CIRCULATION IN THE BLACKWOOD RIVER ESTUARY

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ABSTRACT

The Blackwood River Estuary, including Hardy Inlet, is a permanently open, bar-built estuary on the south Western Australian coast. It has been included in the proposed Geographe Bay, Leeuwin-Naturaliste, Hardy Inlet marine conservation reserve, to be created by 2005. There is therefore a need to better understand processes in the estuary. This study examines circulation patterns in the estuary to assess the dominant factors influencing circulation, and assess any changes to the system since the mid 1970’s.

Field studies were conducted in the estuary, with an ADCP situated in the Blackwood River for a 22-day period, producing valid results from 27th April – 10th May 2001. A transect of the river on the 10th May 2001 provides temperature, salinity and dissolved oxygen data for comparison.

Results from CTD sampling indicate strong stratification throughout the estuary during the summer period, with temperatures displaying a longitudinal temperature gradient upstream. A persistent sub-surface temperature peak is shown, due to transport of warm water upstream at mid-depths. Salinity results show a sharp halocline at approximately 2 m, with little vertical flux across isohalines. These properties are similar to those observed in the estuary in 1974.

ADCP results show that the tidal action is the dominant factor in circulation during the summer phase. This is most pronounced near the bed, where the dredged channel may shelter bottom waters from other factors. There is a phase difference of approximately 70° between surface and bottom waters, resulting in a 4-hour tidal lag. The estuary appears to be in a period of flood-dominance, but this may be due to the positioning of the ADCP.

Predictions of rainfall in south Western Australia show a decrease in rainfall and discharge, indicating the estuary will reside in the summer phase for longer each year. This may prove to be important in the management of a marine reserve.
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1 INTRODUCTION

The Blackwood River estuary is a permanently open, bar-built estuary on the south Western Australian coast (figure 1.1). It has developed into a basin on a coastal plain, fed primarily by the rivers of the Blackwood and Scott. These two rivers exchange near Molloy Island (figure 1.2). Seasonally, marine influences in the Blackwood River can be detected as far as 40 km from the mouth.

The town of Augusta, Western Australia’s third oldest settlement, lies on the banks of the inlet. It was settled in 1830, and since this time the estuary has had significant value to the town. The inlet is now used predominantly for recreational pursuits, including fishing, sailing, windsurfing and other water sports.

In 1970 parts of the estuary and surrounding land were pegged for mining and dredging of heavy minerals. This prompted a thorough environmental study of the Blackwood River Estuary, including hydrographic surveys, water characteristics and dynamics and ecology of the estuarine system. The details and conclusions of this study are summarised in Hodgkin (1978). Since this time, little research has been done in the estuary.

In 1994, the Marine Parks and Reserves Selection Working Group (MPRSWG) identified the Geographe Bay, Leeuwin-Naturaliste and Hardy Inlet region as a possible marine conservation reserve. The region was identified as having high conservation values due to its wide range of habitats and distinct coastal types. As a part of this region Hardy Inlet was recognised as an important feeding ground and refuge for bird life. It was recommended that: “The estuary of the Blackwood River, including the Deadwater, Swan Lake, Hardy Inlet, Molloy Basin and the tidal parts of the Scott and Blackwood Rivers be considered for reservation as a marine reserve for dual recreation and conservation purposes…the estuarine reserve should be continuous with the eastern portion of the proposed Leeuwin-Naturaliste marine reserve” (MPRSWG 1994).
Figure 1.1: Location of proposed Geographe Bay, Leeuwin-Naturaliste, Hardy Inlet reserve. (Source: MPRSWG 1994)
In 1997 the region was announced a priority for consideration for marine conservation reserve status (Thomson-Dans et. al. 2003), and a community consultation process started. After the recent creation of the Jurien Bay Marine Park, the state government committed to creating the Geographe Bay, Leeuwin-Naturaliste and Hardy Inlet region into a marine park by 2005. The inclusion of the Blackwood River estuary in a marine reserve will ensure the long-term conservation and management of the local environment, protection of marine species and their habitats, and a resource for education, recreation and tourist programs (MPRSWG 1994).

In order to successfully conserve and manage the region, there is a need to better understand the circulation and flushing regimes of the inlet. The hydrodynamics of the Inlet were described in Imberger et. al. (1976), but no study on the estuary has been done since. Through examining changes to the circulation since this time and the important factors in mixing the estuary, the system can be better understood, and therefore better managed. This may reduce the chances of the Inlet being plagued with problems seen in similar south Western Australian estuaries, often associated with increases in nutrients and increased flushing times.

This study will attempt to describe the present circulation patterns and characteristics of the Blackwood River estuary. The study will increase the understanding of the system to be included in the proposed Geographe Bay-Leeuwin Naturaliste-Hardy Inlet conservation reserve, and provide a better understanding in order to ensure greater management of the region. In order to achieve this, the objectives of the study are:

- A review of past literature relevant to the Blackwood River Estuary and the circulation patterns of an estuary. This will provide the background for examining field data and comparisons.

- Analysis of recent field data from the Blackwood River estuary, and comparison with previous studies. This will give an understanding of the dominant processes driving circulation.

The first chapter of the report incorporates the relevant literature review, including discussion of estuarine circulation, the setting of the estuary and circulatory processes. The second and
third chapters of the report outline the methodology involved with the study, and a presentation of results. These chapters will be divided into the major components of the study, with sections for CTD and ADCP data.

Figure 1.2: Main features of the lower Blackwood River Estuary. (Source Hodgkin 1978)
2 BACKGROUND AND LITERATURE REVIEW

The Blackwood River estuary was heavily studied during the 1970’s after claims were lodged to dredge the inlet. Almost all of the literature and research conducted on the estuary system is from this period. Hodgkins (1978) presents a summary of the technical reports conducted on the estuary, so is the main source of background reading. His report featured a summary of the work done by Imberger et. al. (1976) on the hydrodynamics and circulation of the estuary, among others. Since this time, little work has been undertaken on the estuary.

This chapter will provide a background to the Blackwood River estuary, with a review of relevant literature. It provides background theory on mixing and circulation in estuaries, as well as previous studies on the Blackwood River estuary.

In this chapter, references to “the estuary” are to the tidal Blackwood River estuary. References to Hardy Inlet or “the inlet” refer to the main basin located in the estuary (figure 1.2). The river referred to is the Blackwood River, except where mention of the Scott River is made. The “channel” refers to the dredged navigation channel through the estuary, evident in figure 1.2. Other locations referred to in the estuary are shown in figure 1.2.

2.1 Physical setting of the Blackwood River Estuary

This chapter will review the physical setting and characteristics of the Blackwood River estuary. The geomorphology of the catchment and bathymetry of the estuary will be examined, along with the regions climatic conditions.

2.1.1 Regional Climate

The mediterranean climate of the south Western Australian region is characterised by large seasonal changes. These are controlled by the seasonal north-south movement of the anticyclonic belt of pressure systems (Hodgkin 1978). As the belt moves northwards in winter, it results in strong westerlies. Summer winds are predominantly easterly, with winds at Cape Leeuwin tending south easterly (Hodgkin 1978). The higher ground of the Leeuwin peninsula has been found to deflect the winds at Augusta.
Figure 2.1 shows rainfall from two sites on the Scott River. Both plots show strong correlation in rainfall patterns. As is shown from the 2 locations, over 75% of the annual rainfall in the region falls between May and September, with low rainfall over the summer months. East of the Darling scarp rainfall decreases sharply, and in the eastern catchment evaporation rates are greater than rainfall (Hodgkin 1978).

Winter rainfall is shown in figure 2.1 to constitute the majority of annual rainfall to the Blackwood River catchment. Rainfall throughout winter is largely associated with progressive troughs and the dominant westerly winds. The instability created in the westerly air stream causes heavy showery rains. The main depression track of this system is located south of the Western Australian coastline, and results in mean rainfall decreasing away from the south west corner of the state (Wright 1974).

Summer rainfall in south Western Australia has been shown to be low. The small inter-annual variability is associated with the formation of meridional troughs linking the equatorial and temperate low-pressure bands. These systems move easterly and produce short, high intensity periods of rainfall (Wright 1974).
Figure 2.2 shows the total annual rainfall for the two locations. Over the recorded period, the annual rainfalls range from 600-1400 mm yr$^{-1}$, with no large changes in rainfall levels.

Studies by CSIRO (2001) have predicted the effect of climate change on rainfall for Australia, and are shown in figure 2.3. They show a predicted decrease in rainfall for south Western Australia, including the Blackwood River catchment.
2.1.2 Geomorphology of the Catchment

The Blackwood River extends more than 300 km inland, from the headwaters in the Lake Dumbleyung area to the mouth at Augusta. Its catchment area, 20 461 km² is second in the south western estuaries only to the Swan-Avon system (Morrissy 1974). Currently, approximately 85 % of the catchment has been cleared for agricultural purposes (Berti 2002).

The upper catchment, lies on the Precambrian Shield, a plateau that rises to approximately 300 m above sea level. Bettenay & Mulcahy (1972) divide the region into zones of old drainage, mature drainage and rejuvenated drainage. These are demonstrated in figure 2.4.

Figure 2.3: Predicted effects of climate change on rainfall (CSIRO 2000)
The lower estuary, between the Darling and Dunsborough faults, is known as the Donnybrook Sunklands (Hodgkin 1978). Generally, drainage in the north of the sunklands is to the Blackwood River, while the south drains to the Scott River. In this southern region, the streams are not defined, with low profiles and cases of sheet drainage often seen during heavy flows.

### 2.1.3 Bathymetry of the Blackwood River Estuary

The major bathymetric features of the Blackwood River estuary have been described by Imberger et. al. (1976) and summarised by Hodgkin (1978). Figure 2.5 shows the bathymetry of the estuary.
The Blackwood River Estuary is a permanently open, bar-built estuary. The mouth cuts a narrow but relatively deep channel through the wave-built barrier beach into Flinders Bay. The bar is generally less than 2 m deep in summer, with a deep trough at the mouth. The inlet is almost all shallow (under 2 m), with a deep, dredged navigation channel in the centre. The channel was dredged first in 1956 and again in 1973 (Hodgkin et. al. 1978).

The river mouth has only once been recorded as closing completely. From 1925-1935 the bar silted up and the mouth moved 2 km east from the present location. In 1945 it closed completely, causing flooding, and the bar was again cut at the present site. The channel remaining from the 1930-1945 period is known as the Deadwater. It is a shallow channel, which was described in Imberger et. al. (1976) as up to 5 m deep in parts. It is now almost entirely less than 1m deep, and is shallowing from its eastern end.
Inland of the Deadwater, and connected via a winding tidal channel, is Swan Lake. Originally a freshwater lake, it was filled with seawater in the 1920’s, and is now highly saline. It is separated from the Deadwater by coastal dunes, and is mostly less than 2 m deep.

