($(Ca,Mg)CO_3$) being most common. Accessory phases include magnetite (Fe_3O_4), chromite ($FeCr_2O_4$), hematite (Fe_2O_3), goethite ($FeO(OH)$), ilmenite ($FeTiO_3$), rutile (TiO_2), limonite ($FeOH.nH_2O$), barite ($BaSO_4$), anhydrite ($CaSO_4$), apatite ($Ca_5(PO_4)_3(OH,F,Cl)$, fluorite (CaF_2) and monazite ($(Ce,La,Th)PO_4$), and rare to trace amounts of native copper, metallic gold and electrum (Au–Ag alloy) have been reported.

The ecological impact of ARD on Macquarie Harbour has received little attention until recently. Acid drainage from the King River has been implicated as a potential contributing factor in a number of significant fish losses incurred by a fish farm in Macquarie Harbour (Wood 1991). If ARD is proven to be a key issue in local fish kills, it is likely that periodic flushing 'events' may have a more significant short-term impact on the ecology of the harbour than those caused by sustained but lower level acid/metal release.

Carpenter et al (1991) provided an excellent base of fundamental chemical and biochemical data on Macquarie Harbour water and sediments. One conclusion of particular relevance to this study is the identification of significant bacterial populations in harbour sediments. Similar microbial biomasses were reported from three sediment samples analysed, but differences in the relative abundance of phospholipid-derived fatty acids at each site indicated variable microbial community structures. Significant populations of anaerobic bacteria were present in sediments near the mouth of the King River, and biomarkers for sulphate reducing bacteria were present in all samples.

3 Field work

3.1 Introduction

Thirty-four person days of field work were conducted on the King River delta and sediment bank deposits between 28 July and 3 August 1995. The field component consisted of:

- installing and surveying mini-piezometers in key locations (see Sediment sampling) within the delta and sediment bank deposits;
- sampling groundwater from the piezometers and selected surface water;
- determining field chemical parameters for groundwater samples from piezometers (pH, redox potential (Eh), Conductivity (EC);
- filtering and acidifying groundwater samples from the piezometers for trace metal analysis;
- measuring groundwater levels and water level recovery rates in piezometers to establish hydrogeological conditions;
- drill testing and geological logging at selected locations;
- determining field chemical parameters (pH, Eh, EC) for groundwater and surface water from numerous localities (eg traverses on delta);
- extensive shallow auguring (0.1 to 1.5 m) for geological samples and hydrogeological data;
- limited surveying to assist with mass balance calculations based on aerial photo analysis.

3.2 Sediment sampling

Introduction

Tailings sediment samples were collected from four types of deposit.

- Sediment taken from the King River delta (plate 1).
- Sediment taken from banks along the King River, which can be broadly divided into (a) mounded banks above Teepookana (plate 2), and (b) lower relief banks downstream (plates 3 and 4).
- Sediment taken from the bed of the King River.

Grab samples from surface and near-surface environments were obtained by shovel, and hand augers permitted sediments from as deep as 1.5 m to be retrieved. Sonic drilling techniques enabled partial sediment recovery from as deep as 7.5 m, and percussion drilling permitted sampling from around the cutting head. All of these techniques resulted in significant physical disruption of tailings material. Samples from water saturated zones were collected with their pore water to minimise chemical modification during storage. River bottom samples were stored in 50 mL LDPE screw-top bottles and other sediment samples were collected in 250 mL screw-top LDPE bottles. Samples were transferred to large insulated coolers after each day's field work.

Drilling

Banks/delta

Two holes were drilled in tailings material; one in the delta (DEL-C1: between DEL-WS7 and DEL-WS8) was terminated at 5.5 m (figure 2, plate 5), and the other in Bank R (R-C1: 10 m south of R-WS2) was completed to a depth of 7.45 m (figures 3 and 4). A hand-held sonic drill rig fitted with a self-locking tool for recovering sediment cores was employed to assist with continuous sampling. The unconsolidated sediment was logged and sampled. Sample numbers and descriptions are included in Appendix 1, and geological logs for the drillholes are included in Appendix 2.

River bottom

Sampling of river bottom sediment was coordinated by Helen Locher (MLRRDP – Project 4) using the sonic drilling equipment located on a small barge. Seven holes were completed at 5 sites in the King River, and station locations are indicated on figure 5. Fifty-eight subsamples of this material stored in 50 mL LDPE bottles were made available to this study group for mineralogical and chemical evaluation. Brief sample descriptions are provided in Appendix 1.

Auger and grab samples

Sixty-five samples of tailings material were collected over a range of depths from both mounded and flat overbank deposits and the delta using shovel and hand augers. Some additional grab samples were retrieved from the base of the piezometer drillholes from the cutting head of a hand-held percussion drill rig. These samples were taken close to the monitoring zone, to permit comparison between water chemistry and mineralogical analysis. Sample location information is provided on figures 2 and 4, and Appendix 1.

Plate 1 View from the north-west margin of the south lobe of the delta at the tidal interface zone, looking to the south-east. This plate highlights the delta's low relief and lack of vegetation.

Plate 2 View of the downstream end of Bank N, looking down river. Trees that were established and growing within tailings and subsequently died are common, and sparse new vegetation is evolving. Ephemeral waterways are developed on the landward-side of the crest of the bank.

Plate 3 Typical view of Bank H, looking downstream. The King River is on the left, and an ephemeral creek is evident on the far right. The remains of numerous immature trees that must have been established in the tailings are distributed across the bank. Little new growth is evident.

Plate 4 View of Bank D, looking upstream. Numerous tree stumps are distributed throughout. Three piezometers installed in the bank are visible as white poles.

