This dissertation is submitted as a partial requirement for the degree of Bachelor of Engineering (Applied Ocean Science) at the University of Western Australia.
ABSTRACT

The Blackwood River estuary is the largest river by flow volume in south west Australia. The estuary is under increasing pressure from climate change, dryland salinity, tourism and aquifer extractions. This study aimed to determine the current state of the estuary and the dominant estuarine processes, and to make predictions about the future of the estuary. To fulfill the objectives of the study, field work and hydrodynamic modeling were undertaken.

Initial field measurements revealed that bottom waters in the tidal river of the estuary were saline and low in oxygen, most likely due to low rainfall throughout the catchment in the previous six months. The later field measurements were consistent with two storm events throughout the catchment having begun to flush the river. Modeling using HAMSOM provided information about the conditions that would completely flush the entire estuary. Previous estimates of the river flow required to flush the estuary were overestimated compared to the model results. High surge was associated with increased salt transport into the estuary as expected. Comparison of the field and model data suggested that the model overestimated tidal lag in the estuary.

The dominant process affecting salinity structure in the estuary was streamflow. Tidal straining was evident in the salinity data, but not dominant in the overall energy balance. In the absence of streamflow, the estuary remained stratified, with gravitational circulation dominant. Climate change and aquifer extractions may decrease streamflow in the future, which would decrease both the oxygen supply to the estuary and the oxygen content in bottom waters. If dryland salinity results in an increase in the salt content of the river flow, the gravitational circulation in the estuary could be disturbed. Further research is recommended to determine the effect of increased salinity on ecological communities in the Blackwood, and to determine if the decrease in river flow in 2006 is due to climate change or natural variability of the river system.
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1.0 INTRODUCTION

1.1 Rationale

The Blackwood River estuary extends from Augusta through a large catchment in south west Australia, encompassing many unique ecological communities. The survival of these communities is dependent on the physical characteristics of the estuary. Changes to the estuarine dynamic sequence could impact on organisms in the estuary, excluding species that can no longer survive. In 1997, the Department of Conservation and Land Management (CALM) proposed the creation of the Capes Marine Park, extending from Busselton to Hardy Inlet, to preserve the distinctive coastal types and the wide range of habitats with high conservation value within the area.

In September 2006, the Indicative Management Plan for the Proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet Marine Park was released for public comment. Under this plan, three areas of the Hardy Inlet (North Bay, Deadwater and Swan Lake) would be classified as ‘sanctuary zones’, where recreational and commercial fishing is forbidden. The remainder of the estuary would be classified as ‘general use’, with no limitations on use. The estuary is a popular tourism area, with fishing, boating and other water based activities common throughout Hardy Inlet and the Blackwood River itself. Increasing tourism in the Margaret River – Augusta shire could impact negatively on the estuary’s flow characteristics in the future, through wastewater disposal, groundwater pollution and increasing recreational use of the estuary. Understanding the current dynamics of the estuary is necessary to effectively manage the tourism demands of the future.

Approximately 85% of Blackwood River catchment is cleared for farming and is either affected by dryland salinity or is vulnerable to salinity problems in the future. Widespread dryland salinity may alter the salinity of river water downstream. In addition, the Water Corporation proposes to extract water to supplement water resources from the Yarragadee aquifer, which underlies the Blackwood River catchment. This could decrease river flows in the future, and affect water quality in the Blackwood River. Climate change models predict that rainfall in the south west could significantly decrease in the future. In combination, the effects of dryland salinity, aquifer extractions and climate change may significantly alter flow in the Blackwood River, which could
disturb the flow dynamics of the estuary. Understanding the current flow characteristics and flushing dynamics of the Blackwood River estuary is necessary to allow changes to the flow regime to be predicted.

Intense field work undertaken in 1974 as part of an extensive mineral sands mining environmental assessment provided a basis for the project. The 1974 study relied solely on field data, because numerical modeling was not available at the time, so numerical modeling has not been undertaken for this estuary system. Numerical modeling can identify the dominant forces affecting the dynamics of an estuary. Studies associated with the impact of dryland salinity and the effect of the Yarragadee extractions provided further background information for this project.

1.2 Aim

The aim of this project was to examine the physical characteristics of the Blackwood River estuary and determine the extent and impact of estuarine processes. The motivation for the project was to increase the understanding of estuarine dynamics in the Blackwood River estuary, in order to better manage and protect the area.

1.3 Objectives

The objectives of this project were:

1. To collect dissolved oxygen, temperature and salinity data from the Blackwood River;
2. To model the Blackwood River Estuary system using hydrodynamic modeling;
3. To determine the flow conditions which completely flush the estuary;
4. To compare field results with previous studies in the Blackwood River;
5. To determine the dominant estuarine processes in the estuary; and
6. To make predictions about the future of the estuary specifically associated with reduced flow and increased salinity.

The methodology required to fulfill these objectives therefore had two main components: (1) field work in the Blackwood River, and (2) hydrodynamic modeling. Field work was undertaken in a section of the Blackwood River to determine the condition of the estuary and the extent of
salt water intrusion at the time of sampling. Hydrodynamic modeling was used to supplement and validate the field work and also to provide a view of the whole estuary as a system over a period of 24 days. The modeling provided information about processes that could only be implied from field data.

The modeling and field work were interpreted together to establish important processes in the system. Comparisons were also made between the current results and the results of past studies in the Blackwood River. The results were used to make predictions about how issues such as dryland salinity, Yarragadee aquifer extractions and climate change could affect the estuarine dynamics of the Blackwood River estuary.

The Blackwood River estuary is an important area for tourism, fisheries and conservation. A thorough understanding of the dominant processes in the estuary is necessary for effective future management.

A literature review is presented in Chapter 2, which describes relevant estuarine theory and previous work in the Blackwood River estuary. The aim of this section is to provide the background necessary to understand the motivation for the current project. The methods section in Chapter 3 outlines the field techniques and modeling used to fulfill the objectives. The results of the field work and hydrodynamic modeling are presented in Chapter 4, and discussion and analysis of the results are in Chapter 5. Conclusions are presented in Chapter 6, with recommendations for further work in Chapter 7.
2.0 LITERATURE REVIEW

An understanding of estuarine processes is required to analyse the Blackwood River Estuary. This literature review begins by describing the Blackwood River catchment. Estuarine processes are described in general and with application to the Blackwood River. The fundamental details of the hydrodynamic model used in this project are also described. Lastly, a review of the current knowledge of the Blackwood River and other south west Australian estuaries is provided.

2.1 Setting of the Catchment

The Blackwood River extends for 330 km throughout south west Australia, from Augusta inland to Dumbleyung and Narrogin (Figure 2.1). The Blackwood River drains a catchment of 28,000 km², including the salt affected wheatbelt and forest country (Brearley 2005). The estuary opens to the Southern Ocean at the Hardy Inlet in Augusta, which is sheltered by Cape Leeuwin. The river is considered estuarine until a point 42 km from the mouth. The physical setting of the catchment is relevant to the specific characteristics of the estuarine system.

Figure 2.1: The catchment of the Blackwood and Scott Rivers in south west Australia (Brearley 2005).
2.1.1 Climate

The climate of south west Australia is controlled by the seasonal movement of a belt of high pressure systems from west to east over the continent. The belt migrates northward in winter, resulting in winter storms that bring cold, moist air off the ocean. During summer, easterly winds transport dry, warm air from the desert. These easterly winds are moderated in the afternoon by the strong sea breeze system (Brearley 2005). The wind patterns can influence the mixing in an estuary, and a sufficiently strong wind blowing long enough will completely mix water in some estuaries from top to bottom (Beer 1997). Hardy Inlet is located on the southern edge of Western Australia, and experiences south west winds during winter and south east winds during summer (Bureau of Meteorology 2006). Wind data from Cape Leeuwin indicate that the average wind speed is 25 km/hr with gusts of over 100 km/hr possible (Bureau of Meteorology 2006). The impact of winds on vertical mixing in the estuary has not been quantified.

The average annual rainfall in the Blackwood River catchment varies from 1200mm in the south-west to 400mm in the north-east of the basin (Mayer et al. 2005). The isohyets, or lines of equal rainfall, are shown across the catchment in Figure 2.1 above. Rainfall becomes more variable inland and to the north and east (Brearley 2005).

The climatic pattern of Western Australia impacts upon the estuaries of the south west. Winter rain periods cause moisture to accumulate in the soils of the catchment, until creeks and rivers start to flow toward the sea (Brearley 2005). Summer rainfall can have a detrimental impact, because the dry landscape is vulnerable to erosion, particularly in agricultural areas with little vegetative cover (Brearley 2005). The climate of the south west creates seasonal flow characteristics in the Blackwood River system.

Rainfall has decreased in the south west since 1930, but runoff has increased due to rising groundwater levels (Brearley 2005). Climate change predictions by CSIRO (2001) due to the greenhouse effect show that rainfall in south west Australia could decrease by 60% by 2070 (Figure 2.2). Reduced rainfall in the future will affect the flow characteristics of the Blackwood River Estuary, by reducing flow and possibly increasing salinity (Mayer et al. 2005). Climate change may also cause increased flooding, but further research is needed to confirm this prediction (DEH 2003).
2.1.2 Geomorphology

The Blackwood River basin has an area of about 28,000 km² (Mayer et al. 2005). Bettenay and Mulcahy (1972) divide the catchment of the Blackwood River into four zones (Figure 2.3). The zone of old drainage in the eastern most part of the catchment is gently undulating land with quartz soils, poor drainage and rivers that flow infrequently. Further west, the zone of mature drainage is characterized by u-shaped valleys, with exposed laterite soils and seasonally flowing rivers. The zone of rejuvenated drainage is the lowest part of the catchment on the Precambrian Shield. This zone has v-shaped valleys with exposed granite rock and more runoff than the previous two zones. The portion of the catchment west of the Darling Fault is the Donnybrook Sunklands. This area has sandy sedimentary rocks. The river cuts meandering courses through
deep channels to the mouth. The estuarine extent of the Blackwood River system is confined to the Donnybrook Sunklands.

**Figure 2.3:** The catchment of the Blackwood River, showing fault lines and drainage zones (Hodgkin 1978).

### 2.1.3 Bathymetry

The physical characteristics of south west estuaries are determined largely by the seasonal pattern of winter wet and summer dry (Imberger et al. 1976). The bathymetry strongly influences the flow patterns and flushing in the Blackwood River estuary. The digitized bathymetry of the Blackwood River estuary from 2002 is shown in Figure 2.4. The bathymetry and morphology of the estuary are described in detail by Hodgkin (1978) and Imberger et al. (1976) and the main features of the whole river system shown in Figure 2.5 are summarised here. Figure 2.6 shows the geomorphology of the lower Blackwood estuary as it was in 1974 in greater detail. Note that for the remainder of this document ‘Hardy Inlet’ refers to the part of the estuary from the ocean entrance to Molloy Island.
Figure 2.4: The bathymetry of the Blackwood River Estuary, extending from the Hardy Inlet at the bottom of the figure to Warner Glen Bridge at the top of the diagram (Hunt 2003). Colours indicate depth in the estuary.
Figure 2.5: The Blackwood River Estuary from the estuary mouth at the bottom of the diagram, upstream to the estuarine limit, approximately 42 km from the mouth (Hodgkin 1978).
The river mouth cuts through a wave built barrier beach by a deep tidal channel into Flinders Bay (Imberger et al. 1976). During the decade of 1925 – 1935, the bar silted up and the entrance to the estuary moved 2 km eastward (Hodgkin 1978). In 1945, high river flow caused the entrance to silt up completely, causing flooding that was only relieved when the bar was manually cut through by digging and dynamite (Brearley 2005).

To the east of the entrance is a transient lagoon feature called Deadwater, which formed in the 1930 – 1945 period as a result of the moving entrance (Hodgkin 1978). Since that time, Deadwater has become progressively shallower over time and dunes surrounding it have been eroded. Since 1998, the sandbar between the Deadwater and the estuary has eroded, such that the Deadwater is now an arm of the inlet (Brearley 2005). Inland of Deadwater is Swan Lake, which was a shallow seasonal freshwater lake until the 1920s when the stream connecting it to the estuary was allowed to scour out and seawater flowed back into the lake (Imberger et al. 1976).
The ‘inlet channel’ refers to that part of the estuary from the entrance of the estuary to Point Irwin. The inlet is 3 km long and 0.5 km wide, with depths ranging from 2 – 8 m (Hodgkin 1978). The total area of the inlet is approximately 9 km$^2$. There is a large amount of mobile sand in the southern part of the inlet, and this causes significant seasonal differences in the inlet (Hodgkin 1978). The inlet is filled with 5 m of sediment, which have been scoured since the Holocene marine transgression 7000 years ago by flood flow from the riverine reaches of the Blackwood (Hodgkin & Hesp 1998).

The ‘basin’ is the portion of the estuary from Point Irwin to the mouth of the tidal river. This area is approximately 7.2 km$^2$ and is mostly under 2 m in depth (Imberger et al. 1976). A boat channel was first constructed in the eastern part of the basin in 1956, and the channel follows approximately the line of a natural channel in the basin (Imberger et al. 1976).

Upstream of Molloy Island, the estuary splits into the Blackwood and Scott Rivers. The Blackwood River north of Molloy Island is tidal. Between Molloy Island and Alexandra Bridge, the Blackwood River has a well defined channel of similar dimensions to the boat channel in the lagoon, with lateral lagoons and swamps where tributaries enter the river (Imberger et al. 1976). The river is narrow between Alexandra Bridge and Warner Glen Bridge, with depths of approximately 5 m. Numerous holes are present in this part of the river, with some holes at sharp bends being up to 22 m deep (Imberger et al. 1976). A rock bar is present past Warner Glen Bridge, approximately 42 km from the mouth, and the river is not navigable past this point. The Blackwood River is considered to be estuarine at least to this point, where the shallow rock bar less than 1 m in depth prevents the penetration of marine water any further upstream (Imberger et al. 1976).