The inlet is connected to the mouth by a deep, dredged channel. The channel is between 2 and 8 m deep and the upstream part of the channel is relatively stable. In the lower part of the channel, near the entrance to the Deadwater, is a large bank of mobile sand that shifts seasonally.

The estuarine basin of Hardy Inlet is approximately 3 km long and km wide, with two shallow bays to the west and north (West Bay and North Bay respectively). The main channel, which runs through the centre of the basin, is between 120 and 150 m wide, with the remainder of the basin composed of wide marginal platforms of less than 1m. Due to the shallow platforms, the basin volume compared to the estuary as a whole is relatively small, when compared to other estuaries of the south west.

The Scott River discharges to the Blackwood River through a 2 m channel to the north of Molloy Island, and through the shallow Scott and Molloy Basins to the south of the island. The upper Blackwood estuary, upstream of Molloy Island, is mostly between 5 and 10 m deep, with deeper holes in the riverbed. The deepest of these is 22 m deep and only 50 m in diameter.

### 2.2 Hydrodynamics of the Blackwood River Estuary

An estuary is defined as a semi-enclosed basin where river water mixes with seawater (Fischer et. al. 1979). The interactions and movements of the marine and fresh water bodies therefore play an important role in the mixing and circulation patterns in the estuary. These interactions and processes are described as the hydrodynamics of the estuary.

This section includes discussion of both baroclinic and barotropic forcing. The dominant barotropic forces of the estuary are the tidal regime, Coriolis force and atmospheric pressure variations. The principal baroclinic forces are the changes in the density field caused by buoyant freshwater flows. Other factors that may influence the circulation patterns in the estuary are also discussed.
2.2.1 Tidal Regime

The seaward boundary of an estuary is influenced by the local tidal regime. The seaward movement of water on an ebbing tide, and landward flow on a rising tide can aid in mixing and drive circulations in the basin. This section will outline the relevant tidal theory, and review tidal climates of the estuary.

Pugh (1987) states that tidal variations can be represented by \( N \) number of harmonic terms. The harmonic terms are given by the following equation:

\[
H_n \cos(\sigma_n t - g_n)
\]  
\text{Equation 2.1}

where \( H_n \) is an amplitude, \( g_n \) is a phase lag from the equilibrium tide at Greenwich and \( \sigma_n \) is an angular speed.

Imberger et. al. (1976) recorded tides in Flinders Bay, and compared the dominant constituents measured with recognised figures from the Australian National Tide Tables. The differences are shown in table 2.1. The principal constituents in the Bay are found to be \( K_1 \) and \( O_1 \), \( M_2 \) and \( S_2 \). Using these constituents, the nature of the tides can be described using the form factor. This relates the influence of the diurnal constituents, \( K_1 \) and \( O_1 \), to the semi-diurnal constituents, \( M_2 \) and \( S_2 \), as shown below:

\[
F = \left[ \frac{H_{K_1} + H_{O_1}}{H_{M_2} + H_{S_2}} \right]
\]  
\text{Equation 2.2}

where:

\[ F = 0 \text{ to } 0.25 \]  
semi-diurnal

\[ F = 0.25 \text{ to } 1.5 \]  
mixed, mainly semi-diurnal

\[ F = 1.5 \text{ to } 3 \]  
mixed, mainly diurnal

\[ F > 3.0 \]  
diurnal
The form factor gives an approximate representation of the full tidal characteristics (Pugh 1987). The form factor for the Blackwood River estuary is calculated below, using figures from the Australian National Tide Tables (2003).

\[
F = \left( \frac{0.09 + 0.156}{0.05 + 0.07} \right) = 2.05
\]

The form factor of 2.05 indicates the tides of the Blackwood River estuary are mixed, but mainly diurnal.

Imberger et. al. (1976) also showed that the amplitude of the diurnal components was over twice that of the semi-diurnal components resulting in a mixed, but predominantly daily tide (shown in table 2.1). However, due to the differing frequencies of the constituents, twice a month the K2 and O2 constituents interfere destructively, allowing a small semi-diurnal tide to become apparent. This is common in the south west of Western Australia, and has been detailed in Hodgkin & Di Lollo (1958).

Table 2.1: Comparison of averaged measured tidal constituents with Australian National Tide Tables. Adapted from Imberger et. al. (1976).

<table>
<thead>
<tr>
<th></th>
<th>O1</th>
<th>K1</th>
<th>M2</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured avg.</td>
<td>299</td>
<td>0.15</td>
<td>316</td>
<td>0.20</td>
</tr>
<tr>
<td>Aust. Nat. T.T</td>
<td>297</td>
<td>0.156</td>
<td>319</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The sand bar at the mouth of the inlet damps the tidal exchange, reducing the tidal range and causing a phase lag in the estuary. Imberger et. al. estimated daily tides in Seine Bay to average 70 % of those in Flinders Bay, and semi-daily tides 50 %. They measured a phase lag across the bar of 1-2 hours. It was estimated that the high water propagation time was approximately 2 hours, and the low water between 3-5 hours.

During the winter conditions of high river flow, the tides at the mouth are suppressed by freshwater outflow, and the water level builds up in the Blackwood River. This has previously caused flooding of the Alexander and Warner Glen bridges (Hodgkin 1978). The tidal excursion into the river part of the estuary on a maximum tide is about 5 km.
Table 2.2: Tidal levels in Flinders Bay (ANTT 2003).

<table>
<thead>
<tr>
<th></th>
<th>HAT</th>
<th>MHHW</th>
<th>MLHW</th>
<th>MSL</th>
<th>MHLW</th>
<th>MLLW</th>
<th>LAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.51</td>
<td>1.09</td>
<td>0.86</td>
<td>0.83</td>
<td>0.78</td>
<td>0.56</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The tidal levels for Flinders Bay are shown in table 2.2. The table shows the spring tidal range of 0.53 m, and the neap tidal range of 0.08 m. This demonstrates that the Blackwood River estuary can be classified as a microtidal environment.

2.2.2 Tidal Asymmetry

Tidal asymmetry is important in the morphological evolution of estuaries and coastal lagoons (Ranasinghe & Pattiaratchi 2000). When the falling tide persists longer than the rising tide, the resulting flood currents are stronger, and the system is referred to as flood-dominated. Ebb-dominated refers to a system in which the falling tide is shorter than the rising tide and the generated ebb currents are stronger. Speer and Aubrey (1985) found that estuaries without extensive tidal flats were often flood-dominated systems.

Ranasinghe and Pattiaratchi (2000) described the effect of tidal asymmetry in similar south Western Australian estuaries where diurnal tides dominate. They found that velocity asymmetry in diurnal estuaries on the Western Australian coastline were not due to the basin hypsometry, as can be the case in semi-diurnal estuaries (van de Kreeke 1988). The tidal asymmetry was found to be a function of the oceanic forcing. Ranasinghe and Pattiaratchi (2000) stated the occurrence of ebb or flood dominance can be ascertained from oceanic tidal elevations, but not the degree of dominance.

2.2.3 Tidal Mixing in an Estuary

The tidal regime of an estuary can greatly influence mixing. Fischer et. al. (1979) outlines two ways in which this is done. The most obvious of these is through the back and forth oscillation of the tides, creating a shear near the bed. Maximum mixing in estuaries and lagoons occurs when the estuary is narrow and the tidal period is similar to the time required for cross sectional mixing.
The second important characteristic of tidal flows is the residual circulation. The loose definition of the residual is the velocity field resulting from averaging the velocity at every point in the estuary over an entire tidal period. This residual current is generally one or two orders of magnitude less than the currents themselves, but can potentially dominate the overall distribution of characteristics such as temperature and salinity (Pugh 1987). The residual current may be caused by bathymetric irregularities, density differences, wind stress, changes in atmospheric pressure or reflection of tidal currents. The classic estuarine circulation pattern is shown in figure 2.6. It shows the buoyant freshwater layer often evident in estuaries, resulting in a net seaward flow at the surface, and a net landward flow at the riverbed caused by tidal action.

Figure 2.7: Residual profile from the Blackwood River estuary in 1974 (Hodgkin 1978).

Figure 2.7 shows the residual profile for the Blackwood River estuary from Hodgkin (1978). It was averaged over a 24-hour period, and shows the differences in dominant tidal phases through the water column. Near the surface the flood phase appears to be a lot stronger than the ebb, with a large positive residual current, contradicting figure 2.6. At mid depths the currents appear to be stronger on the ebb phase, while at the bottom they are slightly stronger.
again in the flood. The residual profile demonstrates there may be different factors affecting circulation at different depths throughout the water column.

### 2.2.4 Non-Tidal Water Level Fluctuations

Water level in the estuary can also be influenced by non-tidal factors. Due to the small tidal ranges of south Western Australia, non-tidal fluctuations are of the same order of magnitude as tidal changes, and are often not periodic. Hodgkin (1978) summarised the causes of water level change shown in table 2.3.

<table>
<thead>
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<th>Approx. max. range (cm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
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<td>40</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>100</td>
</tr>
<tr>
<td>Barometric Pressure</td>
<td>5-9 days</td>
<td>60</td>
</tr>
<tr>
<td>River flow / mouth bar</td>
<td>Irregular</td>
<td>0</td>
</tr>
<tr>
<td>Isostatic sea level</td>
<td>1 year</td>
<td>30</td>
</tr>
<tr>
<td>Isostatic</td>
<td>10+ years</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2.3: Causes of water level changes in the Blackwood River estuary, and their approximate range. Adapted from Hodgkin (1978).

Imberger et. al. (1976) stated that the tidal range was superimposed over 5-9 day water level fluctuations due to meteorological effects. The meteorological effects are a result of variations in atmospheric pressure and are described by the following equation:

\[
\Delta \eta = \frac{\Delta P_A}{\rho g} \quad \text{Equation 2.3}
\]

This is referred to as the inverted barometric effect. \( \Delta \eta \) is the variation in sea level from the mean, and \( \Delta P_A \) the variation in atmospheric pressure. Hodgkin estimated that the influence of barometric pressure at Augusta would be similar to that measured at Fremantle, approximately 1.8cm/mb.

### 2.2.5 Continental Shelf Waves
The passage of weather systems over coastal boundaries can result in continental shelf waves, due to variations in atmospheric pressure and the action of associated wind stress (Gill & Schuman 1974). On the continental shelf the inverted atmospheric effect is not valid, and Robinson (1964) introduced the concept of continental shelf waves. Hamon (1966) applied this concept to the Western Australian coastline, where these long period waves usually originate from the passage of anticyclones.

Continental shelf waves on the Western Australian coastline propagate parallel to the coast and can travel up to 1000-2000 km alongshore. They have periods of between 10 and 20 days, and can travel up to 6 ms\(^{-1}\) (Chua 2002). They have a time lag down the coast, and would be expected to attenuate considerably away from the associated weather system (Gill & Schuman 1974).

Continental shelf waves have the potential to influence water levels in estuaries and embayments, and therefore influence the circulation patterns. On the estuaries of south Western Australia, with low tidal ranges, the long period waves may reduce the potential to flush and exchange estuary waters. They can also influence mean water levels over the period of a month, but due to the low occurrence of these waves it may prove to be of little consequence (Chua 2002).

In Western Australia, the weather systems associated with continental shelf waves are generally more prevalent during summer. The effects may therefore exhibit a seasonal nature, with variations in sea level greatest during summer. However, due to the fact that the majority of the largest longshore continental shelf waves on the coast are generated in the north west, up to 2500 km north, local passage of weather systems during winter may be of greater importance.

### 2.2.6 River Inflow

Freshwater inflow into Hardy Inlet occurs through the Blackwood and Scott Rivers. The Blackwood River has the highest mean annual discharge of the south west river systems, with the Scott only contributing approximately 11% of the discharge into the estuary (Hodgkin 1978). Morrissy (1974) stated that salinity in the river increased with distance inland, and that only the lower estuary and tributaries could be classified as freshwater. This is due to the pattern of land clearing in the catchment, decreasing rainfall inland and the reversed sequence
of valley forms. Figure 2.8 shows the mean monthly discharges from the Blackwood and Scott Rivers since 1983.

![Graph of mean monthly discharges from the Blackwood and Scott Rivers](image)

**Figure 2.8: Mean monthly river discharges from the Blackwood and Scott Rivers. (WRC 2003)**

River flow exhibits an even greater seasonality than rainfall, with 97.5% of runoff during the months of June to November (figure 2.7). During summer a small flow continues to the estuary and maintains stratification in the inlet. There is also a large discrepancy between high (August) and low (February) flows. This is due to the fact that the rate of runoff depends not only on rainfall, but also on the soil conditions at the time (Hodgkin 1978). Hodgkin (1978) gives further details of river flow from Darradup and Nannup, but notes that the data from Darradup does not represent the volume entering the estuary.

Hodgkin (1978) and Imberger et. al. (1976) describes salinity and temperature conditions in the estuary. They show that during the summer conditions, salinity in the basin and inlet is greater than 30 ppt. The Blackwood River is stratified and has an abrupt halocline at 1.5m. The difference between surface and deep-water salinity increases towards the head of the estuary. As river flow increases, the halocline at the head of the estuary is depressed, and low salinity water moves further downstream. This progresses to a winter condition, where almost all the saline water is forced out of the estuary, and salinity is less than 5 ppt.
The temperature of the inlet is also seasonally dependent. During summer, with the large input of solar heating in the shallow basin, Hodgkin describes a “hot house effect,” characteristic of south western estuaries where a halocline is formed. Below the halocline the water is several degrees hotter than the surface waters, and a sharp thermocline develops.

### 2.2.7 River Bend Flow

Current velocities and directions can vary across the width of a river. This is especially evident in river bends and meandering channels. In a river bend, water flowing along the outside of the bend has a higher velocity than water along the inside, in order to keep a constant water level across the width.

Changes in current directions can be especially obvious in the ebb and flood cycle of tides. At a river bend, the ebbing tide will be flowing in a direction consistent with the upstream channel orientation. The flooding tide will be flowing in a direction consistent with the downstream channel. In a river bend this may cause measured currents to have different orientations in ebb and flood phases (Pattiaratchi pers. comm. 2003).

![Figure 2.9: Diagram showing the effect of river bend flow](image)

### 2.2.8 Seasonal Cycle

The large freshwater inflows into the Blackwood River estuary can lead to large density differences in the water column. Although the Blackwood has the highest mean annual
discharge of any river in south Western Australia (Morrissy 1974), the flow is highly seasonal, and can vary seasonally by a factor of 1000.

Freshwater entering the estuary through the Blackwood and Scott Rivers is of very low salinity. Being less dense than the inlet water, it forms a seaward flowing surface layer. This results in vertical stratification in the inlet, with the saline marine water at the bottom, moving back and forth with the tide. The protruding tongue of marine water is known as a salt wedge. The internal density differences created due to the stratification can cause mixing of the two water bodies within the inlet.

In the Blackwood River estuary, the characteristics of marine and fluvial inflows lead to a seasonal cycle of dynamic conditions. They are described by Imberger et. al. and classified as a summer condition, a winter condition, and a salt wedge transition period. The condition of the estuary is controlled by freshwater discharge into the estuary, rather than tidal forcing, and can be seen in figure 2.10.
Figure 2.10: Longitudinal salinity profile showing seasonal changes throughout 1974. The first profile shows the summer condition, and the cycles through a transition phase, to winter condition, and back to the start of a transition phase. Source: Hodgkin 1978.

The profile from 11/04/74 shows the summer condition in the inlet. In this period the figure shows the seawater protruding up into the tidal river, with river inflow only influencing the surface layer of the upper estuary. Imberger et. al. (1976) suggested that the summer condition applied when the river discharge fell below $0.25 \times 10^6$ m$^3$ per day. At this time the inlet is virtually marine, with salinity in the basin over 30 ppt. There is strong stratification in the inlet, the estuary is tidally dominated, and mixing during this period is due to tidal currents. The summer condition was established by early January. It was observed that under
these conditions, the upstream salinity showed no response to the increase in river flow at the head of the estuary for more than 38 days.

The second profile (16/05/74) shows the beginning of the transition phase between summer and winter conditions. This would occur when the discharge is still below $2 \times 10^6$ m³ per day. The high salinity water is able to enter the basin with the tide, forming a salt wedge in the river. It was found that as the salt wedge propagated upstream and mixed with less saline water, it formed a “jet” of intermediate density water, which can travel up to 10 km upstream on an incoming tide. This jet occupies the intermediate layers and through entrainment with the freshwater can produce a salinity gradient in the surface layers.

As river discharge increases again the estuary becomes less saline. This is demonstrated in the profiles of 09/06/74 and 20/06/74. It was observed that when the discharge exceeded $20 \times 10^6$ m³ saline intrusion into the estuary was prevented, and the inlet stayed fresh throughout. This is the winter condition, and is best demonstrated by the profile from 09/06/74. In this phase the lower estuary was still regarded tidal, as the fresh outflow slackened in a flooding tide. However, the tidal action was unable to pump saline water into the estuary. Hodgkin (1978) stated that at this time the system could only be regarded estuarine in a crude geographical sense, as it resembled a fast flowing river with considerable head upstream.

During the winter phase, Imberger et. al. showed that the entire estuary was flushed within two days. During their period of observation the winter condition lasted between 6 and 8 weeks, but this is entirely dependent on flow rate. In other years this condition may develop as early as April or, if the flow never exceeds $20 \times 10^6$ m³ per day, may not develop at all.

The last profile (20/10/74) shows the return to a transition salt wedge phase. As the flow slows below $20 \times 10^6$ m³ per day, seawater is able to enter the estuary underneath the outgoing freshwater, and a salt-wedge forms in the inlet channel. As the tide falls, the upper part of the wedge is entrained with the fresh outflow, increasing the halocline between the 2 layers. Mixing occurs outside the mouth, resulting in intermediate density water flowing back into the estuary. The inlet can respond to a decrease in river flow rapidly, changing to a transitional condition in one day or less.

Imberger et. al. (1976) stated that during their period of observation, the estuary was in the winter phase for approximately 10% of the year, summer condition for 42% and a salt wedge
condition for 48% of the year. However, as previously stated, this was entirely controlled by river discharge, and can vary from year to year.

### 2.2.9 Horizontal Mixing

Dependent on the condition of the estuary, the circulation patterns of the Blackwood River estuary are influenced by horizontal mixing. The characteristics of the horizontal mixing are presented in terms of the winter and summer conditions discussed in the previous section. Mixing is described in the lagoon, around Molloy Island and the Deadwater and Swan Lakes, as recorded by Imberger et. al (1976).

#### 2.2.9.1 Winter Lagoonal Mixing

Throughout this phase of the seasonal cycle, the mean water level is approximately 0.2m above the annual mean, and the main lagoon is completely covered with water. The Blackwood and Scott River water flowed through the basin in three main channels, to the inlet channel where it flowed to sea. Velocities in the channels ranged from approximately 0.3 ms\(^{-1}\) to a maximum of 0.8ms\(^{-1}\), with velocities in the shallower areas of the order of 0.2ms\(^{-1}\). Measurements of velocities in North and West Bays ranged from 0 – 0.1 ms\(^{-1}\).

From rhodamine dye experiments and observations, Imberger et. al. determined that the main lagoonal area was completely flushed during a tidal period. They estimated that the North and West Bays would receive an approximate increase in volume of 30-40 % over a tidal period, resulting in them being completely flushed over several tidal cycles.

In the winter phase, it was estimated that the Scott River contributed between 5 and 30 % of the flow of the Blackwood. The Scott water enters the Blackwood River to the north and south of Molloy Island, but remains as a separate water body. The two bodies are of different colour, and remain relatively unmixed through the basin. The water bodies stay separate as they flow through the inlet, with the Scott water flowing along the eastern margin, and the Blackwood water occupying the central and northern sections. This was demonstrated in the rhodamine dye release. The dye was only released into the Blackwood River, and was not detected at all in the eastern parts of the basin. There was a slight mixing at the interface of the bodies due to the turbulent flow during the 3 km stretch to the basin, but this was minimal.
Almost all mixing of the water bodies occurred after they had discharged at the mouth of the estuary.

### 2.2.9.2 Summer Lagoonal Mixing

During the summer phase river discharge in the estuary is less than tidal movement across the lagoon, and upstream flow occurs. Between January and March the flow is entirely tidal, with large parts of the lagoon exposed. The water levels in the estuary at this time are between 0.1 and 0.2 m below the annual mean.

As in the winter phase, the river water and water from the North and West Bays flows across the lagoon and down the Inlet channel on a falling tide. However, due to the lower velocities, little will flow further downstream than Thomas Island. Measurements during the summer condition gave maximum flow rates of 0.15 ms\(^{-1}\) and 0.55 ms\(^{-1}\) downstream, indicating the velocities in the dredged channel of the lagoon were much higher than any other region of the estuary. The difference between the summer and winter conditions however, was that water entering the inlet channel was unlikely to reach the mouth before the tide turned again. On a rising tide this means that water is entering the lagoon through both the channel and the river. Results from the dye test indicate that after a week, up to 10 % of the dye could still be in the estuary, demonstrating low exchange rates during summer.

Imberger et. al. also estimated the dispersion rates in the lagoon, and found that decreasing depth in the direction of flow results in larger dispersion coefficient values. They estimated that due to dispersion effects, the lagoon would become completely marine in approximately one month. It was concluded that during the summer and salt wedge phases, the combined effects of decreased flux, convection, dispersion, wind induced turbulence and the shallowness of the lagoon, ensure that considerable mixing occurs in the lagoon. The lagoonal water is swept back and forth down the inlet channel and Blackwood River, and circulates around Thomas Island and into West and North Bays.

### 2.2.9.3 Circulation Around Molloy Island

Molloy Island is situated at the meeting point of the Blackwood and Scott Rivers. Scott River water flows through the channel around the north of the island, or the narrower channel to the
south east of the island. It then flows from the shallow Molloy basin to the inlet and out to sea.

The main circulation around Molloy Island is dominated seasonally by the flux from the Scott and Blackwood Rivers, and the tidally induced currents. Imberger et. al. (1976) stated that the shallow bank at the southern end of the south channel is an important factor on the circulation around Molloy Island.

2.2.9.4 Exchange with the Deadwater and Swan Lake

Imberger et. al. (1976) again described the exchange of water between the Deadwater, Swan Lake, the Inlet channel and the sea. Considerable exchange occurs between the Deadwater and Swan Lake, but due to the shallow channel between the two, is restricted to the surface layer. This surface water may be fresh after heavy rain during winter, but increases in salinity with a decrease in discharge, and by summer seawater directly enters the lakes.

Measurements recorded by Imberger et. al. showed that the deeper layers of the Deadwater remained saline all year, while the surface layers reflected the conditions at the estuary mouth. During winter the lakes were fresh to a depth of 2 m, with salinity below this depth reaching 26 ppt. As river flow decreases the saltwater replenishes the salinity of the bottom waters, and eventually increases surface salinity. By the end of summer the eastern extremes of the Deadwater and Swan Lakes are slightly hypersaline, and whilst stratified little mixing takes place.

2.2.10 Heating

The heating and cooling of a water body, leading to changes in the density field, is a form of baroclinic forcing and can drive circulation. In summer, the water body receives solar radiation and heats up during the day, then loses heat at night through evaporative cooling. The cooler surface water sinks, mixing the water body.

Imberger et. al. (1976) suggested a model explaining the high temperatures seen in the upper estuary during summer. This is demonstrated by figure 2.10.
The figure shows the process leading to an accumulation of heat in deep water. The solar radiation during summer heats the lower salinity water, and loses heat at night through evaporative cooling. A small amount of the solar heat penetrates the surface layer, and heats the water directly below the interface. This mechanism was observed several times, and can result in a maximum just below the halocline.

At this depth there is a jet of continuous upstream flow, resulting in movement of heat upstream and heat accumulation at the head of the estuary. The deep water is not cooled by evaporation as no mixing occurs across the halocline (Hodgkin 1978).

Although the heating led to a movement of water upstream, Imberger et. al. stated that solar heating was significant only from the temperature aspect.

### 2.2.11 Coriolis Force

The Coriolis force is an inertial oscillation caused by the earth’s rotation (Cushman-Roisin 1994). The Coriolis parameter \( f \) is defined as:

\[
f = 2\Omega \sin(\phi)
\]

**Equation 2.4**

Where:
- \( \Omega \) is the earth’s angular velocity \( (\Omega = 7.272 \times 10^{-5} \text{ rad/s}) \).
- \( \phi \) is the latitude of the water body \( (\phi = 34^\circ \text{ S}) \).
Therefore, at 34º S the Coriolis parameter is approximately equal to 8.13 x 10⁻⁵ s⁻¹.

In the southern hemisphere $f$ is negative, imposing an anti-clockwise circulation. Officer (1976) stated that the Coriolis force can cause river flow to be displaced to the left hand side of the estuary in the southern hemisphere, resulting in a less saline and thicker flow on this side.

Officer (1976) states that Coriolis force needs not be included in the basic balance of forces for the majority of shallow, narrow estuaries. Fischer et. al. (1979) stated that the influence of the Coriolis could be determined by the Rossby number for barotropic flows. The Rossby number is the ratio of the period of rotation to the time of advection. It is given by the following formula:

$$R_0 = \frac{U}{fL}$$  \hspace{1cm}  \text{Equation 2.5}

Where:
- $U$ is the characteristic velocity scale.
- $L$ is the characteristic length scale of the water body.
- $f$ is the Coriolis force.

If the Rossby number is less than one, then the water body would be expected to be influenced by rotational effects. If the number is large, then the fluids momentum would be expected to overcome the effects of the Coriolis.

Using the Rossby number, we can determine if the Coriolis parameter is an important factor in the circulation of the Blackwood River estuary. If we assume the characteristic velocity scale to be the average of values found by Imberger et. al. (1976) in the channel and shallows of the lagoon (0.4 ms⁻¹), and the characteristic length scale of the inlet to be 3 km:

$$R_0 = \frac{0.4}{(8.13 \times 10^{-5})(3000)}$$

$$R_0 \approx 1.64$$
Therefore, the water body of the estuary would be expected to overcome the effects of rotation, and the Coriolis force would not be significant in circulation.

### 2.2.12 Estuarine Classification

Due to the broad diversity of systems described by the definition of an estuary, no single scheme has sufficiently classified estuaries into categories. The first method of classification proposed was geomorphological. Under this classification scheme, the Blackwood River estuary is classified as a bar-built estuary. Bowden (1967) and Pritchard (1967) proposed classifying estuaries in terms of three hydrodynamic categories; sharply stratified estuaries, partially stratified estuaries and well mixed estuaries. Hansen and Rattray (1966) proposed a salinity classification method. Classification of the Blackwood River estuary based on hydrodynamics and salinity are described below.

Hansen & Rattray (1966) proposed that gravitational circulation in estuaries depended on two dimensionless parameters. They proposed a two-parameter classification scheme using stratification and circulation, which identified seven estuarine types. These are shown in figure 2.12. Hansen & Rattray suggested the following essential independent parameters:

\[
\frac{\delta S}{S_0} \quad \text{Equation 2.6}
\]

\[
\frac{u_s}{U_f} \quad \text{Equation 2.7}
\]

The first describes the ratio of the top to bottom salinity difference to the mean salinity over the section, and the second the ratio of the net surface current to the mean freshwater velocity through the section.

The classification types range from type 1, where the flow is seaward at all times, and the salt transfer process is controlled by diffusion, to type 4 salt-wedge estuaries, where stratification is large. In attempting to classify a system such as the Blackwood River estuary, seasonal variations are important. During winter, \(U_f\) is approximately 0.6 ms\(^{-1}\), and taking \(u_s\) as approximately 0.2 ms\(^{-1}\), \(U_f/ u_s\) is 3. From the profiles shown in figure 2.12, \(\delta S / S_0\) is
approximately 1. From figure 2.12, during winter the estuary would be classified as type 2b, a well-mixed estuary where advection and diffusion are important in the flux of salt. In summer, when \( \delta S \) and \( U_f \) are both close to zero, the estuary would be classified as a type 3b estuary. This indicates that advection accounts for 99% of the upstream salt flux.

\[ R = \frac{\left( \frac{\Delta \rho}{\rho} \right) g Q_f}{W U_t^3} \]  
\text{Equation 2.8}

where:
- \( \rho \) is the density of the water body
- \( g \) is gravity
- \( Q_f \) is the freshwater discharge
- \( W \) is the width of the estuary
- \( U_t \) is the r.m.s. tidal velocity
The estuarine Richardson number expresses the likelihood that a buoyant discharge mixes vertically in a river flow. If $R$ is very large we expect strong stratification, and flow to be determined by density currents. If $R$ is small we expect the estuary to be well mixed.

Once again, the classification of the Blackwood River Estuary is highly seasonal. During summer, as $Q_f$ tends to zero, so does the Richardson number, indicating the dominant forcing is due to tidal action. During winter, as the freshwater discharge increases, $R$ is large. This indicates the estuary could be classified as strongly stratified and controlled by density currents.
3 METHODOLOGY

The previous sections provide the background and framework for the study to be done. This chapter outlines the methodology involved in the study, and is divided into three sections.

The first two sections of this chapter outline methodology and procedures for processing previously unanalysed field data used in the study. The field data was collected during 2001, with measurements made using a conductivity, temperature and depth probe and an Acoustic Doppler Current Profiler.

The third section of this chapter outlines the process involved with digitisation of the estuary bathymetry. Data for this stage was provided by the Department for Planning and Infrastructure (DPI).

3.1 Conductivity, Temperature, Depth Probe Data

Conductivity, temperature and depth (CTD) data supplied was collected on the 10th May 2001, from 11 sites in an 11km stretch of the Blackwood River. Data was collected from just north of Molloy Island (34°15.578’ S, 115°12.587’ E), upstream to the Alexandra Bridge (34°09.995 S, 115°11.598 E). The sampling sites are indicated in figure 3.1.

The Conductivity, Temperature and Depth probe is a multi-parameter instrument which measures and records conductivity, temperature and pressure as it is lowered through the water column. This enables the analysis of salinity, temperature and depth among other parameters.

The CTD probe contains three internal sensors (one each for temperature, conductivity and pressure), around which water flows for measurement. The signals from the three sensors are then transmitted to the surface.

Across the sampling transect, readings were recorded at 0.5 and 1 m intervals, in depths of between 4.5 and 12 m.
Figure 3.1: Blackwood River Estuary, indicating CTD sampling sites 1-11. The ADCP was located at site 3.

The data was processed using MATLAB, for determination of the factors influencing temperature, salinity and DO distributions, and comparison with salinity and temperature data from 1974.

### 3.2 Acoustic Doppler Current Profiler Data

An Acoustic Doppler Current Profiler (ADCP) was deployed in the Blackwood River for a period of 22 days between the 18th April and 10th May 2001. The profiler used was a 1200
kHz upward looking instrument, manufactured by RD Instruments. The instrument has a blanking distance of 0.5 m and the height of the profiler is 0.4 m, so no data is recorded within 1 m of the riverbed.

