4	bridge	-0.02	-0.18	+0.08		+0.07		-0.01	
R5		-0.02	+0.01	-0.05		-0.03		0.00	
Q1		+0.12	-0.12	-0.17		-0.12		+0.19	
Q2	Reach 3	X	+0.05	-0.03	-0.32	+0.25	+0.00	-0.50	X
Q3	d/strm of	+0.03	+0.10	-0.06	-0.18	-0.04	-0.06	-0.01	0.00
Q4	bend	+0.04	+0.10	-0.11		-0.02		+0.06	
Q5		-0.01	+0.02	-0.03		-0.01		+0.01	
N1		+0.01	-0.02	+0.02		0.00		-0.04	
N2	Reach 3	-0.04	+0.05	+0.04		-0.02		-0.02	
N3	d/strm of	0.00	-0.02	-0.02		0.00		+0.01	
N4	gentle	0.00	-0.04	+0.03		0.00		-0.01	
N5	bend	+0.14	-0.01	0.00		0.00		+0.01	
O1		+0.02	-0.09	-0.02		+0.09		-0.01	
O2	Reach 3	+0.05	-0.15	+0.28	-0.03	-0.20	-0.11	+0.10	-0.11
O3	middle of	-0.04	-0.22	+0.30	+0.04	+0.01	-0.01	+0.04	+0.02
O4	straight	-0.01	+0.02	+0.01		+0.01		-0.01	
O5	channel	+0.01	0.00	0.00		0.00		0.00	
Ma1		-0.03	+0.02	-0.05		+0.05		-0.04	
Ma2	Reach 3	+0.03	-0.04	-0.01		+0.17		-0.22	
Ma3	u/strm of	0.00	0.00	+0.01		0.00		-0.02	
Ma4	point bar	+0.01	-0.02	+0.02		0.00		0.00	
Ma5		-0.01	+0.01	-0.01		0.00		0.00	
Mb1		+0.53	-0.46	+0.04		+0.06		0.00	
Mb2	Reach 3	+0.45	-0.50	-0.11	-0.13	-0.10	-0.11	+0.12	+0.01
Mb3	d/strm of	+0.71	-0.59	-0.23	-0.30	-0.10	-0.18	+0.18	0.00
Mb4	point bar	0.00	+0.01	0.00		0.00		-0.01	
Mb5		-0.01	-0.01	-0.01		-0.01		0.00	
H1		+0.01	-0.04	+0.09		-0.02		-0.05	
H2	Reach 4	-0.03	+0.05	-0.10		-0.01		+0.03	
H3	straight	-0.03	-0.03	+0.06		-0.02		+0.03	
H4	channel	+0.01	+0.03	-0.03		-0.01		+0.01	
F1		-0.21	+0.30	-0.33		+0.11		-0.15	
F2	Reach 4	+0.03	0.00	-0.20		0.00		-0.04	
F3	nose of	-0.01	+0.02	-0.02		0.00		0.00	
F4	gentle bend	0.00	+0.03	-0.02		-0.09		+0.02	
F5		-0.01	0.00	-0.01		-0.02		+0.01	
D1		-0.36	X	X		-0.03		-0.08	
D2	Reach 4	+0.09	-0.12	+0.40		-0.26	-0.31	+0.09	-0.03
D3	nose of	+0.25	-0.21	+0.15	+0.13	-0.05		-0.12	
D4	gentle bend	-0.04	+0.01	+0.04		-0.02		+0.02	
D5		-0.01	+0.04	0.00		0.01		-0.01	
C1		-0.13	+0.01	+0.05		+0.17		-0.21	
C2	Reach 4	+0.34	-0.31	+0.15		-0.31		+0.22	
C3	nose of	-0.03	+0.03	-0.18		X		+0.03	
C4	gentle bend	0.00	+0.01	0.00		0.00		0.00	

X' = missing data
'+' = net deposition
'-' = net scour

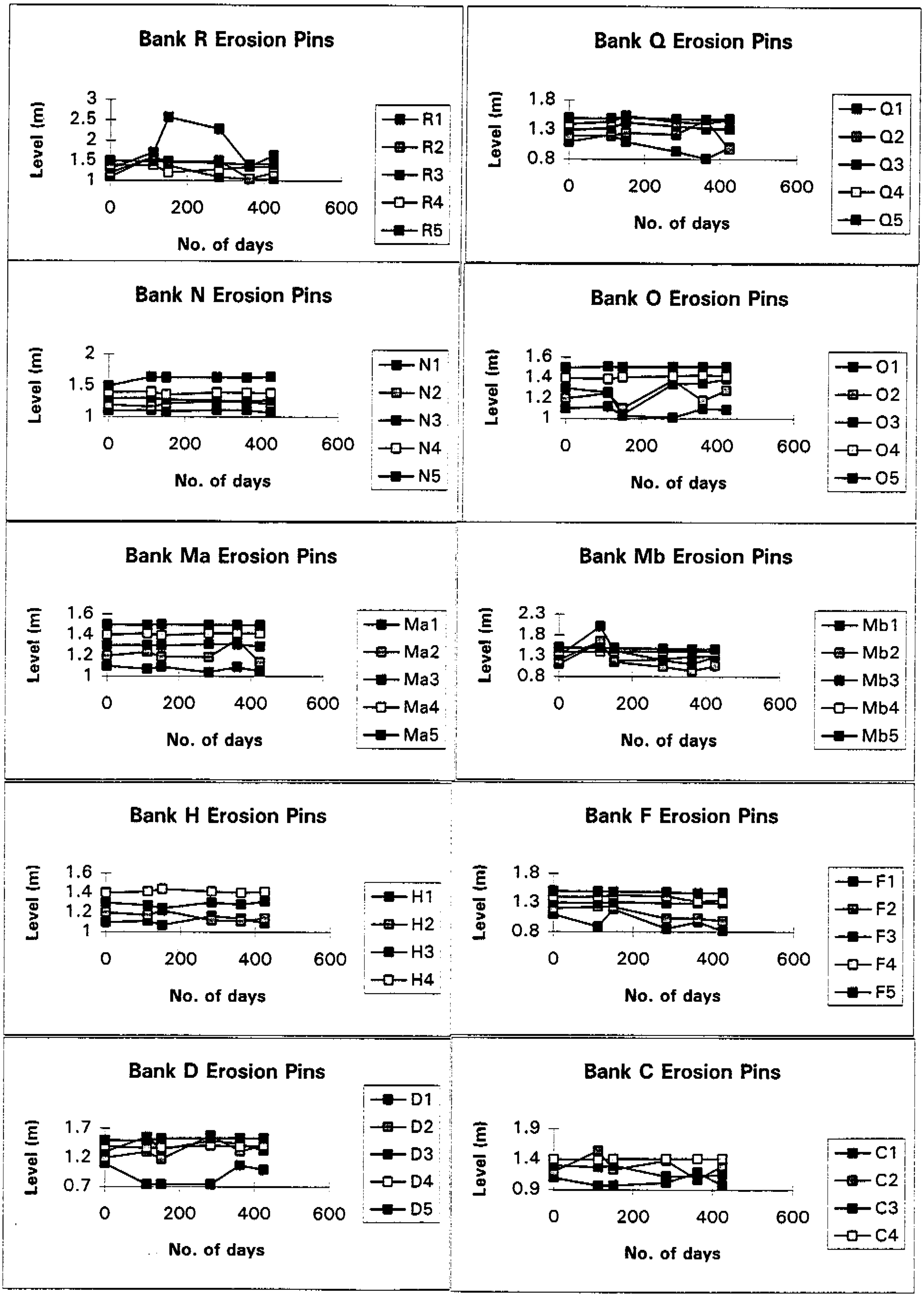


Figure 5.1 Erosion pin results

5.3 Future bank stability

It is difficult to say at this stage how extensive the bank erosion will be. Numerous factors can contribute to bank stability, such as sediment characteristics, flow and hydrograph characteristics, storm characteristics, time intervals between events, antecedent soil moisture conditions, and the incidence of frost (Hooke 1979). Of the observed erosion processes in the sediment banks, slumping appears to be the most significant in terms of potential bank retreat. In general, banks with a higher clay content are more resistant to slumping than coarser, sandier material. The rate of rise of discharge and the antecedent precipitation were found to be extremely important variables in Hooke's (1979) study. Twidale (1964) found that wet bank slumping was an important process causing banks to retreat, and that the soaking of a bank due to a high flood leaves the banks highly unstable.

The surface material in the banks is highly erodible, being predominantly sands, but underlying material has varying amounts of silts and clays. The results from the augering survey support the hypothesis that the mine tailings in the King River are draped over natural banks formed under conditions prior to discharge of tailings. The results in Appendix 2 show that the original banks are largely sandy clay loams with 30–40% silts and clays. One hypothesis is that bank erosion will not extend into the natural sediment banks because of their more cohesive character. This is debatable considering the lack of vegetative cover compared to original conditions, and considering the rapid and frequent fluctuations in river level due to power station operations.

The driving forces that cause bank failure are directly proportional to specific weight, bank height and slope angle, whereas bank stability increases with increasing cohesion and angle of friction (Osman & Thorne 1988). It has been seen on the King River banks that the fresh tailings provided a cohesive cover which is no longer available. Also the removal of the fresh tailings wedges on the lower slopes of the banks by the frequent rise and fall of the river level will cause a steepening of the banks which will reduce their stability.

Bank failure is closely linked to the processes of bed degradation and lateral erosion. Lateral erosion and bed degradation increase the bank height and causes it to steepen which reduces the stability of the bank (Borah & Bordoloi 1989). Banks collapse when the critical bank height for mass failure is obtained; this leads to rapid widening and input of disturbed bank material into the channel, but then is followed by bank stability in its new configuration (Thorne et al 1983). So the main question with the King River is, given the present susceptibility to bank retreat (non-cohesive surface material, loss of cohesive protective layer, likely steepening of bank angle), how far back from the present waters edge will erosion proceed? It may be that the hydraulic geometry provides the limiting factor to bank retreat; ie channel width proceeds to the point where stream energy is too low to cause subsequent erosion.

A hypothesis to be explored is that that the river 'faces' of the banks will actively erode in the short term, but the banks will not erode extensively back the 50–100m away from the river. This is because of the relatively resistant character of the original levee bank deposits, and because flows are no longer as high as they were in the past. Sediments in the high banks in reach King3 will no longer be inundated and should be well protected from erosive forces.

If this hypothesis is correct for most banks, it is assumed that the faces of the banks will erode back from the river much farther than the original levee bank. Based on this assumption, table 5.3 provides an estimate of bank erosion volumes. For this table it is conservatively assumed that no sediment bank will erode more than 5m back from the waters edge; banks above Quarter Mile Bridge (25m wide or less) will not erode further back than

2m. This is a modification to table 4.1 which was a preliminary estimate of total sediment storage in the river banks. Using this rather crude approach, a maximum of 218,000 tonnes of sediment is anticipated to be readily erodible from the sediment banks over the next few years.

Table 5.3 Estimates of extent of erosion of sediment banks

Reach above stn. no	Av. bank height (m)	Av. tailings depth (m)	Bank width eroding (m)	Total bank length (m)	Sed.bank vol (m^3)
4					
5					
6	5	1.25	2	450	1125
7	5	1.25	1	500	625
8	6	1.50	1	600	900
9	5	1.25	1	250	313
10	5	1.25	2	2820	7050
11	5	1.25	2	1100	2750
12	6	4.50	5	1070	24075
13	5	3.75	5	850	15938
14	5	3.75	5	850	15938
15	4.5	3.38	5	1300	21938
16	3.75	2.81	5	680	9563
17	3.25	2.44	5	1500	18281
18	2	1.00	5	100	500
19	1.8	0.90	5	2850	12825
20	0.8	0.40	5	2200	4400
river mouth	0.5	0.25	5	1000	1250
Total =				**17120 km**	**136219 m3**
					x 1.60
				= 217950	**Tonnes**

The overlay of the 1898 Mount Lyell railway survey with the present day 1:25,000 map may indicate if and where the banks have extended. If any extension is evident, it is expected to be on the downstream sides of the existing banks. The overlay may show which sections of banks do not have the protective levee banks and so are most susceptible to bank retreat.

5.4 Summary

This section has presented some monitoring data on bank stability and discussed some of the processes most dominant on the King River banks. Erosion pins and scour chains have illustrated how dynamic the processes of scour and deposition were on the sediment banks within the range of water level changes due to power station activities. Erosion processes of rilling, tunnelling, slumping and bank collapse are increasingly evident as the fresh grey tailings out of the mill are no longer constantly replenishing the bank surfaces. The likely extent of erosion of the sediment banks now that the mine is closed is unknown, but if the hypothesised levee configuration of the original banks is correct and most of the bank sediments are stored behind the original levees and out of reach of the now reduced peak flows, then a probably maximum bank erosion is in the order of 218,000 tonnes of sediment, over an unknown period of years.

Because of the interrelated nature of bank stability, lateral erosion and bed degradation, it is necessary to consider future bank stability in conjunction with sediment transport occurring within the river channel. The following sections, sections 6 and 7, review the results of suspended and bed load transport monitoring conducted pre- and post-mine closure.

6 Suspended sediment transport

6.1 Sampling methods

Map 6.1 shows the locations of suspended sediment monitoring equipment used on the King River and just outside the river in Macquarie Harbour.

Automatic water samplers have been installed at stations 2, 4, 13 and 18 (see plate 6.1). These locations were chosen to represent the Queen River (below the tailings source), and the upper, middle and lower reaches of the King River below its confluence with the Queen.

Turbidity meters have been established alongside the automatic water samplers at Stations 13 and 18 (plate 6.2), and also outside the river at three locations (there is a third turbidity meter in Macquarie Harbour at Sophia Point, not shown on this map). The turbidity meters in the King River also record temperature and conductivity, and the Harbour turbidity meters also record temperature. The meters have been continuously recording since December 1993. Turbidity levels have been correlated to suspended sediment concentrations through the development of suspended sediment-turbidity rating curves, as shown later in this section.

Plate 6.3 shows a depth-integrated water sampler which has been used to test the representability of the automatic water samplers and other point samples as compared to the sediment load passing through a river cross-section at any given time.

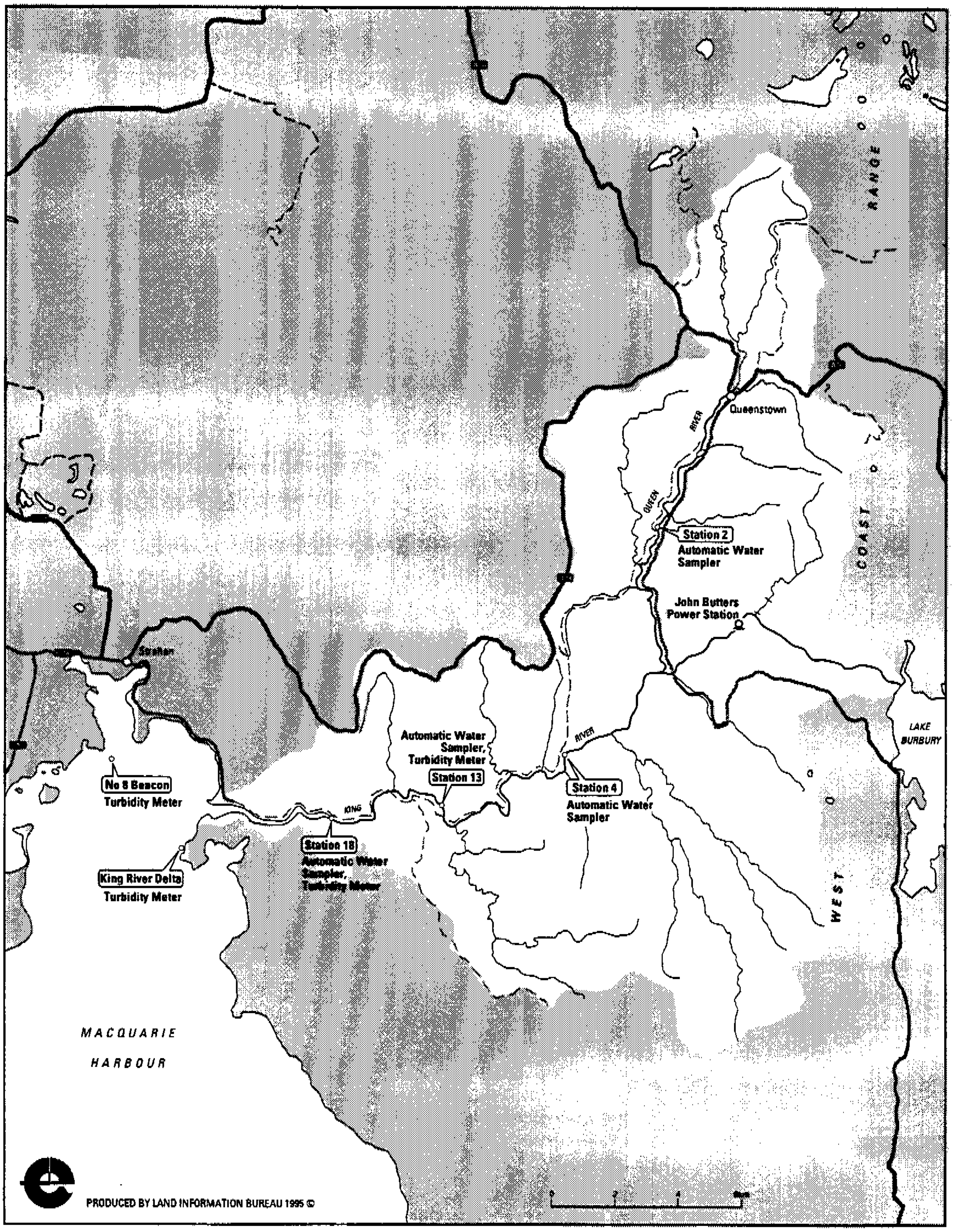
Table 6.1 provides a summary of the suspended sediment sampling exercises which have been and are planned to be conducted for this King River sediment study. In addition to representability tests of the auto samplers, other exercises which have been conducted have looked at variability in sediment concentrations using different sampling techniques, variability across a channel cross-section, variability along length of river, and time series looking at changes in concentrations at different locations over time under various conditions of flow. Results are summarised in the following sections, which have been split to discuss pre- and post-mine closure separately.

6.2 Results pre-mine closure

6.2.1 Representability

Table 6.2 gives an idea of the variability in suspended sediment concentrations with different measuring techniques and locations from some exercises conducted pre-mine closure.

In the comparison of sampling techniques, concentrations in the Queen River varied +/- 3.6% around the mean concentration for five consecutive depth-integrated samples, and varied between 3.6–4.9% above and below the mean for grab samples taken with different size sample bottles.



