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Bypassing of Dredged Littoral Muddy Sediments Using a Thin Layer Dispersal Technique

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ABSTRACT

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Maintenance dredging of the navigation approach channel to Pine Harbour Marina is necessary to remove muddy sediment which accumulates as a result of depositional processes due to flocculation and the littoral "turbid fringe". Based upon analysis of the muddy sedimentation processes in the adjacent embayment a "thin layer" dredgings disposal method was instigated. This novel technique required a detailed monitoring program based upon a wide range of field measurements including turbidity and suspended sediment loads, detailed hydrographic surveys of the dredging disposal ground, high resolution side-scan sonar survey, SCUBA observations of sedimentation rods, and regular helicopter flights to obtain oblique air photo records. The results consistently demonstrated that thin layer disposal was achieved, and no mound of muddy deposits accumulated.

Application of a 1-D numerical model of mud resuspension under storm waves realized suspended sediment concentrations similar to those measured in waters discharging from the adjacent catchment, and indicated that the erodibility of the bottom sediment in the disposal area was unlikely to change as a result of the disposal. It is thus most unlikely that muddy material would migrate from the disposal grounds to the adjacent beaches.

ADDITIONAL INDEX WORDS: *Littoral muddy sediments, thin layer dispersal technique.*

INTRODUCTION

Pine Harbour Marina is located in the sheltered Turanga-Waikopua embayment east of Auckland City, New Zealand (Figure 1). The marina approach channel crosses a broad intertidal zone, and since construction has regularly required maintenance dredging of mainly fine sand and muddy material. Upon applying for a dredging and disposal consent there was public opposition to disposal of the dredgings in the littoral environment for fear that the muddy sediment would migrate to, and despoil, the adjacent beaches, which are typically of sheltered harbour type (HEALY *et al.,* 1996). Accordingly a "thin layer dispersal" method was proposed for dredged material disposal, and a monitoring program instituted to check that the disposed material did not migrate to the adjacent beaches.

The purpose of this paper is to report on the results of the monitoring after the first annual dredging operation, and to apply a model (MEHTA and LI, 1997) to the results to assess the likelihood of the bottom muddy sediment becoming resuspended under design storm wave conditions, and advected and deposited on adjacent beaches.

BACKGROUND

The Turanga-Waikopua embayment is protected from Pacific ocean swell by the offshore islands of the Hauraki Gulf. In outline plan it is roughly V-shaped with fetch of only ~4 km for the predominant southwesterly winds at high tide, and depths of 2–4 m relative to Chart Datum (C.D.). Longest fetch however is from the northwest so that the highest wave energies come from that direction, but the long term wave power resultant, which drives the net littoral drift northwards across the marina navigation approach channel, is from the southwest.

The marina was constructed in 1986, at which time the navigation approach channel was excavated through a 1000 m broad intertidal shore platform with onlapping Holocene marine sediments. The channel had a design depth of 2.4 m relative to chart datum (C.D.). Within 2 years the approach channel required dredging (HEALY, 1994), with the zone of maximum deposition located along the 400 m closest to the marina entrance. However in recent years the issue of dredge spoil disposal became an emotive issue (RYAN and HEALY, 1991) and the proposed Auckland Regional Coastal Plan required that all dredgings should be disposed of at the edge of the continental shelf in water depths of > 200 m.

In 1994 the regulatory authorities were persuaded that the material deposited and trapped in the navigation channel, which texturally comprised a mixture of fine sand and mud (Figure 2), and for which testing had shown was chemically uncontaminated, comprised the natural littoral drift and should be bypassed and allowed to continue in the littoral system (HEALY, 1994). Accordingly in late 1994 the accu-

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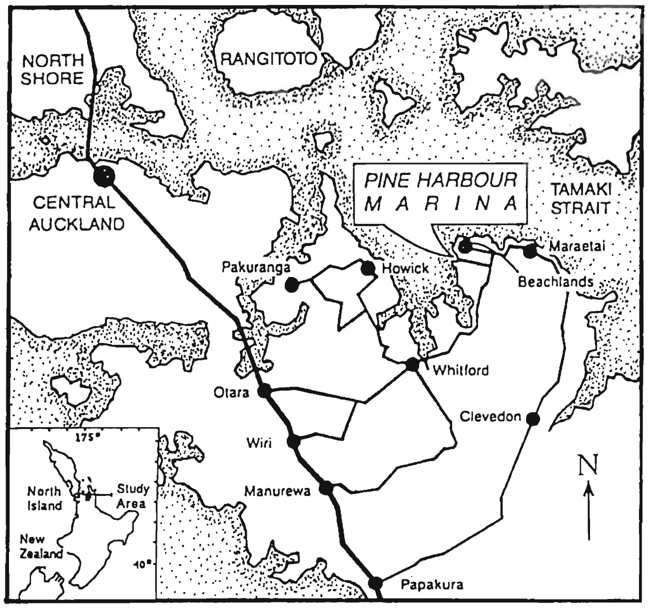

Figure 1. Location of Pine Harbour Marina in the Turanga-Waikopua embayment, Auckland, New Zealand.

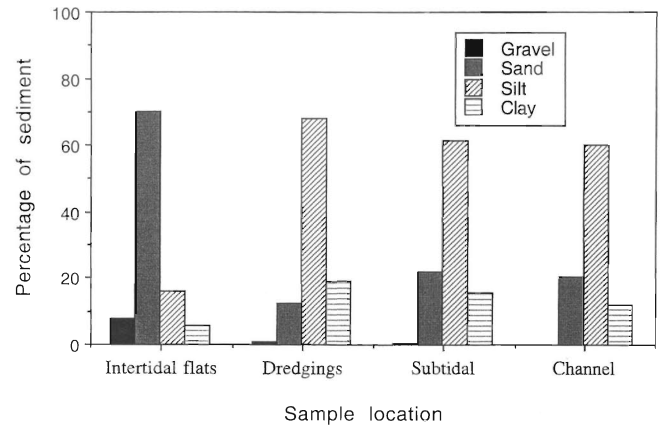

Figure 2. Texture of sediments in the navigation channel and surrounding littoral environment (from HULL, 1996).

mulation of muddy sediment deposited in the channel was dredged using a digger mounted on a barge (Figure 3), and side-casted into a mound of muddy material about 50 m broad and 0.5 m high alongside the channel. Monitoring of the side-casted dredgings was carried out over the next year (HULL, 1996), but unfortunately some of the muddy material became transported back into the channel by the reverse littoral drift processes.

Figure 3. The dredging of muddy sediments from the marina approach channel using a digger mounted on a barge.

