Effects of Sediment Dynamics on the Navigability of the Murchison River Ocean Entrance, Western Australia

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Cover Photo: Murchison River ocean entrance, view from the south
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ABSTRACT

In Kalbarri, the Murchison River entrance provides access to the Indian Ocean for vessels. A navigable channel through the entrance is achieved through an annual maintenance dredging program in October, but problems with navigation generally arise towards the end of winter each year.

Increasing coarseness of sediments within the channel has caused concern, as sediment grain size is directly related to dredging productivity and costs. The movement of dredge spoil after disposal is also of concern, as there is evidence to suggest that dredged material is making its way back to the entrance channel. The effects of river flows on the entrance channel are also of particular interest, as these infrequent events have the potential to dramatically alter the morphology and navigability of the entrance channel.

The near-shore wave climate at the dredge spoil disposal sites has been modelled using the 3rd generation wave model SWAN, to determine the likely direction of longshore sediment transport of different sized sediment grains under different conditions. The model output suggests that while finer sediments at the sites have a more northerly tendency of transport, during the prevailing wave conditions, higher energy storm events have the potential to transport coarser sediments south, towards the entrance. The transport of coarse material from the dredge spoil back to the entrance is likely to have contributed to the increasing coarseness of sediments in the channel.

From analysis of sediment samples before and after the river flow in 2005, it is clear that river flows have a significant effect on the coarseness of sediments within the entrance. In periods of no significant river flows, the coarseness of sediments in the channel increases due to the lack of input of fine riverine sediments. After a river flow, riverine sediments accumulate in the entrance, decreasing the coarseness of the material.

Aerial photography has been utilised to assess shoreline change attributed to river flows. It is apparent that river flows cause shoreline retreat and significantly alter the size and morphology
of the Kalbarri sand spit. The shoreline retreat from river flow amounts to a wider entrance. While this effect is caused by large river flows, it has been found that small to moderate flows have effects on the channel that are either insignificant or short-term.

When the method of inlet stability analysis is applied, it is likely that the equilibrium cross-section of the Murchison River entrance throat is not reached before dredging each year. The restriction of the channel due to sediment deposition is limited by a lack of sediment supply on the Kalbarri coast.
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1 INTRODUCTION

1.1 Motivation

The Murchison River Entrance provides access to the Indian Ocean for vessels in Kalbarri, which include boats from the Western Rock Lobster fishing fleet, wetline fishing boats and charter and tour boats catering for the visitors to this popular tourist destination.

The Department for Planning and Infrastructure (DPI) is responsible for an annual dredging programme with dredged volumes in the order of 35,000m³. Dredging is conducted in October to create a navigable entrance channel for the commencement of the Western Rock Lobster season in mid November. By the end of winter each year, problems with navigation have usually arisen, with larger boats unable to use the channel under all conditions. DPI is interested in gaining a better understanding of the coastal processes in Kalbarri, so that the current dredging practice might be improved.

1.2 Aim

The aim of this project is to investigate the sediment dynamics of the Murchison River entrance and at the locations where dredge spoil is deposited.

1.3 Objectives

At the beginning of this project, DPI identified 3 main objectives that they desired to have addressed:

1. Ascertain the causes/processes behind the increase in coarseness of sediments in the entrance,
2. Determine the near-shore wave climate and sediment transport characteristics at the two dredge spoil disposal locations, and
3. Assess the effects of river flows on the morphology and navigability of the Murchison River entrance.
1.4 Previous Studies

Previous studies on the wave climate and sediment dynamics of the Kalbarri area have been quite limited, with most available information coming from dredging contract documents. A comprehensive study was prepared for the Department of Marine and Harbours in 1989 and subsequent studies have generally used the information presented in this report for further analysis. No work has been done to assess the longshore sediment transport on the coastline north of Kalbarri. This is an important focus, as dredge spoil material that is removed from the Murchison River estuary is deposited north of the entrance.

1.4.1 Kalbarri Marina and Estuary Investigations (DMH, 1989)

This investigation gives a broad description of the Kalbarri coastal and estuarine processes. Offshore and nearshore wave climate data was produced by analysing wave hindcast data, and the environmental setting, including geology, climate, hydrodynamic processes and oceanography, is defined. Basic wave modelling was performed to assess the longshore sediment transport capacity of the coast south of Kalbarri, with estimates given of up to 530,000m³ of material per year. These estimates of potential sediment transport were found to be far in excess of the actual estimated littoral transport of 27,000m³ per year. The investigation also produced a loose estimate for the Murchison River’s natural bypass capacity (amount of material the estuary can remove from itself) of 10,000m³ per year. Northerly sediment transport along the coast north of the entrance was assumed to be less than south of the entrance, because of a differing orientation of the coastline. The potential for southerly sediment transport along the coast north of the entrance was not considered.

Historical aerial photographs of the estuary were analysed to make some qualitative conclusions, including the finding that sediment trapped in the entrance continues to grow until a portion is flushed out by an infrequently occurring flood flow. Aerial photography analysis also identified the potential for sediment to be transported over the low area of Oyster Reef, with the subsequent run-off transporting material into the entrance channel. Inlet stability analysis was also performed using two different methods, arriving at stable inlet areas of 110m² and 150m². These values are likely to be erroneous though, because the calculations are made on the assumption
that “the regional tides are semi-diurnal”, which is incorrect, as Kalbarri experiences diurnal tides.

1.4.2 Kalbarri – Murchison River Mouth, Improvements to Boating Access (CIES, 1996)

This investigation was performed to evaluate strategies for improving vessel access in Kalbarri. It bases much of its findings on the information provided in *Kalbarri Marina and Estuary Investigations* (DMH, 1989), and looks at options such as river training walls, alterations to the dredging program, and even cutting a new channel through Oyster Reef.

The report reviews the littoral drift estimate given in DMH (1989) and arrives at a new estimate of 33,000m³ of material per year. This estimate is based on an examination of sediment accumulation patterns within the estuary. River floods are also described, including identification of significant historical river flows, and other observations from the Murchison River flood record. A table is presented showing calculations of flow rates for different return periods.

The investigation briefly explains the concept of inlet stability, but indicates that this theory is not applicable to the Murchison River estuary, because it is “clearly dynamic under the influence of extreme flood events”. The report also indicates that inlet stability is subject to natural variation from meteorological and hydrodynamic conditions, and “given the lack of information available for Kalbarri, it is impossible to determine the behaviour of the Murchison River ocean entrance brought about by these changes”.

1.5 Current Dredging Program

Details of the current maintenance dredging program for the Murchison River entrance are given in contract documents presented to DPI annually, with the most recent by JFA (2004). The current contract has a value in the order of $250,000 to $300,000, depending on cost variations from year to year. Dredging in the Murchison River ocean entrance is performed in October each year for the opening of the Western Rock Lobster fishery. A navigable channel is required by the
5th of November, so that Rock Lobster vessel operators can test equipment and vessels before the season start date on the 15th of November.

Volumes of material dredged from the entrance vary from year to year, but the current contract stipulates that no less than 20,000m³ will be dredged in any session. The average dredged volume is around 35,000m³, and this material has been identified in JFA (2004) as medium to coarse sands. The current program involves dredging to create a final channel with a design depth of 1.8m Chart Datum (Kalbarri Chart Datum is 0.58m below sea level), and channel slope batters of 1:5.

Of the dredged material removed from the channel (dredge spoil) around 5,000m³ is used for beach renourishment at Chinaman’s Beach, and the remaining volume is transported north of the river entrance via a pumping system and pipeline, where it is discharged into the ocean. In the current contract, two disposal site options north of the entrance are identified. Disposal site A is located 900m north of the Kalbarri navigation leads, or about a kilometre north of the entrance. Disposal site B is located a further 400m north of disposal site A. While disposal site B has been used in the past, site A is the default option.

In recent years, the coarseness of dredged material has been observed to be increasing. Because the variation in material coarseness is directly related to the production rate of the dredge (JFA, 2004) this increase in coarseness is of some concern. It has also meant that pumping the full distance to disposal site A has become more difficult.

Once the spoil has been deposited north of the Murchison River entrance, it is expected that due to prevailing wind and wave conditions “natural processes will disperse the spoil northwards as part of the normal process of longshore sediment transport” (JFA, 2004). While this statement is made, contract documents also identify that there is some significant anecdotal evidence suggesting that dredge spoil travels south after being discharged, and makes its way back into the entrance via a ‘gap’ (low point) on Oyster Reef. It is suggested that wave action is able to transport water and sediment over the gap and into the shallow area behind the reef. From here the water and sediment is likely to flow back into the entrance channel (JFA, 2004).
2 ENVIRONMENTAL SETTING

2.1 Location

The town of Kalbarri is situated at the Murchison River mouth on the Western Australian coast some 600km north of Perth.

Figure 2.1: Location map of Kalbarri
2.2 Geology and Geomorphology

Kalbarri is situated within the Carnarvon Sedimentary basin, the coastal zone of which is formed mostly of continental sedimentary rocks from the Silurian period (Hocking, 1991). In the Kalbarri area, these rocks are predominantly Tumblagooda Sandstone, which outcrops in a number of locations to form headlands, coastal cliffs and reef platforms (Hocking, 1991). The Tumblagooda Sandstone is overlain by thin tertiary deposits of Pleistocene Tamala limestone and Holocene sands (DAL, 2001).

Figure 2.2: Geology and landform in vicinity of Kalbarri (Chalmers 1983)
The Murchison River estuary is classified as an inter-barrier estuary, with a narrow entrance channel leading into a wider, coast-parallel lagoon (Hodgkin and Hesp, 1998). The Murchison River is shallow with a limited tidal exchange and is estuarine for 12 to 20km upstream of the entrance (Hesp, 1984). The most important features of the Murchison River entrance are Oyster Reef (an outcrop of Tamala limestone to the north of the entrance which acts to permanently fix its location) and the Kalbarri sand spit, a depositional feature protruding from the southern side of the entrance, that is associated with the meandering path of the channel entrance (DMH, 1989).

Figure 2.3: Aerial photograph of Murchison River ocean entrance, with some key features marked

Other important features of the estuary are the region of shallow water situated landward of Oyster Reef, associated with a gap or low point on Oyster Reef that is located at the northern
point of the shallow water area, and Chinaman’s Beach, a popular beach that is renourished annually with material obtained from maintenance dredging.

Immediately offshore of the Murchison River entrance is a small area where the seabed becomes significantly deeper than the surrounding areas. This deep area has been identified as a former river bed of the Murchison River, during a period of sea level much lower than present.

The continental shelf offshore of Kalbarri is around 70km in width, and typified by a moderate shelf slope (DAL, 2001). Offshore of Kalbarri, the most important feature is the Houtman Abrolhos Islands, an archipelago of 122 small islands and associated reefs, situated to the southwest of Kalbarri, just landward of the 100m depth contour. The only other offshore feature of significance is Big Bank, a string of reef banks with depths of around 44 – 92m, located west of Kalbarri close to the continental shelf edge (Chubb, Barker et al. 1994).

2.3 Meteorological Conditions

Kalbarri experiences a subtropical Mediterranean climate, with hot dry summers and cool wet winters. The prevailing weather conditions of south-western Australia are governed by an eastward moving subtropical high pressure belt dominated by anticyclones (Gentilli, 1971). During winter, this pattern is periodically disrupted by storms generated by mid-latitude depressions, while the summer conditions are dominated by a strong sea breeze system (Gentilli, 1971). At Kalbarri, the summer sea breeze system is particularly energetic and results in consistent strong afternoon winds from the south to southwest (DAL, 2001).