Map 6.1 Locations of suspended sediment monitoring equipment

Plate 6.1 Automatic water sampler station housing

Plate 6.2 Turbidity meter alongside auto sampler intake

Plate 6.3 Floc as seen under the scanning electron microscope

Table 6.1 Summary of suspended sediment sampling exercises

Purpose of Exercise	Stn. No.	Date	Details	Flow (m3/s)	Conditions	Mill Down
Comparison of sampling techniques	2	06/06/93	5 x 310ml, 5 x 70 ml, 5 x DI			
	5	06/10/93	5 x 310ml, 5 x 70 ml	90	rising	
	5	06/11/93	5 x 310ml, 5 x 70 ml	85	maybe dropping	X
	15	06/11/93	5 x 310ml, 5 x 70 ml, 5 x DI	85	maybe dropping	X
	13	24/6/93	10 x 250ml, 10 x DI	25.1	maybe dropping	X
	18	23/6/93	10 x 250ml, 10 x DI	36.5	maybe dropping	
Decanting of DI samples into smaller bottles	2	06/06/93	2 x DI into 310ml, 2 x DI into 70ml			
	15	06/11/93	2 x DI into 310ml, 2 x DI into 70ml	85	maybe dropping	X
Variability across x-section	2	06/06/93	R, L and C DI samples, R(M), L(M), C(B) & C(T)			
	15	06/11/93	R, L and 4xC DI samples	85	maybe dropping	
	13	24/6/93	2 x DI for each R,CR,C,CL,L column	25.1	maybe dropping	X
	18	23/6/93	2 x DI for each R,CR,C,CL,L column	36.5	maybe dropping	
Variability along length of river	20-9	06/07/93	310ml samples, moving upstream	4	maybe rising	
	4-20	06/10/93	310ml samples, moving downstream	90	rising	
	20-4	06/10/93	310ml samples, moving upstream	90	rising	
	20-4	06/11/93	310ml samples, moving upstream	85	maybe dropping	X
	4-20	06/11/93	310ml samples, moving downstream	85	maybe dropping	X
	6-20	22/6/93	250ml samples, moving downstream .	12	maybe dropping	
	4-20	28/9/93	330ml samples, moving downstream	98	steady	
	3	02/09/94	330ml sample (700m below confluence)	5	steady	
	15-5	10/2/94	330ml samples, moving downstream	7	steady	
Variability with depth	13	24/6/93	C column, every 20 cm	25.1	maybe dropping	X
	18	11/4/95	Point samples at 2 columns, every 0.2m	78	dropping	X
	2,4,13,18	29/5-2/6/95	Point samples at 2 columns, every 0.2m			X
Tributary contributions	Virginia Crk.	06/11/93	310ml sample			
	Swift Crk.		310ml sample			
Purpose of Exercise	**Stn. No.**	**Date**	**Details**	**Flow (m3/s)**	**Mill Shutdown Periods**	
Time series	2	18-29/6/93	1/day at 1400		19/6, 20/6, 24/6	
		30/6-23/7/93	1/day at 1400		5/7, 20/7	
		23/7-1/8/93	1/day at 1400		30/7	
		30/3-5/4/95	4-hourly samples		X	
	4	12-29/6/93	1/day at 0900	3-148	19/6, 20/6, 24/6	
		30/6-17/7/93	1/day at 0900	3-86	5/7	
		22/7-17/8/93	1/day at 0900	4-90	30/7, 6/8	
		3-12/9/93	1/day at 0900	3-103	4/9, 5/9, 10/9	
		28-29/9/93	auto samples, variable interval	3-98		
	13	24/6/93	Grab sample every 15 minutes	20	X	
		21/6/94	Hourly auto samples	80		
		20-21/11/94	Hourly auto samples	3-90		
		21-23/11/94	3-hourly auto samples	3-8		
		23-24/11/94	Half-hourly auto samples	3-90	24/9	
		8-12/1/95	6-hourly auto samples	2-70	X	
		23-24/1/95	Hourly auto samples	2-70	X	
		26-27/4/95	Variable interval	?	X	
	18	21/6/94	Hourly auto samples	80		
		20-21/11/94	Hourly auto samples	3-90		
		21-23/11/94	3-hourly auto samples	3-8		
		23-24/11/94	Half-hourly auto samples	3-90	24/11	
		9-12/1/95	4-hourly auto samples	2-70	X	
		16-17/1/95	Hourly auto samples	2-70	X	
		23-24/1/95	Hourly auto samples	2-70	X	
"72-hour" exercises	4,13,18	15-18/2/94	Hourly auto samples	5-76	14-15/2, 17/2 (2 hours)	
	2,4,13,18	27/6-1/7/94	Hourly auto samples	4-100		
	2,4,13,18	19-23/6/95	Hourly auto samples		X	
Event sampling	18	?				
	2	14/5/94	15 minute intervals, 5 auto samples			
	13	18/05/94	15 minute intervals, 24 auto samples	134		
	4	18/05/94	10 minute intervals, 24 auto samples	134		
	13	?	Hourly auto samples			
Purpose of Exercise	**Stn. No.**	**Date**	**Details**	**Flow (m3/s)**	**Gauged?**	**Mill Down**
Representability of auto sampler	2	23/7/93	DI and point samples at six columns; concurrent auto samples every 15 mins	8.7	Yes	
		Week of 29/5-2/6/95		?	Planned	X
	4	21/7/93	DI and point (T,M,B) at five columns; concurrent auto samples every 15 mins	76.18	Yes	
		29/9/93	2 x DI for each R,CR,C,CL,L column concurrent auto samples every 10 mins	98	No	
		Week of 29/5-2/6/95		About 8	Planned	X
	13	26/1/94	DI and point (T,M,B) at five columns; concurrent auto samples every 15 mins	71.17	Yes	
		06/01/94	6 x DI samples across x-section concurrent auto samples every 10 mins	9.72	Yes	
		02/07/95	Point samples (T,M,B) at 7 columns; concurrent auto samples every 15 mins	70.08	Yes	X
		10/4/95	Point samples (T,M,B) at 6 columns; concurrent auto samples every 10 mins	83.6	Yes	X
		Week of 29/5-2/6/95		About 8	Planned	X
		Week of 19-23/6/95		About 6	Planned	X
	18	25/1/94	DI and point (T,M,B) at five columns; concurrent auto samples every 15 mins	54.86	Yes	
		16/2/94	2 x DI for each R,CR,C,CL,L column concurrent auto samples every hour	76	No	
		06/02/94	9 x DI samples across x-section concurrent auto samples every 10 mins	8.14	Yes	
		02/09/95	Point samples (T,M,B) at 7 columns; concurrent auto samples every 15 mins	69.4	Yes	X
		11/4/95	Point samples (T,M,B) at 8 columns; concurrent auto samples every 10 mins 6 x DI samples across x-section	78.5	Yes	X
		12/4/95	Point samples (T,M,B) at 7 columns; concurrent auto samples every 10 mins	8.74	Yes	X
		Week of 29/5-2/6/95		About 8	Planned	X
		Week of 19-23/6/95		About 6	Planned	X

* refers to post-mine closure

X refers to periods when the mill was not discharging tailings

Table 6.2 Variability in suspended sediment concentrations

COMPARISON OF SAMPLING TECHNIQUES

STN.		Depth-integrated bottles						310-ml bottles						70-ml bottles						
NO.	DATE	No.	Min	Max	Mean	SD	%	No.	Min	Max	Mean	SD	%	No.	Min	Max	Mean	SD	%	
2	6/6/93	5	15895	17207	16564	597	3.6	5	16242	17637	17129	621	3.6	5	13439	15144	14277	694	4.9	
5	10/6/93							5	1138	1544	1362	199	14.6	5	703	1484	1166	298	25.5	
5	11/6/93							5	256	312	290	21	7.2	5	134	256	211	46	21.9	* no tailings
15	11/6/93	5	306	337	315	13	4.1	5	129	318	218	76	34.7	5	55	192	151	57	37.8	* no tailings

STN.		Depth-integrated bottles						250-ml bottles					
NO.	DATE	No.	Min	Max	Mean	SD	%	No.	Min	Max	Mean	SD	%
13	24/6/93	10	580	628	604	16	2.7	10	579	642	611	20	3.3
18	23/6/93	10	661	813	733	42	5.8	10	693	782	738	32	4.3

DECANTING OF DEPTH-INTEGRATED INTO SMALLER BOTTLES

STN.		310-ml bottles						70-ml bottles						
NO.	DATE	No.	Min	Max	Mean	SD	%	No.	Min	Max	Mean	SD	%	
2	6/6/93	2	17378	17545	17461	118	0.7	2	14301	15638	14969	945	6.3	
15	11/6/93	2	316	368	342	37	10.9	2	207	300	253	66	26.0	* no tailings

VARIABILITY ACROSS CROSS-SECTION

STN.		Depth-integrated bottles						
NO.	DATE	No.	Min	Max	Mean	SD	%	
2	6/6/93	7	11320	14174	12548	1050	8.4	
15	11/6/93	6	194	3336	271	53	19.5	* no tailings
13	24/6/93	10	541	590	565	15	2.6	
18	23/6/93	10	511	789	674	76	11.2	

VARIABILITY WITH DEPTH

STN.		Depth-integrated bottles					
NO.	DATE	No.	Min	Max	Mean	SD	%
13	24/6/93	7	560	627	598	20	3.4

SD - Standard Deviation

% - Percentage difference between standard deviation and the mean

Samples taken with 310mL bottles (wide mouth) had a slightly higher mean concentration than the depth-integrated bottles, whereas the 70mL (narrow mouth) bottle gave a lower concentration. In general the 70mL bottles were consistently under-representative compared to the 310mL bottles, and had a much higher standard deviation. The percentage difference between the mean 310mL results and depth-integrated results was 3.4% which is consistent with the variability amongst the individual type of sample.

The depth-integrated suspended sediment concentrations for King River samples as compared to 250-mL narrow-mouthed bottles were incredibly similar in their mean concentrations and narrow range of results.

When depth-integrated samples were decanted into smaller sample bottles, the 310mL bottles tended to have slightly higher sample concentrations than the original depth-integrated sample, and the 70mL bottles slightly lower. This trend was similar under conditions of no tailings being discharged, although there was a higher range of concentrations amongst the sub-samples.

The standard deviations amongst samples were considerably higher when no tailings were being discharged in the river, and the grab samples were very under-representative of the depth-integrated samples. The variability in concentrations across the cross-section was noticeably higher than when tailings were being discharged.

Variability amongst depth-integrated samples across the cross-section and with depth showed a range of sample concentrations 2.6–11.2% above and below the mean when tailings were being discharged, and 19.5% above and below the mean without tailings being discharged.

These results give some feel for the range in suspended sediment concentrations occurring with samples successively collected in the same spot and fashion, as well as the variability between sampling techniques. In conclusion, grab samples could be considered reasonably representative of results which would have been obtained using depth-integrated samples while the mine was discharging its tailings, but not when tailings are no longer discharged. Use of the depth-integrated sampler is always preferred over other sampling techniques, but even more particularly during periods without tailings being discharged.

Tests have been conducted at each of the four stations to test how the automatically collected water samples relate to the total suspended sediment in the river cross-section at which they are located. Results are shown in table 6.3.

Table 6.3 Representability of auto samplers pre-mine closure

Stn. No	**2**	**4**	**13**		**18**	
Date	23/7/93	21/7/93	26/1/94	1/6/94	25/1/94	2/6/94
No samples	4	4	5	6	5	9
Total gauged discharge	8.7	76.2	71.2	9.7	54.9	8.1
Depth-integrated samples						
Min. sediment concentration (mg/L)	2952	419	180	353	184	69
Max. sediment concentration (mg/L)	3578	503	212	389	278	158
Total cross-section sediment load (kg/sec)	**30.00**	**33.56**	**13.95**	**3.69**	**13.12**	**1.06**
Auto samples						
In. auto sampler concentration (mg/L)	3382	402	185	328	189	50
Max. auto sampler concentration (mg/L)	3775	444	206	343	273	62
Mean auto sampler concentration (mg/L)	3579	417	195	335	225	56
Total auto sampler sediment load (kg/sec)	**31.14**	**31.78**	**13.86**	**3.26**	**12.33**	**0.45**

For these representability tests of the auto samplers, depth-integrated samples were taken at a number of verticals across each cross-section while the auto sampler was regularly sampling. Widths, depths and current velocities were also measured at regularly spaced intervals across the cross-section. Suspended sediment concentrations were extrapolated for each column by assuming a linear variation between the measured depth-integrated samples. The sediment load was calculated by multiplying the suspended sediment concentration for each vertical by its respective area discharge. The mean suspended sediment concentration for the automatically collected samples was multiplied by the total discharge.

Overall the auto samplers are shown to be remarkably representable of their cross-sections, except at low flow at Station 18. At low flow the sampler intake at Station 18 is out of the main current, but a correction factor of 2.35 can be applied to the sediment loads measured from the auto sampler. Application of a correction factor to point sample concentrations to make them representative of the concentrations in the cross-section as a whole was recommended by Leeks (1984).

These representability tests were all conducted under conditions of steady flow, and nothing is known about representability of the samplers during unsteady flow conditions. During conditions of rising or falling flow levels there would be a marked gradation of concentrations with depth, as material is lifted into suspension or settles back onto the bed. Because the water level rises very quickly with the turning on of the power station, the material is probably lifted into suspension very quickly. With the fall in water level with the power station turning off, it is probably necessary to linearly extrapolate the correction factor between the different flow levels.

6.2.2 Particle characteristics

Particle size has been measured using the Malvern Laser Scatterer, typical results for which are shown in fig 6.1.

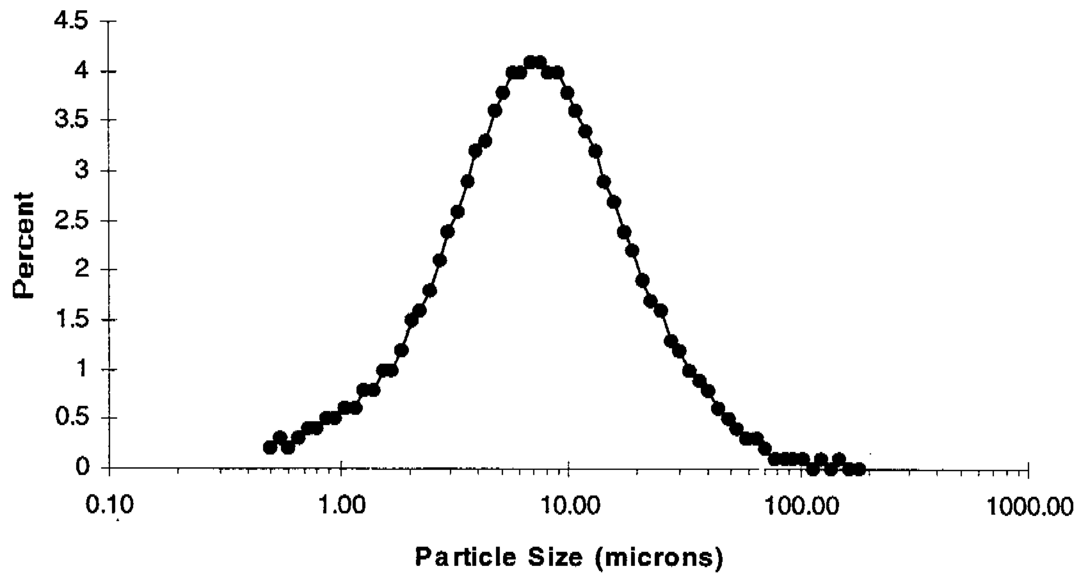


Figure 6.1 King River suspended sediment particle size distribution

Suspended sediments in the King River almost invariably had a median grain size of 7–8 μm using the laser scatterer, somewhat finer than the 11 μm measured at the tailings outfall which suggests that some material may have settled out. Table 6.4 shows the particle size results for numerous suspended sediment samples analysed, and they were remarkably consistent. Some of the samples at Station 2 had a particle size more consistent with the outfall samples, in the range of 11–12 μm. The Station 4 samples were slightly coarser (8–9 μm), and interestingly enough several Station 5 samples were in the range of 30 μm.

All of these laser scatterer results were after using ultrasonics on the samples. When the samples were first put into the sampling chamber the readings were regularly considerably higher, and steadily reduced with stirring time. Examination of a water sample using a Scanning Electron Microscope (SEM) found that flocs in the order of 30 μm in diameter form under certain conditions of water and particle surface chemistry.

Discussions with Dr. Ron Beckett at the CRC for Freshwater Ecology at Monash's Caulfield campus led to the investigation of particle surface charges using electrophoretic mobility measurements as an indication of the conditions under which flocs will form. Preliminary results are presented in table 6.5.

The results show that the particles coming down the Queen River are positively charged, and those in the King River negatively charged (presumably due to organic coating), and so flocculation is most likely to occur at the confluence of the two rivers (depending on relative flows). Two students from the CRC for Freshwater Ecology pursued the issue of flocculation in the King River system for research work required for their degrees. The usefulness of their results is still being evaluated. One major problem with this work is the alteration of the samples with storage time, as can be seen in table 6.5 with the pH changes between the field and the lab.

Some microprobe analyses were conducted on King River suspended sediment filter residues, with typical results shown in fig 6.2. The results confirmed that the particles were alumino-silicates, with varying amounts of potassium, iron, and occasionally magnesium, aluminium and sulfur.

6.2.3 Spatial variability

Figure 6.3 illustrates the variations in point sediment concentration across the channel cross-section at the four stations at which auto samplers are located, Stations 2, 4, 13 and 18, and provides a comparison with depth-integrated samples where taken. Velocities are shown as well, and the velocity-concentration correlation coefficient. The depths of samples are shown as top, middle and bottom, which are at 2/10, 5/10 and 8/10 of the total vertical depth for each respective vertical.

The Station 2 cross-section shows some variation in suspended sediment concentrations, between 2952 and 3646 mg/L, but no consistent trends with depth or distance across the cross-section. The depth-integrated sample in the 1.8m vertical was within the range of the three point sample concentrations in that vertical, whereas the concentration of the depth-integrated sample in the 3.3m vertical was higher than the corresponding point samples.

Station 4 shows a range of concentrations between 367 and 581. As with Station 2, there are no consistent trends with depth or distance across the cross-section. The depth-integrated sample concentrations were generally lower than the corresponding point samples with the exception of the 2.06m vertical, for which the depth-integrated concentration was noticeably higher.

The concentrations for Station 13 range from 179 to 331 mg/L. There is a tendency in each vertical for slightly higher concentrations with depth, with the greatest range in the 17m vertical. There is also a tendency for slightly higher concentrations in the deeper verticals compared with those closer to the banks. The depth-integrated sample concentrations tended to be lower or at the low end of the range of point sample concentrations in the corresponding verticals.

Table 6.4 Suspended sediment particle size measurements

Stn. No.	Sample Loc'n	Sample Type	Date Collected	Date Analysed	Median Particle Size (microns)			
					Test 1	Test 2	Test 3	Average
13	R	DI	24/6/93	27/7/93	7.82	7.78	7.78	7.79
	CR	DI			7.55	7.58	7.63	7.59
	C	DI			8.02	8.21	8.47	8.23
	CL	DI			7.57	7.60	7.60	7.59
	L	DI			7.39	7.39	7.41	7.40
13	C	Grab-1	24/6/93	27/7/93	7.63	7.64	7.64	7.64
	C	Grab-2			7.77	7.78	7.73	7.76
	C	Grab-5			7.63	7.67	7.69	7.66
	C	Grab-10			7.62	7.65	7.69	7.65
	C	DI-1	24/6/93	27/7/93	7.54	7.59	7.62	7.58
	C	DI-2			7.45	7.47	7.45	7.46
	C	DI-5			7.61	7.73	7.82	7.72
	C	DI-10			7.50	7.54	7.63	7.56
18	R	DI	23/6/93	28/7/93	7.76	7.78	7.70	7.75
	CR	DI			7.91	7.87	7.84	7.87
	C	DI			7.76	7.75	7.68	7.73
	CL	DI			8.09	8.01	7.99	8.03
	L	DI			7.71	7.71	7.70	7.71
18	C	Grab-1	23/6/93	28/7/93	7.81	7.78	7.73	7.77
	C	Grab-10			8.04	8.02	7.92	7.99
	C	DI-1	23/6/93	28/7/93	7.87	7.81	7.80	7.83
	C	DI-10			7.82	7.79	7.74	7.78
5	SSv1a	decant	10/06/93	3/08/93	30.27	32.11	30.28	30.89
	SSv1	grab	10/06/93	6/08/93	37.04	32.13	30.94	33.37
	SSv2a	decant	11/06/93		9.21	9.43	9.50	9.38
TP	SSva	decant	11/06/93	3/08/93	9.62	9.70	9.38	9.57
2	SSv-DIa		6/06/93	3/08/93	11.68	11.78	11.79	11.75
	SSva				11.21	11.15	11.19	11.18
20	C	grab	22/6/93	6/08/93	6.85	6.72	6.71	6.76
19	C	grab			7.02	6.96	6.91	6.96
18	C	grab			7.23	7.15	7.17	7.18
17	C	grab			7.19	7.15	7.13	7.16
16	C	grab			7.26	7.25		7.26
15	C	grab			7.49	7.44		7.47
14	C	grab			7.14	7.15		7.15
13	C	grab			7.48	7.48		7.48
12	C	grab			7.09	7.05		7.07
11	C	grab			7.38	7.27	7.19	7.28
10	C	grab			7.40	7.27	7.21	7.29
9	C	grab			7.48	7.33	7.24	7.35
8	C	grab			7.55	7.40	7.24	7.40
7	C	grab			7.51	7.14	7.05	7.23
6	C	grab			6.87	6.79	6.75	6.80
4	L	DI	21/7/93	23/8/93	8.65	8.65		8.65
	LC	DI			9.34	9.23	9.22	9.26
	C	DI			8.70	8.67		8.69
	R	DI			9.14	9.10		9.12
4	C	grab-hour1	21/7/93	23/8/93	9.56	9.55		9.56
	C	grab-hour2			8.50	8.57	8.59	8.55
	C	grab-hour3			8.58	8.65	8.69	8.64
	C	grab-hour4			8.40	8.36		8.38
	C	grab-hour5			8.42	8.34	8.28	8.35
2	C	DI	23/7/93	23/8/93	8.27	8.20		8.24
	C	grab-hour1			13.25	12.81	12.76	12.94
	C	grab-hour2			8.20	8.16		8.18
	C	grab-hour4			7.75	7.69		7.72
	L	point (top)			8.18	8.08		8.13
	C	point (top)			7.52	7.46		7.49
	C	point (middle)			7.34	7.28		7.31
	C	point (bottom)			8.04	7.98	7.96	7.99

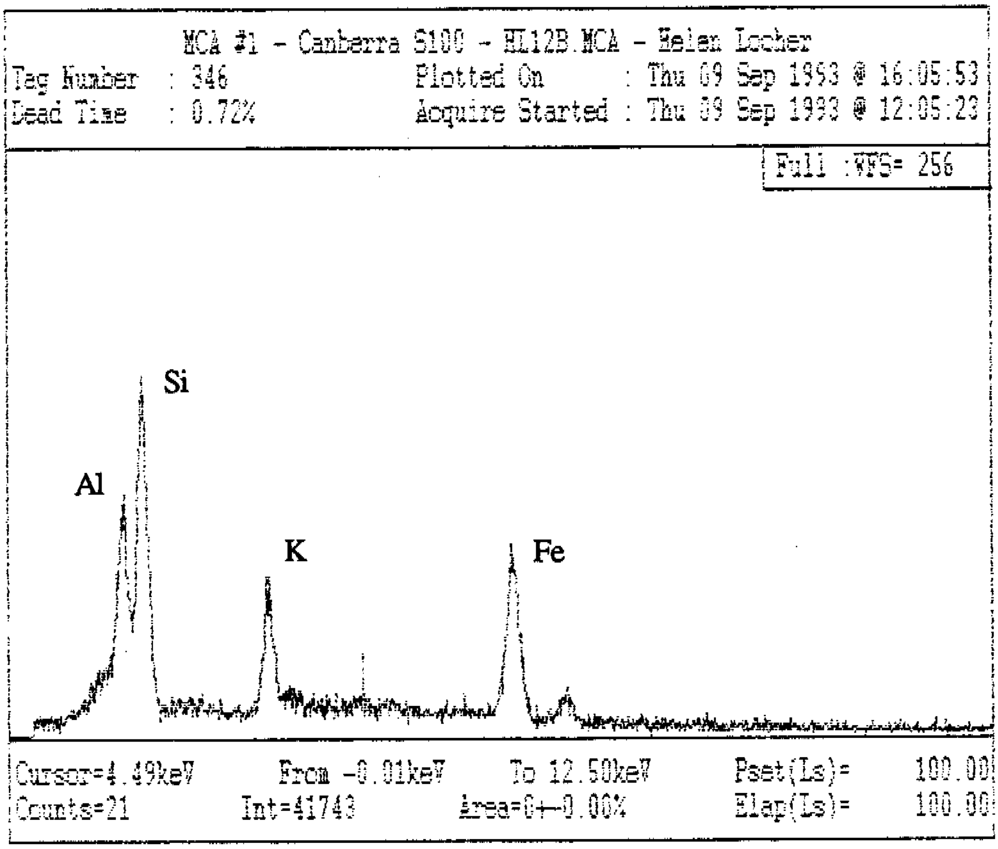


Figure 6.2 Microprobe analysis of King River suspended sediments

Table 6.5 Electrophoretic mobility measurements

	Field 28/9/93			Lab. 11/11/93	
Station	**Cond. uS/cm**	**Temp. °C**	**pH**	**pH**	**Mean mobility**
20	102	10		6.48	-2.1
18	63	9.7		6.49	-1.9
15	97	9.5	4.8	6.39	-1.2
12	63	9.4		6.32	-1.5
9	63	9.3		6.29	-1.6
4	63	9.2		6.2	-1.6
3	70	8.9	5.51	5.86	-2.3
				2.91	-0.4
				4.65	-1.6
				7.84	-2.3
				9.35	-2.2
2	970	12.7	4.25	4.99	0.3
				3.04	0.23
				4.92	0.37
				6.55	-0.05
				9.21	-1.4
Q>K	253	9.5	5.5	3.43	0.07
				2.91	0.1
				5.18	0.26
				7.13	-0.1
				9.12	-1.7
K>Q	47	9	5.75	6.22	-1.3