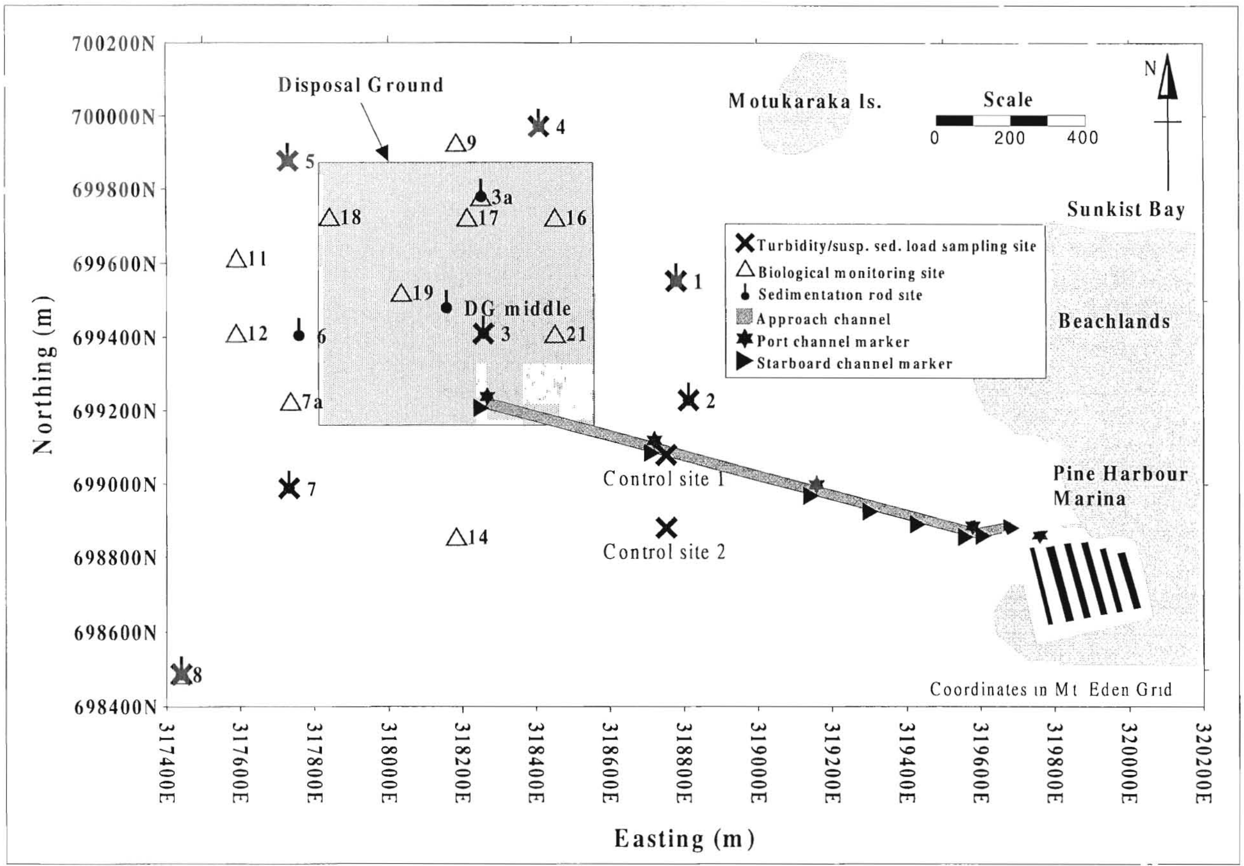

Figure 4. Pine Harbour Marina maintenance dredging and disposal monitoring sites.

In 1997 the marina sought a long term (15 years) consent for dredging and disposal. Rather than persist with the immediate downdrift bypassing mechanism, it was argued that in view of: (i) the high level of natural muddy sediment entering the embayment from the surrounding catchment; (ii) the large area of muddy sediments comprising the embayment sea floor; (iii) the observed episodic wave-induced resuspension of muddy material from the sea floor and the littoral turbid fringe zone; (iv) the volume of muddy sediment to be dredged and disposed of within the system being only a small proportion of muddy sediment naturally depositing in the embayment on an annual basis; and (v) the dredged sediment being part of the natural littoral system which would have migrated or been deposited over or within the embayment anyhow if it had not become trapped in the navigation channel; then the most appropriate disposal method was for a "thin layer" dispersal over an area of similarly naturally muddy adjacent sea floor (HEALY, 1997). This argument was accepted by the consent granting authority and long term permits issued for dredging and thin layer disposal.

As a condition of the consents granted, a substantial monitoring program was required. This included water quality (turbidity and suspended sediment concentration) monitoring downstream of the dredging and disposal operation, and hydrographic and side-scan sonar survey of the area dredged and the disposal ground before, during, and after each annual dredging program. Ecological impact monitoring was likewise required before, during, and after each annual dredging program (COLE, 1998). Disposal monitoring included SCUBA observation of the sea floor, and oblique air photographs of the turbidity generated from the dredging and disposal operation.

The monitoring program objectives were to confirm that "the dredging activity does not cause the release of sediment into the surrounding environment at levels in excess of those naturally experienced", and that "the marine disposal activity does not cause significant adverse effects upon the benthic organisms present in the [Turanga-Waikopua] embayment or cause the release of sediment into the environment surrounding the disposal site at levels in excess of those naturally experienced".

Because the technology and operating procedures for this type of dredging and disposal were not established, there was a degree of experimentation of procedures and this was recognized in the permits granted. Initially the dredge operator estimated some 8–10 weeks of work. The actual dredging was commenced on 05 September 1997 and was completed on 10 October 1997, mainly because the digger mounted on the

Table 1. *Suspended sediment load and turbidity measured during the maintenance dredging on 05 September 1997. All turbidity measurements are in NTU units measured by a Yeokal Model 608 turbidimeter. See Figure 4 for locations. Sampling depth refers to depth from water surface, generally the mid-depth of the water column.*

Sampling Date: 05 September 1997 **High Tide:** 09:14 hrs **Low Tide:** 14:52 hrs
Dredging Commenced: 06:50 hrs **Dredging Completed:** 12:10 hrs

