ANALYSIS OF FREMANTLE INNER HARBOUR SILTATION PATTERNS

A Thesis written for the completion of the degree:
Bachelor of Environmental Engineering

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Dear Sir or Madam,

I hereby submit this thesis, “Analysis of Fremantle Inner Harbour Siltation Patterns” which forms part of the requirements for completion of the degree of Bachelor of Environmental Engineering.

Yours truly,

Mark Nicholls
ABSTRACT

Situated in the mouth of the Swan River on the west coast of Australia, Fremantle Harbour is the major port for Western Australia. Analysis of bathymetric surveys of the Inner Harbour has revealed that areas of the harbour are becoming silted, which can impact future shipping activities. This CEED project sponsored by the Fremantle Port Authority determined factors causing siltation in the Inner Harbour and predict future depths of the harbour.

Analysing the bathymetry data from surveys of the harbour, a channel was found to have formed in the Inner Harbour. The meandering nature of this channel was found to be responsible for the patterns of siltation and erosion. An ADCP survey of harbour currents confirmed the finding of the meandering channel. Regression analysis of the bathymetry data allowed a model to be produced that could predict future harbour depths.
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Introduction

This thesis, titled “Analysis of Fremantle Inner Harbour Siltation Patterns”, is the result of an industry based project (CEED) run by the University of Western Australia’s Centre for Water Research (CWR) and the Fremantle Port Authority (FPA). The project was initiated by the FPA to give the organisation an insight into the issues surrounding siltation within the Fremantle Inner Harbour. With the larger cargo ships having a clearance of only a metre from the bottom of the Inner Harbour, processes causing a decrease in the depth of the harbour need to be understood by the FPA. Maintenance dredging is costly and needs to be planned for well in advance, making being able to predict where and when siltation is likely to occur important in the long term planning strategies of the FPA.

A meeting between the FPA, CWR and the author set the following three main objectives for the project.

1. Determine the sources of siltation in the Inner Harbour
2. Analyse which factors are the most important in causing the distribution of siltation in the Inner Harbour
3. Develop a predictive model for future siltation in the Inner Harbour

Successful completion of objective 1, “determining the sources of siltation in the Inner Harbour”, would give the FPA a model to allow them to better understand where silt comes from. Analysis determined the contributions made by the incoming ocean flow, downstream river flow and redistribution of material from erosion within the harbour to the siltation. FPA data from past dredging reports and current meter readings at the Fremantle Railway Bridge were used for this analysis.

The second objective; “determining the factors that are affecting the distribution of silt within the Inner Harbour”, requires identification of which factors are controlling the distribution of silt and the relative importance of each factor. The FPA needs such information to understand why and where siltation will occur.
Introduction

The third objective requires the production of a mathematical model that can be used to predict the build up of silt in the Inner Harbour. It needs to be a piece of working software or algorithm that can be used to predict the future depths of the harbour. Using this model the FPA wants to forecast the timing of future dredging projects required to maintain a safe shipping depth throughout the harbour. The model will be devised from survey data gathered by the FPA over the past 10 years.

The thesis contains a run down of the history of the Fremantle Inner Harbour, a review of the relevant literature that has developed the science of physical sedimentology and case studies that illustrate how siltation has affected other ports and estuaries around the globe. The methods that were used to achieve the three outcomes will then be discussed, followed by the results that were produced by these methods. Each of the three outcomes for the project will then be discussed in light of the results that were produced and the literature that was reviewed.
2. Background

This chapter shows the location, geographical features and history of engineering developments within the Inner Harbour. It illustrates how changes to the bathymetry of the harbour and the construction of structures on the edges of the harbour has led to a change in the equilibrium siltation conditions and changed the hydrodynamics of flow through the harbour.

2.1. Site of Fremantle Harbour

The Fremantle Harbour is located on the west coast of Australia 22 kilometres from the city of Perth. It is divided into an Inner and Outer Harbour. The Fremantle Outer Harbour is a large area stretching from north of the Swan River entrance to include most of Cockburn Sound to south and nearly to Rottnest in the east.

Figure 2.1: Extent of Fremantle Outer Harbour (source: FPA 2003)

The Inner Harbour is contained within the Swan River estuary (see Figure 7.1). It stretches inland from the river mouth to the Railway Bridge as shown in Figure 2.2. From Figure 7.1, note that the Swan River bends before entering the harbour underneath the Railway Bridge. Construction of the North and South Moles has provided a harbour that is protected from large ocean swells. Berths line both sides of the Inner Harbour, with the Northern Quay the dock for most of the large freight and livestock vessels, and the Victoria Quay containing passenger vessels, car carriers and other smaller ships.
Shipping activities within both the Inner and Outer Harbour are controlled by the Fremantle Port Authority (FPA). The port handles 34% of Western Australia’s exports and 90% of total imports. Future expansions of the Outer Harbour could result in lesser demand for the use of the facilities within the Fremantle Inner Harbour.

### 2.2. Engineering Developments in the Inner Harbour

The Swan River Estuary was a relatively natural system before construction of the Fremantle Inner Harbour. Figure 2.3 shows a map of the Swan River mouth prior to the Inner Harbour construction works. At this time, it can be seen that the estuary was only around 2 metres deep and the river’s path had a gradual bend before discharging into the ocean between Rous Head and Arthur Head. A limestone ridge at the river mouth prevented shipping access from the ocean. This limestone ridge would have also limited the amount of oceanic sediment entering the harbour and the flushing of built up sediment from upstream out into the ocean. Note also the grey strip that follows the path of the river before curving to exit at the bottom of the map. This strip signifies the location of a paleochannel, the location of the ancient flow path of the Swan River. The Fremantle Inner Harbour began construction in 1892 with work starting to build the
North and South Moles based on the designs of C.Y. O'Connor. The removal of the limestone bar from the river entrance in 1895 and subsequent dredging left the harbour at a depth of around 9.14 metres, when complete in 1902. Major dredging works occurred between 1913 and 1929, deepening the harbour to nearly 11 metres. At the same time the berths were extended in the Inner Harbour eastwards to Railway Bridge.

![Figure 2.3](image1)

**Figure 2.3: Swan River mouth before construction of the Inner Harbour (Hodgkin et al. 1998)**

Since then, modifications have occurred to deepen the harbour and in the construction of Rous Head, North Quay and Victoria Quay. The most recent dredging operation occurred in 1989 when dredging deepened the Inner Harbour to around 14 metres. Since that time, maintenance dredging has been required to sustain the depth, as siltation has accumulated in areas of the Inner Harbour. A contour map of the depth of the harbour in 2002 is shown in Figure 2.4. These changes to the depth and structure of the Fremantle Inner Harbour have led to changes in the physical characteristics of the Swan River. One such change is the movement upstream of the salt wedge from near the mouth to around Midland /Guilford during summer (Stephens et al. 1997). Although the salt...
wedge extends to Midland, the Inner Harbour can still be classified as part of the Swan River Estuary, with the salinity of water in the harbour decreasing during peak winter river flows. The following section discusses results from previous studies of the flow patterns in the Inner Harbour.

![Contour map of the Fremantle Inner Harbour depths in April 2002](image)

### 2.3. Flow Behaviour of the Fremantle Inner Harbour

The Fremantle Inner Harbour has been the site of numerous studies into the hydrodynamics, siltation patterns and sediment characteristics of the port for use in dredging procedures. A study undertaken before dredging of the harbour to 14 metres in 1989 produced a report by Buchan entitled “River and Tidal Flow Regimes – Fremantle Inner Harbour” that contains a thorough investigation into the hydrodynamic regimes within the harbour. The study analysed tidal patterns in the harbour by using current measurements at the Railway Bridge and Forrest Landing, together with tide gauge readings made at Forrest Landing. These measurements were made by FPA equipment prior to the 1989 dredging works. The significance of the report was the finding that the pattern of tidal flow through the estuary was an ‘S’ shape that left stagnation zones in
the vicinity of berths 4 and 5 at North Quay and G and H berths on the Victoria Quay side of the harbour. This flow path is illustrated in Figure 2.5, shown below.

Figure 2.5: ‘S’ shaped flow path found in the Inner Harbour from current sampling in 1989
(Source: Buchan 1989)

The study also empirically derived some equations relating current velocities to the measured tidal height at Forrest Landing.

\[
V(t) = 1.5H(t - \tau) \quad \text{Railway Bridge (RB)}
\]

\[
V(t) = 0.6H(t - \tau) \quad \text{Forrest Landing (FL)}
\]

where \( H \) is the forest landing tide height measured at time \( t-\tau \) (m)

- \( V \) is the easterly vector component of the current velocity (m/s)
- \( \tau \) is the time lag between currents and tides (s) (3 hours for RB and 4 hours for FL) (Buchan 1989).
The reliability of this relationship was very low however, with the data points quite scattered. A more reliable relationship that was discovered by the study was between peak current velocity and the tidal range:

\[ V_{\text{peak}} = 1.0 H_{\text{range}} \]  
**Railway Bridge**

\[ V_{\text{peak}} = 0.5 H_{\text{range}} \]  
**Forest Landing**

These relationships had a correlation of 0.8 and so were more reliable predictors of the current patterns (Buchan 1989). This relationship shows that there are much stronger tidal currents at the Railway Bridge compared to at Forest Landing, which is situated closer to the ocean.

The field test also measured the salinity and temperature of the water at different locations and different depths. These measurements were used to track the movement of the salt wedge through the estuary under different tidal conditions. At all locations in the Inner Harbour, it was found that the water had the same density as saltwater (35 ppt) at depths greater than 7 metres, indicating that the salt wedge extends throughout the estuary along the bottom (Buchan 1989). In areas that experience high velocity tidal currents, the water reached 35 parts per thousand throughout the water column at the end of the flood tide. Other regions that didn’t experience large tidal currents still had a layer of fresh water at the surface (Buchan 1989). These results indicate that as the salt water enters the estuary on the flood tide, it replaces all of the fresh water except in the stagnant zones. As the ebb tide began, the salt water at the surface left the estuary and was replaced by fresher water from further up the estuary. This resulted in strong density gradients that cause stratification. The strongest of these gradients occur just after the low tide, when the density changes from 28 to 35 parts per thousand over the depth range of 3 to 7 metres (Buchan 1989).

These measurements and field-testing are only a starting point to understanding the patterns of siltation that are occurring in the Inner Harbour. Since these tests were undertaken, the harbour has been dredged twice; once to deepen the harbour to 14 metres, and the other time to remove built up silt maintaining the required 14 metres depth. The effects of the deepening need to be quantified by field measurements, but intuitively, the harbour deepening will have allowed the salt wedge to intrude further up
the estuary, will have slowed the tidal and river currents down and may have altered the ‘S’ pattern of circulation through the estuary by removing the bathymetric features that affected the estuary currents.
3. Processes behind sediment movement

Chapter 2 built the scenario around which the problem of siltation is based by describing the location and giving a description of the changes that have occurred in the Fremantle Inner Harbour. During this chapter, background into the processes that cause sediment to move in water bodies will be discussed. Cases where siltation has caused problems in other estuaries and harbours will also be discussed to develop methods that have been used in other locations to investigate siltation issues.

3.1. Stokes’ Law

One of the basic physics principles that effects the transportation sediment is Stokes’ Law. The law is used to calculate the terminal settling velocity of objects through a fluid medium. Stokes’ Law can be stated as (Massey 1972):

\[
V = (2gr^2) \times \left( \frac{\rho_1 - \rho_2}{9\mu} \right)
\]

Equation 3-1

where

- \( V \) is the terminal velocity of the particle
- \( g \) is the acceleration due to gravity
- \( r \) is the radius of the particle
- \( \rho_1 \) is the density of the particle
- \( \rho_2 \) is the density of the supporting fluid
- \( \mu \) is the viscosity of the fluid (Massey 1972)

From Equation 3-1, it can be seen that the controlling factors behind the maximum speed an object can fall at are the comparative density of the particle to its medium, the radius of the particle and the viscosity of the fluid medium. To apply Stokes’ Law it is assumed that the particle is spherical.