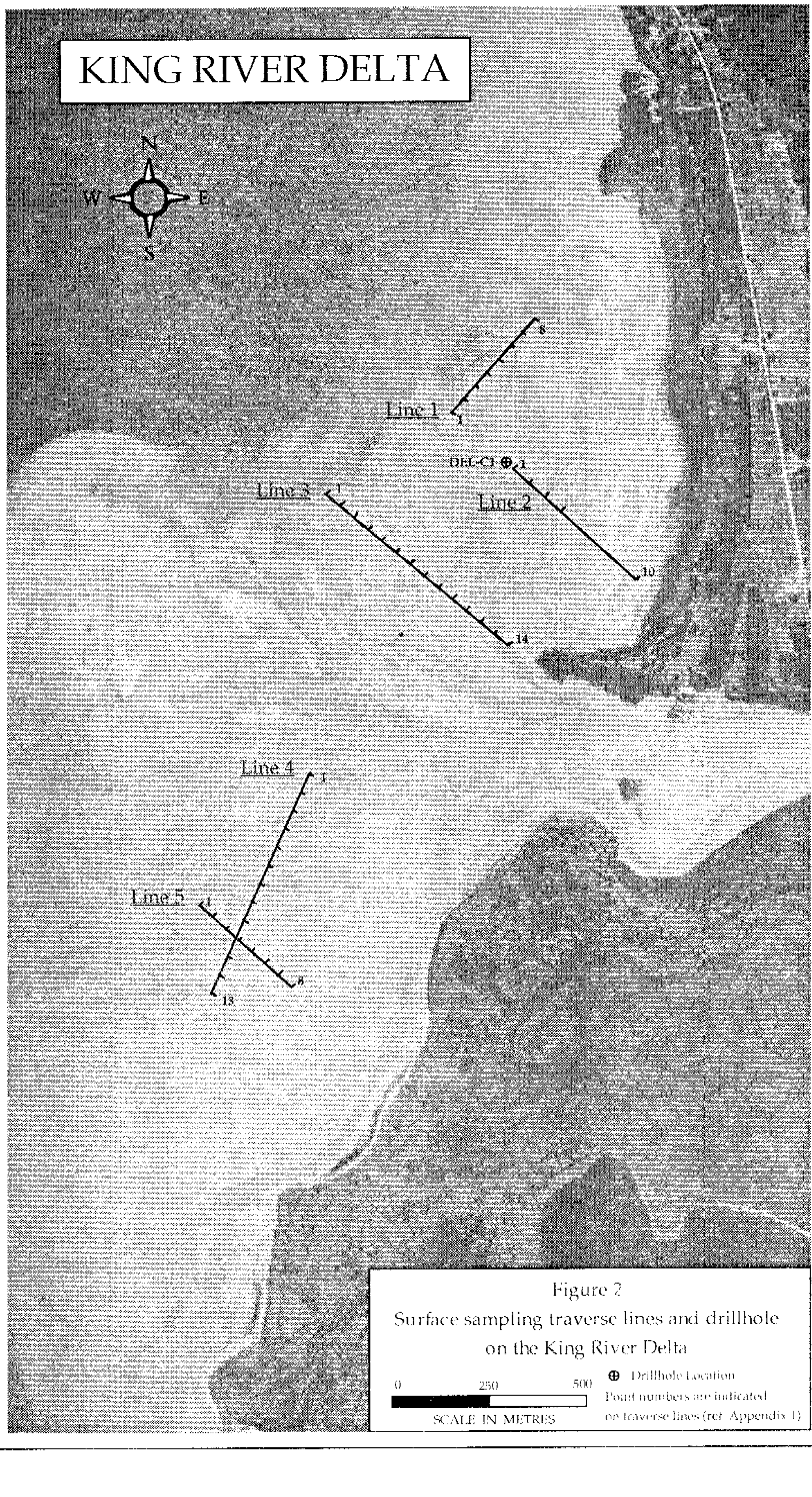

Figure 2
Surface sampling traverse lines and drillhole on the King River Delta

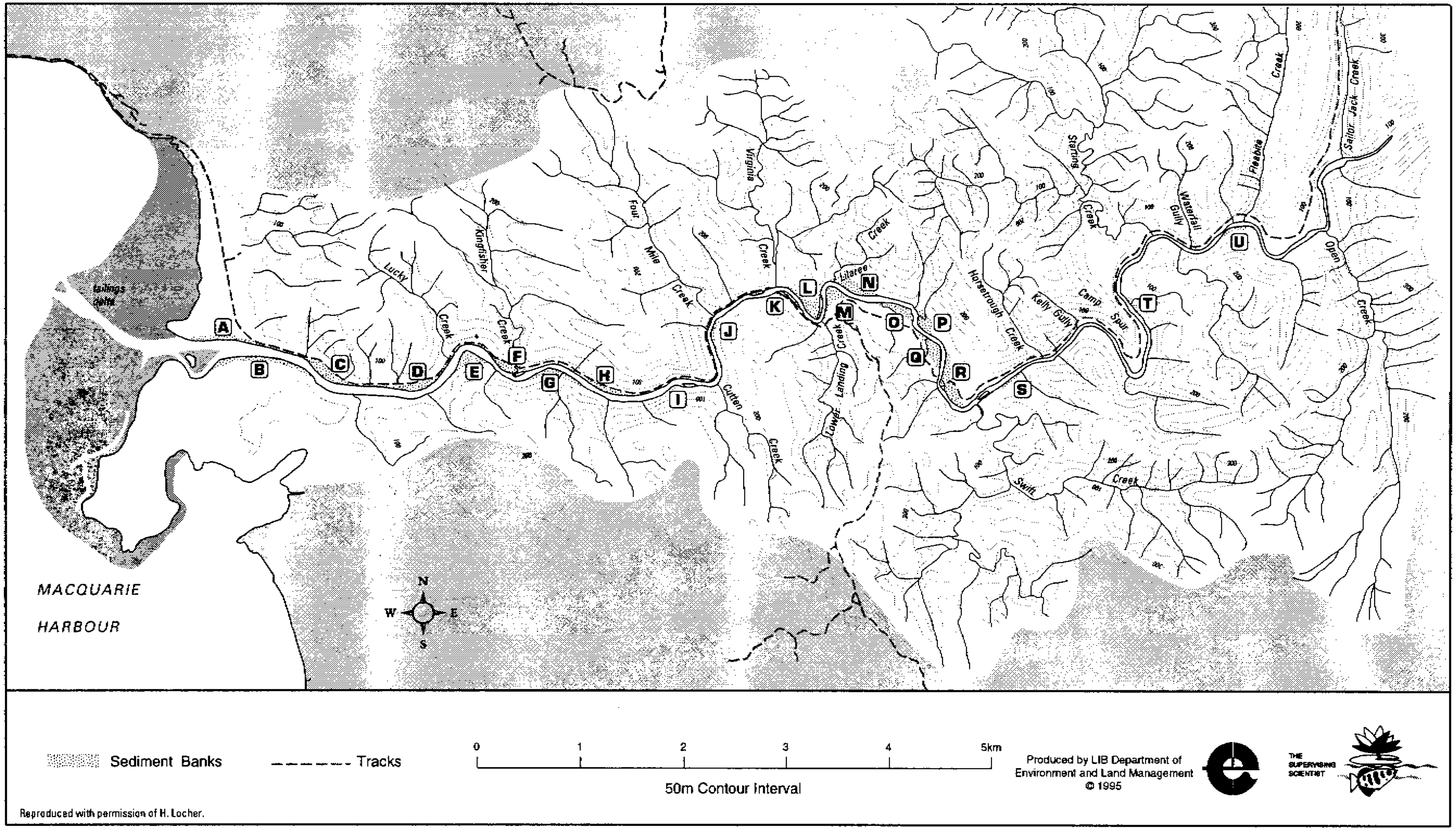

Figure 3 Location and designation of the King River sediment banks

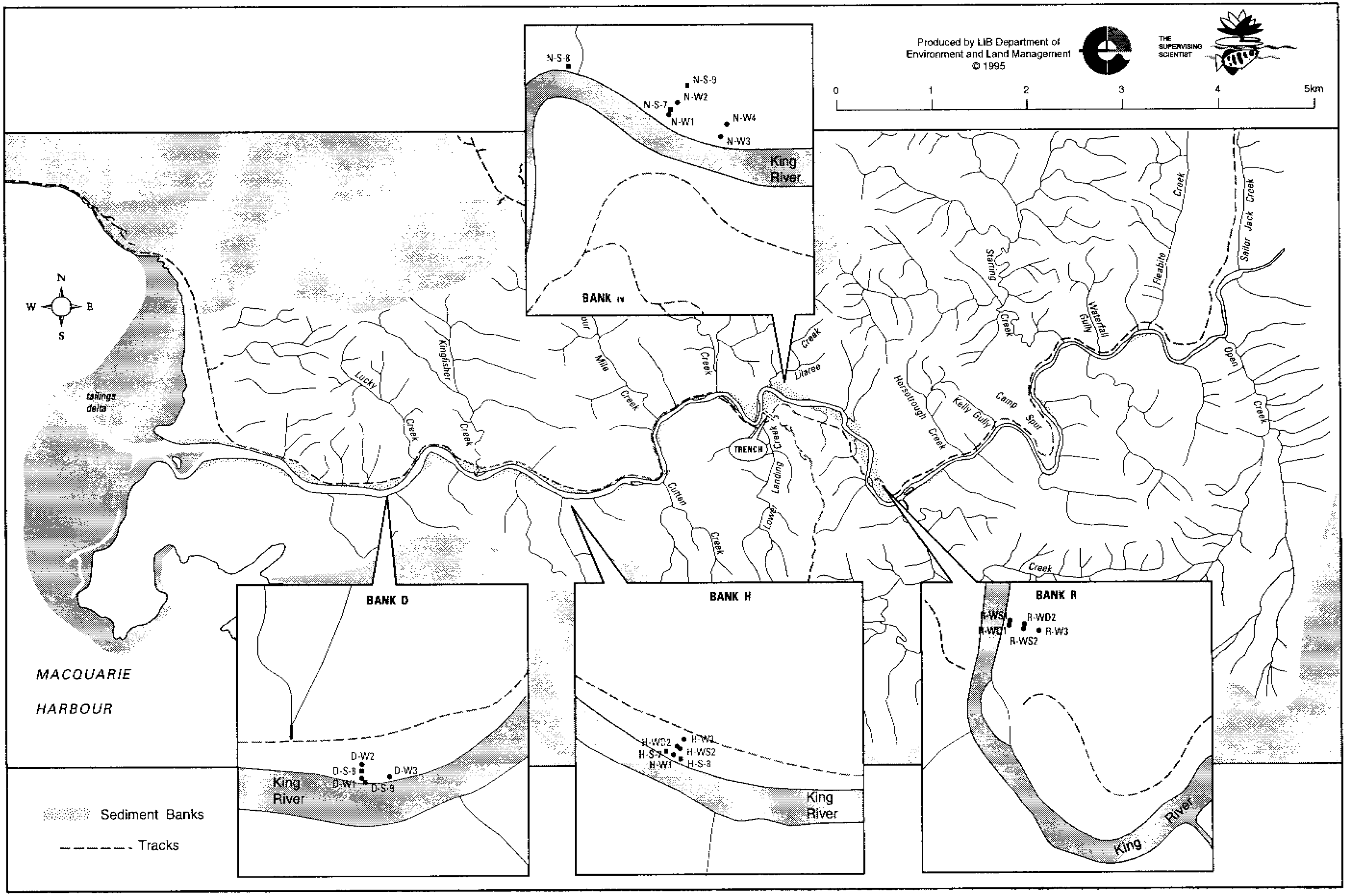

Figure 4 Piezometer locations on the King River sediment banks

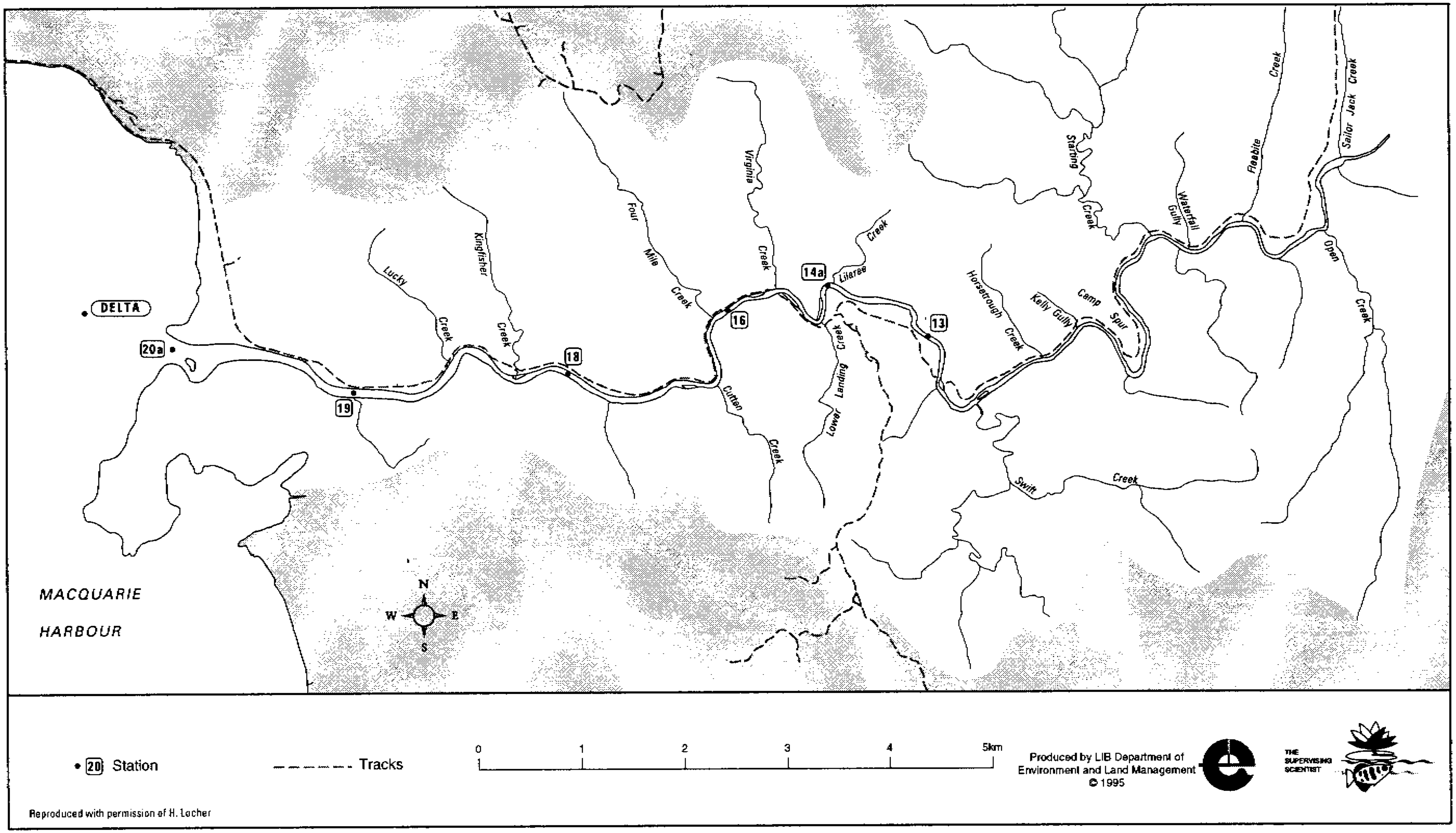

Figure 5 Location of drillholes by Helen Locher (After Locher 1995)

3.3 Hydrogeology

Groundwater monitoring network

A suite of temporary mini-piezometers was installed in sediment banks and the delta. These were designed to provide groundwater samples and water level and recovery data from discrete locations. These data are essential to determine hydraulic gradients, hydraulic conductivity and groundwater flux through the saturated sediments towards the river or harbour. Piezometers were installed in Banks R, N, H and D, along the north side of the King River and in both the north and south lobes of the delta. On each bank, at least 2 piezometers were located perpendicular to the river in order to determine groundwater flow rates towards the river, the most likely receptor of groundwater. A transect of monitoring bores was completed perpendicular to the tidal interface on the north and south lobe of the King River delta, two transects were completed, one perpendicular to the tidal interface and the other perpendicular to the King River channel. Two piezometers completed at different depths were installed in at least one location at most sites to provide information on vertical hydraulic gradients and changes in groundwater chemistry with depth. In total, 35 piezometers were installed in the tailings deposits: 5 in Bank R, 4 in Bank N, 4 in Bank H, 3 in Bank D, 9 in the north lobe of the delta and 10 in the south lobe of the delta. Sediment bank locations are provided on figure 3, and piezometer locations are provided on figures 4 and 6.

Piezometer design, construction and installation

The piezometers were designed to be temporary, allowing a large number to be easily installed. Piezometers on the higher sediment banks (Banks R, N and H) were installed using a hand-held percussion drill with a 40 mm cutting head. This method smears the cuttings along the upper portion of the borehole, above the groundwater monitoring zone. The piezometers