The Blackwood River is the main source of water inflow to the Hardy Inlet, with the Scott River contributing only 11% of the discharge to the estuary (Hodgkin 1978). Although the catchment of the Blackwood is sixty-six times larger than the catchment of the Scott, the Blackwood only contributes five to six times the volume of water as the Scott because the Scott drains an area of much higher rainfall (Brearley 2005). The Scott River discharges to the Blackwood River through a 2 m channel upstream of Molloy Island and through the shallow Scott Basin, and is
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2.1.4 Salinity in the catchment

Salinity is a major environmental issue throughout south west Australia. It is estimated that 85% of the land in the Blackwood River catchment is cleared, with forested areas around Nannup the only remaining naturally vegetated land (Brearley 2005). Land clearing has resulted in at least 13% of the land in the catchment becoming afflicted by salinity (CENRM 2005). When deep rooted vegetation with high transpiration rates (mostly trees) is removed and replaced with shallow rooted crops with lower rates of transpiration, the underlying watertable rises (Williams 1999). Naturally occurring salts in the soil are mobilized, and deposited at the surface after evaporation, which results in waterlogged and salt stressed vegetation (Williams 1999). About 40% of the upper Blackwood catchment is waterlogged, making the remaining vegetation vulnerable to floods and erosion (Brearley 2005). The Water Corporation predicts a doubling of salinity in the Blackwood River over the next 50 years due to dryland salinity (CENRM 2005).

Historically, the Blackwood River has been a freshwater river. However, due to dryland salinity in the large agricultural upper catchment, the river has become brackish to moderately saline (Strategen 2005b). Hodgson et al. (2004) suggests that levels of revegetation as high as 75 – 100% are required throughout the agricultural portion of the catchment to halt the rising groundwater levels.

Approximately 47% of the Scott River catchment is cleared, but this land is not yet affected by salinity. There are other water quality problems associated with the Scott River’s catchment, with high rates of fertilizer application increasing the nutrient loading of the river to the Hardy Inlet (Brearley 2005).

There have been several studies that concentrate particularly on the Blackwood River catchment and the effects of increasing dryland and irrigation salinity. Hodgson et al. (2004) estimate that around 37,000 hectares of the Blackwood’s catchment is at risk of salinisation, and that only high levels of revegetation can reverse the salinity problem in the south west. There is also growing evidence that salt concentrations over a long period have sub lethal effects on species and
ecosystems (Goss 2003). Studies such as these highlight the importance of considering the Blackwood River estuary as a function of its entire catchment.

Salinity in the Blackwood River flow may eventually increase if dryland and irrigation salinity continues to spread throughout the catchment. Many streams and rivers in south west Australia are already marginal in quality, brackish or saline, with the salinity of 66% of rivers increasing since 1983 (Mayer et al. 2005). Four of the seven rivers in the Blackwood River Basin are classified as moderately saline, and the lower Blackwood River has become progressively more saline since the 1940s (Mayer et al. 2005). The mobilization of salt to rivers could have severe implications for the dynamics of the estuary.

2.1.5 Flora and Fauna

The flora and fauna that inhabit the Blackwood River system range from common aquatic species to specialized endemic species. To inhabit an estuary, flora and fauna need to be able to withstand extreme physical, chemical and biotic conditions (Brearley 2005). Organisms require high salt tolerance to cope with long temporal extremes of salinity (Hodgkin & Hesp 1998). There are very few published data about the specific salinity tolerances of Western Australia’s freshwater flora and fauna.

The stratified nature of estuaries increases productivity because at the interface between fresh and salty water, particles flocculate out of the water column, forming a rich sediment that feeds primary producers such as seagrasses (Mann 2000). Species assemblage, phytoplankton bloom potential and eutrophication are therefore controlled by freshwater discharge in an estuary (Chan & Hamilton 2001). If dryland salinity throughout the catchment resulted in increased salinity in river flow, water quality could significantly impact on the organisms living in the estuary.

Despite the harsh conditions experienced in estuaries, many organisms inhabit the Blackwood River estuary. There is a successful fauna of resident estuarine invertebrate animals, and a smaller group of animals that live in the estuary only during the summer marine phase (Brearley 2005). There are very few plants growing in the Hardy Inlet compared to other estuaries in the south west (Brearley 2005). Hodgkin (1978) found four species of seagrass in the estuary, including *Halophila ovalis*, which is present in the lower reaches of the estuary. The mostly marine conditions during summer force many freshwater species to be either excluded from the
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Literature Review

estuary or moved upstream to fresher waters. The period that the estuary spends in summer (salty) and winter (fresh) phases therefore determines the biological communities present in the estuary.

The Leeuwin Current carries tropical life southwards along the Western Australian coast, and results in the high catches of fish and mud crabs in Hardy Inlet (Brearley 2005). Recreational fishing is widespread throughout the Blackwood River system. Yellow-fin whiting and sea mullet are the two main species targeted by commercial operators in Hardy Inlet, and the size of commercial catches has been stable since 1996 (Fisheries 2005). The black bream was a popular recreational species in the past, but numbers seriously declined in the 1980s. The decline may have been caused by overfishing, or by declining water quality (Brearley 2005). Numbers of black bream in the estuary are now increasing again (Brearley 2005).

Biota are an important part of the sediment dynamics of an estuary, with some studies finding that biota can alter sediment erosion rates by more than two orders of magnitude (Uncles 2002). The effect of the biota in the Blackwood River estuary on the sediment is unknown, but with fossil deposits found in the Hardy Inlet aged between 3380 and 4475 years old, it is possible that biota have influenced the dynamics of the estuary in the past (Hodgkin & Hesp 1998). These deposits are now buried beneath 5 m of sediment in the Inlet.

Recent research indicates that biological – physical interactions in estuaries are much more important than previously understood (Uncles 2002). Studies of estuaries around the world could benefit from incorporating the effect of biological processes on sediment transport and morphodynamics into estuarine models (Uncles 2002). Little is known about the relationship between biological and physical processes in the Blackwood River estuary, and as such, it is important to conserve and protect the existing flora and fauna, in order to protect the entire estuary.

2.1.6 Water quality

Estuaries in south west Australia are particularly vulnerable to nutrient enrichment because of their evolutionary history of oligotrophic conditions (Brearley 2005). The Blackwood River estuary is currently below ANZECC guidelines for total nitrogen, total phosphorus and
chlorophyll \(a\) (Brearley 2005). However, changes to the catchment and reductions in river flows are increasing nutrient loading (Brearley 2005). The Scott River contributes approximately 40% of the phosphorus loading to the Hardy Inlet, despite the river only accounting for between 5 and 10% of river flow (Brearley 2005). This is due to inputs from domestic animals and fertilizer in the Scott River catchment. This poses a threat to the estuary because increased nutrient concentrations can impact on the organisms living in the estuary.

The dissolved oxygen content of the Blackwood River directly influences the respiration and health of aquatic organisms, and is determined by both physical and biological processes (CENRM 2005). Oxygen can enter water from the atmosphere, and this aeration process is increased by the presence of rocks or cobbles which break the surface of the water, resulting in increased water turbulence (CENRM 2005). Oxygen can also enter the water body through photosynthetic processes (Brearley 2005).

Low oxygen conditions can facilitate the release of nutrients such as nitrate and phosphate from sediments into the water column (Brearley 2005). Dissolved oxygen varies diurnally, with oxygen levels often decreasing overnight, when light levels decrease and aerobic respiration occurs (Brearley 2005). ANZECC guidelines stipulate that dissolved oxygen concentrations of less than 2.0 mg/L can make respiration difficult for most fish species and are detrimental to fish over long periods of time (CENRM 2005). Brearley (2005) suggests that levels of at least 5.0 mg/L are required in south west Australian estuaries to maintain healthy freshwater systems. Oxygen saturation of less than 50% can increase the potential for desorption of nutrients from sediments (CENRM 2005).

An example of the impact that water quality can have on the ecology of the Blackwood River Estuary was seen on 27 May 2006, when between 500 and 1000 mullet and black bream died in the Blackwood River between Molloy Island and Alexandra Bridge (Augusta Margaret River Mail 2006). Rain earlier in May transported organic material to the river, reducing the oxygen supply in the water (Augusta Margaret River Mail 2006). An algae bloom of *Karlodinium micrum* occurred prior to the fish kill, adding to the low oxygen levels in the bottom waters of the river. Periodic anoxia occurs in shallow, seemingly well mixed systems along much of Australia’s south coast (Davis & Koop 2006). Native fish species that occur in the Blackwood River require permanent water of adequate quality and suitable habitat (Strategen 2005b). Fish
kills are rare in the Blackwood, but this most recent kill highlights the vulnerability of the system to increased organic inputs.

Catchment scale control of nitrogen and phosphorus sources is needed in south west Australia to protect systems like the Blackwood River. Low adsorptive sandy soils transmit even moderate fertilizer applications to streams through surface and shallow sub-surface pathways in Western Australia (Davis & Koop 2006). As development and tourism expand in the region, it is possible that nitrogen and phosphorus loading to the Blackwood River estuary could increase in the future unless properly managed.

2.1.7 Public usage of the estuary

The town of Augusta is located on the banks of the Hardy Inlet. The shire of Augusta-Margaret River has a population of approximately 11,000, with over 500,000 tourists visiting the region every year (Trail 2005). Infrastructure such as reticulated water and sewerage does not exist in many areas, which presents a pollution threat and could impact on water quality in the Blackwood (Trail 2005). The increase in tourism over the last 5 years has also led to an increasing demand for recreational boating facilities.

In 1997, the Department of Conservation and Land Management (CALM) proposed the formation of the Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet Marine Park (Figure 2.7). This was in response to the increasing pressure on the area and the need to conserve natural habitats, while still allowing public access. Under this plan, three areas of the Hardy Inlet (North Bay, Deadwater and Swan Lake) would be classified as ‘sanctuary zones’, with the remainder of the estuary classified as ‘general use’. Effective management of the public usage of the estuary requires a thorough understanding of the dynamics of the estuary.
2.2 Estuarine processes

Estuaries have been defined by many authors for over 50 years, since Pritchard (1952). Definitions differ but one of the most useful definitions is:

‘an estuary is a narrow, semi-enclosed coastal body of water with a free connection with the open sea, at least intermittently, within which the salinity of the water is measurably different from the salinity in the open ocean’ (adapted from Cameron and Pritchard (1963)).

The Blackwood River estuary has a permanent connection with the Southern Ocean and the salinity within the estuary is usually measurably less than the salinity of the open ocean year round.

Estuarine processes are complex, with many processes of varying timescales affecting estuarine dynamics (Figure 2.8). The mixing of salt and fresh water in an estuary is dependent on many factors, including topography, river flow and tidal action (Dyer 1997). Since early studies such as Pritchard (1952), there has been a shift away from focusing on mean conditions, and more recognition for the role of tidal mixing and turbulence, and changes occurring over a tidal cycle (Uncles 2002). This section outlines estuarine processes in general, and describes the processes that are relevant to the Blackwood River Estuary system.
2.2.1 Tidal influence

Estuaries have open connections to the ocean, and as such, the volume of water in an estuary will rise and fall with the tides (Beer 1997). The volume of water in an estuary depends on the tide level and the exchange of water between ocean and estuary is driven in part by tidal activity. The total volume of water exchanged between an estuary and the open sea over a complete tidal cycle is called the ‘tidal prism’ (Beer 1997).

The tides also influence estuarine mixing processes. In a tidal estuary, the water at the edge of the estuary will be saltier than the water in the middle during downstream flow (Beer 1997). During upstream flow, the water in the middle of the estuary will be saltier than the water at the edge (Beer 1997). Tides can also propagate a salt wedge up and down the length of an estuary, which happens in the Swan – Canning estuary near Perth (Pattiaratchi pers. comm.).

Tidal straining is a process where the isohalines (the lines connecting points of equal salinity) are displaced by tidal currents, such that the isohalines become distorted and secondary currents can be generated (Uncles 2002). The strength of the tidal currents can therefore affect the stratification in an estuary. When tidal straining is occurring, maximum near-bed stratification occurs during late ebb tide and minimum near-bed stratification occurs during late flood tide (Uncles 2002).

The nature of a tide at a particular location depends on the dominant tide generating forces (Beer 1997). There are four main tidal constituents which affect the tide in Flinders Bay, which is the...
bay where the Blackwood River meets the Southern Ocean. $O_1$ refers to the main lunar diurnal component, $K_1$ is the lunisolar diurnal component, $M_2$ is the main semidiurnal lunar component and $S_2$ is the main semidiurnal solar component (Beer 1997). Imberger et al. (1976) measured the principal tidal harmonic constituents using tidal gauges in Flinders Bay. These results are compared to the Australian National Tide Tables 1975 in Table 2.1. The comparison of these data is good, with the exception of some small differences in the phase of the tidal components ($g^\circ$).

**Table 2.1:** Comparison of the principal harmonic constituents in Flinders Bay with the Australian National Tide Tables (Imberger et al. 1976).