2.3.1 High pressure systems

The normal breakdown of the high pressure belt into anticyclonic cells causes the prevailing air circulation in south-west Australia to be anticlockwise (Gentilli, 1972). In summer, this high pressure belt is located between the latitudes of 35°S to 45°S, and causes south-westerly winds, while in winter the belt moves north to between 26°S and 34°S resulting in easterly winds.
During the 3 – 10 day cycle of anticyclones crossing the coast, calm periods also typically occur (Gentilli, 1972).

2.3.2 Mid-latitude depressions

Generally, in the summer months, mid-latitude depressions are situated too far south to have a significant affect on the Kalbarri region. During winter mid-latitude depressions occur much further north, due to the northward migration of the high pressure belt, and have the propensity to cause highly energetic storm conditions (Gentilli, 1972). While no information is available specifically for Kalbarri, the conditions experienced during the storms associated with mid-latitude depressions have been well documented for south-western Australia. Wind speeds in the range of 15 – 29m/s are typical, accompanied by much stronger gusts (Steedman, 1982) and wind directions during mid-latitude depressions vary from northwest to southwest, with the strongest winds usually from the northwest (Silvester, 1987). Mid-latitude depressions are often associated with large rainfalls, which can affect the Kalbarri area by causing flows in the Murchison River.

2.3.3 Tropical cyclones

Tropical Cyclones are extremely severe low pressure systems that occur infrequently in Western Australia during the summer months. Tropical Cyclones form in tropical latitudes and on average will impact the Western Australian coastline about twice per year (Gentilli, 1972). Tropical Cyclones directly affecting Kalbarri are rare and have usually been downgraded to rain bearing depressions. Their effects on the area can still be quite significant, especially by causing large rainfall in the Murchison River catchment, causing large river flows. The largest flow rate on record for the Murchison River was in March 1975, and was caused by a large rain bearing depression formed from a dissipating Tropical Cyclone (CIES, 1996).
2.3.4 *Sea breeze system*

Southwest Australia has one of the strongest sea breeze systems in the world. Even for this stretch of coast, the Kalbarri sea breeze system is considered to be particularly energetic. On the southwest coast, the sea breeze system results in winds frequently exceeding 15m/s (Pattiaratchi, Hegge et al., 1997), and with wind speeds often approaching that experienced during storm conditions (Gentilli, 1971). In Kalbarri, winds generated by the sea breeze system are generally from the south to southwest (DAL, 2001).

2.3.5 *Extreme wind conditions*

Extreme wind events play an important role in nearshore processes, because the extreme waves and currents generated during these conditions have the potential to cause rapid movement of sediments in the nearshore zone, and other significant and lasting effects on the coastal area. Information on the typical wind speeds experienced during different extreme wind events have not been collated for the Kalbarri area. However, similar data from other locations on the south-west coast of Australia is applicable, because the same weather systems are experienced with similar intensity for the majority of this stretch of coast. An account of the major storm winds experienced in Cockburn Sound, WA is given by Steedman (1982), the results of which are shown in Table 2.1 below. The table shows that storms due to extra tropical cyclones (mid-latitude depressions) have the highest wind speeds and longest duration of all extreme wind events impacting the Cockburn Sound area. These results are likely to be the same in the Kalbarri area.
2.4 Murchison River Flows

The Murchison River has a catchment of approximately 82,300km² (DMH, 1989). Observations of river flow history are based on stream gauge measurements at the Emu Springs gauging station, and have been recorded from 1967 onwards.

Table 2.1: Extreme wind conditions for Cockburn Sound WA (Steedman, 1982)

<table>
<thead>
<tr>
<th>Storm type</th>
<th>Principle months of occurrence</th>
<th>Typical storm average wind speed &amp; duration</th>
<th>Typical extreme 30 min average wind speed</th>
<th>Typical wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissipating tropical cyclone</td>
<td>December - April</td>
<td>10 - 25 ms⁻¹ 5 - 15 hours</td>
<td>25 - 30 ms⁻¹ 25 ms⁻¹</td>
<td>All Directions (dependant on eye location)</td>
</tr>
<tr>
<td>Squalls</td>
<td>December - April</td>
<td>15 - 20 ms⁻¹ 2 - 4 hours</td>
<td>25 ms⁻¹</td>
<td>All Directions</td>
</tr>
<tr>
<td>Extra tropical cyclones (&quot;Gales&quot;)</td>
<td>May - October</td>
<td>15 - 29 ms⁻¹ 10 - 40 hours</td>
<td>20 - 25 ms⁻¹ 20 - 25 ms⁻¹</td>
<td>South south-west to north</td>
</tr>
<tr>
<td>Tornadoes (&quot;Cock-Eye-Babs&quot;) †</td>
<td>December - April</td>
<td>15 - 25 (??) ms⁻¹ &lt; 1 hour</td>
<td>30 (??) ms⁻¹ 30 (??) ms⁻¹</td>
<td>All Directions</td>
</tr>
<tr>
<td>Thunderstorms</td>
<td>December - April</td>
<td>10 - 25 ms⁻¹ 1 - 2 hours</td>
<td>15 ms⁻¹</td>
<td>All Directions</td>
</tr>
</tbody>
</table>

† no measurements (estimated)

Figure 2.4: Map of Murchison River showing location of gauging station
The flood history of the Murchison River until 2000 is shown below in figure 2.5 and clearly illustrates the episodic nature of river flows (CIES, 1996).

![Murchison River Flood Record](image)

**Figure 2.5: Murchison River flood record**

The maximum flow on record was observed in 1975, with other significant flows in 1974, 1980, 1989, 1992, 1995 and 2000. The Murchison River has no clearly distinguished pattern of flooding, with several years experiencing multiple flows, and other years experiencing no significant flows. There are no discernible trends, such as would result from changing land and water use patterns or climate change (CIES, 1996).

The main flow season for the Murchison River is between February and August (CIES, 1996), which suggests that river flows are dominated by rainfall events from mid-latitude depressions. While the peak flow is likely to have been caused by very large rainfall from a dissipating tropical cyclone, these systems generally do not produce significant flows (CIES, 1996). The peak observed flow has been calculated to have a return period of 250 years. Flow rates for other return periods are given in table 2.2 below.
<table>
<thead>
<tr>
<th>Return Period</th>
<th>Flow Rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 in 3 year flow</td>
<td>220</td>
</tr>
<tr>
<td>1 in 5 year flow</td>
<td>330</td>
</tr>
<tr>
<td>1 in 10 year flow</td>
<td>460</td>
</tr>
<tr>
<td>1 in 30 year flow</td>
<td>680</td>
</tr>
</tbody>
</table>

Table 2.2: Murchison River return period flow rates (CIES, 1996)

2.5 Wave Climate

2.5.1 Offshore wave climate

The offshore wave climate of Kalbarri has never been directly measured, and the only existing information comes from hindcast data. The hindcast technique uses sea level synoptic charts for the point of wave data generation and oceanic areas from which distant swells may arrive (Oceanroutes, 1989). A year of 6-hourly wave heights, directions and periods were generated for a point centred on latitude 28°S at the 100m depth contour using this method for the year of 1984 (DMH, 1989). The main findings from this hindcast data are summarised in table 2.3 below.

<table>
<thead>
<tr>
<th>Wave Parameter(s)</th>
<th>Range</th>
<th>% Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>4 &lt; T &lt; 9s</td>
<td>90.7</td>
</tr>
<tr>
<td></td>
<td>4 &lt; T &lt; 5s</td>
<td>46.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Significant Wave Height</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hs &gt; 4m</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Hs &lt; 1m</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1.5 &lt; Hs &lt; 2.5m</td>
<td>55.6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height and Period</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 &lt; Hs &lt; 3.5m</td>
<td>71.5</td>
<td></td>
</tr>
<tr>
<td>4 &lt; T &lt; 9s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>210 &lt; D &lt; 250°</td>
<td>61.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height and Direction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 &lt; Hs &lt; 3.5m</td>
<td>44.9</td>
<td></td>
</tr>
<tr>
<td>210 &lt; D &lt; 250°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Period and Direction</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5 &lt; T &lt; 8s</td>
<td>49.2</td>
<td></td>
</tr>
<tr>
<td>210 &lt; D &lt; 250°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Summary of hindcast data for offshore Kalbarri (DMH, 1989)
2.5.2 Nearshore wave climate

Waves were also hindcast for a shallow water site approximately 3 nautical miles offshore of Kalbarri. This inshore wave hindcast only encompassed shorter period seas generated by local winds, and did not include swells generated at distant areas (DMH, 1989). Again, a year of 6-hourly wave heights, directions and periods were generated for this shallow water site. The main findings from this hindcast data are summarised in table 2.4 below.

<table>
<thead>
<tr>
<th>Wave Parameter(s)</th>
<th>Range</th>
<th>% Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>T &lt; 4s</td>
<td>91.7</td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>Hs &lt; 1m</td>
<td>64.9</td>
</tr>
<tr>
<td>Direction</td>
<td>150 &lt; D &lt;180°</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>190 &lt; D &lt;220°</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 2.4: Summary of hindcast wave data for nearshore Kalbarri

2.6 Long Period Water Level Fluctuations

Long period water level fluctuations are important in terms of coastal processes, because they can significantly alter the height of the sea level at the coast, thus changing the region of the shore that waves and currents are able to influence. In more sheltered environments, such as estuaries, these water level fluctuations are often the most important hydrodynamic forces that occur. Long period water level fluctuations important for the Kalbarri area are tides, storm surges, seiches and continental shelf waves.

2.6.1 Tides

Limited tidal measurements have been made for Kalbarri, with only a few months of historical water level data recorded inside the Murchison River estuary. Tidal predictions for Kalbarri are available from a number of sources, including the Department of Defence (DoD, 1999). Tides in Kalbarri are predominantly diurnal in nature (one tidal cycle per day) and limited in range, falling into the microtidal classification (DoD, 1999). Typical daily tidal ranges for Kalbarri are
around 0.7m during spring tides, and 0.3m or less during neap tides. The highest astronomical
tide for Kalbarri is 0.6m above mean sea level.

2.6.2 Storm surges

During storm events barometric and wind effects can cause significant storm surges. The
importance of storm surge on beach processes and morphology is most significant when surge
levels exceed the tidal range, as is the case in south-western Australia (Jackson, Nordstrom et al.,
2002). In extreme storms the surge in Geraldton (150km south of Kalbarri) can exceed 1 metre
above the astronomical tide level (PHC, 1989). Extreme storm surges in Kalbarri are likely to be
similar to this level, which is significantly larger than the tidal range.

While storm surges act to increase the water level at the coast, different meteorological
conditions may cause the opposite to occur. Under conditions of strong offshore winds, and high
barometric pressure, very low water levels typically occur at the coast, sometimes referred to as
“negative surges” (DMH, 1989).

Seasonal shifts in the sea level also occur due to meteorological effects. Typically, the mean sea
level at Geraldton rises 0.1 metre during winter and falls 0.1 metre during summer (Rogers,
2001), and a similar seasonal sea level change would be expected at Kalbarri.

2.6.3 Seiches

Seiches are long period water level oscillations that occur in enclosed or semi-enclosed basin
conditions. External forcing conditions, such as the passing of a weather system, initiate the
oscillations, which continue for some time after the forcing conditions have ceased (CERC,
2002). A documented seiche exists between the continental shelf edge and the coast. This seiche
has amplitude in the order of 0.1 to 0.3m, and at Geraldton, has a period of 4hrs. The seiche is
likely to have a similar period in Kalbarri to Geraldton, because the width and mean depth of the
shelf is similar.
2.6.4 Continental shelf waves

Continental shelf waves occur along the southwest coast of Australia, with amplitudes of about 0.3m (DMH, 1989). They are generally caused by the passage of low pressure systems across the coast. They propagate south along the coast, with periods of 5 – 20 days, and wavelengths of a few thousand kilometres (Hegge, Eliot et al., 1996).