installed in these boreholes were constructed from 6 m lengths of 25 mm internal diameter (id) Class 12 PVC, the bottom 25 cm of which was slotted by a hacksaw. The slotted interval was covered with 100 µm nylon sieve mesh which was attached to the base plug and extended 30 cm above it. After the well screen and casing was lowered in the open borehole, the saturated sediments tended to collapse around the piezometer, and open annular space in the unsaturated zone was backfilled with cuttings from the borehole. The piezometer was capped and a slot made below the cap to equalise atmospheric pressure across the PVC wall. Construction details for the 25 mm piezometers are shown in figure 7.

Piezometers in the shallowest bank (Bank D) and the north and south lobes of the delta were installed manually using a combination of auguring and hand driving. Where possible, piezometers were installed by driving a piece of 50 mm id PVC casing to the desired final depth of the well. Piezometers were then lowered into the casing and the casing was extracted. In these locations, piezometers were constructed of 3 m lengths of 40 mm id Class 9 PVC. The lower 25 cm were slotted by hacksaw, and, like the 25 mm id piezometers, the slotted interval was covered with 100 µm nylon sieve mesh. Piezometers were backfilled when necessary, however, in most cases, the water table was sufficiently close to the surface that the saturated sediments collapsed around the borehole. Excess lengths of pipe were trimmed with a hacksaw, the piezometer capped, and a slot made below the cap to equalise atmospheric pressure across the PVC wall. Construction details for the 40 mm piezometers are shown in figure 7.

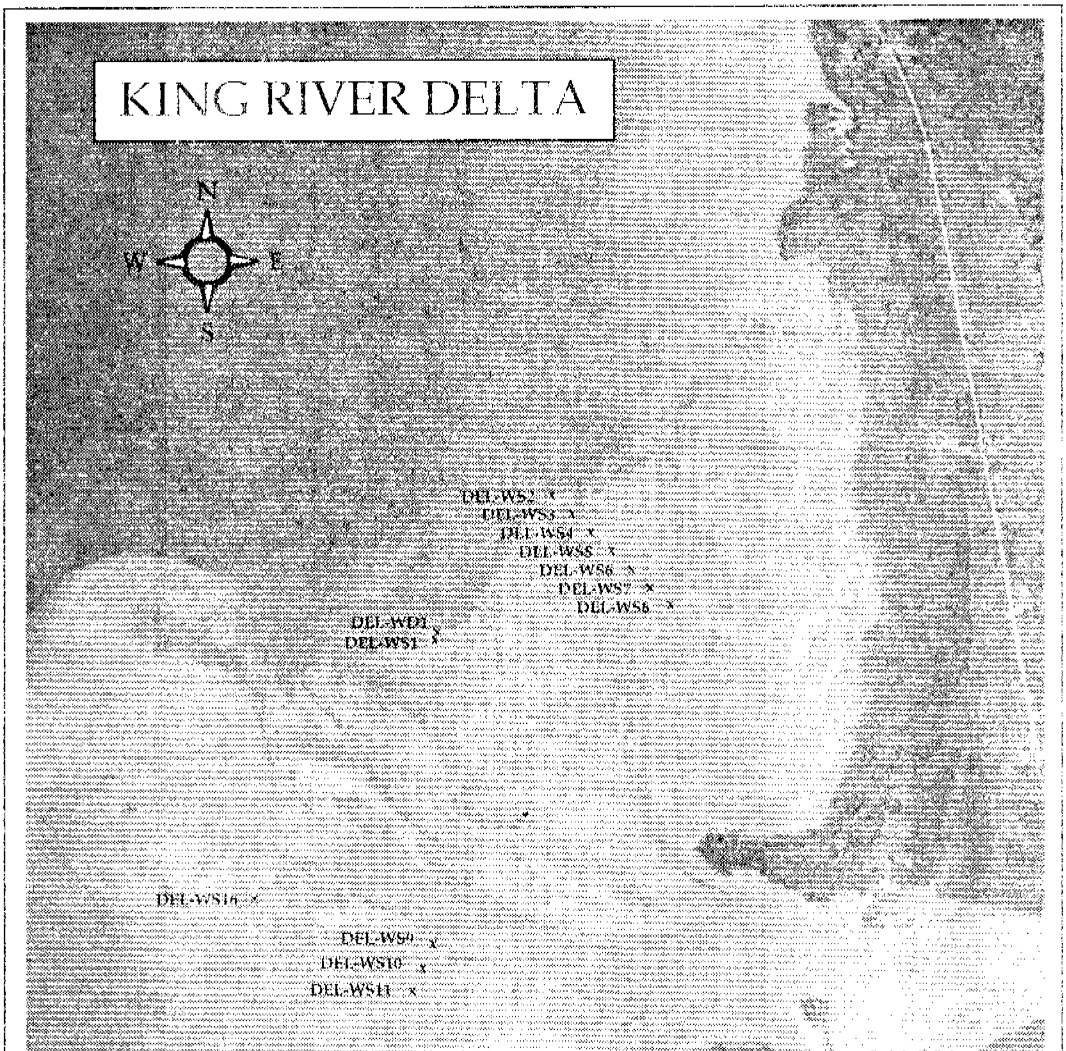

Figure 6
Piezometer locations on the King River Delta

Piezometer monitoring

Groundwater levels were measured in each borehole using an electric down-hole water-level tape. These levels were measured relative to the surface-water levels (ie King River or Macquarie Harbour) at each site at the time of water sample collection, allowing hydraulic gradients relative to the nearest surface-water body to be calculated. Water levels were also measured after sampling so that hydraulic conductivity values could be estimated for each borehole. Surveying was conducted with chain, compass and spirit level.