<table>
<thead>
<tr>
<th></th>
<th>$O_1$</th>
<th>$K_1$</th>
<th>$M_2$</th>
<th>$S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$g^\circ$</td>
<td>$H_m$</td>
<td>$g^\circ$</td>
<td>$H_m$</td>
</tr>
<tr>
<td><strong>Average in Flinders Bay</strong></td>
<td>299</td>
<td>0.15</td>
<td>316</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>Australian National Tide Tables</strong></td>
<td>295</td>
<td>0.15</td>
<td>327</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Semidiurnal tides have two high water levels in 24 hours, whereas diurnal tides have only one high water level in 24 hours. By determining whether semidiurnal or diurnal components are more dominant, the type of tide can be predicted. The form factor ($F$) describes the tide at a particular location using the amplitudes of the tidal constituents, as shown below:

$$F = \frac{H_{K_1} + H_{O_1}}{H_{M_2} + H_{S_2}}$$

*Equation 2.1*

where

- $0 < F < 0.25$ semi-diurnal
- $0.25 < F < 1.5$ mixed, mainly semi-diurnal
- $1.5 < F < 3.0$ mixed, mainly diurnal
- $F > 3.0$ diurnal

Using the magnitudes from Table 2.1:

$$F = \frac{0.20 + 0.15}{0.05 + 0.07}$$

$$F = 2.92$$
A form factor of 2.92 indicates that the tide at Flinders Bay is mixed, but mainly diurnal. Mainly diurnal tides are common along the south west coast of Western Australia. Tidal ranges along the south west coast are generally around 0.4 m, with a maximum of 1.1 m at Fremantle, and slightly larger ranges at Albany and Esperance (Brearley 2005). These small tidal ranges are termed ‘microtidal’.

Astronomical tides are damped in estuaries, with the amount of damping dependent on the entrance channel, the depth of the channel and the extent of the bar (Brearley 2005). Seine Bay is located within the Hardy Inlet (Figure 2.6), and is protected by the presence of the bar. Imberger et al. (1976) found that daily tides at Seine Bay average about 70% of the daily tides in Flinders Bay. The phase lag across the bar was found to range from 1 to 2 hours.

Tides are further modified by the propagation across the shallow basin in the Blackwood River estuary. The rate of propagation depends on the amount of friction the tide needs to overcome. The propagation time of the tides through the estuary depends on the water level, with propagation times of approximately 2 hours at high water and 3 to 5 hours at low water (Imberger et al. 1976). Under high river flow conditions, tides are not propagated within the estuary, causing water levels to increase in the tidal river (Hodgkin 1978). During August 1974, high river flow resulted in water levels 6 m above normal summer levels at Warner Glen Bridge, while the 1964 floods caused the bridge to be completely underwater (Hodgkin 1978). During these floods, tides were not propagated up the river.

The tidal conditions of the Blackwood have affected the evolution of the morphology of the estuary. Tidal asymmetry occurs when the duration of the falling tide does not equal the duration of the rising tide (Ranasinghe & Pattiaratchi 2000). When the duration of the falling tide exceeds that of the rising tide, the system is ‘flood dominant’, while a system where the duration of the rising tide exceeds that of the falling tide is ‘ebb dominant’ (Ranasinghe & Pattiaratchi 2000). The degree of tidal velocity asymmetry, combined with the streamflow and baroclinic circulation, determine the long term erosion and accretion trends in an estuary (Ranasinghe & Pattiaratchi 2000). The velocity profiles of Hunt (2003) indicate that in the Blackwood River estuary flood cycle was stronger than ebb, resulting in a flood dominated tidal asymmetry. This result remains to be verified though, as the profiles were taken on a spring tide, and the positioning of the current profiler may have given an inaccurate representation of the system (Hunt 2003).
2.2.2 Non-tidal water level variation

Non-tidal forces also influence the water level in the Blackwood River Estuary. ‘Surge’ refers to water level changes that are not associated with tides or wind generated wave action, including the effects of barometric pressure, wind set down, wind set up and seiching (Jackson et al. 2002). Although astronomic tides have a range of only 0.7 m in the estuary, Imberger et al. (1976) found that the extreme range of water level in the Blackwood was 1.3 m, so surge can be equally as important as tides. In estuaries, seasonal water level changes associated with flood discharge can also contribute to non-tidal water level fluctuations (Jackson et al. 2002). Surge causes a variation in the location on the beach profile where wave processes may operate, and is expected to be of greatest importance in locations that are sheltered from both waves and tides, such as near the head of estuaries (Jackson et al. 2002).

Atmospheric pressure changes occur due to the passage of the band of high pressure systems across south west Australia. An increase in atmospheric pressure causes a depression in water level, and a decrease in atmospheric pressure allows water levels to rise, illustrated in Figure 2.9 and according to the relationship:

\[ \Delta \eta = \frac{\Delta P}{\rho g} \]

Equation 2.2

where \( \eta \) is the water level variation from the mean, \( \Delta P \) is the change in atmospheric pressure, \( \rho \) is the density of the water and \( g \) is gravitational acceleration (Dean & Dalrymple 2002). This is the inverse barometric effect. The pressure decrease due to the passage of Cyclone Vanessa in 1976 resulted in an increase in water level in the Blackwood River estuary, which caused the rock bar in the mouth of the Scott River to be completely submerged (Hodgkin 1978).
Seiching is an important oceanic process that affects water level on the scale of minutes and hours. Seiches are oscillations of water bodies, which can be initiated by passing storms and winds in enclosed and semi enclosed basins. Hardy Inlet is sheltered from south west winds and swell by Cape Leeuwin (Hodgkin & Hesp 1998). Seiching may occur on a scale of centimetres in the lagoon of the Hardy Inlet, but is unlikely to occur anywhere else in the estuary.

Continental shelf waves are long period waves that are propagated along the continental shelf, often generated by tropical cyclones in north west Australia. These waves are propagated down the coastline at speeds of approximately 500 km/day, and affect water levels for periods of about two weeks (Brearley 2005). The effects of continental shelf waves increase as the waves travel southward so estuarine water level in the Blackwood can be significantly affected by cyclones in the north of the state (Pattiaratchi pers. comm.).

Mean sea level change can affect the water level in the Blackwood River, over periods of years to decades. Water levels fluctuate with the formation and melting of polar ice sheets. The low lying land around estuaries is popular for urban development, so even small magnitude sea level changes can have significant impacts in estuaries (Brearley 2005). If current trends continue, climate change models predict an average of 53 cm increase in water level in the next 100 years (White & Church 2006). Although the magnitude of sea level increase depends on the climate
model used and assumptions of the author, an increase of even 20 cm in the low lying Blackwood River estuary would significantly alter the human usage and ecology of the estuary.

2.2.3 **Estuarine mixing processes**

Many authors have contributed to the knowledge of estuarine processes. Early studies recognized the fundamental elements of estuarine dynamics, but the development of numerical models and software in recent years has greatly assisted in advances in the understanding of complex processes (Uncles 2002).

The dominant estuarine mixing processes in the Blackwood River estuary affect the dynamics of the estuary. The balance between stratification and mixing is crucial to estuarine dynamics because the density gradient in a stratified fluid is resistant and requires an extra velocity shear to cause mixing (Dyer 1997). Mixing processes decrease stratification in the water column by decreasing the density difference between bottom and surface waters. The mixing of salt and freshwater in estuaries occurs by a combination of turbulence generated by shear at the sea bed and turbulence generated by shear at the halocline (Dyer 1997).

2.2.3.1 **Internal mixing**

There are three modes of internal mixing that are important in estuaries: entrainment, turbulent diffusion and internal waves. The instabilities that form at the interface between fluids depend on the thickness of the velocity and density interfaces (Dyer 1997).

Entrainment is a one way process where a less turbulent water mass becomes drawn into a more turbulent layer (Dyer 1997). This process occurs in stratified fluids where the estuarine Richardson number is greater than 0.25 (see Section 2.2.8.1 below). When a light surface layer is passed over a static denser layer, the density interface remains smooth for small current shear (Dyer 1997). As the shear increases, the interface becomes disturbed by waves, which eventually break and elements of the denser water are ejected from the crests into the lighter water above (Dyer 1997). The breaking internal waves cause entrainment of salt into the upper layers of the fluid. Mixing can occur in an estuary with no mean shear, and entrainment can occur in an
otherwise undisturbed flow (Imberger et al. 1976). In most estuaries, both mixing and entrainment are responsible for the exchange to some extent.

Turbulent diffusion is different from entrainment in terms of the degree of turbulence between the fluid layers. The induced baroclinic velocity field due to the tidal force will have shear that may lead to instability and turbulence generation (Imberger et al. 1976). In fluids where estuarine Richardson number is less than 0.25, turbulent diffusion can occur (Dyer 1997). The instabilities that form between the layers of fluid are called ‘Kelvin-Helmholtz instabilities’, which billow and collapse, causing the density interface between the fluids to increase in width (Dyer 1997). Another type of internal mixing is caused by internal waves, which are wave features along the fluid interface with longer periods than the instabilities caused by entrainment and turbulent diffusion (Dyer 1997).

2.2.3.2 Other mixing processes

Turbulence generated at the boundaries of the flow causes mixing, such as wind at the air water interface, or the turbulence at a boundary layer (Imberger et al. 1976). The frictional drag at the seabed produces a velocity shear and turbulence is created by the flow over and around the roughness elements of the bed (Dyer 1997). In most estuaries, mixing is a combination of internal mixing processes and boundary generated turbulence. In highly stratified estuaries, internally generated turbulence is more important than boundary generated turbulence (Dyer 1997). The opposite is true in well mixed estuaries, where boundary turbulence dominates over internally generated turbulence.

The primary flow is usually driven by the slope of the tidal wave, with wind stresses and internal density variations of lesser importance (Fischer et al. 1979). Estuarine flow also oscillates, resulting in complex, unsteady and spatially variable flow (Fischer et al. 1979). Mixing results from a combination of small scale turbulent diffusion and a larger scale variation of the field of advective mean velocities (Fischer et al. 1979).

Wind can be a dominant mixing process in the open ocean and in lake systems. The wind has little chance to generate currents in long narrow estuaries (Fischer et al. 1979). Imberger et al. (1976) concluded that wind is not a dominant input to the Blackwood River Estuary, although it
does contribute to the mixing properties of the surface layer, particularly in the lagoon. More recent research in other estuaries suggests that wind mixing may indeed be significant in the lagoon of the Hardy Inlet, where water level is shallow (Uncles 2002). Hearn and Robson (2002) found that wind mixing produced channel exchange in the Harvey estuary in south west Australia. Wind set-up was about 20% of the exchange due to tides, so wind had a small but physically significant effect. Although the basin of the Harvey estuary is larger than the Hardy Inlet lagoon, wind may still be important in the Blackwood River estuary.

2.2.4 Gravitational circulation

The dynamics of estuaries are further complicated by gravitational circulation, which is driven by pressure gradients. The pressure at any depth in the estuary is composed of two parts: one part is due to the density distribution, which depends on temperature and salinity, and the other part is due to the slope of the free surface (Dyer 1997). Flow driven by density is ‘baroclinic circulation’, as distinct from ‘barotropic circulation’ which is driven by the sea surface gradient. Gravitational circulation is driven either by baroclinic forces, by barotropic forces, or by a combination of the two forces.

A longitudinal density gradient is a characteristic of many estuaries, extending from the less dense freshwater at the river end to the denser seawater at the mouth. Freshwater river flow is an input of buoyancy, mass and momentum (Imberger et al. 1976). Gravitational circulation in partially mixed estuaries is a bidirectional flow with a surface current flowing seaward and a landward near-bed flow (Ribeiro et al. 2004). The dominant factor in the dynamic balance of partially mixed estuaries is the interaction between the surface barotropic tide and the steady horizontal density gradient (Dyer 1997).

The barotropic velocity field generates turbulence at the seabed and at the sides of the estuary, which results in mixing (Imberger et al. 1976). In partially mixed estuaries, the form of the salinity profile remains similar throughout the tide as it is advected backwards and forwards (Dyer 1997). Barotropic and baroclinic gradients alternately oppose and reinforce each other on the ebb and flow tides, which are considered the primary mechanisms causing vertical shear in the residual flow (Dyer 1997). In well mixed estuaries, there are generally significant longitudinal
salinity gradients. These gradients provide the main mechanism for upstream dispersion of salt, which counteracts the downstream advection of the river flow (Dyer 1997).

Solar radiation can be an important input into lake and river systems. Energy received by surface heating from the sun can stabilize the water column and increase stratification (Gale et al. 2006). Heating is important in closed lake systems that have no tidal or river input, but it is not considered important in a permanently open estuary such as the Blackwood River estuary, which has an open exchange with the ocean (Gale et al. 2006).

2.2.5 Dynamic sequence

The Blackwood River is the largest river by flow volume in the south west (Mayer et al. 2005). Estimates of annual flow in the Blackwood River range from 622 GL (Morrissy 1974) to 925 GL (Hodgkin & Hesp 1998), depending on the location where flow data were collected. The hydrology of the Hardy Inlet is largely influenced by the Mediterranean climate of the area, because the dynamics of the estuary are almost completely controlled by the freshwater discharge at the head of the estuary (Imberger et al. 1976). Tides are more important for smaller time scale processes, and often influence the actual vertical structure of the estuary (Imberger et al. 1976). There are two sources of water to the estuary: marine saltwater from the ocean, and fresh water flowing from the Scott and Blackwood Rivers. The season determines the relative influence of freshwater and saltwater.

The sequence of conditions in the Blackwood River Estuary depends on season and river discharge. Increased river flow causes both a downstream movement of the salinity intrusion and a more rapid circulation of water, which leads to a more rapid exchange of freshwater with the ocean (Dyer 1997). The salt wedge structure of the estuary during much of the year determines gravitational circulation and mixing processes. In the Blackwood, the effect of temperature on density is considerably less than the effect of salinity over naturally occurring ranges (Imberger et al. 1976). The entire dynamic sequence is described in detail by Hodgkin (1978) and Imberger et al (1976), and the main features of this sequence are outlined here. Figure 2.10 shows the flow required for each condition, with flow data that were extrapolated from Darradup to Warner Glen Bridge by Imberger et al (1976). Figure 2.11 shows salinity profiles for the whole estuary from April to October 1974.
Figure 2.10: The total flow per day entering the estuary, estimated at Warner Glen Bridge during 1973 – 1974, and the condition of the estuary with each flow rate (Hodgkin 1978).