Site	Time	Sampling Depth (m)	Turbidity (NTU)	Susp. Sediment Load (mg/l)	Wind Speed (knots)	Wind Direction	Wave Height (m)	Rain	Tide
Control Site 1. (a)	14:52	1.5	4.2	30.2	5	SE	0.10	nil	slack
Control Site 1 (b)	14:54	1.5	4.2	26.8	5	SE	0.10	nil	slack
Control Site 1 (c)	14:55	1.5	4.2	27.0	5	SE	0.10	nil	slack
Control Site 2 (a)	15:01	1.6	4.3	31.0	5	SE	0.10	slight	slack
Control Site 2 (b)	15:03	1.6	4.3	32.8	5	SE	0.10	slight	slack
Control Site 2 (c)	15:05	1.6	4.3	32.0	5	SE	0.10	slight	slack
1	14:04	1.2	2.6	30.0	2	SE	0.05	nil	ebb
2	14:25	1.0	4.0	25.2	calm	—	0.10	nil	ebb
3	09:40	0.2	3.4	30.4	2	E	0.10	nil	ebb
3	09:41	1.0	3.1		2	E	0.10	nil	ebb
3	09:42	2.0	3.4		2	E	0.10	nil	ebb
3	09:43	3.0	4.0		2	E	0.10	nil	ebb
3	09:44	4.0	5.8		2	E	0.10	nil	ebb
3	09:45	5.0	6.2		2	E	0.10	nil	ebb
3	14:30	2.0	3.8	30.8	5	SE	0.10	nil	ebb
4	14:35	1.7	6.1	32.4	5	SE	0.15	nil	ebb
5	14:40	2.2	4.2	37.6	7	SE	0.15	nil	ebb
7	14:45	1.5	4.3	38.8	5	SE	0.15	nil	ebb
8	14:50	1.0	2.2	27.2	5	SE	0.15	nil	ebb

barge was required for another contract. The monitoring program envisaged a "before dredging, during dredging and after dredging" set of surveys for bathymetry, side-scan sonar, and benthic ecology. In the event, due to inclement weather, only the 'before' and 'after' monitoring for bathymetric, side-scan, and ecological surveys were carried out. Notably however these surveys were able to be carried out immediately after the cessation of dredging so that maximal effect of those activities on the environment were able to be measured. Monitoring sites are illustrated in Figure 4.

TURBIDITY AND SUSPENDED SOLID CONCENTRATION DURING THE DREDGING AND DISPOSAL

Fortnightly monitoring runs were required and were carried out on 05 September, 19 September, and 03 October 1997 at the sites given in Figure 4. Samples were collected as 3 replicates at mid water depth, on the ebb tide, and notes were taken on the wind and wave conditions at time of sampling. Results of the turbidity and suspended sediment load

Table 2. *Suspended sediment load and turbidity measured during the maintenance dredging on 19 September 1997. All turbidity measurements are in NTU units measured by a Yeokal Model 608 turbidimeter. See Figure 4 for locations. Sampling depth refers to depth from water surface, generally the mid-depth of the water column.*

Sampling Date: 19 September 1997 **High Tide:** 09:05 hrs **Low Tide:** 14:38 hrs
Dredging Commenced: 06:10 hrs **Dredging Completed:** 13:15 hrs

Site	Time	Sampling Depth (m)	Turbidity (NTU)	Susp. Sediment Load (mg/l)	Wind Speed (knots)	Wind Direction	Wave Height (m)	Rain	Tide
Control Site 1. (a)	12:10	1.6	5.4	32.0	5	NW	0.10	nil	ebb
Control Site 1. (b)	12:11	1.6	5.4	35.8	5	NW	0.10	nil	ebb
Control Site 1. (c)	12:16	1.7	5.5	29.4	5	NW	0.10	nil	ebb
Control Site 2. (a)	12:24	1.5	5.7	37.6	5	NW	0.10	nil	ebb
Control Site 2. (b)	12:26	1.5	5.8	30.0	5	NW	0.10	nil	ebb
Control Site 2. (c)	12:27	1.5	6.2	33.8	5	NW	0.10	nil	ebb
1	13:09	0.8	5.7	35.2	7	N	0.10	nil	ebb
2	13:05	1.0	17.8	52.8	5	N	0.10	nil	ebb
3	13:15	1.6	6.0	30.6	5	N	0.15	nil	ebb
4	13:20	1.6	5.3	27.4	7	N	0.15	nil	ebb
5	13:28	2.1	4.4	29.8	5	N	0.10	nil	ebb
7	13:37	1.7	4.7	17.8	5	N	0.15	nil	ebb
8	13:41	1.1	23.5	48.4	8	N	0.15	nil	ebb

Table 3. *Suspended sediment load and turbidity measured during the maintenance dredging on 03 October 1997. All turbidity measurements are in NTU units measured by a Yeokal Model 608 turbidimeter. See Figure 4 for locations. Sampling depth refers to depth from water surface, generally the mid-depth of the water column.*

Sampling Date: 03 October 1997 **High Tide:** 08:29 hrs **Low Tide:** 14:06 hrs
Dredging Commenced: 05:50 hrs **Dredging Completed:** 16:09 hrs

Site	Time	Sampling Depth (m)	Turbidity (NTU)	Susp. Sediment Load (mg/l)	Wind Speed (knots)	Wind Direction	Wave Height (m)	Rain	Tide
Control Site 1 (a)	11:25	1.8	4.6	30.6	8	NW	0.20	nil	ebb
Control Site 1 (b)	11:26	1.8	4.5	33.2	8	NW	0.25	nil	ebb
Control Site 1 (c)	11:28	1.8	4.6	28.0	8	NW	0.25	nil	ebb
Control Site 2 (a)	11:33	1.7	5.6	20.2	8	NW	0.40	nil	ebb
Control Site 2 (b)	11:34	1.7	5.7	35.6	8	NW	0.40	nil	ebb
Control Site 2 (c)	11:36	1.7	5.7	29.0	8	NW	0.40	nil	ebb
1	11:44	1.0	6.8	31.0	7	NW	0.25	nil	ebb
2	11:53	0.8	7.1	31.0	7	NW	0.20	nil	ebb
3	12:02	1.6	6.3	29.4	8	NW	0.20	nil	ebb
4	12:13	1.8	2.6	25.2	8	NW	0.20	nil	ebb
5	12:21	1.6	6.4	29.4	5	NW	0.30	nil	ebb
7	12:34	2.0	5.3	29.4	5	NW	0.30	nil	ebb
8	12:45	1.0	17.6	74.0	8	NW	0.30	nil	ebb
8	12:46	0.1	61.0	140.0	8	NW	0.30	nil	ebb

(ssl) along with the environmental conditions at the time of collection are given in Tables 1, 2, and 3.

05 September 1997

Winds were calm and waves low. Suspended sediment load in the navigation channel was ~ 28 mg/l (turbidity ~ 4.2 NTU), which was marginally lower than at the control site away from the channel (ssl ~ 32 mg/l, turbidity ~ 4.3 NTU) taken as representative of the background level. Highest suspended sediment load was measured at site 7 (39 mg/l, turbidity ~ 4.3 NTU),) associated with discharge of muddy water from the Turanga Creek catchment from a rainfall event in the prior 24 hours. Turbidity values around the disposal ground are all similar to background levels.

