Dispersal of dredging plumes in Tauranga Harbour, New Zealand: A field study

Mariana C. Cussioli[1], **Karin R. Bryan**[1], **Conrad A. Pilditch**[1] **and Willem P. De Lange**[1]
[1] University of Waikato, Hamilton, New Zealand; mc204@students.waikato.ac.nz

Abstract

Water quality standards associated with dredging have become more stringent, requiring better monitoring and prediction. Here, we describe the dynamics and development of plumes generated during two dredging cycles and how they vary with respect to time and distance from the dredging activity. Backscatter signals were measured using a boat-mounted acoustic Doppler current profiler (ADCP) and total suspended solid concentrations (TSS) were determined from water samples. Results show that background TSS ranged from 7 to 9 mg l^{-1} whilst dredging plumes exhibited a vertical gradient of TSS ranging from 9 to 15 mg l^{-1} near the surface (0–2 m), and 24 to 70 mg l^{-1} near the bottom (10–12 m). ADCP transects conducted during and after dredging showed that the plume dissipated from the dredged area within 1 hour. Final transects (~1 hour after the dredging ended), revealed backscatter signals ranging from background levels to ~1.2 times greater than the background. Based on TSS concentrations and time for plume dispersion, previous studies indicated that a plume with duration of 1 to 2 hours and TSS concentration around 70 mg l^{-1} is below the threshold for causing serious impacts to the biota; therefore, only minor effects can be expected for the two dredging plumes monitored.

Keywords: Dredging, dredging plume, ADCP, backscatter signal, suspended solids concentration.

1. Introduction

In ports and harbours, routine dredging activity is needed to maintain and deepen navigation channels. Dredging can generate high quantities of suspended sediments, which are transported from dredged area by currents, and deposited on the seabed [19] [22] [23]. For example, a trailing suction hopper dredge (TSHD) can elevate turbidity close to the seabed by disturbing the bottom sediments by the draghead, and at the surface due to the overflow, whereby surplus water is discarded to increase hopper capacity. The dimensions and dispersal dynamics of a plume are determined by the dredging strategy (e.g. dredge volume, frequency, duration and method) and local sediment and hydrodynamic characteristics [6]. The complexity of these underlying factors and their potential interactions pose difficulties in predicting plume dynamics and behaviour.

Suspended sediments caused by dredge plumes and their potential impacts on marine flora and fauna are a key concern for environmental managers. For example, high suspended sediment concentrations (TSS) can reduce the feeding efficiency of filter feeding bivalves, and reduce light penetration thus affecting primary producers such as seagrasses [6] [10] [12] [15]. However, ecological effects are usually only considered significant when TSS caused by dredging is higher than the natural variation owing to storm events, wave-action, and river discharges [6]. Sediment plumes from maintenance dredging are usually of short duration, and most studies show that high TSS is mostly confined to the immediate environs of the dredging vessel and decays rapidly with time and distance from the dredge [5][16]. The rate of TSS reduction depends on the characteristics of the area being dredged, the spatial and temporal extent of the plumes and the areas of potential impact [17]. Given the transient nature of dredge plumes (which can disperse rapidly both vertically in the water column, and transversely across the harbour), the use of acoustic technologies, with high spatial and temporal resolution, for tracking plumes is an advance over the use of point sample measurements [19].

Through the application of the acoustic method, our aim was to track the plumes created during maintenance dredging in Tauranga Harbour, with the objective of describing their dynamics and development with time and distance from the dredging area and compare TSS values with background levels. Improving our understanding of dredge plume dynamics and dispersal will facilitate improvements to predictive models, dredge operation planning and reduce environmental impacts.

2. Study Area

Tauranga Harbour is an estuarine lagoon, located at 37˚40'S and 176˚10'E, on the east coast of New Zealand's North Island, comprising an area of about 200 km^2 [14]. Intertidal flats separate the lagoon into two main areas, the northern and the southern basins. It is predominantly a shallow harbour, with an average depth at low tide of 3 m [21]. The tides in Tauranga Harbour are semi-diurnal and have a tidal range of 1.62 m for spring tide and 1.24 m for neap tide [8] and 60% of the harbour is intertidal sandflats [14]. The Harbour has two tidal inlets, one at each end of Matakana Island. The more important inlet for navigation is the south-eastern end bounded by the rocky headland of Mt. Maunganui, where it is also the entrance to the Port of Tauranga [3]. The Port of Tauranga was officially established in 1873 and dredging activities at the port started about 100 years afterwards, in 1968, and occurred until 1978, restarting in 1991. The main dredging projects were aimed at deepening and widening of the shipping channels. To maintain channel depths that are adequate for navigation, maintenance dredging was regularly carried out approximately every two years since 1992 [18] and presently, the Port undertakes it annually.