STATION 2 - 23/7/93

Gauged Discharge = 8.7 cumecs

LEFT BANK — RIGHT BANK

Horiz'l Dist.	0m	0.8m		1.8m		3.3m		4.3m		7.3m		9.8m		11.6m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.714	2952	1.182	3318		3094							
Middle (5/10)				0.457	3280	1.296	3074	1.515	3568	1.596	3032	1.336	3646	
Bottom (8/10)				0.217	3446		2827							
Vert'l Depth	**0m**	**0.84m**		**1.11m**		**0.91m**		**0.72m**		**0.53m**		**0.43m**		**0m**
DI					3308		3143		3578					

Velocity - concentration correlation = 0.033

STATION 4 - 21/7/93

Gauged Discharge = 76.18 cumecs

LEFT BANK — RIGHT BANK

Horiz'l Dist.	0m	6.75m		12.75m		17.25m		20.75m		26.25m		40.25m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.925	573	2.319	445	2.743	386	2.846	441	2.748	399	
Middle (5/10)		1.048	465	1.996	536	1.777	481	2.526	449			
Bottom (8/10)		0.496	581	1.163	533	0.048	367	0.846	469	1.932	498	
Vert'l Depth	**0m**	**1.33m**		**1.50m**		**2.06m**		**1.75m**		**1.42m**		**0m**
DI			425		448		503		426, 413			

Velocity - concentration correlation = -0.347

STATION 13 - 26/1/94

Gauged Discharge = 71.17 cumecs

LEFT BANK — RIGHT BANK

Horiz'l Dist.	0m	8m		17m		26m		35m		44m		51.5m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.470	185	0.918	210	0.941	206	0.963	193	0.628	179	
Middle (5/10)		0.534	181	0.947	237	1.026	219	1.103	202	0.695	187	
Bottom (8/10)		0.473	193	0.801	331	0.855	240	0.823	221	0.639	196	
Vert'l Depth	**0m**	**1.77m**		**2.77m**		**2.50m**		**1.99m**		**1.10m**		**0m**
DI			180		212		192		199		180	

Velocity - concentration correlation = 0.316

STATION 18 - 25/1/94

Gauged Discharge = 54.86 cumecs

RIGHT BANK — LEFT BANK

Horiz'l Dist.	0m	5m		14m		26m		38m		47m		58.0m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.570	132	0.761	276	0.819	245	0.853	251	0.691	192	
Middle (5/10)		0.503	341	0.668	265	0.863	265	0.847	256	0.794	212	
Bottom (8/10)		0.406	243	0.592	342	0.749	283	0.678	415	0.510	229	
Vert'l Depth	**0m**	**2.16m**		**1.53m**		**1.60m**		**1.55m**		**1.62m**		**0m**
DI			245		265		231		278		188	

Velocity - Concentration Correlation = -0.037

Figure 6.3 Suspended sediment spatial variability pre-mine closure

The concentrations for Station 18 range between 132 and 415 mg/L. Again, there is a tendency in each vertical for slightly higher concentrations with depth, with the exception of the 5m vertical. There is also a tendency for slightly higher concentrations in the more central verticals than closer to the banks. The depth-integrated sample concentrations were within the range of point sample concentrations for the corresponding verticals at 5m and 38m, but at the bottom or below the range of point samples for the 14m, 26m and 47m verticals.

The pronounced uniformity of the suspended sediment concentrations across the cross-section at Stations 2 and 4 indicates that most of the suspended material is washload, in this case derived from the mine's continuous discharge of tailings, rather than resuspended bed material (Colby 1963). At Stations 13 and 18 the results suggest that there is still a large percentage of washload, but the slightly higher concentrations with depth indicate a component of resuspended bed material as well. Boliang and Zhan (1982) and Nordin and Dempster (1963) reported uniform concentrations of suspended sediments across channel cross-sections in the Yellow River and Rio Grande, but these were hyperconcentrated flows with concentrations in the range of 400 g/L not uncommon.

6.2.4 Temporal variability

Two 72 hour intensive suspended sediment sampling exercises were conducted prior to the mine ceasing the discharge of tailings, one in February and one in June 1994. These exercises involved setting the automatic water samplers at Stations 2, 4, 13 and 18 to sample at regular intervals (usually hourly) while the power station came on during the day and off at night for three consecutive days. These exercises had three main purposes:

1 to determine how suspended sediment concentrations at each station vary with the rise and fall of the hydrograph;

2 to assess how suspended sediment concentrations varied between stations; and

3 to correlate turbidity measurements to suspended sediment concentration.

Figures 6.4 and 6.5 show the results at stations 4, 13 and 18 for these two exercises. The power station release patterns are seen to have a significant influence on suspended sediment concentrations in the King River while the mine is still operating. Measured concentrations rose from several hundred to 10,000 mg/L with the initial discharge of water from the power station, flushing the sediment which had deposited with the power station off, and sending this sediment wave downstream. Sediment exhaustion effects are evident as the initial sediment flush subsides and a lower suspended sediment concentration is transported at the constant flow rate released from the power station.

To date only sediment concentration data is available for field exercises such as those shown in figs 6.4 and 6.5. A difficulty with this study has been in obtaining flow data for the entire river, as Reach King4 is tidally influenced. Mike-11, an unsteady flow modelling package developed by the Danish Hydraulics Institute, is being utilised to model flows so that sediment loads can be determined, and therefore whether net scour or deposition is occurring within different river reaches. Hydraulic variables required for sediment transport equations will also be obtained from Mike-11 which will be utilised in predictive sediment transport work for this river system. Flow and sediment transport modelling is further discussed in section 8.

6.2.5 Turbidity data

Turbidity meters have been continuously recording every ten minutes at Stations 13 and 18 in the King River, as well as at stations in the harbour outside the river mouth, since December 1993. The intention for the turbidity meters in the King River is to correlate them with suspended sediment concentrations, whereas those in the harbour are to monitor the timing and movement of suspended sediment plumes coming out of the river mouth.

Turbidity data from Stations 13 and 18 while the mine was still releasing its tailings has been collated into month-by-month plots of turbidity against time.

The turbidity instruments have required more attention than initially realised, as the lenses tended to foul from the silt being transported down the river, and the electronic components of the instruments were very vulnerable to corrosion. The turbidity monthly results will be plotted against flow, and evaluated to correct or cull data from periods where turbidity readings were clearly drifting or unusable. Figure 6.6 illustrates how the turbidity instrument readings (as well as the concurrently recorded conductivity) vary with river level and with suspended sediment concentrations, an understanding of which will help in evaluating when turbidity data is straying or unusable. Of note is the limited range of the turbidity meter readings compared with the range of suspended sediment concentrations in the river. Also, the river level rise precedes the rise in suspended sediment concentrations, unlike a normal flood hydrograph where the suspended sediment peak precedes the flood peak. This difference is due to the absence of a natural run-off component to the hydrograph found in unregulated rivers.

KING RIVER

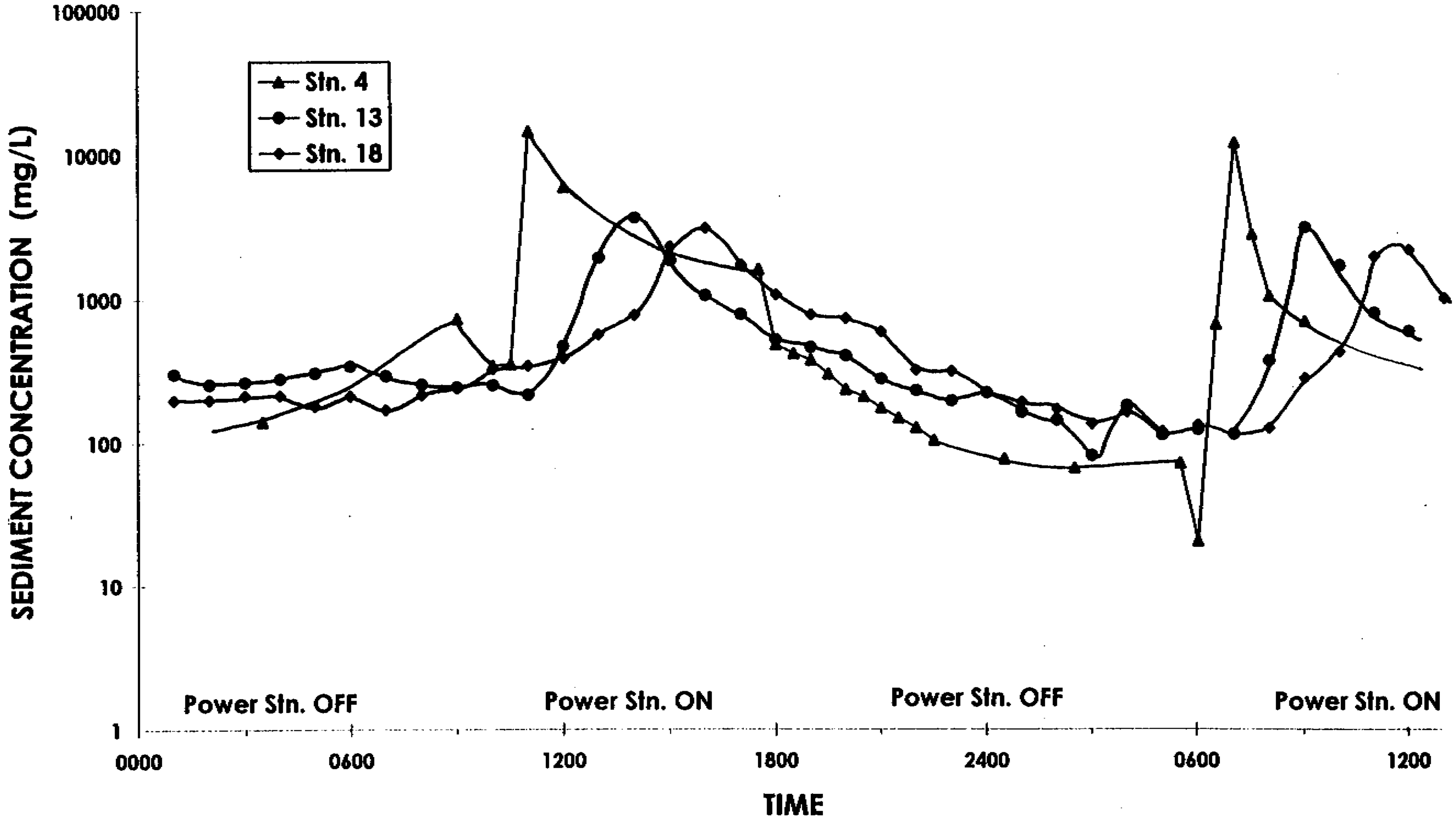


Figure 6.4 Influence of power station on suspended sediment concentrations 17–18/2/94

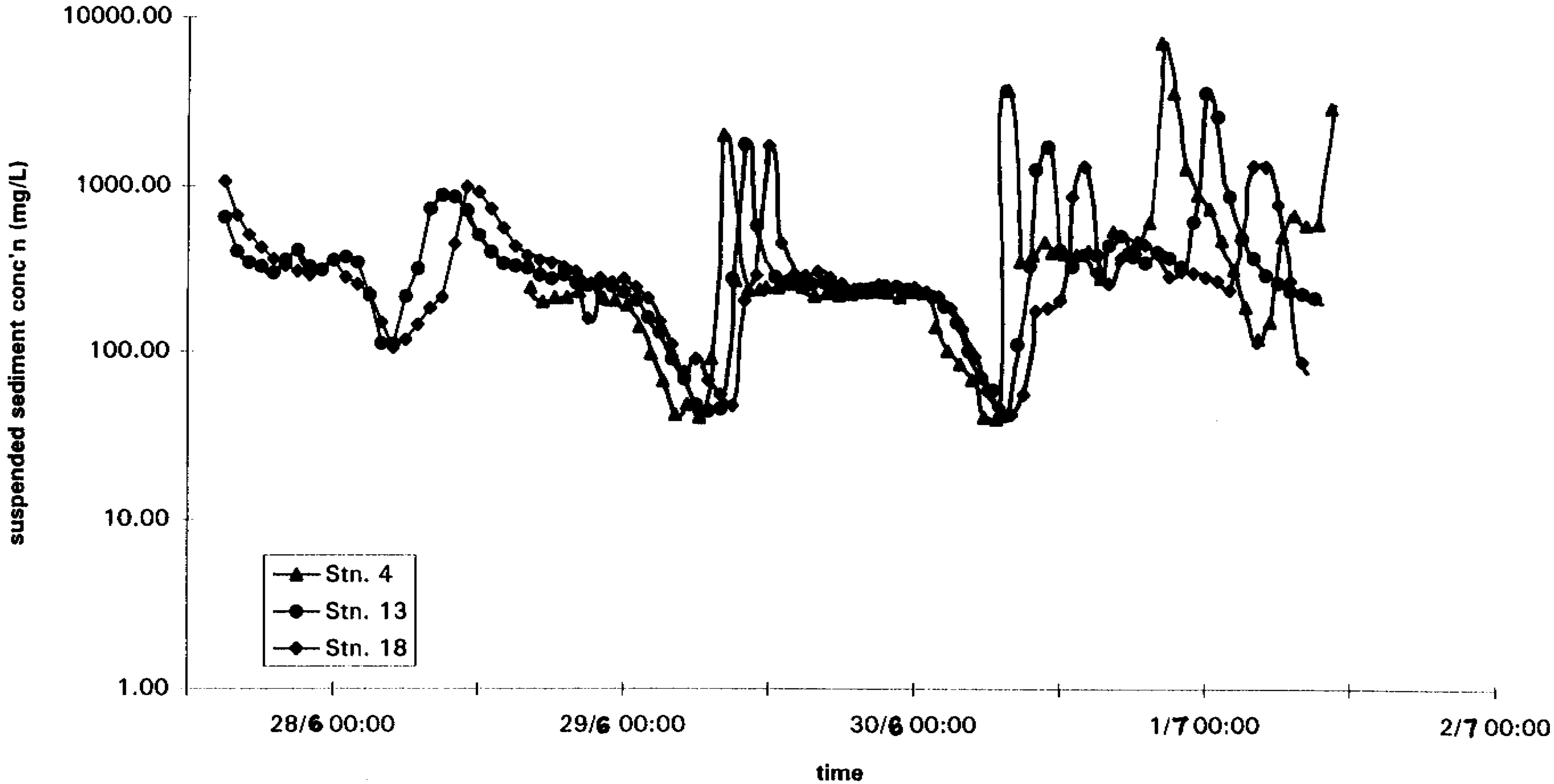


Figure 6.5 Influence of power station on suspended sediment concentrations 27/6–1/7/94

Table 6.6 shows the dates of rating curve exercises and changes to the instruments during 1994.

Table 6.6 Turbidity meter exercises and adjustments 1994

Date	Exercise
17–18 February 1994	Rating curves
14–15 June 1994	Formazin calibration
27 June – 1 July 1994	Rating curves
4 August 1994	Reduced gain / TAIN workshop

Rating curve exercises were conducted as part of the 72 hour exercises described above, with the resultant curves shown in figs 6.7 and 6.8. The peak suspended sediment concentrations were culled from these data sets in the formulation of these curves, because they all corresponded to the highest turbidity instrument reading of 510.

Rating curves of turbidity instrument readings against formazin (the turbidity standard) was also developed for both the Station 13 and 18 turbidity meters, with the intention of being able to compare the King River rating curves with other published curves. The results are shown in fig 6.9a. Between 1500 and 2000 Ftu (formazin turbidity units) these curves start doubling back at a maximum turbidity instrument reading of between 400 and 450; why they did not go to the full 510 range of the instrument is unknown. Figure 6.9b shows these same curves with a y-axis maximum of 1500 Ftu for Station 13 and 2000 Ftu for Station 18.

These results emphasise the problem of insufficient range of the turbidity meter instrument readings to cover the range of suspended sediment concentrations (100–10,000 mg/L) in the King River under normal operations of the power station.

The instruments were taken back to the manufacturer's workshops (TAIN, Box Hill, Melbourne, Victoria) in August 1994, where the gain controls were reduced to make the instruments less sensitive and so able to give readings at the higher suspended sediment concentrations. The instruments were then calibrated in the workshop against samples of dried mine tailings (from the Mount Lyell mill) which were mixed with distilled water to the desired concentrations. The subsequent rating curves, shown in fig 6.10, are not considered as good as a rating curve developed in the field because of the other influences of colour, variations in particle size and shape, occurrence of flocs, etc. However, it is the only rating curve available to this study (pre-mine closure) since the gain control was changed, as another field calibration was not able to be obtained prior to the mine's closure. Lines of best fit will be calculated for all the rating curves as was done in fig 6.7.

6.3 Results post-mine closure

6.3.1 Representability

Since the mine closed in December 1994, the suspended sediment concentrations have lowered significantly in the Queen and King Rivers, and the water colour has become extremely variable depending on rainfall, flow conditions, pH and run-off from the Mount Lyell lease site.

Two exercises comparing the auto samplers to the suspended sediment concentrations across the cross-section at Stations 13 and 18 have been conducted, one in February and one in April 1995. January and February 1995 were extremely dry months on Tasmania's west coast, and with the first rains in March large plumes of suspended sediment were visible in Macquarie Harbour, so the river had not adjusted significantly to the cessation of tailings discharge at the time of the February 1995 exercise. Table 6.7 shows the results of representability tests of the auto samplers from these stations.