19 September 1997

Conditions were similarly calm on this day. Suspended sediment load at the control site was ~ 34 mg/l (turbidity ~ 5.8 NTU), which again exceeded levels within the channel sampling site (ssl ~ 32 mg/l, turbidity ~ 5.4). Highest recorded was at site 2 just north of the channel (ssl—52.8, turbidity—17.8 NTU), and this reflects the ebbing tide carrying a plume of high ssl originating from the dredging operation. Values of ssl were equivalently high at site 8 near the Turanga Creek mouth (ssl—48.4 mg/l, turbidity—23.5 NTU) and this illustrates the background discharge from the catchment is as high as the plume caused by the dredging operation at site 2. Values around the disposal ground are otherwise all similar to background levels indicating that there was not an advection of extremely turbid water from the disposal ground—a condition necessary if mud was to be advected from the disposal site and become redeposited on adjacent beaches.

03 October 1997

Conditions were more windy and choppy for this monitoring run, and previously there had been marked rainfall in the catchment. Suspended sediment load in the channel and control site were all close to 30 mg/l (turbidity ~ 5 NTU). But remarkable was the suspended sediment load of 140 mg/l (turbidity—61 NTU) in surface waters at site 8, representing the natural discharge from the Turanga catchment. This is an order of magnitude greater than levels measured in the direct dredging plume as represented by the site 2 values above. The Turanga catchment discharge plume is identified in the photo records for that day (Figure 5).

The results of the turbidity and suspended sediment load monitoring show that:

- The trigger level stipulated in the consent for the dredging and disposal of 20 mg/l suspended sediment load above ambient background was not exceeded;
- The highest suspended sediment load attributable to dredging was at site 2 on 19 September (52 mg/l), and this was equivalent to natural discharge of suspended sediment load from the Turanga Creek on that day; and
- The highest suspended sediment loads recorded from the Turanga Creek on 03 October 1997 were about five times higher than that associated with the dredging on that day.

EXTENT AND DURATION OF TURBIDITY FROM THE DISPOSAL

A field experiment was undertaken to assess the persistence of turbidity from release of the dredged material into the water column when the dredge/barge was in the disposal ground. Two experiments were undertaken, on 05 September and 19 September 1997, and both gave similar results (Figure 6a, b). The survey vessel followed the dredge/barge as it was disposing of the dredged material into the water column, and near surface water samples from within the trailing plume of the barge were collected and the distance from the barge measured.

The results show that close to the barge as it is discharging sediment the NTU values are expectedly high at 25–30 NTU, which would have been associated with a suspended sedi-

Figure 5. Turbid plume due to natural catchment discharge of high natural suspended sediment loads from the adjacent Turanga catchment.

ment load of about 50–70 mg/l in the trailing plume. But at distances greater than about 250 m from the barge the water turbidity reduced to levels close to background (~ 9 NTU), suggesting that the duration of the turbid plume during the disposal operation was just a few minutes (5–15), which is consistent with observations on muddy dredge spoil disposal in Poverty Bay (KENSINGTON, 1990; SANDER, 1993; WOOD, 1994).

The dredging activity in the navigation approach channel also gave rise to a turbid plume, which on the ebb tide flowed northward and on the flood tide was often taken into the marina basin. The plume from the dredging operation was more persistent than for the disposal operation because the dredging was always close to the same location and arose from continuous disturbance of the approach channel sea bed by the dredging activity.

Comparison of turbidity from the dredging operation and the natural estuarine wave-agitated turbid fringe based upon visual colour photography and measured turbidity intensity showed that the dredging and disposal operation induced less turbidity than occurs naturally from discharge from the adjacent catchments (see Figures 5 and 13). Another source of localized turbidity was seen to come from wave erosion of slumps from cliff collapse at certain locations in the embayment (HEALY, 1997).

MODELING RESUSPENSION AT THE DISPOSAL SITE

A question naturally arises as to the potential effect of disposing dredged material at the disposal site on water column turbidity. In order to simulate this effect, we ran a fine-grained sediment resuspension model (MEHTA and LI, 1997).

This is a 1-D code which simulates the time-evolution of suspended sediment concentration profile under a progressive wave field, or waves and a superimposed (weak) current. In this model the time-varying concentration profile may be simulated for 1) fluid mud subjected to wave motion or waves plus a weak current, and 2) a sediment bed subjected to a steady or quasi-steady current, wave motion or waves plus a weak current. For fluid mud resuspension, the entrainment of fluid mud into the water column and its redeposition can be simulated to be one that modulates the wave-induced sediment diffusion, without however changing the wave-induced flow field. For bed resuspension the erosion of sediment from bed into the water column and its redeposition can be simulated under a current, under wave motion, or under a wave and a weak current.

A coordinate system was set in such a way that the interface of water column and fluid mud or bed is defined as 0, the vertical suspended sediment transport is described by the (wave-mean) vertical settling-diffusion equation as a particular case of the general mass conservation equation:

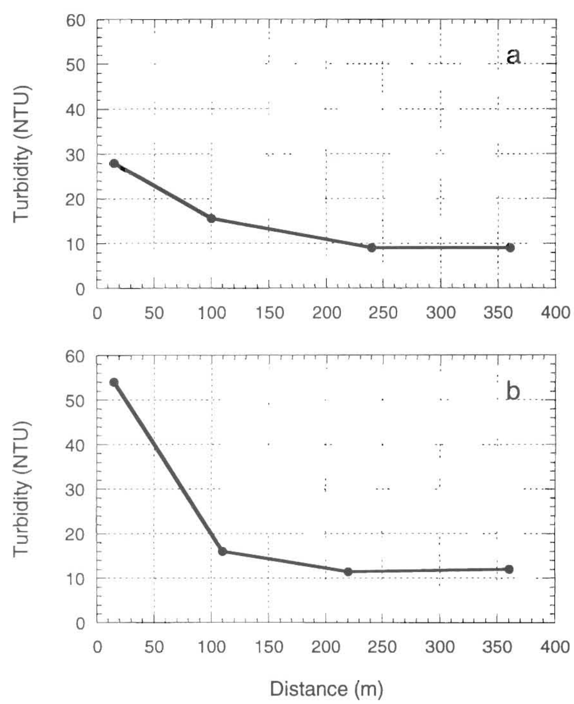

Figure 6. Turbidity of the surface water (0.2 m from the water surface) at different distances behind the barge during the spoil disposal monitoring days of: (a) 05 September 1997 and (b) 19 September 1997. The width of the plume was about 10–15 m and the background turbidity was ~ 4 NTU.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z} + W_h C\right) \quad (1)$$

where K is the diffusion coefficient, W_h is the settling velocity, and C is the sediment concentration in water. The detailed description of this model is given by MEHTA and LI (1997).