Piezometer installation and monitoring parameters are presented in table 1, and cross sections of the piezometers from the banks and delta are displayed in figures 8 to 18. Piezometers accessed groundwater in the sediment bank deposits and delta from 50 to 700 cm below the ground surface.

Groundwater and surface-water sampling and field analysis

Twenty-four to 48 h after installation of the piezometers, groundwater was extracted from each well and discarded to remove potential contamination introduced during construction and emplacement, and to ensure the collection of a representative groundwater sample.

A 15 mm outer diameter (od) PVC jerk pump was employed to recover groundwater samples from the 25 mm id piezometers, and 25 mm od open-tube PVC bailers were used for the 40 mm id piezometers. These instruments were flushed/washed with the local groundwater prior to sampling. Wherever possible, 1000 mL of groundwater was taken from each piezometer and stored in two 500 mL LDPE screw-top bottles which had been thoroughly rinsed with the incoming sample. Conductivity, pH and Eh readings were taken in the field on one of the 500 mL aliquot's while the other was divided in two subsamples. The first consisted of a 250 mL sample of unfiltered groundwater stored in an acid-washed HDPE screw-top bottle. The second sample was delivered in stages into the top of a 60 mL syringe containing a Sartorius silica pre-filter and Sartorius millipore 0.45 μm filter in series, and filtered into another 250 mL acid-washed HDPE screw-top bottle. Acidification requirements were determined on the basis of field pH readings and sample volume (normally 250 mL), and the required volume of reagent grade 1.0 M HNO_3 was added by syringe to the filtered sample, after an equivalent volume of sample was removed. Groundwater sample numbers are derived directly from their associated piezometer (ie DEL-WS8-UU and DEL-WS8-AF represent the Unfiltered–Unacidified and Acidified–Filtered groundwater samples from the delta piezometer DEL-WS8).

All water samples were transferred directly to a large-volume insulated cooler in the field and maintained at temperatures close to or below their initial temperature until delivered to the laboratory.

Forty filtered/acidified and unfiltered/unacidified groundwater and surface-water samples were collected and submitted to Amdel for analysis. Three harbour water samples were taken near to the piezometers (DEL-WS25 next to DEL-WS2, DEL-WS42 next to DEL-WS12, and DEL-WS45 next to DEL-WS15 during high tide), at the same time as the piezometers were sampled. Samples DEL-WS22 and DEL-WS29 represent duplicates of samples DEL-WS2 and DEL-WS1 respectively, and were taken for BOD analysis and to assist evaluation of laboratory analytical precision.

Groundwater pH, EC and Eh at the water table in the delta were measured by excavating shallow holes and inserting the probes into the resulting pools of water along traverse lines

Table 1 Field data from piezometers

Peizometer Number	Location	Date Installed	Depth from Surface (cm)	Height above Ground (cm)	Screen Length (cm)	Distance from Mark to Top of Screen (cm)	Distance from Mark to Base of Screen (cm)	Water Level Recorded (Date)	Water Level Recorded (Time) ± 5 min.	Depth to Pore Water from Mark (cm)	Water Level Recorded after Sampling (Time)	Depth to Pore Water from Mark (cm)	Height difference relative to local Reference Piezometer (cm)	Vertical Height from Mark to Surface Water (cm)	Horizontal Distance from Reference Piezometer to Surface Water (cm)	Associated Sediment Samples
DEL-WS1	**Delta - North Lobe**	**28/7/95**	**72.5**	**87**	**36**	**123.5**	**159.5**	**1/8/95**	**9:20 AM**	**88**			**Reference**	**88**	**0**	
DEL-WD1	Delta - North Lobe	28/7/95	114.2	85	36.8	162.4	199.2	1/8/95	9:25 AM	86			-0.5			
DEL-WS2	**Delta - North Lobe**	**28/7/95**	**88.2**	**90.3**	**38**	**140.5**	**178.5**	**1/8/95**	**9:10 AM**	**82**			**Reference**	**82**	**0**	**DEL-S1**
DEL-WS3	Delta - North Lobe	28/7/95	49.3	73.3	36.1	86.5	122.6	1/8/95	9:05 AM	76			3.5			DEL-WS3-S
DEL-WS4	Delta - North Lobe	28/7/95	103.4	76.5	37	142.9	179.9	1/8/95	9:00 AM	78			7.2			DEL-S2
DEL-WS5	Delta - North Lobe	28/7/95	54.7	67.3	37	85	122	1/8/95	8:55 AM	78			10			DEL-WS5-S
DEL-WS6	Delta - North Lobe	28/7/95	119	75.5	36.5	158	194.5	1/8/95	8:50 AM	91			24.7			DEL-S3
DEL-WS7	Delta - North Lobe	28/7/95	114.4	75.2	37	152.6	189.6	1/8/95	8:45 AM	96			28.5			
DEL-WS8	Delta - North Lobe	28/7/95	124.1	76.2	35.5	164.8	200.3	1/8/95	8:40 AM	94			31.6			DEL-WS8-S
DEL-WS9	**Delta - South Lobe**	**29/7/95**	**66.9**	**59.3**	**31.3**	**94.9**	**126.2**	**31/7/95**	**4:30 PM**	**70**			**Reference**	**77.5**	**13.5**	**DEL-WS9-S**
DEL-WS10	Delta - South Lobe	29/7/95	51.2	62	32	81.2	113.2	31/7/95	4:33 PM	74			11.8			DEL-WS10-S
DEL-WS11	Delta - South Lobe	29/7/95	127	56	33	150	183	31/7/95	4:35 PM	64			5.1			DEL-S5
DEL-WS12	**Delta - South Lobe**	**29/7/95**	**49.9**	**70.6**	**32.5**	**88**	**120.5**	**31/7/95**	**5:00 PM**	**104**			**Reference**	**104**	**0**	**DEL-WS12-S**
DEL-WD12	Delta - South Lobe	29/7/95	210.1	94.9	37	268	305	31/7/95	5:02 PM	84			-22.2			
DEL-WS13	Delta - South Lobe	29/7/95	56.4	107.9	31.5	132.8	164.3	31/7/95	4:57 PM	106			-1			DEL-WS13-S
DEL-WS14	Delta - South Lobe	29/7/95	110.6	91.2	32.3	169.5	201.8	31/7/95	4:55 PM	89			-14.3			
DEL-WS15	**Delta - South Lobe**	**29/7/95**	**104.4**	**100.4**	**37**	**167.8**	**204.8**	**31/7/95**	**5:17 PM**	**84**			**Isolated**	**84**	**0**	**DEL-S6**
DEL-WS16	**Delta - South Lobe**	**29/7/95**	**115**	**100**	**31**	**184**	**215**	**31/7/95**					**Isolated**			**DEL-S7**
DEL-WS17	**Delta - South Lobe**	**29/7/95**	**124.6**	**98.8**	**36**	**187.4**	**223.4**	**31/7/95**	**4:40 PM**	**136**			**Isolated**			**DEL-S8**
R-WD1	**Bank R**	**28/7/95**	**562**	**80**	**30**	**612**	**642**	**31/7/95**	**1:43 PM**	**353.7**	**2:53 PM**	**357**	**Reference**	**384**	**539**	**R-WD1-S**
R-WS1	Bank R	28/7/95	489	89	37.3	540.7	578	31/7/95	1:40 PM	480.5	2:50 PM	501	6.4			R-WS1-S
R-WS2	Bank R	28/7/95	570	74	29.4	614.6	644	31/7/95	1:37 PM	571.1	3:01 PM	575	199.9			R-WS2-S
R-W2D	Bank R	28/7/95	699	44	29	714	743	31/7/95	1:34 PM	539.2	2:57 PM	639	167.9			R-W2D-S
R-W3	Bank R	28/7/95	394	45	30	409	439	31/7/95	1:30 PM	345.5	3:04 PM	345	-9.5			R-W3-S
N-W3	**Bank N**	**29/7/95**	**343**	**91**	**36**	**398**	**434**	**31/7/95**	**9:10 AM**	**319.3**	**10:40 AM**	**318**	**Reference**	**535**	**1493**	**N-W3-S**
N-W1	Bank N	29/7/95	486	83	36	533	569	31/7/95	11:20 AM	389			57.4			N-W1-S
N-W2	Bank N	29/7/95	415	89	32	472	504	31/7/95	11:00 AM	382			65.6			N-W2-S
N-W4	Bank N	29/7/95	334	84	35	383	418	31/7/95	9:05 AM	210.6	10:10 AM	211	27.4			
H-W1	**Bank H**	**28/7/95**	**335**	**73**	**30.5**	**377.5**	**408**	**1/8/95**	**1:07 PM**	**271**	**5:02 PM**	**326**	**Reference**	**292.9**	**569**	**H-W1-S**
H-WS2	Bank H	28/7/95	345	72	29	388	417	1/8/95	1:15 PM	222	5:00 PM	277	24.8			H-WS2-S
H-WD2	Bank H	28/7/95	453	84	29	508	537	1/8/95	1:20 PM	310	4:58 PM	313	35.7			H-WD2-S
H-W3	Bank H	28/7/95	355.5	72.2	31	396.7	427.7	1/8/95	1:25 PM	339	4:56 PM	355	23.6			H-W3-S
D-W1	**Bank D**	**29/7/95**	**132**	**47**	**32**	**147**	**179**	**1/8/95**	**3:30 PM**	**124**			**Reference**	**126.2**	**3.81**	
D-W2	Bank D	29/7/95	62	48	35	75	110	1/8/95	3:40 PM	80			12.2			
D-W3	Bank D	29/7/95	137	54	31	160	191	1/8/95	3:50 PM	124			-7.2			

Local reference piezometer is printed in bold.