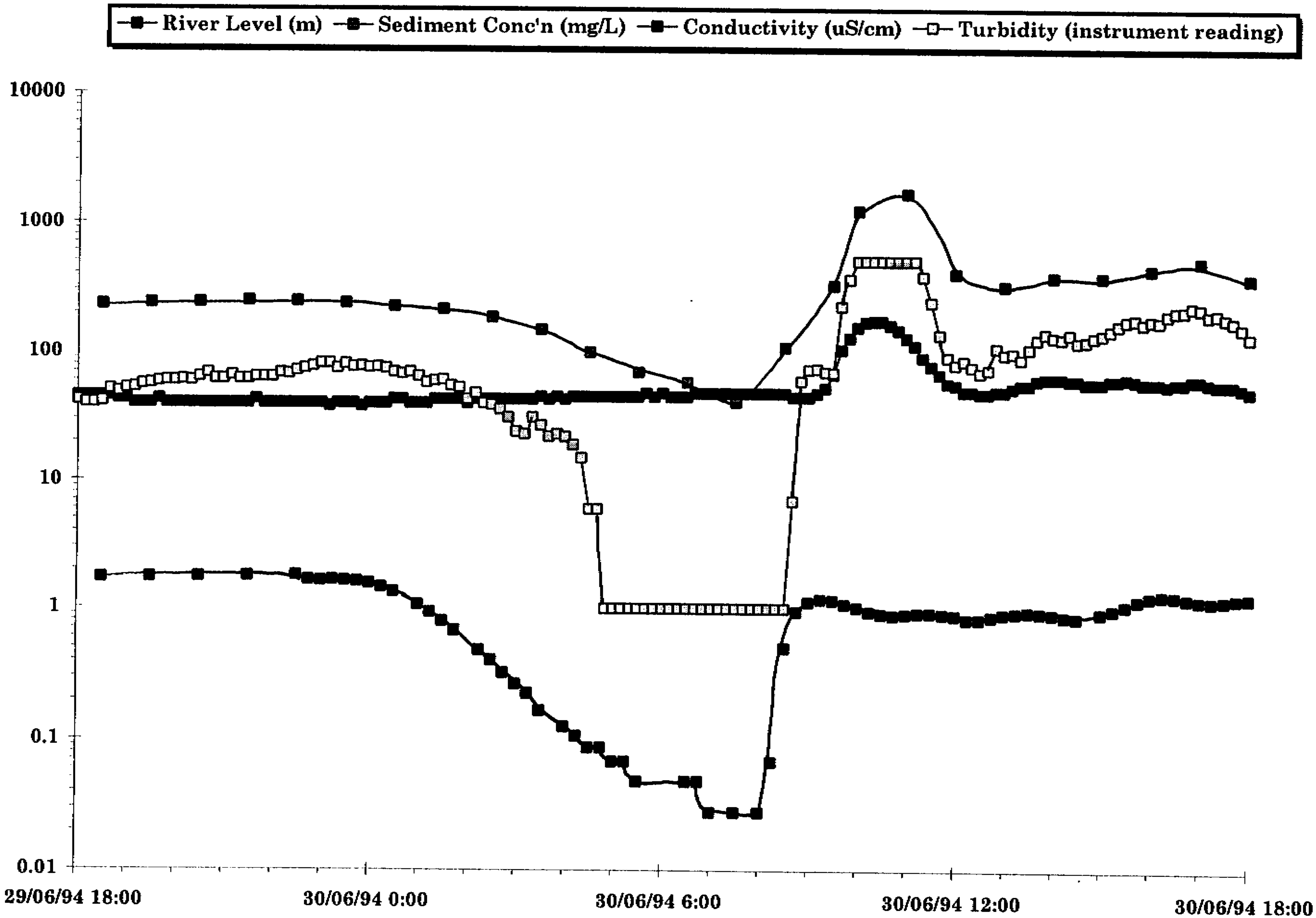


Figure 6.6 Variations in turbidity, conductivity and suspended sediment with river level

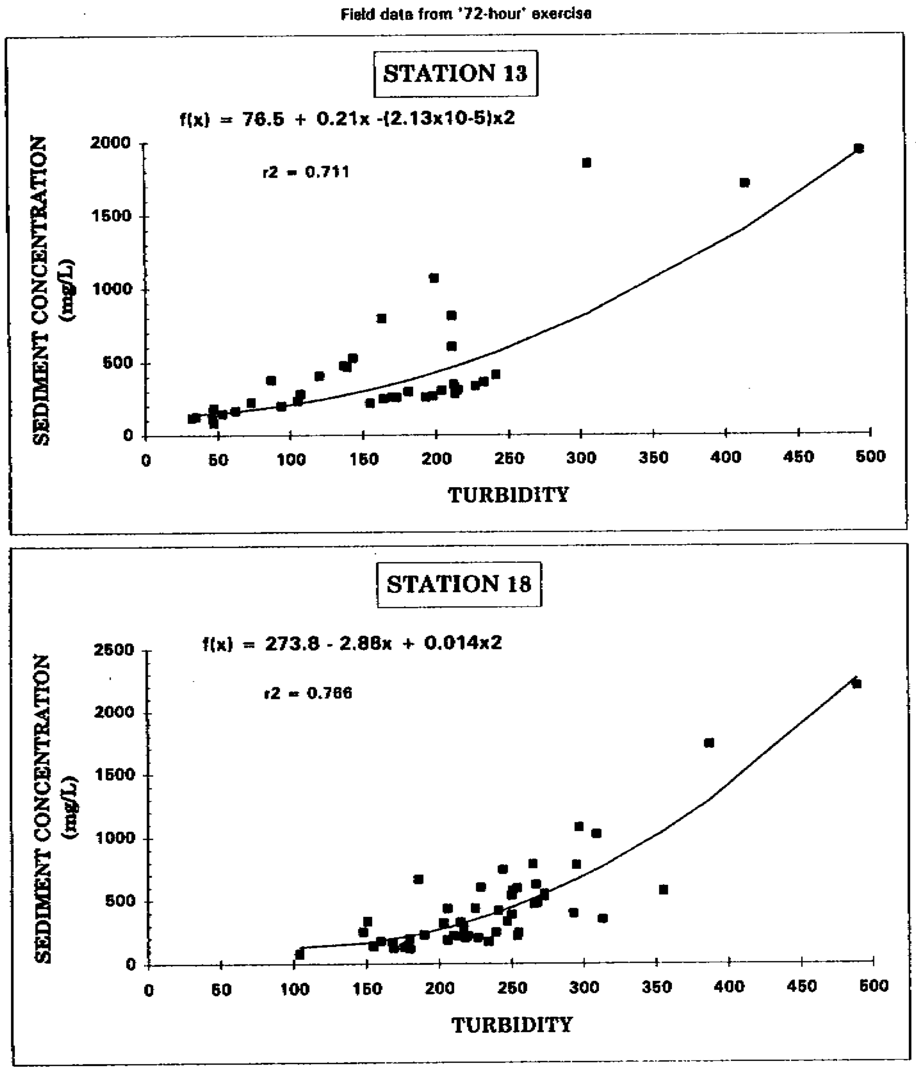


Figure 6.7 Suspended sediment/turbidity rating curves 17–18/2/94

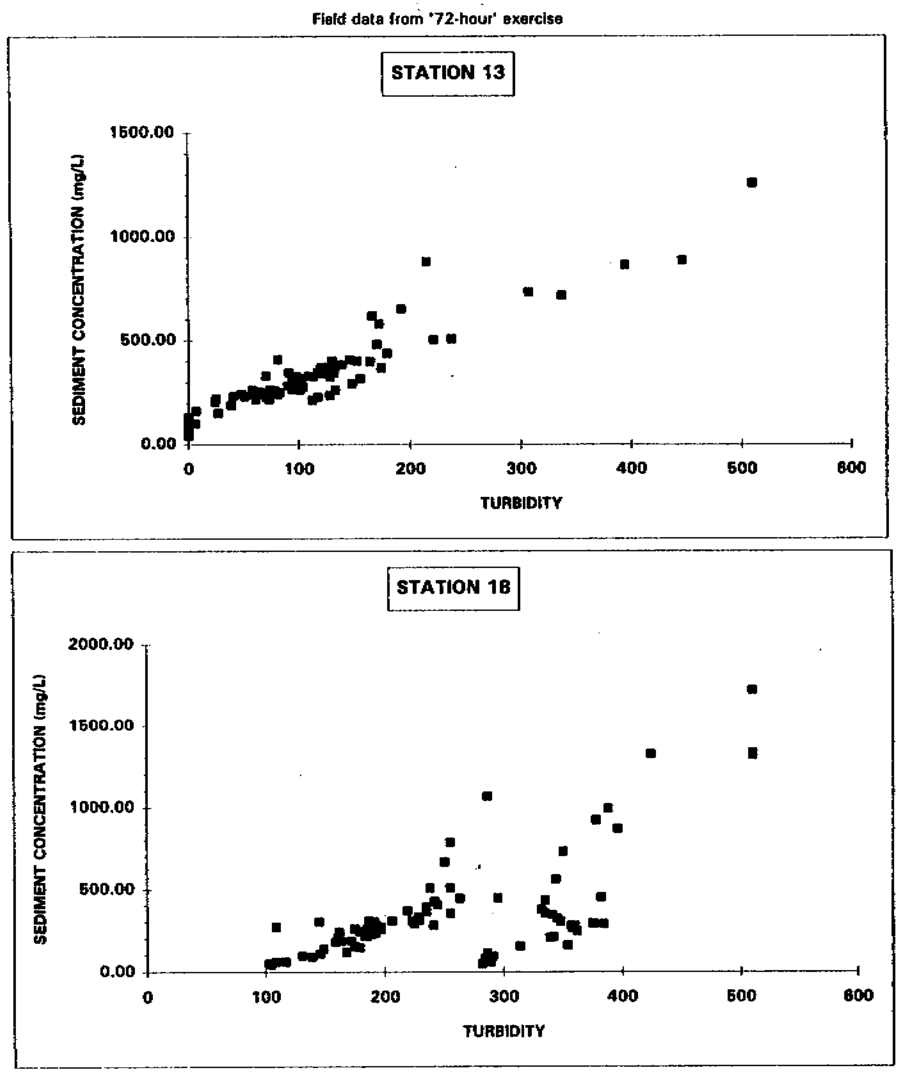


Figure 6.8 Suspended sediment/turbidity rating curves 27/6–1/7/94

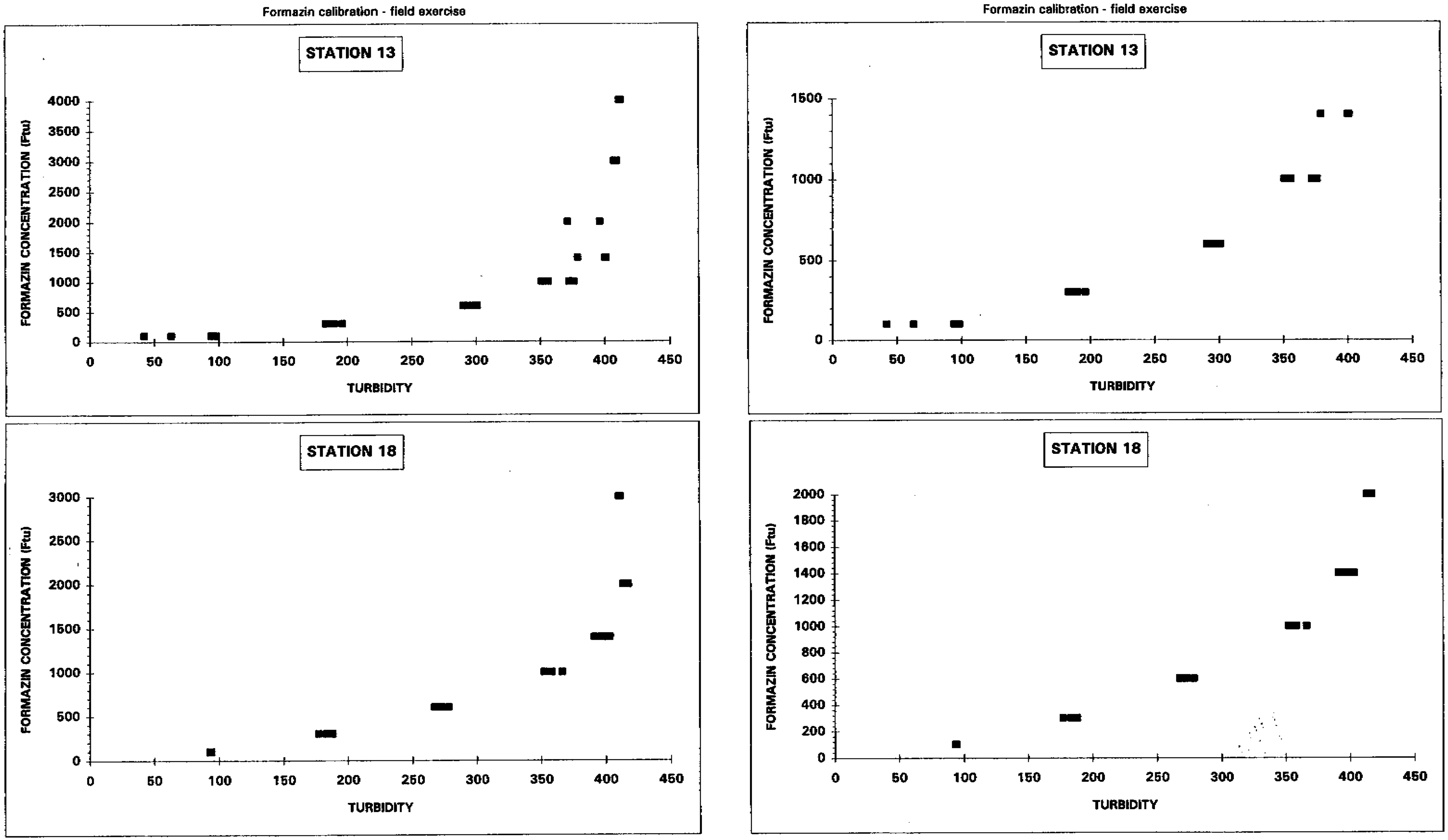


Figure 6.9 Formazin/turbidity rating curves 14–15/6/94

These results show none of the consistency of the comparable results pre-mine closure, shown in table 6.3. The Station 18 sampler at the higher flow levels shows consistent under-representation of the autosampler by 2.6–2.8 times. At low flow the auto sampler is more representative, but the concentrations are so low as to raise questions about the significance of any differences, especially in consideration of the propagation of errors arising from sample collection, filtering and weighing of the filter residues. The February results for Station 13 unfortunately need to be discounted because the flow level was rising during the exercise. The April results show a good consistency between the auto sampler and the sediment passing through the cross-section, but again some questions can be raised about how meaningful variations are given such low sediment concentrations.

One problem with these particular sample sets is that only point samples and not depth-integrated were collected. The integration across the cross-section to obtain a cross-sectional sediment load was done by averaging the point-sample results in a particular vertical. A comparison of depth-integrated suspended sediment concentrations with point sample concentrations within the same vertical was not always consistent, as discussed in section 6.2.3.

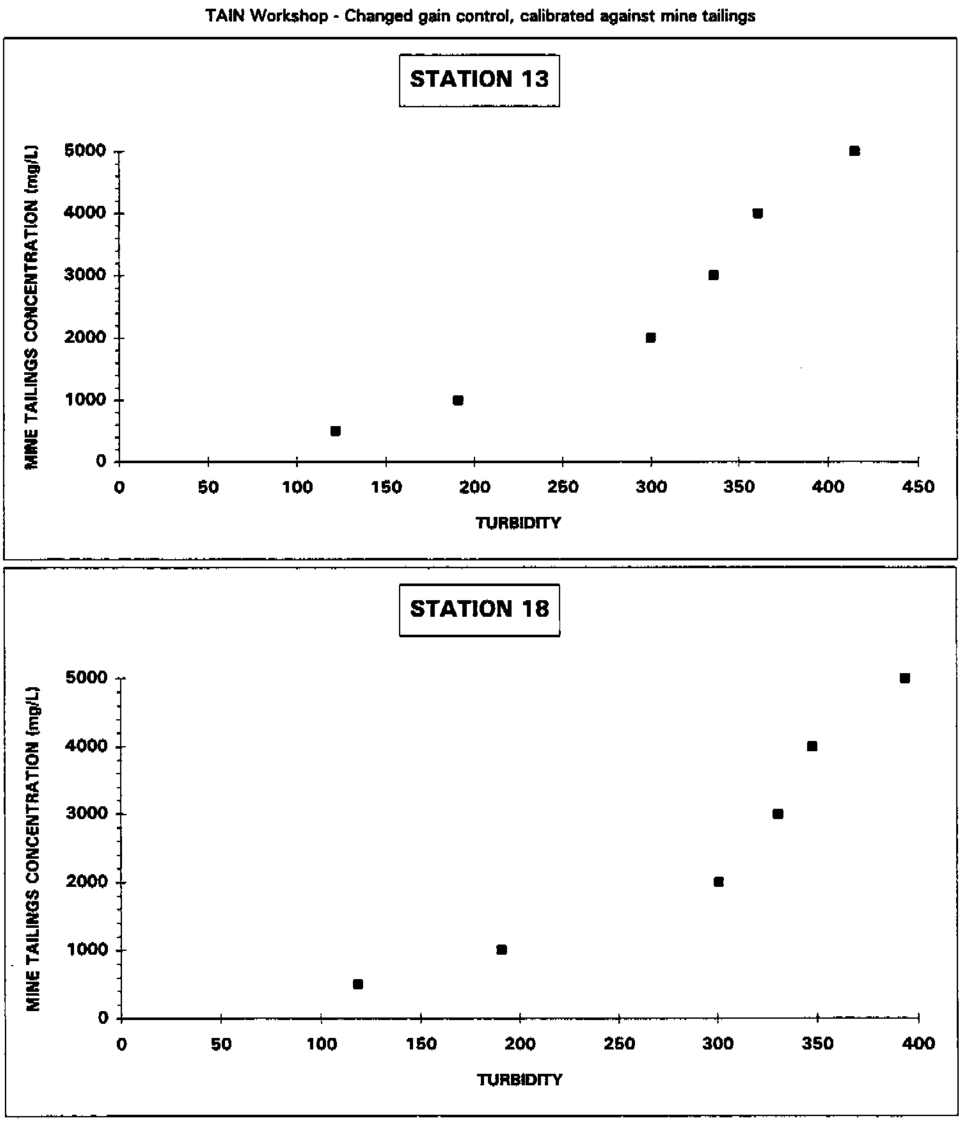


Figure 6.10 Suspended sediment/turbidity rating curves 4/8/94

Table 6.7 Representability of the auto samplers post-mine closure

Stn. No	13		18		
Date	7/2/95	10/4/95	9/2/95	11/4/95	12/4/95
No samples	7	6	7	8	7
Total gauged discharge	70.08	83.6	69.4	78.5	8.74
Point-integrated samples					
Min. sediment concentration (mg/L)	160	15.7	214	27.2	16.9
Max. sediment concentration (mg/L)	1354	18.4	393	71.6	23.1
Total cross-section sediment load (kg/sec)	49.96	1.42	24.55	4.08	0.18
Auto samples					
Min. auto sampler concentration (mg/L)	184	14.6	111	13.2	13.4
Max. auto sampler concentration (mg/L)	1006	20.1	157	59.6	21.7
Mean auto sampler concentration (mg/L)	413	18.1	127	19.8	17.3
Total auto sampler sediment load (kg/sec)	**28.94**	**1.51**	**8.81**	**1.55**	**0.15**

STATION 13 - 7/2/95

Gauged Discharge = 70.08 cumecs

LEFT BANK — RIGHT BANK

Horiz'l Dist.	0m	2m		7m		13m		18m		25m		31m		38m		46m		50m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)				0.423	277	0.831	431	0.841	449	1.023	593	1.047	636	0.965	1284	0.506	1072	
Middle (5/10)		0.279	160	0.465	340	0.777	451	0.900	539	0.978	717	1.127	943	0.919	1271			
Bottom (8/10)				0.389	322	0.684	451	0.762	513	0.852	643	0.973	818	0.874	1508	0.515	1207	
Vert'l Depth	**0m**	**0.48m**		**1.80m**		**2.68m**		**2.72m**		**2.48m**		**2.04m**		**1.92m**		**1.00m**		**0m**

Velocity - concentration correlation = 0.405

STATION 13 - 10/4/95

Gauged Discharge = 83.6 cumecs

LEFT BANK — RIGHT BANK

Horiz'l Dist.	0m	3.5m		11.5m		19.5m		27.5m		35.5m		43.5m		51.5m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.468	16.6	0.764	16	0.920	15.4	1.105	17.6	1.206	16.6	0.942	15.6	
Middle (5/10)				0.672	17.2	0.966	21.7	1.131	15.6	1.159	17.4	0.868	16.7	
Bottom (8/10)		0.381	20.1	0.692	16.7	0.712	17.5	1.027	16.7	0.935	16.1	0.751	14.7	
Vert'l Depth	**0m**	**1.08m**		**2.36m**		**2.91m**		**2.50m**		**2.14m**		**1.27m**		**0m**

Velocity - concentration correlation = -0.175

STATION 18 - 9/2/95

Gauged Discharge = 69.4 cumecs

RIGHT BANK — LEFT BANK

Horiz'l Dist.	0m	6m		14m		22m		30m		38m		46m		54m		58.2m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.705	256	0.882	304	0.943	294	0.982	311	0.913	319	0.945	315	0.367	194	
Middle (5/10)		0.609	295	0.773	338	0.837	364	0.880	404	0.900	382	0.857	357	0.387	218	
Bottom (8/10)		0.451	309	0.659	441	0.726	410	0.783	465	0.695	461	0.710	464	0.130	231	
Vert'l Depth	**0m**	**2.00m**		**2.06m**		**1.96m**		**1.60m**		**1.68m**		**1.80m**		**1.48m**		**0m**

Velocity - Concentration Correlation = 0.437

STATION 18 - 11/4/95

Gauged Discharge = 78.5 cumecs

RIGHT BANK — LEFT BANK

Horiz'l Dist.	0m	2.5m		6.5m		14.5m		22.5m		30.5m		38.5m		46.5m		54.5m		58.2m
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.345	15.9	0.664	102.1	0.891	17.7	0.914	22.6	1.060	35.4	1.125	50.9	0.966	25.2	0.383	30.4	
Middle (5/10)		0.188	17.0	0.522	42.3	0.681	16.5	0.799	22.5	1.011	35.2	1.068	47.0	0.756	42.5	0.305	25.4	
Bottom (8/10)		0.176	50.1	0.330	35.0	0.730	78.3	0.657	169.8	0.833	109.3	0.916	82.2	0.680	40.1	0.229	27.2	
Vert'l Depth	**0m**	**1.68m**		**2.34m**		**2.03m**		**2.12m**		**1.86m**		**1.70m**		**1.94m**		**1.72m**		**0m**
DI																		

Velocity - Concentration Correlation = 0.150

STATION 18 - 12/4/95

Gauged Discharge = 8.74 cumecs

RIGHT BANK — LEFT BANK

Horiz'l Dist.	0m	3.0m		11.0m		19.0m		27.0m		35.0m		43.0m		51.0m		56.0
		vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	vel.	conc'n	
Top (2/10)		0.032	17.2	0.151	17.8	0.189	19.0	0.199	20.6	0.252	19.9	0.253	20.6	0.154	17.4	
Middle (5/10)		0.119	17.7	0.149	18.8	0.133	16.6	0.166	21.1	0.235	24.9	0.265	23.0	0.179	21.2	
Bottom (8/10)		0.083	15.8	0.140	16.6	0.110	18.8	0.130	20.1	0.187	23.6	0.175	25.8	0.110	23.2	
Vert'l Depth	**0m**	**1.52m**		**1.06m**		**1.26m**		**0.88m**		**0.80m**		**0.90m**		**1.12m**		**0m**
DI																

Velocity - Concentration Correlation = 0.545

Figure 6.11 Suspended sediment spatial variability post-mine closure

6.3.2 Particle characteristics

No analyses of suspended sediment particle characteristics have been conducted since the mine has ceased to discharge its tailings. Samples will be collected from the June sampling exercises for particle size distribution and SEM analyses.