From SCUBA observations (HEALY, 1997), we considered the natural bottom to be a consolidated bed, whereas the disposed material was assumed to be a soft slurry. Given this distinction, sediment resuspension at this site was simulated as follows. Based on available hydrographic information for the region, the estimated long term rate of sedimentation in the channel, and the need to simulate realistic episodic scenarios for turbidity in the water column, we selected the following nominal values of the key variables: water depth 3 m, current speed 0.15 m/s, characteristic settling velocity of mud flocs 2 mm/s, wave height 1 m and period 3.5 s.

Results from running the model showed that in the predisposal condition, bottom mud was easily resuspended (Figure 7) and generated a surficial (equilibrium) concentration of 0.45 kg/m^3 (450 mg/l). The predicted concentration after disposal (Figure 8) was found to be 0.43 kg/m^3 (430 mg/l). These concentrations are sensitive to the erosion threshold of mud and are upper limits—the respective mean values being about ⅓ of these, *i.e.,* ~150 and ~143 mg/l, which is closely similar to values actually measured in waters discharging from the adjacent catchment on 03 October 1997. Irrespective of the actual magnitudes, the simulations indicate that the erodibility of bottom sediment in the disposal area, which seems naturally high, is unlikely to change measurably as a result of disposal of the muddy dredgings.

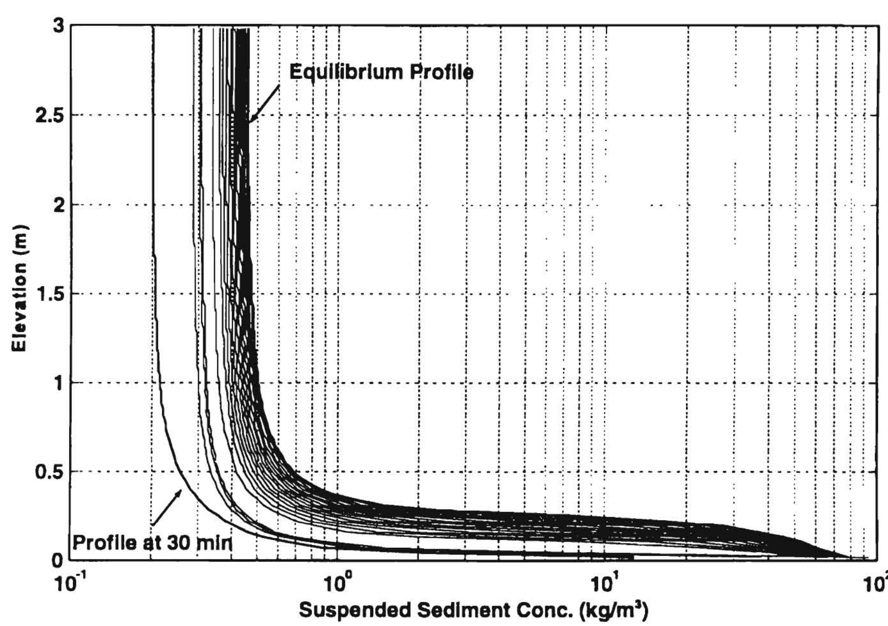

Figure 7. Time evolution of suspended sediment concentration profile over natural bed at the disposal site. Profiles are every 30 min starting with initiation of 1 m wave action over the bed. The water column is assumed to be initially free of suspension.

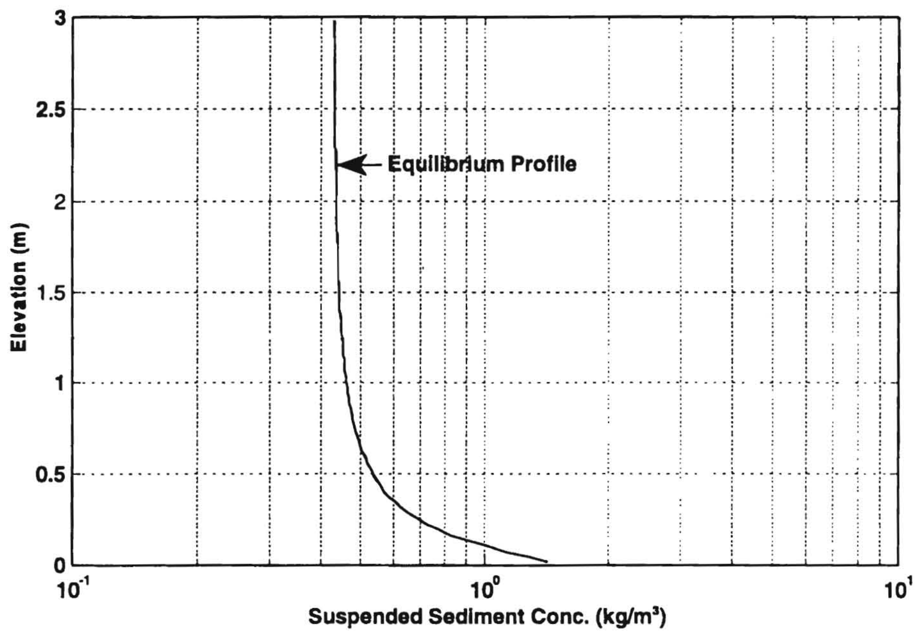

Figure 8. Equilibrium profile of suspended sediment concentration under 1 m waves at the disposal site after dredged material disposal. Profiles evolving with time have been omitted.

HYDROGRAPHIC SURVEY OF CHANNEL AND DISPOSAL GROUND

Estimates of the volume dredged were made by comparing detailed hydrographic surveys, and volumes checked against loads transported in the dredge/barge for every round trip reported by the dredge operator. Two hydrographic surveys of the channel were undertaken, a "before dredging" survey (01 September 1997) and an immediate post-dredging survey (12 October 1997). The data were collected by a Furuno digital echo sounder linked to Differential GPS (DGPS), and entered to HYDRO software for post-processing. The data were smoothed and plotted by use of SURFER software.

Initial comparisons suggest that some 2400 m^3 have been dredged from the channel. However the relative error in this estimate is quite large, and indeed the uncertainty of estimate is of order 7800 m^3. The estimate from comparison of bathymetric surveys compares quite well with a volume estimate of $\sim$2450 m^3 reported by the dredge operator.

Hydrographic survey was also undertaken of the disposal ground, pre- and post-dredging disposal. Figure 9 illustrates the bathymetric difference between the two surveys. An area in the center of the disposal ground has evidently increased in elevation by about 20 cm, but clearly there is no large or discrete mound of dumped material.