Another important assumption is that the viscous forces of the fluid are sizeably greater than the inertia forces acting on the particle so that the inertia forces can be ignored. The ratio of inertia to viscous forces is expressed as the Reynolds Number;
so that small Reynolds Number conditions of less than 1 are required for Stokes’ Law to hold (Allen 1985).

The \( r^2 \) term at the start of Equation 3-1 shows that the size of the particle is the most influential term in the equation so that, for a given fluid, larger particles will settle through the fluid quicker than smaller particles. Applying this principle to the case of particles with the same density moving down a river with a constant velocity, the larger particles will be deposited before the smaller ones, leaving a pattern of sediments along the river bottom moving from larger particles upstream to small particles downstream (Allen 1985). The same principle can be applied to the density of particles. If the material was all the same size, denser particles would be deposited further upstream than less dense particles.

The density of the supporting fluid is the other factor that can affect the terminal velocity of a particle falling through the fluid. In highly stratified water conditions, this factor can affect the settling velocity of a particle, because the density of the fluid increases with depth. This means that particles will slow down as they move through the fluid in stratified conditions, and will stop dropping if the density of the fluid becomes equal to the density of the particle.

As mentioned previously, Stokes’ Law is only valid for conditions with a Reynolds’ number of less than 1. A larger Reynolds’ number means that inertial forces are dominating the fall of the particle so that a drag coefficient needs to be considered. When the Reynolds’ Number is between 1000 and 100,000 or greater than \( 1 \times 10^7 \), this drag coefficient is fairly constant so that Stokes’ Law can be rewritten as:

\[
V = k \left( \frac{(\rho_1 - \rho_2) \times gD}{\rho_1} \right)^{\frac{1}{2}}
\]

**Equation 3-3: Terminal velocity of a particle with large Reynolds’ Number**
where \( k \) is a function of the drag coefficient and \( D \) is the diameter of the particle.

### 3.2. Shear Stress

Sediments on the bottom of water bodies can be lifted into the water column through a process called resuspension. Behind this process is the mechanism of shear stress. Shear stress is the resistance of an object to a fluid flowing past it (Massey 1972). The relationship for shear stress can be given by:

\[
\tau = \mu \frac{\partial u}{\partial y}
\]

**Equation 3-4**

where \( \tau \) is the shear stress and \( \frac{\partial u}{\partial y} \) is the ratio of the change of velocity with respect to the change in distance in the \( y \) direction.

Equation 3-4 makes the calculation of \( \tau \) difficult, because the rate of change of velocity in the \( y \) direction needs to be measured. Instead, the quadratic friction law gives a simpler relationship between shear stress and water velocity. The relationship is given by:

\[
\tau_0 = \rho C_D u^2
\]

**Equation 3-5**

where \( \rho \) is the water density, \( C_D \) is a dimensionless friction factor and \( u \) is the water velocity (Allen 1985). If the velocity is measured at a height of 1 metre from the bed \( C_D \) can be assumed to be 0.003 (Soulsby 1983).

### 3.3. Bedload Transport

Bedload transport is the rate at which mass of sediment is moved along the bed by water movements. It is expressed in units of g cm\(^{-1}\) s\(^{-1}\). Bagnold formulated one of the first bedload equations in 1963 as (cited in Soulsby 1983):

\[
q_{ab} = \frac{\rho_s}{(\rho_s - \rho) g} \times K \sigma
\]
Analysis of Fremantle Inner Harbour Siltation Patterns  Processes behind sediment movement

**Equation 3-6**

where K is an efficiency factor
- \( q_{sb} \) is the bedload transport
- \( \rho_s \) is the density of the sediment particles
- \( \rho \) is the density of water

and \( \omega \) is the power exerted on the bed by the water, equal to \( \rho u^3 \).

The constant K has been found to be dependent on the size of the sediment grains and whether the shear stress is greater than a critical value at which first bedload transport occurs. Gadd et al. (1978) derived a new equation that included the critical shear within it as a critical velocity term. This equation is:

\[
q_{sb} = \beta(U_{100} - U_{CR})^3
\]

**Equation 3-7**

where \( U_{100} \) is the water velocity at a metre from the bed, \( U_{CR} \) is the threshold velocity at a metre from the bed at which bedload first begins and \( \beta \) is determined by the sediment grain size (Gadd et al. 1978). It should be noted that \( U_{CR} \) is also dependent on the sediment grain size (Signell et al. 2000). \( \beta \) values were consequently found in a laboratory experiment (Soulsby 1983). These are listed in Table 3-1.

**Table 3-1: Critical velocity and \( \beta \) for different mean particle size distributions (Soulsby 1983)**

<table>
<thead>
<tr>
<th>d50 Particle Size (( \mu m ))</th>
<th>( \beta ) (g cm(^{-4}) s(^{-2}))</th>
<th>( U_{CR} ) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>7.22E-5</td>
<td>16</td>
</tr>
<tr>
<td>450</td>
<td>1.73E-5</td>
<td>19</td>
</tr>
</tbody>
</table>
4. Factors Affecting Silt Distribution

In chapter 3 the processes involved in the movement of sediments were introduced. These processes were physical processes such as Stokes’ Law, shear stress and bedload transport. This chapter will build on these foundations by discussing the factors that could be affecting the distribution of sediment throughout the harbour. These factors include shipping, tidal and river flow, harbour structures and the erosion/siltation characteristics of river bends. Section 2.3 has discussed previous studies of the tidal characteristics of the Inner Harbour. This chapter will focus on shipping and river bend flows.

4.1. Shipping

The Inner Harbour is an active port so that shipping is one activity that may have a large effect on the movement of silt around the harbour. The numbers of ships that use each of the berths on the Northern Quay side of the Fremantle Inner Harbour are listed in Table 4-1. Of these berths, 6, 7 and 9 are the most frequently used. The ships docking on the Northern Quay can have a clearance of less than one metre from the harbour bottom (Parker 2001). Movement of these large ships can cause sediment to be stirred up within the harbour. On the Victoria Quay side of the harbour, the berths are usually used only for passenger ships, car carriers and other small draught vessels, so that the impact of shipping on sediment movement will not be as pronounced. The location of the two quays was illustrated in Figure 2.2 and the berth positions are shown in Figure 4.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Berth 5</th>
<th>Berth 6</th>
<th>Berth 7</th>
<th>Berth 9</th>
<th>Berth 10</th>
<th>Berth 11</th>
<th>Berth 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>55</td>
<td>52</td>
<td>71</td>
<td>47</td>
<td>20</td>
<td>75</td>
<td>186</td>
</tr>
<tr>
<td>1996</td>
<td>129</td>
<td>129</td>
<td>79</td>
<td>73</td>
<td>21</td>
<td>39</td>
<td>78</td>
</tr>
<tr>
<td>1997</td>
<td>12</td>
<td>235</td>
<td>96</td>
<td>106</td>
<td>13</td>
<td>79</td>
<td>61</td>
</tr>
<tr>
<td>1998</td>
<td>13</td>
<td>198</td>
<td>153</td>
<td>171</td>
<td>25</td>
<td>93</td>
<td>57</td>
</tr>
<tr>
<td>1999</td>
<td>3</td>
<td>138</td>
<td>141</td>
<td>144</td>
<td>40</td>
<td>93</td>
<td>70</td>
</tr>
<tr>
<td>2000</td>
<td>9</td>
<td>158</td>
<td>142</td>
<td>159</td>
<td>32</td>
<td>91</td>
<td>75</td>
</tr>
<tr>
<td>2001</td>
<td>9</td>
<td>149</td>
<td>160</td>
<td>159</td>
<td>25</td>
<td>79</td>
<td>65</td>
</tr>
</tbody>
</table>
The propellers of both the cargo ships and the tugs used to move them cause of sediment movement. Ships are towed in to the harbour head first, and are rotated by tugs in the centre of the harbour so that they can travel headfirst when they are moved out of the harbour again. This standard path of ship movement and rotation could lead to a pattern of erosion through the centre of the harbour. Large volumes of water are moved when ships are pushed onto the berth and pulled off them by tugboats. With only a small gap between the bottom of the ship and the harbour floor, large currents will be induced by water being forced out from between the ship and the harbour, or back in again as the ship is pulled away from the dock.

**4.2. River Flow**

The discharge of runoff into the river network can carry weathered material with it and deposit the material within the river. Large flow events can then flush this sediment out and into the sea. Whether the Swan River is the source of the siltation within the harbour will be discussed in this section.

Wolanski et al. (2001) explored the issue of the sources of silt in the far north of Western Australia. The Ord River was used as the study area and the network offered a unique opportunity to compare the siltation in a river system largely disturbed by...
An analysis of Fremantle Inner Harbour Siltation Patterns

Factors Affecting Silt Distribution

humans with a system still in its natural state. This is because the network comprises of two large catchments that meet at the ocean outlet. The Eastern Arm of the system contains several dams including the one that created Lake Argyle, whereas the unpopulated Western Arm still has its natural hydrological flow patterns (Wolanski et al. 2001).

Comparison of the bathymetry of the western network from 1969 to 1999 shows no significant siltation over that time period (Wolanski et al. 2001). Only seasonal siltation occurs so that the long-term volume of siltation in the system is at equilibrium. This is in stark contrast to the eastern network, which has shown significant build up of silt since the original survey in 1969 (Wolanski et al. 2001). The construction of the dams in the eastern side of the river network has meant that the flow of water between the estuary and upstream is controlled. Nearly all of the silt carried by runoff through the eastern river network is caught upstream of the dams and the dams also control the peak flows through the network by attenuating flood peaks after high rainfall events. This means that the high siltation rate in the downstream estuary must have been caused by tidal pumping from the ocean (Wolanski et al. 2001).

It could have been thought that because the dams were trapping the sediment, the rate of siltation in the estuary and downstream areas of the river would have been greater if the dams were not in place. But the dams prevent flushing of sediment out to sea during peak flow times, so that silt from the ocean can build up without flushing (Wolanski et al. 2001). In the naturally occurring Western Ord river system, siltation occurs seasonally from both tidal pumping and erosion brought downstream by rivers, yet no long term build-up of silt occurs because peak flows wash the sediment out of the river and estuary (Wolanski et al. 2001). Therefore comparisons between the 1969 and 1999 bathymetry of the river networks shows no build-up of silt in the west but rapid human induced silt build-up in the eastern system.

The findings can’t be applied directly to the Fremantle Inner Harbour case because of differences in the size of tides, rainfall patterns and magnitude of catchment areas of the two regions. What can be taken from this report is that both tides and rivers can be significant sources of silt. It also shows that any build up of silt within the harbour is
caused by the system being out of equilibrium so that flushing of the harbour isn’t large enough to counter the rate of siltation.

A study into Port Hedland Harbour by Paul et al. (1974) also tried to determine sources of sediment within an estuarine harbour. Although the report had inconclusive findings as to the exact sources of silt, the report’s findings indicated that ocean inputs were significant in cyclonic events while at other times the 6 tidal creeks were significant sources year round. The report suggested that plans to construct dams across some of the tidal creeks would successfully reduce the silt build-up in the harbour (Paul et al. 1974). Again though, the applicability of these findings to the Fremantle Harbour is low given the strong tidal forcing of the Port Hedland study area and the large flood flow rates of the tributaries.