The April 1995 filter samples showed a rich reddish staining presumably from iron hydroxide flocs coming out with storage time. The influence of these flocs on suspended sediment concentrations is not yet known. The occurrence of flocs with sample storage time and their influence on suspended sediment concentrations was tested during the week of 19 June 1995.

6.3.3 Spatial variability

Figure 6.11 shows the variability of suspended sediment concentrations across the cross-section at Stations 13 and 18 during the February and April 1995 sampling exercises. For both stations, there is a notable drop in concentrations between the February and April exercises, as much of the finer stored tailings have been cleared out the river system during the periods of high rainfall in March 1995. The February results for Station 18 show a distinct increase in suspended sediment concentrations within the vertical, implying a significant component of resuspended bed load material. This trend can be seen in some of the verticals in the February Station 13 and April Station 18 results, but other verticals show highest concentrations in the middle sample or even at the top of the vertical. The flow level was actually rising during the sampling period at Station 13 on 7 February 1995, so the variations in concentration across the cross-section shown reflect the change in flow.

6.3.4 Temporal variability

Another 72 hour exercise similar to that conducted during February and June 1994 will be conducted during the week 19 June 1995.

6.3.5 Turbidity data

Turbidity data for the King River since the mine closed has been separated into monthly plots of turbidity against time. As for the pre-mine closure data, turbidity will be plotted against flow, bad data culled or corrected, and the appropriate rating curves applied to obtain continuous suspended sediment concentrations. Table 6.8 shows the dates of rating curve exercises and changes to the instruments during 1995.

Table 6.8 Turbidity meter rating curve exercises and adjustments 1995

Date	Exercise
23–24 January 1995	Rating curves
26–27 April 1995	Rating curves
14 May 1995	Increase of gain (in field)
19–23 June 1995	Planned rating curves/Formazin calibration

Rating curves for turbidity–suspended sediment concentration are shown in figs 6.12 and 6.13. The spread of data seen in the January 1995 exercise probably reflects the instability of the system given the recent mine closure, as discussed in Section 6.3.1 with the February versus April representability exercises. The data from the April rating curve exercise looks much more 'settled', but the narrow range of suspended sediment concentrations and turbidity instrument readings shows a need to increase the gain control to increase the sensitivity of the instruments. This was done on 14 May 1995, and the next rating curve exercise will be developed from the data set of the June 1995 72 hour exercise.

Field data - two water level rises and falls from power station operations

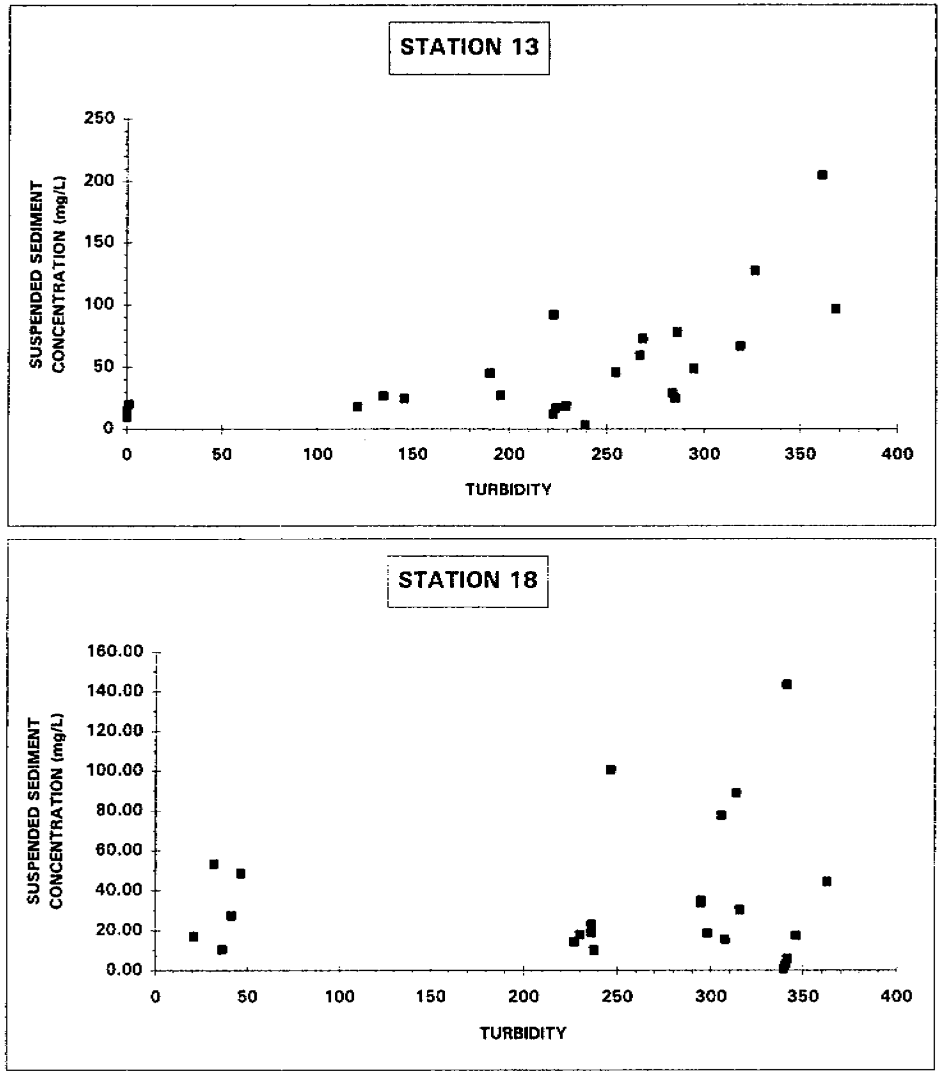


Figure 6.12 Suspended sediment/turbidity rating curves 23–24/1/95

Field data - rise in water level with power station turning on

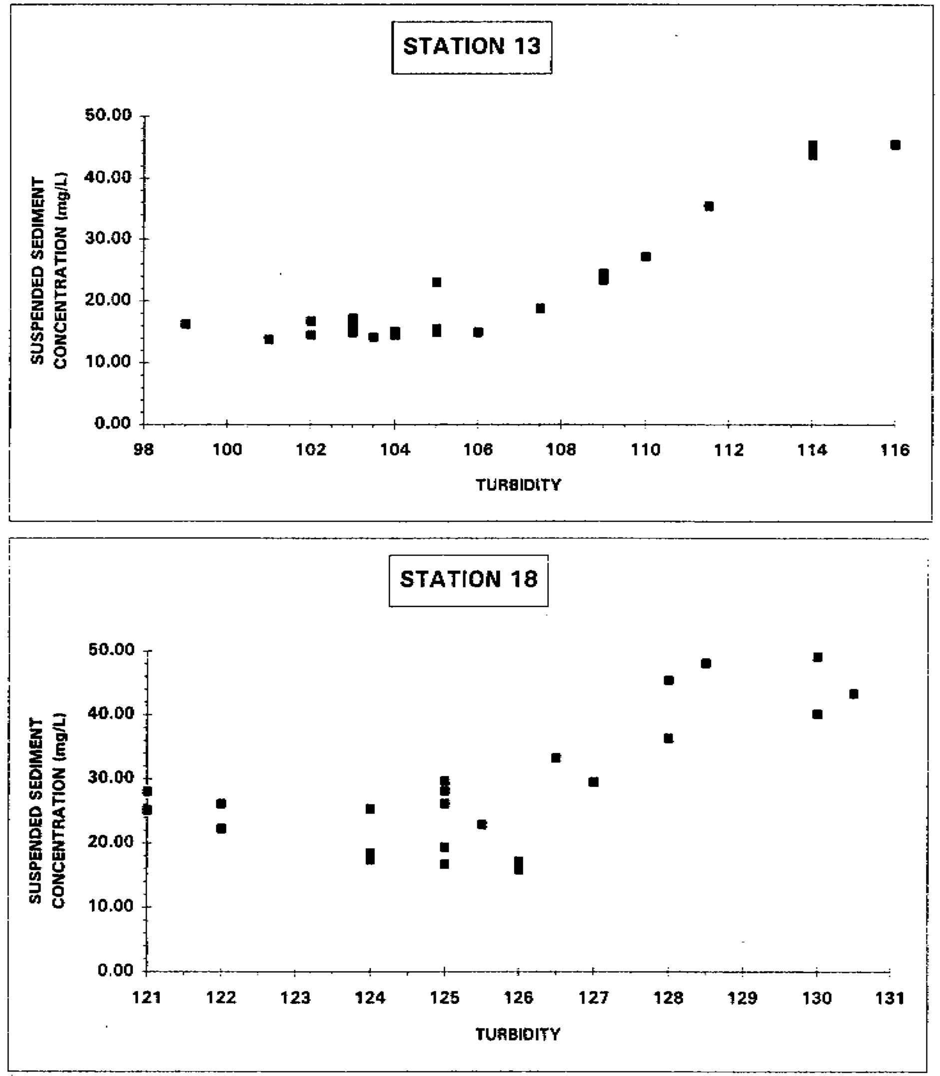


Figure 6.13 Suspended sediment/turbidity rating curves 26–27/4/95

6.4 Summary

This section has reviewed results obtained by this study on suspended sediment transport in the Queen and King Rivers. While the mine was discharging its tailings, suspended sediment concentrations were relatively uniform across the channel cross-section and with depth, so that samples collected from automatic water samplers on the side of the river were generally representative of the sediment loads going past that point in the river. Particle sizes were also very uniform, approximately 7–8 µm in the King River, although flocs of up to 60 µm have been seen under the SEM and are believed to occur under certain mixing conditions at the confluence of the Queen and King Rivers. The power station's operations have been shown to have a significant influence on suspended sediment transport in the King River, with concentrations rising from 100 to 10,000 mg/L due to the initial flush of water with the power station coming on line, and this sediment wave clearly traceable as it propagates downstream. Turbidity meters at two stations have been continuously monitoring suspended sediment concentrations in the lower King River since December 1993. Suspended sediment data will be combined with flow data to determine sediment loads, and hence net deposition or scour in defined reaches of the river.

Since the mine has closed, suspended sediment concentrations have dramatically lowered to 10–20 mg/L, and the auto samplers are far less representative of the cross-sections.

Since the mine has closed, the predominant mode of sediment transport has shifted from suspended load to bed load. Bed load transport is reviewed in section 7.

7 Bed load transport

7.1 Sampling method

Sediment being transported in the river as bed load has been measured using a Helley-Smith bed load sampler. The sampler is set on the river bottom with the aperture facing upstream for a set period of time. The sample collected in the attached mesh bag is then dried and weighed, to give a trap weight in grams per second. The bed load transport rate at a given cross-section is computed by measuring separate trap rates at given distances across the cross-section and then integrating the results over the channel width.

Bed load samples have been collected from the stations shown on map 7.1. Table 7.1 summarises the stations, dates and flow levels at which bed load samples have been and are intended to be collected.

7.2 Results pre-mine closure

7.2.1 Measured bed loads

Bed load measurements made prior to the cessation of mining discharges are summarised in fig 7.1. Collection of these samples is quite time-consuming and expensive, as to obtain a total bed load transport rate from any one cross-section at one flow level takes several hours of time. The results shown in fig 7.1 show no consistent correlation with discharge, but there are not enough measurements at any one station to really see any trends. As well, there is only a limited range of flow rates in the King River due to the power station operations. The station for which the most measurements exist, Station 13, shows no trend at all against flow. The only trend evident is the obvious grouping of data for the stations in reach King3 as compared to those in reach King4; the stations farther downstream tend to have the higher measured bed load transport rates. This data will be evaluated against flow characteristics such as bed velocity, shear stress and stream power, although it is understood that there may be no unique functional relationship with any of these variables (Yang 1973).

Table 7.1 Summary of bed load samples collected

Pre-mine closure			Post-mine closure		
Stn.	**Date**	**Flow rate (m^3/s)**	**Stn.**	**Date**	**Flow rate (m^3/s)**
2	7/12/94	1.9	2	May 1995	~5
9	4/10/94	114	9	May 1995	~80
11	4/10/94	114		"	~100
	14/10/94	80	11	May 1995	~80
	8/12/94	86		"	~100
13	28/4/94	77	13	7/02/95	70.1
	29/6/94	98		10/04/95	83.6
	5/10/94	107		May 1995	~80
	14/10/94	80		"	~100
	8/12/94	86	16	May 1995	~80
16	12/10/94	88		"	~100
	13/12/94	71	18	9/02/95	69.4
18	29/4/94	89		11/04/95	78.5
	12/10/94	88		12/04/95	8.74
	15/10/94	6.4		May 1995	~80
	22/11/94	6		"	~100
	13/12/94	71	19	May 1995	~6
19	10/10/94	110		"	~80
	15/10/94	6.4		"	~100
	22/11/94	6	20	May 1995	~6
20	10/10/94	110		"	~80
	15/10/94	6.4		"	~100
	22/11/94	6			
	24/11/94	93			

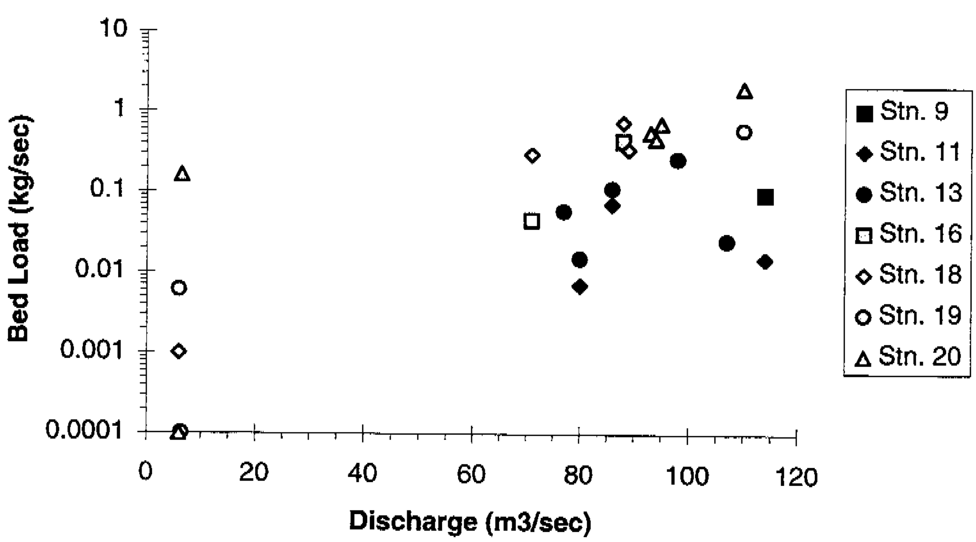
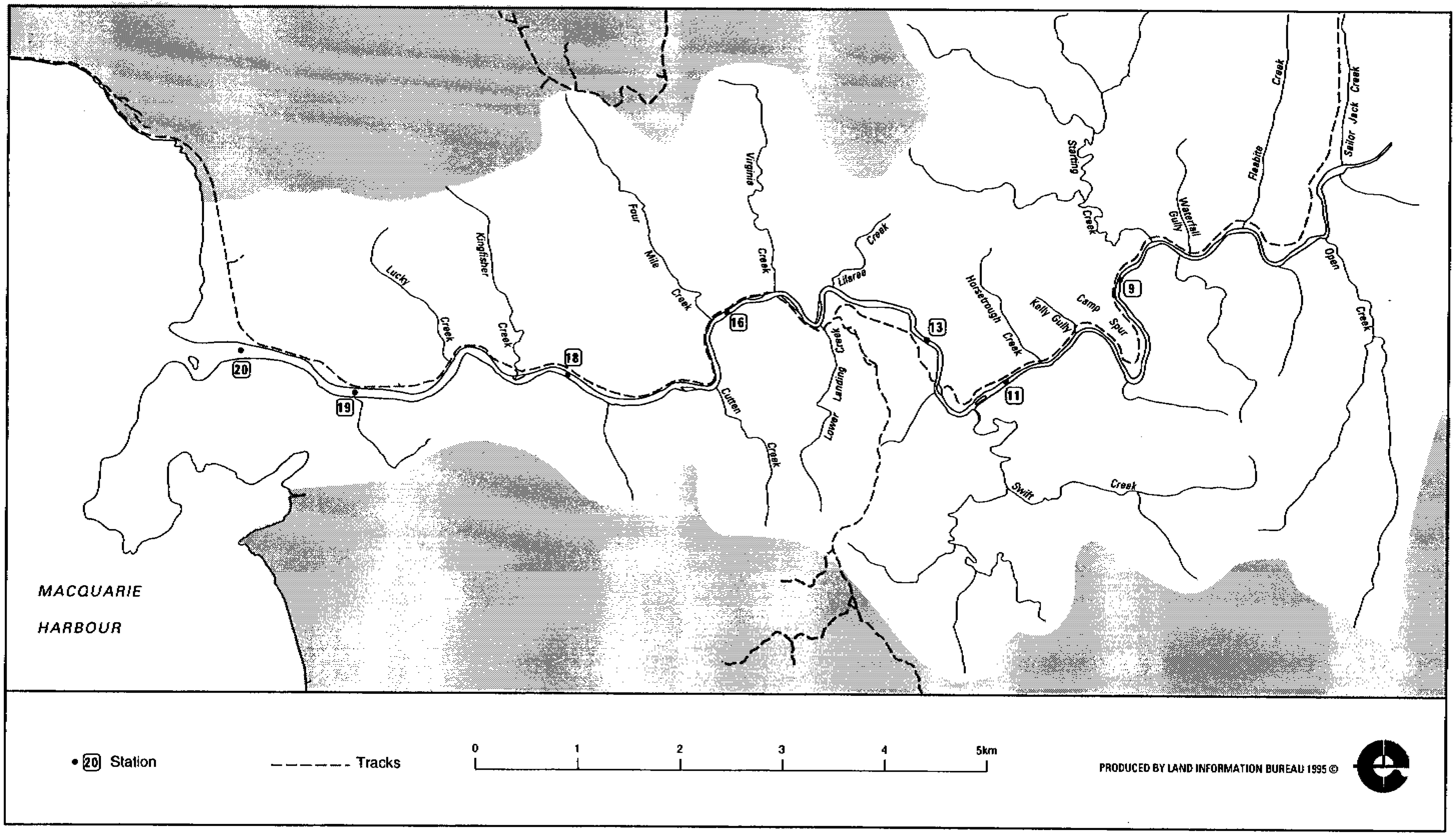


Figure 7.1 King River bed load samples 1994



Map 7.1 Bed load sampling locations

The data from Stations 13 and 18, which have the most measured bed load transport rates, is more closely examined in fig 7.2. In this figure, each data point is labelled with the total volume of water discharged in the 72 hour period prior to the bed load measurement. The results show that at Station 13, the higher bed load transport rates are associated with the lower prior discharge volumes, suggesting that bed load transport is supply limited and the higher prior discharge volumes have flushed through much of the sediment supply. At Station 18, on the other hand, the higher bed load transport rates are associated with the higher prior discharge, suggesting that there is no shortage of sediment supply and the higher prior discharges bring downstream a higher supply level. This is consistent with the relative storages of river bottom sediments between reach King3 and King4 as was presented in section 4.

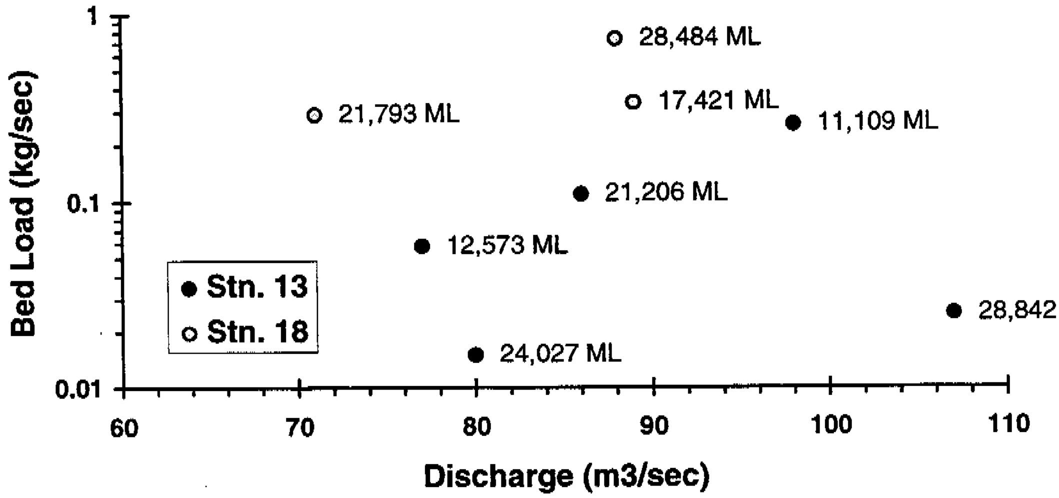


Figure 7.2 Bed load as related to prior discharge volumes

Some bed load measurements were also taken on one occasion in the Queen River below the Lyell Highway bridge in Queenstown, in December 1994 prior to the mine's closure and when the flow rate was 1.9 m^3/sec. The measured bed load transport rate was 2.185 kg/sec, or 188.81 tonnes/day. This represents 4.6% of the 4,109.6 tonnes/day of tailings which the mine was discharging prior to closure.

7.2.2 Particle characteristics

Particle size and characteristics in the King River were surprisingly variable across the cross-section, and between stations and flow levels, as illustrated in plates 7.1 to 7.3. Plate 7.2 of the Station 18 samples across the cross-section are particularly dramatic, as the particle size varied between small pebbles to silt-sized These samples are presently being sieved for particle size distributions.

7.3 Results post-mine closure

7.3.1 Measured bed load

A sample set comparable to that shown in fig 7.1 is presently being collected in the King River. Bed load samples collected post-mine closure will be plotted against flow and compared to the results pre-mine closure.