Figure 2.11: Salinity profiles from site 0 (ocean) on the right side to site 210 (upstream of Warner Glen Bridge) on the left side showing the changes from the summer condition (11-4-74) to the winter condition (20-10-74) (Hodgkin 1978). The lines shown are isohalines, which indicate lines of equal salinity.
Imberger et al (1976) found that when river flow to the estuary exceeds 20 GL per day, salt water does not intrude and the estuary is fresh throughout. This is the winter condition, as shown in Figure 2.11 (20-10-74). Tidal currents that pump in seawater are not strong enough to overcome the strong freshwater flow. The estuary is a fast flowing river with a considerable head of water in the upper estuary. In years of low river discharge, it is likely that the winter condition is never achieved. During the winter condition, the flow is fully turbulent, with vigorous vertical mixing. The whole volume of the estuary is exchanged on a time scale of 2 days (Imberger et al. 1976).

When river flow is below 20 GL per day, salt water can flow into the estuary beneath the outflowing freshwater on the incoming tide. This forms a salt wedge. The ‘salt wedge condition’ is the transition between the summer and winter conditions, shown in Figure 2.11 (16-5-74) (Imberger et al. 1976). On the outgoing tide, the upper portion of the salt wedge is entrained with the outgoing flow. Mixing occurs outside the mouth, and water of intermediate salinity returns into the estuary. The exchange for the bottom waters is of the order of days.

If river flow decreases to less than 2 GL per day, high salinity water can traverse the basin with rising tides and cascades into the deeper water upstream to form a salt wedge in the tidal river. The response to changes in river flow is slower in the tidal river than in the basin, because of the large distance between the tidal river and the mouth of the estuary, and because of the effect of the shallow basin. The adjustment of the salt wedge structure in the inlet channel following changes in river flow is rapid (less than one day), whereas the adjustment in the tidal river is of the order of a few days to a week.

Very low summer flows (less than 0.25 GL per day) in the Blackwood River Estuary allow salt water to penetrate most of the estuary. The inlet is virtually marine, with salinities over 30 throughout. This summer condition is established around January, and is shown in Figure 2.11 (11-4-74). The estuary is tidally dominated and the small river flow has negligible effect on the currents. A small freshwater input at the head maintains a fresh layer in the upstream part of the estuary. Vertical exchange is inhibited, and the exchange time for the bottom waters is several weeks (Imberger et al. 1976).
It should be noted that the field work by Imberger et al (1976) to determine the river flow was undertaken during 1974, when winter flow was the highest on record. Some of the estimates made may therefore be overestimated compared to normal flow conditions. The gauging station used by Imberger et al (1976) was located at Darradup, 65 km upstream of Warner Glen Bridge, as this was the only operating gauging station at the time. River flow entering the estuary was extrapolated from flow data at Darradup, but 80% of the water entering the estuary is from areas downstream of Darradup (Hodgkin 1978). This may have contributed to errors in the flow estimates of Imberger et al (1976).

The historic mean monthly river discharge for the Blackwood River is strongly seasonal and highly predictable with generally low variability each month (Pettit et al. 2001). River flow increases as a result of increased rainfall on average around July. There is a considerable time lag between the early rains and the response of river flow. Once the river is flowing, the low salinity freshwater pushes seaward, resulting in the winter condition returning around July or August, with the upper estuary and basin fresh throughout.

### 2.2.6 Potential energy anomaly

The potential energy anomaly (Φ) is defined as ‘the amount of energy required per unit volume to change a stratified water column to its corresponding homogenous state’ (Ranasinghe & Pattiaratchi 1999). The potential energy anomaly is a useful technique for investigating the physical processes governing vertical mixing and stratification (Gale et al. 2006). Using the following energy balance, the contribution of each term can be determined using the following equation for the change in potential energy anomaly with time:

\[
\frac{d\Phi}{dt} = \frac{1}{320} g h^4 \left(\frac{d\rho}{dx}\right)^2 + \frac{1}{2} \rho \frac{d\bar{u}}{dx} \left(\frac{d\rho}{dx}\right) + \frac{g \rho \beta s P}{3\pi} - \frac{4}{h} \rho \delta - \frac{4}{h} k_D \rho \bar{u} - \frac{4}{h} k_s \rho_a \frac{W^2}{h}
\]

Equation 2.3

where \( h \) = water depth, \( K_z \) = vertical eddy viscosity, \( \rho \) = water density, \( \bar{u} \) = depth integrated current, \( \beta \) = coefficient of saline contraction, \( s \) = salinity, \( P \) = precipitation, \( \varepsilon \) = tidal mixing efficiency, \( k_D \) = drag coefficient for bottom stresses, \( \bar{u} \) = mean tidal current, \( \delta \) = wind mixing efficiency, \( k_s \) = drag coefficient for surface stresses, \( \rho_a \) = density of air and \( W \) = mean wind speed.
The first term represents gravitational circulation, the second term represents energy from tidal straining, the third term represents rainfall input, the fourth term represents tidal mixing and the fifth term represents wind mixing (Ranasinghe & Pattiaratchi 1999). When the change in potential energy ($d\Phi/dt$) is positive, the water column is stable and stratified, and when $d\Phi/dt$ is negative, the water column remains well mixed in the vertical (Gale et al. 2006).

Ranasinghe and Pattiaratchi (1999) successfully applied this method to Wilson Inlet, Western Australia. This analysis revealed that solar heating dominated stratification processes, and that convective cooling and wind mixing caused vertical mixing at night (Ranasinghe & Pattiaratchi 1999).

2.2.7 Flushing time

The flushing time is often calculated for estuaries because of its ecological implications. The flushing time is the time required to replace the existing freshwater in the estuary at a rate equal to the river discharge (Dyer 1997). When flushing time is long, bottom waters in particular can become hypersaline and anoxic, affecting ecological communities. Flushing influences chemical transformations, denitrification and nutrient uptake in estuaries (Ensign et al. 2004). The flushing time also has applications for pollution dispersion in an estuary, because it determines how quickly the pollutant is discharged into the ocean (Dyer 1997).

There are many methods for calculating flushing time. The ‘fraction of freshwater’ method calculates flushing time based on freshwater flushing due to river flow (Dyer 1997). The ‘tidal prism’ method calculates flushing time from the flushing due to the exchange of water by the tide (Dyer 1997). The fraction of freshwater method is useful in estuaries with significant freshwater flow, whereas the tidal prism method is more applicable to estuaries with very little freshwater flow (Sheldon & Alber 2006). The freshwater river flow in the Blackwood River estuary is sufficient to use the fraction of freshwater method (Pattiaratchi pers. comm.). Other methods for calculating flushing time require velocity and tidal data which are not readily available.
2.2.8 Estuarine classification

There are three types of estuarine classification that can be applied to the Blackwood River estuary: the Hansen-Rattray classification, the estuarine Richardson number and the morphological classification.

2.2.8.1 Hansen-Rattray classification

In estuaries, the dominant density variations arise from salinity differences, so classification of estuaries is often by vertical salinity structure (Beer 1997). The Hansen-Rattray classification classifies estuaries in this way.

The balance between gravitational circulation and tidal mixing determines whether an estuary is stratified, since gravitational circulation increases stratification and tidal mixing decreases stratification. Based on this concept, Hansen and Rattray (1966) classify estuaries by two dimensionless parameters: the stratification parameter and the circulation parameter. The stratification parameter is the ratio of the top to bottom salinity difference to the mean salinity over the section, while the circulation parameter is the ratio of the net surface current to the mean freshwater velocity through the section (Hansen & Rattray 1966):

\[
Stratification \; parameter = \frac{\delta S}{S} \quad \text{Equation 2.4}
\]

\[
Circulation \; parameter = \frac{U_s}{U_f} \quad \text{Equation 2.5}
\]

where \( S \) is the time-mean salinity, \( u_s \) is the longitudinal time-mean velocity at the surface \( z = 0 \) and \( U_f \) is the integral mean velocity.

This classification has resulted in the widespread use of the Hansen-Rattray diagram (Figure 2.12). By calculating the stratification and the circulation parameters, the diagram can be used to classify an estuary. Hansen and Rattray (1966) describe the estuary types found on the Hansen-Rattray diagram (Figure 2.12). The ‘well mixed’ estuary has slight stratification, with net flow seaward at all depths and upstream salt transfer is by diffusion. The ‘partially mixed’ estuary has a reversed flow at depth, with both diffusion and advection contributing to upstream salt transport. In a ‘fjord’ estuary, the system is stratified and advection accounts for more than 99%
of the upstream salt flux. ‘Salt wedge’ estuaries are similar to fjord estuaries, but with even greater stratification. Estuaries in the salt wedge condition have a high density, saline body of water intruding into the estuary from the ocean underneath the fresh water flowing from the river. The Hansen-Rattray classification is useful, but does require that all necessary parameters have been measured. It should be noted that position within the estuary and season can also influence the classification.

![Hansen-Rattray diagram](image)

**Figure 2.12:** The Hansen-Rattray diagram for estuarine classification, which uses the stratification and circulation parameters defined above (Dyer 1997).

2.2.8.2 Estuarine Richardson number

The ‘Estuarine Richardson number’ is another method for classifying estuaries (Fischer et al. 1979). The Estuarine Richardson number, $R$, expresses the likelihood that a buoyant discharge mixes vertically in a river flow:

$$ R = \frac{\Delta \rho g Q_f}{\rho W U_t^3} $$

**Equation 2.6**

where $U_t$ is the root mean squared tidal velocity, $W$ is the channel width, $Q_f$ is the discharge flow of freshwater and $\Delta \rho$ is the density difference between the two water bodies.
If R is very large (R > 0.8), the estuary will be strongly stratified and the flow dominated by density currents, whereas if R is small (R < 0.08), the estuary will be well mixed and density effects can be neglected (Fischer et al. 1979). For 0.08 < R < 0.8, estuaries are in transition between well mixed and strongly stratified (Fischer et al. 1979).

During summer in the Blackwood River, the freshwater flow (Q_f) decreases, so R would be small and density effects are not important. Summer flow is therefore dominated by tidal mixing. In winter, the freshwater flow increases, R increases, the estuary is strongly stratified and density currents dominate. This classification is particularly useful as it reflects the changing condition of the estuary with season, but as with Hansen Rattray classification, the calculation requires large amounts of information.

2.2.8.3 Morphological classification

Hodgkin and Hesp (1998) reviewed estuarine evolution and proposed an estuarine classification system according to geomorphology. This classification reflects the Pleistocene inheritance and the changes that have occurred in south west estuaries since the Holocene marine transgression (Hodgkin & Hesp 1998). Table 2.2 and Figure 2.13 show the main elements of this classification. The Blackwood River estuary is classified morphologically as a valley estuary (Hodgkin & Hesp 1998).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description of estuary</th>
<th>Orientation to coast</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riverine</td>
<td>Narrow riverine channels</td>
<td>Roughly perpendicular</td>
<td>Murchison</td>
</tr>
<tr>
<td>Inter-barrier</td>
<td>Elongate lagoons</td>
<td>Parallel</td>
<td>Leschenault</td>
</tr>
<tr>
<td>Valley</td>
<td>Drowned valleys</td>
<td>Roughly perpendicular</td>
<td>Swan Canning</td>
</tr>
<tr>
<td>Basin</td>
<td>Rivers meander across a depression</td>
<td>Perpendicular</td>
<td>Wilson</td>
</tr>
</tbody>
</table>

There are four stages of isolation defined for estuaries, depending on whether the estuary is permanently open, seasonally open or closed, normally closed or permanently closed (Brearley 2005). Permanently open estuaries have bars and tidal deltas which obstruct tidal exchange but rarely close the estuaries (Hodgkin & Hesp 1998). The entrance of the Hardy Inlet has migrated eastward twice in the last 130 years, but has only closed once in that time, so it is classified as
being in the permanently open isolation stage (Hodgkin & Hesp 1998). The morphological classification accurately describes the shape and formation of the Blackwood River estuary, but is limited because it does not predict the processes that operate within the estuary.

Figure 2.13: Geomorphic types and features of estuaries of south west Australia (Hodgkin & Hesp 1998).

2.3 Modeling

Three dimensional numerical modeling is a useful tool for describing the hydrodynamic characteristics of an estuary. Models can incorporate wind and tidal data to give accurate predictions of flow and flushing. When the results of a hydrodynamic model were compared to field results in the Hudson River estuary, Warner et al. (2005) found that the model accurately represented temporal variations in salinity and currents. The model showed stratification extending all the way to the surface, when there was actually a well mixed surface layer present. These authors also found that the salinity within the domain was very sensitive to the specification of the salinity at the boundary.

Hydrodynamic models are utilized by many authors to study estuaries, and many aspects of modeling are similar regardless of the location of the estuary. An idealized estuary 3-D model was developed to confirm Hansen-Rattray scaling relations for a theoretical estuary and found that time dependence is an essential consideration if stratification varies with the magnitude of turbulent mixing (Hetland & Geyer 2004). The results of this study indicate that estuarine
stratification and exchange are independent of the magnitude of turbulent mixing and depend only on estuarine geometry and freshwater discharge. This indicates that hydrodynamic modeling using inputs of bathymetry and river flow can effectively model estuarine processes.

2.3.1 Fundamental equations

Three dimensional numerical models are based on fundamental fluid mechanics equations, including conservation of mass, conservation of momentum, and conservation of other scalar variables such as salinity and temperature.