A study into siltation sources in the Rotterdam port also had some significant findings. Of the 8 million tonnes of silt that was deposited in the harbour per year, the study found that the majority of the silt was entering the estuary from the ocean, with only 10-20% estimated to be from upstream (de Kok et al. 1996). Another source of silt that was detailed in the article was the reallocation of silt from the disposal of past dredging operations. Often the dredged material is dumped out at sea where it can wash back into the estuary system. Because the dumped material will be unstable on the ocean floor, it can easily become suspended in the water column and flow back towards the estuary or harbour by currents induced by wind or tide. The Rotterdam report estimated that 30% of the sediment that had been dumped from dredging returned to the harbour (de Kok et al. 1996). When dredging occurs at the Fremantle Port Authority, the company undertaking the dredging procedures have different disposal options including a disposal site at Rous Head, on the Northern side of the Inner Harbour (Fremantle Port Authority Marine and Technical Services 1997).

C.Y O’Connor, the engineer of the Fremantle Port Authority investigated the likelihood of the ocean being a source of sediment in the Inner Harbour development. His findings in 1891 were that the “drift of sand across the harbour mouth is minimal” (Golder 1999). Deepening of the harbour since its development to 14 meters means that the salt
wedge from the ocean responsible for bringing in oceanic sediments has been able to extend further into the Swan River Estuary so that CY O’Connor’s findings may now be incorrect.

### 4.3. Tidal Flow

Before dealing with how tides influence siltation in estuaries, some tidal terminology needs to be introduced. Tides are caused by the gravitational attraction of water to the Moon and, to a lesser extent, the sun so that water is pulled towards the Moon to form a bulge. As the Moon rotates above the Earth, the bulge of water follows it so that alternate high and low water levels are experienced. From this, the ebb flow during the tide occurs when water is changing from the high tide to the low tide while the flood tide occurs as the water depth is increasing towards high tide. Spring tides are when the largest difference between tides occurs, generally at full moon when the tidal forces are strongest, leading to both strong ebb and flood conditions. Neap tides are the opposite, occurring under the new moon when the Sun and Moon are on opposite sides of the Earth, so their gravitational forces on the water partly cancel out.

Friedrichs et al. discuss the effects of tidal asymmetry on sediment transport in their article on the York River Estuary in the United States. Tidal asymmetry is caused by the flood and ebb tides being of different size and strength so that the currents associated with the tide flooding and ebbing are disproportionate. Of particular importance, were their observations that asymmetric tidal patterns cause the ebb tide to increase the salinity stratification of the water column and that the flood tides decrease the stratification by moving salt water over fresh water. This results in higher shear during the flood tide so that there is a greater chance of erosion, and hence transport, of material (Friedrichs et al. 2000).

During flood tides in estuaries, there is a movement of water into the estuary from the ocean. Water then leaves the estuary on the ebb tide and is replaced by fresh water from the river. Figure 4.2 illustrates the action of tides within the estuary. The flood tide is moving dense ocean water through the estuary so that strong currents will be induced along the estuary bed. On the ebb tide however, the less dense river water will flow
strongly along the surface, with lower velocities closer to the bed being induced. The result of this circulation is that along the bed of the estuary, there will typically be stronger currents during the flood cycle than the ebb. At the surface, the opposite behaviour is found, with the ebb currents having stronger current velocities than the flood.

![Profile of net residual current](image)

Figure 4.2: Estuary tidal action on the ebb and flood tide (Courtesy: O’Callaghan)

The tides in the Fremantle Inner Harbour change their frequency from diurnal to semidiurial during the tidal cycle. Diurnal tidal patterns are exhibited during spring tides while semidiurnal tidal patterns occur during the neap tides (Buchan 1989). The currents caused by the tides in the harbour are not very large when compared to ports in the north of Australia with the maximum current speed measured at Forrest Landing during Buchan’s study period being 0.3 m/s during the neap tidal periods and exceeding 0.4 m/s during spring tides. The current meter at the Railway Bridge experienced higher flows during the study period, with a maximum of 0.6 m/s during spring tides (Buchan 1989). The tidal excursion estimated from the current data at the Railway Bridge was 15 kilometres and 10 kilometres was estimated as the tidal excursion from Forrest Landing (Buchan 1989).

The flood tides at the harbour bring water in through the moles to increase the depth of the harbour while the ebb tides empty the harbour by flowing out to sea. Measurements detailed in Buchan’s report indicate that at the Forrest Landing site, which is close to the ocean, the currents from the flood tide at a depth of 3 metres were stronger than the currents during the ebb tide and on average had a longer duration (Buchan 1989).
opposite case was discovered at the Railway Bridge, although the flood tide still had a longer duration. This indicates the relative strength of the influence of the ocean compared to the river on the two locations. This result may have changed since harbour deepening in 1989 will have increased the influence of the ocean so that the Railway Bridge may now have stronger flood currents near the bed.

4.4. Characteristics of River Bend Flow

The natural flow path of a river is not a straight line. Rivers like to meander so that the result is that the water velocity changes across the width of the river when flowing through river bends. As mentioned in chapters 3.1 and 3.2, changes in water velocity are important when considering where siltation takes place because slower water currents allow silt to more readily fall out of suspension. By the same token, in areas where the water is travelling at a large velocity, there is more potential for sediment to be resuspended so that erosion takes place.

As water moves around the outside of the river bend, it moves faster than the water around the inside of the bend. Centrifugal forces push the water towards the outside of the bend so that a sloping water surface is formed, as shown in the left pane of Figure 4.3. The centrifugal force has a magnitude of \( \frac{\rho U^2}{r} \). This force decreases with depth as the water velocity (U) becomes affected by friction with the river bed (Allen 1985). On the outside of the bend there is a slightly higher water surface than on the inside of the bend. The sloping water height creates a pressure gradient of magnitude \( \rho \times g \times \frac{dh}{dr} \) (Nm\(^{-3}\)) (Allen 1985).
Figure 4.3: Centrifugal forces caused by flow of water around a channel bend create a sloping water surface (van Rijn 1990)

The centrifugal force dominates at the surface waters, causing water to flow towards the outside of the bend. With depth, the centrifugal force becomes smaller while the pressure gradient is kept constant so that water is forced towards the inside of the river bend (Allen 1985). This sets up the secondary circulation shown in Figure 4.4, where water flows towards the outside of the bend at the surface, and towards the inside along the bottom. Sediment can be transported from the outside of the bend towards the inside, allowing siltation of the inside of channel bends and erosion of the outside (Allen 1985).

Hibma et al discuss the mechanisms behind the formation of meandering channels based on their modelling results. The study involved setting up a model river that consisted of a straight channel and simulating river flow through it. Major findings from their report are that meandering channels begin from perturbations in the channel surface that cause flow to deviate away from the channel direction. (Hibma et al. 2003). This deviation results in curving flow paths that continue downstream. The study found that the wavelength of these flow paths increase with distance downstream. This increase of wavelength is particularly noticed in natural river systems where usually the river system gets wider with distance downstream (Hibma et al. 2003).
The findings from Hibma et al.’s research related meandering channel wavelength to distance downstream. However, this finding did not give any relationship between the meandering channel wavelength and any other river characteristics. Empirical studies from North America related channel wavelength to bankfull discharge. Carlston (cited in Allen 1985) found this relation to be:

\[ L = 24.5Q_b^{0.62} \]

where \( Q_b \) is the bankfull discharge and \( L \) is the wavelength. As \( Q_b \) can in turn be related to the channel width, the meandering channel wavelength was found to be close to 12 times the channel width (Allen 1985).
5. Methodology

The Fremantle Port Authority has provided four sets of data to be used to investigate the Inner Harbour siltation patterns. These are:

- bed sediment samples from past dredging records
- current data measured from the Railway Bridge between 2000 and 2003
- past bathymetric data of the Fremantle Inner Harbour
- ADCP data from 2001

During the following chapter, the methods that have been used in analysing this data to address the objectives are discussed. The results produced from the methods discussed in this chapter are shown in chapter 6.

5.1. Sediment Samples

Numerous bed samples of the Inner Harbour have been taken by FPA consultants. These were taken in February, March and July 1988 and in 2001. Sampling was done by extracting sediment from 300 mm below the bed. Results of particle size distribution analysis of these samples were provided. The most complete testing of the harbour was the July 1988 samples, with this data set being used for calculations during the project. The locations of where the samples were taken from in the harbour are illustrated in Figure 5.1.

Particle size distributions are measured by passing the sample through a series of screens that reduce in gap size through the series (Buller et al. 1979). By measuring the relative weight of sediment trapped in each screen, the percentage of weight of the sample that passes through can be calculated. This means that the $d_{50}$ particle size can be defined as the size of particle that has 50% of the sample finer by mass. The mean grain size can be calculated from the percentage of sediment in the different size categories by the formula (Buller et al. 1979):
The July 1988 survey was the most comprehensive data set. It was used to calculate the mean grain size throughout the harbour. Mean sediment sizes for these locations (locations shown in Figure 5.1) are shown in Table 5-1. The average mean grain size of all these locations was calculated as being 3.37 mm. This was used as the model grain size for calculations of sediment transport. Plots of the $d_{50}$ grain size through the harbour were also made to find any correlation between $d_{50}$ size and location within the harbour.
Table 5-1 : Mean grain sizes at locations taken during July 1988 sampling

<table>
<thead>
<tr>
<th>Location</th>
<th>Easting</th>
<th>Northing</th>
<th>$\bar{x}$ (mm)</th>
<th>Location</th>
<th>Easting</th>
<th>Northing</th>
<th>$\bar{x}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>382000</td>
<td>6454140</td>
<td>1.12</td>
<td>K</td>
<td>381450</td>
<td>6453700</td>
<td>0.35</td>
</tr>
<tr>
<td>B</td>
<td>379973</td>
<td>6452608</td>
<td>1.12</td>
<td>L</td>
<td>381560</td>
<td>6453910</td>
<td>0.31</td>
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<tr>
<td>C</td>
<td>381453</td>
<td>6453704</td>
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<td>M</td>
<td>381660</td>
<td>6454020</td>
<td>0.25</td>
</tr>
<tr>
<td>D</td>
<td>381386</td>
<td>6453872</td>
<td>0.33</td>
<td>N</td>
<td>381690</td>
<td>6454090</td>
<td>0.40</td>
</tr>
<tr>
<td>E</td>
<td>382004</td>
<td>6454170</td>
<td>1.22</td>
<td>O</td>
<td>381480</td>
<td>6453440</td>
<td>0.17</td>
</tr>
<tr>
<td>F</td>
<td>381998</td>
<td>6454108</td>
<td>3.91</td>
<td>P</td>
<td>381320</td>
<td>6453220</td>
<td>0.10</td>
</tr>
<tr>
<td>G</td>
<td>381998</td>
<td>6454108</td>
<td>2.60</td>
<td>Q</td>
<td>381160</td>
<td>6453045</td>
<td>0.44</td>
</tr>
<tr>
<td>H</td>
<td>381050</td>
<td>6453300</td>
<td>0.79</td>
<td>R</td>
<td>379980</td>
<td>6452950</td>
<td>0.17</td>
</tr>
<tr>
<td>I</td>
<td>381280</td>
<td>6453550</td>
<td>2.74</td>
<td>S</td>
<td>380080</td>
<td>6453050</td>
<td>13.45</td>
</tr>
<tr>
<td>J</td>
<td>381290</td>
<td>6453560</td>
<td>34.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2. Current Bridge Data

Current strength and direction were measured at the Railway Bridge (location shown in Figure 5.2) from the 18/10/2001 to the 1/4/2003. The current meter was attached to a float so that it was held constantly at 3 metres below the water surface. At this location, the harbour is about 9 metres deep. This meant that the meter was about six metres from the bottom of the harbour, depending on the tide. Measurements were taken every five minutes. Spikes in the measured current velocity meant that the data needed to be searched manually for good sections where current velocities were at plausible values. The two reasons for analysing this data were to see if there was a tidal asymmetry at the Railway Bridge and to calculate the bedload transport.