However, one must be aware that in muddy bottom sediments there often occurs a layer of fluid mud with different density properties so that it is possible to obtain a false bottom reading on an echo sounder. This is a well recognized phenomenon internationally (CHANDRAMOHAN, 1997). For this case a false bottom echo caused by fluid density differences above the deposited mud might suggest more deposition than occurred in reality.

Hydrographic survey demonstrates clearly that thin layer dispersal has been achieved and that the most intense disposal was in the central area of the disposal ground. As seen below, this is consistent with the side-scan sonar survey.

SIDE-SCAN SONAR SURVEY OF DISPOSAL GROUND

A pre- and post-dredging side-scan sonar survey was undertaken of the disposal ground using a Klein 595 side-scan sonar system with dual 100 kHz and 500 kHz transducers, using DGPS for position fixing. The pre-dredge side-scan survey results show a very regular uniform sonograph pattern over the entire disposal area comprising random 'speckles' over a featureless surface (Figure 10a) which subsequent SCUBA observations showed to be a soft muddy bottom.

However the post-dredging side-scan survey clearly identified where the dredged material deposited on the sea floor. The track of the dredge/barge on a disposal run could be identified from discrete 'plops' on the side-scan trace caused by the digger scooping material into the 'glory hole' on the barge, from where it was washed by turbulent cyclone pump flow into the sea water column and the coarser fractions settled onto the sea floor. Visual inspection of the post-dredging side-scan traces (Figure 10b) suggest that the effect of each discrete deposition was small and resulted in $<$ 20 cm elevation change of the sea floor. Figure 11 is an interpretation of the intensity of dredging disposal. It shows the overall area where evidence of disposal could be detected—very clear on

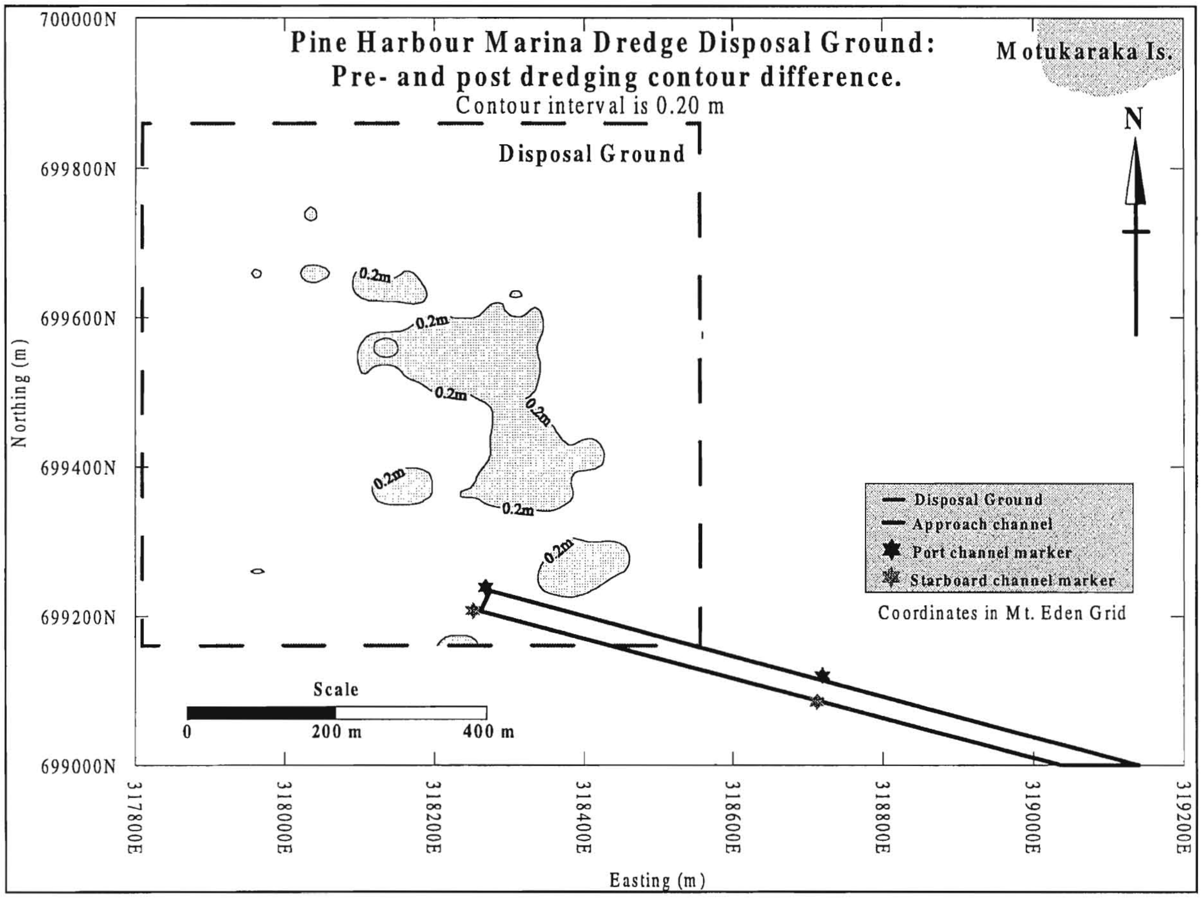

Figure 9. Comparison of the pre-and post-disposal bathymetric surveys of the disposal ground. Contour interval is 0.2 m.

the sonographs—and the intensity of discrete disposal deposition 'plops'. The center of the disposal area contained the most intense pattern of disposed sediment.

Overall the side-scan sonar survey showed that: the location of material disposed from the dredge/barge could be detected; the disposal operation achieved wide spatial distribution over the designated ground; and there was no evidence of a built dump mound or migration of muddy material 'en masse' from the disposal ground. All of these are consistent with achieving a thin layer disposed for the muddy dredgings.

SEDIMENTATION RODS

Sedimentation rods were placed on the sea floor (Figure 4) to check the variation of the sea floor sediment elevation as an indicator of sediment transport over the sea floor. If the deposited sediment were to migrate onshore as a cohesive mass (MATHEW and BABA, 1996), for example, then evidence of transport across the sea floor would likely be registered on the sedimentation rods. The rods were emplaced by SCUBA divers and revisited on 19 September and 06 October 1997.

Rod measurements showed that variation in the sea floor was typically of order 1 cm, which is close to the error expected in this type of measurement. Clearly there has been little change in sea floor topography around the sedimentation rods. Again this is consistent with other monitoring observations that the material once disposed has not collected as a mud mound and subsequently migrated by bedload transport to other areas in the bay.