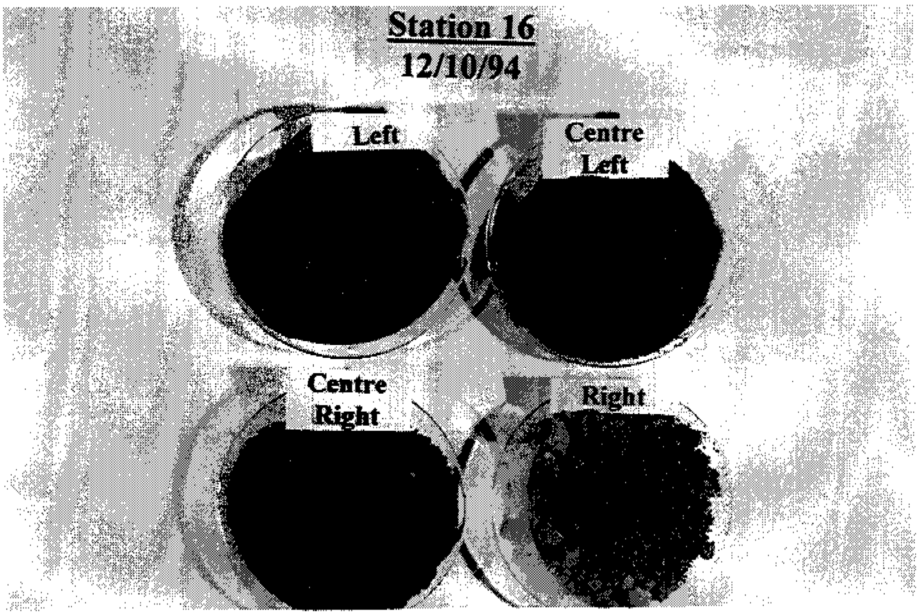


Plate 7.1 Bed load pre-mine closure: Station 16

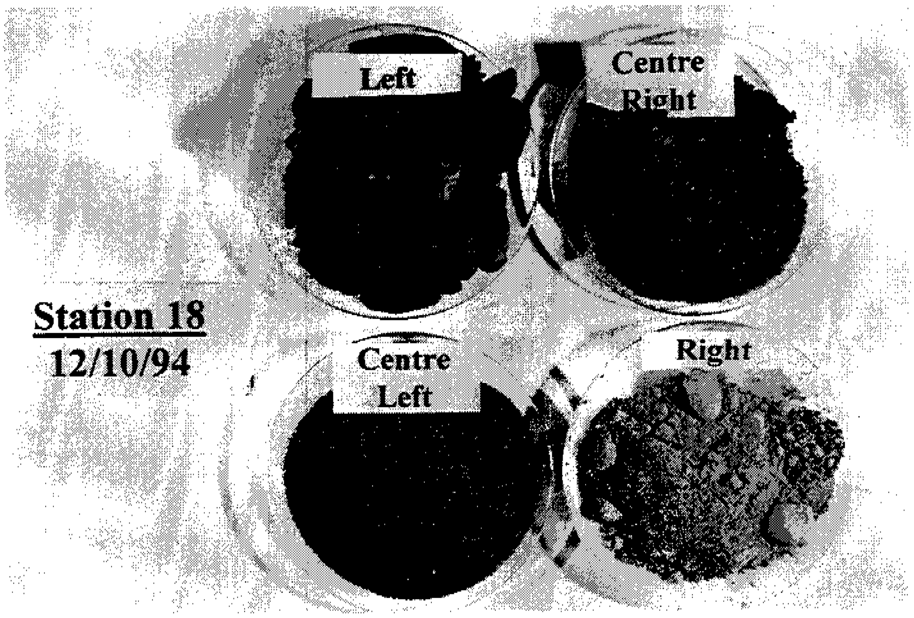


Plate 7.2 Bed load pre-mine closure: Station 18

7.3.2 Particle characteristics

Some photos are available of bed load characteristics post-mine closure, as shown in plate 7.4. The only observable difference at this stage is that a small component of orange/red bank sediments are becoming apparent in the bed load samples as the old tailings banks are starting to erode. Again, these samples will be sieved for determination of particle size distribution.

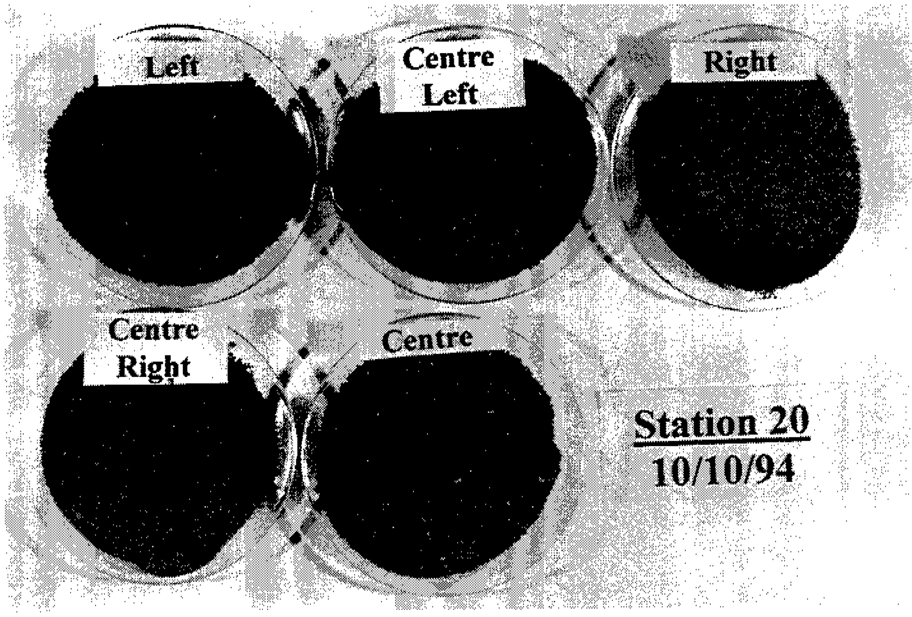


Plate 7.3 Bed load pre-mine closure: Station 20

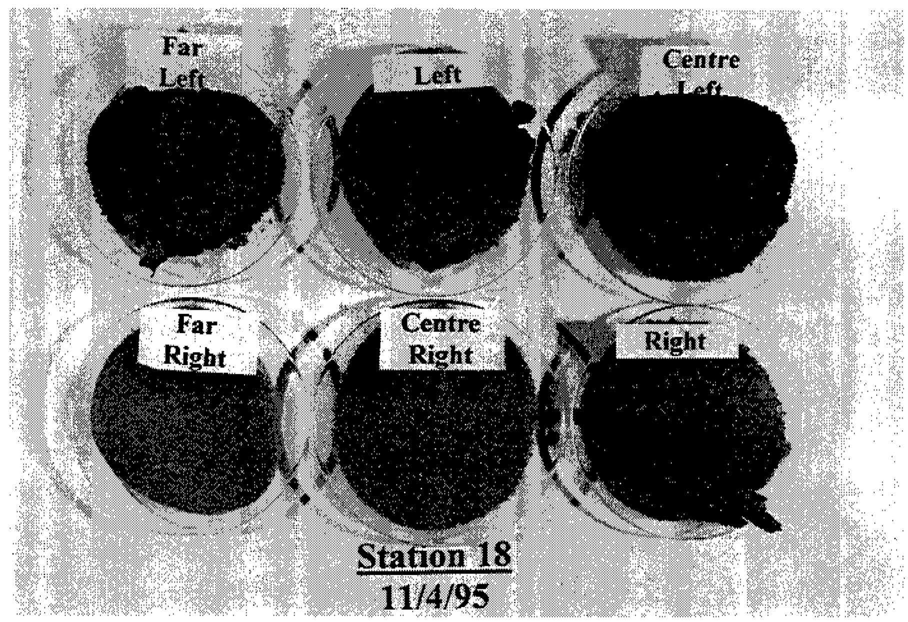


Plate 7.4 Bed load post-mine closure: Station 18

7.4 Summary

This section has presented the results of bed load sampling using a Helley-Smith bed load sampler. The results show no apparent trends with flow levels. There appears to be a measurable difference in bed load transport patterns between reaches King3 and King4. In reach King3 the bed load transport rate seems to be strongly influenced by prior discharge conditions, which affects the sediment supply available to transport. Transport in reach King4, on the other hand, is transport-limited rather than supply-limited. Particle characteristics are surprisingly variable, ranging from fine silt to coarse gravel across a single cross-section. More bed load samples are being collected during May and June 1995 to compare post-mine closure with pre-mine closure transport rates.

Because of the time, expense and difficulties in obtaining a comprehensive bed load data set from the field, it is necessary to extend the measured data set with bed load transport equations. The measured bed load will provide the calibration data to ensure that the most appropriate and realistic sediment transport equation is utilised. Sediment transport modelling is discussed in the following section.

8 Modelling

8.1 Sediment transport equations

Numerous sediment transport equations have been developed dating back as far as 1879. Table 8.1 provides a summary of sediment transport equations found in a review of the literature. These equations are listed in order of year of development, and identify whether they calculate bed load only, suspended and bed load separately, or determine a total sediment load. Unfortunately many of these equations are based on flume studies in laboratories with very uniform sediments and flow conditions, and are often found to be far from satisfactory when applied to real river situations. The 'challenge' is to carefully evaluate the conditions of derivation, variables used and major assumptions of the different equations and to choose that most appropriate to the river needing to be modelled.

At present there is no evidence that equations which deal with bed load and suspended load separately are of any more value than those which lump the two transport modes together (DHI 1993). One difficulty is defining the lower limit at which suspended sediment ceases and bed load transport starts. Suspended transport is defined as when the entire motion of the solid particles is surrounded by fluid, but particles can also move by saltation (jumping or skipping along the bottom) so the transition is not always clear. A number of suspended sediment transport relationships have been developed, and fall into either 'diffusion-dispersion' or 'energy' theories. One of the most widely used is Einstein's diffusion-dispersion theory, and is recommended over the energy theories of Rubey, Knapp, Bagnold and Velikanov because experimental evidence suggests it better fits observed data (Keller 1994).

The bed load equations all predict the sediment carrying capacity of a river, which is defined as the maximum bed load that a stream in equilibrium can possibly carry at the given hydraulic and sediment conditions. They traditionally fall into three groups, reflecting slightly different approaches used: Duboys-type, Schoklitsch-type and Einstein-type equations. Duboys is considered the classical form of bed load equation, and relates bed load discharge to the difference between the actual and critical shear stress on the bed. Schoklitsch follows a similar form of equation, but uses the difference between the water discharge rate and the critical water discharge at which the bed material starts to move. These equations are based on experimental results only, whereas Einstein's equations have a semi-theoretical background. The Einstein-type equations assume that fluid forces acting on bed sediments fluctuate randomly due to turbulence, and so use probability concepts which relate instantaneous hydrodynamic life forces to the particle's weight. Later sediment transport relationships have used other principles such as mean velocity and unit stream power, and these need to be investigated more thoroughly. Another option is to use the 'modified Einstein method' which extrapolates measured suspended load data down through an unsampled zone near the bed, and adds this to an incremental bed load determined from a shear stress relationship.

Table 8.1 Sediment transport formulas

SEDIMENT TRANSPORT FORMULAS	YEAR	USE	TYPE
Duboys	**1879**	Qb	critical shear stress
Meyer-Peter	**1934**	Qb	semi-critical shear stress
Schoklitsch	**1935**	Qb	critical discharge
Shields	**1936**	Qb	critical shear stress
Kalinske	**1947**		critical shear stress
Meyer-Peter & Muller	**1948**	Qb	semi-critical shear stress
Einstein-Brown	**1950**	Qb	turbulent forces
Einstein Bedload Function	**1950**	Qb	turbulent forces
Laursen	**1958**	Qb	critical shear stress
Rottner	**1959**	Qb	
Yalin	**1963**		
Blench Regime Formula	**1964**	Qb	
Colby	**1964**	Qb	mean velocity
Bishop et al	**1965**	Qt	turbulent forces
Bagnold	**1966**	Qt	gravity forces
Engelund-Hansen	**1967**	Qt	
Inglis-Lacey	**1968**	Qt	mean velocity
Toffaleti	**1969**	Qb & Qs	
Ackers-White	**1972**	Qt	dimensional analysis
Yang	**1973**	Qt	
Engelund-Fredsoe	**1976**	Qb & Qs	
Yang	**1976**	Qt	
MacDougall			
Zanke	**1979**	Qb & Qs	
Yang	**1979**	Qt	unit stream power
Karim	**1981**	Qt	
Ranga Raju, Garde & Bhardwaj	**1981**		effective shear stress
Parker, Klingeman & McLean	**1982**		effective shear stress
van Rijn	**1984**	Qb & Qs	gravity forces
Schoklitsch-Milhous	**1987**		critical discharge

The next stage of this study is to complete a more comprehensive review of the sediment transport equations presented above. This will be done by completing table 8.1 in terms of the underlying principles used in the equations. Other review tables which will need to be completed are table 8.2 on the conditions of development and any restrictions on intended usage of the equations, table 8.3 on the parameters used in the different equations, and table 8.4 which summarises the findings of various reviews of sediment transport equations. The equations will also be reviewed on how well results have compared to field data as collected for this study. The choice of equation will also be influenced by whether it uses imperial or metric units, how easily it lends itself to a spreadsheet or computer program, and if it is already available in a commercial software package.

A preliminary attempt was made to test the results of various transport equations against a realistic set of hydraulic conditions at the two stations on the King River for which the most sediment transport measurements have been made. The equations tested were those which looked the most appropriate from the information presently available in tables 8.1 to 8.4. The results, shown in table 8.5, were found to be wildly varying which reflects the different approaches used by the different equations. Additionally, some of the equations are based on the median particle size only and others calculate transport rates for the different size fractions. Note that the Engelund-Fredsoe and Van Rijn calculations are for bed load only, whereas the others are for total load. The value for measured sediment load was collected at a time when the mine was still discharging its tailings and so a large percentage is wash load (passing through the cross-section from upstream sources, in this case the mine) rather than suspended bed material. Engelund-Fredsoe and Van Rijn both have suspended sediment equations available, which will give an indication of what percentage of the measured suspended load is derived from the bed rather than the wash load.

Although the numbers in table 8.5 are very preliminary, they do give an indication of how much higher the predicted sediment transport is compared to any measured transport rates in the river. One hypothesis is that the high suspended load may somehow suppress the bed load transport rate, as it has been associated with dampening flow velocities (Coleman 1986); the post-mine closure bed load sample results will test this hypothesis. The cohesive nature of the tailings may also have affected the measured results by providing a greater resistance to the initial motion of the sediments.

One of the equations which has performed well in the reviews of sediment transport equations in the literature is the Ackers-White equation, which calculates a total sediment load. It is one of the equations incorporated into the sediment transport module of Mike-11, a commercial river modelling package available to this study. It also lends itself readily to incorporation into a spreadsheet as shown in table 8.6. This spreadsheet has been modified from one obtained from John Tilleard of Ian Drummond and Associates in Sale, Victoria, after consultation with one of the equation's developers Peter Ackers who did some work with John Tilleard. The spreadsheet calculates a theoretical sediment transport capacity (T) for each individual size fraction for a given reach of the river, and then tests this against the sediment available to determine the actual sediment transport.

One difficulty with the spreadsheet in table 8.6 is in the determination of the sediment supply available. To compare the sediment available with the theoretical transport capacity (bottom of table 8.6), a time rate must be given to the sediment supply to obtain a rate in kg/sec. This is useful for modelling a situation in which the sediment has not yet been discharged into the river system, and will be discharged at a known rate. It is not intended to be used in cases where significant deposits already exist spread throughout the river system. It may be interesting to use this approach with the scenario of no tailings in the river system, and 'supplying' them at the known rate of 1.5 million tonnes/year and at the known particle size distribution over time. The channel geometry in the lower King River would have to be hypothesised. However, this exercise could be time consuming and not provide any meaningful results.

A concern with sediment transport equations in general is the use of one particle size distribution, a mean velocity and channel gradient for a reach when field data shows how highly variable the parameters can be at a given cross-section, not to mention a reach as a whole. Plates 7.1 to 7.3 clearly illustrated that there is not a single particle size distribution which represents the load being transported past a river cross-section. A better understanding of the uses and limitations of sediment transport models will be gained following attendance at a conference in London in mid-September on hydraulics research and its applications. The organiser of the conference is Dr. Rodney White from the Wallingford Hydraulics Institute, who is the one of the developers of the Ackers-White equation, and it is likely that other researchers in the sediment transport field will also be in attendance.

Table 8.2 Conditions of development of equations

SEDIMENT TRANSPORT FORMULAS	CONDITIONS OF DEVELOPMENT					NOTES
	Flumes	River Data	Sediment Size (mm)		Specific Gravity	
Duboys	★		0.3-5.0	well-sorted		
Meyer-Peter	★		3.1-28.6	well-sorted		Invalid for fine sed., or where sign. flow resistance due to bed forms
Schoklitsch	★		0.3-5.0	well-sorted		Invalid for streams with considerable bed material in suspension
Shields	★		1.7-2.5	well-sorted	1.06-4.2	
Kalinske						Only for uniform grain shape; not accurate with low Tc/To
Meyer-Peter & Muller	★		0.4-30.0	graded	various	Invalid for flows with large suspended load
Einstein-Brown	★		0.3-7.0	well-sorted	various	
Einstein Bedload	★		fine sands	graded		Experiments conducted under plane bed conditions
Laursen	★		0.088-4.08	sorted & graded	2.65	Intended only for natural sediments with specific gravities of 2.65
Rottner						
Yalin						
Blench Regime	★		0.3-7.0	well-sorted		Intended only for sand streams in regime
Colby	★	★				Series of curves, best suited to sands 0.2-0.3 mm
Bishop et al						
Bagnold						
Engelund-Hansen	★		0.19-0.93			Not for rippled beds or seds < 0.15mm; only for dune covered beds
Inglis-Lacey						
Toffaleti						
Ackers-White						Does not account for unsteady flow conditions or graded sediments
Yang ('73)						
Engelund-Fredsoe						
Yang ('76)						
MacDougall						
Zanke						
Yang ('79)						Can be applied to flows with different types of bed forms
Karim						
Ranga Raju et al	★	★	wide range			
Parker et al						Appropriate for gravel bed streams only
van Rijn	★	★			various	Restricted to flow conditions with no bed forms
Schoklitsch-Milhous						

Table 8.3 Parameters required for equations

SEDIMENT TRANSPORT FORMULAS	Sediment Data		Fluid Data			Flow Data					
	Sediment Diameters	Spec. Wgt. Sediment	Spec. Wgt. Water	Viscosity	Water Temp.	Mean Flow Velocity	Mean Flow Depth	Shear Velocity	Bed Shear Velocity	Energy Slope	Discharge per unit width
		γ	γ	ν	T	V	d	u*	u*b	S	q
Duboys											
Meyer-Peter											
Schoklitsch	Dsi									★	★
Shields											
Kalinske											
Meyer-Peter & Muller	D90, Dsi	★	★			★			* (or Rb & S)		
Einstein-Brown	D50	★	★	★					* (or Rb & S)		
Einstein Bedload											
Laursen											
Rottner											
Yalin											
Blench Regime											
Colby	D50										
Bishop et al											
Bagnold											
Engelund-Hansen	D50	★	★			★		* (or R & S)			
Inglis-Lacey	D50	★	★	★		★	★				
Toffaleti	D65, Dsi	★	★	★	★	★	★			★	
Ackers-White	D35	★	★	★		★	★	* (or S)			
Yang ('73)	D50										
Engelund-Fredsoe	D50	★	★	★		★	★			★	
Yang ('76)	D50	★	★	★		★	★			★	
MacDougall											
Zanke											
Yang ('79)											
Karim	D50	★	★	★			★			★	★
Ranga Raju et al											
Parker et al											
van Rijn	D16,50,84,90	★	★	★		★	★			★	
Schoklitsch-Milhous											

Table 8.4 Reviews of sediment transport equations

SEDIMENT TRANSPORT FORMULAS	REVIEWS									
	Nakato (1990)	White et al (1975)	Yang & Wan (1991)				Herbertson (1969)	De Vries (1989)	ASCE (1971)	
			flumes	rivers	rivers, high Qs	rivers, low S			Niob. R.	Col. R.
Duboys									-	-
Meyer-Peter									-	-
Schoklitsch	*								*	*
Shields							-		-	-
Kalinske							-			
Meyer-Peter & Muller	-	-					*		*	*
Einstein-Brown	*						★		-	-
Einstein Bedload		*	-	★	★	*			*	*
Laursen			*	-	*	-			*	★
Rottner		★								
Yalin										
Blench Regime									*	*
Colby			*	*	★	*			★	★
Bishop et al		*								
Bagnold		-								
Engelund-Hansen	*	★	★	-	★	-			★	★
Inglis-Lacey	*								★	*
Toffaleti	★	*	-	★	*	*			★	★
Ackers-White	★	★	★	*	*	*				
Yang ('73)			★	★	*	★				
Engelund-Fredsoe	-									
Yang ('76)	*									
MacDougall										
Zanke										
Yang ('79)										
Karim	*									
Ranga Raju et al										
Parker et al										
van Rijn	-									
Schoklitsch-Milhous										
Nakato (1990)	Compared with measured suspended sediment loads on Sacramento River, California									
White et al (1975), Yang & Wan (1991)	Compared with a wide and extensive range of flume and river data									
Herbertson (1969)	No data, just comparison of underlying principles and assumptions									
ASCE (1971)	Niobrara R. total load measured directly, S=.0013, d50=0.283; Colorado River susp. sed. load measured and total load calculated using modified Einstein procedure; S=0.0002, d50=0.320 mm									