Conservation of mass

Assuming an incompressible fluid, conservation of mass is given by:

\[
 \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

where \( u, v \) and \( w \) are the velocity components in the \( x, y \) and \( z \) directions respectively.

Conservation of momentum

Conservation of momentum in the \( x \) and \( y \) directions is described by the Navier-Stokes equations.

In the \( x \) direction:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + f v + \frac{\partial}{\partial x} \left( A_H \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y} \left( A_H \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z} \left( A_H \frac{\partial u}{\partial z}\right)
\]

In the \( y \) direction:

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + f u + \frac{\partial}{\partial x} \left( A_H \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y} \left( A_H \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z} \left( A_H \frac{\partial v}{\partial z}\right)
\]

where \( u(x, y, z, t), v(x, y, z, t), w(x, y, z, t) \) and \( p(x, y, z, t) \) are the velocity components and pressure fluctuations, and \( A_H \) and \( A_v \) are the horizontal and vertical kinematic eddy viscosities.
Assuming that the pressure gradient is exactly matched by the gravity force, the pressure distribution is hydrostatic and conservation of momentum in the z direction becomes:

\[
\frac{\partial p}{\partial z} = -\rho g
\]

2.3.2 The Hamburg Shelf Ocean Model

The Hamburg Shelf Ocean Model (HAMSOM) is a three dimensional primitive equation numerical model, which was originally developed for the North Sea, but has also been adapted to model coastal waters. A full description of the model is given in Backhaus (1985) and Stronach et al. (1993), and the main features of the model are described here.

HAMSOM is a three dimensional baroclinic primitive equation model based upon a semi-implicit discretisation (Backhaus 1985). The model allows for variable x and y grid spacing, and variable vertical layer sizes. The model uses fixed permeable interfaces between layers. The equations of continuity and momentum are vertically integrated over a depth range of h, corresponding to a computational model layer of the same thickness. At the sea surface, kinematic boundary conditions are applied, and at the sea floor quadratic bottom stress terms are applied. HAMSOM can be applied in a fully barotropic or fully baroclinic mode. A number of boundary conditions are necessary for HAMSOM to function. At closed boundaries, no flux conditions must be prescribed, whilst at open boundaries, water level and flow conditions must be prescribed.

HAMSOM has been successfully adapted and applied to many Western Australian areas, including the Swan River estuary (Burling 1994), Wambro Sound (Gersbach 1993) and Wilson Inlet (Ranasinghe & Pattiaratchi 1998). The attenuation of the tide as it travels up the estuary is accurately reproduced in applications of the model in Western Australia (Ranasinghe & Pattiaratchi 1998). It is not possible for any field program to sample every point in an estuary, so HAMSOM is a valuable tool that can be used to supplement field work.
2.4 Previous studies of the Blackwood River system

There have been a number of studies undertaken which focused on the Blackwood River. These previous studies are described in detail here, to emphasize areas that require further understanding.

2.4.1 Environmental studies from 1974-1976

Plans to mine mineral sands from the Hardy Inlet were proposed by the Project Mining Corporation in 1973 (Estuarine and Marine Advisory Committee 1976). The Environmental Protection Authority recommended that no further action be taken until further research was undertaken into the impacts of mineral dredging on the ecology of the Blackwood River. The Blackwood River thus became the focus of an extensive investigation by Imberger et al. (1976) from 1974 – 1975. The environmental work had two components:

1. to predict the effects of mining and dredging on the estuary; and,
2. to understand the working of the Blackwood estuary ecosystem as the basis for making decisions about the management of the Blackwood and other estuaries in south west Australia (Hodgkin 1978).

The study involved many types of sampling and observations, including measuring the physical parameters of the river and estuary over a period of months to observe flow dynamics. Horizontal and vertical velocities and sediment transport were calculated to predict the impact of sand dredging. Water quality and biological sampling were also undertaken. After the results of the study were published, the Environmental Protection Authority recommended that the dredging should not be approved, on the basis that the dredging could have a negative impact on the ecology of the estuary.

The extensive environmental work undertaken was uncommon in the 1970s. The Blackwood study has provided a background for understanding other estuarine systems in south west Australia (Brearley 2005). However, because this work was undertaken over 30 years ago, many advances have since been made in estuary science, with numerical modeling and more powerful instruments now available to assist research. There is now more focus in estuarine science on
processes occurring within one tidal cycle (Dyer 1997). In addition to this, no measurements or predictions of dissolved oxygen concentration in the water were made in the 1974 study. It is therefore necessary to revisit some of the aspects of the research undertaken by Imberger et al. (1976) and apply recent findings. This will be undertaken as part of the current work.

2.4.2 **Hunt (2003)**

Hunt (2003) studied the circulation in the Blackwood River Estuary. Data were collected from an Acoustic Doppler Current Profiler (ADCP) located approximately 2 km north of Molloy Island, deployed in April 2001. Hunt (2003) also used data from Conductivity Temperature Depth (CTD) sampling, which was undertaken between Molloy Island and Alexandra Bridge in May 2001. Results showed that tidal action was the dominant mixing force in summer. A longitudinal temperature gradient upstream was found, similar to previous data from 1974. Tidal asymmetry was found in the estuary, with the system being in a state of flood dominance.

The conclusions of this study were limited by the positioning of the current profiler in the estuary. Hunt (2003) created a digitized bathymetry for the Blackwood River Estuary (Figure 2.4), using depth data from Augusta, upstream to around Warner Glen Bridge, but hydrodynamic modeling was not undertaken.

2.4.3 **WA State Government Yarragadee investigations**

Due to recent shortages in water supply in Perth, the Western Australian State Government is investigating alternative sources of water within the state. One proposed option is to use water from the Yarragadee aquifer. The Yarragadee aquifer is the deepest aquifer in south west Australia, and contains 800,000GL of water that is up to 36,000 years old (Brearley 2005). The State Government’s proposal involves the abstraction, treatment and conveyance of 45 GL/year of groundwater from the Yarragadee formation from the eastern side of the Blackwood Plateau for supply into Perth’s scheme water (Strategen 2006).

There is concern that extractions from the Yarragadee aquifer could have the potential to reduce flows of fresh water to the Blackwood River. As a result, the Water Corporation undertook environmental impact assessments in the Blackwood. Many data have been collected, including flow and water quality data, as well as fauna and flora sampling. This work found that although
the tributaries to the Blackwood have high water quality and are relatively undisturbed, the water quality of the Blackwood River itself is low (Strategen 2005a).

The Water Corporation’s investigations included assessment of the flow requirements necessary to maintain the ecological values of the river. This study found that 25 – 30% of current flow is required to maintain the current ecological values (Strategen 2005b). However, the Water Corporation has to date made no allowance for the effect of climate change on the project. Climate change combined with the impact of the aquifer extractions may have a combined detrimental effect on the estuary.

The investigations into the impact of the Yarragadee water extractions are detailed with regards to the rivers and tributaries upstream of Hut Pool, but make no predictions about the impact on the estuary downstream. The Water Corporation’s investigations assume that since the estuary is highly tidal, it is considered ‘beyond the influence of any perceived impacts of the Yarragadee proposal’, with a loss of river flow into Hardy Inlet considered of ‘low likelihood’ (CENRM 2005). However, the predicted 10% decrease in river flow and 13% increase in river salinity as a result of the extraction could have a significant impact on the dynamics of the estuary and this possibility has not yet been addressed by estuarine modeling. The Yarragadee extraction project is awaiting approval from the Environmental Protection Agency.

2.4.4 Western Australian estuaries

Studies which have focused on estuaries throughout Western Australia and the world are generally relevant to the current study. However, due to the specific climate, landforms and oceanographic conditions of south west Australia, studies on south west estuaries are most relevant to the current work.

Wilson Inlet is a partially open estuary located near the town of Denmark in the south west, approximately 250 km east of the Blackwood. Ranasinghe and Pattiaratchi (1999) found that diurnal heating strongly influenced the stratification in winter, and that strong sea breezes mixed the water column in summer. The flushing time for the bottom waters in Wilson Inlet is around one year (Ranasinghe & Pattiaratchi 1998). Diurnal heating may be important to the dynamics of
the Blackwood River estuary, but strong sea breezes are unlikely to be as important because of the protection offered by Cape Leeuwin.

The major influence on the flushing of the estuary at Wilson Inlet was streamflow, with tidal exchange, wind and channel location having only a minimal effect (Ranasinghe & Pattiaratchi 1998). Kurup et al. (1998) also found that freshwater inflow was the most important mechanism affecting the salt wedge position in the Swan River estuary in Perth. The effect of streamflow on estuarine flushing in the Blackwood River estuary has not been investigated by hydrodynamic modeling.
3.0 METHODS

The methodology required to fulfill the objectives of this project had two main components: (1) field work in the Blackwood River, and (2) hydrodynamic computer modeling. The field work provided real data from one small section of the estuary, and modeling was used to provide information about the whole estuary as a dynamic system. The field work was also used to validate the model. The field and modeling results were then analysed together to determine dominant conditions and processes in the Blackwood River estuary.

3.1 Field Work

Field work was undertaken by boat in the Blackwood River, Western Australia, on 17 June 2006, and two weeks later on 1 July 2006, to determine the condition of the tidal river. The research vessel was a 5.5 m aluminium boat, which was launched on both days from the Alexandra Bridge public boat ramp.

3.1.1 Long term sensor

A sensor was moored in the Blackwood River for a period of two weeks to collect physical parameters over a period of two weeks. A Greenspan conductivity temperature depth and dissolved oxygen probe was deployed in the Blackwood River on 17 June 2006 for a 14 day period. This probe recorded conductivity, temperature, depth and dissolved oxygen concentration.

The sensor was deployed approximately 200 m south of Alexandra Bridge, as close to Alexandra Bridge as was safe to avoid boat traffic (site 1 on Figure 3.1). An echo sounder onboard the research vessel was used to determine the depth of the river across its width at this point. The probe was deployed in the deepest part of the river, which was approximately 5.5 m, to ensure that the sensor was located in the main flow channel of the river. This location was therefore most likely to experience significant intertidal and intratidal variation in water level, salinity and temperature.
The probe was anchored to the river bed with lead weights to prevent any movement of the probe over the 14 days (Figure 3.2). The probe was suspended in the water column such that the probe was 1.25 m from the bottom of the river, which prevented the probe becoming buried in the sediment. A buoy suspended underwater approximately 0.70 m above the probe was used to keep the probe buoyant in the water column. The sensor was therefore 4.25 m below the water surface at the time of deployment. Two surface buoys were used for easy location of the equipment.

The record time on the probe was set to 5 minutes, with a scan time of 30 seconds, so that the probe turned on once every 5 minutes, sampled the water for 30 seconds, and stored the average of each of the four parameters (depth, conductivity, temperature and dissolved oxygen) over the 30 second period. One data point was recorded for every 5 minutes that the probe was in the water, resulting in a total data set of approximately 4640 lines over 14 days.

The CTDDO probe was retrieved by boat on 1 July 2006. Fourteen days of data were collected, with four parameters successfully recorded on the sensor: depth, temperature, conductivity and dissolved oxygen. However, the dissolved oxygen data proved to be unreliable, with negative dissolved oxygen concentrations logged so these data were discarded. Conductivity data are analogous to salinity, and conductivity data were converted to salinity using routines in MATLAB. It should be noted that when calculated in this way salinity has no units. The results were plotted in MATLAB and Fourier transforms were performed on the data to determine the dominant frequencies of variation in the data.

Albany was the closest location to Flinders Bay for which tidal data could be obtained. The water level data collected by the long term sensor was compared to the ocean water level variation at Albany, with data collected and supplied by the Department of Planning and Infrastructure (DPI). For simplicity, the water level at Flinders Bay was assumed to be the same as at Albany. The tidal lag was calculated as the average time difference between high water at the ocean and high water at Alexandra Bridge.
Figure 3.1: The location of the 19 sampling sites between Alexandra Bridge and Warner Glen Bridge. Drop sampling was undertaken at each of the 19 sites on both field days. The long term sensor was deployed at site 1.
3.1.2 Vertical sampling

In addition to the long term sampling, the length of the river between Alexandra Bridge and Warner Glen Bridge was also sampled at 19 sites on both field days using a CTDDO sensor that was lowered from the boat, to provide a longitudinal transect of the tidal river. The sensor used for these measurements was a SeaBird Electronics 19plus (SBE19+) probe, which measured conductivity, temperature, depth and dissolved oxygen (Figure 3.3).
The SBE19+ instrument was used at 19 sites, approximately 0.5 km apart, upstream of Alexandra Bridge (Figure 3.1). There were 15 sites between Alexandra Bridge and Warner Glen Bridge, one site in Chapman Brook and three sites between Warner Glen Bridge and the rock bar that is believed to be the upper limit of estuarine influence. Sampling beyond the rock bar was not possible due to shallow water and submerged rocks, which created depths of less than 1 m in some areas, and this area was not navigable by boat.

The SBE19+ instrument samples continuously at 4 Hz, with a temperature sensor accurate to 0.0002 °C and salinity accurate to 0.0005 S/m (SeaBird Electronics 2005). The sensor was turned on before each site was sampled, and switched off after sampling was completed. The internal pump in the instrument switched on when it was placed in water. The pump drives water through the instrument, and measures the salinity, temperature and dissolved oxygen. Depth was recorded by a pressure sensor on the instrument.
At each site, the SBE19+ probe was held at the surface for approximately 15 seconds to allow water to begin to pump through the instrument. The bubble release from the top of the pump stopped when the pump was filled with water and ready to sample. Once the bubbles ceased to be released, the instrument was lowered slowly to the sea bed. When it reached the bottom of the water column the instrument was pulled back up to the boat.