3 MORPHODYNAMICS RELEVANT TO KALBARRI

3.1 Sediment Mobility

When evaluating sediment transport at a particular site, it is important to understand the concept of sediment mobility. Sediment mobility is the idea that a particular particle of the sediment that makes up the seabed will not move until some threshold flow condition is exceeded. If sediment mobility does not occur, then transport of that sediment particle does not take place. Sediment mobility is an important concept that can be applied to dredge spoil disposal, to determine how sediment transport differs for different types of sediments.

One threshold condition that is commonly used is the critical mobility parameter (Shield’s parameter), \( \theta_c \). To understand the critical mobility parameter, the forces that act on a submerged sediment particle must first be considered.

3.1.1 Forces acting on a sediment particle

The forces acting on a submerged sediment grain can be summarised into four categories:

- Gravitational forces, including the weight and buoyancy of the particle,
- Lift forces, resulting from the Bernoulli Effect due to fluid flow over the particle
- Drag forces, from flow over the particle, and
- Frictional forces, due to the reaction between the particle and other components of the seabed it is contact with.
Drag forces are the most important factor in the mobilisation of sediment grains, and as such the drag force is sometimes referred to as the “mobilising force” (USACE, 2001). In general, the drag force is not used in sediment mobility calculations. Instead, the drag force is usually expressed as the shear stress ($\tau$). Shear stress formulae can be manipulated to find $\tau_{\text{max}}$, the maximum shear stress at the seabed, and from this $\tau_c$, the critical shear stress, which is defined as the shear stress required to mobilise sediment (USACE, 2001). In cases where surface waves are the primary cause of mobilising flow, a suitable wave theory must be selected before calculations to find $\tau_c$ can be applied.

### 3.1.2 Selection of suitable wave theory

Formulae related to fluid dynamics under waves differ depending on the type of wave in question, so it follows that before a wave theory can be selected, basic wave parameters such as period, height, and water depth must be known. The most basic type of waves is linear (Airy) waves, which are basically sinusoidal in profile. They occur in conditions where wave heights are small and intermediate to deep water conditions are satisfied. As wave heights increase, wave breaking occurs or when shallow water conditions are satisfied, higher order wave theories become applicable.

Le Méhauté (1976) presented the following graph to illustrate the approximate limits of validity for the most commonly used wave theories.
For the purposes of this study, only shallow water waves near the breaking limit will be considered in detail. Figure 3.1 suggests that cnoidal theory should be used for calculating peak orbital velocity under these conditions. However, it is considered that while cnoidal theory provides the best mathematical approximation of shallow water waves near the breaking limit, predictions using linear (Airy) theory agree with actual measurements to a higher degree (Dean and Dalrymple, 1991). Dean (1974) produced the following figure which shows the ranges at which wave theories exhibit the highest degree of analytical validity.
Once a suitable wave theory has been selected, calculations to find $\tau_{cr}$ can be applied.

### 3.1.3 Maximum shear stress

In the case where surface waves are the primary cause of mobilising flow, shear stress at the seabed is expressed as $\tau_{max}$, the maximum shear stress in a wave cycle. $\tau_{max}$ is given by the following equation:

$$\tau_{max} = \frac{1}{2} g' \omega U_{max}^2$$

(1)
Where $\rho$ is the density of the fluid, $f_w$ is the wave friction factor and $U_{max}$ is the peak orbital velocity at the seabed. Therefore, calculations of $\tau_{max}$ first require the calculation of $f_w$ and $U_{max}$.

### 3.1.4 Peak Orbital Velocity

$U_{max}$, or peak orbital velocity, is the maximum instantaneous fluid velocity experienced under a passing wave. Under a shallow or transitional water wave, fluid particles move in an elliptical orbit, while under deep water waves the orbit is circular (USACE, 2001), as defined in the following figure:

**Figure 3.3: Fluid particle displacement under waves (USACE, 2001)**

Under shallow or transitional water waves, fluid orbits become increasingly flattened with depth, until at the seabed there is no vertical component of the orbital velocity. The result of this is that calculations for peak orbital velocity at the seabed under these waves can be obtained by evaluating the peak horizontal velocity, and neglecting velocity in the vertical direction.
For linear wave theory, peak orbital velocity at the sea bed can be simplified to the following equation:

\[ U_{\text{max}} = \frac{\pi H_s}{T_p} \frac{1}{\cosh(kh)} \]  

(2)

Where \( H_s \) is the significant wave height, \( T_p \) is the peak spectral period, \( k \) is the local wavenumber \((2\pi \text{ divided by wavelength})\) and \( h \) is the water depth.

### 3.1.5 Wave friction factor

The wave friction factor is used in the calculation of maximum shear stress to allow for friction from the fluid – seabed interaction. An approximation for wave friction factor was developed by (Swart, 1974), which is dependant on both the wave parameters, and bed roughness, \( R \):

\[ f_w = \exp \left[ -7.02 + 5.5 \left( \frac{A_0}{R} \right)^{0.12} \right] \quad \text{for } \frac{A_0}{R} > 1.57 \]  

\[ = 0.3 \quad \text{for } \frac{A_0}{R} < 1.57 \]  

(3)

\[ A_0 = \frac{T_p}{2\pi} U_{\text{max}} \]  

(4)

This approximation for the wave friction factor is only applicable in the turbulent case, which should be tested for.

### 3.1.6 Critical mobility parameter and the modified Shield’s diagram

Once the maximum shear stress at the seabed has been calculated using equation (1) for a given set of wave conditions, sediment mobility calculations can be performed using the modified Shield’ diagram:
Where \( s \) is the specific gravity of sediment particles that make up the seabed, \( D_{50} \) is the median grain size, \( \nu \) is the fluid viscosity (10\(^{-6}\) in water) and \( u_{cr} \) is the critical dimensionless friction velocity given by:

\[
u_* = \left( \frac{\tau}{\rho} \right)^{\frac{1}{2}}
\] (5)

In the case of \( u_{cr} \), \( \tau_{cr} \) is used in place of \( \tau \). If there is a particular sediment with known \( D_{50} \) and known specific gravity, and it is subjected to wave action from waves with known characteristics, the modified Shield’s diagram can be used to predict whether that sediment will become mobilised or not.

Firstly, the dimensionless grain size parameter, \( D_* \), is calculated using the equation given in the diagram, and from this, the corresponding value for critical mobility parameter, \( \theta_{cr} \), can be found.
Substituting equation (5) into the equation for $\theta_{cr}$ given in the diagram, and rearranging gives the following equation for the critical shear stress:

$$\tau_{cr} = \theta_{cr}(s-1)\rho g D_{50}$$  \hspace{1cm} (6)

If the maximum wave induced shear stress from equation (1) is less than the critical shear stress calculated using equation (6), the sediment is unlikely to become mobile. Conversely, if the maximum wave induced shear stress exceeds the critical shear stress, the sediment is likely to become mobile.

### 3.2 Modes of Sediment Transport

After sediments become mobile, they can be transported in one of two different manners. In conditions where the threshold parameters are only marginally exceeded, sediment transport occurs as grains rolling, sliding or jumping (saltating) along the bed (USACE, 2001). This mode of sediment transport is known as bed load transport.

As flow intensity is increased, individual grains change transport from rolling and sliding to making extended jumps, and only coming in contact with the seabed for a fraction at a time (USACE, 2001). This mode of transport is known as suspended load transport. Suspended load transport is important for evaluating the sediment transport characteristics of a particular site, because under suspension grains are more susceptible to the influence of other forces, such as longshore currents.

#### 3.2.1 Threshold for suspension

The threshold conditions for sediment suspension are based on the Rouse parameter, $P$. The Rouse parameter is the ratio of settling velocity to vertical fluctuations, and is given by the following equation:
Where $\kappa$ is von Karman's constant (0.408), $u_*$ is the dimensionless friction velocity given in equation (5) above, and $w_s$ is the settling velocity given by:

$$w_s = \frac{1}{18\mu} (\rho_s - \rho) gD^2$$

(8)

Where $\mu$ is the dynamic fluid viscosity ($\mu = \rho v$), $\rho_s$ is the sediment density, and $D$ is the sediment diameter. From this, the criteria for suspension can be written as:

$$P = \frac{w_s}{\kappa u_*} \begin{cases} > 2.5; & \text{no suspension;} \\ 1 < P < 2.5; & \text{incipient suspension;} \\ P < 1; & \text{full suspension.} \end{cases}$$

Incipient suspension can be defined as the lowest level of suspension (minor saltation). These criteria can be rewritten in terms of shear stress to give:

$$\tau_{\text{max}} < \rho w_s^2 \quad \text{no suspension}$$
$$\tau_{\text{max}} > \rho w_s^2 \quad \text{incipient suspension}$$
$$\tau_{\text{max}} > 6.25 \rho w_s^2 \quad \text{full suspension}$$

From these criteria, we can predict whether a particular grain size undergoing transport will be in the bed load or suspended load.
3.3 Longshore Sediment Transport

Longshore sediment transport, also known as littoral transport, is transport of sediments parallel to the shore, primarily within the surfzone. Longshore transport is specifically important for sediment transport into the Murchison River entrance and transport of dredge spoil material after deposition. Once sediment particles are mobilised by wave action in the surfzone, longshore currents, with fluid velocities well below those required for sediment mobility, are able to influence the direction of transport of the particles (Komar, 1998). Longshore current velocities have been found to be relatively constant over depth (Visser, 1991), and have typical mean values of 0.3 m/s or less (USACE, 2001). While longshore transport can be driven by a number of different means, the process considered most significant for this study is longshore currents generated by waves breaking at an angle to the shore.

On most coasts (including that at Kalbarri) waves arrive at the shore from different quadrants, producing day to day and seasonal changes in sediment transport direction. Longshore currents are created by an oblique wave approach, because these waves have a longshore component of radiation stress (momentum flux). The radiation stress component is given by the following equation:

\[ S_{xy} = \frac{n}{8} \rho g H^2 \cos \alpha \sin \alpha \]  

(7)

From this equation, it can be seen that the main factors affecting determining wave induced longshore currents are H, the wave height and \( \alpha \), the angle between the wave crest and bottom contours. \( n \), the ratio of wave group speed and phase speed is approximately 1 in shallow water conditions.

An analytical solution for longshore current velocities is given by (Longuet-Higgins, 1970), for general assumptions including small wave crest angle to bottom contours, uniformly sloping beach and longshore homogeneity of bathymetry and wave heights. Under these assumptions, the longshore sediment velocity in the surfzone is given by:
Where $\beta^*$ is the modified beach slope, $C_f$ is the bottom friction coefficient and $\gamma_b$ is the breaker depth index.

In Kalbarri, the predominant offshore wave direction is from the southwest, and prevailing sea breezes occur from the south to southwest. South of the Murchison River entrance, the coastline bears east of north, and so it is likely that the prevailing sediment transport direction is north along the coast. North of the Murchison River entrance, the coastline bears west of north, and so the northerly transport is likely to be less significant.

For Kalbarri, the strongest winds with the longest duration occur during mid-latitude depressions. During these storms, where strong winds are often experienced from the northwest, the potential for sediment transport south along the coast exists, especially for the coastline north of the Murchison River entrance.