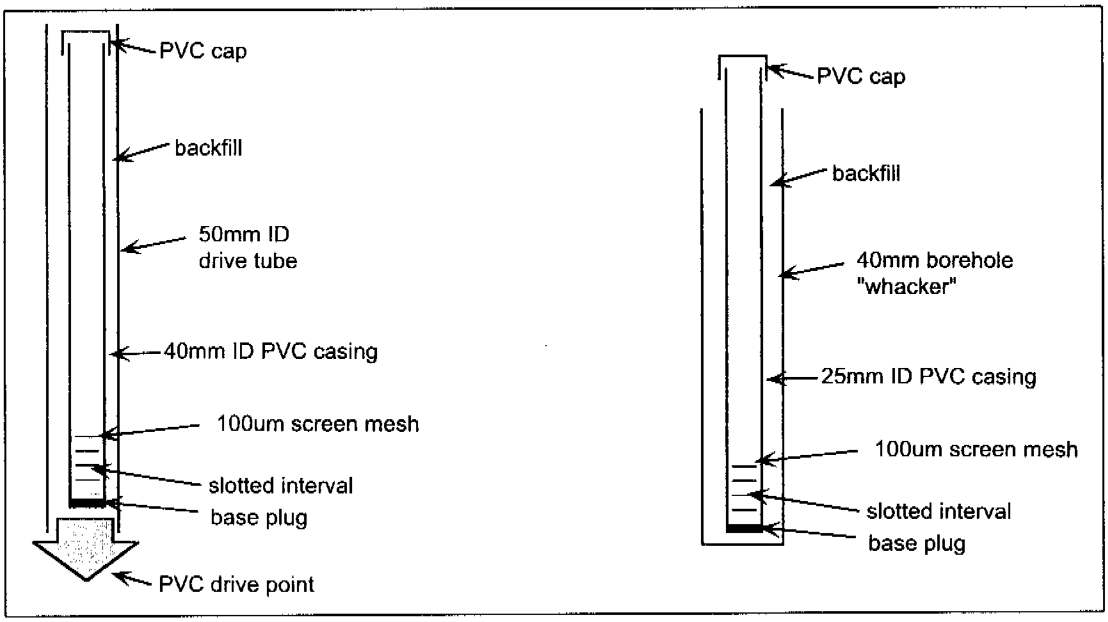

Figure 7 Design of piezometers

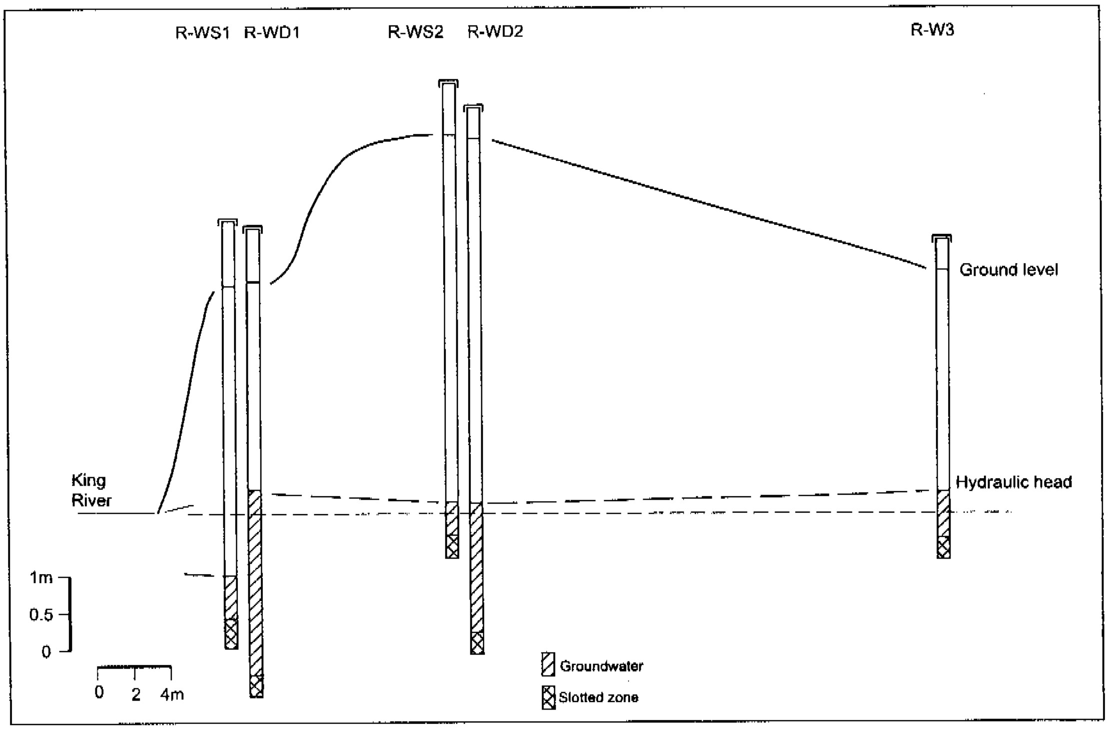

Figure 8 Cross section of Bank R showing piezometers; view facing downstream and river level rising rapidly while sampling

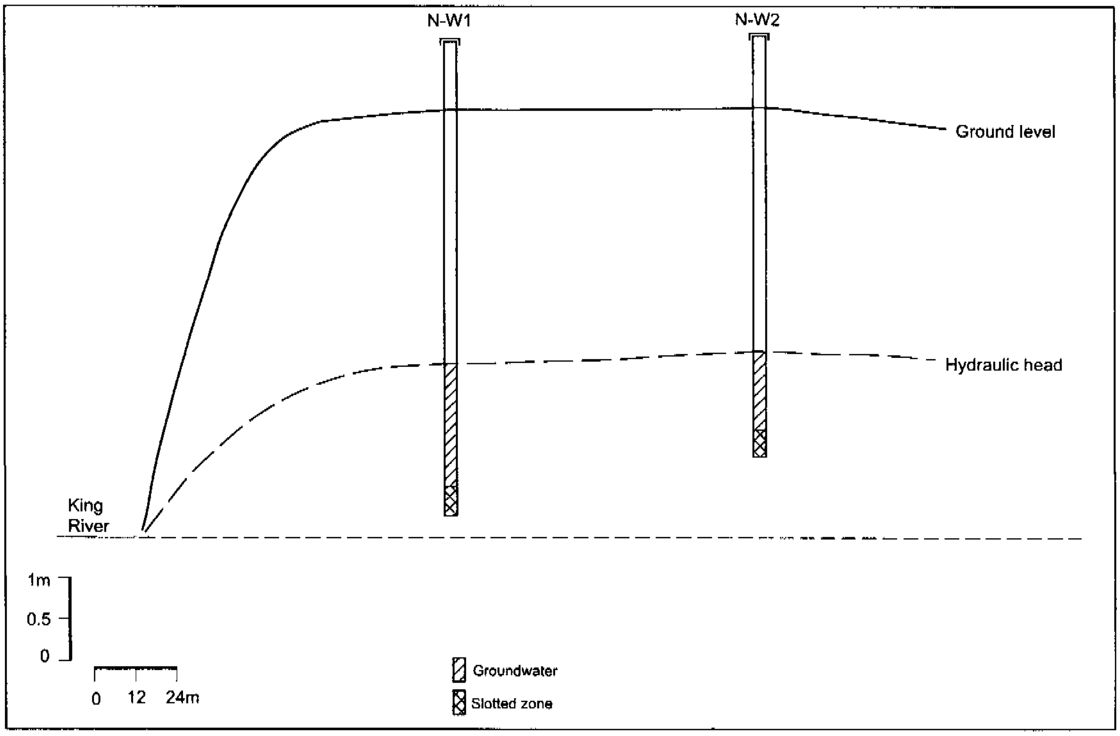

Figure 9 Cross section of Bank N showing piezometers; view facing downstream and river level very low during sampling