DREDGE DISPOSAL PATH

Disposal paths of the dredge as located by DGPS and traced by the barge operator during the disposal operations, are plotted and shown in Figure 12. The area of intensive disposal coincides with the areas identified as the most intense pattern of disposal from the side-scan imagery and slight sea floor elevation by the bathymetric survey.

EFFECTS OF DISPOSAL ON BENTHIC ECOLOGY

Impacts on the benthic ecology from the dredging disposal are reported by COLE (1998). The total number of individuals at both control and dump ground sites declined slightly between pre- and post-monitoring surveys. The decrease at the dump ground was of a larger magnitude, but the difference between control and dump ground sites was smaller than the temporal change at the control site.

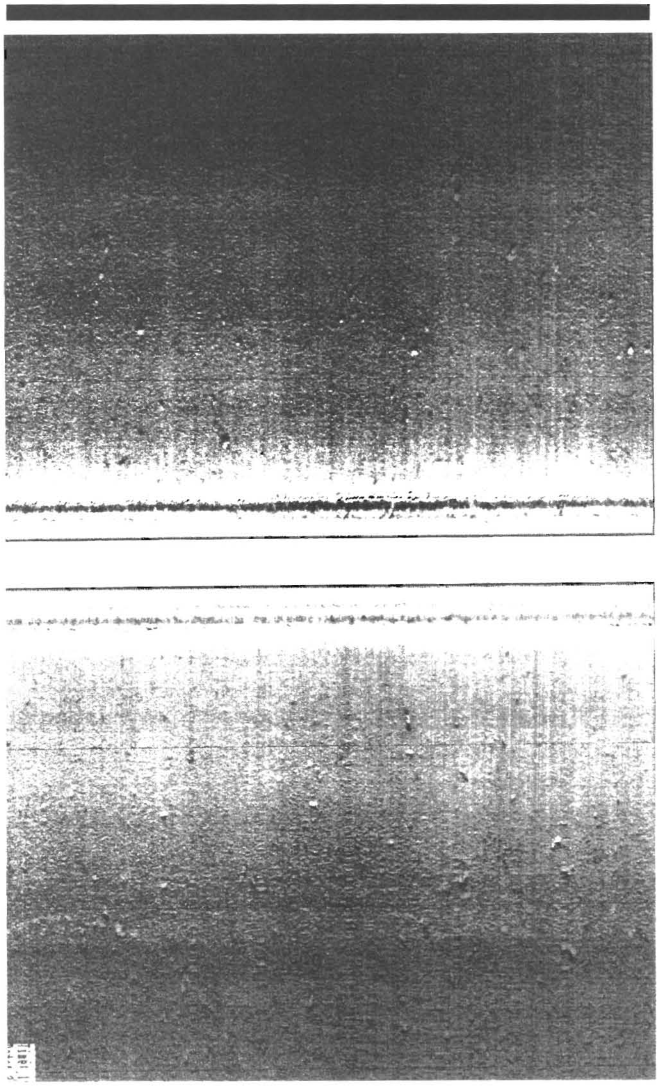

Figure 10a. Side-scan sonar imagery of the pre-disposal survey showing featureless bottom of the disposal ground.

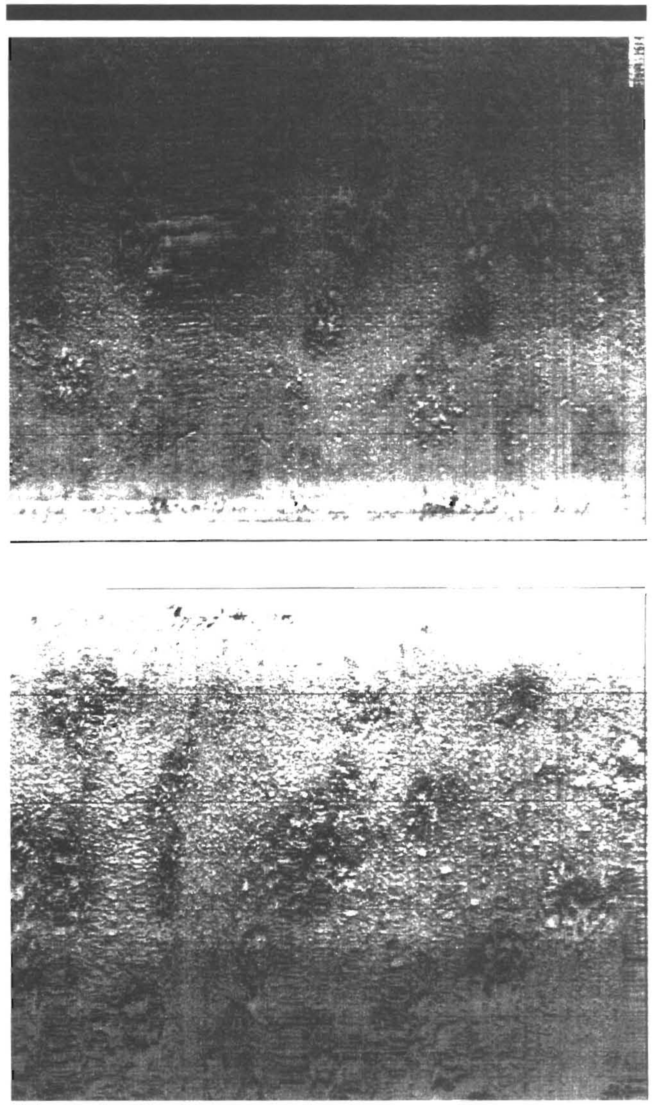

Figure 10b. Post-disposal side-scan sonar imagery showing deposits of dredged material on the seabed.

The number of species declined through time at the dump ground, and increased through time at the control areas. However, the change was small (in the order of 10%, or 2 species per sample). Before the dredging operation, the fauna was dominated by a single bivalve species. That bivalve species was absent in the second survey, when another bivalve became more abundant at the dump ground site than at the control sites.

A more equitable distribution of individuals among species was visible after disposal, at both dump ground and non-dump ground sites. The fauna did not become dominated by 1 species, as is predicted by some disturbance models.

The taxa which demonstrate the most severe or clear dumping impacts are polychaetes (*Aglaophamus macroura, F. Euclymeninae, & Labiosthenolepis laevis*). Other species which fail to demonstrate the effect include: other polychaetes (*Lumbricalus aotearoae*), a crab (*Macrophthalmus hirtipes*), mysid shrimps, and the whelk (*Cominella adspersa*).

Given that the second survey was immediately at the end of dredging when maximum impact would be detected, the lack of general effects on the fauna is noteworthy: Clearly (i) the fauna appears to be resilient to the impact, and (ii) temporal variability at the control site is also large for some taxa.