Assumptions that needed to be made during the analysis of this data were that the height of the current meter from the bottom of the estuary remains constant throughout the tidal cycle and that the water conditions throughout the year while sampling are fully mixed. The first assumption is required because although the current meter moves up and down in relation to the estuary bottom with the ebb and flood tide, to estimate the current velocity at the bed, a constant height needs to be assumed. The second
assumption is required so that the water velocity and direction at the estuary bottom can be related to the values measured six metres from the bottom.

Figure 5.2: Position of the Railway Bridge current meter highlighted by the red circle.

The current data recorded from the Railway Bridge was analysed in terms of the frequency of the direction of the currents and the average current speed in each direction.

5.2.1. Bed Velocities

The current meter is situated about 6 metres from the bed of the estuary. To calculate bedload transport using Equation 3-7, the velocity at 100 cm from the bed needs to be known. The equation for the velocity of currents near the bed as a function of distance from the bed is given by (Soulsby 1983):

\[
\bar{u}(z) = \frac{u_* \ln(z)}{\kappa} \left( \frac{z}{z_0} \right)
\]

Equation 5-2

By solving simultaneously with \( U_{100} \) and \( U_Z \) as the values for \( u(z) \) for the two equations and rearranging the equation to cancel \( u_*/\kappa \), this equation can be simplified to the form:

\[
U_{100} = U_Z \left( \frac{\ln(100) - \ln(z_0)}{\ln(z) - \ln(z_0)} \right)
\]

Equation 5-3

The value for \( z_0 \) is conventionally given by the bed’s grain diameter divided by 30 (Soulsby 1983). \( U_{100} \) values were estimated at the Railway Bridge using this technique,
with the current meter velocities at a height of 6 metres from the bed as $U_Z$ and the average grain size of the harbour used to calculate $z_0$. Note that Equation 5-2 is only valid near the bed, so using this equation on data measured 6 metres from the bed may not be valid.

### 5.2.2. Bedload Transport

Before calculating the bedload transport, the critical velocity required to move the average sediment size in the harbour needed to be calculated. As discussed in section 5.1, the average sediment size in the harbour was calculated as being 3.37 mm. $\beta$ and critical velocity data with respect to sediment sizes that were taken from experiment analysis was displayed in Table 3-1. Using a linear scaling relationship between the measured particle sizes, an estimate for the critical velocity and $\beta$ for a particle with a size of 0.337 cm could be made. This method estimated $U_{CR}$ as 17.58 cm/s and $\beta$ as $3.2 \times 10^{-5}$ g cm$^{-4}$ s$^{-2}$. Using Gadd’s sediment transport equation (Equation 3-7) estimates of bedload transport could be made. Bedload transport occurred whenever the estimates of bedload current velocity exceeded the critical velocity.

As bedload transport has a direction and magnitude, it could be split into vectors showing the transport in x and y directions. The x-direction corresponded with east to west movement, and the y vector contained sediment movement along the north-south axis.

### 5.3. Analysis of Bathymetric Data

The methods used to analyse the bathymetry data files are discussed in this section. To see the results that were developed from this analysis, please refer to chapter 6.3. A discussion of these results is then contained in section 7.3. The bathymetry data that was measured is accurate to plus or minus 0.1 metres.

The depth of the harbour has been measured by the FPA using sonar surveying over a number of years. The number of points that were measured in each survey changed over the years, with more detailed information being gathered in the later surveys. The date of each survey and the number of points measured are displayed in Table 5-2.
### Table 5-2: Bathymetry data measured by the FPA

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>January</td>
<td>19 248</td>
</tr>
<tr>
<td>1992</td>
<td>March</td>
<td>17 423</td>
</tr>
<tr>
<td>1994</td>
<td>August</td>
<td>14 899</td>
</tr>
<tr>
<td>1995</td>
<td>November</td>
<td>19 801</td>
</tr>
<tr>
<td>1996</td>
<td>November</td>
<td>64 044</td>
</tr>
<tr>
<td>1997</td>
<td>May</td>
<td>50 539</td>
</tr>
<tr>
<td>1999</td>
<td>February</td>
<td>27 283</td>
</tr>
<tr>
<td>1999</td>
<td>November</td>
<td>90 778</td>
</tr>
<tr>
<td>2000</td>
<td>June</td>
<td>48 494</td>
</tr>
<tr>
<td>2001</td>
<td>May</td>
<td>52 816</td>
</tr>
<tr>
<td>2002</td>
<td>April</td>
<td>76 893</td>
</tr>
</tbody>
</table>

Two of the data sets could not be used to contrast siltation in the Inner Harbour. The 1989 data was measured in the lead up to the dredging works later that year, which deepened the majority of the harbour to 14 meters. The 2002 data could not be used because the harbour was bar swept prior to the survey. Bar sweeping involves dragging a heavy bar behind a boat to level out built up erosion. An area that should be ignored when viewing the results of the plots of the bathymetry data is where berths 1 and 2 are located on the North Mole (see Figure 2.2). The berths were extended into the harbour so that the area is actually filled in. The area can clearly be seen in Figure 2.4 as the bright red triangular section of depth around 9 metres.

#### 5.3.1. Use of SURFER

The computer software package SURFER was used to handle the bathymetry data. The package uses the measured depths to interpolate the depths of the harbour across a defined grid. For the interpolation, the method triangulation with linear interpolation was used. This method was chosen for this application because the degree of accuracy that would be achieved by using other methods was not worth the extra computational time. The grid that was created to cover the Inner Harbour had a grid spacing of 10 meters and extended from easting 380500 to 382200 and northing 6452600 to 6454400.
This represents an area of 3.06 square kilometres. The same grid dimensions and interpolation method were used for each year’s bathymetry data, regardless of the number of points that were measured each year.

**Volume Function**

The SURFER function VOLUME was used to calculate the net siltation or erosion between successive years for the entire Inner Harbour. The function acts by subtracting the depths of the harbour in the grid files from a set depth. In this case a depth of 20 meters was used, because the entire harbour is shallower than 20 metres. The volume of material above 20 metres depth was calculated for each year’s data, so that a comparison of the volume of silt in the Inner Harbour each year could be made.

**Residual Function**

To extract the depths that were interpolated across the grids (formed using the grid function), the ‘residual’ function in SURFER was utilised. To begin with, the easting and northing locations of each point in the grid were listed in EXCEL. A value of zero was assigned as the depth of these locations. By importing this list into surfer, the difference between the depth from the interpolated grid and the depth of zero from the EXCEL list is calculated by running the ‘residual’ function.

By using the standard 10-metre grid spacing and set limits, the residual function was used to extract the depth of the harbour at the points that were required for each bathymetry survey. The residuals and their associated locations were all imported into EXCEL. The EXCEL function ‘linest’ was then utilised to produce an equation for a line of best fit for each data point running through the depths for each survey year. The slope of the line was then used as the rate of change in siltation at each point.

The equation for the line of best fit of the form:

\[ z(t) = z(t_0) + (t_0 - t) \times r \]

*Equation 5-4: Linear regression*

(where \( z \) is the predicted depth at time \( t \), \( r \) is the rate of change of depth and \( t_0 \) is the time that the first survey took place) was used so that future depths of the harbour could
be predicted based on the assumption that the depth is changing linearly with time. The ‘linest’ function calculates r and uses the initial time (April 1992) as to.

The slope of the linear trend in change of depth was used in the results when plotting the rate of change of depth. This rate of change of depth with time will be different than the rate of change of depth that would be calculated by subtracting the 1992 depths of the harbour from the 2001 harbour depths and then dividing by the time between these two surveys, and would give a better long term value for the long-term rate of change of depth.

Future predictions that were made using the model required the assumption that the changes in depth of the harbour were relatively small so that water movements within the harbour were not affected. This assumption was required, because if the harbour depth changes rapidly flow rates and flow paths can be altered. Large depth changes would alter where deposition and erosion would take place, so that the approach of basing future depth changes on what happened in the past by a linear regression would not be valid. An exact figure cannot be put on what rate of change of depth would significantly affect the flow paths through the harbour, because it will be dependant on depth, with deeper sections of the harbour able to accommodate larger rates of the change than shallower sections without impacting on flow. The fact that changes in depth will affect the flow patterns in the Inner Harbour limits the predictive capabilities of the model to shorter timeframes.

5.4. ADCP Data

An Acoustic Doppler Current Profiler (ADCP) was used to survey the Inner Harbour from the 7th to the 9th of February in 2001. The profiler measures current velocities and directions at a series of set depths as it makes transects of the harbour. The first depth the profile was taken at was 3.5 metres below the surface, followed by 4.4 metres below sea level and then measurements were taken at 1-metre intervals to a depth of 14.4 metres. In some locations, the harbour is less than 14.4 metres deep. At these locations, measurements were only recorded at depths above the surface of the harbour.
The profile was recorded over a three day period between the 7th and 9th of February 2001. The survey began at 11:49 on the morning of the 7th of February and finished at 8:13 am on the 9th. However a few hours break were taken at the early hours of both mornings of the survey. The profiling coincided with spring tides in the Inner Harbour, so that the maximum current velocities would be picked up.

While surveying, transects were made along the length of the harbour. These transects were traced many times during the survey of the harbour. The transect paths are shown in Figure 5.3. To complete one round of these transects took about an hour and a half.

The time of the low and high tides and their predicted strengths within the harbour during the survey are listed in Table 5-3, with the measured tidal heights being shown in Figure 5.4. The purpose of analysing the ADCP data was to show the flow path of water through the harbour on the ebb and flood tides. These will be strongest in the middle of the ebb or flood part of the tidal cycle. Therefore ADCP transects were extracted from the data that were taken in the midpoint of either ebb or flood tides. Unfortunately, the
break that was taken by the surveyors each morning correlated with the middle of the ebb tides. This meant that the transects that actually were measured closest to the middle of the ebb tide were taken instead.

Table 5-3: Tidal behaviour during the ADCP survey (Dept of Defence 2001)

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/2/2001 5:41 AM</td>
<td>Low tide (0.3 metres)</td>
</tr>
<tr>
<td>7/2 9:07 PM</td>
<td>High Tide (1.1 metres)</td>
</tr>
<tr>
<td>8/2 6:15 AM</td>
<td>Low Tide (0.3 metres)</td>
</tr>
<tr>
<td>8/2 9:55 PM</td>
<td>High Tide (1.1 metres)</td>
</tr>
<tr>
<td>9/2 6:45 AM</td>
<td>Low Tide (0.3 metres)</td>
</tr>
</tbody>
</table>

The time of the transects that were extracted are listed in Table 5-4. As can be seen the times during the flood tides are in the middle of the tidal cycle, but the ebb transects are not as close to the middle, so may have measured the tide turning between the flood and the ebb. The times taken to complete the transects are also shown in Table 5-4 as being between one and a half to two hours. The assumption made when analysing the results is that all measurements were actually taken at the same time, so that results are showing the instantaneous flow of water through the harbour. This assumption is made on the basis that the currents did not change in strength or direction while the transect was being made.

Table 5-4: Time of measurement of extracted transects

<table>
<thead>
<tr>
<th>Time of transect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect A</td>
</tr>
<tr>
<td>7/2/2001 12:30 to 2:32 PM</td>
</tr>
</tbody>
</table>
The current velocities measured in each transect were plotted, and also used to analyse the shear within the harbour. To calculate shear stress, the quadratic friction law shown in Equation 3-5 was used. The gradient of shear stress with distance along the length of the harbour was calculated from the values produced by Equation 3-5 and plotted. To calculate the gradient along the length of the harbour the reference x-y axis shown in Figure 2.2 was rotated clockwise by 40 degrees so that the new y-axis ran parallel to the harbour’s length.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Date</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect B</td>
<td>8/2</td>
<td>1:34 to 2:56 AM</td>
</tr>
<tr>
<td>Transect C</td>
<td>8/2</td>
<td>2 to 3:26 PM</td>
</tr>
<tr>
<td>Transect D</td>
<td>9/2</td>
<td>1:57 to 3:45 AM</td>
</tr>
</tbody>
</table>
6. Results

The methods that were used in the analysis of the data that was provided by the FPA were discussed in chapter 5. The following chapter displays the results produced by the data analysis before chapter 7 discusses the importance of these results.