Since the SBE19+ probe sampled continuously, physical parameters were recorded both on the way down and on the way up through the water column. The data used here were the data from the downward drop, because this was when the water column was unperturbed. The data collected on the way up may have been inaccurate due to movements caused by the probe on its initial downward drop.

A handheld global positioning instrument (GPS) was used to note the location of each of the 19 sites on the first day of field work on 17 June 2006. It was therefore possible to sample at the same sites on the second sampling day 1 July 2006 by navigating to these GPS locations. This eliminated a source of error in the comparisons between the two sampling days, because there is likely to be some spatial variation in physical properties in the river. The two sampling days were 2 weeks apart and were sampled at approximately the same time of day, on a rising tide, so the tidal conditions were assumed to be similar.

The drop data were downloaded from the instrument on return from field work. Only one line of data was plotted for each depth, so where one depth had more than one line of data, repeated lines were deleted. The transects were plotted using the ‘pcolor’ routine in the program MATLAB, with shading ‘flat’, for salinity, temperature and dissolved oxygen between Alexandra Bridge and Warner Glen Bridge. Data were initially averaged and interpolated across the transect, but the variation between sites was not evident. As such, the data were not interpolated or averaged between sites, so that the variation between each of the 19 sites could be observed.

3.1.3 Rainfall data

Rainfall data were obtained from the Bureau of Meteorology for four sites throughout the Blackwood River catchment, to determine relationships between rainfall and river flow. The four
sites were chosen because they are all within the catchment, and represent the wide variety of conditions that exist within the catchment. The four sites were Cape Leeuwin, Witchcliffe, Bridgetown and Wagin (Figure 3.4). Cape Leeuwin has the highest annual rainfall (998.5mm), followed by Bridgetown (832.1mm), with the lowest annual rainfall at Wagin (436.1mm). Average rainfall data were not available for Witchcliffe, but annual rainfall at Karridale, 10 km south of Witchcliffe, is 1194.6mm.

Figure 3.4: The location of the four sites in the Blackwood River catchment that were chosen as rainfall sites (adapted from Hodgkin (1978)).

3.2 Modeling

Hydrodynamic modeling was undertaken as part of this project for two reasons: (1) to attempt to validate the field data collected in the Blackwood River and (2) to observe changes over the whole estuary as a system, as field measurements could not be made over the whole estuary due to time constraints.

3.2.1 Model Inputs

Hydrodynamic modeling was undertaken using the Hamburg Shelf Ocean Model (HAMSOM) to determine the dominant forces in the estuary, as well as to validate the data collected in the field work. The model was initially calibrated with a data set that had already been modeled, to ensure
that the results were as expected. Once the results were as expected, the model was applied to the Blackwood River estuary.

HAMSOM uses fixed permeable interfaces between layers and the equations of continuity and momentum are vertically integrated over a depth range of ‘h’, corresponding to a computational layer of the same thickness. The model was set up with 10 layers of varying depths: 1 – 2 m, 2 – 3 m, 3 – 4 m, 4 – 6 m, 6 – 8 m, 8 – 10 m, 10 – 15 m, 15 – 20 m and 20 – 25 m. The layers were chosen to account for water depths of up to 20 m in the tidal river, as well as to provide the necessary detail for the shallower depths of around 2 m in the lagoon.

There were three inputs to the model:
1. The bathymetry of the estuary,
2. Oceanic tidal data, and
3. River flow data.

The bathymetry of the estuary was taken from data plotted by Hunt (2003). These data were collected by the Department of Marine and Harbours, now the Department of Planning and Infrastructure, in 2002. To enable input into HAMSOM, all depths in the bathymetry grid were rounded to the nearest integer, with points on land set to a depth of 0 m. This digitization may have caused slight discrepancies in the output from HAMSOM, particularly in the shallow areas of the lagoon that are between 1 and 2 m in depth. A grid cell was considered estuarine if more than 50% of the cell was in the estuary.

The grid compiled by Hunt (2003) was composed of squares of size 100m by 100m (Figure 2.4 in Chapter 2 above). To provide more detail of the estuary, which is less than 100m wide in the tidal river, the grid was interpolated to create grid squares of size 50m by 50m. The bathymetry grid extended from the mouth of the estuary at Augusta, upstream to approximately the junction of Chapman Brook with the Blackwood River (field sampling site 16, Figure 3.1). The grid extended eastwards to just east of Molloy Island, where the Scott River flows into the Hardy Inlet, creating a grid 159 squares wide (east-west) and 524 squares long (north-south). The Scott River itself was not included in this modeling.
3.2.2 Boundary and initial conditions

There were two boundaries that required boundary conditions to be inputted: (1) the Blackwood River where it flowed in at the top of the grid, and (2) the ocean at the bottom of the grid where the estuary is open to the ocean. The ocean boundary required water level data to simulate the tidal forcing of the ocean. Oceanic water level data were collected at Albany, which was considered close enough to the mouth of the estuary to be accurate. These data were obtained from the Department of Planning and Infrastructure. The ocean water level was set to 0m at the mouth of the estuary at time 0. The river flow data for the top boundary were obtained from the Department of Water for the ‘Hut Pool’ gauging station, which is 43 km upstream of Hardy Inlet. Hut Pool was the closest gauging station to the top of the bathymetry grid.

The initial conditions in the estuary also needed to be inputted. Ideally, the initial salinity used in the model would have been based on recent field data, but time constraints prevented the entire estuary from being sampled in this project. The salinity distribution in the estuary was therefore initialized using salinity data collected in April 1974 by Imberger et al. (1976). These data were chosen to initialize the system because they most closely resembled the salinity data collected in the current study in the tidal river.

Figure 3.5 shows a transect of the initial salinity distribution used for all model runs. The initial condition was such that the salinity at the mouth of the estuary was 35, which is the salinity of seawater, and the water at the head of the estuary was fresh, with salinity 2. The salinity in between the head and the mouth gradually increased moving toward the ocean, with distinct isohalines (lines of equal salinity) separating the fluids of differing salinities.

Based on the findings of Imberger et al. (1976), temperature was set to 17°C for the whole system, because the influence of temperature on density is considerably less than the effect of salinity over naturally occurring ranges. Water level elevation was initially set to 0 m above mean sea level throughout the entire estuary, to ensure the model was initially steady.
3.2.3 Model treatments

HAMSOM was used to model six conditions to determine the dominant forcing mechanisms in the estuary (Table 3.1).

Table 3.1: Summary of the treatments (or ‘runs’) that were modeled using HAMSOM.

<table>
<thead>
<tr>
<th>Run</th>
<th>River flow</th>
<th>Water Level Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 GL/day</td>
<td>Tide only</td>
</tr>
<tr>
<td>2</td>
<td>4.8 GL/day</td>
<td>Tide only</td>
</tr>
<tr>
<td>3</td>
<td>17.5 GL/day</td>
<td>Tide only</td>
</tr>
<tr>
<td>4</td>
<td>0 GL/day</td>
<td>Tide and surge</td>
</tr>
<tr>
<td>5</td>
<td>4.8 GL/day</td>
<td>Tide and surge</td>
</tr>
<tr>
<td>6</td>
<td>17.5 GL/day</td>
<td>Tide and surge</td>
</tr>
</tbody>
</table>

Three river conditions were inputted for the river boundary condition, using monthly river flow data from the Department of Water’s gauging station at Hut Pool, from 1983 to 2005. Firstly, the data were sorted by season. The ‘average flow’ value used for runs 2 and 5 was the average flow for winter since 1983. The ‘high flow’ value used for runs 3 and 6 was the maximum flow for winter since 1983. River flow therefore had the following three treatments:

Figure 3.5: The initial salinity transect through the estuary for all modeling runs. Colours indicate salinity, with salt water red and freshwater blue.
1. no flow (0 GL/day),
2. average flow (4.8 GL/day), and
3. high flow (17.5 GL/day).

Two different tidal conditions were inputted for the ocean boundary condition. The water level data were initially smoothed for input into HAMSOM, which cannot function with small frequency changes in water level. The data were then altered such that the ‘tide and surge’ water level data used for runs 4 – 6 included periodic and non periodic components, whereas the ‘tide only’ water level data used for runs 1 – 3 had only the periodic tidal component of water level. Figure 3.6 shows the two sets of tidal data used as inputs at the oceanic boundary for the 24 days that the model simulated. Tidal condition therefore had the following two treatments:

1. tide and surge, and
2. tide only.

Figure 3.6: The data inputted for the oceanic boundary, showing the ‘tide and surge’ water level data used for runs 4 – 6 and the ‘tide only’ data used for runs 1 – 3.
The effect of wind was ignored in the hydrodynamic model, based on the conclusion by Imberger et al. (1976) that wind is not a dominant input to the Blackwood River Estuary. This assumption is justified in calculations performed below.

### 3.2.4 Model Outputs

The model ran for the maximum time available, simulating 24 days of flow in the estuary. The time step on the model was 20 seconds to accurately represent changes on the relatively small scale of the bathymetry. A data file was outputted to show the salinity and water level conditions every hour over the 24 day simulated period. HAMSOM can provide the user with many types of output data, but only two of its outputs were used here: water level elevation and salinity. These outputs were chosen because they provided information about the estuarine processes in the system.

#### 3.2.4.1 Salinity output

Salinity was outputted to show the mixing and movement of salt and fresh water in the estuary. Salinity was outputted from each layer at thirty positions throughout the estuary, which were spaced approximately 750 m apart, creating a transect extending from the mouth of the estuary up river to close to Warner Glen Bridge.

The program MATLAB was used to create a ‘jpeg’ image of the salinity transect for every hour of the 24 days that the model simulated, creating a total of 576 images for each of the six model runs. The transect images were combined to create a QuickTime movie, which showed changes over the modeling period. The QuickTime movies revealed the major differences between each of the model runs, particularly between the three types of river flow. There were visible differences in the QuickTime movies between zero, average and high river flow, but the differences between the two tidal conditions, ‘tide and surge’ water level and ‘tide only’ water level, were more subtle. The surface and bottom salinity at three locations throughout the estuary (the ocean entrance, midway through the estuary and the tidal river) were therefore plotted over time to highlight the differences between the tidal conditions. The salinity outputs were also used
to calculate the stratification in the water column over the simulation period. Stratification was calculated as the difference between the surface and bottom salinity.

3.2.4.2 Water level outputs

Water level elevation was outputted for five evenly spaced locations in the estuary, from the ocean to Warner Glen Bridge, to show the changes in tidal range as the tide propagated upstream. The water level elevation at each of the five positions was plotted in MATLAB to show the changes in tidal range moving upstream from the ocean over the simulation period.

The tidal lag of the water level elevation as it moved upstream was calculated by finding the average time between high water at the ocean entrance and high water at the other four sites in the estuary.

3.3 Potential energy anomaly

The potential energy anomaly was calculated to determine the dominant processes influencing stratification and mixing in the estuary. As described in section 2.2.6 above, the potential energy anomaly energy balance is described by the equation:

\[
\frac{d\Phi}{dt} = \frac{1}{320} \frac{g^2 h^4}{K \rho} \left( \frac{d\rho}{dx} \right)^2 + 0.031 g h u \left( \frac{d\rho}{dx} \right) + \frac{g \rho \beta s P}{2} - \frac{4}{3\pi} \frac{\partial_k D \rho}{h} \frac{u^3}{h} - \frac{\partial_k \rho}{h} \frac{W^3}{h} \tag{Equation 3.1}
\]

The anomaly was calculated for the estuary from the ocean to Warner Glen Bridge. Calculation of the potential energy anomaly required many parameters, which had to be measured, estimated or calculated (Table 3.2). The third term, which is the potential energy anomaly change due to precipitation, was assumed to be zero due to the relatively low input of rainfall compared to river flow. Solar heating was also not considered in the analysis. The parameters were used to calculate the wind speed required to mix the stratified estuary, which was compared to average wind data taken from the closest Bureau of Meteorology site to the study area at Cape Leeuwin.
Table 3.2: The parameters used to calculate the change in potential energy anomaly. Italicised entries indicate values taken from the results of this project.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>average depth</td>
<td>5 m</td>
<td>bathymetry data</td>
</tr>
<tr>
<td>ρ</td>
<td>water density</td>
<td>1017 kg/m³</td>
<td>model data</td>
</tr>
<tr>
<td>ū</td>
<td>mean current</td>
<td>0.0167 m/s</td>
<td>average flow data</td>
</tr>
<tr>
<td>dp/dx</td>
<td>density gradient</td>
<td>8.71 x 10⁻⁴ kg/m³</td>
<td>model data</td>
</tr>
<tr>
<td>u</td>
<td>tidal current velocity</td>
<td>0.0167 m/s</td>
<td>average flow data</td>
</tr>
<tr>
<td>ρₐ</td>
<td>air density</td>
<td>1.2 kg/m³</td>
<td>Estimate</td>
</tr>
<tr>
<td>Kᵺ</td>
<td>vertical eddy viscosity</td>
<td>0.002 m²/s</td>
<td>Scott (2004)</td>
</tr>
<tr>
<td>ε</td>
<td>tide efficiency</td>
<td>0.0037</td>
<td>Ranasinghe and Pattiaratchi (1999)</td>
</tr>
<tr>
<td>δ</td>
<td>wind efficiency</td>
<td>3.7 x 10⁻³</td>
<td>Ranasinghe and Pattiaratchi (1999)</td>
</tr>
<tr>
<td>kₛ</td>
<td>surface drag coeff.</td>
<td>6.4 x 10⁻³ m²/s²</td>
<td>Ranasinghe and Pattiaratchi (1999)</td>
</tr>
<tr>
<td>kᵰ</td>
<td>bottom drag coeff.</td>
<td>2.5 x 10⁻³ m²/s²</td>
<td>Ranasinghe and Pattiaratchi (1999)</td>
</tr>
</tbody>
</table>

3.4 Flushing calculations

Calculations were performed to determine the flushing time of the estuary under different river flow conditions. The ‘fraction of freshwater’ technique was used, as described by Dyer (1997). By this method, the flushing time of the estuary is described by:

\[
T = \frac{N}{R} \tag{Equation 3.2}
\]

where \(T\) is the flushing time, \(R\) is river flow, \(V\) is the volume of the estuary segment, and \(f\) is the fractional fresh water concentration over the segment, as described by:

\[
f = \frac{S_s - S_n}{S_s} \tag{Equation 3.3}
\]

where \(S_s\) is the salinity of the undiluted seawater, and \(S_n\) is the mean salinity in the given segment of the estuary. \(S_s\) was taken as 35 for seawater, and the mean salinity \(S_n\) was calculated from the salinity distribution shown in Figure 3.5 above.
flushing time was calculated for the whole estuary from the ocean to warner glen bridge, under three river flows (r): lowest summer flow (0.067 gl/day), average winter flow (4.8 gl/day) and high winter flow (17.5 gl/day). the flushing times calculated therefore represented minimum and maximum flushing times. the river flows were the same as the modeled flows, with the exception of low flow, so the flushing times could be compared to the model results.
4.0 RESULTS

The meteorological conditions and river discharge at the time of the field work are presented first in this section to provide the context for the field results. The results from the field and modeling are then presented, together with calculations for potential energy anomaly and flushing times.