### 3.4 Spit Development

Spits are narrow, surface piercing accumulations of sediment extending from a landmass towards a water body (USACE, 2001). They typically form at the mouths of bays and estuaries, growing in the direction of prevailing littoral transport (Masselink and Hughes, 2003). Spits are often linear in shape, but can have a hook (recurve) at the distal (unattached) end (Komar, 1998), from either wave refraction or waves arriving at the spit from different directions.

In many cases a spit acts to deflect the mouth of a river or entrance to a bay in the direction of longshore sediment drift (Komar, 1998). This is the case in the Murchison River entrance, where the Kalbarri sand spit deflects the entrance to the north, before it is forced to turn south again by Oyster Reef. The deflection of the entrance by the spit and reef causes it to follow a meandering route.
Spits are dynamic depositional features that can change rapidly with changes in sediment supply or wave direction. The size and morphology of a spit at a bay mouth or estuary entrance is often controlled by a balance between sediment supply and longshore transport, which act to increase the spit length, and tidal flows through the mouth or entrance, which act to decrease the spit length. Factors such as storm waves and river flows can also cause dramatic and rapid changes to spits.

The basic process of spit formation and development is shown in figure 3.5 below, and can be summarised as follows: sediments are transported along the spit by longshore currents due to oblique wave action. Once these sediments reach the deep water at the end of the spit, the currents slow down significantly, and sediment transport is diminished, resulting in deposition which extends the spit (Masselink & Hughes, 2003).

Two main types of spit development have been identified in the literature, where the spit growth is both persistent and generally constant with time, or growth is pulse driven, resulting in incremental growth patterns (Komar, 1998). Persistent growth occurs when the sediment supply
to the spit is not limited. Incremental growth occurs when predominant longshore drift occurs during storm events,

At Kalbarri it is likely that wave refraction/diffraction at Chinaman’s Point causes the oblique wave action required to maintain sediment transport along the Kalbarri Sand Spit. It is also expected that flood tides have a role in the development of the spit, because it is situated somewhat inside of the estuary, rather than at the actual mouth. Both flood and ebb tidal flows through the entrance are likely to act to decrease the spit length, while storm waves and river flows will cause significant, though less frequent changes.

## 3.5 Inlet Stability

Waves, currents and sediments interact at tidal inlets, with varying effects over the tidal cycle (USACE, 2001). The point of minimum cross sectional area of the inlet channel, known as the throat, is important with respect to coastal engineering, as this is often the location in inlets at which navigation problems arise. Inlet stability analysis is a procedure that is applied to the throat section of inlet channels to predict navigability parameters, especially width and depth, of the channel.

Inlet stability is the concept that a tidally dominated inlet, such as an estuary has an equilibrium channel cross-sectional area. Inlet stability proposes that as wave action supplies sediment to the inlet channel, tending to reduce the cross-sectional area, tidal flows through the channel will scour out any deposits that reduce the channel cross-section below its equilibrium value (USACE, 2001). Inlet stability analysis has been applied to many tidal inlets worldwide, showing an acceptable degree of agreement between predicted and measured cross sections (Bruun 1978).

(Dean, 1971) gave a method for inlet stability analysis based on the tidal prism ($P$) – inlet area ($A_c$) relationship:

$$P = TV_m A_c / \pi$$  \hspace{1cm} (10)
Where $T$ is the tidal period and $V_m$ is the maximum tidal flow velocity at the channel throat. Dean (1971) equated the relationship given above to an empirical tidal prism – inlet area relationship given by (O'Brien, 1931). From this he found the value of $V_m$ required for inlet stability to be about 1m/s. This has since been validated in inlets worldwide (Bruun, 1978).

Depending on the tidal period and tidal prism of the inlet, and using $V_m = 1$, equation (10) can be used to find the equilibrium cross section of the inlet channel.

4 METHODS

The objectives of this study were achieved through five research components:

Sediment samples were collected from beaches in the Kalbarri area and from within the Murchison River estuary and analysed to find grain size characteristics, numerical wave modelling was performed using the wave model SWAN to evaluate wave parameters at dredge spoil disposal sites, these wave model outputs were used to characterise sediment transport at these sites, inlet stability analysis was applied to the Murchison River entrance channel to determine an equilibrium cross section, and aerial photography was analysed to assess the influence of river flows on the entrance.

4.1 Sediment Analysis

4.1.1 Sample collection and preparation

Sediment samples were collected at 18 sites from within the Murchison River estuary, and from the wider Kalbarri coastal area. Where possible, samples were taken from the middle swash zone (determined by observing wave run-up for approximately 1 minute). The locations of samples taken within the estuary are shown in the aerial photograph below:
Figure 4.1: Aerial photograph of the Murchison River estuary, with sample locations marked.

Notice that the spit had a different alignment to that shown by the photograph at the time of sample collection. The actual alignment is sketched onto the photograph in black. Samples taken in the wider Kalbarri area are shown in the following aerial photograph:

1 – Chinaman’s Point, in front of access path, 1m behind reef platform
2 – Chinaman’s Beach west, mid-swash
3 – Chinaman’s Beach east, mid-swash
4 – Sand Spit, west side, mid-swash
5 – Sand Spit, channel end, mid-swash
6 – Sand Spit, east side, mid-swash
7 – Mid-channel, seabed
8 – Shallow area, south end
9 – Shallow area, middle
10 – Shallow area, north end
At each site, two surface samples were taken, approximately 1m apart (in the longshore direction). Samples were collected by scooping an ordinary film canister (obtained from a film processing outlet) into the surface sediments, to yield samples of around 50g. After collection, the samples were sealed in the film canisters, and stored indoors. The sediment samples were placed into clean glass tumblers and 300ml of distilled water was then poured in on top of the samples. The mixture in each tumbler was stirred vigorously, and left to stand for 5 minutes. After this time, each tumbler was viewed for the amount of suspended solids in the water.

Samples that did not show evidence of large amounts of suspended solids, i.e. clear water above the sediments at the bottom of the tumbler, were decanted (water poured off) taking care not to lose any sediments. Samples that showed a degree of suspended solids after 5 minutes of settling.
time were left to stand over night before decanting. The process of washing and decanting was then repeated for all samples.

After decanting the sediment-water mixtures for the second time, samples were removed from the glass tumblers and placed in individual aluminium take-away containers. These containers were then placed in a conventional oven on a low heat (50°C). Once dry, samples were transferred back into clean, dry film canisters for storage, before being subjected to sieve analysis to determine grain size characteristics.

4.1.2 Sieve Analysis

The standard grain size sieve analysis test determines relative proportions of different grain sizes as they are distributed among certain size ranges. The test uses a stack of sieves with apertures becoming increasingly smaller from top to bottom. Usually a pan is used to collect any particles passing through the bottom sieve in the stack. A sediment sample is placed in the top sieve, and shaken using a mechanical sieve shaker. The different grains fall through the stack of sieves until each reaches a sieve that is too fine for it to pass. Sieve apertures are often measured in phi (Φ), where the aperture size in millimetres is given by \(2^{-\Phi}\).

For this study, a stack of 12 sieves were used, with apertures at half phi intervals from \(4\Phi\) to \(-1\Phi\), as well as a \(-2\Phi\) sieve, and a pan to collect particles that passed through the finest sieve. Samples were weighed and placed in the top of the sieve stack. The entire stack did not fit on the available sieve shaker, so the stack was first shaken by hand for about 1 minute, then the top four sieves were removed and the remaining sieves were placed on the sieve shaker, and shaken vigorously for approximately 10 minutes. After shaking, the mass of sediment in each sieve (and the pan) was weighed and recorded. While two samples were collected from every site in this study, due to equipment availability, only one sample from each site has been analysed.

Data from the sieving process was entered into the ‘Multiple Sample Data Input Screen’ of the MS Excel based program GRADISTAT (Blott, 2000). From this screen, statistics were calculated for each sample.
4.1.3 Historical sediment data

Over the past four years, sediment samples have been collected from within the entrance, and analysed as part of the management of the dredging program. Raw data from these samples was available for this study, and this data has also been entered into GRADISTAT to give sample statistics for historical sediment samples.

4.2 Numerical Wave Modelling

The numerical wave model SWAN (Simulating Waves Nearshore) was used to model the nearshore wave climate at the options for dredge spoil disposal sites.

4.2.1 SWAN wave model details

SWAN is a numerical wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries (Booij et al., 2004). It is a third generation model, encompassing sources and sinks of wave generation. SWAN calculates wave propagation processes including: propagation through geographic space, refraction and shoaling due to spatial variations in bathymetry and currents and transmission through, blockage by or reflection against obstacles. SWAN is also able to account for the following wave generation and dissipation processes: wind generation, wave-wave interactions, dissipation through whitecapping and bottom friction and dissipation by depth-induced wave breaking (Booij et al., 2004). Wave diffraction effects can also be simulated by SWAN by applying directional spreading of the waves.

Outputs of wave data from SWAN have been validated in a number of situations, and the program has been shown to adequately model wave parameters in situations where wave diffraction and reflection effects are limited (Booij, Ris et al., 1999).

4.2.2 Modelling design

Modelling was performed with the major aim of producing one year of 3-hourly wave data for the nearshore zone at the dredge spoil disposal locations. This was achieved by a two stage
modelling process, whereby a 1000m resolution bathymetric grid was used to model waves offshore of Kalbarri, and this modelled data was then used as an input into a nested 100m grid of the nearshore Kalbarri area.

Before the main model simulation was run, two ‘stationary’ model runs were performed to test the model setup, and to evaluate basic wave parameters experienced under two important wind and offshore wave conditions. The first stationary run was based on typical sea breeze conditions, and used a wind speed of 5.5m/s from 180°, coupled with a significant offshore wave height of 2.94m, from 222° with a peak period of 11.7s. The second stationary run was based on typical storm conditions, using a wind speed of 10m/s from 315°, with a significant offshore wave height of 5m, from 246° with a peak period of 13.32s.

The main, ‘non-stationary’ model was run using the input data discussed in the following section.

4.2.3 Input data

Input data had to be converted to a specific format so that it could be utilised by SWAN. This was done using a MATLAB based GUI (Graphical User Interface) program written by CWR graduate Ben Hollings

Wind

Wind data for Kalbarri is only recorded between the hours of 6am and 6pm, so 3-hourly continuous data from Geraldton for the year of 2004 was used instead. While Geraldton is located about 150km south of Kalbarri, and wind readings are taken at the Geraldton airport located several kilometres inland, this data was considered the best available for this simulation. Wind data from Geraldton is recorded and archived by the Bureau of Meteorology (BOM).

BOM wind data is presented as wind speed in kilometres per hour, and direction as a bearing. SWAN requires that this wind data be converted into x and y components (east-west and north-south components) in metres per second
Water Level

Historical water level data is not available for Kalbarri, so for this model 3-hourly tide predictions were used for the year of 2004. Tide predictions were generated using the program WXTide32, relative to Mean Sea Level.

Offshore Waves

Real, measured wave data is not available for Kalbarri, so hindcast data was used in this simulation. Hindcast wave data for the year of 2004 (3-hourly data) was obtained from the Wave Watch 3 – Global Wave Hindcast Model (WW3) for the location at latitude 28°S, longitude 113.75°E. Wave parameters included in the WW3 data are significant wave height, peak spectral wave period and peak spectral wave direction.

Coarse Bathymetry

A coarse bathymetric grid was created from bathymetric files that are part of the Australian Bathymetry and Topography Grid (CoA, 2003), with a resolution of about 1000m, encompassing the area offshore of Kalbarri to just past the continental shelf edge. This coarse bathymetry also extended north and south to include features like the Abrolhos Islands. The coarse bathymetric grid was originally in terms of latitude, longitude and depth, but this was converted to easting, northing and depth to allow compatibility with the nested bathymetric grid.