AIR PHOTO RECORDS

At times of the monitoring runs, high angle oblique air photos were taken to provide a visual record of conditions at the time of monitoring. These clearly show that the surrounding catchments and the wave agitated estuarine turbid fringe provide much greater generation of turbid water with higher suspended sediment loads which impact over much larger areas of the embayment than the dredging and disposal activity (Figure 13).

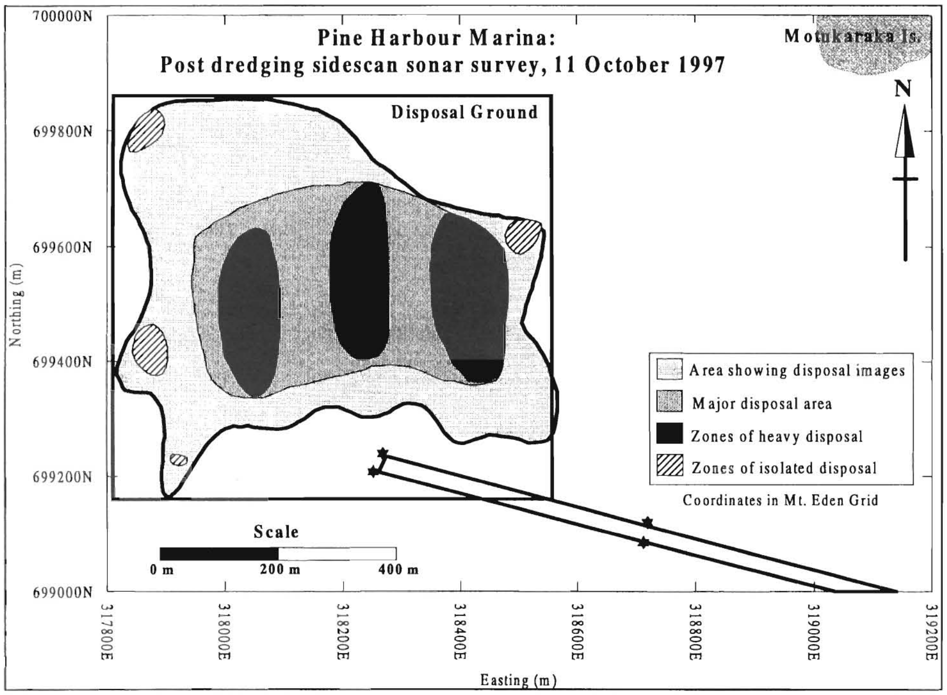

Figure 11. Interpretation of sea bed patterns from the post-disposal side-scan sonar survey of the disposal ground.

EFFECTS ON SURROUNDING BEACHES

Public concern that the dredging and disposal operation would induce muddy despoilation of the adjacent beaches around the wider embayment was a major issue. Thus during the monitoring period photographs were taken at various locations north of the marina and immediately onshore of the disposal operation to record the state of the beach sediments and especially to observe for any mud deposit on the surrounding beaches arising from advection of muddy turbid water or sediment from the disposal area. Visual comparison of the photographic record suggests that no detectable changes have occurred to the surrounding sandy intertidal or beach environments in terms of sedimentation patterns during the monitoring period, and no mud deposition was observed on the beach sands between the Marina and Sunkist Bay beach.

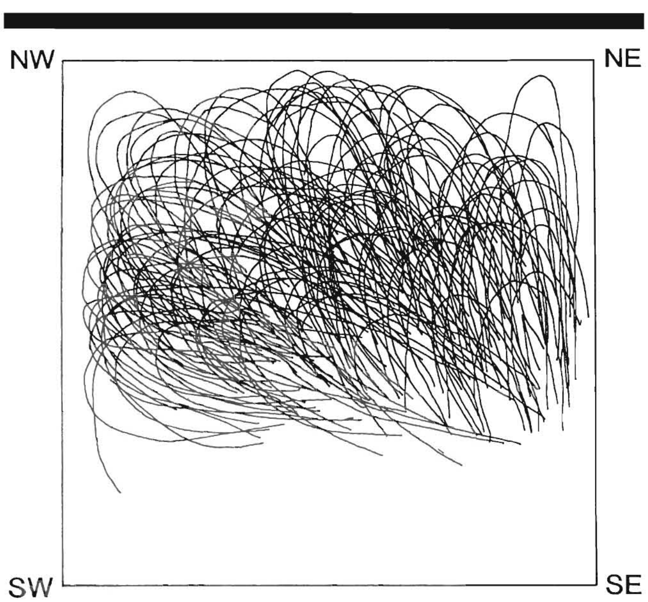

Figure 12. Cumulative plot of the dredge disposal paths.

CONCLUSIONS

The purpose of the dredging and disposal monitoring program was to detect whether the operations caused any significant deleterious effects on the surrounding environment. Of major concern to the public was the possibility that sediment dumped might then become transported resulting in mud deposition on the nearby beaches, or exacerbate shoaling problems at an anchorage in a nearby estuary.

The turbid plume from the disposal site was of high suspended sediment load close to the dredge/barge, but at ~250 m distance from the barge the plume suspended sediment values were low, indicating that the turbidity plume was a transient feature which typically lasted 5–15 minutes. Compared to natural turbidity plumes from local catchments the dredge-induced turbidity plume was of much less intensity and suspended sediment concentration.

It is clear from the bathymetric and side-scan sonar surveys and sedimentation rod data that thin layer disposal was

Figure 13. Turbidity and high suspended load from the estuarine turbid fringe and from the stream adjacent (to the right) of the marina flowing under the influence of southwesterly winds into the marina approach channel, where muddy deposition occurs. Such "natural" turbidity is higher than measured at the monitoring sites related to the dredging.

achieved, and that deposited material has not subsequently migrated 'en masse'. Although the dredging and disposal operations generate some turbidity, it is much less than was measured as occurring naturally within the embayment from runoff and discharge from the surrounding catchments. Cliff slumping and wave erosion of the slump material also produced noticeable turbidity in the embayment.

A 1-D model of the time evolution of the suspended sediment concentration profile under storm waves demonstrated that erodibility of the bottom sediment in the disposal area after dumping was unlikely to change as a result of disposal. It is also evident that no detectable changes have occurred to the surrounding intertidal or beach environments in terms of sedimentation patterns.

Thus the objectives of the monitoring program to (i) confirm that the dredging activity does not cause release of sediment into the surrounding environment at levels in excess of those experienced naturally, and (ii) to confirm that marine disposal of muddy sediments by the thin layer disposal technique does not cause significant adverse effects upon the benthic organisms or cause the release of sediment into the environment surrounding the disposal site at levels in excess of those naturally experienced, have been achieved.

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