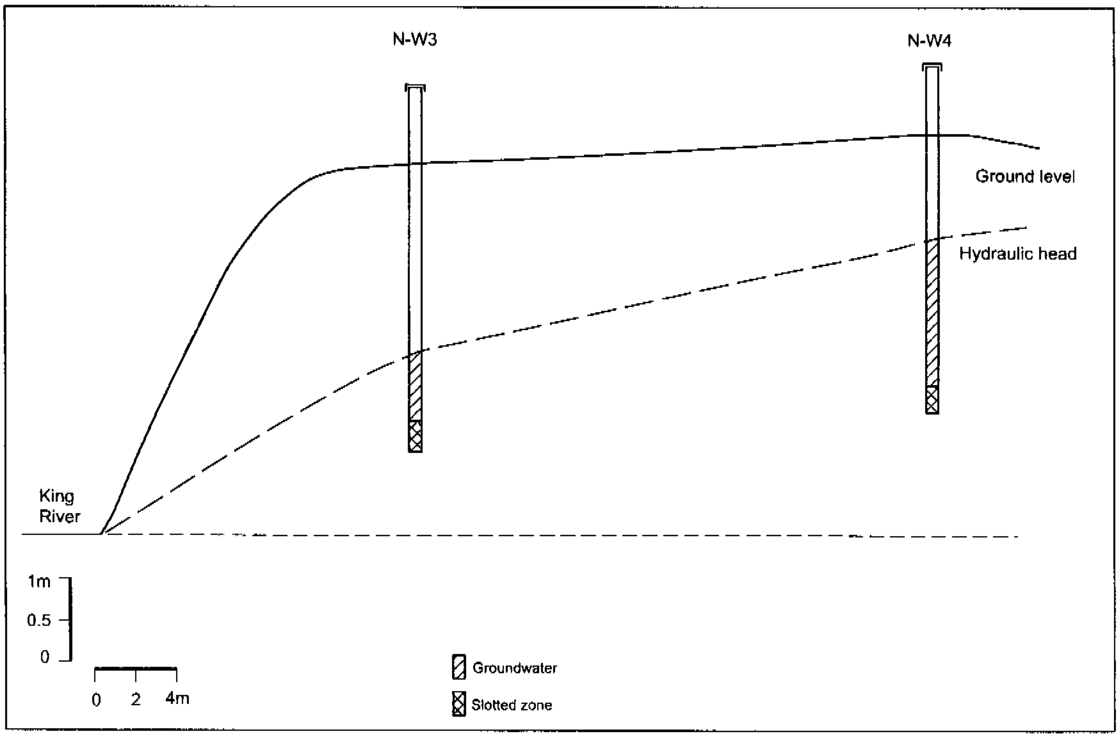

Figure 10 Cross section of Bank N showing piezometers; view facing downstream and river level very low during sampling