4.1 Forcing in the system

4.1.1 Rainfall and atmospheric pressure

Prior to the field sampling period, rainfall levels throughout the Blackwood River catchment were very low. Figure 4.1 shows the rainfall decile ranges for locations throughout Western Australia. The rain received in the Blackwood River catchment over the period 1 January – 30 June ranges from ‘average’ in inland areas, to ‘lowest rainfall on record’ near the coast. Over this six month period, the south west coastal region had between 40% and 60% of its average rainfall (Bureau of Meteorology 2006). Rainfall during June was particularly low, with locations throughout the Blackwood River catchment receiving at most 40% of the mean monthly rainfall for June (Bureau of Meteorology 2006).

Figure 4.2 shows the rainfall throughout the Blackwood River catchment over the period of field work, taken from Bureau of Meteorology records. Over the study period, rainfall was greatest at the two sites closest to the ocean, Witchcliffe and Cape Leeuwin. Rain fell at all sites except Wagin on 13 June, with Witchcliffe receiving the most rain (32.4mm). Two other large rainfall events were on 20 June and 28 June, with all four sites recording large amounts of rainfall. Figure 4.2 also shows a smaller rainfall peak on 1 July, but since this was the day that the long term sensor was retrieved, this rainfall was unlikely to have impacted on the data collected.

Figure 4.3 shows the atmospheric pressure at three sites in the catchment over a one month period around the field work, as recorded by the Bureau of Meteorology. A low pressure system passed over the catchment on 20 June, resulting in a minimum pressure of 1004.4 hPa. A second, less intense system passed over the area late on 27 June, decreasing pressure to 1008.7 hPa.
Figure 4.1: Rainfall deciles for Western Australia, for the period 1 January – 30 June 2006 (Bureau of Meteorology 2006).

Figure 4.2: The rainfall at four locations throughout the Blackwood River catchment, over a one month period starting prior to when the long term sensor was deployed and extending until after it was retrieved (Bureau of Meteorology 2006).
4.1.2 River flow

River flow to Hardy Inlet is highly seasonal (Figure 4.4). Data collected by the Department of Water over a 10 year period at Hut Pool show high seasonality, with highest flow occurring two thirds of the way through the year around late winter. The highest flow in the last 10 years was in 1996, when flow at Hut Pool reached almost 34 GL/day. Between 2001 and 2004, flow was always less than 8.6 GL/day, with flows in 2001 the lowest in the 10 year period. Average winter flow is 4.8 GL/day, average summer flow is 0.098 GL/day and average annual flow is 1.6 GL/day. There is significant variation in river discharge between years.

The flow in the first five months of 2006 at Hut Pool was very low, with only a fifth of the average flow recorded (Figure 4.5). Flow normally increases significantly in July, but flow at Hut Pool did not show a significant increase in flow until early August. River flow was therefore well below average during the period of field work (17 June – 1 July).
Figure 4.4: Flow data from Hut Pool, 43 km up river from the mouth of estuary, for the period 1995 – 2005 (Department of Water 2006).

Figure 4.5: Flow data from Hut Pool 2006 from March 2006 to August 2006, plotted against average flow (Department of Water 2006).
4.2 Field data

4.2.1 Long term sensor

Figure 4.6 shows the raw data collected from the Conductivity Temperature and Depth (CTD) sensor deployed at Alexandra Bridge over the two week period 17 June – 1 July 2006. The average results from the long term sensor are summarized in Table 4.1. Dissolved oxygen data were also collected, but these data were unreliable after 1 day, and these data were discarded.

![Figure 4.6: The long term data collected from the CTD deployed at Alexandra Bridge from 17 June 2006 – 1 July 2006.](image-url)
Table 4.1: Summary statistics for long term data from Alexandra Bridge.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Error</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>3.46</td>
<td>0.0017</td>
<td>3.24</td>
<td>3.72</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>19.5</td>
<td>0.0048</td>
<td>18.9</td>
<td>20.1</td>
</tr>
<tr>
<td>Salinity</td>
<td>29.4</td>
<td>0.0038</td>
<td>28.7</td>
<td>29.9</td>
</tr>
</tbody>
</table>

For most of the two week period that the long term sensor was deployed, there was one high water level daily and one low water level daily, representing the tidal fluctuations at Alexandra Bridge. The average amplitude of the tidal variation was 0.28 m. The long term salinity and temperature results varied with tidal fluctuation. On flood tide when water level increased, salinity increased and temperature decreased. As water level decreased on the ebb tide, salinity decreased and temperature increased. Salinity was maximum at high tide and minimum at low tide.

Salinity decreased slightly over the two week period, from 29.5 on 17 June to 29.25 on 1 July. Temperature also decreased slightly over the two weeks, from just above 20°C on 17 June to 19°C on 1 July.

A Fourier analysis showed that water level, salinity and temperature all had significant peaks in energy at the frequency of the diurnal tide, with the largest peak at the diurnal period of 24 hours and a smaller peak at the semi-diurnal period of 12 hours. This indicated that the diurnal tide had the largest influence on water parameters. The salinity data were the exception to this, with a peak at 7 hours that was larger than the semi-diurnal peak, and not explained by any tidal constituent or other water level variation. The Fourier analysis for the water level data is presented in Figure 4.7 and the remaining analyses for salinity and temperature are presented in Appendix A.
The tidal pattern in the water level was disturbed for approximately 24 hours around 20 and 28 June, when there was no longer an obvious high and low water. The salinity and temperature on these two days were also different, with temperature showing larger variations on the 20 June. Salinity decreased over the 24 hour period around 28 June.

Figure 4.8 shows the water level variation around mean water level for the ocean at Albany, and for the long term sensor deployed at Alexandra Bridge in the Blackwood River. The water level at Albany was assumed the same as the ocean water level at the mouth of the estuary. The amplitude of the water level changes at Albany was much greater than in the Blackwood, with tidal ranges at Albany averaging 0.66m over the study period, while the range in the Blackwood was only 0.28m. High tide in the Blackwood was reached after high tide had already occurred at Albany, with an average lag time of 3.45 hours. The Albany water level data showed more variation on a shorter time scale, with more small peaks and troughs over a day than the data from the Blackwood. Alexandra Bridge is protected from the shorter period oceanic water level variations that affected water level at Albany, such as seiches and swell.
results

Figure 4.8: Water level variation around mean water level at Albany and at the site of the long term sensor at Alexandra Bridge in the Blackwood River over the two week study period.

4.2.2 Vertical sampling

The data collected from the drop sampling undertaken on 17 June and 1 July between Alexandra Bridge and Warner Glen Bridge are presented in Figure 4.9 and Figure 4.10 respectively. The data were not averaged between sites, so that the variations between sites could be seen. The temperature data show little variation along the transect on both sampling days. The average temperature of the transect was 16.6°C on both sampling days, with average surface temperature 16.7°C and average bottom temperature 16.5°C. On both sampling days, the water at site 1 (at Alexandra Bridge) had a lower temperature than any other sites.

Salinity showed much greater variation than temperature between the two sampling days. A salt wedge is evident until approximately 8 km upstream of Alexandra Bridge on 17 June. Strong stratification was present in the water column at the point where the salt wedge met the fresher water, with salinity changing from 15 to 25 over 2 m depth. Salinity was low at the surface at
most sites between 8 and 14 km upstream of Alexandra Bridge, with surface salinities of approximately 2, and bottom salinities approaching 30.

There was a large decrease in salinity on 1 July across the whole transect. The average salinity of the transect on 17 June was 16.3, and the average salinity decreased to 9.5 on 1 July. The freshwater also extended almost the whole length of the transect on 1 July, and extended deeper into the water column than on 17 June.

**Figure 4.9:** Temperature, salinity, dissolved oxygen concentration and oxygen saturation at each of the sites along the transect between Alexandra Bridge and Warner Glen Bridge on 17 June, 2006.
Dissolved oxygen concentrations were higher at the surface than at the bottom of the water column on both days. Dissolved oxygen concentrations were generally higher on the second field day. Average surface dissolved oxygen concentrations were 7.6 mg/L on 17 June and 8 mg/L on 1 July, while average bottom concentrations were 4.1 mg/L on 17 June and 5.5 mg/L on 1 July. Oxygen saturation data showed the same trends, with an average surface saturation of 78% and average bottom saturation of 56%.

A number of sampled sites up the river were significantly deeper than the surrounding sites. For example, the 10m deep site just south of Warner Glen Bridge was a deep hole surrounded by much shallower sites. This hole had saltier water than the surrounding sites, with salinities at 10m depth that were 3 times as saline as surface salinities. Oxygen at the bottom of hole was very low with saturation less than 10% and concentrations less than 1 mg/L.
There were patches of water with high salinity and low oxygen at the bottom of the water column along each transect. For example, on 17 June, there was a patch extending from 5.5 – 8 km upstream from Alexandra Bridge, with salinity 25, dissolved oxygen concentration close to 0mg/L and oxygen saturation less than 30%. There were at least 8 sites on 17 June that had salty (salinity around 30), low oxygen water (less than 30% saturated) at the river bed. The surface water at these sites was fresher (salinity 8), with more oxygen content (8 mg/L, greater than 70% saturated).

The number of high salinity, low oxygen patches had decreased by 1 July, with only four sites still stratified. These sites included the 10 m deep hole and three other sites: site 2 (2 km from Alexandra Bridge), site 4 (4 km from Alexandra Bridge) and site 9 (8 km from Alexandra Bridge). Each of these sites had high salinity, low oxygen water at the river bed, with significantly fresher water at the surface.

### 4.3 Modeling

#### 4.3.1 Salinity output

The first output used from the hydrodynamic modeling was the salinity output. QuickTime movies produced in MATLAB showed the major salinity changes throughout the estuary over the simulation period, with visible differences between zero river flow, average river flow and high river flow. The initial salinity distribution is shown in Figure 3.5 (Chapter 3 above) and the final salinity distributions are shown in Figure 4.11 for each of the six model runs.

For the two model runs with zero river flow (runs 1 and 4), the salinity distribution in the estuary after 24 days was similar to the initial condition. The isohalines (lines of equal salinity) were less defined than in the initial condition, but the basic pattern of salty water at the ocean entrance and fresh water at the river end of the transect was still present. The QuickTime movies showed the tidal cycle pushing saline seawater into the estuary with the flood tide, and the same water being advected back on ebb tide. There was a time lag between the tide entering the estuary and water upstream responding, as the tide was propagated upstream. The incoming dense seawater entered the estuary close to the river bed. These images show that there was very little horizontal mixing over the tidal cycle.
The model runs with average river flow (runs 2 and 5) had similar final salinity distributions, with salinities of between 2 and 3 throughout the whole estuary at day 24. Initially, the less dense freshwater flowing from the river flowed across the surface of the saltier water. By day 15 of these two model runs, freshwater had advected halfway down the estuary, with much of the saltier water displaced and pushed out of the estuary. The estuary was almost totally flushed with freshwater of salinity just greater than 0 by day 24, with only a small amount of saltier water present at the mouth of the estuary, with salinity 3. Tidal variations were evident in the QuickTime movie, but had diminished influence on salinity compared to the river flow.

The two model runs with high river flow (runs 3 and 6) showed fresher water throughout the estuary than the average river flow runs, with average salinities after 24 days of less than 2. The freshwater had advected halfway down the estuary by day 3 of the simulation period. The estuary was mostly flushed with freshwater by day 15. The final condition of the estuary had only a small amount of slightly saltier water, with salinity slightly less than 2, at the ocean edge of the estuary. The remainder of the estuary was fresh with salinity close to 0. Tidal variations were still present in the QuickTime movie, but the strong river flow had a much greater impact on salinities than tidal fluctuations.

Figure 4.12 shows the salinity variations along a transect of the estuary over one tidal cycle, for run 1 (tide only, zero river flow). The images start at mean water level and show the transect every 3 hours as the ebb tide flowed out and the flood tide flowed back into the estuary. By late flood tide at \( t = 23 \) hours, saltwater had again intruded into the estuary at the bottom of the water column.