The ADCP is stationary on the riverbed, and emits acoustic beams from a transducer. The beams are scattered by small particles and zooplankton moving with the currents, and the reflected beams measured by the sensor. The ADCP measures the beams at discrete levels throughout the water column in both east/west and north/south directions. It can then resolve three-dimensional currents, as well as the depth of water at that time.

Bins were located at intervals of 0.3 m throughout the water column, and recorded current velocities in north/south and east/west components every 5 minutes. Currents in the north and east directions are measured as positive, and currents flowing south and west measured as negative velocities. The instrument was located in the Blackwood River, at site 3 shown in figure 3.1.

The ADCP data was analysed using RD Instruments WinADCP, and exported as text files for processing in MATLAB. As the CTD data was collected while the ADCP was operating, some comparison of the two data sets is enabled.

### 3.2.1 Period of record

Although the ADCP data was collected continuously for 22-days, not all of the data from this period could be used in the study. After initial analysis of ADCP current velocities, there appeared to be a 60-hour anomalous period after approximately 5 days of sampling. Depths from this period showed a water level drop of over 1 m, and bins near the surface recorded zero velocities.

The pitch and roll of the profiler was analysed in WinADCP, and found to be unusually high for this entire 60-hour period. The high values suggested that the profiler may have been moved for this period into a region of decreased water depth, then replaced. This is consistent with the temperature, depth and current measurements from the time.
Due to the sensor movement, the data from this period had to be discarded. As a result, the ADCP data now consists of a continuous 323-hour sampling period after the movement, from the 27th April to 10th May 2001. Data from the omitted period is included in appendix 3.

### Table 3.1: Summary of ADCP and CTD data collection

<table>
<thead>
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<th>Method</th>
<th>Location</th>
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<th>Interval</th>
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<tbody>
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<td>ADCP</td>
<td>Blackwood River</td>
<td>27/04/01 : 10/05/01</td>
<td>5 mins.</td>
</tr>
<tr>
<td>CTD</td>
<td>Blackwood River</td>
<td>10/05/01, 09:00 – 13:00</td>
<td>~20 mins.</td>
</tr>
</tbody>
</table>

### 3.3 Digitisation of the Bathymetry

The bathymetry of the Blackwood River estuary was digitised in order to assess the impact variations in bathymetry may have on circulation. It also provides the background for future numerical model studies on the estuary.

For the purposes of this study, this meant the bathymetric detail from the mouth of the estuary to Warner Glen Bridge, approximately 35 km upstream. The majority of this region is included in the Department of Marine and Harbours (now DPI) map number 698 (Hardy Inlet), which includes soundings up until 2002. The upper Blackwood River is not included in this map however, with the only bathymetric soundings in the river from 1974. These are shown in the Public Work Department maps P48913-1-6 and P48913-1-7, and were used to map the remainder of the estuary. All maps used were on the scale of 1:15000.

The area mapped encompasses over 200 km$^2$, of which the estuary occupies less than 15%. The chosen spatial resolution was 100 m x 100 m, with an included cell considered estuarine if more than 50% of the cell was in the estuary.

The DPI hydrographic charts were overlain with a scaled grid in order to average the bathymetry over 100 m x 100 m squares. Once a cell was determined to be estuarine, with the remaining dry cells set to 0, then contour lines or spot soundings included in the cell were averaged over that cell. The missing cells were filled in based on lines of contour. After completing the extent of the estuary, the bathymetry was compared with digitised sounding transects supplied by the DPI. These mainly encompassed the navigation channel in the inlet, and the region near the estuary mouth. Finally, all points were adjusted to account for the
DPI’s sounding datum, 0.83 m below MSL. Once completed, the grid consisted of 261 cells in the longitudinal direction, and 80 cells in the latitudinal direction.

Figure 3.2: Bathymetry of the Blackwood River Estuary. Colour indicates depth.
4 RESULTS

The field results from the study will serve as a basis for comparison with previous studies of the estuary, as well as validation of the numerical model. Current data will be analysed to examine the dominant factors in circulation in the estuary. Differences throughout the water column will also be examined.

4.1 Blackwood River Discharge

The Water and Rivers Commission supplied discharges and flow rates from the Blackwood River. Discharges for the 14-day period prior to CTD sampling are shown in figure 4.1.

![Blackwood River daily discharges](image)

Figure 4.1: Blackwood River daily discharges for 27th April to 10th May 2001 (WRC, 2003).

The figure shows two large increases in river flow during the period. The first, between the 5th and 7th May, shows an increase of approximately $4 \times 10^4$ m$^3$ over 2 days. The second, in the day before sampling, shows an increase of $6 \times 10^4$ m$^3$ in one day.
During the period, the river discharge is below $0.25 \times 10^6 \text{ m}^3\text{day}^{-1}$, the figure Imberger et. al. (1976) stated was the upper limit for the summer, or stratified, condition of the estuary. Figure 4.1 demonstrates that the estuary is therefore in the summer phase throughout the sampling period. Figure 4.2 shows the river discharges since 1983, along with the threshold for summer and winter flows.

![River discharge since 1983](image)

**Figure 4.2:** Plot of Blackwood River discharge since 1983. The blue line indicates the threshold for the winter condition, and the red line shows the threshold for the summer condition.

Figure 4.2 shows that the estuary does not often reach the flushed winter condition, and most years oscillates between the summer and transition conditions. The 2001 flow was especially low, discharge being an order of magnitude less than in years of high flow.

### 4.2 CTD data

The CTD data was collected from 11 sites across an 11km transect (figure 3.1). The data was collected for comparison with previous field studies, and to examine temperature, salinity and dissolved oxygen changes, both throughout the water column and across the transect.
4.2.1 Temperature

The temperature profile across the transect is shown in figure 4.3. Site 1 is downstream, and site 11 is upstream.

Figure 4.3 shows a strong increase in temperature with distance upstream, with the minimum temperature at site 1, and maximum temperature at site 11. The maximum temperatures at each site were also increasingly closer to the surface at each site upstream, with all sites exhibiting a peak in temperatures at depths of between 1 and 4 m. These features are shown clearly in the contour temperature plot for the transect.
Figure 4.4: Temperature contours in the Blackwood River. Sampling sites are indicated with crosses.
(l:r= sites 1:11)

Figure 4.4 shows temperature contours across the transect. It clearly shows the increasing temperatures upstream, with an increase of approximately 3.2º C over the 11 km.

The contour plot again demonstrates the decreasing depth of the temperature peaks at each site. From the contour plot it is also clear that water depth decreases upstream, with numerous bathymetric changes within the transect. The decreasing depth of peak temperatures is most likely caused by the decreasing depth of the water column. At the upstream sites temperatures at the bed and surface are approximately equal.

The appearance of peak temperatures in the middle of the water column indicate a transfer of heat downstream at mid-depth. This may be due to the tidal action during the sampling period, which will be discussed. Figure 4.5 shows the tidal action during the sampling period.
Figure 4.5: Tidal regime for three tidal cycles. Red section shows the tidal movement during CTD sampling.

The figure above was taken from ADCP results, which will be discussed in length in later sections. It demonstrates that during CTD sampling the tide was beginning to change from a flood to ebb phase. This may effect the temperature profile across the sampled transect, and may cause the transfer of heat indicated in figure 4.4.

### 4.2.2 Salinity

Salinity data was obtained from the CTD probe. Maximum salinity of approximately 31 ppt was found at site 4, and minimum salinity of approximately 15.5 ppt at the surface of site 11. The salinity profile across the transect is shown in figure 4.6.
Figure 4.6: Salinity profile from 11 sites in the Blackwood River.

The salinity data at depth is well correlated across most of the transect, with maximums in the range 30-32 ppt. There is also a large increase in salinity with increasing depth, evident across the entire transect.

At the surface, salinities decrease upstream, with site 11 having the minimum salinity. At most sites there is a sharp halocline at a depth of between 1 and 2 m, with increases in salinity of up to 12 ppt over 1m. Sites 1-4 exhibit a 2 m layer of low salinity water, above a sharp halocline. Below the halocline all sites show relatively constant salinities.
The salinity contour plot for the Blackwood River shows a layer of lower salinity water near the surface. This layer is approximately 2m deep, with salinities below this depth in the range 28 - 31 ppt. Similarly to the temperature profile, the salinity profile indicates the increasing thickness of the lower salinity layer downstream is due to the increasing water depth.

Between sites 1 and 4 there appears to be a pocket of higher salinity water below a depth of 4m. This is likely to be due to the greater depth of water in this region, creating a small trough, effectively trapping the higher salinity water. This suggests that bathymetric irregularities can alter the salinity structure of the water column.

The region of low salinity water at the surface is likely to be caused by freshwater inflow from the Blackwood River. Figure 4.1 showed the Blackwood River flow rates for the 14-day period before sampling. The figure showed a large increase in river discharge in the 5 days prior to sampling. This is consistent with the lower salinity layer near the surface. Water at greater depth remains unaffected by the increases in freshwater flow.
Figure 4.8: Temperature / Salinity Diagram for the Blackwood River.

Figure 4.8 shows the temperature / salinity diagram for the transect. From the diagram it is evident that the water column consists of two major water bodies, the freshwater river flow and the tidal seawater. At several sites, especially those towards the inlet (sites 1-4), there appears to be more than two water bodies. This may be due to greater mixing in the water column, between the incoming tide and river flow. The flooding tide may have caused an intrusion of previously mixed water into the tidal river downstream. As the sampling period was shown to be on a changing tide, it is likely this mixed water has not yet exited the river, and influences the downstream sites.

4.2.3 Dissolved Oxygen

Dissolved Oxygen (DO) measurements were taken at discrete heights throughout the water column. The DO profile for the transect is shown in figure 4.9.
Figure 4.9: Dissolved oxygen concentration for 11 sites on the Blackwood River.

Figure 4.9 shows a decrease in DO concentrations with depth. This can be seen in all sites, but is more evident upstream. The figure shows DO concentrations below a depth of 1m decreasing upstream. This is especially evident near the bed, where site 1 has the highest DO concentration, and site 11 the lowest. Above the 1.5 m level the upstream sites have the highest DO concentrations. Sites 10 and 11 have approximately 9 mg/L DO, while sites 2 and 4 are closer to 7 mg/L.

Figure 4.6 showed a halocline at approximately 1.5 m depth in upstream sites. Below this point the lack of mixing may be causing deoxygenation of bottom waters, as can be seen at site 11.
4.3 ADCP data

The ADCP was stationed in the Blackwood River between 18th April and 10th May 2001. As previously stated, the data analysed was for a continuous period from 27th April to 10th May. Data from the ADCP was collected for determination of the dominant factors affecting circulation in the estuary and comparison with previous studies.

4.3.1 Current Roses and Correlations

![Current roses from the ADCP.](image)

Clockwise from top left, roses are for heights of 1.62m, 3.42m, 5.22m and 6.72m above the riverbed.

By analysis of current roses and correlation of N/S and E/W data, and from the orientation of the river, the current directions can be resolved into up-stream and cross-stream.
The current roses indicate the dominant flow directions are close to SW/NE. The consistent appearance of two frequently occurring current orientations in all 4 roses, indicate the ADCP may have been located near a slight bend in the river. One of the dominant orientations would be attributable to the ebb tide and the other to the flood.

The plots show that currents at greater depth appear to flow more predominantly upstream during the sampling period, while at the surface (6.72 m) they are more consistently downstream. There also appears to be a frequently occurring (12-16 %), low velocity northward current at the surface. This indicates that the surface currents may be related to factors other than simply tidal action and river orientation.

Figure 4.11: Scatter plots comparing North/South and East/West data. Clockwise from top left, plots are from 1.62m, 3.12m, 4.92m and 6.72m (surface) above the riverbed respectively.

Figure 4.11 shows a correlation of N/S and E/W currents throughout the water column. Most depths show a linear relationship, with dominant orientations appearing similar to those shown in the current roses.

The plot from 4.92m shows a strong correlation, although currents fall in a large range. There appears to be a dominant orientation NNE/SSW, with little scatter. The plot from 3.12m
indicates a similarly strong linear correlation, with data falling in a smaller range. The orientation of the currents at this depth appears to be more N/S than at higher levels.

Currents from the bottom of the water column appear to be generally weaker than other depths, falling in the range $-0.1 \text{ to } 0.1 \text{ ms}^{-1}$ (NS) and $-0.05 \text{ to } 0.05 \text{ ms}^{-1}$ (EW). The small magnitude of EW currents and orientation of dominant directions indicate that the majority of flow near the bottom is upstream/downstream. This shows that at greater depth tidal action may greatly influence currents.

Currents at the surface have a larger range than at greater depths. There appears to be a weak linear correlation in the currents, but this is much less evident than at greater depths. The larger range of currents and the weaker correlation indicate surface currents may be influenced by factors such as atmospheric variation and wind as much as by tidal action.

Colour and vertical plots of the east/west and north/south data are included in appendix 5.

### 4.3.2 Tidal Regime

The tidal regime in the estuary is evident in the cycle of currents measured by the ADCP. Figure 4.12 shows the current cycles for the sampling period throughout the water column.
The tidal cycle of ebb and flood phases is evident in the measured velocities, especially closer to the bottom. At heights of 1.02m and 3.12m the tidal cycle on river currents is evident. They clearly show a series of spring tidal cycles between hours 180 and 300, followed by the smaller neap tides. The velocities near the bottom demonstrate that tides are predominantly diurnal, with a tidal period close to 24 hours. The strength and clarity of the tidal cycle near the riverbed indicates the large effect tidal action has on bottom circulation.

Currents at the surface demonstrate less of a distinct cycle than at depth. This indicates surface currents are greatly affected by factors other than the tides, and cross-stream currents may be strong near the surface. At greater depths the strong cycle demonstrates the dominance of upstream/downstream currents. Bathymetric features may limit cross-stream currents at these depths.

At the beginning of the sampling period, the surface currents indicate much stronger flood (positive) phases than the ebb (negative). This continues throughout the sample period until approximately hour 460. After this time an increase in freshwater flow causes extended periods of negative currents.
Figure 4.13: Current velocities perpendicular to the river channel. Heights above the riverbed are inset.

Figure 4.13 shows the measured currents in the cross-stream directions, or perpendicular to the main direction of flow. The surface plot shows the strongest currents in the cross-stream directions, and velocities tend to decrease from the surface to the riverbed. This is to be expected from the influence of the channel bathymetry and the external factors influencing surface currents.

Generally, the currents are on the order of 0.05 ms$^{-1}$. Currents measured at the riverbed show small variation, and are consistently low. The top two plots show some stronger currents, in both the positive and negative directions. The majority of cross-stream sites are possibly influenced by local wind patterns, which would not influence deeper waters.

The cycle of currents - due to the tidal cycle - is less obvious in the cross-stream directions, but still evident. There does not appear to be any dominance of the ebb or flood phase in producing stronger currents, but a more symmetric cycle still appears. The appearance of the cycle diminishes towards the surface, where there is a lot of external noise.
The measured currents were plotted against the water depth in order to show the cycle of rise and fall of water level in the estuary. A 20-hour period of comparison is shown in figure 4.14.

Figure 4.14: Comparison between measured currents and depth.

Figure 4.14 shows the correlation between measured water depth and currents. The red area shows the flooding tide, with the mentioned tidal lag. It demonstrates that at the end of the flood phase at the surface, water depth is at its highest. As expected, as the currents begin to ebb, water level decreases, and is at its lowest at the end of the ebb.
Circulation in the Blackwood River Estuary

Results

Figure 4.15: Plot of current velocities through the water column. The top plot shows currents at the surface for the sampling period. Positive velocities are in the upstream direction.

Figure 4.15 shows currents through the water column over the sampling period. The tidal cycle is again evident as bands throughout the water column. For the first 70 hours positive velocities near the surface seem to extend longer than negative velocities, indicating movement upstream. This may be a result of winds at the surface overcoming the tidal action for this period.

The colour plot again shows the tidal cycle is much more clearly represented near the bed, than near the surface. There is a lot of external noise near the surface and a much less clear cycle. The current velocities are shown to be stronger closer to the surface, possibly due to other influences.

Figure 4.15 indicates a tidal lag between the bottom and surface waters. This is obvious at the start of the sampling period when currents near the bottom are positive (flooding), and those higher in the water column are still negative (ebbing). Figure 4.16 shows the cross power spectrum between the surface and bottom.
Figure 4.16: Power cross spectra between top and bottom of the water column. The green and blue lines show the top and bottom respectively, with the red line showing the 95% confidence interval. The dashed black line indicates the dominant frequency.

From figure 4.16 the dominant frequency was determined to be 20.83 Hz. This frequency corresponds to a particular phase angle, shown in figure 4.17. The phase angle was determined to be approximately 70.7º. Converting this to a time difference:

\[
Lag = 70.7 \left( \frac{24}{360} \right) \\
Lag = 4.71
\]

Therefore there is a time lag between the surface and bottom of approximately 4 hours and 42 minutes.
4.3.3 Velocity Profiles

The velocity profile indicates the dominant directions of flow for the sampling period. Figure 4.18 shows the mean velocity profile.

Figure 4.18: Mean velocity profile for the sampling period.
The velocity profile shows the mean velocities for the period are consistently positive at all depths. There is a region of large positive velocities at heights of 5.62-6.02 m above the bed. After this peak, the average velocities decrease in the intermediate layers, with mean currents of approximately 0.005 ms$^{-1}$. Further towards the riverbed the mean velocities increase, to approximately 0.08 ms$^{-1}$. The residual profile for the sampling period is shown in figure 4.19.

![Figure 4.19: Residual profile over a single spring tidal cycle.](image)

The residual shows a similar profile to the mean velocity profile. However, the currents at each point are consistently lower than the mean velocity profile. At mid depth, the mean current is negative, elsewhere it is positive. The dominance of the flood currents at the surface is demonstrated in both the residual profile and the mean velocity profile.
Figure 4.20: Consecutive spring flood and ebb tidal profiles.

The flood profile shows a strong positive current at all depths as expected. It is strongest between 3 and 6 m, reaching approximately 0.635 ms\(^{-1}\) at 5.52 m. The ebb phase shows strong negative velocities below a depth of 5 m, with strongest currents at a height of 3.12 m. Between 5 and 6 m currents are positive, indicating that at this depth the tide has not yet changed. Near the surface the currents are negative, possibly due to the freshwater outflow, which was seen earlier to influence the surface layer.
Figure 4.21: Difference between maximum flood cycles on the spring and neap cycles.

Figure 4.21 shows the differences between the maximum flood tides for both the spring and neap tides. Near the surface and riverbed velocities from spring and neap cycles are similar, with the neap slightly weaker. However in the intermediate layers of the water column the spring cycle is shown to be much stronger. Velocities at 3.72 m above the riverbed in the spring cycles are an order of magnitude bigger than the neap cycles, and a similar trend is shown between 2 and 5 m above the riverbed.

4.3.4 Current Vectors
The plot above shows velocity vectors at sampled depths throughout the water depth. Figure 4.22 shows the flood phase at hours 213 and 214, where the currents are positive in the entire water column, and the ebb phase at hours 221 and 222. In this tidal cycle the flood and ebb currents near the bed appear to be equal. At a depth of approximately 5m the flood currents appear to be a lot stronger than the ebb, as shown at hours 214 and 222 respectively.

The tidal lag between the surface and the riverbed is also evident in figure 4.22. The tide can be seen to change at the bed in hour 217, while the surface currents are still strongly positive. By hour 221 the surface currents have reversed, demonstrating the approximate 4-hour lag between the bed and the surface. This change in tide is contrasted in the next two figures, where the influence of the two increases in freshwater river discharge can be seen. Figure 4.23 shows the first increase in flow, causing currents at the surface to flow downstream against the tide.
The intrusion of freshwater discharge is first seen at hour 456, when the current at the surface first becomes negative. It turns against the tide and flows downstream as the water at mid depth is still in a flood phase. After the changing of the tide, it is still observed to be negative (hour 468).
Figure 4.24 shows the next increase in freshwater flow on the 9\textsuperscript{th} May. At hour 481 the current at the surface reverses against the tide and is seen to flow downstream throughout the period shown. The currents at the surface are consistently strong for over 12 hours, and compared with the last increase in river discharge there appears to be an increase in the thickness of the out-flowing layer. The final plot (hour 495) shows the opposing flooding tide reducing the velocity of the downstream surface flow.

### 4.3.5 Tidal Spectra

The analysis of spectral densities and frequencies can determine the dominant force influencing currents. The comparison of spectral densities from the surface and bottom are shown in figure 4.25.

![Figure 4.25: Spectral density plots from the surface (top) and bottom (bottom) of the water column. ‘5d’ is the 5-day frequency, ‘24h’ the diurnal frequency and ‘12h’ the semi-diurnal frequency.](image-url)
The large peak in the bottom plot corresponding to the 24-hour frequency indicates the dominance of diurnal tides at the riverbed. The peak shows the dominance of the diurnal tide over semi-diurnal tides (12-hour) and atmospheric variations (5-day).

The bed plot shows a smaller, but significant peak at the 12-hour frequency. This indicates the mixed nature of the tides in the estuary. There appears to be a dominant frequency on a period of approximately 2 days, possibly due to the passage of weather systems. The variations in atmospheric air pressure are indicated by the 5-day frequency, and are shown to have some influence in current velocities by the small peak in spectral density.

The spectral data plot from the surface velocities exhibits much more constant densities. The effects of the 5-day, diurnal and semi-diurnal variations have spectral densities of the same order of magnitude, indicating that no one period dominates at the surface. The diurnal tide does have the greatest spectral density, but is relatively similar to the other two periods.
5 DISCUSSION

All field data collected was done under the seasonal summer condition of low freshwater inflow. Therefore discussion of the dominant physical factors driving circulation is only directly applicable to periods of low discharge. Although some indication can be given of patterns throughout the year, these cannot be determined conclusively without more extensive fieldwork.

5.1 Changes to River Discharge

Monitoring of river discharge into the Blackwood River estuary has shown that the estuary has only received the required discharge to reach the winter condition 6 times since 1983. The winter condition is the only time when the estuary is fresh throughout, and as discharge decreases the estuary is unlikely to become completely fresh. Although the condition of the estuary remains dependent on the river discharge at the head of the estuary, this suggests that more increasingly the estuary is residing in the salt-wedge, transition and the stratified, summer regimes.

The decreases in river discharge associated with decreases in rainfall in the eastern catchment mean that the summer and transition periods may be of greater importance to the management and conservation of the estuary. As the estuary is only completely fresh during the winter condition (6 times since 1983), the prevalence of the summer and transition conditions will result in increasing stratification of the estuary for extended periods of time. As was stated by Hodgkin (1978), increasing stratification of the estuary reduces the health of the system and will result in decreased dissolved oxygen concentrations.

Figure 2.3 shows the predicted impact of climate change on rainfall (CSIRO 2000). It shows an estimated 20 % decrease in rainfall by 2030, and up to 60 % decrease by 2070. If the predictions by CSIRO (2000) are accurate, or even approximately close, the estuary may only reach the winter condition in rare years. The estimated decreases are consistent with the summer condition persisting for much of the year.

It must be noted that in comparing the years of 1974 and 2001, the discharges of both years were vastly different. In 1974 the estuary received the greatest discharge recorded at that time,
resulting in a fully flushed estuary during July and August. In 2001 the estuary received its lowest river inflow for over 20 years. Due to the fact that Imberger et. al. (1976) conducted field studies over the entire year comparison between the two is enabled, but the great difference in discharges between the two years needs to be noted.

5.2 Temperature

Temperature in the Blackwood River shows a longitudinal gradient upstream, with surface temperatures ranging from 16.5 °C at site 1 to 21 °C at site 11. The persistent peaks in temperature at mid-depth indicate convection in this region, with little vertical transfer between layers. This condition has been established over the summer period, as deep water gains heat from the surface with little mixing.

The water body receives large inputs of solar radiation during the day, heating the surface layer, with a small amount of this heat reaching the intermediate depth. During the night, via evaporative cooling, the surface of the water body cools, resulting in instability in the surface layer. The layer overturns, causing mixing above the thermocline. The intermediate layers remain unmixed, and continue to increase in temperature throughout the summer period.

The dominance of the flood currents at the mid levels, as seen in figure 4.18, causes transport of heat upstream, resulting in the observed temperature gradient. The effect can be seen in several south Western Australian estuaries (Hodgkin 1978), but the increased effect in the Blackwood is likely to be due to the greater length of the estuary.

The rising tide prior to temperature sampling may contribute to the peaks at mid-depth. Water from the shallows of the inlet would have received considerable solar heating over the morning. This warm water was then transported upstream on the rising tide, in the upstream jet shown in the velocity profiles. This will add to the increase in temperature at mid-depths seen at all sites.

The cooler waters towards the inlet are a result of the marine influence. The ocean water has a small seasonal range of approximately 6°C (Hodgkin 1978), which is reflected in waters closer to the seaward boundary. The downstream waters will therefore not reach the high temperatures seen in the river. This adds to the longitudinal gradient shown in the contour profiles of the estuary.
The more extensive tidal mixing closer to the seaward boundary of the estuary would also contribute to the cooler temperatures seen in downstream sites. The greater velocity of tidal currents closer to the ocean will cause increased turbulent mixing between surface and bottom layers. The resulting lower temperatures can be seen in the temperature contour plot of the Blackwood River (figure 4.4). Further towards the mouth of the estuary it can be assumed this effect would be greater, with greater vertical mixing.

The bathymetry of the estuary appears to influence the temperature only by increasing the depth of the thermocline as water depth increases. This can be seen in the temperature contour of the estuary, where the deeper downstream sites show a sub-surface peak at a greater depth than in upstream sites.

From the temperature contour and profile, it appears that temperature of the water body is the cause of stratification during summer. However, salinity has been shown to have a much greater effect on density than temperature, with a 4°C change in temperature the equivalent of a 1 ppt change in salinity Imberger et. al. (1976). This implies that during the winter phase the salinity structure will be the cause of any stratification in the estuary.

### 5.3 Salinity

Salinity in the sampled lower Blackwood River is seen to decrease with distance from the seaward boundary. This is consistent with previous knowledge of estuarine circulation, and to be expected. Downstream, marine water increases salinity, and upstream salinity is lowered by freshwater discharge. There appears to be little transfer of momentum to cause mixing between isohalines, shown by the discrete contours in figure 4.7.

A layer of low salinity water was shown to occupy the surface waters of the estuary. This layer increases in thickness and salinity downstream, demonstrating a longitudinal salinity gradient. As shown in figure 4.1, the river discharge increased before the day of sampling, producing a lower salinity layer at the surface. The effect of the increase indicates that larger river discharges may greatly alter the salinity of the estuary.
The increase in thickness of the surface layer towards the mouth of the estuary may be due to the previous increase in river discharge, 5 days prior to the sampling period. The smaller increase may have produced a similar low saline layer that has remained in the surface waters since, but slowly increased in salinity due to tidal mixing in the estuary.

Salinity below the halocline (2 m) appears relatively constant throughout the Blackwood River, with a range of approximately 1.5 ppt across 11 km (figure 4.7). The salinity below 2 m is almost entirely above 30 ppt. The high salinity indicates the extent of tidal influence in the estuary, with marine water increasing salinity through the entire estuary over summer.

It was found that there was a region of high salinity deep water in the downstream sites. This can be attributed to the increasing water depth in this part of the Blackwood River. The local bathymetry shows an effective trough in this region, which may limit mixing between the deeper water layer and overlaying layers. Salinity in this trough is unlikely to decrease quickly until the winter condition sets in.

Imberger et. al. (1976) found that during the summer condition of 1974 all water in the inlet was greater than 30 ppt. The Blackwood River exhibited a similar longitudinal salinity gradient, with a halocline at approximately 1.5 m, and salinity below the halocline approximately 30 ppt. The salinity conditions of the estuary during the summer period are therefore found to be very similar between 1974 and 2001.

The temperature / salinity diagram for the Blackwood River shows the presence of the different water bodies influencing the estuary. The upstream sites showed the influence of two water bodies, one of high salinity and one of lower salinity. These are the seawater and the freshwater river discharge respectively.

The downstream sites appear to show the influence of more than two water bodies of differing characteristics. This is due to the increased mixing of water in the lower estuary on previous tides. As the tide floods and mixes the water, some seawater remains in the estuary and mixes with residing estuary water. This results in intermediate water bodies, displaying characteristics of both freshwater and seawater. The turbulent mixing of water exiting the Blackwood River was also described by Hodgkin (1978), based on observations and salinity data from the estuary.
The movement of water upstream, as described in section 5.3 and shown by figure 4.18, as well as the salinity structure in the estuary, is consistent with the salinity classification calculated in section 2.2.12. From the classification system proposed by Hansen and Rattray (1966), the estuary was classified as type 3b, where 99% of the upstream salt flux is caused by advection.

### 5.4 Dissolved Oxygen

Dissolved oxygen concentrations generally decrease with distance upstream and with depth in the Blackwood River. The increase in DO with depth indicates deeper waters are not being effectively mixed, and reinforces the stratification during the summer condition. This may provide a greater threat to the health of the system if the summer condition persists for longer periods due to decreases in river discharge.

The increase in DO concentrations downstream is attributed to increased mixing occurring between water layers closer to the seaward boundary. In this part of the estuary, tidal action increases mixing between surface and bottom layers, increasing oxygenation.

Imberger et. al. (1976) conducted little DO sampling, and as a result comparison is not really relevant. The changes in DO concentrations throughout the estuary are probably to be expected at the sites and times sampled. Much more extensive DO sampling would be required to gain any further conclusions on oxygen levels in the estuary.

### 5.5 Dominant Current Directions

The currents were resolved into upstream and cross-stream directions, seen in the current roses. These plots appear to show two dominant directions for all heights above the riverbed. The appearance of two frequently occurring currents is likely to be due to the orientation of the river in the vicinity of the ADCP. North of the sampling location is a slight bend in the river channel, which results in the ebb and flood phase currents to flow on slightly different alignments. This is consistent with knowledge of river bend flow discussed in section 2.2.7.

The dominant directions shown are generally consistent at all depths. At all sites the flood currents appear to be dominant, with the exception of the surface rose, where the ebb is both
stronger and more frequent. This is consistent with the basic model of estuarine gravitational circulation described in Fischer et al. (1979).

The scatter plots of N/S and E/W currents support the current rose data. They are well correlated and show similar dominant directions to the current roses. Most show only a small range of directions and current velocities.

### 5.6 Tidal Cycle

The currents measured throughout the water column were plotted and compared (figure 4.12), showing a consistent cycle at all depths. The observed cycle is due to the tidal regime, and shows a period of approximately 24 hours, demonstrating the dominant diurnal period.

The effect of the tides becomes clearer closer to the riverbed (figure 4.12). At a height of 3.12 m the tidal cycle of spring and neap tides has become clear, and is similar at the bed. In these plots the maximum velocities are not as large as near the surface, and there appears to be a greater symmetry between flood and ebb phases.

The plots of currents in the cross-stream direction show, to some extent, a similar cycle. The velocity range at all depths is lower, and again the cycle is much clearer near the riverbed. At the surface there is less of a cycle than in the upstream plots, which is to be expected. Local winds and the effect of low tidal range may influence the cross-stream currents.

#### 5.6.1 Tidal Asymmetry

The vertical plots (figure 4.12) show a definite tidal asymmetry near the surface. The flood phases are shown to be longer early in the sampling period, and ebb phases longer towards the end. This indicates that when river discharge is low, there is water movement upstream, which reverses with increases in discharge. Ranasinghe and Pattiaratchi (2000) showed that other diurnal estuaries of south Western Australia (Swan River estuary, Wilson Inlet and Peel-Harvey estuary) also displayed interchanging periods of ebb and flood dominance. They stated that the asymmetry is a result of generation of overtides.
The mean velocity profiles and residual currents of the estuary both demonstrate the tidal asymmetry of the estuary. The flood currents are shown to dominate, and result in much stronger currents than the returning ebb, demonstrating the flood-dominated tidal asymmetry. This is especially true near the surface. The upper layers are most influenced by freshwater discharge, and the mean profile demonstrates that when discharge is low, upstream water movement at these depths may occur. This results in water in the upper estuary displaying marine properties.

The residual current over a 24-hour (tidal) period was plotted (figure 4.19). This demonstrated a similar shape to the mean velocity profile, although currents appeared to be of slightly lower magnitude. Again, the residual current showed upstream movement near both the surface and riverbed, with a mid region of approximately equal ebb and flood phases. This is consistent with the residual profile shown in Imberger et. al. (1976), included in section 2.2.3.

The direct comparison of ebb and flood phases of the tidal cycle confirms the result that the flood cycle is stronger than the ebb, with a flood dominated tidal asymmetry. The flood profile is of the expected traditional mean velocity profile, while the ebb cycle still shows some upstream flow at a height of approximately 6 m above the bed. This may be due to the tidal lag between bottom and surface waters. As previously described, there exists a tidal lag through the water column, meaning that the “ebb” period may not be ebbing throughout the entire water column. Near the surface, the tide may actually still be flooding, which will cause the appearance of upstream currents on the ebbing tide.

It needs to be noted that the flood and ebb profiles were sampled on a spring tide. As shown in figure 4.21, the spring tide is much stronger than the neap, especially in the mid depths of the water column. Therefore sampling of the flood and ebb phases on a neap tide may yield different results.

Overall, the rising tide was shown to be longer then the falling tide, as well as producing flood currents with higher velocities (figures 4.12, 4.15, 4.18, 4.20). This may be a result of the ebb and flood currents not being exactly aligned, as discussed in section 2.2.7. The ADCP was positioned on a flood-preferred path, highlighted by the longer duration of the flooding tide, and faster flood currents produced. The result may have been different had it been positioned on the ebb-preferred path.
The occurrence of different flood and ebb paths is confirmed by figure 4.10. The roses indicate two frequently occurring current directions, for the flood and ebb respectively. The faster flood currents may then be a result of the positioning of the instrument, and not a true result of the flood-dominant tides.

5.6.2 Tidal Lag

Cross-spectral analysis and current measurements (figures 4.15 – 4.17) have shown the existence of a significant tidal lag between the bottom and surface waters. The lag results in bottom currents reversing on the tide before the surface waters, and means that the surface and near-bed currents may at times be flowing in opposite directions.

The tidal lag of surface waters has been described in many other waterways. Vennell (1994) stated the lag was due to the effects of bottom friction interfering with the oscillating flow. In the Blackwood River estuary the effects of the bottom friction and local bathymetry are therefore thought to produce a phase difference between near bottom and near surface waters.

5.6.3 Influence of River Discharge

The plots of velocity vectors (figures 4.22 – 4.24) throughout the water column indicate some of the features described above. The influence of the increases in freshwater inflow on the 5th and 9th May, and the continuous downstream flow after these periods, is illustrated in figures 4.23 and 4.24 respectively. The figures indicate how large river discharges would dominate estuarine circulation, especially at the surface.

5.6.4 Dominant Frequencies

Analysis of the measured current frequencies recorded in the estuary show the dominance of diurnal tides. As expected, the 24-hour tidal cycle is shown to have a greater effect on currents during the summer period than either 12-hour tides, or atmospheric variations on the order of days. This is consistent with the findings of Imberger et. al. (1976), and other south Western Australian estuaries (Hodgkin 1978).

Spectral density comparison of currents from the surface and riverbed indicate that the diurnal tides dominate circulation at the riverbed. This may be primarily due to the bathymetry of the
estuary, and the effect of the dredged navigation channel. The channel acts to shelter the deeper waters from other factors that may otherwise influence circulation. Due to the nature of the estuary, it may concentrate tidal energy to the dredged channel.

Currents at the surface showed the influence of several physical forcings. However, they appeared to be reliant on low riverine inputs from the Blackwood River. The change in direction of currents as freshwater discharge increased shows the dominance of freshwater inflow on circulation near the surface. In the absence of large river discharge, the diurnal and semi-diurnal tides, and atmospheric variations, all appear to influence circulation.

### 5.7 Implications for a marine reserve

Implications of the dominant factors influencing circulation will be of increased importance with the creation of the regions marine reserve. The increasing duration of the stratified estuary may then be of much greater importance in maintaining the health of the system.

During the summer period of 2000, the estuary was subject to potentially toxic blue-green algae blooms (WRC 2000). This came during a 3-year period of low discharge, in which the riverflow into the estuary did not come close to the threshold for the winter condition (figure 4.2). The estuary would have experienced extreme stratification, decreasing dissolved oxygen concentrations and causing an algal bloom.

As rainfall predictions have shown, the discharge into the estuary is likely to continue to decrease, decreasing the potential of the estuary to completely flush. Stratification of the estuary will therefore continue to be a problem. In order to counter the stratification, other management practices may have to be implemented to maintain the health of the system. If algal blooms persist in the estuary, methods such as nutrient reduction plans for the cleared catchment may need to be investigated.

The presence of the tidal asymmetry is important in terms of sediment transport in the estuary. Maintenance of the channel and possible nutrient transport make sediment transport mechanisms important. Although outside the scope of this study, sediment transport in the estuary should be investigated and monitored.
6 CONCLUSIONS AND RECOMMENDATIONS

A study of the dominant influences on circulation in the Blackwood River estuary was conducted. Previous research had highlighted the dominance of river discharge in driving the seasonal circulation of the estuary. This study suggests that under the summer condition, the tides are the dominant factor influencing circulation.

The dominance of the diurnal tidal regime was shown to be much greater at the riverbed. Local bathymetric irregularities may act to concentrate the tide towards the bottom of the water column, effectively sheltering the depths from external influences. At the surface, above the dredged channel, currents are influenced by 24-hour and 12-hour tides, as well as variations on the order of days. It can be concluded that the dredged channel influences circulation in the estuary.

The tidal asymmetry of the Blackwood River estuary was highlighted by the study. Tidal asymmetries in diurnal systems are generally a result of the generation of over-tides, and have been shown to interchange between periods of ebb- and flood-dominance. This study was carried out during a period of flood-dominance.

A phase difference was found to exist between surface and bottom waters, with the bed velocities leading the surface by 70°. This resulted in a 4-hour tidal lag between the surface and riverbed. It is thought to be a consequence of the effect of bed friction and the oscillating motion of the tide.

Temperature and salinity properties were found to be similar to previously described conditions. The stratification during the summer months is temperature driven, and similar to other south Western Australian estuaries. The salinity structure in the estuary was found to show marine influence at depth, with a surface layer displaying the influence of the low river discharge. As the discharge increases, it is thought that the salinity and temperature structures would be drastically altered. Local bathymetric irregularities may also influence deep-water characteristics.

Predictions of climate change effects in south Western Australia indicate that rainfall will continue to decrease in the Blackwood River catchment. Since 1983, the estuary has only been completely flushed with freshwater discharge 6 times, and further decreases in river
discharge will further decrease the occurrence of the winter condition. As a result the winter condition may never be reached, and the stratified condition of the estuary will be of great importance in the management and conservation of the estuary.

The field data processed in this study provides the foundation for a numerical model study of the estuary. This could ascertain seasonal conditions of circulation and how they may be affected by decreasing river discharge. Such a study may require field sampling during periods of increased river discharge. This study also made use of Imberger et al’s (1976) assumption that local winds did not have a significant effect on circulation. In order to validate this, field measurements of wind speeds would be required.

This study has highlighted the need for accurate resolution of the bathymetry of the upper estuary, namely the Blackwood River. This would be necessary in order to successfully model the system. A lack of up-to-date available data makes modelling of the system impractical in the present situation.

The presence of the tidal asymmetry can be important an important factor in sediment transport and the morphological evolution of the estuary. Further studies should concentrate on the transport of sediment into and from the estuary, and impacts on the marine reserve.
### 7 REFERENCES


*Australian National Tide Tables*, 2002.


Circulation in the Blackwood River Estuary

References

Department of Planning and Infrastructure (DPI), 2003. Hydrographic charts No.'s 698 (Hardy Inlet), P48913-1-6 and P48913-1-7, digital sounding files.


Pattiaratchi, C. 2003. Personal communications;


8 APPENDICES
8.1 Appendix 1: Power Cross Spectra from ADCP

Figure 8.1: The surface currents power spectral density and confidence

Figure 8.2: The bed currents power spectral density and confidence
Figure 8.3: The transfer function magnitude between the surface and riverbed currents.

Figure 8.4: The transfer function phase between surface and riverbed currents.
Figure 8.5: The coherence function between the surface and riverbed currents.
8.2 Appendix 2: Acoustic backscatter from the ADCP

Figure 8.6: Acoustic backscatter from the ADCP. Colours show number of counts of returned signals. Note that there appears to be correlation between backscatter and the tidal cycle.
8.3 Appendix 3: Echo Intensity from the ADCP

Figure 8.7: Echo intensity from the ADCP

Figure 8.8: Correlation between echo intensity and water depth. The plots on the left show current velocities and magnitudes.
8.4 Appendix 4: ADCP data from the omitted period

![Graph showing ADCP data](image)

Figure 8.9: Colour plot of whole sampling period, indicating time when profiler was moved.

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8.5 Appendix 5: ADCP E/W Data

Figure 8.10: East/west (u) currents measured by the ADCP.

Figure 8.11: Vertical plot of measured east/west (u) currents from the ADCP.

8.6 Appendix 6: ADCP N/S Data
Figure 8.12: North/south (v) currents measured by the ADCP.

Figure 8.13: Vertical plots of measured north/south (v) currents from the ADCP.