Nested Bathymetry

Depth soundings of the Kalbarri area were provided by DPI, and this data was converted into a 100m resolution bathymetric grid using the MATLAB routine GRIDDATA. The nested bathymetric grid is in terms of easting, northing and depth, where the easting and northing values are for the Australian Geographic Zone 50.

4.2.4 Data extraction

The SWAN modelling returned wave parameters for every cell of the coarse and nested grids, for every 3-hourly time increment. From this very large data set, wave data was extracted for the dredge spoil disposal sites. This was done by obtaining GPS co-ordinates of the disposal sites.
and extracting data from the nearest cell of the wave model. The result was a year of 3-hourly wave data for each disposal site.

4.2.5 Model validation

Unfortunately, no measured data was available to validate the model outputs. As such, it was planned that GPS drifter buoys would be used to measure longshore currents at the disposal sites. Measured data from drifter buoys could then be compared to calculated longshore current speeds using equation (8) so the validity of the wave modelling could be assessed. Unfortunately, only a small number of drifter runs could be completed due to concerns about safety when deploying and retrieving drifter buoys.

Four drifter runs were completed, beginning south of disposal site A, and moving south. The drifter buoy was deployed using a bodyboard and flippers just behind the wave breaking point. From here the buoy was allowed to travel through the surfzone until it washed up on the shore, where it was retrieved. Twice the drifter did not wash up on the shore, and moved outside of the surfzone and had to be retrieved using the bodyboard.

4.3 Sediment Transport Characterisation at Disposal Sites

The output data from the numerical wave modelling procedure was used to characterise sediment transport at the different dredge spoil disposal sites. Outputs from the SWAN model on a 100m resolution bathymetric grid, as used in this simulation, are not considered adequate to describe breaking wave parameters such as breaking wave angle and breaking wave height (Hollings, 2005). As such, for the purposes of this study, sediment transport will be characterised at the closest possible point to each site at approximately 4m depth.

4.3.1 Longshore sediment transport

Longshore sediment transport due to oblique wave approach is evaluated using equations (7) and (8), but these both require breaking wave parameters as inputs. As such, longshore sediment
transport could not be evaluated at the disposal sites. Even longshore transport direction cannot be evaluated exactly without breaking wave direction, but a proxy for this can be calculated by considering the shoreline orientation and approaching wave direction.

The coastline at the disposal sites was mapped by carrying a GPS instrument, and walking along the shore. The GPS instrument used was actually a GPS drifter buoy carried in a backpack which took a GPS reading every second. From these GPS readings, the angle or bearing of the shoreline was evaluated.

It follows that a wave approaching the coast will be normal to the shore if it has a direction perpendicular to the bearing of the shoreline. Therefore a proxy for the longshore transport direction was calculated by finding the shore-perpendicular wave direction at each disposal site, and comparing this to the wave direction data at 4m depth.

4.3.2 Maximum shear stress

Figure 3.2 was used to select linear wave theory for calculating maximum shear stress at the disposal sites. Once this was selected, equations (1) to (4) were used to calculate maximum shear stress at the seabed for each site, using the wave parameters from the SWAN model output. The wave friction factor approximation given in equation (3) requires an input of $R$, the bed roughness factor. For the purposes of this study, a nominal value of 0.001 was used for $R$ in all calculations. In cases where the seabed substrate is known, i.e. smooth sand, rippled sand, reef, seagrass etc, the roughness factor should be calculated, but this was not possible for this study due to the lack of information available on substrate type at the disposal sites. For all maximum shear stress calculations, a value of 1025kg/m³ was used as the value for the fluid density, $\rho$.

4.3.3 Mobilised grain size

To characterise sediment transport at the disposal sites, the modified Shield’s diagram (figure 3.4) was used to find the grain size that is likely to become mobile at each site, under the wave conditions given by the SWAN model output. This grain size value is known as the mobilised
grain size. This aim posed a problem however, as both the dimensionless particle size (D*) and the critical mobility parameter (θ_cr), required for calculating sediment mobility, require that the median grain size (D_{50}) is already known. To overcome this problem an iterative solver was written in MATLAB to evaluate the mobilised grain size. The basic steps used in the iteration are given below:

1. The solver uses an arbitrary initial guess of D_{50} (600 microns).
2. The value for median grain size is used to evaluate D*.
3. The equations given in figure 3.4 are used to evaluate a value for θ_{cr}.
4. The formula for θ_{cr} is rearranged to find a new value for D_{50}.
5. Steps 2 – 4 are repeated.

For all calculations of D* and θ_{cr}, the value for specific gravity (s) used is 2.65. This is a good estimate for the specific gravity of any natural sediment composed of mainly quartz and calcium carbonate (USACE, 2001).

The MATLAB program performed 20 iterations, before giving a final output for the mobilised grain size. The final mobilised grain size and the value given by the previous iteration were compared to ensure that the two values differed by no more than 0.1 microns, signifying that the solver had converged on a solution. The mobilised grain sized solver ‘mobgrain.m’ is given in Appendix A.

4.3.4 Suspended grain size

Similar to the mobilised grain size, the suspended grain size is the grain size likely to be undergoing suspended transport under the given wave conditions. This was calculated in a much more straightforward manner using the shear stress criteria for incipient suspension given in section 3.2.1. For these calculations a value of 2650 kg/m³ was used for the sediment density (ρ_s), given by USACE (2001) as a good estimate for the density of any natural sediment composed of mainly quartz and calcium carbonate.
4.4 Inlet Stability Analysis

The method of inlet stability has been applied to the throat section of the Murchison River entrance channel to find an equilibrium cross-section of this particular location of the inlet. The throat of the entrance has been identified as the section of inlet passing between the tip of the sand spit, the northern bank of the inlet directly north of the spit. This has been identified by considering past surveys of the entrance to identify the section of smallest cross-sectional area.

By rearranging equation (10) to give an expression for \( A_c \), the equilibrium cross-sectional area, the equilibrium cross section has been calculated. For this calculation 1m/s for \( V_m \) (maximum tidal velocity) and a tidal period (\( T \)) of 86400s have been used. A value of \( 2\times10^6 \text{m}^3 \) for the tidal prism given by DMH (1989) has been used.

4.5 Aerial Photography Analysis

Aerial photographs of the Murchison River entrance were provided by DPI. The photographs provided were part of the Department of Land Administration (DOLA) coastal photography runs. Aerial photographs have been used to analyse the size of the sand spit, and the location and width of the entrance channel, under conditions preceding different types of river flows. Photograph analysis has been performed using Geographical Information Systems (GIS) techniques.

4.5.1 Photograph selection

DOLA Coastal photography runs were performed in the Kalbarri area infrequently, usually once every two or three years. From the available photographs a number have been chosen by considering the Murchison River flood record:
The years 1986, 1995 and 1999 have been selected from the available photographs as years of small to moderate river flow, 1975 and 1980 are years of large river flows, and 1969 1979, 1985 and 1990 are years where no significant flow occurred. Photographs from these years have been used so that comparison can be made between years of similar river flow conditions, and the effects on the Murchison River entrance of different flow conditions can be analysed.

4.5.2 Photograph rectification

Normally, the scale and orientation of photographs are rectified using a road line coverage file, which contains the co-ordinates of road intersections that appear in the photographs. For this study, a road line coverage file was not available. Instead, photographs in digital format were rectified using an Arcview shape file.

By taking a photograph that had already been oriented in the north-south direction and loading it into the GIS program Arcview, it was possible to create a file that had arbitrary co-ordinates for the visible road intersections. In Arcview, this file is known as a ‘shape file’. 
The shape file of road intersections and other unrectified aerial photographs were then loaded into the GIS program Arcmap. The points from the shape file were matched with the actual intersections on the photographs using the Georeference toolbar in Arcmap, and the rectified photographs were saved.

4.5.3 Shoreline plots

After rectification, photographs were loaded into Arcview, and the shoreline in the river entrance was recorded, by creating new line coverage files. Vegetation lines are generally used in shoreline analysis, but for this study it was deemed that the waterline would give better indications of river flow effects. After recording the waterline position in the entrance for each rectified photograph, shorelines plots were saved.

Analysis of shoreline plots in this study is purely for qualitative and descriptive purposes. Because the waterline is affected by many factors, including water level fluctuations, these plots cannot be used to accurately measure movement of the coastline between photographs. The fact that a road coverage file was not used in the rectification process also increases the error involved.

5 RESULTS

5.1 Sediment Analysis

The MS Excel based program GRADISTAT calculates a range of different statistics for each sample. For the purpose of this study, the median grain size of the sample, D_{50}, has been used for comparison between samples. D_{50} can be defined as the grain size at which half of the sample (by weight) is larger and half of the sample is smaller. The median grain sizes of samples taken from within the estuary are shown below:
Figure 5.1: Median grain sizes from sediment samples in the Murchison River entrance

From this figure, it can be seen that samples taken from around the spit (samples 2, 3, 4 and 5) have median grain sizes in the range of 300 – 500 microns. The three samples taken from the shallow area to the north of the entrance (samples 8, 9 and 10) are considerably coarser, in the range of 750 – 800 microns, and there is a decreasing trend in coarseness in these three samples as we move from north to south. The sample taken from within the channel (sample 7) is also considerably coarser than those samples taken from around the spit. Sample 1, taken from the beach at Chinaman’s Point is also fairly coarse.

The median grain sizes of samples taken from the wider Kalbarri coastal area are shown in the following figure:
Figure 5.2: Median grain sizes from sediment samples in the Kalbarri area

This figure shows that, in general, coastal sediments on Kalbarri beaches are much coarser than those within the Murchison River entrance, with the finest being sample 13 (Siphon Road carpark) at 606.9 microns. Sample 18, taken upriver of the Fishing Boat Harbour is considerably finer than the other samples shown in this figure.

GRADISTAT has classified the sediments around the spit, and the sample collected upriver as ‘medium sands’ while all other samples collected in the study fell into the range of coarse to very coarse sands.

Sediment samples from previous years were collected in a variety of locations, but only one location is consistent between all years. Fortunately, this location is the spit, which happens to be
an area of interest in this study. Raw data from samples taken from the spit in previous years have been collected and analysed using GRADISTAT to find the median grain size. Where more than one sample was taken, the D50 values have been averaged. The results of the historical sample analysis are shown in the figure below. The average of the median grain size values from samples collected in this study is also included.

![Sediment Grain Sizes in the Murchison River Entrance - By Year](image)

**Figure 5.3: Sediment grain sizes in the Murchison River entrance -by year**

For the years 2001 to 2004 a clear increasing trend of about 50 microns per year can be seen in the average D50 sizes, peaking at around 700 microns in 2004. The average median grain size of sediments collected in this study is significantly finer than any of the previous four years, with an average of around 400 microns.
5.2 Numerical Wave Modelling

5.2.1 Stationary model runs

The outputs from the stationary model runs have been used to evaluate the general wave climate patterns at Kalbarri. The following figure shows wave heights experienced offshore of Kalbarri under typical sea breeze conditions:

![Wave Heights for offshore Kalbarri – Sea Breeze Conditions](image)

The Abrolhos Islands, which are clearly visible to the southwest of Kalbarri, can be seen from this figure to offer a significant amount of protection from waves to the Kalbarri area. The wave ‘shadow’ behind the island chain extends north of Kalbarri under sea breeze conditions.