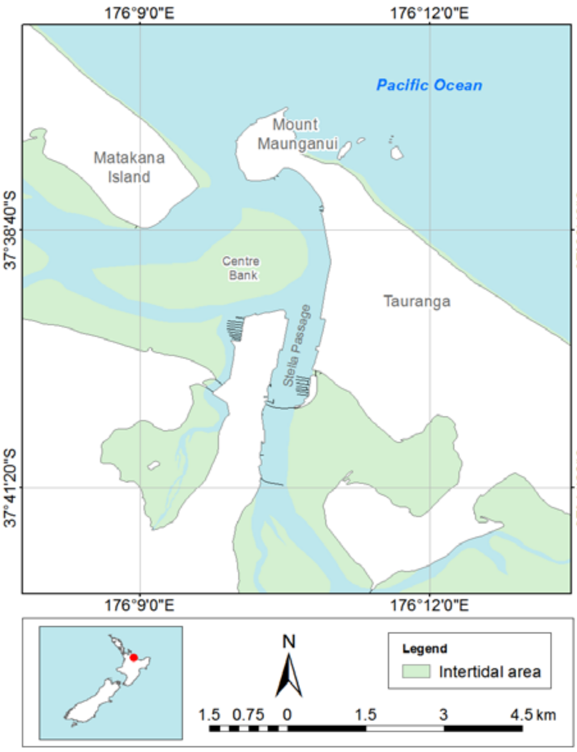


Figure 1 Map of New Zealand (small map) showing the location of the study area (red point) and a more detailed map of Tauranga Harbour (large map). The dredged area described in this paper is at south of Mount Maunganui, in the Stella Passage (176°10'37.665"E 37°39'54.72"S).

3. Methods

A maintenance dredging event occurred in October 2014 and the sediment plumes generated by the dredging activities were monitored between 13th and 16th October 2014. In this paper we present two monitoring periods (dredging cycles) conducted on 15th October, Monitoring-1 and Monitoring-2 (hereafter M1 and M2, respectively), which tracked the dredging plume in the morning and afternoon, respectively (Table 1).

The dredging was carried out using the TSHD “Pelican” (Van Oord) which has a hopper capacity of 965 m^3, 63 m in length and 11 m in width. The draft when loaded is 3.7 m. During M1, dredging started at 08:15 and finished at 08:45 (Table 1). The sailing time to and from the dumping site was 45 and 30 minutes, respectively, and dumping duration was 5 minutes. In M2, the dredging time was from 12:25 to 13:15. However the dredging duration was 30 minutes so there was an operational delay of 20 minutes of the dredge. The sailing time to and from dumping site was 40 and 20 minutes, respectively, and dumping duration was also 5 minutes. Both dredging activities occurred in Stella Passage inside an area noted as H1 (Figure 3, thin black line).1,283 and 1,187 tons of material were dredged during M1 and M2 respectively. Both sediment types were composed mainly of sand. On 15th October, low tide was 0.2 m at 05:49 and high tide was 1.8 m at 12:15. Therefore, the M1 monitoring was conducted during flood tide and the M2 during ebb tide. The monitoring period covered the end of the spring tide.

Based on the method developed in [7], dredging plumes were tracked using backscatter signals measured by a boat-mounted acoustic Doppler current profiler – ADCP (Workhorse Teledyne RD Instruments 1200 kHz). Acoustic backscatter is proportional to the concentration of suspended particles in the water. Transects along and across the main current direction were made during and after dredging until the plume signal declined to background levels, and therefore difficult to detect, or until time or technical limits were imposed. Six and 9 transects were completed for M1 and M2, respectively. Plume backscatter signals were compared with averaged profiles of background values determined from transects conducted immediately before each dredging monitoring.

Additional measurements were carried out to complement the study: water temperature, salinity and suspended solids concentration. Temperature and salinity were measured using a CTD (SBE 19plus V2 SeaCAT) and casts carried out before dredging started for background conditions and at the end of each monitoring period. Water samples for total suspended solids concentration (TSS) were collected at the surface, mid-depth and bottom using a Schindler-Patalas trap and retained in 1 l bottles until filtering, which occurred less than 24 hours after sampling.

Table 1 Start and end time for measurements carried out during M1 and M2 in order to characterize the area before, during and after dredging. Times are in New Zealand Standard Time (NZST).

	Monitoring-1		Monitoring-2	
Time (NZST)	**Start**	**End**	**Start**	**End**
Monitoring	07:11	09:35	12:13	14:28
Background sampling				
CTD	07:13		12:16	
Water surface	07:25		12:17	
Water mid-depth	07:22		12:16	
Water bottom	07:20		12:14	
Transects	07:21	07:59	12:18	12:33

Plume sampling				
Dredging	08:15	08:45	12:25	13:15*
Transects	08:15	09:36	12:34	14:28
Water surface	08:30		12:45	
Water mid-depth	08:31		12:43	
Water bottom	08:35		12:41	
CTD	9:37		14:28	

* M2 dredging time was reduced to 30 minutes following an operational delay of 20 minutes.

TSS was determined according to the method described in [1]. The method consists in filtering known volumes of water using pre-rinsed and pre-weighed filters, drying samples in oven at 105˚C for 18 hours minimum and reweighing them. The total TSS (mg l^{-1}) is given by the difference between the weight of the filter after and before filtering.

4. Results

4.1 Monitoring-1 (M1)

Surface temperature was ~1˚C higher at the water surface than at the bottom, but there were no differences between CTD casts made before (07:13) and after (09:37) the dredging monitoring (Table 2). Before dredging monitoring, there was a vertical salinity gradient with slightly higher levels at the bottom compared with the surface, but differences were weaker at the end of the monitoring period. Thus, there was no strong evidence of water column stratification that could influence the distribution of the plume.

Table 2 Temperature and salinity for M1 and M2. Results from CTD casts conducted before dredging and after each monitoring.

	Temperature (˚C)		**Salinity**	
Monitoring-1	**Before**	**After**	**Before**	**After**
Surface	16.6	16	32.3	33.3
Bottom	15.6	15.4	34	33.8
Monitoring-2				
Surface	15.2	15.4	34.4	34.5
Bottom	14.5	15.2	34.9	34.6

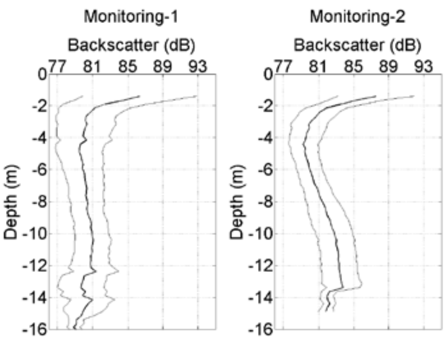


Figure 2 Averaged background backscatter profiles (thick line) ± standard deviation (thin lines) determined from transects conducted immediately before M1 (left) and M2 (right). Note the greater variability of backscatter at the surface.

Background backscatter for M1 (determined from transects conducted previous to the dredging monitoring) was highest (~84.4 dB ± 5.6) at the surface (<2 m depth) and was consistently lower (~80 dB ± 2) below this depth (Figure 2 – left). Background concentrations determined by TSS were 7 mg l^{-1} at the surface, 9.5 mg l^{-1} at mid-depth and 9 mg l^{-1} at the bottom. TSS concentrations were lower at the surface, thus was inconsistent with our ADCP transect data. During the dredging, the TSS concentration was 9, 13 and 70.3 mg l^{-1} at the surface, mid-depth and the bottom, respectively.

During dredging, ADCP measurements (Transect 1, Figure 3) detected an initial plume ~350 m long with a vertical gradient of backscatter ranging from 1.4 to 1.25 times greater than the background at the surface and the bottom, respectively (Figure 4a). After 10 minutes, in transect 2 the plume length at this position was >250 m with the highest relative backscatter (1.3) occurring at lower depths (below 8 m) compared to observations during transect 1 (Figure 4b).

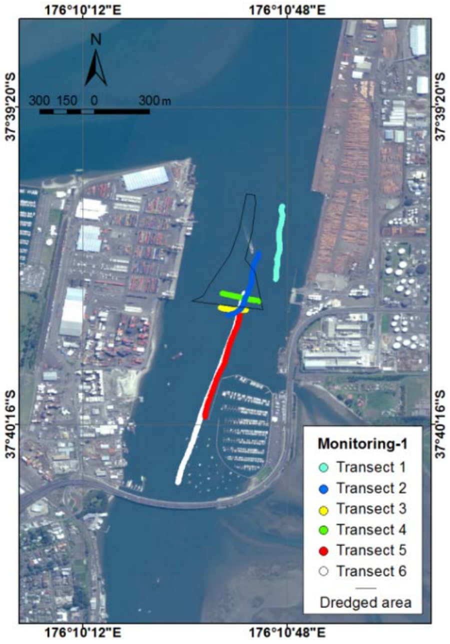
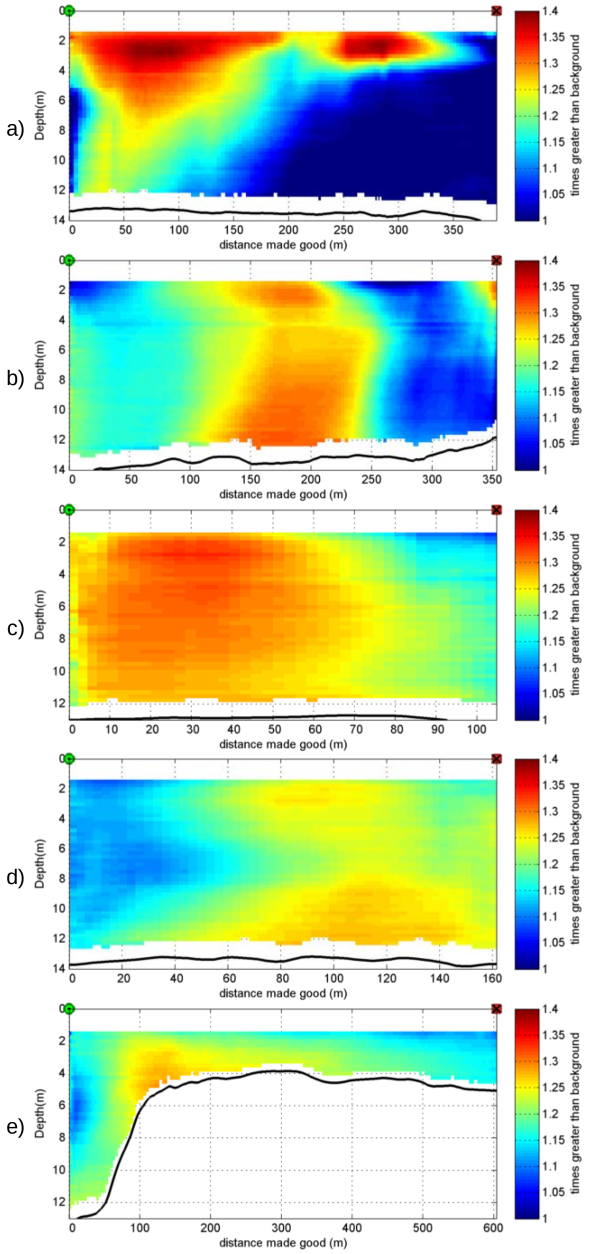


Figure 3 Map of the Stella Passage showing transects 1 to 6 conducted during and after dredging in M1. Thin black line delimits the dredged area.

Ten minutes following the end of the dredging, 2 parallel transects (3 and 4) revealed a plume >70 m in length with concentrations 1.35 to 1.30 times greater than background and higher concentrations at the surface. Diffuse areas of the plume (1.2 times greater than background) extended 30 m either side of the central plume area (Figure 4c and d).

Transects running longitudinally to the channel (5 and 6) 20 and 35 minutes after the dredging ended, revealed plume movement towards the south according to the direction of the currents and flood tide (Figure 4e and f). Along these transects, there was an abrupt change in the bathymetry, from a maximum of ~12 m to ~5 m depth. The plume presented maximum backscatter around 1.3 to 1.15 times the background as plume drifted from the deeper to the shallow area and measured ~600 m at the transect 5, and 800 m at transect 6. After 55 minutes of monitoring, the plume appeared to dissipate and was no longer detectable within the dredging area.



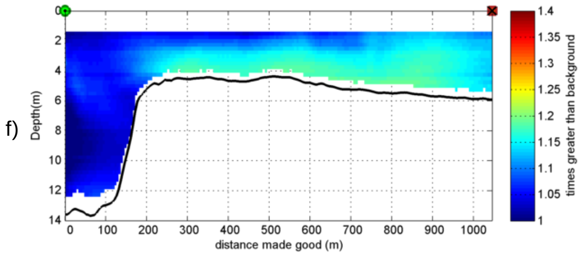


Figure 4 Profiles of Transects 1 to 6 conducted during and after dredging in M1 (Figure 3). Shading indicates backscatter greater than background and white areas represent the bottom and bins not measured by the ADCP. On top of each transect, a green circle is the start point and a red square is the end point, here described as geographic position (N – north, S – south, E – east and W – west). Start time, and start and end position for each transect follows (a) 08:15 N-S; (b) 08:27 N-S; (c) 08:56 E-W; (d) 08:58 W-E; (e) 09:05 N-S; and (f) 09:21 N-S.

4.2 Monitoring-2 (M2)

Similar to M1, salinity and temperature did not vary noticeably through the water column or between CTD casts (Table 2) and background backscatter was also highest (~85.4 dB ± 3.4) at the surface (<2 m depth) and decreased towards the bottom (~80 ± 1.8) (Figure 2 – right); However, below a depth of 7 m, the background backscatter signal slightly increased (~82.5 ± 1.8). Background TSS concentrations were 6.7 mg l^{-1} at surface, 8.7 mg l^{-1} at mid-depth and 9.6 mg l^{-1} at the bottom, very similar to the M1 and also the opposite of the background ADCP profile (Figure 2 – right). Water samples collected during dredging produced TSS concentrations of 14.9, 21.6 and 24 mg l^{-1} at the surface, mid-depth and the bottom, respectively.

ADCP transect 1, at the beginning of the dredging, detected a plume with signal 1.35 to 1.4 times greater than background extending for ~60 m and a diffuse area of the plume 1.2 times greater than background extending ~30 m on the side of the central plume area. After 30 minutes, transects in the centre of the dredging area (2 and 3) showed a surface plume (< 6m) 1.15 to 1.2 times greater than background.

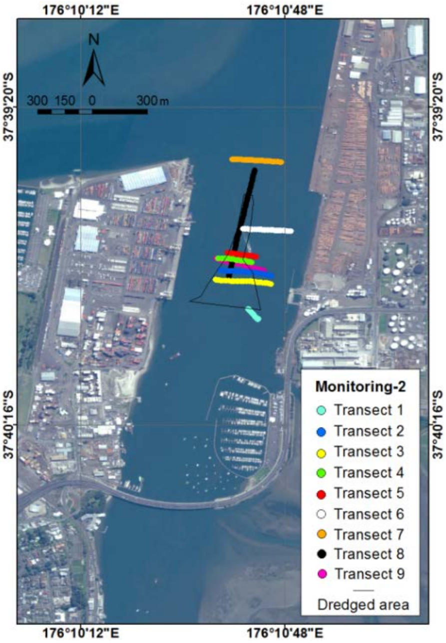
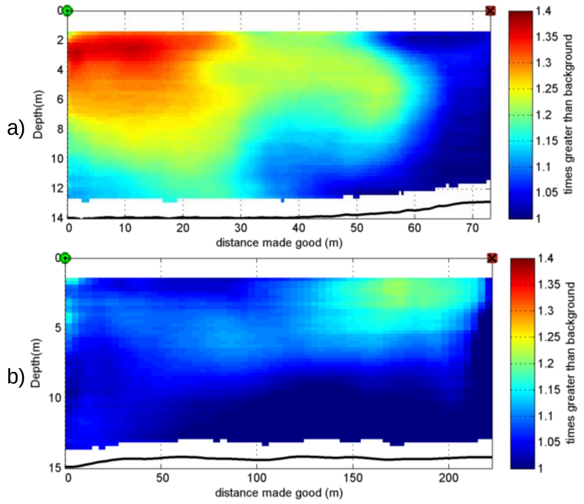


Figure 5 Map of the Stella Passage showing transects 1 to 9 conducted during and after dredging in M2. Thin black line delimits the dredged area.

After dredging finished, a series of parallel transects were made in the direction of flow, from transect 4 to transect 7, and showed plumes with maximum backscatter ranging from 1.4 (transect 4) to 1.15 (transect 7) times greater than the background with plumes usually measuring 100 m long. A longitudinal transect (8) made perpendicular to the previous transects showed backscatter similar to background levels. A comparison between one transect conducted just after dredging ended and another transect 50 minutes later (4 and 9) showed that levels had reduced to background levels within and near the dredging area.



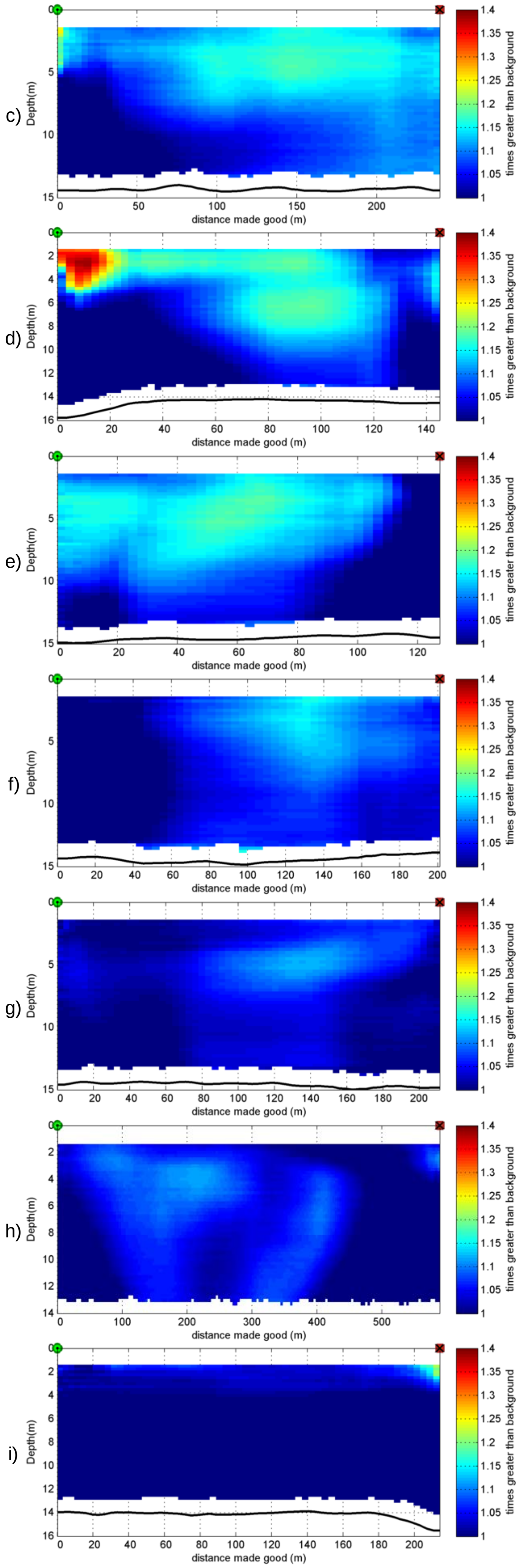


Figure 6 Profiles of Transects 1 to 9 conducted during and after dredging in M2 (Figure 5). Shade indicates backscatter greater than background and white areas represent the bottom and bins not measured by the ADCP. On top of each transect, a green circle is the start

point and a red square is the end point, here described as geographic position (N – north, S – south, E – east and W – west). Start time, and start and end position for each transect follows (a) 12:44 W-E; (b)12:55 E-W; (c)12:58 W-E; (d)13:16 W-E; (e)13:18 E-W; (f)13:25 W-E; (g)13:37 E-W; (h)13:45 S-N; and (i)14:07 E-W.

5. Discussion

Dredging plumes during M1 and M2 dissipated quickly, as shown by the rapidly-decaying backscatter signal during the first 10 minutes of dredging, which is in accordance with other studies [2] [20]. For example, [11] found a decrease of three orders of magnitude in suspended sediment concentration occurred in less than 3 minutes in a zone close to the dredging.

After dredging started, during M1, the plume was initially concentrated in the surface layers, but later descended in the water column, with deflections in backscatter signals in the direction of the current at the mid-depth ranges. These observations are indicative of material settling from the upper plume and the effect of currents on the plume motion. The plume was transported by the flood tide to the south of the dredging area; the abrupt change in bathymetry (from 12 m to 4 m), the shallow waters, and structures made it difficult to complete the survey and detect plume boundaries in this area. Furthermore, shipping traffic in the area added further complications. The turning and berthing of a large container ship generated a plume that was visibly evident in the area being monitored for the dredging plume. Therefore, the plume observed during the dredging monitoring potentially included not only the plume from the dredging but also from other contributors, such as ship movement disturbing the sediments. It was not possible to separate the ship effects from the dredging activity in the dredge plume data since the dredging was carried out very close to the berthing area. In M2, plume signals were easier to distinguish from the background and allowed a more comprehensive plume tracking. Manoeuvring of ships that were smaller than the one observed in M1 appeared to contribute less to the TSS concentrations. Transects conducted during dredging indicate that the plume drifted in the direction of the ebb tide currents and was more concentrated at surface and mid-depths.

After 1 hour, measurements obtained in the proximity of the dredged area, showed that the backscatter signal was close to the background levels for both monitoring periods. However, backscatter signals in profiles conducted within the plume track in M2 showed a more rapid reduction in concentrations compared to the plume from M1, suggesting a more rapid dissipation of the ebb tide plume. Just before the end of the monitoring, further away from the dredging area, the last observations collected showed that the plume from M2 shifted northward and backscatter signal was close to the background levels, whilst the plume from M1 was lower concentration but still detectable (1.15 to 1.2 greater than background) at ~1 km south. The estimation of the concentration of the residual plume could have been influenced by the fact that the background backscatter was measured in deeper areas, whilst the residual plume was detected in the shallow areas, thus potentially representing differences between background turbidity levels at the two locations.

The effects on biota were evaluated according to concentrations found in our TSS analysis and the time for plume dispersion detected in the transects. Other sources of contamination that could affect the biota, such as heavy metals and other possible dredge-related impacts were not considered in this study. Although studies have demonstrated negative effects caused by dredging plumes on the biota [13], our study suggests that the range of TSS and the duration of plume observed during the monitoring would have no adverse effects on key species in Tauranga Harbour such as bivalves: cockles (*Austrovenus stutchburyi*), pipis (*Paphies australis*) and seagrass (*Zostera muelleri*). Pipis, which are considered to be sensitive to increases in TSS, would only be negatively affected if exposed to concentrations of 150-200 mg l^{-1} for 5 days [9]. Seagrass can be moderately to severely impacted at TSS levels of > 75 mg l^{-1}; however, the duration of the plume resulting from dredging is unlikely to be long enough to adversely affect seagrass condition [4].

6. Conclusion

Backscatter signals during dredging showed concentrations up to 1.4 times greater than background and analysis of TSS for water samples collected in the dredging plume presented maximum concentration of 70 mg l^{-1}. However, it should be noted that discrete point samples cannot always represent the real concentrations due to the ephemeral nature of the plume. After dredging ceased, backscatter levels in the dredged area reduced to background levels in 1 hour or less, and our results suggest that the ebb tide plume dissipated faster than the flood tide plume. Previous studies indicated that a plume with duration of 1 to 2 hours and TSS concentration ~70 mg l^{-1} is below the threshold for causing serious impacts to the biota; therefore, only minor effects can be expected for plumes with the same characteristic of the two dredging plumes here described. Our preliminary results for Tauranga Harbour although the plume dissipated more quickly on the outgoing tide, and dredging on the outgoing tide only will provide the least likelihood of impacts, we also show that dredge operators should be able to continue working on both tides because the flood tide plume was also dissipated within an hour. This fast dissipation time is likely due to the strong flushing that occurs inside of the entrance and the generally sandy sediments. Upcoming capital dredging may uncover a greater range of particle sizes, and so monitoring of the plume is ongoing with greater potential mitigation strategies in place should the plume dissipation rate decrease.

7. Acknowledgements

The authors wish to thank Rowan Johnstone and Lance Wood from Port of Tauranga, the Pelican dredger crew, and the University's technical staff Dirk Immenga, David Culliford and Rex Fairweather; Victor Godoi, Martin Poot, Svenja Schwichtenberg and Nicole Sturgess for helping with the fieldwork; Janine Ryburn and Annette Rodgers for assistance with laboratory analysis; and Shawn Harrison for help with MATLAB codes. This work is part of a PhD project funded by the Doctoral Scholarship from the Port of Tauranga.

8. References

[1] APHA (1997). 2540 D Total suspended solids dried at 103-105°C.: American Public Health Association (APHA), American Water Works Association, Water Environment Federation.

[2] Bohlen, W.F.; Cundy, D.F., and Tramontano, J.M. (1979). Suspended material distributions in the wake of estuarine channel dredging operations. Estuarine and Coastal Marine Science, Vol. 9, No. 6, pp. 699–711.

[3] Davies-Colley R.J., Healy T.R. (1978). Sediment and hydrodynamics of the Tauranga entrance to Tauranga Harbour. New Zealand Journal of Marine and Freshwater Research, 12, pp. 225–236.

[4] Doorn-Groen, S.M. (2007). Environmental Monitoring and Management of Reclamations Works Close to Sensitive Habitats. Terra et Aqua, Vol. 108, pp. 3–18.

[5] Duclos, P.-A., Lafite, R., Le Bot, S., Rivoalen, E., and Cuvilliez, A. (2013). Dynamics of turbid plumes generated by marine aggregate dredging: an example of a macrotidal environment (the Bay of Seine, France). Journal of Coastal Research, Vol. 29, No. 6A, pp. 25–37.

[6] Erftemeijer, P.L.A., and Lewis, R.R.R. (2006). Environmental impacts of dredging on seagrasses: A review. Marine Pollution Bulletin, Vol. 52, pp. 1553–1572.

[7] Flaim, B.K. (2012). Sediment dispersion at the new Auckland marine disposal ground, Northeast New Zealand. Doctoral dissertation, University of Waikato, Hamilton, New Zealand.

[8] Heath, R.A. (1985) A review of the physical oceanography of the seas around New Zealand - 1982. New Zealand Journal of Marine and Freshwater Research, Vol. 19, No. 1, pp. 79–124.

[9] Hewitt, J. E., and Norkko, J. (2007). Incorporating temporal variability of stressors into studies: An example using suspension-feeding bivalves and elevated suspended sediment concentrations. Journal of Experimental Marine Biology and Ecology, Vol. 341, pp. 131–141.

[10] James, M., Probert, K., Boyd, R., and Sagar, P. (2009). Biological resources of Otago Harbour and offshore: assessment of effects of proposed dredging and disposal by Port Otago Ltd. Report prepared by NIWA for Port Otago Limited (NIWA Client Report: HAM2008-152; NIWA Project: POL08201).

[11] Nichols, M., Diaz, R.J. and Schaffner, L.C. (1990). Effects of hopper dredging and sediment dispersion, Chesapeake Bay. Environ. Geol. Water Sci. Vol. 15, No. 1, pp. 31–43.

[12] Nightingale, B., and Simenstad, C.A. (2001). Dredging activities: marine issues. Report prepared by Washington State Transportation Center for Washington State Transportation Commission (TRAC Technical Report WA-RD 507.1).

[13] Onuf, C.P. (1994). Seagrasses, dredging and light in Laguna Madre, Texas, U.S.A. Estuarine, Coastal and Shelf Science , Vol. 39, pp. 75–91.

[14] Park, S. (2004). Aspects of mangrove distribution and abundance in Tauranga Harbour. Report prepared by Stephen Park for Environment Bay of Plenty (Environmental Publication 2004/16).

[15] Park, S.G. (1999). Changes in abundance of seagrass (Zostera spp.) in Tauranga Harbour from 1959-96. Report prepared by S. G. Park for Environment Bay of Plenty (Environment BOP Environmental Report 99/30).

[16] Priestley, S.J. (1995). Measured environmental impacts of dredging operations. Transactions on the Built Environment, Vol 8.

[17] Puckette, T.P. (1998). Evaluation of dredged material plumes - physical monitoring techniques (No. TN DOER-E5). Vicksburg, MS: US Army Engineer Research and Development Center.

[18] Sinner, J., Clark, D., Ellis, J., Roberts, B., Jiang, W., Goodwin, E., Hale, L., Rolleston, S., Patterson, M., Hardy, D., Prouse, E., and Brown, S. (2011). Health of Te Awanui Tauranga Harbour (Manaaki Taha Moana Research Report No. 1; Cawthron Report No.1969).

[19] Smith, J.E., Friedrichs,C. (2011). Size and settling velocities of cohesive flocs and suspended sediment aggregates in a trailing suction hopper dredge plume. Continentl Shelf Research, Vol. 31, No. 10, pp. S50–S63.

[20] Smith, G.G.; Weitz, N.; Soltau, C.; Viljoen, A.; Luger, S., and Maartens, L. (2008). Fate of fine sediment from dredger-based mining in a wave dominated environment at Chameis Bay, Namibia. Journal of Coastal Research, Vol. 24, No. 1, pp. 232–247.

[21] Tay, H.W., Bryan, K.R., Pilditch, C.A., Stephen, P., and Hamilton, D.P. (2012). Variations in nutrient concentration at different time scales in two shallow tidally dominated estuaries. Marine and Freshwater Research, Vol. 63, pp. 95–109.

[22] USACE. (1983). Engineering and design: dredging and dredged material disposal (Engineer manual No. EM 1110-2-5025). Washington D.C.

[23] Wilber, D.H., and Clark, D.G. (2001). Biological effects of suspended sediments: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries. North American Journal of Fisheries Management, Vol. 21, No. 4, pp. 855–875.