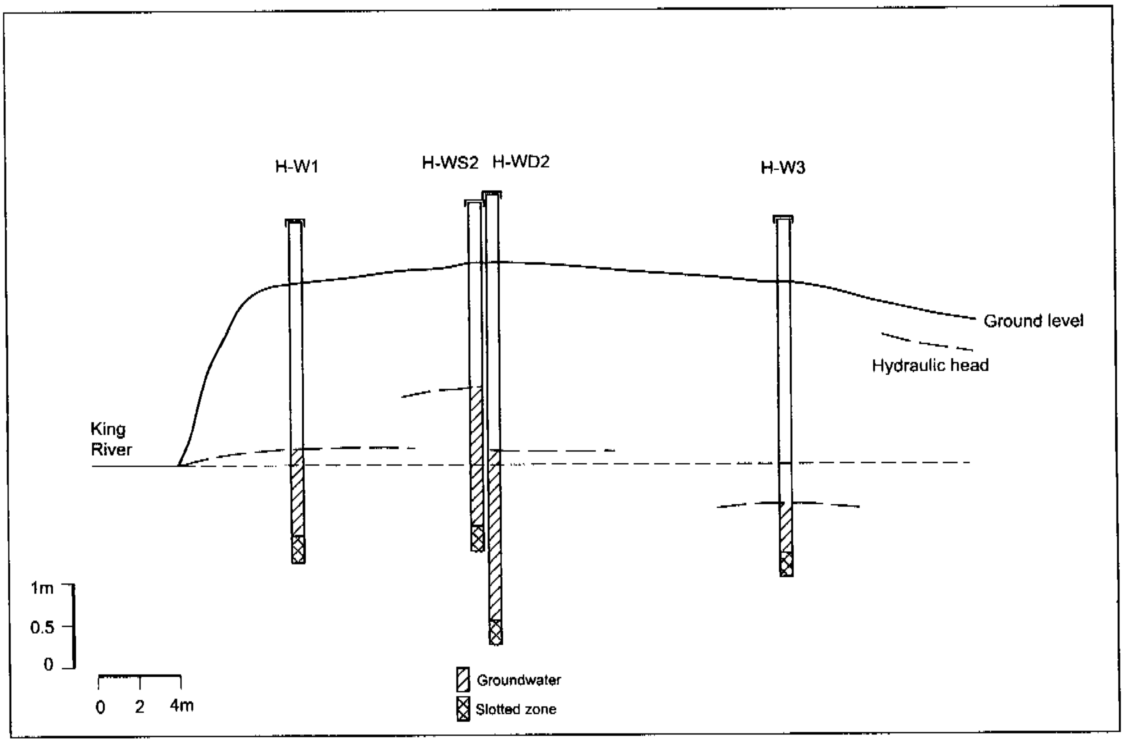

Figure 11 Cross section of Bank H showing piezometers; view facing downstream

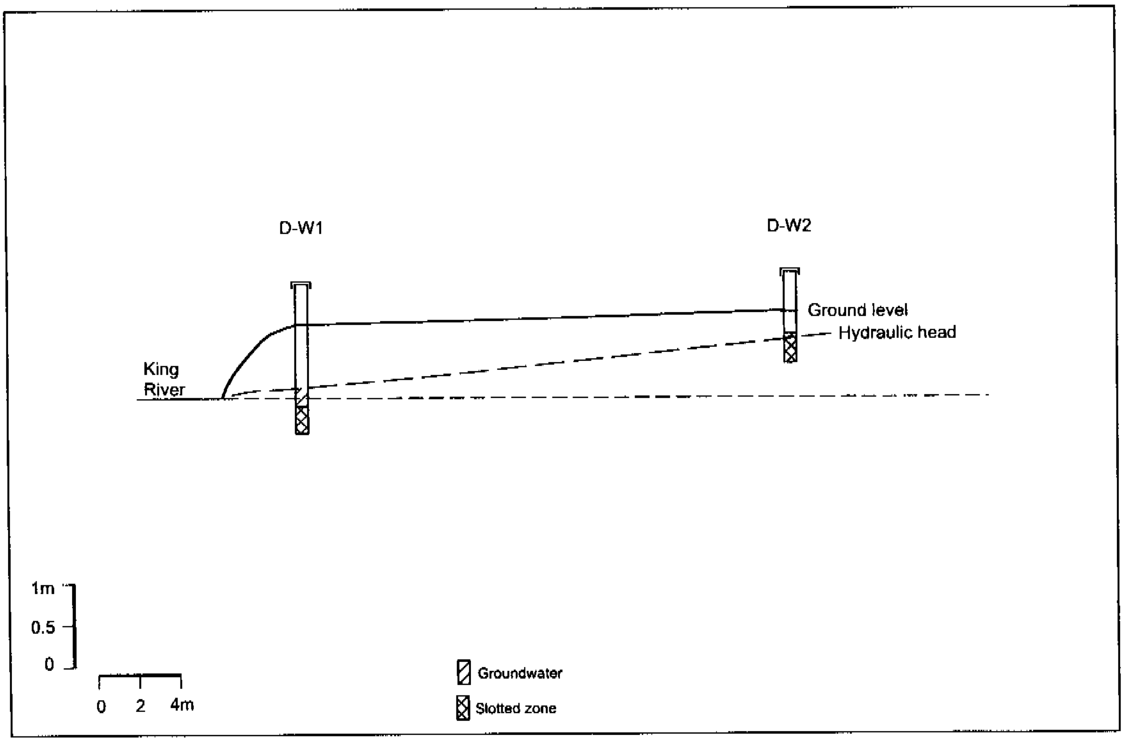

Figure 12 Cross section of Bank D showing piezometers; view facing downstream

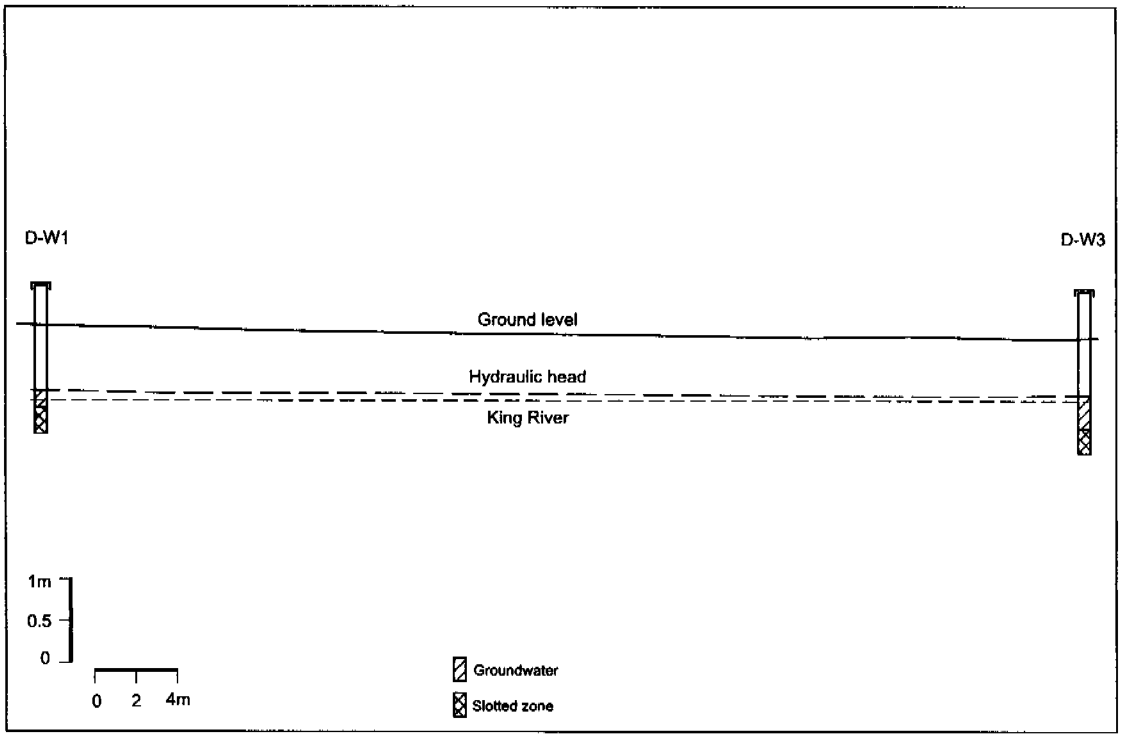

Figure 13 Longitudinal section of Bank D showing piezometers; long section parallel to King River with the view looking towards Bank D

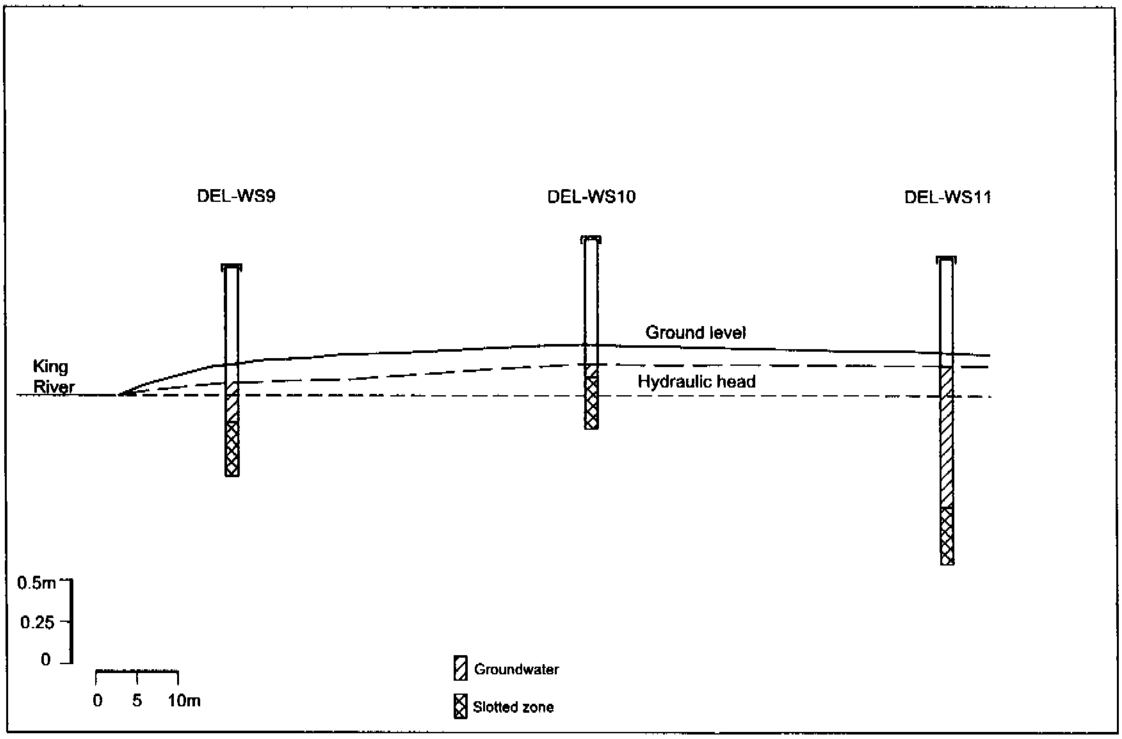

Figure 14 Cross section of south lobe of the delta showing piezometers perpendicular to King River; view facing east

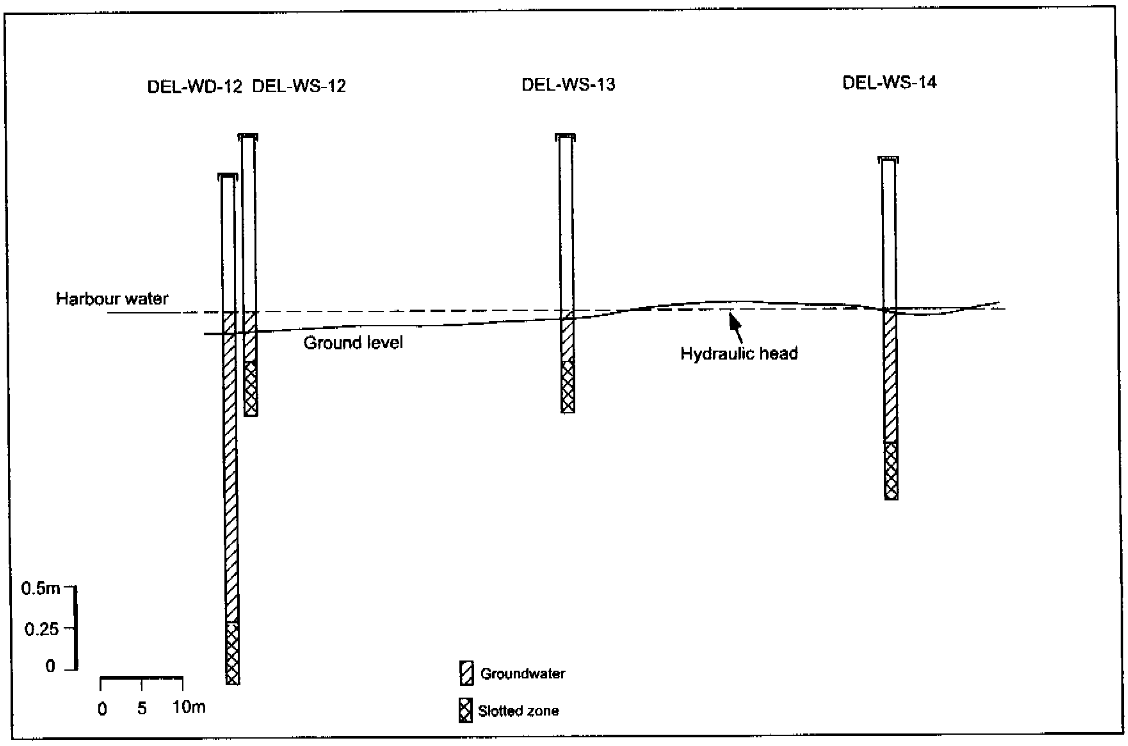

Figure 15 Cross section of south lobe of the delta showing piezometers perpendicular to Macquarie harbour; view facing northeast and tide level rising during sampling

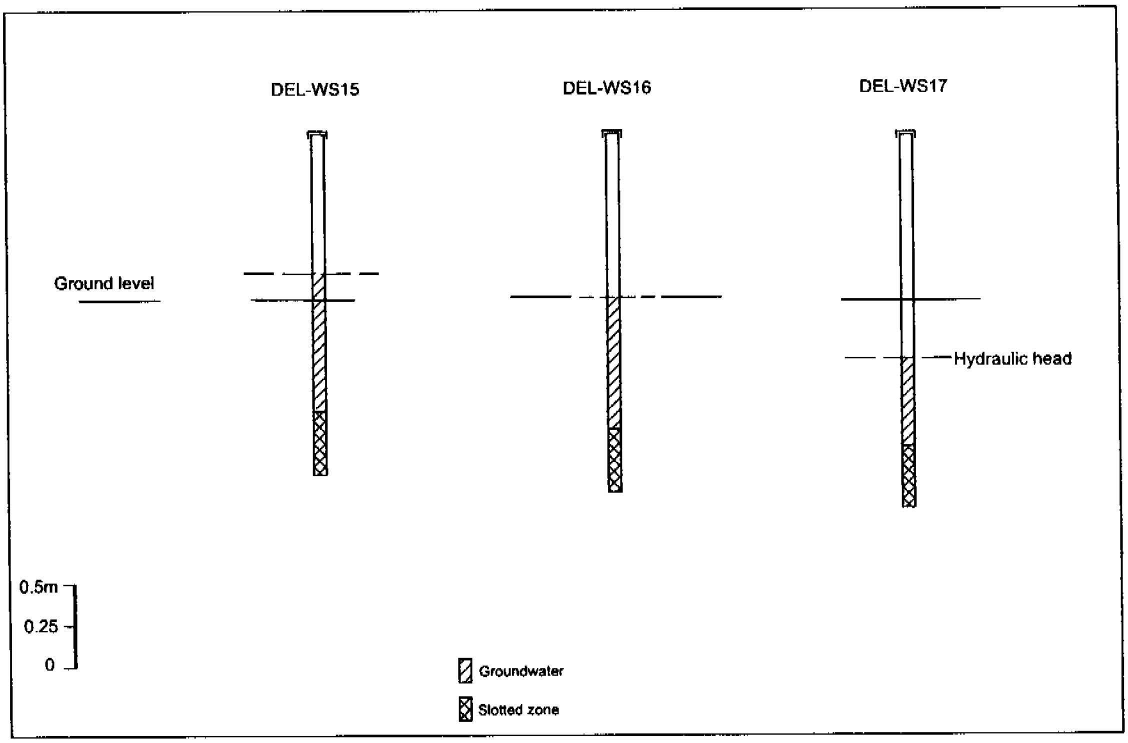

Figure 16 Miscellaneous piezometers from the south lobe of the delta; no defined horizontal spatial relationship between piezometers