The following figure shows wave heights experienced offshore of Kalbarri under typical storm conditions:
Figure 5.5: Wave Heights for offshore Kalbarri - Storm Conditions

From this figure we can see that the Abrolhos Islands do not offer protection to the Kalbarri area from waves under storm conditions. The wave shadow from the islands moves a significant distance south during storms.

The following figure shows wave heights experienced nearshore at Kalbarri under typical sea breeze conditions:
From this figure we can see that an area of wave sheltering is developed in the nearshore region south of the Murchison River entrance.

The corresponding figure of wave heights for nearshore Kalbarri during storm conditions is shown below:
From this figure, we can see that the sheltered region south of the Murchison River entrance that is present during sea breeze conditions does not appear during storms.

### 5.2.2 Significant Wave Height

The following table has been constructed from data extracted from the non-stationary model run, and shows the annual percentage of different wave heights at disposal site A:

<table>
<thead>
<tr>
<th>Significant Wave Height (m)</th>
<th>Disposal Site A</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 0.5</td>
<td>0.5 - 1</td>
<td>1 - 1.5</td>
<td>1.5 - 2</td>
<td>2 - 2.5</td>
<td>2.5 - 3</td>
<td>&gt; 3</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Annual Percentage</strong></td>
<td>0.00</td>
<td>1.23</td>
<td>25.35</td>
<td>44.35</td>
<td>20.74</td>
<td>6.56</td>
<td>1.78</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Modelled significant wave heights at disposal site A
The table shows that at site A, more than 90% of all waves have significant heights of between 1 and 2.5m. 44.35% of all waves are in the range of 1.5 to 2m, significant wave heights less than 0.5m were not found to occur for 2004.

The same information, but for site B is shown in table 5.2 below:

### Significant Wave Height (m) - Disposal Site B

<table>
<thead>
<tr>
<th>Significant Wave Height (m)</th>
<th>Annual Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>0.00</td>
</tr>
<tr>
<td>0.5 - 1</td>
<td>1.20</td>
</tr>
<tr>
<td>1 - 1.5</td>
<td>17.05</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>43.25</td>
</tr>
<tr>
<td>2 - 2.5</td>
<td>33.38</td>
</tr>
<tr>
<td>2.5 - 3</td>
<td>4.99</td>
</tr>
<tr>
<td>&gt; 3</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 5.2: Modelled significant wave height at disposal site B

Similar wave height statistics to site A occur at site B, with again, more than 90% of all significant wave heights in the range of 1 to 2.5m, and no wave heights less than 0.5m modelled. The main difference between the wave height statistics for the two sites is that at site B, more waves have significant heights in the range of 2 – 2.5m and less occur in the 1 – 1.5m range.

### 5.2.3 Wave Direction

Wave directions have also been extracted from the model for the disposal sites. Annual percentages of wave directions are shown below for site A:

### Wave Direction (deg) – Disposal Site A

<table>
<thead>
<tr>
<th>Wave Direction (deg)</th>
<th>Annual Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 220</td>
<td>0.1</td>
</tr>
<tr>
<td>220 - 225</td>
<td>0.5</td>
</tr>
<tr>
<td>225 - 230</td>
<td>0.9</td>
</tr>
<tr>
<td>230 - 235</td>
<td>2.1</td>
</tr>
<tr>
<td>235 - 240</td>
<td>2.4</td>
</tr>
<tr>
<td>240 - 245</td>
<td>5.0</td>
</tr>
<tr>
<td>245 - 250</td>
<td>13.7</td>
</tr>
<tr>
<td>250 - 255</td>
<td>56.3</td>
</tr>
<tr>
<td>255 - 260</td>
<td>18.2</td>
</tr>
<tr>
<td>260 - 265</td>
<td>0.8</td>
</tr>
<tr>
<td>&gt; 265</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 5.3: Modelled wave direction at disposal site A

Only a small range of wave directions are experienced at site A, with almost 90% of wave directions modelled in the range of 245° - 260°. The range of 250° – 255° is the predominant scope of wave directions for the site, with an annual percentage of 56.3%.

Wave directions modelled for site B are shown below:
Wave Direction (deg) - Disposal Site B

<table>
<thead>
<tr>
<th>Annual Percentage</th>
<th>0.03</th>
<th>0.38</th>
<th>2.70</th>
<th>9.22</th>
<th>84.59</th>
<th>3.07</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>240 - 245</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>245 - 250</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 - 255</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>255 - 260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 260</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Modelled wave direction at disposal site B

The modelled data indicates that site B experiences a much smaller range of wave directions than site A, with 97% of all waves in the range of 240° - 260°. The table above also indicates that the wave directions at site B are more westerly than at site A, with 84.59% of wave directions in the range of 255° – 260°.

5.2.4 Peak Wave Period

Peak spectral wave periods have also been extracted from the model for the disposal sites. The peak spectral period is the period of the highest energy wave modelled at the given time. Annual percentages of peak spectral periods are shown below for site A:

<table>
<thead>
<tr>
<th>Annual Percentage</th>
<th>0.07</th>
<th>1.13</th>
<th>4.10</th>
<th>16.47</th>
<th>32.08</th>
<th>33.41</th>
<th>12.80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 - 9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 - 11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 - 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 - 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5: Modelled wave period at disposal site A

The table above shows that more than 80% of the highest energy waves at site A have periods of between 9 and 14s. Peak spectral periods of less than 7s are rare, occurring less than 1.5% of the time.

Annual percentages of peak spectral periods are shown below for site B:
The table above shows that peak spectral wave periods occur with similar annual percentages at both sites. Again, more than 80% of the highest energy waves at site B have periods of between 9 and 14s, and at site B, peak spectral periods of less than 7s are even rarer than at site A, occurring less than 0.65% of the time.

### 5.3 Sediment Transport Characteristics at Disposal Sites

Sediment transport at the disposal sites has been characterised by considering the sizes of sediment grains undergoing different types of transport, and their likely direction of longshore transport.

#### 5.3.1 Longshore transport

The result of mapping the shoreline at the disposal sites is that a shore-normal wave direction has been found. The coastline orientation was found to be very similar at all disposal sites, with the coast angling west of north at a bearing of approximately 345°. It follows from this that the wave direction perpendicular to the shore is 255°.
As the wave direction normal to the shore has been found, a proxy for the longshore sediment transport direction can be suggested, by assuming that when the wave direction at the disposal site exceeds 255°, longshore currents, and therefore longshore sediment transport will occur in a southwards direction. Conversely, wave directions less than 255° will drive longshore sediment transport north along the coast.

5.3.2 Mobilised grain size

The grain size likely to become mobile under the waves at the disposal site has been calculated from the modified Shield’s diagram, using wave parameters extracted from the numerical wave model. In the following figure, mobilised grain sizes have been plotted against the incident wave direction for Site A:
Figure 5.9: Mobilised grain size versus wave direction - site A

The 255° shore-normal wave direction has also been marked onto the figure, and the likely direction of longshore transport indicated. Each point on the plot can be interpreted as a 3-hourly data point showing the likely direction of transport and size of a sediment grain mobilised by the wave conditions at that time.

It is clear from the plot that far more data points are located to the left of the 255° wave direction line, indicating longshore transport to the north. The maximum density of data points can be seen in the wave direction range of 250° - 255°, and mobilised grain size range of 1.25mm – 2mm. There is a clear trend in mobilised grain sizes shown in the figure, where data points to the right of the 255° wave direction line, are associated with larger mobilised grain sizes.
The following figure shows the same information as that in figure 5.9 above, but for Disposal Site B:

![Mobilised Grain Size versus Wave Direction - Disposal Site B](image)

**Figure 5.10: Mobilised grain size versus wave direction - site B**

At Site B, different trends can be seen. From the plot, more data points can be seen located to the right of the 255° wave direction line, indicating longshore transport to the south. The maximum density of data points is located in the range of 257° – 259° for wave direction, and from 1.5mm – 2.25mm for mobilised grain size. Similar to Site A, there is a clear increase in mobilised grain sizes to the right of the 255° wave direction line.

### 5.3.3 Suspended grain size

Similar plots to those presented above in 5.3.2 have been generated for the disposal sites, but now showing the suspended grain size versus wave direction. Data extracted from the wave model has been used to apply suspension threshold criteria to find the grain size likely to be
undergoing suspended transport under the given wave conditions. The following figure shows suspended grain sizes versus wave direction for disposal site A:

![Suspended grain size versus wave direction - disposal site A](image)

Figure 5.11: Suspended grain size versus wave direction - site A

Again, the 255° wave direction line is marked on the plot, and the likely direction of longshore sediment transport is indicated. Each point on the plot can be interpreted as a 3-hourly data point showing the likely direction of transport and size of a sediment grain undergoing suspended sediment transport from wave conditions at that time.

Similar to the mobilised grain size plot for Site A, more data points are located to the left of the 255° wave direction line, indicating a higher frequency of longshore transport to the north. The highest density of data points is located in the range of 250° – 255° for wave direction, and 0.16mm - 0.2mm for the suspended grain size. Larger suspended grain sizes are located to the right of the 255° wave direction line.
The following figure shows the same information as in figure 5.7 above, but for disposal site B:

![Suspended Grain Size versus Wave Direction - site B](image)

**Figure 5.12: Suspended grain size versus wave direction - site B**

As can be observed in the mobilised grain plots, at site B, different trends from site A exist. From the plot, more data points are situated to the right of the 255° wave direction line, indicating longshore transport to the south. The maximum density of data points is located in the range of 257° – 259° for wave direction, and from 0.17mm – 0.21mm for suspended grain size. As in figure 5.7, there is an increase in suspended grain sizes to the right of the 255° wave direction line.

### 5.4 Inlet Stability Analysis

As outlined in section 4.4, equation (10) has been used to calculate an equilibrium cross-sectional area for the throat section of the Murchison River entrance channel. The calculated cross-section is 72.7m². The average depth in the throat section, for a range of different channel widths is given below:
<table>
<thead>
<tr>
<th>Channel Width (throat section) (m)</th>
<th>Average Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.205</td>
</tr>
<tr>
<td>55</td>
<td>1.315</td>
</tr>
<tr>
<td>50</td>
<td>1.446</td>
</tr>
<tr>
<td>45</td>
<td>1.607</td>
</tr>
<tr>
<td>40</td>
<td>1.808</td>
</tr>
<tr>
<td>35</td>
<td>2.066</td>
</tr>
<tr>
<td>30</td>
<td>2.410</td>
</tr>
</tbody>
</table>

Table 5.7: Range of channel widths and depths for throat section, based on equilibrium cross-section

5.5 Aerial Photography Analysis

Aerial photographs have been analysed to produce shoreline plots using GIS techniques. Shoreline plots for years where no significant river flows occurred (1969 and 1979) are shown in the figure below:
Figure 5.13 Murchison River entrance shoreline after no significant river flows (1969 and 1979)

Both shorelines exhibit a large, developed spit, and a narrow throat section of the channel. The plot from 1979 shows a recurve (hook) at the distal end of the spit, and as a result of this, the channel throat is in a more easterly location than in 1969.

The following figure shows shoreline plots from 1995 and 1999, preceding small to moderate river flows:
Figure 5.14: Murchison River entrance shoreline after moderate river flows (1990 and 1999)

Again, both shorelines exhibit a large, developed spit, with both showing evidence of a recurve at the distal end. 1999 exhibited a longer spit than in 1990, but the north bank of the channel throat section is located farther north, resulting in a similar width throat section in both years. The shoreline plots for years where moderate river flows occurred are not dissimilar to those from years where no river flows occurred, with similar sized spits and a similar width channel.