Table 8.5 Calculated versus measured sediment transport rates

LOCATION	STATION 13			STATION 18		
HYDRAULIC VARIABLES	Q=71.17 m3/sec v=0.76 m/sec	S=0.00025 Rh=1.8m	w=51.5m d50=0.186mm	Q=54.86 m3/sec v=0.63 m/sec	S=0.00015 Rh=1.49m	w=58.0m d50=0.141mm
EQUATION	CALCULATED BED LOAD (tonnes/day)	MEASURED SUSP. LOAD (tonnes/day)	CALCULATED TOTAL LOAD (tonnes/day)	CALCULATED BED LOAD (tonnes/day)	MEASURED SUSP. LOAD (tonnes/day)	CALCULATED TOTAL LOAD (tonnes/day)
Laursen			660.29			429.38
Colby			22.44			11.258
Inglis-Lacey			4179.2			3024.87
Engelund-Hansen			2129.05			614.9
Ackers-White			1479.51			518.23
Engelund-Fredsoe	275.19	1205.28	1480.47	100.91	1133.55	1234.46
Van Rijn	135.38	1205.28	1340.66	53.26	1133.55	1186.81
Yang			781.35			208.36
MEASURED	**9.85**	**1205.28**	**1215.13**	**25.92**	**1133.55**	**1159.47**

Table 8.6 Ackers-white spreadsheet

INPUT DATA - KING RIVER STATION 13

HYDRAULIC PROPERTIES	
Hydraulic gradient - i	0.00025
Hydraulic radius - R	1.8
Velocity - v	0.76
Discharge - Q	71.17
g	9.81
s	2.8
nu	0.000001307
(g(s-1)/nu^2)^(1	21783.62
v*	0.0664

SEDIMENT SUPPLY SIZE (mm)	%	VOL. (m3)	MASS (kg)
		165000	2.97E+08
2.36	0.36	594	1.07E+06
1.18	0.47	775.5	1.40E+06
0.600	1.56	2574	4.63E+06
0.500	1.45	2392.5	4.31E+06
0.425	2.65	4372.5	7.87E+06
0.355	8.38	13827	2.49E+07
0.300	10.6	17490	3.15E+07
0.250	22.56	37224	6.70E+07
0.212	18.61	30706.5	5.53E+07
0.180	11.49	18958.5	3.41E+07
0.150	10.87	17935.5	3.23E+07
0.075	9.99	16483.5	2.97E+07
0.000	0.99	1633.5	2.94E+06
	99.98	164967	2.97E+08

CALCULATIONS - ACKERS-WHITE PARAMETERS

PHI	D(mm)	Dgr	n	A	m	C	Fgr	Ggr	x (kg/L)	Theoretical Transport Capacity (T) (kg/s)
-8	256	5576.61	0	1.7	1.5	0.025	0.0342	0.00E+00	0.00E+00	0.00E+00
-7	128	2788.30	0	1.7	1.5	0.025	0.0416	0.00E+00	0.00E+00	0.00E+00
-6	64	1394.15	0	1.7	1.5	0.025	0.0516	0.00E+00	0.00E+00	0.00E+00
-5	32	697.08	0	1.7	1.5	0.025	0.0650	0.00E+00	0.00E+00	0.00E+00
-4	16	348.54	0	1.7	1.5	0.025	0.0828	0.00E+00	0.00E+00	0.00E+00
-3	8	174.27	0	1.7	1.5	0.025	0.1066	0.00E+00	0.00E+00	0.00E+00
-2	4	87.13	0	1.7	1.5	0.025	0.1384	0.00E+00	0.00E+00	0.00E+00
	3.36	73.19	0	1.7	1.5	0.025	0.1479	0.00E+00	0.00E+00	0.00E+00
	2.83	61.65	0	1.7	1.5	0.025	0.1580	0.00E+00	0.00E+00	0.00E+00
	2.38	51.85	0.0398	0.1719	1.526	0.0272	0.1734	1.86E-05	7.60E-08	5.41E-03
-1	2	43.57	0.0821	0.1748	1.562	0.0296	0.1910	7.19E-04	2.73E-06	1.95E-01
	1.68	36.60	0.1245	0.1780	1.604	0.0314	0.2109	2.09E-03	7.41E-06	5.27E-01
	1.41	30.71	0.1671	0.1815	1.655	0.0325	0.2334	4.10E-03	1.35E-05	9.61E-01
	1.19	25.92	0.2083	0.1852	1.713	0.0327	0.2580	6.61E-03	2.03E-05	1.45E+00
0	1	21.78	0.2506	0.1893	1.783	0.0321	0.2863	9.75E-03	2.79E-05	1.99E+00
	0.84	18.30	0.2931	0.1938	1.868	0.0307	0.3184	1.35E-02	3.59E-05	2.56E+00
	0.71	15.47	0.3339	0.1985	1.965	0.0286	0.3533	1.76E-02	4.38E-05	3.12E+00
	0.59	12.85	0.3790	0.2042	2.092	0.0258	0.3969	2.29E-02	5.29E-05	3.77E+00
1	0.500	10.89	0.4192	0.2097	2.227	0.0229	0.4411	2.86E-02	6.17E-05	4.39E+00
	0.420	9.15	0.4616	0.2160	2.396	0.0197	0.4938	3.60E-02	7.25E-05	5.16E+00
	0.350	7.62	0.5060	0.2233	2.607	0.0164	0.5565	4.66E-02	8.70E-05	6.19E+00
	0.300	6.54	0.5435	0.2300	2.818	0.0137	0.6165	5.92E-02	1.04E-04	7.39E+00
2	0.250	5.45	0.5878	0.2386	3.114	0.0108	0.6968	8.24E-02	1.34E-04	9.56E+00
	0.210	4.57	0.6302	0.2475	3.452	0.0084	0.7846	1.21E-01	1.84E-04	1.31E+01
	0.177	3.86	0.6718	0.2571	3.845	0.0063	0.8825	1.94E-01	2.74E-04	1.95E+01
	0.149	3.25	0.7137	0.2677	4.316	0.0047	0.9949	3.50E-01	4.62E-04	3.29E+01
3	0.125	2.72	0.7564	0.2794	4.888	0.0033	1.1257	7.54E-01	9.27E-04	6.59E+01
	0.105	2.29	0.7988	0.2921	5.563	0.0023	1.2743	1.99E+00	2.28E-03	1.62E+02
	0.088	1.92	0.8417	0.3061	6.379	0.0016	1.4466	6.95E+00	7.40E-03	5.27E+02
	0.074	1.61	0.8839	0.3212	7.333	0.0010	1.6404	3.31E+01	3.28E-02	2.34E+03
>4	0.0625	1.36	0.9250	0.3371	8.435	0.0007	1.8563	2.24E+02	2.08E-01	1.48E+04

CALCULATIONS - ACTUAL SEDIMENT TRANSPORTED

Theoretical Transport Capacity (T) (kg/s)	D (mm)	SEDIMENT VAILABILIT (kg)	SEDIMENT PRODUCTION (kg/s)	PROPORTION OF T	Cum Proportion	Sediment Transported (kg)
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
0.00E+00		0	0.00	0.00	7.12	0.00E+00
5.41E-03	2.38	1069200	0.03	6.27	7.12	1.55E+05
1.95E-01	2		0.00	0.00	0.85	0.00E+00
5.27E-01	1.68		0.00	0.00	0.85	0.00E+00
9.61E-01	1.41		0.00	0.00	0.85	0.00E+00
1.45E+00	1.19	1395900	0.04	0.03	0.85	1.40E+06
1.99E+00	1		0.00	0.00	0.82	0.00E+00
2.56E+00	0.84		0.00	0.00	0.82	0.00E+00
3.12E+00	0.71		0.00	0.00	0.82	0.00E+00
3.77E+00	0.59	4633200	0.15	0.04	0.82	4.63E+06
4.39E+00	0.500	4306500	0.14	0.03	0.79	4.31E+06
5.16E+00	0.420	7870500	0.25	0.05	0.75	7.87E+06
6.19E+00	0.350	24888600	0.79	0.13	0.71	2.49E+07
7.39E+00	0.300	31482000	1.00	0.14	0.58	3.15E+07
9.56E+00	0.250	67003200	2.12	0.22	0.44	6.70E+07
1.31E+01	0.210	55271700	1.75	0.13	0.22	5.53E+07
1.95E+01	0.177	34125300	1.08	0.06	0.09	3.41E+07
3.29E+01	0.149	32283900	1.02	0.03	0.03	3.23E+07
6.59E+01	0.125		0.00	0.00	0.00	0.00E+00
1.62E+02	0.105		0.00	0.00	0.00	0.00E+00
5.27E+02	0.088		0.00	0.00	0.00	0.00E+00
2.34E+03	0.074	29670300	0.94	0.00	0.00	2.97E+07
1.48E+04	<0.0625	2940300	0.09	0.00	0.00	2.94E+06

Table 8.7 Hydraulic variables from Mike-11

Date	Tide	Q	STATION 9							STATION 11							STATION 13						
			y	Rh	A	Q	v	b	S	y	Rh	A	Q	v	b	S	y	Rh	A	Q	v	b	S
	Level	m3/s	m	m	m2	m3/s	m2	m	m/m	m	m	m2	m3/s	m2	m	m/m	m	m	m2	m3/s	m2	m	m/m
12/7/94	Low	3.121	2.50	0.35	11	3.11	0.28	31	0.0013	1.46	0.30	11	3.14	0.29	35	0.00035	0.92	0.91	37	3.21	0.09	39	0.0005
	High	3.052	2.50	0.35	11	3.06	0.28	31	0.0013	1.45	0.30	11	3.08	0.28	35	0.00035	0.91	0.91	37	3.08	0.08	39	0.0005
13/7/94	Low	76.6	4.51	2.00	90	76.83	0.85	45	0.0013	3.20	1.80	89	76.91	0.86	48	0.00048	2.17	1.70	83	77.01	0.93	51	0.00043
	High	77.47	4.51	2.00	90	77.33	0.86	45	0.0013	3.21	1.80	89	77.1	0.87	48	0.00048	2.17	1.70	83	77.1	0.93	51	0.00043
29/6/94	Low	98.63	4.86	2.30	110	99.05	0.90	48	0.0013	3.52	2.00	100	99.01	0.99	49	0.00049	2.48	2.00	105	98.98	0.94	56	0.00041
	High	98.44	4.86	2.30	110	98.87	0.90	48	0.0013	3.52	2.00	100	98.88	0.99	49	0.0005	2.48	2.00	105	98.89	0.94	56	0.00041

Date	Tide	Q	STATION 16							STATION 18							STATION 19							STATION 20						
			y	Rh	A	Q	v	b	S	y	Rh	A	Q	v	b	S	y	Rh	A	Q	v	b	S	y	Rh	A	Q	v	b	S
	Level	m3/s	m	m	m2	m3/s	m2	m	m/m	m	m	m2	m3/s	m2	m	m/m	m	m	m2	m3/s	m2	m	m/m	m	m	m2	m3/s	m2	m	m/m
12/7/94	Low	3.121	0.43	1.10	53	3.6	0.07	50	0.00016	0.25	0.69	38	3.85	0.10	55	0.0002	0.22	0.75	62	3.91	0.06	85	0.000004	0.22	0.60	82	4.29	0.05	130	0
	High	3.052	0.53	1.20	58	2.69	0.05	50	0.00007	0.46	0.79	44	2.55	0.06	55	5E-06	0.48	0.88	76	-1.78	-0.02	89	0	0.48	0.70	119	-1.18	-0.01	150	0
13/7/94	Low	76.6	1.45	2.00	110	77.13	0.70	57	0.00023	1.13	1.10	70	77.19	1.10	60	0.00014	0.71	1.00	90	77.3	0.86	90	0.00017	0.51	0.74	120	77.4	0.65	152	0.00015
	High	77.47	1.45	2.00	110	77	0.70	57	0.00022	1.14	1.10	70	76.9	1.10	60	0.00014	0.75	1.10	94	76.6	0.81	90	0.00014	0.59	0.82	125	76	0.61	160	0.00012
29/6/94	Low	98.63	1.75	2.30	125	98.94	0.79	60	0.00024	1.38	1.40	88	98.93	1.12	61	0.00018	0.84	1.20	110	98.93	0.90	91	0.00021	0.59	0.82	125	99.32	0.79	160	0.0002
	High	98.44	1.75	2.30	125	98.87	0.79	60	0.00024	1.39	1.40	88	98.82	1.12	61	0.00018	0.86	1.20	110	98.65	0.90	91	0.00019	0.64	0.89	133	97.67	0.73	170	0.00017

8.2 Flow modelling

This study is using Mike-11, a one-dimensional unsteady flow modelling package developed by the Danish Hydraulics Institute, to develop a flow model for the King River. The need for a flow model is due to the tidal influence in reach King4. The determination of flows will enable calculation of sediment loads from all of the measured suspended sediment concentration data, and hence the determination of net scour and deposition in different river reaches. Additionally, Mike-11 will be used to obtain the hydraulic variables required by the sediment transport equations discussed above.

Mike-11 requires considerable input data to run. The King River model is using flow at Station 3 (the confluence of the King and Queen Rivers) as the upstream boundary condition, and the No 8 Beacon tide gauge in Macquarie Harbour as the downstream boundary condition. 23 channel cross-sections have been put into the model, most of them based on survey data collected during 1994, but some of which are estimated (eg outside edge of the delta, Macquarie Harbour at the No 8 Beacon, King River in the gorge section). Calibration data is obtained from the water level recorders at Station 13 and Cutten Creek.

The initial calibration effort used data from a 48 hour survey of the tidal zone as represented in fig 3.8. The model required such different friction coefficients for the low flow as compared to the high flow, however, that it was unable to be calibrated with the Station 13 and Cutten Creek data at both flow levels (eg the model set-up which enabled calibration with the power station on would not calibrate when the power station was off). Plate 8.1 shows the river bottom at Station 4 with the power station off, and clearly shows the very high bottom surface friction at low flow. Another source of difficulty may possibly have to do with the high suspended sediment load in the river altering the parameter relationships on which the Mike-11 flow model is based; it will be interesting to use a flow data set from the river since the mine has closed down to see if the calibration is more successful.

The model was calibrated against steady flow at several flow levels (3, 77 and 99 m^3/sec) and the friction coefficients which enabled calibration at low flow were very different from those used at high flow. Results for selected stations such as those shown in table 8.7 have been extracted from the calibrations at the three steady flow levels, and it is intended to run two more steady flow levels of 45 and 110 m^3/sec to generate rating curves for each of the selected stations. These hydraulic variables can be used to calculate sediment transport such as with the Ackers-White spreadsheet shown in table 8.6.

The sediment transport module of Mike-11 will be obtained soon and will be tested with the model set-up for the Mike-11 hydrodynamics module. It may prove quite important for the sediment transport module to be able to route a hydrograph through the hydrodynamics module, so that prior flow conditions are considered. This will be further investigated.

8.3 Summary

This section has introduced the work done on flow and sediment transport modelling. Flow modelling is required due to the tidal zone in the lower King River, and Mike-11 is being employed for this purpose. To date the calibration has not been satisfactory, which may have something to do with the influence of the high suspended sediment concentrations in the river, or the highly variable surface frictions at different flow levels, or the very sudden changes in flow levels with the power station operations. Sediment transport modelling is desirable to extend the very limited bed load transport data sets, but a lot of work is required to determine how best to utilise the sediment transport equations available in the literature. It may turn out that they provide little use at all, as most are based on flume studies under very uniform and controlled conditions and can not cope with local variabilities as found in nature. The engineering equations also calculate the maximum sediment transporting capacity of the river under the given hydraulic conditions, and do not readily take into account situations where the transport is supply-limited.

It is evident that considerably more work needs to be done in this study to complete the data collection and analysis and progress the modelling work. The next and final section summarises what has been learned about sediment transport, storage and deposition in the King River system, and the further work that is intended in this study.

Plate 8.1 Station 4 with power station off

9 Summary and further work

9.1 Present state of knowledge

This report has presented results of two years of work towards a PhD degree which has a further eighteen months until completion. This research investigating the river response to 78 years of artificially high sediment loads from a copper mine, monitoring the river response to the sudden cessation of this sediment load, and identifying means of influencing the river response to minimise downstream environmental impacts. Prior to the commencement of this research work, very little information was available on sediment transport and deposition in the Queen and King Rivers. This working paper documents the considerable amount of information gained to date about sediment storage and transport in the King River.

A scenario of river response to 78 years of artificially high sediment loads can be detailed from the data which has been presented in this report. The river system was naturally a gravel bed river with gravel carried as bed load and absolutely no sediment carried in suspension (similar to other west coast rivers in Tasmania). The King River channel itself is an old infilled valley, with gravels found as deep as 45m below sea level several kilometres upstream of the river mouth.

Due to the very fine nature of the tailings coming out of the mill, the vast majority of mine wastes have been carried in suspension through the river system and deposited in the delta at the mouth of the King River or out on the harbour floor. The smelter slag and the coarser fraction of the tailings have not made it out of the river system, and have infilled the last 7–8 km of the King River to a level just below sea level. This sand and fine gravel material is transported as bed load. During peak storm events, material carried in suspension has overtopped the natural levee banks beside the river and trapped the sediments as the flood waters have subsided. Successive flood events over the last 75 years have built very large sediment banks above the tidal zone of the river, but banks remain relatively flat within the tidal zone as they are more regularly inundated. There has been little to no change in the planform of the river, due to its confined nature, so most of the change to the hydraulic geometry of the channel has been aggradation of the banks and bed.

Since 1992 the flow patterns in the King River have dramatically altered, due to the commencement of regulated flows from the King River power scheme. The very high sediment banks in the last 5–8 km of the King River are no longer inundated as the peak flows are reduced to 30% of the pre-power station peak flows. The absence of major flow events has resulted in increased depositional rates in the river mouth just upstream of the delta. The commencement of braiding is evident in the last few kilometres of the King River, a response to excessive sediment loads which the river does not have the energy to transport. The processes of scour and deposition on the sediment banks have become very dynamic with the regular rise and fall of water levels due to the power station operations, but there has been little to no net growth of the sediment banks since 1992.

The power station's operations were shown to have a significant influence on suspended sediment concentrations within the King River channel while the mine was still discharging tailings. Sediments settled out of suspension when the power station was turned off, and a back-up of tailings continuously supplied from the Queen River was created just below the confluence of the King and Queen Rivers. This back-up of tailings was all lifted into suspension with the first flush of water released from the power station, and created a wave of very high suspended sediment concentrations which could be traced as it propagated downstream. Major plumes of suspended sediment appeared in Macquarie Harbour after extended periods with the power station off line.

Since the mine has ceased to discharge tailings into the river system, the river is in a state of readjustment which is presently being monitored. Suspended sediment concentrations have reduced to orders of magnitude less pre-mine closure concentrations, which makes bed load transport of the sands and fine gravels stored in the river bed the predominant sediment transport mode. The sediment banks are highly susceptible to erosion due primarily to the loss of the fresh cohesive tailings coating the bank surfaces. The limiting factor on bank retreat may be the original levee banks. Bank stability needs to be assessed in conjunction with the potential for lateral erosion and bed degradation in the river channel.

9.2 Further work

The immediate task at hand is to complete the field work identified within the body of this report which will allow comparison of the pre- and post-mine closure sediment transport and bank erosion processes.

Only limited further work is planned in this study on the sediment storages and bank stability. Particle size and copper analyses will be completed on the auger samples, and the auger holes and bank profiles surveyed to enable better mapping and characterisation of the mine-derived sediments. Drill cores will be collected from six locations along the King River bed to obtain a better picture of bed sediment characteristics and the potential for future scour. The overlay of the digitised 1898 railway map with the present day topographic map will be evaluated in terms of sediment storage patterns, to identify sections of the sediment banks most susceptible to erosion now that the mine has closed. The erosion pins and scour chains will continue to be monitored at least until July 1995, and probably on an occasional basis after that. A rough assessment of the bank stability will be made based on the particle size, angle of repose and flow characteristics, but no specific tests or additional measurements (eg of shear strength) are planned.

Most of the work which will be pursued in the completion of this PhD study relates to suspended and bed load transport and modelling. Calibration of the Mike-11 flow model will be further pursued, which will enable flows to be identified for the suspended sediment concentrations which have been collected in the field, and therefore sediment loads within different river reaches to be determined. Flow data will also be assigned to the turbidity data which will then be reviewed, rating curves will be applied as appropriate, and time series analyses conducted on the continuous data.

Bed load will be evaluated in more detail within each cross-section, looking at flow velocities, depths and particle sizes within the relevant verticals within the cross-section. Because of the limited nature of these data sets, they will be need to be extended using a suitable sediment transport equation.

A more thorough review of the sediment transport equations available in the literature will be conducted as a priority. The sediment transport modelling capabilities of Mike-11 will also be reviewed. It is believed that the data set collected in this study provides a good basis for sediment transport modelling. The best approach to modelling of sediment transport in the King River, and hence predicting future scour and deposition, needs to be determined based on discussions with those working in this field.

The main emphasis of this PhD study is the assessment of river response, which was defined in section 1 to include changes to the hydraulic geometry of the river channel, changes to extent, physical characteristics and stability of the sediments in storage, and changes in the physical characteristics, concentrations and transport patterns of suspended and bed load sediments. There are several extremal hypotheses relating to river response and the tendency towards equilibrium conditions which can be tested with the data collected in this study. Examples of these extremal hypotheses are the principle of minimum stream power and the principle of maximum sediment efficiency, which define the state towards which the channel geometry tends to adjust. An understanding of the equilibrium state towards which the river system is tending will enable management decisions to be made with a much greater likelihood of success.