6.1. Sediment Sampling

The figures displayed below are from the sediment sampling of the Inner Harbour in July 1988. The particle size distributions from most of the sampling locations that were shown in Figure 5.1 are plotted in Figure 6.1. The $d_{50}$ particle sizes of all of the July 1988 sampling locations that were within the Inner Harbour were selected and plotted as a contour map in Figure 6.2. This second figure is coloured so that large $d_{50}$ particle sizes are coloured light blue, and the smallest particle sizes are coloured dark blue and grey.

![July 1988 d50 Particle Sizes](image)

*Figure 6.1: Particle size distributions of sampling from July 1988*
6.2. **Railway Bridge Current Measurements**

Chapter 5.2 discussed the methods that were used to analyse the data measured at the Railway Bridge. A discussion of the results that are shown below appears in chapter 7.2.

6.2.1. **Current Velocities**

The following plots show the results from analysis of the data from the Railway Bridge in terms of current directions and average current speeds. Only data from 2002 and 2003 are shown, although the 2001 data set showed similar behaviour.

The histogram shown in Figure 6.3 indicates the dominant flow direction of currents in the harbour during 2002. These dominant flow directions illustrate the direction of the ebb and the flood tides at the Railway Bridge. Note that the ebb tide is moving water to the west and the flood tide is moving water to the east. Figure 6.4 follows by showing the average current speeds at the Railway Bridge in each direction. The average current speeds are shown in units of centimetres per second. The data from 2003 was analysed in the same way, to produce Figure 6.5 and Figure 6.6.
Figure 6.3: Histogram of current directions measured in 2002 from Railway Bridge

Figure 6.4: Average current velocities in 2002 measured at Railway Bridge
Figure 6.5: Histogram of current directions in 2003 at Railway Bridge

Figure 6.6: Average current velocities measured in 2003 at Railway Bridge
6.2.2. Bedload Transport

Rather than calculating the bedload transport over the whole year’s data set, 30-day periods were taken from different times during the 2001 and 2002 surveys, while the entire 90-day sample from the 2003 data set was analysed. In 2001, the analysed time period was between the 300th and 330th day of the year. 2002 focussed between 100 and 130 and the first 90 days of 2003 were analysed.

Shown below are three diagrams produced from each year’s current measurements. The first plot in each series shows the currents that were estimated at one metre above the harbour bed using the current meter data and Equation 5-2. Plots of the bedload transport in the x-direction follow these over either a 30 or 90-day time period. In the plots, positive bedload transport \( q_x \) indicates sediment moving in an easterly direction (upstream) and a negative bedload transport indicates that the sediment is moving westerly (downstream). The final plot in each of the series shows the cumulative bedload transport in the x-direction.

Figure 6.7: Current velocities estimated at 1 metre above the bed at Railway Bridge during 2001
Figure 6.8: Bedload transport in the x-direction based on estimated bed velocities at Railway Bridge

Figure 6.9: Cumulative bedload transport in the x direction during 2001 at Railway Bridge
Figure 6.10: Current velocities estimated one metre above the bed at Railway Bridge during 2002

Figure 6.11: Bedload transport in the x-direction during 2002 based on estimated bed velocities at Railway Bridge
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Figure 6.12: Cumulative bedload transport in the x direction during 2002 at Railway Bridge

Figure 6.13: Current velocities estimated one metre above the bed at Railway Bridge during 2003
Figure 6.14: Bedload transport in the x-direction during 2003 based on estimated bed velocities at Railway Bridge

Figure 6.15: Cumulative bedload transport in the x direction during 2003 at Railway Bridge
6.3. **Bathymetry Data**

6.3.1. Change in Siltation

From the sets of bathymetry data, the change in the volume of silt accumulated in the Inner Harbour can be calculated. As discussed in section 5.3.1, the ‘volume’ function in SURFER can calculate the volume of material above a certain horizontal plane. For calculating the rate of change of siltation in the Inner Harbour, the volume of solids above 20 metres was chosen because the Inner Harbour does not get deeper than 18 metres in any year. In this analysis the data measured in 2002 was included despite the bar sweeping of the harbour, because no material was removed during the sweeping so that the accumulation of silt would be the same.

<table>
<thead>
<tr>
<th>Survey Time</th>
<th>Volume of Sediment (m$^3$)</th>
<th>Change in Volume Between Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar-92</td>
<td>5468925</td>
<td></td>
</tr>
<tr>
<td>Aug-94</td>
<td>9923993</td>
<td>4455067</td>
</tr>
<tr>
<td>Nov-95</td>
<td>5857162</td>
<td>-4066831</td>
</tr>
<tr>
<td>Nov-96</td>
<td>6105404</td>
<td>248243</td>
</tr>
<tr>
<td>May-97</td>
<td>6586234</td>
<td>480830</td>
</tr>
<tr>
<td>Feb-99</td>
<td>6348906</td>
<td>-237329</td>
</tr>
<tr>
<td>Nov-99</td>
<td>6352954</td>
<td>4049</td>
</tr>
<tr>
<td>Jun-00</td>
<td>6227866</td>
<td>-125089</td>
</tr>
<tr>
<td>May-01</td>
<td>6952640</td>
<td>724775</td>
</tr>
<tr>
<td>Apr-02</td>
<td>6498788</td>
<td>-453852</td>
</tr>
</tbody>
</table>

An alternative approach to taking away the bathymetric surface from a set plane (such as the 20 metre plan) is to take away two bathymetric surfaces from each other. Although this method will yield the same volume of silt, SURFER also calculates the area of the harbour that has had a decrease in depth (been silted) and the area that has had an increase in depth (been eroded). By taking away all years from the 2002 bathymetry levels, the following areas were calculated.
Table 6-2: Areas of erosion and siltation relative to 2002 depths

<table>
<thead>
<tr>
<th>Time period</th>
<th>Area of siltation (m$^2$)</th>
<th>Area of erosion (m$^2$)</th>
<th>No Change (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar-92</td>
<td>340117</td>
<td>407795</td>
<td>2312088</td>
</tr>
<tr>
<td>Aug-94</td>
<td>568551</td>
<td>266036</td>
<td>2225413</td>
</tr>
<tr>
<td>Nov-95</td>
<td>361445</td>
<td>425143</td>
<td>2273413</td>
</tr>
<tr>
<td>Nov-96</td>
<td>359949</td>
<td>455964</td>
<td>2244088</td>
</tr>
<tr>
<td>May-97</td>
<td>325531</td>
<td>504732</td>
<td>2229738</td>
</tr>
<tr>
<td>Feb-99</td>
<td>238698</td>
<td>586602</td>
<td>2234700</td>
</tr>
<tr>
<td>Nov-99</td>
<td>174329</td>
<td>652871</td>
<td>2232800</td>
</tr>
<tr>
<td>Jun-00</td>
<td>267640</td>
<td>560672</td>
<td>2231688</td>
</tr>
<tr>
<td>May-01</td>
<td>488544</td>
<td>362931</td>
<td>2208525</td>
</tr>
</tbody>
</table>

6.3.2. Predictive Model Results

From the predictive model that was produced by the methods discussed in section 5.3, the depth of the harbour in future years could be predicted. The model was based on the assumption that the changes in depth would not impact the flow regimes in the Inner Harbour so that the linear trend in depth changes can be used to predict future depths. The following plots show how the bathymetry of the harbour is predicted to evolve. The first plot, Figure 6.16 shows the actual depth of the harbour in 2001, and is followed by plots of the difference in the depth of the harbour between these actual 2001 depths and the depths predicted in future years. The three plots following Figure 6.16 use the same colour and spatial scales. Note that siltation (decreases in harbour depth) is shown by the positive values coloured from green to red and the values of erosion (increases to the depth of the harbour) are negative with colours ranging from blue to black.
The 2001 actual harbour depths, as shown in Figure 6.16, indicates the extent of the dredging works from 1989. The majority of the Inner Harbour was dredged to 14 metres, shown by the blue areas of the harbour. However, the green area in the east of the Inner Harbour was not dredged and has a depth of mostly 10 metres. The shallower section closer to the Small craft pens becomes as shallow as 4 metres. A channel has been eroded through the easterly part of the harbour, as indicated by the line of 13 metres depth cutting through the shallower section.

Figure 6.16: Actual depth of the Inner Harbour in 2001
Figure 6.17: The change in depth between the actual 2001 bathymetry and the predicted 2002 depths.

Figure 6.18: The change in depth between the actual 2001 bathymetry and the predicted 2006 depths.
From Figure 6.17 to Figure 6.19, the evolution of the future Inner Harbour depths can be seen. The main areas where erosion is predicted are the channel that cuts diagonally across the harbour, the area in front of berths 3, 4 and 5, berth 9 on the North Quay and other patches in the north east of the harbour. The major siltation areas are in front of berth 7, adjacent to the small craft pens and along Victoria Quay.

Plotting the projected change of depth over this period is useful in visualising where the siltation and erosion take place. By extending this projection out to 2100, a better view of the relative rates of siltation can be viewed. The actual values in this projection are implausible, as areas of the harbour end up rising above the water level. Instead of being used as an actual prediction the plot can be used to show the relative erosion and siltation rates. This plot is shown in Figure 6.20. The important feature of this map is the rapid siltation that is predicted in front of the small craft pens area in the northeast of the harbour. With an increase in depth of around 100 metres in just over 100 years, this represents a rapid rate of siltation. The other areas of siltation are again in front of berth 7 and along the north-eastern side of Victoria Quay. The colour scale for this map
shows increasing harbour depth as negative numbers, coloured from blue, through purple, to black and decreasing depth from green to pink. For the most part, the intervals on the scale are 5 metres, however, the increments of changes in depth that are less than 5 metres are smaller, so that if the harbour depth changes by less than a meter it is not coloured.

Figure 6.20: Difference in depth between actual bathymetry data from 1992 and predicted harbour depth in 2100

Another way of showing the relative depth changes is by calculating the rate of change if depth. From the linear regression that was the basis of the predictive model, the rate of change of siltation could be calculated as the slope of the line. A plot of this in relation to the harbour is shown in Figure 6.21. Like Figure 6.20, this map highlights the same areas of siltation and erosion. The colours ranging from green to red indicate that the area has had net siltation over the range of surveys while blue to black represent different rates of erosion. Note the rates of erosion and siltation are relatively slow
across most of the harbour. In most areas of siltation, the harbour’s depth is decreasing by around 0.1 metres per year. Similar erosion rates are occurring across most of the areas with a trend of increasing depth. Adjacent to the small craft pens however, the depth of the harbour is decreasing rapidly, at a rate of just below 1 metre per year.

The reliability of the predictive model can be shown by plotting the variance between the predicted harbour depths and the measured depths. This method required predicting depths of the harbour for the same time as the data was recorded. With \( n \) being the number of surveys and \( D \) the depth of the harbour, the formula used to calculate this standard deviation is (from Johnson et al. 1996):

\[
S_D = \sqrt{\frac{\sum_{i=1}^{n} (D_{\text{predicted}} - D_{\text{Measured}})^2}{n - 1}}
\]

\textit{Equation 6-1: Standard deviation of predictive model}
The calculated standard deviations are plotted in Figure 6.22. The deviation of the model from the measured values is coloured from green to blue, with green indicating a low level of deviation and blue a large amount of deviation. The peak deviation is found around the small craft pen area.

Another method of ascertaining whether the linear regression models the measured data closely is by calculating the confidence intervals for the data. The 95% confidence intervals are mapped for the 2001 predictions in Figure 6.23, after being calculated using the t-distribution method (Johnson et al. 1996). These were calculated using the formula:

\[ I = \pm t_{n/2} \times S \times \sqrt{\frac{1}{n} + \frac{(x - \bar{x})^2}{S_{xx}}} \]

where \( t_{n/2} \) is the value from the t-distribution for the 95% confidence level and seven degrees of freedom.

S is the standard error

n is the number of depth measurements

x is the length of time between the predictions (May 2001) and the first survey

\( \bar{x} \) is the average time of the measurements
$S_{xx}$ is the standard deviations of the x variables.

The largest confidence intervals are around the area near the small craft pens, where there is a 95% confidence level the depth of the harbour is about plus or minus around 1 metre from the predicted depth.

![Figure 6.23: Confidence intervals of predicting the depth of the harbour in 2001](image)

### 6.4. ADCP Data

#### 6.4.1. Current Velocities

From the four series of transects that were listed in Table 5-4, the following four plots of current velocities were produced. The vectors in each plot have the same scale, with the largest current velocities being shown by the red larger vectors and the weaker currents shown by the blue smaller vectors. All current velocities are measured in metres per second. The vector plots were produced using a similar method to the plots of bathymetry, with linear interpolation used within SURFER to create a grid file that could be plotted across the Inner Harbour. As shown in Figure 5.3, the series of transects covered the harbour in six individual transects, so that a fairly dense number of measurements were used to interpolate across the area shown in the figures below. As
can be seen by the direction of the vectors, transects A and C were taken during the flood tide and transects B and D during the ebb tide.

Figure 6.24: Current vectors from transects A

Figure 6.25: Current vectors in the Inner Harbour from transects B
Figure 6.26: Current vectors in the Inner Harbour from transects C

Figure 6.27: Current vectors in the Inner Harbour from transects D
6.4.2. Shear Stress Gradients

Section 5.4 discussed the methods used to calculate the gradient in shear stress through the harbour. The colour scale in the four diagrams below show yellow through to purple areas having a positive gradient of shear stress, and green to blue having a negative gradient in shear stress. As previously mentioned in section 5.4, areas with a negative shear stress gradient indicate where the harbour bed could be eroding, while a positive shear stress gradient indicates areas where possible siltation could be occurring. The calculations performed to produce these plots involved the same transect data from the current velocity plots shown above. The shear stress gradients are all displayed in units of Newton’s per square metre.

Figure 6.28: Shear stress gradient in the length-wise direction of the Inner Harbour for transects A
Figure 6.29: Shear stress gradient in the length-wise direction of the Inner Harbour for transects B

Figure 6.30: Shear stress gradient in the length-wise direction of the Inner Harbour for transects C
Figure 6.31: Shear stress gradient in the length-wise direction of the Inner Harbour for transects D
7. Discussion

This chapter contains a discussion of the results that were displayed in chapter 6. These results were based on the methodology outlined during chapter 5 and the knowledge developed during chapters 2 and 3. The discussion will involve interpreting the information from the displayed diagrams and plots to achieve the three aims for this project, as discussed in chapter 1.

7.1. Sediment Samples

The results from analysing the sediment samples of the Inner Harbour taken in July 1988 were shown in Figure 6.1 and Figure 6.2. The sampling locations were shown in Figure 5.1 so that in the plot of particle size distributions (Figure 6.1), samples B, R and S were all taken outside the Inner Harbour; in the entrance channel and Rous Head, while sites E, A and G were taken closest to Railway Bridge. From the graph, it is impossible to find any relationship between the sediment in the harbour and sediment from the ocean. For instance, the sample taken at J has a very large proportion of large sediment, while neighbouring K has a very small proportion of large particle sizes. Both J and K are close to the centre of the harbour. Sites A, E and G are also extremely close together, and their particle size distributions are vastly different.

Figure 6.2 is a contour plot of the d50 particle sizes of all of the samples taken within the Inner Harbour in July 1988. Although there appears to be a relationship of increasing particle size with distance from the ocean, no confident conclusions should be drawn from the figure. This is because there were a low number of sampling points taken, so that one sample with a large value has a large effect on the interpolated sediment sizes that were shown. This can be seen in the figure, with a sample point near the small craft pens having a large d50 particle size so that it appears that there is a strong relationship between sediment size and distance from the ocean.

Therefore, from the analysis of the sediment sampling data from July 1988, no conclusions about the sources of silt can be made. This is because along the length of the Swan River, there are a series of basins that trap sediment being carried downstream.
An Analysis of Fremantle Inner Harbour Siltation Patterns

(Pattiaratchi 1996). These basins are wide and deep, so the current velocities of the river through them are typically very slow, allowing sediment to be deposited. The locations of these basins can be seen in Figure 7.1, with basins including Perth Water and the wide section of the river opposite Pelican Point. By comparing the width and depth of these basins to the Inner Harbour, it can be predicted that the current velocities within these basins will be much slower than the current velocities in the harbour (Pattiaratchi 1996). This means that if any sediment is so small that it passes through the basins without being deposited, it will also be too small to be deposited in the harbour.

![Figure 7.1: Swan River bathymetry (Stevens et al. 1997)](image)

The basin closest to the harbour is at Blackwall Reach, seen as the deepest section approximately 10 kilometres upstream from the harbour entrance. This basin acts as a trap in the opposite direction, trapping oceanic sediment being carried upstream with the flood tide (Pattiaratchi 1996). Any sediment that is carried into the harbour from
upstream and that is deposited in the harbour will therefore have been picked up between Blackwall Reach and the Railway Bridge. This sediment will have the same characteristics as sediment in the ocean. Therefore regardless of the direction of bedload transport, the sediment will have characteristics of oceanic sediment. For this reason, it would be expected that this analysis of sediment samples would not be able to determine the source of the silt in the harbour. Sediment samples from much further upstream would be required so that a comparison between riverine sediment and oceanic sediment could be made.

7.2. Current Data

Because the sediment sampling of the harbour could not conclusively determine the source of silt in the Inner Harbour, the data measured by the current meter at Railway Bridge was used to try and achieve this objective.

7.2.1. Current Velocities

From the analysis of the Railway Bridge data, the direction of the flood and ebb currents in 2002 and 2003 have been found. These were shown in Figure 6.3 and Figure 6.5 as the directions that occur with the highest frequency. Comparisons between the two figures show that the dominant ebb and flood tide directions are constant between the two data sets. It can be seen from these two plots that the ebb and the flood tides do not flow in opposite directions. Taking compass bearings clockwise with north as 0 degrees, the flood tide flows on a bearing of 120° and the ebb at 290°. The kink in the ebb and flood tide illustrates the bend of the Swan River past the Railway Bridge.

Taking these directions, the average current speeds of the ebb and flood tide in 2002 and 2003 can be found by looking at Figure 6.4 and Figure 6.6. In both years, the ebb tides had much stronger average currents than the flood tides, with an average of 40 cm/s in both years on the ebb, and averages of 35 and 30 cm/s on the flood in 2002 and 2003 respectively. However, this asymmetry would be expected because of the nature of ebb and flood tidal flows through estuaries as discussed in section 4.3. The current meter was situated 3 metres from the surface of the river, and about 6 metres from the harbour bed. This would position the current meter in the section of the water column that has stronger ebb tidal currents than flood.
7.2.2. Bedload Transport

Bedload transport was modelled to occur whenever the currents estimated near the bed exceeded the critical velocity required to move the average grain size in the harbour. The current speeds that were estimated one metre from the bed are shown in Figure 6.7, Figure 6.10 and Figure 6.13 for 2001, 2002 and 2003 respectively. Whenever these currents exceeded 17 cm/s, bedload transport was calculated so that Figure 6.8, Figure 6.11 and Figure 6.14 were produced.

The plots do not show bedload over the entire year, only 30-day sections during 2001 and 2002 and a 90-day period in 2003. The 2001 and 2003 plots of bedload transport show that the dominant direction of sediment movement is downstream in a westerly direction. The 2002 data shows the opposite behaviour, however the plot is dominated by a singular large current in the easterly direction.

Another way of viewing the bedload transport is by looking at the cumulative or net sediment transport shown in Figure 6.9, Figure 6.12 and Figure 6.15. From the plot, the magnitude of each tidal event that caused sediment to move can be seen. The end total bedload transport in 2002 was only at 1000 g/cm. This was in the upstream direction, but a much lower value than the 2001 and 2003 cumulative sediment transport rates. Both the 2001 and 2003 plots indicate net sediment transport occurred in the downstream direction. In all cases, there were only a few major events that caused the sediment to move.

The 2001 and 2003 results are contrary to those typically found in tidal estuaries. As discussed in section 4.3, flood currents are typically stronger at the estuary bed than the ebb currents, and therefore would typically move a greater amount of sediment. The reason for the contradiction is that the current meter measured the flood and ebb tides at a height of 6 metres above the harbour bed. These measurements were near the water surface in a section that has stronger ebb currents than flood currents. The mathematical formula that was used to estimate the bed velocity (Equation 5-2) does not take this into account. Therefore the ebb current velocity estimated near the bed will be overestimated and the flood current will be underestimated. This means that no confident statement
can be made about the direction of sediment movement at the Railway Bridge based on the current meter measurements. The dominant direction of sediment movement could therefore be upstream, carrying oceanic sediment on the flood tide.

Both methods used to determine the source of silt proved inconclusive. The bathymetry of the Swan River means that all of the sediment entering the Inner Harbour had oceanic sediment characteristics, regardless of direction of sediment movement. Because of this the sediment origin could not be determined by comparing Inner Harbour sediment characteristics to oceanic sediment characteristics. The analysis of the data recorded by the Railway Bridge current meter was also inconclusive because the meter was situated too far from the bottom for reliable estimates of bed velocity to be made. Therefore, the first objective of this project, to determine the sources of silt in the harbour, could not be met with the data that was provided. The sediment traps along the length of the Swan River mean that the accumulated sediment will have originated from the ocean.

7.3. Bathymetry Data

The methodology that was used to analyse the bathymetry data was discussed previously in chapter 5.3, with the results shown in chapter 6.3. In the section below, these results are interpreted and discussed.

7.3.1. Change in Siltation

The change in siltation of the entire harbour was illustrated in Table 6-1, as calculated by the change in volume of material above 20 metres. The table showed siltation as the change in volume between successive bathymetric surveys. The net change in the volume of siltation in the Inner Harbour between March 1992 and April 2002 was an increase of 1,029,863 m$^3$. With a harbour area of 83,167 m$^2$, this relates to an average reduction in depth of about 0.123 m/year. It should be noted that the average harbour depth does not decrease every year, with four surveys showing the depth of the harbour to have increased since the previous bathymetric survey.

Table 6-2 showed the relative cross-sectional areas of the parts of the harbour that are being silted and eroded. These were taken with respect to the 2002 surveyed depths rather than successive years. The table shows that the size of the areas eroding and
silting change considerably, even between successive years. In most of the years, the areas of erosion are actually larger than the siltation areas. This means that although the average decrease in depth of the harbour was estimated at about 0.1 metres per year, it is actually much larger in the areas that are actually being silted. Therefore, although across much of the harbour siltation will not be a major issue, there are areas that are silting fairly rapidly.

7.3.2. Predictive Model Results

The predictive model was based on the assumption that the depth of the harbour was changing linearly with time. The results of the model were firstly shown by plotting the change in depth between the measured 2001 values and forecasted future depths. Figure 6.17 is the first of these, showing the predicted change in depth between 2001 and 2002. A contour map of the harbour depth in 2001 is shown in Figure 6.16, so that the predicted depth of the harbour in 2002 can be visualised by adding the depth changes to these actual depths. From Figure 6.17, it can be seen that the change in depth of the harbour over the period of a year is fairly small in most places, having changed by up to just over 0.1 metres in most locations. Because the levels in the colour scale are quite large, it is hard to ascertain an accurate rate of siltation from the changes over one year. There is still a fairly extensive area that has been predicted to have a change in depth of less than 0.1 metres.

By 2006, the model shows that the areas of siltation and erosion have grown, as shown in Figure 6.18. Most of the areas in the harbour that are being silted have only had a decrease in depth of around 0.5 metres since 2001. However an area close to the small craft pens has become about 6 metres shallower. The erosion is confined to the centre of the harbour and along North Quay. Within much of these areas of erosion, the harbour has become between 0.1 and 0.5 metres deeper. Small sections of the harbour are eroding faster however, with a section on the North Quay that is adjacent to the extension of berths 3 and 4, and a patch in the middle of the harbour becoming up to 0.8 metres deeper over the 5 years.
The next time period for depth changes is illustrated in Figure 6.19, where the change in depth predicted between 2001 and 2010 is shown. The trends seen from Figure 6.18 continue, but now that the change in depth is plotted over a longer period, more accurate estimates of the annual average change in depth can be made. Again, the area adjacent to the small craft pens has the most rapid siltation rate, with the area becoming about 9 metres shallower over the 9 years. This rate of siltation, about a metre per year, is very rapid, so will be a problem for the FPA in the future. The change in depth ranges from between 1.5 to 0.1 metres for the rest of the areas that are being silted. The rate of erosion is similar to the rate of siltation for much of the harbour, with the depth of the harbour increasing by 3 metres at the location with maximal rate of erosion.

The predictive model will not be very accurate over this 9 year time period in some areas of the harbour. For instance, the harbour was only 4 metres deep around the small craft pens in 2001, where the depth of the harbour is predicted to decrease by around 9 metres by 2010. As the depth continues to decrease in this area, an equilibrium may be met because the currents can become quicker as the water becomes shallower. This could create erosive conditions that control the build up of sediment. The sediment would then be distributed to other parts of the harbour. Alternatively, as the depth decreases further, water flowing past this area may follow the path of least resistance so that the currents are reduced in the area, allowing deposition to continue. Once a shallow sand bar forms, it will grow in area as deposition continues.

From Figure 6.19, it can be seen that the areas of erosion appear to be forming a channel that runs diagonally through the harbour. This channel is shown more clearly when the model is used to make a long-term prediction of the depth of the Inner Harbour. A long-range depth prediction of the Inner Harbour is shown in Figure 6.20, where the changes in depth between what was measured in 1992 and the depth of the harbour predicted in 2100 is shown. Note that this is not what the author is proposing the change in the harbour depth will be in 100 years time, rather the long range prediction is being shown to better illustrate the trends in siltation and erosion in the harbour. Around the small craft pens, the depth has changed by just less than 100 meters in the 100 years, so the rate of change is about a metre per year. The erosion in the harbour centre has caused
deepening of around 20 metres over the 100 years, so at a rate of around 0.2 metres per year. For the most part, the rest of the harbour that is silting has decreased in depth by around 5 metres. Therefore, the siltation rate through much of the harbour is 0.05 metres per year.

A superior method of visually showing the rate of change of the depth throughout the Inner Harbour is to plot the value of the slope of the linear regression used as the basis for the predictive model. This data was plotted in Figure 6.21. It should be noted that this method calculates different rates of change to the method used when analysing the changes in volume of sediment above 20 metres, as discussed in section 7.3.1. This initial method calculated the change in volume of the harbour between 1992 and 2002 and divided through by the area of the harbour to estimate the rate of change of depth as increasing by around 0.1 metres per year. Problems with this method were that it did not calculate siltation rates for specific locations and the result was dependent on only two surveys, from 2002 and 1992. By using the slope of the linear regression, the rate of change calculation for the harbour reflects long-term changes over the 9 surveys, without being as sensitive to the initial and final survey measurements.

Figure 6.21 is repeated in Figure 7.2 below, but with the major areas of siltation and erosion that were identified circled. Along Victoria Quay are three of the major patches of siltation. The other major patch of siltation is in front of berth 7 of North Quay. Along with the rapid siltation adjacent to the small craft pens, this area represents the most concern to the FPA. This is because the North Quay is used for the large container vessels that require the largest clearance from the bottom.

From this plot of the rate of change of depth, a more accurate estimate of the rate of change of depth can be made than from forecasting the future depth of the harbour. Three of the siltation patches circled in Figure 7.2 are causing the harbour to decrease in depth by only around 0.1 metres per year. The other patch of siltation near the small craft pens has a siltation rate of about 1 metre per year. The erosion is most rapid in the area next to the extended berth 3 and 4 with a deepening rate of 0.4 metres per year. In the other three areas that are circled, the rate of erosion is less than 0.2 metres per year.
Under the assumption that the areas of erosion are where the strongest currents are flowing, the dominant flow path of water through the Inner Harbour can be seen from the predictive model. Much of the erosion is connected to form a channel that runs through the harbour. This flow path is laid over the rate of change of depth from the predictive model in Figure 7.3. Taking the ebb tide as an example, water enters the harbour under the Railway Bridge and flows in an arc past A and around towards C. On the inside of this arc is the area with the most rapid siltation in front of the small craft pens. This rapid siltation can be accounted for by the fact that the river is constricted under the Railway Bridge. The river is also shallow under the Railway Bridge so that the currents are strong in this region. On entering the Inner Harbour, the river becomes wider and deeper over a short distance. At the Railway Bridge, the river is only about 150 metres wide, but by the time it flows around to B, the harbour has increased its width to over 400 metres. The depth of the harbour nearly doubles between the Railway Bridge and C. This means that sediment being carried downstream will be deposited as these currents are slowing down.
From C the water moves in another arc to D, before moving diagonally across the harbour and bending again to flow between North and South Mole near F. Again on the inside of the bend past D there is another patch of siltation. This patch lies in the first section of deep water in the Inner Harbour, as the dredging works from 1989 extended to the red line across the harbour adjacent to C. The relationship between areas that are being silted and the depth of the Inner Harbour can be seen more clearly by examining Figure 7.4, which shows the rate of change of depth of the harbour above a surface map of the harbour depths in 2001.

The Inner Harbour is a tidal system, so the water also moves in the opposite direction on the flood tide. As the water enters the harbour through the moles at F, it needs to move in a bend to align itself with the harbour. It continues by moving diagonally across the harbour to D, before moving in another bend to align itself so that it can move upstream under the Railway Bridge. It can be seen that the layout of the harbour is causing this flow behaviour, with the harbour itself being an engineered straight channel with sharp bends on either side so that on both the ebb and flood tide, the water must follow an arc through the harbour.
In section 7.1, it was concluded that the sediment that is deposited within the Inner Harbour originated from the ocean. This may appear to be contradictory as sediment is deposited downstream from any changes to the depth or width of the harbour. However, silt is carried upstream by the flood tide and either deposited because the currents are not strong enough to lift the sediment up into the shallower sections, or it is washed through the harbour on the stronger flood tides and then carried back downstream on the weaker ebb and deposited where the harbour becomes deeper or wider.

![Figure 7.4: Rate of change of depth in the Inner Harbour above a surface map of the actual depth of the Inner Harbour in 2001](image)

The section of the flow path that moves diagonally across the harbour contains erosion rates of 0.2 metres per year. The diagonal path follows closely the path of the ancient Swan River paleochannel, so that the higher rate of erosion could be caused by loose sediment trapped in the paleochannel being easily eroded. This part of the harbour is also used to turn the ships around, so shipping movements could also cause the higher erosion rate.
The erosion and siltation patterns in the Inner Harbour are similar to what is seen in river channels that are meandering. As discussed in section 4.4, meandering channels characteristically erode the outside of river bends and silt the inside because of the relative current speeds between the outside and inside of the bend. This is similar to the situation in the Inner Harbour, where the flow path bends in an ‘S’ shape between the moles and the Railway Bridge. Siltation is occurring on the outside of the bends and erosion on the inside.

This ‘S’ shaped flow path is similar to the one discovered in the Inner Harbour in 1989 by Buchan, as shown in Figure 2.5. The flow path discovered by Buchan was made before the last major harbour dredging and was discovered by analysing current data rather than long term changes in the depth of the harbour. Despite the change in depth since 1989, the flow path still meanders through the harbour. However, an accurate comparison cannot be made between the findings of this study and Buchan’s because of the different methods used to find this flow path. By looking at the erosive patterns within the Inner Harbour, this study has located the dominant flow path through the harbour over a longer time period than Buchan.

As discussed in section 4.4, Allen (1985) gave an empirical relationship between channel width and bend length for meandering channels found in rivers. The relationship shows that the length of the river meander is typically 12 times the size of the width of the channel. Figure 7.5 shows half the wavelength of the meandering channel in the upper part of the harbour. It would be expected that if this were part of a meandering channel conforming to the empirical relationship, the length of this channel would be 6 times its width. Each arrow in the figure represents the channel width of the dominant flow path through the harbour. It can be seen that the half wavelength of this part of the channel is close to being six times the channel width. The second bend in the harbour is about the same width and length as the first, so the empirical relationship holds there as well. This validates the assertion that the flow path in the harbour is behaving like a meandering channel.
The predictive model was based on the assumption that the harbour’s depth will be changing linearly with time. To investigate the validity of this assumption, the model was used to predict the depths of the harbour for the same dates as the bathymetric surveys of the harbour were done. The deviation between these predicted depths and the measured harbour depths were calculated and plotted in Figure 6.22. The diagram shows that for nearly all of the harbour, there was very little difference between the predicted and measured depth of the harbour. The standard deviation through most of the harbour is less than 0.2.

However two locations have a much greater standard deviation. The area in the corner near berths 3 and 4 has a large standard deviation, so that any prediction of depth in this area cannot be made with any certainty. The other area with a large standard deviation lies adjacent to the small craft pens, correlating with the area with the fastest rate of change of depth. This is expected, because as the changes are larger, it is harder to fit a regression to them. The trend of rapid siltation is still going to be valid, however exact future depths of the harbour cannot be accurately predicted.
This reliability analysis only shows how the model deviates from the past measured values, which were used in the construction of the model. It does not indicate that the model will accurately predict the future depths of the harbour, rather shows that the assumption that the depth of the harbour is a linear function of time was accurate for most areas of the Inner Harbour.

Another way of describing the validity of the assumption of linear changes of depth with time is to calculate confidence intervals for the model. The 90% confidence intervals for the model’s prediction of the 2001 harbour depths are shown in Figure 6.23. The confidence intervals describe the size of the deviation from the predicted depth that the actual depth lies within with a 90% confidence level. A small confidence interval means that the linear regression is accurately predicting the depth of the harbour, while a large confidence interval indicates that the actual harbour depth could considerably different from the predicted depth. The advantage of showing the confidence interval is that it shows a value in metres for the accuracy of the model.

From the plot in Figure 6.23, fairly constant confidence intervals across most of the harbour are seen. Larger confidence intervals are seen in the areas with the largest deviation, as shown in Figure 6.22. The smaller confidence intervals that are seen through most of the harbour show that the below 0.2 metres. This means that there is a 90% confidence level that the model’s predicted depth is within 0.2 metres of the actual depth. Because the rate of change of the depth of much of the harbour is either plus or minus 0.1 metres per year, having a confidence interval of about the same scale means that the trend of either erosion or siltation is being correctly shown by the linear regression. Closer to the small craft pens, this confidence interval is fairly large, around 3.5 metres. This means that the depth of the harbour in this area cannot be as confidently predicted.