The following figure shows shoreline plots from 1975 and 1980, after large river flows:
Both shorelines after large river flows exhibit a very small spit, appearing more like a salient in size and shape. The diminished spit size has resulted in a wide throat section of the channel for both 1975 and 1980. 1975 exhibited a longer spit than in 1980, but the north bank of the channel throat section is located farther north, resulting in a similar width throat section in both years. The shoreline plots for years where large river flows occurred are significantly different to those from years where moderate or no river flows occurred, with a much smaller spit and wider throat section of the channel.
6 DISCUSSION

6.1 Sediment analysis

The results from sediment analysis show that samples collected from around the sand spit and upriver of the Fishing Boat Harbour are medium sands and that other samples collected in this study fall into the range of coarse to very coarse sands. However, the timing of sample collection is likely to have biased some of the calculated grain sizes.

Samples taken from around the spit were collected shortly after or possibly during the end of a river flow. It is likely that these samples had a larger amount of fine material than is typical for samples from the spit, due to an input of finer fluvial sediments from the river system. Sediment samples collected at the spit a few months later than those analysed were available for observation, and from comparison with the analysed samples appeared to be coarser. It is likely that the river flow caused deposition of fine sediments at the entrance, and because surface sampling was utilised in this study, these finer sediments were collected.

The dominance of fine grained sediments in the entrance is likely to have been short-lived, and after the river flow ceased, input of marine sediments to the entrance is likely to have increased the median sediment grain sizes again. This means that the sharp decrease in grain sizes from previous years shown in figure 5.3 above is not likely to have been indicative of the actual sediments present in the entrance.

Although the sediments around the spit are not likely to be as fine as indicated by the samples collected in this study, the input of finer sediments is still likely to have decreased the median grain size of samples in the entrance, but probably not to the degree that the sediment analysis indicates. A rough estimate of the actual median grain size of sediments in the entrance is probably around 600 microns. This suggests that river flows are likely to be a significant factor in the increasing coarseness of sediments observed in the entrance. In the years 2001 – 2004 where no river flows occurred, there was no input of finer fluvial sediments from the river
system, and the average median grain size of samples taken from the spit increased steadily. In 2005 a river flow occurred, and the sediment sizes around the spit are likely to be finer than the previous four years.

The likely decrease in coarseness of sediments within the entrance has some important implications for dredging parameters. The decrease in coarseness of sediments around the spit is likely to have applied to material removed from the entrance channel by maintenance dredging. As dredge material coarseness is directly related to dredge production rates, it is likely that production will have increased this year, compared to previous years. It is also probable that due to the finer dredge spoil, that pumping the full distance to disposal site A is likely to be easier. While dredging for 2005 has been completed, information regarding dredge and pump productivity rates were not available for this study.

Another implication of dredged material being finer than in previous years is that turbidity at the dredge and the disposal site may have increased from previous years due to a larger proportion of the grains undergoing suspended transport. However, the likelihood of increased turbidity is not certain, because the degree of turbidity associated with dredging and disposal of dredge spoil is also strongly influenced by factors such as tides and wave energy.

6.2 Numerical Wave Modelling

6.2.1 Stationary model runs

The stationary model runs indicate that wave heights in Kalbarri are much higher during storm conditions where strong winds typically occur from west to northwest, because the sheltering effects of the Abrolhos Islands and the coast south of Kalbarri are insignificant during these conditions.

This is important because it implies that due to the larger wave conditions experienced at Kalbarri there is a greater propensity for sediment transport during storms. Since strong winds are likely to occur from the west to northwest during these storms, there is a potential for wave
directions to become more westerly, and thus altering the longshore sediment transport characteristics at the coast.

6.2.2 Comparison of wave climate at disposal sites

From the data extracted from the numerical wave model for sites A and B, it can be concluded that wave heights at both sites are very similar, but with slightly larger wave heights at site B. Because more than 90% of all waves fall into the range of 1 to 2.5m at both sites, the wave climate can be defined as falling into the ‘high energy’ classification.

Peak spectral wave period statistics for both sites are also very similar, with more than 80% of peak spectral periods occurring in the range of 9 – 13s. This statistic, coupled with the fact that modelled peak spectral periods less than 7s rarely occurred for either site, indicates that both sites are dominated by swell waves.

The main difference in modelled waves between the two sites occurs in the wave direction statistics. Wave directions at site B fall into a much smaller range than at site A, and generally occur from a more westerly direction than at site A. Due to the orientation of the coast at the disposal sites, this implies that there is a greater potential for transport south along the coast at site B compared with site A.

It is interesting that such a significant difference in wave directions could be determined for the two sites, which are only separated by 400m. It is possible though, that some element of the topography offshore of site B causes a larger degree of wave refraction compared to offshore of site A, resulting in the more westerly wave directions at site B. Since the nearshore bathymetric grid has a resolution of 100m, it is possible that there is some bathymetric feature that occurs in the grid offshore of site B that does not affect waves arriving at site A.
6.2.3 Model validation

Validation of the SWAN model was planned to be carried out by comparing predicted longshore current speeds and direction, calculated from data extracted from the model, with longshore current speed and direction measured using a GPS drifter buoy. However, this validation could not be carried out because WW3 wave data was not available for the time the drifter buoy was being deployed.

The drifter buoy data is of some use though, because wind speed and direction was available for the same time as longshore current data was measured. One hour after the drifter runs were performed, a wind reading was recorded, with a wind speed of 15km/h, and a direction of 4° (northerly). One data point from the wave model inputs, had a wind speed and direction of 14km/h and 7°, offshore waves were similar to the prevailing wave conditions with $H_s = 2.5m$, $T_p = 11.2s$, and $D_p = 225^\circ$. At this time, the wave model outputted a wave direction at disposal site A of 256.5°, indicating that longshore transport to the south would be likely. Longshore currents to the south were measured by the GPS drifter buoy, providing a weak validation to the wave model. The unfiltered buoy data is presented in the following figure:
6.2.4 Limitations of numerical wave modelling

A degree of caution must be employed when considering the data produced from the numerical modelling performed in this study. Some important limitations do exist which significantly decrease the certainty of the accuracy of the modelled data.

General limitations occur in the process of numerical modelling, because modelling tries to describe natural processes that exhibit a certain degree of randomness with ordered mathematics. In some cases the mathematics describes the natural processes inadequately, resulting in modelled data that does not reflect real, measured data. For the SWAN model in particular, this occurs when diffraction and reflection of waves occur. Other limitations of the SWAN model are
associated with general assumptions, such as the wind field is constant over the modelled area, and inputted offshore wave heights are spatially uniform over the model boundary.

Numerical modelling in this study has been performed using a 100m resolution bathymetric grid for the near-shore Kalbarri area. When considering shallow water waves, relatively small bathymetric features can have significant effects on wave parameters. The 100m grid is not able to encompass all bathymetric features that are likely to affect wave parameters at the disposal sites, decreasing the degree to which modelled data can be relied on.

Wind data for Kalbarri was not usable in this model simulation, and as such, wind recordings taken from a site inland, 150km to the south had to be used. This is also likely to have contributed to error involved.

The fact that the model output cannot be validated against any real measured wave data means that the accuracy of its predictions cannot be assessed. The best that can be done to assess the accuracy of the model is to consider the outputted data and to make ‘common-sense’ judgements as to whether these outputs match observed wave characteristics at the sites. Most of the observations, made by dredge operators and engineers, of the waves at the disposal sites agree with the classification of a high energy, swell dominated wave climate.

Observations of the likely wave directions at the site are related to the direction of transport of dredge spoil after disposal. These observations will be examined in the following section.

6.3 Sediment Transport Characteristics at Disposal Sites

6.3.1 General transport characteristics

If the mobilised grain size plots for both sites are considered, it can be seen that mobilised grain sizes are almost always greater than 1mm. As dredge spoil material is likely to have a median grain size in the range of 600 microns, this suggests that in most conditions, the majority of dredge spoil material is likely to be mobile after discharge into the water.
The suspended grain size plots for both sites have different implications however, with the majority of suspended grains in the size range of 150 – 200 microns. This suggests that only the finer portion of dredge spoil is likely to be undergoing suspended load sediment transport, and as such, only these finer grains are likely to be significantly influenced by longshore currents.

6.3.2 Sediment transport characteristics – disposal site A

Both the mobilised grain size and suspended grain size versus wave direction plots for site A, indicate that for the majority of time, mobile and suspended grains at this site are likely to be undergoing transport to the north. This could be expected, because more than 70% of modelled waves at site A have directions less than 255°, indicating longshore sediment transport to the north.

However, while the fine material in the range of 150 to 200 microns is likely to be transported north relatively rapidly due to the larger influence of longshore currents on these particles, the transport of grains larger than 200 microns is likely to be much slower.

The trend of larger mobilised and suspended grain sizes to the right of the 255° wave direction line indicates that at site A, there is a greater potential for larger sized grains to be transported south. In other words, for the majority of the time, large grains at site A are predicted to move slowly north in bedload transport, until waves from directions greater than 255° occur, when there is a greater potential for these large grains to become suspended and therefore move rapidly south. These wave conditions with directions greater than 255° are likely to be attributed to storm conditions.

This process of finer grains moving north and coarser grains moving south from disposal site A is likely to have contributed to the increase in coarseness of sediments within the Murchison River entrance. Once coarse grains have been transported south from disposal site A, it is likely that they are transported back into the entrance via the gap in Oyster Reef and the associated shallow area behind the reef.
6.3.3 Sediment transport characteristics – disposal site B

Both the mobilised grain size and suspended grain size versus wave direction plots for site B indicate that for the majority of time, mobile and suspended grains at this site are likely to be undergoing transport to the south. This could be expected, because more than 85% of modelled waves at site B have directions exceeding 255°, indicating longshore sediment transport to the south.

Similar to site A, the trend of larger mobilised and suspended grain sizes to the right of the 255° wave direction line indicates that at site B, there is a greater potential for larger sized grains to be transported south. This means that under most conditions, fine sediments at site B will be transported rapidly south, and coarser sediments will be transported slowly southwards, as bedload transport. Under some conditions, most likely due to storms, this coarser material is also likely to become suspended and be transported south more rapidly.

6.3.4 Comparison of sediment transport characteristics at disposal sites

By looking at the likely direction and modes of transport of sediments at the disposal sites, an interesting finding has emerged, showing that there is a reversal in the modelled direction of sediment as we move from site A to site B.

At site A, most of the modelled longshore sediment transport occurs to the north, with longshore sediment transport to the south occurring much less frequently. At site B, most of the modelled longshore sediment transport occurs to the south, with transport to the north much more infrequent. This suggests that sediments (especially coarse sediments undergoing bedload transport) located between the two sites are likely to remain in this area until such time as the infrequently occurring situations arise, where sediments are transported north of site B or south of site A.

Because there is evidence to suggest that discharged dredged material is transported south along the coast and back into the entrance, in the past, dredge contractors have tried to pump material to site B to increase the time taken for the spoil to reach the entrance. However, from the
modelled sediment transport characteristics of the sites, it can be seen that modelled longshore sediment transport is actually more southerly at site B, indicating that pumping the extra 400m to site B is not likely to be a cost effective exercise.

6.3.5 Limitations of sediment transport characterisation

Caution must be taken when using the data presented to characterise the sediment transport at the disposal sites. The sediment transport characteristics have been calculated from the numerically modelled wave data for the disposal sites, and as such the limitations that increase the uncertainty of the accuracy of the wave data also apply to the sediment transport characteristics.

One factor that increases the level of uncertainty of the modelled sediment transport data is that the characteristics described for each site do not agree with observations of the actual sediment transport at the sites. Generally when dredge spoil is discharged at site A, the beaches to the south of this point accrete rapidly, suggesting that the prevailing sediment transport at site A is to the south. This is opposite to what the modelled data indicates.