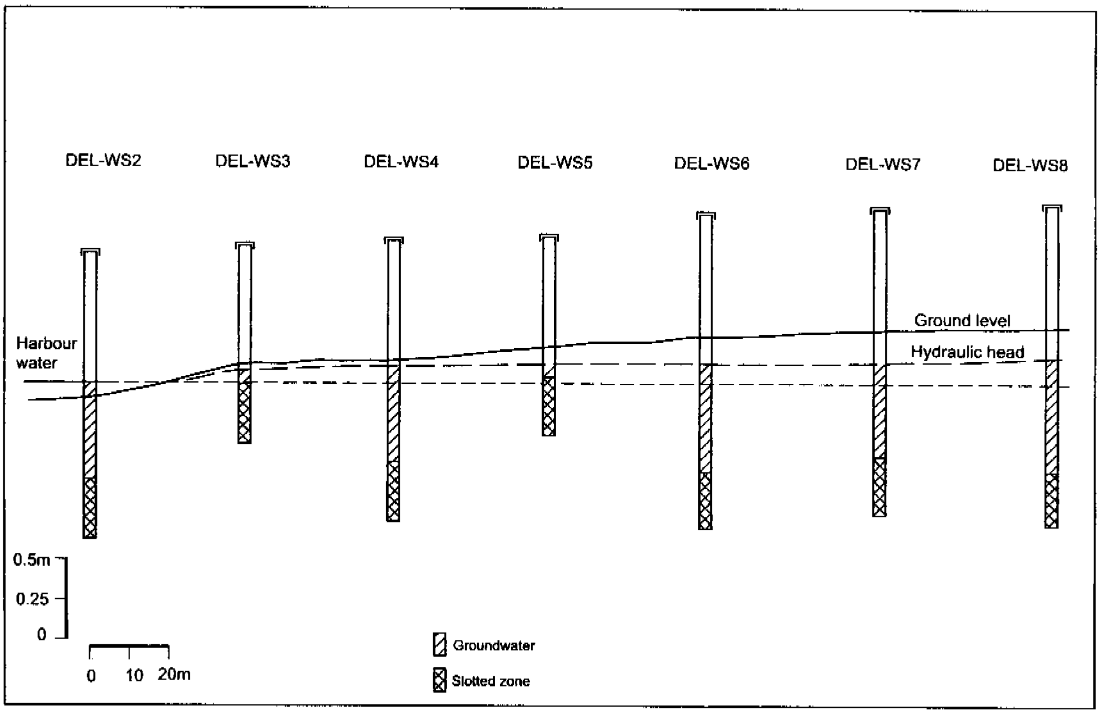

Figure 17 Cross section of north lobe of the delta showing piezometers perpendicular to Macquarie harbour; view facing northeast

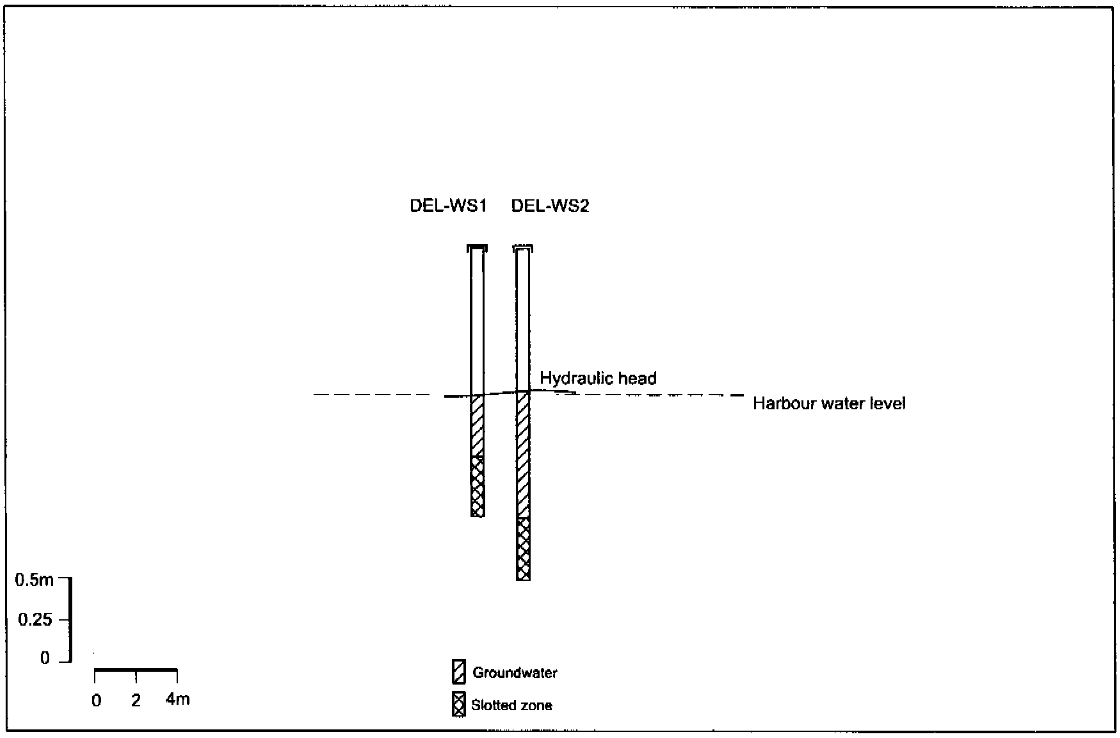

Figure 18 Cross section of north lobe of the delta showing piezometers near Macquarie harbour; view facing northwest

over the delta. The location of the traverses is shown on figure 2 and results are displayed on figures 19 to 21. Traverses were designed to coincide with the location of piezometers to permit comparison between surficial and deeper groundwater.

Field analytical procedures

A TPS meter and an Ionode Intermediate Junction, epoxy body, glass bulb pH electrode (IJ40) were used to measure the pH of water samples from piezometers, excavations and spot surface-water locations. Prior to measurement, the electrode was calibrated using pH 6.88 and pH 4.01 buffer solutions at a similar temperature to the water samples. The same meter and an Ionode ORP electrode were used to measure Eh. Zobells solution was used as a standard. Redox potential (Eh) readings of Zobells solution were consistently within ±20 mV of the expected Eh value. A TPS meter and electrical conductivity probe was used to measure electrical conductivity (EC, μS/cm) in each of the samples. The EC probe was calibrated for temperature against a standard solution of KCl. Water temperature was measured with a mercury bulb thermometer.

4 Laboratory analytical work

4.1 Water chemistry

The HDPE bottles containing the groundwater samples were transported in the large-volume insulated coolers packed with ice. Sufficient ice was used to ensure that some was still present when opening the coolers after transit. Samples were sent to the NATA-registered Amdel laboratory in Adelaide.

All samples were analysed for pH and EC. Acidified samples were analysed for Na, K, Ca, Mg, Cl, SO_4, P and metals and unacidified samples were measured for nitrate, bicarbonate and a selected suite of metals. The metals measured were: As, Sn, Mo, Cr, Zn, Cd, Pb, Ba, Co, Fe, B, Si, Mn, V, Cu, Ag, La, Ni, Y, Al and Sr. For seven of the acidified samples, Se, Sb, Tl and Hg were also measured.

4.2 Sediment chemistry and mineralogy

Preparation procedures

Sediment samples were transferred from their insulated field container to a refrigerator, and maintained at 4°C. In order to minimise exposure of sulphide material to air, ≈100 g representative subsamples of 80 moist to saturated sediments were placed into plastic Petric dishes and stored in vacuum desiccators. The samples were dried over a 7 to 10 day period by maintaining very low internal pressures. Samples that resisted complete dehydration were installed into an oven at 50°C whilst still in the desiccator, and under vacuum. Sediment required for microscopy, XRD analysis, bulk chemical analysis, SEM work and leach tests were all taken from the vacuum-dried subsamples.

Bulk chemical analysis

Approximately 20 to 30 g batches of 80 vacuum-dried sediment samples were dispatched to Amdel (Adelaide) for analysis in 50 mL HDPE screw-top bottles. Sediments were subjected to acid digestion and analysed by ICP for Na, K, Ca, Mg, P, Cu, Fe, Mn, Zn, Pb, As, Ni, Cd, Co, Cr, V, Ag, Sn, Mo, Bi and S.