The confidence intervals are a function of the standard deviation as well as the number of data points used in the regression. Because only 9 surveys were used, the confidence intervals are quite large. The data from future surveys of the harbour can reduce the confidence intervals if they are in line with the linear regression of the predictive model.
7.4. **ADCP Survey**

7.4.1. **Current Velocities**

The analysis of the bathymetry data gave an indication of the dominant flow path through the harbour based on the changes of depth over a 10-year period. Because this analysis is based on measurements made on an annual basis, no direct inferences about the typical tidal movement of water can be made. To show whether the typical tidal movement follows the bending flow path through the harbour, the ADCP current data was analysed. Looking at both ebb and flood tide investigates whether the water follows this path in both directions.

From Figure 6.24 and Figure 6.26, the current velocities at the bed during two flood tidal periods can be seen. By looking at the strongest velocity vectors at any line across the harbour, a dominant flow path can be seen. In both cases, the strongest vectors are seen in the downstream part of the harbour. The flow path can be seen much more clearly in the plot of transects C than A, with strong currents meeting to form a path line along the entire length of the harbour. The flow path can be seen in A, but eddying in some parts of the harbour make it harder to discern the flow path from these transects.

The tidal velocities measured closest to the harbour bed in consecutive ebb tidal periods are plotted in Figure 6.25 and Figure 6.27. A dominant flow path in the harbour is hard to find from these plots because there is a lot of lateral currents. This could be because transects B and D were not taken right in the middle of the ebb tide. Because the survey was stopped overnight, no data was recorded during the period of strongest ebb tides, so data closer to the high tide was chosen. This could mean that the tide was still turning when the measurements were taken, or that the currents are not flowing as strongly as they should be. However, closer to the moles, the strongest currents can be picked out in both plots. The flow path of these currents seems to be forming a bend as the water passes through the moles and into the harbour, as predicted by the model.

If the recorded current vectors are laid over the plot of the rate of change of depth from the predictive model, it can be seen whether the strongest vectors are occurring at the
same place as the erosion. These are shown in Figure 7.6 and Figure 7.7 for transects C and B respectively.

From Figure 7.6, the erosion and strong current vectors match extremely well. The strong currents overly the areas of erosion around the moles where the water enters the harbour. From here, the flow path moves diagonally across the harbour following the erosive channel towards North Quay. The flow path then straightens before curving to move out under the Railway Bridge. Although not clearly shown, there appears to be some eddying around the patches of siltation along the Victoria Quay side of the Inner Harbour.

![Figure 7.6: Flood current vectors from transects C plotted over the rate of change of depth in the Inner Harbour](image)

The currents at the bed from transects B on the ebb tide are shown in Figure 7.7. Although the flow path in the harbour from transects B is distorted by eddying in the upper part of the harbour, towards the ocean the strongest currents appear to be in the same location as the regression shows erosion. Strong currents again move diagonally
across the harbour following the channel of erosion towards Victoria Quay. As the water moves out through the moles, the strongest currents can again be seen to move in a curve out towards the ocean. Around the upper section of the harbour, there is a lack of data points, and those that are plotted show water moving in lateral directions, indicating eddying.

On both the ebb and flood tides, the ADCP data shows that the dominant flow through the harbour follows the meandering channel discovered from analysis of the bathymetry data. The flood currents show this behaviour extremely well, while the ebb currents were not as clearly shown because of a sparsity of data points in the upper part of the harbour and because the data was measured close to the change in tidal direction.

Figure 7.7: Current vectors from the ebb tide measurements of transect B, on top of the rate of change of depth of the Inner Harbour

The difference between the meandering channel behaviour in the harbour and the behaviour commonly seen in rivers is that water moves in both directions through the harbour. In river systems, the water flows in one direction so that once the bend
has formed water continues following this sinusoidal curve to the ocean. As the harbour is a tidal system, bends on either end of the harbour need to make the water follow the same path on the ebb and flood tide. Unfortunately for the FPA, when the Inner Harbour was constructed, the moles formed a bend at the ocean end of the harbour that created a bend with a similar curvature as the natural one near the Railway Bridge. This has meant that water moving through the harbour on the ebb and flood tide follows the same flow path, confounding the siltation and erosion problems in the harbour.

The natural path of the Swan River before construction of the Fremantle Inner Harbour was shown in Figure 2.3. Note that the natural curvature of the river mouth caused deposition of sediment on the south bank of the river, with the erosion around the outside of the bend causing the northern side of the river to be deeper than the inside. By straightening this bend when the harbour was constructed, siltation problems may have been avoided because water entering the harbour on the flood tide would move in a straight line up till the Railway Bridge. A flow path as shown by the blue line in Figure 7.8 would have been expected when the harbour was designed so that relatively straight path of the water would not cause patterns of siltation. However, the construction of the North and South Moles at an angle to the harbour has caused the curvature of the motion to be increased, as shown by the red flow path in Figure 7.8. The meandering channel behaviour occurring on the flood tide has led to the deposition of material on the Victoria Quay.

### 7.4.2. Shear Stress Gradients

The gradients in shear stress calculated from the ADCP data are shown in Figure 6.27 to Figure 6.31. Again, transects A and C illustrate the behaviour on the flood current and transects B and D show the gradient in shear during ebb tides. Positive gradients in shear stress indicate areas of the harbour where siltation could occur and negative gradients in shear stress are where erosion could occur. Note that the possible siltation and erosion that is shown in the plots is based on an instantaneous
measurement of the harbour’s currents and should not be confused with long-term siltation and erosion processes.

Figure 7.8: Original conception of flow through the harbour (blue) compared to the actual flow path through the harbour (red)

Figure 6.28 shows the gradient in shear stress from transects A of the ADCP data set. The diagram shows siltation could be occurring during this time along the Victoria Quay, similar to the area shown by the analysis of bathymetry data. Erosion is shown to be widespread through the harbour, especially the central section. The second diagram based on flood tides, Figure 6.30, used the data from transects C. On this occasion, areas of possible siltation are more prevalent and extend further into the harbour. By following the erosion areas from this plot, the ‘S’ bend flow path through the harbour can vaguely be seen.

The ‘S’ bend flow path can be seen more clearly in the two plots of the gradient of shear stress on the ebb flow; Figure 6.29 and Figure 6.31. The plot of the shear stress gradients from transects B show an area of erosion running diagonally across
the harbour, through the area that has been identified as having a rapid increase in depth. The erosion also continues in an arc and out of the harbour beneath the traffic bridge. Siltation is again found along the North Quay and on the inside of the erosive bends. Figure 6.31 doesn’t show this quite as well, although the strongest negative gradients of shear form the ‘S’ shaped pattern through the harbour.

Despite the fact that the ebb tide transects did not show the dominant flow path through the harbour when their current vectors were analysed, the plots of gradient in shear described the ‘S’ shaped flow path quite well. On the other hand, the shear stress gradient of the flood currents did not clearly show the bending flow path, but the current vectors from the ADCP data of the floods clearly validated the predicted areas of erosion and siltation from the model.
8. Conclusions

The study began with three objectives that needed to be completed, as set by the FPA. These were:

1. Determine the sources of siltation in the Inner Harbour
2. Analyse which factors are the most important in causing the distribution of siltation in the Inner Harbour and
3. Develop a predictive model for future siltation in the Inner Harbour

For the first objective, by studying the bathymetry of the Swan River it was found that the sediment that is being deposited in the Inner Harbour must have originated from the ocean. However, field measurements to validate this finding did not give any conclusive evidence of the source of siltation. Sediment sampling of the Inner Harbour by consultants to the FPA did not prove whether the sediments were oceanic because of the limited number of samples taken and the sampling methods. Analysis of current measurements made at Railway Bridge also proved inconclusive. The current meter was positioned 3 metres from the waters surface, and approximately 6 metres from the bed, so that measurements were made in water depths that have stronger ebb currents than flood currents.

The third objective was achieved by analysing the bathymetry data from surveys of the Inner Harbour between 1992 and 2001. By running a linear regression through the changes in depth of the harbour over time at a number of locations, the rate of change of depth at the locations was calculated. By assuming that future changes in depth would not affect the rate of siltation and erosion in the Inner Harbour, future depths of the harbour could be predicted based on the past changes by extending the linear fit into the future.

The model can be used by the FPA to plan future dredging works. The siltation is a fairly minor issue however, with the depth of the harbour decreasing by a rate of less than 0.1 metres per year in the most part. However isolated areas within the harbour should be a concern to the FPA. The patch of siltation at berth 7 on the North Quay will
need to be monitored. The berth is used for large cargo vessels, with safe clearance from the bottom being a concern in the near future. The waters in front of the Small craft pens also are a concern to the FPA. If the current rate of siltation continues in the area, a sand bank breaching the water surface may develop within the next ten years. This will prevent tugs from accessing their housing pens.

Investigation of the second objective was based on the results found from the predictive model. A meandering channel through the harbour was found to have developed, causing the patterns of siltation and erosion that were evident in the harbour. The layout of the Inner Harbour has created the meandering channel through the harbour. Bends on either end of the harbour have caused the flow of water to move in a ‘S’ shape on both the ebb and the flood tide. Meandering channels are generally associated with rivers, where the water flows in a singular direction. Due to the layout of the harbour, the channel acts in two directions, on both the ebb and flood tides.

The curving nature of this meandering channel was also found through the analysis of the Acoustic Doppler Current Profiler survey of the Inner Harbour from 2001. Extraction of a few sets of transects from the data that correlated to strong ebb and flood tides, plots of the current vectors were used to find dominant flow paths. The ‘S’ shaped flow path was shown clearly on the flood tide, but not conclusively from analysis of the ebb tide data. The ADCP data was further analysed by calculating the gradient of shear stress on the ebb and flood tides. Plotting these gradients showed the ‘S’ shape flow path clearly on the ebb tide.

From an analysis of the changing bathymetry of the Inner Harbour over a ten-year period, the meandering channel behaviour of the dominant flow through the harbour was found. The channel was caused by the layout of the harbour, with bends on either end of the harbour causing an ‘S’ shape flow path on the ebb and flood tides. This behaviour was further shown by analysis of an instantaneous snapshot of the current velocities from the ADCP survey of the harbour in 2001.
9. Recommendations

There is little that can be done to prevent siltation occurring in the Inner Harbour, without reconstructing the harbour’s layout. Because the rate of siltation is so small, maintaining the depth through dredging, bar sweeping and sediment stirring by propellers would be the best action to be taken. However, the rate of siltation was shown to be fairly small across the majority of the harbour, especially near the North Quay, so that maintenance dredging would not be required some time. However, action to remove the sediment build up close to the small craft pens may be required in the near future, with the rapid siltation rate there capable of causing problems to tugboat movements.

Future work into the problem may be required to conclusively determine the sources of silt in the Inner Harbour. Although the sediment entering the harbour should have originated from the ocean, further sediment sampling may provide irrefutable evidence. The current meter at the Railway Bridge could also be reposition closer to bed so that reliable estimations of bedload can be made. If current data was collected at the harbour entrance and combined with further measurements at the Railway Bridge, a determination of the direction of bedload transport at both locations could be made.

Quantification of the effect of shipping activities on the siltation patterns within the Inner Harbour could be conducted. However, shipping activities would play a relatively minor role in the movement of silt when compared to the tides, because the tides applying a continuous force on the sediments, whereas visits by large ships are less regular.

Future bathymetric surveys of the harbour need to be added to the predictive model. This will keep the model up to date with any changes to the linear regression. By updating the model frequently, the forecasting range for predictions will extend further into the future and the confidence intervals will be decreased.
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