Also, when dredge spoil has been discharged at site B, it could be expected that beaches to the south of this point would accrete, because the modelled data suggests that at site B, predominant longshore sediment transport is occurring to the south. However, this is not the case, with no rapid accretion of the beaches south of site B occurring during the discharge of dredge spoil.

While the modelled sediment transport does not appear to agree with observed trends, the modelled data should not be completely discounted. It may not be able to accurately predict the direction of longshore transport at the sites, but the modelling of other factors including mobile and suspended grain sizes are still likely to be useful. General trends, such as the increase in suspended and mobile grain sizes with increasing wave direction are also likely to be correct.
6.4 Inlet Stability Analysis

The major implication of the results from inlet stability analysis, is that to create a channel throat with a depth of 2.38m (1.8m Chart Datum), which is the current design depth after dredging, that also has an equilibrium cross-section, the width of the throat section would need to be around 30m. Typically the throat section of the channel has a width of around 50m, and does not vary greatly from this width. This suggests that the throat section in equilibrium has an average depth of around 1.45m (0.87m Chart Datum).

At the end of winter this year (2005) the Murchison River entrance channel was the most constricted that it has been for many years (Ralph Blundell, pers. comm. 2005). The accretion patterns from 2004 to 2005 can be seen in Appendix C. Crude measurements of the cross-sectional area of the channel throat have been made from the pre-dredging hydrographic survey (Appendix D) from late October this year, with estimates of around 80m² obtained. This suggests that while the entrance channel was considered to be more constricted than is typical at the end of winter this year; the throat section of the channel would have to become even shallower or narrower to be considered at equilibrium.

The Murchison River entrance was considered to be more constricted than is typical before this year’s maintenance dredging program began, and initial calculations show that the throat section did not exhibit an equilibrium cross-section. It follows from this that before the dredging program in other years, where the channel was less constricted; the throat cross-section was greater than the equilibrium value. This means that while the annual maintenance dredging of the Murchison River entrance continues it is unlikely that it will ever be allowed to reach equilibrium, unless the non-typical level of constriction of the entrance that occurred this year becomes more frequent.

Literature on inlet channel equilibrium suggests that if sediment supply is not lacking, and ‘normal conditions are experienced’ (no river flows, or large storms etc occur), that an altered throat section of the channel will be approaching equilibrium after two or three spring-neap tide
cycles (Bruun, 1978). The fact that the Murchison River entrance does not appear to be reaching equilibrium after one year goes against this general observation.

It has been identified that while the potential longshore drift along the coast south of the Murchison River entrance is very large, this potential is not realised due to a lack of sediment supply along this stretch of coast. Coastlines typified by wave cut platforms like at Kalbarri have also been identified as regions where predicted longshore transport is often less than that measured, because the surfzone and therefore longshore currents due to oblique wave action are diminished (DMH, 1989).

It is likely that the lack of sediment supply and the presence of reef platforms near the Murchison River entrance have resulted in an input of sediment into the entrance that is less than predicted. This is likely to be the reason that the entrance does not approach an equilibrium cross-section as rapidly as might be expected.

A major implication of this finding is that sediment supply is likely to be a major controlling factor on the degree to which the channel becomes constricted before annual maintenance dredging in October each year. This means that any way that sediment supply into the Murchison River entrance can be limited is likely to be beneficial in maintaining navigability in the entrance for longer periods of time.

### 6.5 Aerial Photography Analysis

By observing shoreline plots created from aerial photographs, it is clear to see that the effects of large river flows on the Murchison River entrance are quite dramatic. From figure 5.15 above, it can be seen that large river flows in the years 1975 and 1980 were the likely causes of a severely diminished spit resulting in a much wider entrance.

While large river flows have dramatic effects on the morphology of the Murchison River entrance, small or moderate river flows do not appear to cause any significant changes to the entrance. The size of the spit and width of the channel through the throat section of the entrance
is very similar in years where no river flow occurs, to years where a moderate flow occurs. It is possible that immediately preceding a small or moderate river flow that the entrance exhibits some significant changes, but these changes are not evident in photographs taken months later.

By applying inlet stability analysis to the Murchison River entrance, it has been found that because of a sediment supply limitation, the entrance does not appear to rapidly approach equilibrium conditions after some event that alters the morphology of the entrance. Therefore it seems unlikely that if significant changes to the entrance did occur under a moderate flow that the entrance would not exhibit these changes in the aerial photographs analysed. However, if the moderate river flow was accompanied by a significant input of fluvial sediments into the system, a typical morphology in the entrance might be reached more rapidly.

It is important to note that the validity of aerial photography analysis in determining the effect of river flows is heavily dependant on the timing of both the photographs and the river flows. Both photographs analysed to produce figure 5.14 were taken at least 4 months after a river flow occurred, so it is also possible that changes to the Murchison River entrance did occur, but these effects were diminished slowly over the months before the photographs were taken, and as such could not be observed in the shoreline plots.

Another observation that can be made from the shoreline plots is that the location of the entrance throat appears to migrate. In all three shoreline plot figures above (figures 5.13 – 5.15), the channel throat is in a different location in both years, with migration in both the north-south and east-west directions observable. While the entrance throat does migrate, the channel width in this section appears to be relatively constant for years that experienced similar river flow conditions.

In other words, the four shoreline plots for years of moderate or no river flows have similar entrance throat widths, but differing throat locations, and the two shoreline plots for years with large river flows also show similar width throat sections (though wider than those in the years of moderate or no river flows), and differing throat locations.
7 CONCLUSIONS

Marine sediments in the Kalbarri area are classified as coarse to very coarse sands, with median grain sizes of 600 microns and greater. Fluvial sediments from the Murchison River are medium sands with median grain sizes in the order of 300 microns. Sediments that make up the Murchison River ocean entrance are a combination of these two sediment types, and the coarseness of samples taken from within the entrance is highly dependant on the recent relative input from both the marine and fluvial sources.

It is likely that the lack of input of fluvial sediments in the past four years has contributed to the increasing grain sizes recorded in the entrance. Due to a river flow this year, it is expected that the sediments in the entrance are likely to be less coarse than previous years.

Through a numerical wave model simulation it has been found that at the dredge spoil disposal sites, the wave climate can be described as high energy and swell wave dominated. Modelled wave directions at both sites fall mainly into the range of 240° to 260°, with waves at disposal site B likely to be more westerly than at site A.

Using this wave model data, sediment transport characteristics at both disposal sites has been found, indicating that after discharge, all grains from dredge spoil become mobile. However, only grains with diameters less than about 200 microns are likely to become suspended after discharge, and be strongly influenced by longshore currents.

There is a trend of increasing mobile and suspended grain sizes with increasing wave direction, indicating that larger grain sizes are only likely to become mobile when conditions are conducive to transport south along this stretch of coast, such as during storm events. This is a likely cause of the observed increase in dredge spoil coarseness over the last four years.

The application of inlet stability analysis on the throat section of the Murchison River entrance indicates that with a typical width of 50m, the average depth through the throat section at equilibrium is likely to be around 1.45m.
The level of constriction of the entrance observed this year resulted in serious difficulties with navigation, but it has been calculated that these conditions were still less constricted than the equilibrium conditions. It is likely that due to a lack of input of sediments into the entrance, that the equilibrium is not likely to be reached in the time between maintenance dredging sessions.

Aerial photography analysis has been used to determine shoreline plots of the Murchison River entrance under different river flow conditions. It has been found that very large flows have a significant effect on the morphology of the channel. However, the effects of moderate flows are either much less significant or very short-lived.

The migration of the throat section of the entrance channel has also been identified from aerial photograph analysis, with migration in both the east-west and north-south directions observed. Although migration occurs, it appears that the width of the channel throat is not altered significantly.

8 RECOMMENDATIONS

Redesign of the wave model is recommended, using higher resolution bathymetry, and continuous Kalbarri wind data which is not currently available. Through the use of better bathymetry, the wave model could be used to calculate breaking wave parameters, which could be used to calculate the potential longshore transport. This would give a much better description of sediment transport characteristics at the dredge disposal sites.

Future studies should model sediment transport characteristics at potential disposal sites, to assess whether a better location exists for dredge spoil disposal. A better location would exhibit longshore sediment transport characteristics that are not conducive to sediment transport back into the Murchison River entrance.
Modelling of the entrance itself should be performed to analyse the effects of waves and water level fluctuations on the entrance.

Further investigations into inlet stability analysis of the Murchison River entrance should focus on measuring real parameters of the throat section, especially tidal velocities through this section, and changes of cross-sectional area at different points in the tidal cycle.
REFERENCES


Hollings, B. (2005). SWAN GUI, Centre for Water Research, University of Western Australia.


Oceanroutes (1989). One Year Hindcast Database 1984 Offshore Kalbarri, Oceanroutes (Australia) Pty Ltd.


APPENDIX A

Mobilised grain solver for Matlab ‘mobgrain.m’
mobgrain.m

load modelleddata.mat
sze = 2927;

DxA = ones(sze,1), DxB = ones(sze,1);
d50A = 0.001*ones(sze,1), d50B = 0.001*ones(sze,1);
d50A2 = ones(sze,1), d50B2 = ones(sze,1);
thetcrA = ones(sze,1), thetcrB = ones(sze,1);
diffA = 1, diffB = 1;
tmA = DATmax, tmB = DBtmax

for jj = 1:20
    for ii = 1:sze;
        DxA(ii,1) = d50A(ii,1)*((1.585*9.81)/1e-12)^(1/3);
        if DxA(ii,1) <= 4;
            thetcrA(ii,1) = 0.24*DxA(ii,1).^(1);
        end
        if 4 < DxA(ii,1) <= 10;
            thetcrA(ii,1) = 0.14*DxA(ii,1).^(0.64);
        end
        if 10 < DxA(ii,1) <= 20;
            thetcrA(ii,1) = 0.04*DxA(ii,1).^(0.10);
        end
        if 20 < DxA(ii,1) <= 150;
            thetcrA(ii,1) = 0.013*DxA(ii,1).^(0.29);
        end
        if 150 < DxA(ii,1);
            thetcrA(ii,1) = 0.055;
        end
        d50A2(ii,1) = tmA(ii,1)/(thetcrA(ii,1)*1025*9.81*1.65);
        d50A(ii,1) = d50A2(ii,1);
    end
end
for jj = 1:20
    for ii = 1:sze;
        DxB(jj,1) = d50B(jj,1)*((1.585*9.81)/1e-12)^(1/3);
        if DxB(jj,1) <= 4;
            thetcrB(jj,1) = 0.24*DxB(jj,1).^(1);
        end
        if 4 < DxB(jj,1) <= 10;
            thetcrB(jj,1) = 0.14*DxB(jj,1).^(0.64);
        end
        if 10 < DxB(jj,1) <= 20;
            thetcrB(jj,1) = 0.04*DxB(jj,1).^(0.10);
        end
        if 20 < DxB(jj,1) <= 150;
            thetcrB(jj,1) = 0.013*DxB(jj,1).^(0.29);
        end
        if 150 < DxB(jj,1);
            thetcrB(jj,1) = 0.055;
        end
        d50B2(jj,1) = tmB(jj,1)/(thetcrB(jj,1)*1025*9.81*1.585);
        d50B(jj,1) = d50B2(jj,1);
    end
end
APPENDIX B

Aerial photographs used for shoreline analysis
APPENDIX C

Deepening and accretion: pre-dredge 2004 to pre-dredge 2005
APPENDIX D

Pre-dredge Hydrographic Survey – October 2005