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Appendix 1a Summary of gaugings: King River below Sailor Jack Creek

Date and Time	Mean Gauge Height	Discharge	Mean Velocity	Cross-Sectional Area	Wetted Perimeter	Discharge Deviation
	m	m3/s	m/s	m2	m	m3/s
30/11/1993 @ 14:05	0.427	3.082	0.222	13.865	15.486	-0.185
30/03/1988 @ 11:35	0.452	3.689	0.245	15.069	24.392	-0.039
26/03/1985 @ 12:20	0.516	4.669	0.308	15.176	24.126	-0.396
26/03/1985 @ 09:51	0.517	5.367	0.357	15.015	24.422	0.278
04/12/1985 @ 11:40	0.573	6.921	0.413	16.771	31.033	0.390
20/03/1986 @ 09:08	0.677	8.831	0.516	17.100	30.731	-0.871
08/02/1990 @ 12:16	0.705	8.947	0.477	18.747	31.527	-1.196
21/01/1986 @ 13:40	0.723	10.510	0.562	18.715	31.082	-0.820
25/09/1985 @ 13:35	0.855	11.090	0.604	18.365	31.795	-5.751
25/09/1985 @ 11:57	0.856	11.230	0.585	19.195	31.544	-5.652
16/10/1985 @ 10:15	1.228	11.440	0.511	22.410	32.955	-27.161
20/11/1985 @ 12:52	0.762	12.160	0.643	18.923	31.558	-0.670
12/09/1985 @ 14:14	0.919	12.310	0.624	19.720	31.450	-7.609
07/05/1986 @ 12:09	0.771	13.350	0.625	21.381	33.114	0.158
12/09/1985 @ 10:57	0.924	13.520	0.671	20.143	31.715	-6.653
26/02/1986 @ 08:47	0.810	13.700	0.621	22.070	32.525	-1.129
11/09/1985 @ 14:10	0.951	14.890	0.654	22.753	32.746	-6.676
17/02/1987 @ 12:00	0.798	15.440	0.648	23.826	32.541	1.122
10/09/1985 @ 12:34	1.002	15.640	0.673	23.233	32.386	-8.661
07/11/1985 @ 12:05	1.129	16.090	0.620	25.972	33.629	-15.829
10/09/1985 @ 10:41	1.005	16.100	0.668	24.099	32.583	-8.371
22/11/1990 @ 15:13	0.901	18.640	0.711	26.220	33.124	0.507
01/07/1986 @ 12:25	0.926	20.250	0.826	24.528	33.081	-0.021
01/07/1986 @ 10:00	0.935	20.970	0.898	23.351	33.279	0.236
01/09/1989 @ 11:49	0.986	22.360	0.887	25.214	32.643	0.029
21/03/1991 @ 09:35	0.980	23.510	0.867	27.113	32.704	1.492
08/10/1985 @ 11:29	1.209	27.680	1.011	27.370	34.005	-9.599
08/10/1985 @ 13:18	1.197	27.780	1.009	27.540	34.086	-8.672
30/05/1985 @ 10:53	1.172	31.560	1.032	30.568	35.767	-3.193
17/12/1985 @ 11:45	1.134	31.750	1.022	31.070	35.167	-0.492
24/05/1990 @ 12:27	1.250	32.170	1.007	31.946	35.622	-5.736
16/05/1985 @ 10:45	1.166	32.940	0.959	34.359	35.059	-1.412
25/08/1987 @ 11:00	1.130	34.080	1.040	32.773	34.416	2.091
17/12/1985 @ 09:10	1.206	36.700	1.119	32.790	35.141	-0.366
16/08/1990 @ 10:25	1.259	37.940	1.018	37.276	37.067	-0.573
09/04/1986 @ 11:27	1.318	44.400	1.335	33.268	35.360	-0.724
19/08/1986 @ 12:20	1.292	45.880	1.313	34.935	37.188	2.676
19/08/1986 @ 11:10	1.310	46.560	1.327	35.075	37.050	2.030
29/03/1990 @ 11:20	1.417	51.580	1.315	39.225	36.375	1.762
10/07/1989 @ 13:05	1.466	54.610	1.257	43.450	38.518	1.069
28/05/1986 @ 12:33	1.472	59.580	1.355	43.960	37.862	2.564
03/09/1985 @ 11:43	1.542	60.340	1.411	42.773	40.342	-2.277
11/05/1989 @ 12:30	1.645	62.500	1.423	43.930	37.434	-5.228
27/06/1985 @ 11:02	1.557	72.810	1.427	51.035	40.852	8.982
21/07/1993 @ 12:25	1.743	76.180	1.598	47.667	40.681	0.131
31/07/1985 @ 13:13	1.802	88.430	1.697	52.120	42.782	3.612
31/07/1985 @ 10:30	1.846	94.220	1.772	53.160	43.338	5.311
08/01/1987 @ 15:40	2.240	122.60	2.194	55.890	42.804	-7.247
08/05/1985 @ 14:10	1.950	141.80	2.175	65.210	43.083	42.867
29/05/1986 @ 12:15	2.365	144.80	2.362	61.330	43.931	0.390
08/05/1985 @ 12:45	2.040	150.00	2.122	70.683	43.265	41.882
29/05/1986 @ 10:18	2.485	158.60	2.404	65.980	44.121	-0.474
08/05/1985 @ 10:35	2.155	177.30	2.399	73.905	43.304	56.900
20/01/1987 @ 15:20	2.808	205.40	2.868	71.620	43.742	-1.252
20/01/1987 @ 14:07	2.820	207.90	2.914	71.360	44.040	-0.775
23/04/1986 @ 12:11	2.965	226.00	2.775	81.625	44.352	-8.675
20/01/1987 @ 13:00	2.910	227.10	3.029	74.970	44.020	2.555
14/01/1987 @ 15:56	3.170	265.80	2.991	88.875	45.388	-9.294
23/04/1986 @ 09:35	3.174	275.00	3.001	91.645	46.078	-0.902
26/05/1987 @ 13:31	3.505	355.40	3.375	105.30	47.643	6.138
26/05/1987 @ 12:31	3.601	378.90	3.633	104.30	48.125	6.444
26/05/1987 @ 11:10	3.743	396.90	3.389	117.13	47.975	-11.329
26/05/1987 @ 09:45	3.951	475.80	3.653	130.27	52.298	11.882

Appendix 1b Summary of gaugings: King River below Queen River

Date and Time	Mean Gauge Height	Discharge	Mean Velocity	Cross-Sectional Area	Wetted Perimeter	Discharge Deviation
	m	m3/s	m/s	m2	m	m3/s
12/01/1995 @ 15:51	0.703	0.901	0.199	1.882	7.419	-1.217
03/03/1995 @ 08:38	0.678	0.979	0.075	1.814	3.886	-1.013
10/12/1991 @ 14:50	0.835	2.800	0.305	3.019	10.092	0.040
10/12/1991 @ 14:50	0.882	2.865	0.326	3.019	10.092	-0.118
31/10/1991 @ 08:45	0.970	3.847	0.286	3.031	9.496	0.184
23/08/1993 @ 15:00	2.642	71.310	1.847	35.250	32.711	-0.107
16/09/1992 @ 13:44	2.702	74.370	1.954	36.628	30.385	0.113
24/08/1993 @ 12:10	3.296	102.100	1.957	49.793	33.483	-2.870
16/09/1992 @ 10:44	3.208	102.800	1.974	50.628	32.672	2.793
18/06/1994 @ 12:30	5.430	277.000	1.982	133.580	43.333	-0.017

Appendix 1c Summary of gaugings: Queen below Lynchford Camp

Date and Time	Mean Gauge Height	Discharge	Mean Velocity	Cross-Sectional Area	Wetted Perimeter	Discharge Deviation
	m	m3/s	m/s	m2	m	m3/s
03/03/1995 @ 09:20	0.436	0.515	0.307	1.679	6.080	-0.253
12/01/1995 @ 16:35	0.465	0.526	0.175	3.001	7.318	-0.455
04/04/1989 @ 12:48	0.461	0.719	0.401	1.792	6.099	
14/12/1994 @ 08:25	0.467	0.854	0.307	2.787	7.750	-0.142
03/01/1995 @ 14:19	0.502	0.915	0.255	3.591	7.949	-0.353
02/03/1990 @ 07:54	0.472	0.931	0.470	1.983	7.520	
11/02/1988 @ 19:17	0.462	0.987	0.505	1.953	5.698	
12/01/1988 @ 17:30	0.476	1.002	0.447	2.243	10.145	
03/12/1986 @ 09:23	0.470	1.064	0.689	1.545	6.230	
17/11/1992 @ 15:10	0.524	1.093	0.308	3.553	8.444	-0.348
14/03/1990 @ 15:36	0.513	1.173	0.194	6.062	10.985	
23/01/1990 @ 16:45	0.497	1.256	0.461	2.715	7.344	
21/11/1986 @ 08:47	0.520	1.339	0.505	2.655	6.792	
14/12/1987 @ 13:25	0.509	1.383	0.378	3.662	10.830	
10/12/1987 @ 18:15	0.544	1.519	0.423	3.587	11.223	
15/08/1989 @ 09:05	0.547	1.556	0.525	2.965	10.349	
07/09/1989 @ 17:10	0.563	1.606	0.431	3.725	11.198	
16/05/1989 @ 13:50	0.552	1.755	0.581	3.018	8.521	
25/10/1990 @ 16:28	0.558	1.822	0.460	3.959	8.630	0.060
15/09/1992 @ 15:21	0.605	2.051	0.403	5.096	9.994	-0.387
18/07/1986 @ 08:23	0.596	2.151	0.595	3.615	9.543	
21/02/1989 @ 13:15	0.570	2.266	0.637	3.556	9.140	
18/07/1986 @ 09:18	0.594	2.272	0.612	3.714	9.626	
08/08/1986 @ 08:15	0.580	2.293	0.603	3.803	9.659	
13/11/1987 @ 07:50	0.595	2.363	0.781	3.027	11.269	
19/03/1991 @ 17:36	0.614	2.423	0.565	4.285	9.078	-0.181
16/09/1992 @ 08:24	0.657	2.815	0.492	5.720	10.212	-0.677
31/10/1991 @ 10:45	0.650	2.942	0.630	4.670	9.768	-0.395
03/06/1993 @ 11:48	0.646	3.205	0.573	5.591	10.722	-0.045
01/08/1990 @ 16:55	0.639	3.277	0.812	4.035	10.502	0.176
23/01/1987 @ 09:30	0.727	4.428	0.848	5.219	11.537	
22/07/1992 @ 16:25	0.726	4.734	0.901	5.257	11.601	-0.484
18/08/1988 @ 09:15	0.741	5.360	0.793	6.762	12.636	
24/02/1993 @ 14:12	0.774	6.460	1.053	6.138	11.993	-0.149
10/02/1989 @ 08:15	0.818	7.086	1.123	6.308	11.683	
15/01/1987 @ 08:24	0.852	8.295	1.185	6.998	11.950	
15/01/1987 @ 09:03	0.842	8.312	1.242	6.693	11.999	
23/07/1993 @ 00:00	0.833	8.740	1.233	7.088	12.262	0.244
22/06/1993 @ 09:00	0.836	8.822	1.277	6.908	12.050	0.224
13/05/1987 @ 08:44	0.874	9.859	1.331	7.407	11.980	
06/05/1987 @ 08:01	0.886	10.530	1.330	7.917	12.091	
18/06/1994 @ 15:00	0.959	12.260	1.473	8.322	12.355	-0.746
11/06/1992 @ 09:45	0.963	13.360	1.519	8.795	12.593	0.208
21/01/1987 @ 09:14	1.074	16.470	1.766	9.326	12.340	
03/09/1990 @ 15:27	0.995	16.880	1.692	9.974	12.718	2.514
21/01/1987 @ 10:00	1.097	17.270	1.824	9.468	12.359	
18/08/1992 @ 16:15	1.063	17.910	1.690	10.594	13.081	0.939
01/05/1990 @ 11:00	1.099	18.440	1.737	10.615	12.753	
01/05/1990 @ 09:37	1.150	21.840	1.912	11.426	12.954	
07/08/1988 @ 15:14	1.183	22.030	1.889	11.663	13.447	
24/11/1987 @ 17:53	1.195	22.330	1.876	11.901	13.529	
12/09/1990 @ 08:20	1.194	23.420	1.921	12.190	13.584	1.422
07/08/1988 @ 14:29	1.225	24.000	1.924	12.480	13.386	
22/09/1992 @ 13:14	1.330	26.660	1.920	13.887	14.053	-0.559
26/05/1987 @ 11:20	1.410	30.280	1.994	15.184	14.776	
26/05/1987 @ 09:40	1.810	39.280	2.124	18.490	15.698	
26/05/1987 @ 08:36	1.980	48.150	2.305	20.892	16.605	
11/01/1989 @ 07:11	2.465	73.190	2.378	30.783	17.854	

Appendix 2 Auger samples

Auger Hole	AHD Hgt.	Sample Ref.	Sample Depth	Sample Wgt. (wet)	Field Texture	Organics	% Size < 75 um	Copper (mg/kg)
AA1	?	AA1-1	0-40	450	SL		45.42	*
		AA1-2	40-45	80	SL			*
		AA1-3	45-80	380	L	F, S		*
AA2	?	AA2-1	0-40	245	SL		48.88	*
		AA2-2	40-80	255	CL	F, S		*
		AA2-3	80-100	290/240	CL	F, S		*
DD1	?	DD1-1	0-20	240	CS		52.18	*
		DD1-1.5	20-40	350	CS			
		DD1-2	20-40	215	CS			
		DD1-3	40-80	395	CS			*
		DD1-4	160-200	560	CS		19.50	*
		DD1-5	220-240	525	CS			*
DD2	?	DD2-1	0-10	305	S		13.94	
		DD2-2	10-20	206	S		5.56	
		DD2-3	20-30	760	S			*
		DD2-4	30-40	655	S			
		DD2-5	60-80	615	LS	F		*
		DD2-6	80-90	190	L	F		*
		DD2-7	90-100	180	CL	F		
		DD2-8	100-140	555	CL	F	42.01	*
		DD2-9	180-200	235	L	S		
DD3	?	DD3-1	0-10	735	S		3.69	
		DD3-2	25-35	670	S			*
		DD3-3	35-60	1115	S			*
		DD3-4	60-80	350	S			*
		DD3-5	80-130	615	CL	F, S		*
		DD3-6	130-170	475	CL	F, S		
DD4	?	DD4-1	0-5	950	CS			
		DD4-2	5-10	850	CS		0.46	
		DD4-3	10-15	690	CS		5.32	*
		DD4-4	45-60	455	SL	F	19.87	*
		DD4-5	60-85	280	SCL	F, S	45.92	*
		DD4-6	85-100	215	SiCL	F	78.48	*
		DD4-7	110-140	375	SiCL	F, S	71.38	
DD5	?	DD5-1	0-40	230	CS		14.51	*
		DD5-2	40-55	125	CS			*
		DD5-3	55-65	105	CS			*
		DD5-4	65-75	125	SCL	F, S		*
		DD5-5	75-100	230	SiC	F, S	42.93/11.40	*
HH1	3.271	HH1-1	0-25	360	S		11.40	1913.27
		HH1-2	25-50	250	CS		22.77	298.80
		HH1-3	75-100	200	L	F, S	44.02	706.25
		HH1-4	100-200	315	SCL		49.21	119.18
		HH1-5	200-300	315	SCL		57.37	43.60
HH2	3.937	HH2-1	0-150	315	S		5.58	223.88
		HH2-2	150-200	255	S		18.98	518.75
		HH2-3	200-275	180	SCL	F	31.09	1897.06
HH3	3.795	HH3-1	0-125	320	S		5.66	353.17
		HH3-2	125-200	415	CS		20.36	977.75

Appendix 2 Auger samples (cont'd)

Auger Hole	AHD Hgt.	Sample Ref.	Sample Depth	Sample Wgt. (wet)	Field Texture	Organics	% Size > 75 um	Copper (mg/kg)
LL1	5.801	LL1-1	0-25	345	S		6.39	712.04
		LL1-2	70-80	175	CS		11.93	195.94
		LL1-3	80-90	215	SCL	S	27.29	95.80
		LL1-4	180-200	460	CS	F	28.58	35.60
		LL1-5	300-320	365	CS		23.66	
		LL1-6	500-520	450	CS		25.93	29.71
		LL1-7	540-560	495	CS		*	
		LL1-8	580-600	315	SCL	S	39.86	9.08
		LL1-9	640-660		wood			
LL2	6.127	LL2-1	0-20	250	CS	F	12.47	178.08
		LL2-2	60-80	260	SCL		23.91	13.65
		LL2-3	150-180	840	SCL		34.05	10.49
		LL2-4	280-300	505	CS		20.16	
		LL2-5	390-400	470	SCL		52.23	8.24
		LL2-6	400-420	290	SCL		46.50	
LL3	4.661	LL3-1	0-20	310	CS		23.87	1075.49
		LL3-2	60-80	210	CS		39.01	1394.90
		LL3-3	80-100	215	S		9.23	3142.86
		LL3-4	100-120	135	S		10.31	
		LL3-5	140-200	525	SCL		31.46	2521.57
		LL3-6	290-300	430	SCL		*	*
NN1	6.228	NN1-1	20-40	360	CS		4.05	*
		NN1-2	120-140	340	CS			
		NN1-3	200-220	485	SCL	F		*
		NN1-4	220-240	550	SCL	F	63.27	*
		NN1-5	600-630	270	SCL		56.95	*
		NN1-6	650-700	540	SCL	F	41.54	
		NN1-7	700-720	495	L	F	43.95	
NN2	5.866	NN2-1	20-40	400	CS		14.27	*
		NN2-2	90-100	340	CS			
		NN2-3	105-110	590	CS		12.52	*
		NN2-4	155-160	400	CS			*
		NN2-5	180-220	455	SL		10.83	*
		NN2-6	350-400	600	SCL		39.31	*
		NN2-7	450-460	350	SCL	F, S		*
		NN2-8	460-470		wood			
NN3	6.224	NN3-1	20-40	300	CS		9.90	*
		NN3-2	80-100	280	CS		32.42	*
		NN3-3	190-200	260	LS	F	28.24	*
		NN3-4	250-280	300	L	F, S	58.87	*
		NN3-5	450-480	570	C			*
NN4	?	NN4-1	0-20	420	CS	F		
		NN4-2	40-60	510	LS	F		
NN5	?	NN5-1	0-20	410	SiL	F		
		NN5-2	40-60	295	L	F		
NNa	5.824	NNa-1	40-60	460	CS		28.03	*
		NNa-2	160-200	915	CS		51.18	*
		NNa-3	240-260	605	SCL	F		*
		NNa-4	480-520	250	SiC		88.61	*

Appendix 2 Auger samples (cont'd)

Auger Hole	AHD Hgt.	Sample Ref.	Sample Depth	Sample Wgt. (wet)	Field Texture	Organics	% Size > 75 um	Copper (mg/kg)
QQ1	6.964	QQ1-1	0-30	355	CS		3.51	*
		QQ1-2	110-150	325	SCL		28.87	*
		QQ1-3	160-190	295	SL		29.05	*
		QQ1-4	310-350	400	SL			*
		QQ1-5	440-470	440	SL			
		QQ1-6	560-580	660	SL			
		QQ1-7	580-590	285	SL			
QQ2	6.61	QQ2-1	0-40	370	CS		12.05	522.69
		QQ2-2	80-120	395	CS		16.49	172.12
		QQ2-3	120-160	285	SCL		26.73	185.96
		QQ2-4	200-240	525	SCL		68.81	48.85
		QQ2-5	320-360	410	CS			
QQ3	5.863	QQ3-1	0-40	200	CS		5.56	
		QQ3-2	50-60	90	CS		13.39	
		QQ3-3	60-120	340	CS		10.79	*
		QQ3-4	160-190	315	CS		11.31	*
		QQ3-5	190-200	150	SCL	F, S	21.54	*
		QQ3-6	200-215	235	SCL	F, S	31.50	*
		QQ3-6a	215-260	380	SCL	F	33.33	*
		QQ3-7	260-300	370	SCL			*
		QQ3-8	310-340	515	CL		55.52	
QQ4	4.871	QQ4-1	2-85	300	CS		7.79	*
		QQ4-2	85-120	180	SL	F		*
		QQ4-3	120-180	125	SL	F	13.00	*
QA1	6.85	QA1-1	0-40	335	S		6.49	
		QA1-2	80-110	175	S		10.05	*
		QA1-3	110-120	120	CS		12.90	
		QA1-4	125-160	270	CS	F	12.36	
		QA1-5	160-200	205	CS	F	14.92	*
		QA1-6	200-240	410	CS		12.76	
		QA1-7,8	240-280	250	CS		17.31	
		QA1-9	280-320	460	SCL		19.58	*
		QA1-10	320-360	530	SCL		17.00	
		QA1-11	400-580	200	CL		25.50	*
QA2	7.161	QA2-1	140-180	370	SCL		23.05	*
		QA2-2	180-230	345	SCL		20.60	*
		QA2-3	280-300	135	CL		35.98	*
QA3	5.856	QA3-1	40-60	455	CS	F	*	*
		QA3-2	60-90	345	SL		*	*
		QA3-3	90-115	265	L	F, S	*	*
		QA3-4	140-160	300	CL		*	
QB1	3.635	QB1-1	40-80	250	CS		12.69	*
		QB1-2	120-160	195	SL			*
		QB1-3	160-180	165	SCL	S		*
QB2	5.959	QB2-1	40-80	285	CS		16.62	840.10
		QB2-2	160-200	215	SL		18.40	1028.00
		QB2-3	220-240	440	SiC		77.95	72.40
		QB2-4	240-360	515	CL		29.05	138.16

Field Texture:

L - Loam S - Sand SL - Sandy loam
C - Clay SiL - Silty loam
CS - Clayey sand SiC - Silty clay
CL - Clayey loam SCL - Sandy clay loam

Organics: