Coastal Systems Research Group
Ecosystem Services Competence Area

Final Report

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Port of Richards Bay
Expansion Programme:
Turbidity and Total Suspended Solids

March 2013

Report Details

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1. Introduction

Transnet SOC Ltd (hereafter referred to as Transnet) forecasts considerable growth in the volume of cargo imported and exported through the Port of Richards Bay over the next 30 years. This and some inefficiencies associated with the existing port layout led to Transnet identifying several expansion scenarios for the port, to accommodate the forecast growth. It is beyond the scope of this report to document the potential expansion scenarios save to state that the expansion will take place predominantly in the western part of the Bay. Each expansion scenario will require the (capital) dredging and disposal of significant volumes of sediment. A concern in any situation where sediment is dredged is the ecological impact of dredging induced increases in water column turbidity and suspended solids concentrations.

2. Study Objective

The objective of this study was to determine whether there is sufficient turbidity and total suspended solids concentration data from the proposed Port of Richards Bay expansion footprint for the definition of baselines for these water quality indicators, and if so to then define baselines. It became apparent after an analysis of the areas for which data is available that the data is inadequate for establishing baselines for the entire expansion footprint. The only area for which there is a large amount of turbidity and total suspended solids concentration data available is the Mudflats area of the Bay. The habitat (conditions) provided by the Mudflats is, however, different to the remainder of the Bay. This limits the use of baselines defined for the Mudflats in other areas of the Bay. Consequently, the focus of this study shifted to the analysis of existing turbidity and total suspended solids concentration data, to highlight the limitations of the data and to identify future study needs.

3. Study Area

Richards Bay is a semi-enclosed estuarine embayment situated on the subtropical northeast coast of South Africa, in the province of KwaZulu-Natal (entrance at 32°02′E, 28°48′S). The Port of Richards Bay is situated within the Bay (Figure 1). For the purposes of this study the Bay is divided into the following areas: Inner Basin 1, Inner Basin 2, Inner Basin 3 (these are collectively referred to as the Inner Basin complex), Richards Bay Coal Terminal Basin and Mudflats (Figure 1). The Inner Basin complex and Richards Bay Coal Terminal Basin are of a deepwater nature, with a maintained water depth of about 22 meters. The water column over the Mudflats, in contrast, is shallow, with an ‘average’ water depth of about 1 - 2 meters. The Bhizolo Canal, which serves as a conduit for surface runoff, discharges onto the western part of the Mudflats.

Although its primary function is for the trade of bulk cargo the Port of Richards Bay is fairly unique in the context of South African ports since only about 40% of the land surface area has been developed. Large areas of relatively undisturbed natural habitat, including extensive intertidal sand and mudflats, and mangroves exist alongside traditional port infrastructure. These habitats have retained much of their natural functioning and the Bay plays an important role in the life cycles of numerous fish and invertebrates that show an estuarine dependence (Weerts 2002, Weerts and Cyrus 2002, Weerts *et al*. 2003). The Bhizolo Canal, lined by mangroves, offers particularly important habitat for crustaceans, especially juveniles of commercially important prawn species (Weerts *et al*. 2003). These habitats also support high abundances of fish (Weerts 2002). The Bay is ranked 26th amongst South African estuaries in terms of conservation importance (Turpie *et al*. 2002), underlying its ecological importance.

The presence of natural areas in the Bay lends aesthetic appeal and it also serves as an important recreational venue for the local community, being particularly popular for water related activities such as fishing, canoeing and sailing.

4. Background Information on Turbidity and Total Suspended Solids

Turbidity is a measure of water clarity or transparency. More specifically, turbidity relates to the amount of scattering of light by particulate and

Figure 1. Aerial view of Richards Bay showing features and place names mentioned in the text. Aerial view reproduced from Google Earth.

dissolved matter in water (Wetzel 1983, Wilber 1983). This matter includes inorganic solids, such as silt and clay, organic solids, such as (micro)algae and detritus, and dissolved salts. In general the higher the concentration of this matter the more turbid the water. Natural turbidity in coastal ecosystems is caused by colloidal suspension, such as silt and clay introduced by river runoff or through re-suspension of debris in the water column by strong wind and wave action, and in ports by vessel movements (propeller wash) and dredging. Other anthropogenic sources of suspended solids to aquatic ecosystems include stormwater runoff, sewage discharges and industrial wastes.

Total suspended solids is a measure of the dry weight of suspended particulate matter per unit volume of water, and includes the inorganic and organic solids mentioned above but not the dissolved salts. This is because suspended solids are operationally defined as matter retained by a filter of 0.45 µm pore size.

5. Ecological Impacts of Increased Turbidity and Suspended Solids Concentrations

It is not the purpose of this report to provide an extensive review of the ecological effects associated with (anthropogenically) elevated turbidity and suspended solids concentrations. Nevertheless, to provide the reader with a frame of reference it is worthwhile highlighting some effects commonly cited in scientific literature.

Primary producers, including microalgae, macroalgae and submerged vegetation rely on sufficient light for photosynthesis. It is well-known that primary production is depressed in waters where light penetration is limited by turbidity (*e.g.* Cloern 1987, Parr *et al*. 1998, Nicholls *et al*. 2003). In cases where elevated turbidity is a consequence of anthropogenic activities, the depression of primary production has a ripple-like impact on the ecosystem (Rowe *et al*. 2003, Newcombe 2003). This is because microalgae, macroalgae and submerged vegetation comprise the base of the aquatic food web, akin to grasslands and forests in terrestrial ecosystems.

Excessive suspended particulate matter, especially sediment, may adversely affect the feeding rate of invertebrate filter feeders, reducing their growth and productivity (*e.g.* Hewitt *et al*. 2001, Nicholls *et al*. 2003). This occurs when the filter feeding apparatus becomes clogged with fine-grained material or when the energetic return from processing large volumes of organically poor material exceeds the energetic gain (Widdows *et al*.

1979). Fine particles can also coat gill surfaces, isolating them from contact with water and thereby preventing gas exchange. Some bivalves cease filtering at high suspended matter concentrations, reducing the intake of food and hence impacting growth and so on (*e.g*. Foster-Smith 1976).

As is the case for invertebrate filter feeders, fine particles can coat the gill surfaces of fish, isolating them from contact with water and thereby preventing gas exchange. Alternately, larger particles can clog gill lamellae and block water circulation, by creating a dead space between the lamellae, and similarly prevent gas exchange (Sherk *et al*. 1974, 1975, Servizi and Martens 1992, Martens and Servizi 1993). Turbid conditions may enhance the visual contrast of prey items and increase overall feeding rates of some fish, as demonstrated for larval Pacific herring (Boehlert and Morgan 1985). In contrast, excessive turbidity can adversely affect feeding in fish that locate their prey by sight (Minello *et al*. 1987, Hecht and van der Lingen 1992).

It has been postulated that the foraging success of seabirds (and by implication estuarine birds) may be affected by turbid water (COE 1997). Increased turbidity results in longer foraging journeys for adults and increases the risk to chicks through predation, starvation and environmental exposure whilst the adults are foraging. It is for this reason that in some countries dredging windows that only fall outside breeding seasons or migratory periods of aquatic organisms have been invoked to protect species known or strongly suspected of being sensitive to changes in turbidity and suspended particulate matter.

Not all of the effects of turbidity and suspended particulate matter are detrimental to aquatic organisms. Some organisms are adapted to living in areas dominated by fine-grained (muddy) sediment and at the sediment water interface, and are tolerant of high turbidity and suspended particulate matter concentrations. Kiorbe *et al*. (1981) observed that suspended sediment might serve as an additional food source for blue mussels, which are filter feeders that rely on suspended particulate matter as a primary food source. It is reasonable to assume that this effect could apply to other filter feeders, including other molluscs and polychaetes amongst others. Many fish thrive in and indeed actively seek out turbid environments (Blaber and Blaber 1980, Gradall and Swenson 1982, Cyrus and Blaber 1987, Cyrus and Blaber 1992, Gregory and Northcote 1993, Wilber and Clarke 2001). This is presumably attributable to the benefit of reduced risk from predation and increased foraging rates. Also, some fish prefer relatively turbid waters due to their ambush hunting strategy (Wilber and Clarke 2001).

Another potential effect associated with suspended particulate matter occurs when the matter settles on the bottom. The excessive and persistent settling of this matter may cause reduced rates of survival, growth and reproduction in organisms because of the smothering effect of the matter and alteration of the grain size composition of sediment (Bray *et al*. 1997). Some aquatic organisms are, for example, specific in the type of sediment they can survive in (sand versus mud), either because of the need to construct burrows or because of the manner in which they feed. A change in the grain size composition of sediment has obvious implications.

6. The Concept of a Baseline

Although the term baseline is often used to refer to the range of values or concentrations for various parameters in a particular environmental medium (*e.g.* water, sediment) in the absence of an anthropogenic influence, this is technically more correctly referred to as the background. The term baseline refers to conditions in the presence of anthropogenic disturbances, albeit usually for areas where the disturbance is minimal.

Establishing a baseline for physical, chemical and biological parameters in the water column requires the repeated measurement of the parameter of interest under the widest range of conditions (*e.g.* seasonal, tidal, wind) possible in the aquatic system of interest. To establish a baseline for pH, for example, requires that a scientist return to the aquatic system of interest at regular intervals (monthly for at least six months between mid-summer and mid-winter) to measure the water column pH in as many habitats available within the system. This is because the pH of the water column (and indeed other water quality parameters) at any particular position will vary naturally on a daily (tidal and diurnal) and seasonal basis, as well as through the water column and between areas dominated by freshwater inflows and those of a more saline nature (because freshwater naturally has a lower pH than estuarine and marine water). Through repeated measurements the scientist can define the variability of pH, either at the system or habitat scale, and use this variability to define a baseline using some statistical function of the data (pH) distribution.

Although baselines can be established at the regional scale by monitoring different aquatic systems (*e.g.* many estuaries along a section of coast), it is usually more appropriate and practical to define baselines at the system scale (*i.e.* for a single estuary). This is because different systems often have unique biogeochemical characteristics. Baseline definition at the system scale becomes increasingly important if the system of interest is anthropogenically influenced. In other words, a baseline can be established even for an anthropogenically influenced system, to track long-term changes in water and sediment quality because of improved treatment and contaminant source control for example.

To provide an example of how the variability in water column physical and chemical characteristics influences the definition of a baseline, an example from the Richards Bay Coal Terminal expansion dredging compliance monitoring programme is appropriate (Weerts and Newman 2008). For this programme turbidity and total suspended solids concentration measurements were made before dredging required for the construction of Berth 306 commenced, to establish baselines/thresholds for compliance. Monitoring occurred at five stations identified for compliance monitoring in Richards Bay and at seven stations in the neighbouring Mhlathuze River estuary (see further discussion in section 7). For the stations in Richards Bay the surface water turbidity threshold ranged between 13.9 to 47.4 NTU and the suspended solids concentration threshold between 34.5 to 195.0 $mg.l^{-1}$. In the Mhlathuze River estuary, in contrast, the threshold ranged between 24.4 to 248.6 NTU for turbidity and 53.3 to 486.2 $mg.l^{-1}$ for total suspended solids, that is, a considerably wider threshold range compared to Richards Bay. This is a consequence of higher turbidity and total suspended solids concentrations in the water column of the Mhlathuze River estuary. Thus, in addition to station specific differences in thresholds within these systems there were differences in thresholds between the systems.

Various approaches can be used to define baselines for water quality indicators. The most common approach is to use a percentile of the data distribution, such as the 90th percentile, as the baseline. Using a percentile of the data distribution rather than the maximum value takes into account that a small proportion of highly anomalous measurements are usually generated by comprehensive, long-term water quality monitoring programmes. This may, for example, arise because uncommonly heavy rainfall occurred during the monitoring period. Using the maximum value for the parameter of interest if measurements were made during such an uncommon event would result in a baseline that is under-protective of the systems ‘normal’ functioning.

Some water quality indicators show a strong co-dependence. Turbidity, for example, is partly dependant on the concentration of suspended solids in the water column. If the relationship between turbidity and total suspended solids concentrations is strong then a baseline can be defined using some form of regression modelling.

Both approaches are possible for turbidity and total suspended solids, because as stated above turbidity generally increases as the total suspended solids concentration increases. However, the actual approach followed for baseline model definition can only be made after a detailed analysis of the data has been done. There is, for example, sometimes a weak relationship between turbidity and total suspended solids concentrations. In this situation regression modelling is clearly not appropriate for defining a baseline and a statistical function of the data distribution is more appropriate for this purpose.

If the relationship between turbidity and total

Figure 2. Aerial view of Richards Bay showing the positions where *in situ* water quality measurements were made and water samples were collected for turbidity and total suspended solids concentration analysis in the laboratory in February 2013. Aerial view reproduced from Google Earth.

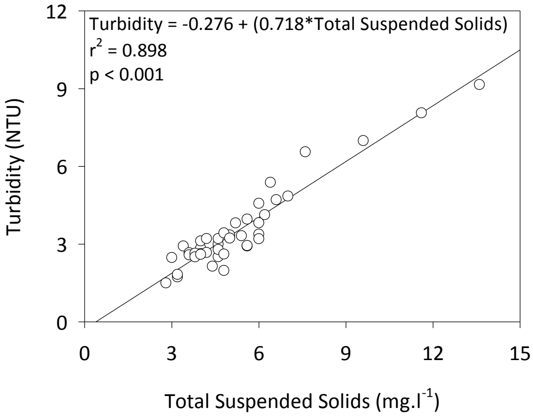

Figure 3. Relationship between the total suspended solids concentration and turbidity of surface and bottom water samples collected from Richards Bay in February 2013.

suspended solids concentration is strong then a benefit of the regression modelling approach is that a predictive model can be defined. The benefit of a predictive model is that turbidity, which is easy and inexpensive to measure, can be used to predict the total suspended solids concentration during compliance monitoring without the need to measure total suspended solids concentrations. The measurement of total suspended solids takes time to complete in the laboratory, must be performed by a specialist laboratory, and is more expensive to measure. The analysis turnaround time is important in the context of compliance monitoring since water quality indicators identified for tracking (non)compliance should, as far as practical, be measurable within timeframes that allow the early implementation of corrective action in the event of non-compliance. There is no point receiving results sometime after an adverse event, when little can be done to correct the situation.

7. Turbidity and Total Suspended Solids in Richards Bay

In February 2013, surface and bottom water samples were collected at 15 stations across the expansion footprint in Richards Bay (Figure 2). The relationship between the turbidity and total suspended solids concentration of these samples was strong (Figure 3). However, the turbidity and total suspended solids concentration at all stations was low (*i.e.* the water was relatively clear). As a result the data range is too narrow for the definition of a predictive model to account for all possible turbidity/total suspended solids concentration scenarios for the water column in Richards Bay. For example, during periods of high rainfall freshwater inflows via the Bhizolo and Mzingazi Canals will introduce suspended material to the Bay, which in turn will influence water column turbidity. It is inevitable that turbidity and total suspended solids concentrations resulting

Figure 4. Aerial view of Richards Bay showing the positions of compliance monitoring stations for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme. Aerial view reproduced from Google Earth.

from this introduction of suspended matter will exceed the turbidity and total suspended solids concentrations presented in Figure 3. Were the data in Figure 3 used to define baselines this could, in the absence of any knowledge on weather conditions prior to monitoring, result in a scientist concluding that the high turbidity and total suspended solids concentrations were associated with dredging (or some other anthropogenic disturbance) when in fact it was attributable to a natural event that was not encapsulated in the data used to define the baseline.

Because the data set for monitoring performed in February 2013 was small and the range of turbidity and total suspended solids concentration was narrow, the data were compared to total suspended solids concentration and turbidity data for 44 water samples collected in Richards Bay between August 2004 and February 2007. These data were collected as part of the previously mentioned Richards Bay Coal Terminal expansion dredging compliance monitoring programme (Weerts and Newman 2008). Only the data generated by monitoring outside of the dredging period was used for this comparison. It should be noted that for the latter monitoring turbidity was measured *in situ* while total suspended solids concentrations were measured in the laboratory, that is, turbidity and total suspended solids concentration measurements were not coincidental. *In situ* measurements of turbidity were made and water samples were collected at five stations, three positioned on the Mudflats, one in the Bhizolo Canal, and the last off the Echwebeni Natural Heritage site (Figure 4).

The above data was also compared to turbidity and total suspended solids concentrations for 24 surface water samples collected in and near Richards Bay in the summer and winter of 2011, for the Port of Richards Bay Long-Term Ecological Monitoring Programme (CSIR 2011). As was the case for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme, for the latter programme turbidity was measured *in situ* and only total suspended solids concentrations were measured in water samples returned to the laboratory.

The range of turbidity and total suspended solids concentrations measured for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme was far wider compared to surveys made in 2011 and 2013. For example, the highest turbidity measured in January 2013 was 9.2 NTU, considerably lower than the 29.9 NTU measured in the Richards Bay Coal Terminal expansion dredging compliance monitoring programme. This is because four of the five

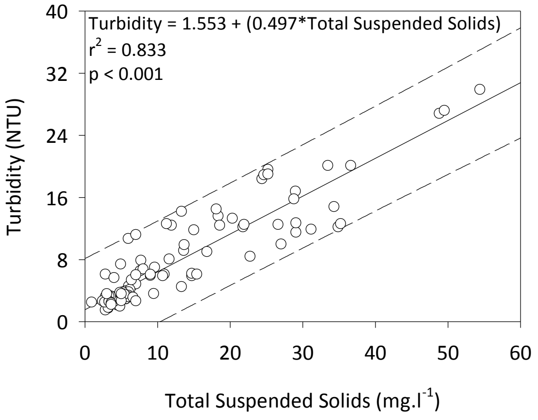

Figure 5. Predictive model based on the relationship between total suspended solids concentrations and turbidity for Richards Bay, using data generated between 2004 and 2013.

monitoring stations for the latter programme were situated on the Mudflats or in the Bhizolo Canal (Figure 4), and because pre- and post-dredging monitoring occurred over a long period that encapsulated variable weather and hydrological conditions. The water column of the Mudflats is shallow, with the result that bottom sediment is frequently re-suspended by wind-induced turbulence. This is not the case for the deepwater areas of the Bay, where wind-induced turbulence has little influence on bottom sediment. Surface runoff also entrains suspended material into the Bhizolo Canal, and in turn onto the Mudflats area. Consequently, turbidity and total suspended solids concentrations on and near the Mudflats and in the Bhizolo Canal are often somewhat higher compared to the water column elsewhere in Richards Bay.

The Richards Bay Coal Terminal expansion dredging compliance monitoring programme data were pooled with the 2011 and 2013 data and a linear regression and associated 99% prediction limits fitted. Two data points that exceeded the upper prediction limit were trimmed and the regression reiterated, under the assumption that these data represented outliers. The relationship is strong enough (Figure 5) to be used for predictive purposes, that is, turbidity can be calculated from total suspended solids concentrations and *vice versa* should one or the other of these parameters not be measured. The predictive model essentially defines the collective baseline for turbidity and total suspended solids for the stations monitored. If a water sample was collected at any point in time from these stations then it would be expected that the data point would fall within the upper and lower 99% prediction limits for 99 out of every 100 samples/measurements if the turbidity and total suspended solids concentrations do not reflect an anthropogenic influence. Furthermore, if the weather and hydrological conditions at the time that water samples were collected and measurements were made for data used to define the model are assumed to encompass the full range of natural variability for Richards Bay, then turbidity and total suspended solids concentrations will not be expected to exceed the highest value/ concentration for the parameters used to define the predictive model. If a turbidity versus total suspended solids concentration data point falls above the upper prediction limit and/or beyond the range of the predictive model, and anomalous weather or hydrological conditions (amongst other possible factors) can be discounted as an influencing factor, then this data point would be taken as being indicative of an anthropogenic influence on the turbidity and total suspended solids concentration (*e.g*. dredging).

The problem with using predictive models as a baseline is that they mask potentially important differences between stations. For example, turbidity and total suspended solids concentrations in the Bhizolo Canal are often higher compared to areas beyond the Mudflats. Applying the predictive model as a baseline to all monitoring stations may be under-protective for some areas, but this would never be identified as problematic simply because the natural variability in turbidity and suspended solids concentrations falls within the model range. It is for this reason that there is merit in defining station (or zone) specific baselines. This was the approach followed for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme, where turbidity and total suspended solids concentration baselines and a threshold for compliance were defined for all compliance monitoring stations. As is evident from Table 1 and as discussed previously, the baselines and hence thresholds varied substantially between stations, even though some stations were separated by only a few hundred meters (*e.g.* stations RBH3 and RBH4; see Figure 4).

The baselines and thresholds provided in Table 1 could be used for the Port of Richards Bay Expansion and the Port of Richards Bay Coal Terminal Development projects if the same stations are used for compliance monitoring during dredging. However, the baselines and indeed the predictive model will not be suitable for compliance monitoring at stations situated in the Inner Basin complex, where turbidity is naturally somewhat lower compared to the Mudflats and Bhizolo Canal. Similarly, the baselines may not be suitable for other sensitive sites in Richards Bay not considered in the Richards Bay Coal Terminal expansion programme.

The natural variability in physical and chemical characteristics of the water column between stations is an important factor to consider, since aquatic organisms living in or on sediment at the Mudflats are probably naturally adapted to (*i.e.* more tolerant of) elevated suspended solids concentrations compared to organisms living in shallow areas in Inner Basin 3, for example, where suspended solids concentrations are usually considerably lower. It is for this reason that baselines may need to be defined for all compliance monitoring stations identified for the Port of Richards Bay Expansion and the Port of Richards Bay Coal Terminal Development projects.

Table 1. Pre-dredge maximum and minimum values and concentrations for turbidity and total suspended solids (TSS), and limits of acceptable change for surface waters at five stations in Richards Bay as defined for the Richards Bay Coal Terminal expansion compliance monitoring programme.

Station		Turbidity (NTU)	TSS ($mg.l^{-1}$)
RBH 1	Minimum	3.3	5.0
	Maximum	10.7	32.5
	Limit	13.9	42.3
RBH 2	Minimum	6.1	4.0
	Maximum	22.2	41.5
	Limit	28.9	53.9
RBH 3	Minimum	9.9	16.0
	Maximum	25.7	26.5
	Limit	30.8	34. 5
RBH 4	Minimum	12.4	17.0
	Maximum	39.5	150.0
	Limit	47.4	195.0
RBH 5	Minimum	9.0	24.0
	Maximum	19.6	36.0
	Limit	23.5	46.8

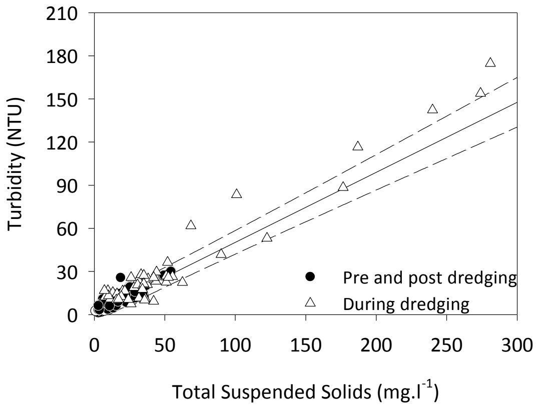

Figure 6. Predictive model for total suspended solids concentration and turbidity for Richards Bay, with data generated during, before and after dredging for the Richards Bay Coal Terminal Basin expansion compliance monitoring programme superimposed.

Superimposition of turbidity and total suspended solids concentration data generated through monitoring performed during dredging for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme onto the predictive model demonstrates that the model provides a reasonable estimate of dredging induced turbidity associated with total suspended solids concentrations less than about 50 $mg.l^{-1}$ (and *vice versa*), but tends to (slightly) underestimate turbidity at higher total suspended solids concentrations (Figure 6). This may have been due to the material (*e.g.* sub-surface sediment) disturbed into suspension by dredging having a different composition to suspended material 'ordinarily' present in the water column of Richards Bay. Regardless of the cause the difference highlights the need to also define the relationship between turbidity and total suspended solids concentrations for simulated dredging conditions (discussed in section 10 of this report).

As mentioned previously, turbidity generally increases when the total suspended solids concentration increases. However, the relationship between these parameters is often poor, either at the system specific level or between sampling sessions made within the same system (*e.g.* Truitt *et al*. 1988). This is because the total suspended solids concentration is a direct function of number, size, and specific gravity of the particles, while turbidity is a direct function of the number, surface area and refractive index of the particles, but is an inverse function of their size (for constant total suspended solids) (Gippel 1988, Clifford *et al*. 1995, Thackston and Palermo 2000). Dissolved substances, which are not part of the suspended solids, can also affect turbidity.

Analysis of data from each of the surveys performed in 2011 for the Port of Richards Bay Long-Term Ecological Monitoring Programme (CSIR 2011) shows that the relationship between total suspended solids concentrations and turbidity was far weaker compared to the relationship for the pooled data, even though all but one of the data points fall within the prediction limits for the model. This is because the predictive model is strongly influenced by total suspended solids concentration and turbidity of water samples collected for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme, and because some samples collected during one of the surveys in 2011 were noted to contain fragments of marine algae. Marine algae fragments contribute considerable weight but have little influence on turbidity. Thus, as stated previously only after the collection of pre-dredging turbidity and total suspended solids concentrations for a compliance monitoring station will it be possible to identify the appropriate approach for defining baselines (*i.e*. regression modelling and/or a percentile of the data distribution).

The predictive model essentially defines the baseline for turbidity and total suspended solids. However, because the model is strongly influenced by data from the Mudflats it is uncertain whether the relationship holds true for all areas of Richards Bay. There is presently too few coincidental turbidity and total suspended solids concentration measurements from other areas of the Bay for the definition of area specific baselines. It is for this reason that it was concluded early in this study that there was insufficient data for the definition of baselines for these parameters across the expansion footprint and possibly other sensitive sites in the Bay (*i.e.* that were not considered in the Richards Bay Coal Terminal expansion programme studies but that may be impacted by the currently proposed expansion programme), with the obvious exception of the Mudflats.

Anchor Environmental (2003) reviewed a large number of mostly laboratory based studies on the effect of suspended particulate matter on a variety of aquatic organisms, namely:

- Finfish – adult, sub-adult, and eggs
- Molluscs – adult, sub-adult, larvae, and eggs
- Crustaceans – adult and sub-adult.

The data set was statistically summarised for acute (less than 96 hours) and chronic (greater than 96 hours) effects. Segregation of effects by exposure duration is a common approach to studying the detrimental effects of chemicals and other materials in water (Suter *et al*. 2000). Most dredging operations are not performed on a continuous basis. That is, there are periods where dredging and re-suspension of sediments is not occurring. Furthermore, dredging operations often move from one area to another over time as sediments are removed. Currents may also carry sediment plumes in various directions, affecting different areas over time. Consequently, continuous exposure of a particular aquatic community to re-suspended sediments on a chronic basis (greater than 96 hours at a time) is less likely to occur near dredging operations compared to more short-term acute exposures. It should not be inferred from this that chronic exposure never occurs during dredging. Rather, it is important to distinguish between the potential for chronic and acute exposures (effects) for any specific dredging situation so that the appropriate effects levels are considered. Overall, several researchers have suggested that use of effects data for chronic exposure periods is less appropriate for dredging operations (Wilber and Clarke 2001, Nightingale and Simenstad 2001).

Anchor Environmental (2003) used the data set to also discriminate between lethal effects (where the effect was mortality) and sub-lethal effects (where the reported effect was some non-lethal response or the maximum level at which no effect was observed). Lethal versus sub-lethal effects is also an important distinction when considering the effects of dredging operations. For example, an aquatic community might be exposed to sub-lethal levels of suspended sediments for a period of several days. This may cause some short-term detrimental effect on the organism, but it does not necessarily imply long-term measurable impacts to survival, growth and reproduction. That is, many species may be able to recover without permanent injury from short-term sub-lethal exposures.

Where various mortality rates were provided for a particular study (*e.g*. 50%, 90% mortality), only the 50% mortality effect level was used. This value is also known as the Lethal Concentration$_{50}$ (LC_{50}) and is a standard approach used for developing water quality standards and conducting risk assessments (Suter *et al*. 2000). The data set for physical effects of suspended particulate matter is summarised in Table 2, for chronic/acute and lethal/sub-lethal effects. As shown in Table 2 there is a relatively wide range of effects levels reported and the effects level is dependent on the duration (chronic versus acute) and type of effect (lethal versus sub-lethal) studied.

It is worthwhile providing a retrospective analysis of some data generated during the Richards Bay Coal Terminal expansion dredging compliance monitoring programme, to demonstrate the utility of a predictive model for turbidity and total suspended solids compliance monitoring and to provide the reader with perspective on the magnitude of impacts associated with dredging related increases in total suspended solids concentrations. Figure 7 compares the 10th percentile effects level derived by Anchor Environmental (2003) to the total suspended solids concentration and turbidity predictive model for Richards Bay, and to total suspended solids concentrations and turbidity measured before, during and after dredging for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme. The 10th percentile concentration was chosen as it represents a reasonably conservative value given the uncertainties of the data set and the variety of organisms tested (Anchor Environmental 2003). As stated previously, the stations monitored for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme were situated on the Mudflats, in the Bhizolo Canal and off the Echwebeni Natural Heritage site (Figure 4). Measurements at all stations were for surface waters with the exception of the station off the Echwebeni Natural Heritage site, where bottom water measurements were also made. No total suspended solids concentrations exceeded the Acute Lethal concentration (Figure 7). However, a low proportion of total suspended solids concentrations exceeded the Chronic Lethal and Acute and Chronic Sub-lethal concentrations. The implication is that during dredging there was a possibility that some organisms may have died or otherwise been adversely affected by the high dredging induced total suspended solids concentrations in the water column. However, the majority of total suspended solids concentrations measured during dredging did not exceed any effects levels and were in fact generally within the range measured before and after dredging. It is important to note that the organisms used in

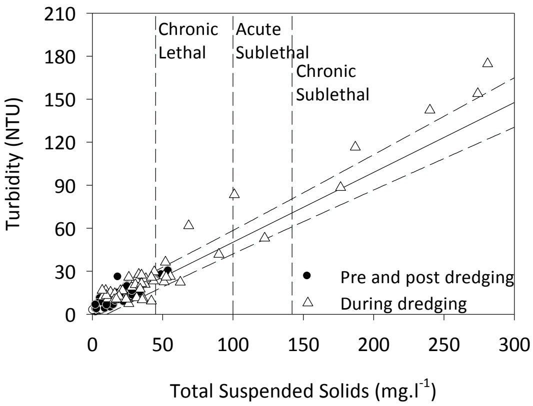

Figure 7. Predictive model for total suspended solids concentration and turbidity for Richards Bay, with data collected during, before and after dredging for the Richards Bay Coal Terminal Basin expansion compliance monitoring programme superimposed. Also superimposed are effects levels derived by Anchor Environmental (2003) (see Table 2).

Table 2. Summary statistics of the effects of suspended particulate matter (mg.l^{-1}) for all species considered by Anchor Environmental (2003).

Endpoint	5th percentile	10th percentile	50th percentile	Sample size
Acute Lethal	500	760	7000	67
Acute Sublethal	76	100	560	50
Chronic Lethal	50	142	2150	59
Chronic Sublethal	22	49	500	68

Figure 8. Aerial view of Richards Bay showing the positions where turbidity was profiled through the water column during and after dredging for the Richards Bay Coal Terminal expansion compliance monitoring programme.

experiments from which the effects levels were derived by Anchor Environmental (2003) do not necessarily reflect the tolerances of organisms in Richards Bay, where the resident organisms will be adapted to the ambient turbidity and total suspended solids concentrations of their habitat and which may or may not naturally be higher than that in habitats to which the experimental organisms were adapted. Analysis of benthic invertebrate communities at each of the stations monitored for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme provided evidence for a probable impact attributable to dredging at station RBH2 (Figure 4). It was not possible, however, to definitively identify the actual factor/s leading to the modified community at this station, even though the often high suspended solids concentrations measured were strongly suspected.

The comparison in Figure 7 is misleading as to the severity of impacts during dredging in some parts of Richards Bay, because the stations were situated some distance from the dredging site. Turbidity was profiled *in situ* at 18 stations positioned in a grid-like manner across the Richards Bay Coal Terminal basin during and after dredging (Figure 8). Total suspended solids concentrations were not measured at these stations. This does not matter since it is possible to broadly infer the total suspended solids concentration associated with each turbidity measurement from the predictive model. The predictive model can also be used to calculate the turbidity associated with each total suspended solids concentration effects level derived by Anchor Environmental (2003). The term broadly is used above since the predictive model can only be used to interpret data that fall within the range of turbidity or total suspended solids concentrations used to define the model, and should theoretically not be extrapolated. Also, the relationship between total suspended solids concentrations and turbidity for the experimental data used by Anchor Environmental (2003) to derive effects levels may not be the same as the predictive model. Assuming that extrapolation of the predictive model is valid then it is apparent that a large proportion of turbidity measured in the Richards Bay Coal Terminal basin during dredging may have been associated with total suspended solids concentrations exceeding the Chronic Lethal and Acute and Chronic Sub-lethal effects levels, and in two cases also the Acute Lethal effect level (Figure 9). In other words, if the effects levels are relevant to organisms in Richards Bay then there was a strong probability that organisms not directly impacted by the actual dredging process (*i.e.* physical destruction) were indirectly affected by

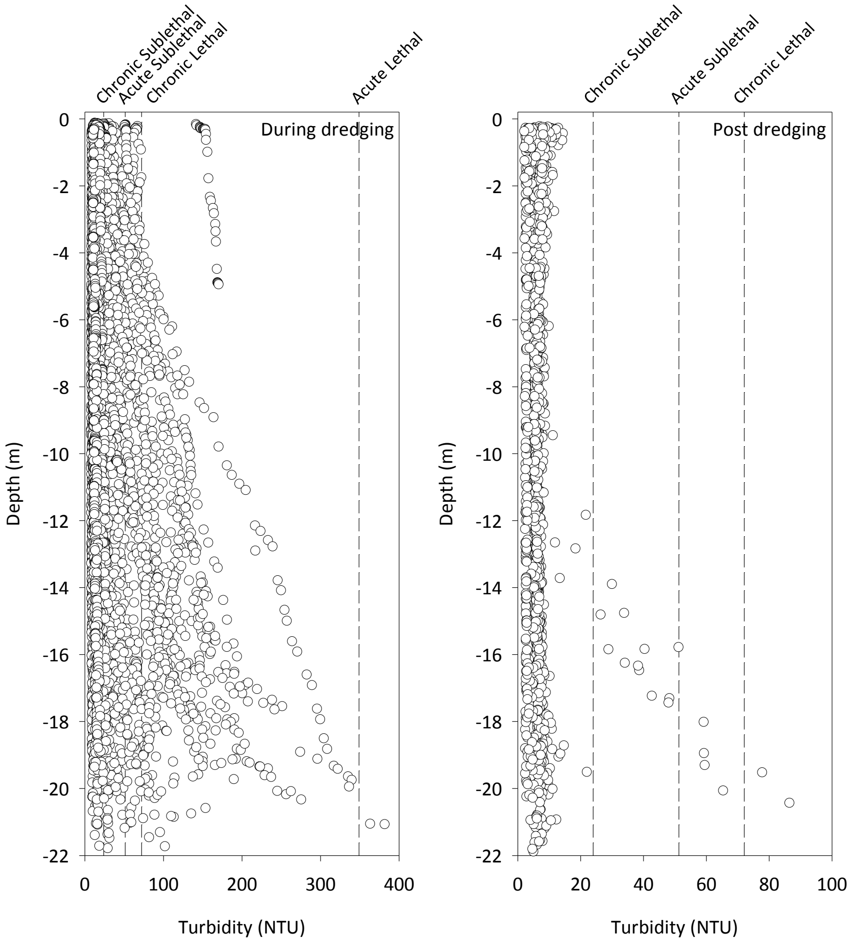

Figure 9. Turbidity profiles measured during (left panel) and after (right panel) dredging for the Richards Bay Coal Terminal expansion programme. Superimposed on the plots are turbidities that correspond to the suspended particulate matter 10th percentile effects levels derived by Anchor Environmental (2003) (see Table 2), as inferred using the predictive model presented in Figure 18.

the high dredging induced total suspended solids concentrations and turbidity. This said, the duration of the elevated turbidity/total suspended solids concentrations and the tolerances of aquatic organisms in Richards Bay is unknown, making it difficult to reach a conclusion on the likelihood of such impacts.

As expected, the vast majority of exceedances of the effects levels were at stations close to the dredging operation (the A and B series of stations in Figure 8). However, depending on which effects level is considered exceedances occurred as far from the dredging operation as the F series of stations in Figure 8. The conclusions reached are thus quite different to those reached using only the data for compliance monitoring stations.

Very few exceedances of effects levels occurred post-dredging (Figure 9; turbidity was not measured pre-dredging). All exceedances of effects levels occurred during a single survey and were restricted to the bottom third of the water column at three stations.

8. Conclusions

There is at present too little data to define turbidity and total suspended solids baselines for all areas of Richards Bay. This is the situation for other South African ports and stems, in part, from the fact that turbidity and total suspended solids are usually not measured coincidentally and turbidity is far more frequently measured compared to total suspended solids. Most of the turbidity and total suspended solids concentration data for Richards Bay is for the Mudflats area, but the conditions in this area are atypical of the rest of the Bay. This is because the water column on the Mudflats is shallow, with the result that bottom sediment is frequently disturbed into suspension by wind induced turbulence. Consequently, turbidity and total suspended solids concentrations in the water column over the Mudflats are frequently higher compared to other areas of the Bay. Baselines defined for stations on the Mudflats for the Richards Bay Coal Terminal expansion dredging compliance monitoring programme can still be used for this area of the Bay, but cannot be used as baselines for other areas.

For other areas of the Bay there are far fewer measurements, typically in the region of three to four per area. This is insufficient for the establishment of baselines, which as a rule of thumb requires 25 measurements and the bulk of the measurements should approximate a normal distribution. There is a large amount of turbidity data for the Richards Bay Coal Terminal Basin, but no attendant total suspended solids concentration data. This data will be useful for establishing baselines for turbidity in this basin. This data will also be useful for estimating the likely impact of dredging induced increases in suspended sediment in the expansion footprint provided the predictive model holds true for the entire Bay and is supplemented by additional measurements made from laboratory-based simulations of sediment re-suspension during dredging.

Due to the limited data for much of the proposed expansion footprint, monitoring/research will be required for the definition of baselines and to estimate the potential ecological risks associated with dredging. Recommended studies in this context are discussed below.

9. Compliance Monitoring Plan for Turbidity and Suspended Solids Concentrations

The dredging compliance monitoring plan for the Port of Richards Bay Expansion and the Port of Richards Bay Coal Terminal Development projects must be formulated as soon as possible, although the thresholds that will be used to track (non)compliance do not need to be defined as yet. The plan must also define management interventions that will be implemented in the event of non-compliance. The early formulation of the compliance monitoring plan will identify the monitoring that needs to be completed prior to the initiation of dredging, for the purpose of defining baselines, thresholds for compliance and so on. A relatively long lead time (at least 6 months) will be required to define baselines for turbidity and total suspended solids (and indeed for other water quality parameters that may need to be monitored). Baselines for these parameters cannot be defined from a single sampling event and the baseline monitoring must capture the widest possible range of natural variability in the relevant areas of Richards Bay. The ideal period for baseline monitoring is from mid-winter to mid-summer, or *vice versa*. It is also necessary to consider the number of data points required to adequately define a baseline. As a rule of thumb a minimum of 25 data points is considered adequate provided that the bulk of the data is normally distributed. The greater the number of data points the greater the confidence in the defined baseline. Thus, if a six month period is allocated for baseline monitoring, it may be necessary to identify zone specific rather than station specific baselines, to ensure there is sufficient data for baseline definition with a high level of confidence.

Defining inappropriate baselines and thresholds for compliance will not only have ecological implications but also project implications - an inappropriate baseline/threshold for compliance may lead to frequent, spurious episodes of non-compliance and unnecessary project delays (and increased costs) if regulatory authorities attach onerous corrective action for each incidence of non-compliance (*e.g.* cease dredging until corrective measures are implemented).

Although this report focusses on turbidity and total suspended solids, based on the experience of the scientists that prepared this report there will inevitably be a request from governmental and non-governmental organisations for the monitoring of a wider suite of water quality indicators before, during and after dredging for the expansion projects. Baseline and compliance monitoring is expensive, particularly if a ‘wish list’ approach is adopted for identifying the parameters that require monitoring. Therefore, the compliance monitoring plan for other indicators of impact in the water column and sediment, including biological parameters, should be defined at the same time that the monitoring plan for turbidity and total suspended solids is defined. Extensive environmental monitoring was performed in Richards Bay between 2004 and 2008 for the Richards Bay Coal Terminal expansion compliance monitoring programme and the lessons learned in terms of what parameters should and should not be monitored must be considered during the formulation of the compliance monitoring plan.

The water quality indicators identified for tracking (non)compliance should, as far as is practical, be easily measured within the timeframe required to initiate corrective action. It is to some extent pointless using parameters that require a long time to analyse in the laboratory for compliance monitoring, since by the time the results are available an adverse ecological effect may already have manifested for some time, or indeed even have dissipated.

Few jurisdictions prescribe an actual turbidity or total suspended solids concentration guideline (threshold) that is applied equivalently to all aquatic ecosystems. This is because baselines for turbidity and total suspended solids concentrations are often system specific. The use of a single guideline/threshold may, therefore, be over- or under-protective for different aquatic systems or even habitats within the system. The most common approach is to define a threshold of compliance as a proportional increase above the baseline. This may necessitate the establishment of baselines for turbidity and total suspended solids in different areas of Richards Bay – this will need to be determined by the compliance monitoring plan. There is, however, good reason to identify a single compliance threshold wherever possible, to avoid overly complex decision-making for corrective action implementation in the event of non-compliance

The compliance monitoring plan must identify ecologically sensitive areas in Richards Bay that warrant particular protection, and determine whether unique thresholds of compliance are required for these areas. This will determine where and how baseline monitoring will be performed. It should be relatively easy to identify ecologically sensitive areas in Richards Bay based on proximity to the dredging footprint, but numerical modelling of suspended sediment dispersion may identify areas not considered from a professional judgement perspective.

10. Key Recommendations

Apart from the recommendations above with regard to the compliance monitoring plan, the following key recommendations arise from this study.

First, baselines for turbidity and total suspended solids should be defined for different habitats (areas) within the proposed expansion footprint. This is recommended in spite of the previously discussed need to formulate the compliance monitoring plan and is motivated by the fact that increases in water column turbidity and total suspended solids concentrations will likely comprise the single most significant ecological impact associated with dredging beyond the actual dredging footprint, where temporary or permanent habitat destruction will be the most significant impacts. Furthermore, this data along with data generated through the recommendation below will be invaluable for estimating the likely ecological consequences of increases in water column turbidity and total suspended solids concentrations when integrated with numerical models of circulation in Richards Bay. Definition of baselines for turbidity and total suspended solids will require the collection and analysis of water samples at monthly intervals over at least a six month period, to encapsulate the widest range of weather and hydrological conditions possible. *In situ* measurements of basic water quality parameters can be made at the same time, at minimal additional cost. These *in situ* measurements will be useful for defining baselines for water quality parameters that will likely require monitoring during dredging (*e.g.* pH, dissolved oxygen concentration). A potentially significant limitation of the above sampling design is that it provides no understanding of the duration of naturally elevated turbidity and total suspended solids concentrations. This is important in the context of compliance monitoring since a rolling average is probably the best approach for determining non-compliance, as opposed to instantaneous measurements. This is because short-term increases in turbidity and total suspended solids concentrations may not require corrective action. If there is no continuous measurement capability, expensive and time consuming corrective action may be implemented based on spurious instantaneous data.

Second, the relationship between turbidity and total suspended solids under simulated dredging conditions should be established in the laboratory for the purpose of compliance monitoring and importantly also the Environmental Impact Assessment process. The objective must be to define relationships for each part of the dredging footprint (*i.e*. expansion area), such that total suspended solids concentrations do not need to be measured during compliance monitoring but can be rapidly inferred from turbidity measurements. This is because the measurement of total suspended solids concentrations takes time to complete, must be performed by a specialist laboratory, and is considerably more expensive to measure compared to turbidity. Turbidity can easily be measured *in situ* by a dredging operator, Transnet personnel, or an Environmental Control Officer should one be appointed. Alternately, and perhaps preferably, telemetered loggers could be deployed to provide real-time turbidity data during dredging. A disadvantage of these loggers is the biofouling of their sensors even when antifouling paints are used and which can invalidate a large proportion of the data. The loggers are also expensive and skilled personnel are required for their calibration and deployment. The benefits of continual real-time data is that management plans can be linked to rolling averages to determine non-compliance, rather than to instantaneous measurements that may or may not capture anomalous events.

Through the above research it will be possible to determine whether sediment from different parts of the expansion footprint will provide a different turbidity to suspended solids signal when disturbed through dredging, and thus whether area specific thresholds should be defined for compliance monitoring. The basic approach should be to collect sediment from different areas of the expansion footprint, add a known mass of the sediment from each area to a settling column in the laboratory, and at specific times remove water samples for coincidental turbidity and suspended solids analysis. This should provide a sufficiently wide gradient of turbidity and total suspended solids concentrations for the definition of a predictive model that will cover all possible conditions associated with dredging. This approach could be extended by also using sediment extracted from sediment cores collected for geotechnical studies, to determine whether a different turbidity and suspended solids signal is likely to emerge when subsurface sediment is dredged. An additional benefit is that it will provide the basis for calibrating instruments deployed to permanently monitor water column turbidity during dredging, should the deployment of such instruments be considered necessary or required by regulatory authorities. Lastly, the data can be integrated with numerical modelling to identify areas of potential impact during the Environmental Impact Assessment process, and thus also inform where compliance monitoring stations should be positioned for maximum benefit (this will also inform where baseline monitoring should be performed).

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