The tidal lag in the estuary is also evident in these images, with the water in the middle of the estuary still flowing seawards even when the tide at the ocean had begun flowing into the estuary. High tide occurred later with increasing distance upstream. The salinity impact of the tidal fluctuations was more pronounced at the ocean edge, with the tidal river showing only small changes in salinity with tide.
Figure 4.11: The final salinity transects through the estuary for each of the six model runs, after 24 days of simulation. Colours indicate salinity, with salt water red and freshwater blue. The ocean entrance is at the left of the images and the river at the right of the images.
Figure 4.12: Images outputted from HAMSOM over one tidal cycle, for run 1 (tide only, zero river flow), showing the salinity transect from the ocean to near Warner Glen Bridge on day 1 of simulation. Water level is initially at mean water level (t = 2 hours) reaching late ebb tide by t = 11 hours and late flood tide by t = 23 hours. Colours indicate salinity, with salt water red and freshwater blue. The ocean entrance is at the left of the images and the river at the right of the images.
4.3.2 Water level output

The second HAMSOM output was the water level output. Figure 4.13 shows the water elevation for runs 1 and 4 at Point Irwin, near the head of the estuary. The surge is plotted on this figure to provide the context for the remaining results. Surge varied over the period of days, and was highest on day 6 and lowest on day 24. Surge changed the water level by up to 15 cm. Clearly, when surge was high, the water level for run 4 was higher than run 1 and when surge was low, the water level for run 4 was lower than run 1.

![Figure 4.13: The water level elevation at Point Irwin for runs 1 and 4, as well as the surge.](image)

Water level data for runs with the ‘tide only’ input (runs 1 – 3) are presented in Figure 4.14 at three locations in the estuary. The tidal range was smallest in the tidal river and largest at the ocean entrance for all river flow conditions, with Point Irwin’s tidal range intermediate. Spring and neap tides were visible at all sites, with small tidal ranges around day 15 indicating neap tides and large tidal ranges around day 10 indicating spring tides.
These data show that when river flow was 0 (run 1), the average water level in the tidal river was the same height as the water in Hardy Inlet. For average river flow (run 2), the average water level in the tidal river was approximately 50 cm higher than at Point Irwin, and for high river flow (run 3), the average river water level was 150 cm higher than at Point Irwin.

The water level results for the ‘tide and surge’ water level data (runs 4 – 6) are shown in Figure 4.15. These data appear similar to the data produced by the model for the ‘tide only’ water level data, with a significant amount of positive head present in the tidal river under average and high flow conditions.

**Figure 4.14:** Water level changes associated with each of the model runs for the ‘tide only’ water level data at three points in the estuary. Model run 1 was with 0 river flow, model run 2 was with average flow and model run 3 was with high river flow.
Figure 4.15: Water level changes associated with each of the model runs for the ‘tide and surge’ water level data at three points in the estuary. Model run 1 was with 0 river flow, model run 2 was with average flow and model run 3 was with high river flow.

The original six runs of the model only outputted water level data for three out of the five required locations in the estuary. Run 1 (tide only, zero river flow) was therefore re-modeled with new output locations to show the tidal propagation up the estuary at all five of the required locations (Figure 4.16). The water level variation at Molloy Island was slightly less than the oceanic tidal variation, and the tidal range decreased moving upstream in the river. The maximum tidal range at Alexandra Bridge was around 0.2 m with a slightly smaller range at Warner Glen Bridge. There was a time lag between high tide at the ocean entrance and high tide further upstream. Table 4.2 presents the average tidal lag times at each of the four locations in the estuary for run 1 of the model, with no river flow and ‘tide only’ water level data. The tidal lag increased as distance from the ocean increased, reaching a maximum of 10.5 hours at Warner Glen Bridge.
Figure 4.16: Water level data from five positions throughout the estuary, for run 1 (tide only, zero river flow) over the 24 simulated days.

Table 4.2: The tidal lag of high tide at four locations in the estuary, from run 1 of model simulation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Time lag of high tide from ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>0</td>
</tr>
<tr>
<td>Molloy Island</td>
<td>1.6 hours</td>
</tr>
<tr>
<td>Lindberg House</td>
<td>3.6 hours</td>
</tr>
<tr>
<td>Alexandra Bridge</td>
<td>7.9 hours</td>
</tr>
<tr>
<td>Warner Glen Bridge</td>
<td>10.5 hours</td>
</tr>
</tbody>
</table>

4.3.3 Stratification

The salinity output from HAMSOM was used to calculate vertical stratification. There was no visible difference in stratification in the QuickTime movies between the model runs that used ‘tide and surge’ water level data (runs 4 – 6) and those that used ‘tide only’ water level data (runs
Firstly, the surface and bottom salinities were plotted for runs 1 and 4. Figure 4.17 shows the surface salinity for runs 1 and 4 and Figure 4.18 shows the salinity at the river bed, at three locations in the estuary. The salinity changes for runs 2 and 5 and for runs 3 and 6 are presented in Appendix B. The bottom salinities tended to be greater than the surface salinities for all runs.

The salinity data at the ocean entrance and the mid estuary point showed variation between tide only runs and ‘tide and surge’ water level runs. The tidal river did not show tidal fluctuations in salinity, with near constant salinity even when river flow was zero. When river flow was greater than zero, the salinity at the mid point of the estuary and in the tidal river quickly dropped to a stable salinity, with no tidal variations visible.

**Figure 4.17**: The surface salinity at three locations in the estuary (ocean entrance, midway through estuary and in the tidal river) for run 1 (‘tide only’ water level data, zero river flow) and run 4 (‘tide and surge’ water level data, zero river flow).
Variations in vertical stratification in the water column were visible over the tidal cycle for all model runs. The variation in stratification over the whole period of simulation for model runs 1 and 4 is displayed in Figure 4.19. The large variation in stratification over the first five days of the simulation was due to the model adjusting to the initial and boundary conditions, and more stable equilibrium conditions were reached after about 5 simulated days.

At the ocean entrance, salt water entered the estuary on the flood tide at the river bed, increasing stratification, before the ebb tide returned the bottom water back to close to its original position, reducing stratification. Maximum stratification therefore occurred during late ebb tide, with minimum stratification during late flood tide. The largest stratification changes occurred during spring tide (days 6 – 12), with the smallest changes during neap tide (days 13 – 17).

When surge was high, the stratification for run 1 was greater than run 4. For example, around day 6 and day 7, the surge was 15 cm above mean water level elevation and the stratification for run 1 was almost twice the stratification of run 4. When surge was low, such as around day 23, the
stratification of run 4 was greater than the stratification of run 1. High surge therefore caused decreased stratification at the ocean entrance and low surge increased stratification at the ocean entrance. When surge was high, there was a net movement of seawater from the ocean into the estuary and when surge was low, there was a net movement of seawater from the estuary to the ocean.

Figure 4.19: Stratification at the ocean estuary interface over the 24 day simulation period for run 4 (‘tide and surge’ water level, zero river flow) and run 1 (‘tide only’, zero river flow).

4.4 Potential energy anomaly

The change in potential energy anomaly showed the relative contribution of mixing and stratification processes in the estuary (Table 4.3). It should be noted that the precipitation term (term 3) was assumed to be 0. These results should be interpreted with caution, due to the estimation of some parameters in the energy balance.

Gravitational circulation was more important than tidal straining at influencing stratification. Tidal mixing was not strong enough to overcome the stratification caused by gravitational circulation and tidal straining. The wind mixing term ranged from $2 \times 10^{-5}$ J m$^{-3}$ s$^{-1}$ for average
wind speeds at Cape Leeuwin (25 km/hr), to $1 \times 10^{-3} \text{ Jm}^{-3}\text{s}^{-1}$ for maximum wind gusts at Cape Leeuwin (120 km/hr). Only wind speeds of greater than 40 km/hr had the energy to overcome stratification and cause vertical mixing.

Table 4.3: The magnitude of each of the terms in the potential energy anomaly balance.

<table>
<thead>
<tr>
<th>Potential energy anomaly term</th>
<th>Magnitude (Jm$^{-3}\text{s}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratifying processes</td>
<td></td>
</tr>
<tr>
<td>Gravitational circulation ($d\Phi/dt)_G$</td>
<td>$7 \times 10^{-5}$</td>
</tr>
<tr>
<td>Tidal straining ($d\Phi/dt)_S$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Mixing processes</td>
<td></td>
</tr>
<tr>
<td>Tidal mixing ($d\Phi/dt)_T$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td>Wind mixing ($d\Phi/dt)_W$</td>
<td>$2 \times 10^{-5} - 1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

4.5 Flushing times

To calculate the flushing time of the estuary, it was first necessary to calculate the average salinity over the estuary, which was calculated from the initial salinity distribution used for all model runs (Figure 3.5). The average salinity across the estuary was calculated to be 15.31. The fractional freshwater concentration was therefore 0.563 for all flushing calculations. The longest flushing time was for low flow summer conditions, with the shortest flushing time for high flow winter conditions (Table 4.4).

Table 4.4: The flushing times for three river flows.

<table>
<thead>
<tr>
<th>River flow rate (R)</th>
<th>Flushing time (T)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009 GL/day</td>
<td>92 days</td>
<td>Low summer flow</td>
</tr>
<tr>
<td>4.8 GL/day</td>
<td>1.3 days</td>
<td>Average winter flow</td>
</tr>
<tr>
<td>17.5 GL/day</td>
<td>8.5 hours</td>
<td>High winter flow</td>
</tr>
</tbody>
</table>
5.0 DISCUSSION

In this section, the results of the field work and modeling are analysed and compared with previous studies. Estuarine processes are discussed with regard to the influence and ecological implications of mixing and stratifying processes. The results are used to make predictions about changes which may result from reduced river flow and increased river salinity.

5.1 River flow

Estimates of the average river flow of the Blackwood River into the estuary vary from 1.7 GL/day (Morrissy 1974) to 2.5 GL/day (Hodgkin & Hesp 1998). The average flow of 1.6 GL/day calculated here was based on the last 10 years of data from Hut Pool and was less than any previous estimates. This could indicate that the Blackwood River flow is decreasing in response to decreasing rainfall in the south west. There has been a reduction in rainfall since the mid 1960s in the south west, which has resulted in a 40% reduction in streamflow over the last 30 – 40 years (CENRM 2005). However, the discrepancy could also be due to the different techniques used for estimating streamflow and the differing locations in the Blackwood River where flow was measured.

5.1.1 Field data

The tidal river between Alexandra Bridge and Warner Glen Bridge was fresher on the second sampling day, most likely due to the two rainfall events throughout the catchment on 20 June and 28 June. Rainfall was recorded throughout the whole catchment during both events. River flow was still below average during the two week period, but was gradually increasing, consistent with increased runoff and infiltration following the storm events throughout the catchment. The increased river flow corresponded to fresher river water on the second sampling day.

The long term sensor at Alexandra Bridge recorded a slight decrease in salinity over the two week deployment period. The results from Imberger et al. (1976) suggested that the sensor would reveal that the river was relatively fresh, but the results showed saline water with salinities around 29, due to the low rainfall and river flow prior to the sampling. The vertical sampling showed that the water column above the sensor was fresh, but freshwater had not extended down
through the water column to the depth of the long term sensor. If the sensor was deployed later in the year, such as around August when river flow was approaching average levels, the salinity in this part of the river would probably have been much lower. Care was taken to ensure that the sensor was not deployed in a hole in the river where dense, saline water had gathered. The water depth at the site of deployment was 5.5 m and the surrounding parts of the river were between 4 m and 8 m, so the deployment site was not significantly deeper than the rest of the river. The salinity profile measured by the sensor was therefore likely to be representative of the conditions in the river at low streamflow.

5.1.2 Model data

The model data support some of the measurements made in the field work. For example, when the modeled river flow was greater than zero, the tidal river was the first area to respond. This was the same pattern observed in the field data on the second sampling day, with freshwater beginning to flow downstream across the top of the water column in response to the increasing river flow. However, the average and high flow conditions modeled in HAMSOM were not similar to the conditions present in the tidal river at the time of sampling, because actual flow over the study period was less than a quarter of the ‘average’ flow that was modeled, so the field work and model results cannot be directly compared.

5.1.3 Flushing

Table 5.1 compares the results of the hydrodynamic modeling with field based predictions made in 1974. Imberger et al. (1976) predicted that flow would need to exceed 20 GL/day for the estuary to be flushed with freshwater throughout. The current study found that river flow as low as 4.8 GL/day could almost totally flush the estuary with freshwater after 24 days and seawater could not overcome the strong river flow. A river flow of 17.5 GL/day flushed the estuary even faster. Although the model used unrealistic river flow conditions, with constant flow over the 24 hours whereas Imberger et al. (1976) used actual field data, this does not explain the differences between Imberger et al. (1976) and this study. A more likely explanation is that the estimate made by Imberger et al. (1976) was overestimated, because the field work was conducted in 1974, a year in which river flow was the highest on record.
Table 5.1: The estuary conditions associated with various Blackwood River flows.

<table>
<thead>
<tr>
<th>River flow</th>
<th>Condition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 20 GL/day</td>
<td>Estuary fresh throughout</td>
<td>Imberger et al. (1976)</td>
</tr>
<tr>
<td>2 – 20 GL/day</td>
<td>Salt wedge in Hardy Inlet</td>
<td>Imberger et al. (1976)</td>
</tr>
<tr>
<td>0.25 – 2 GL/day</td>
<td>Salt wedge in tidal river</td>
<td>Imberger et al. (1976)</td>
</tr>
<tr>
<td>&lt; 0.25 GL/day</td>
<td>Virtually marine throughout</td>
<td>Imberger et al. (1976)</td>
</tr>
<tr>
<td>4.8 – 17.5 GL/day</td>
<td>Estuary fresh throughout</td>
<td>This study (modeled results)</td>
</tr>
</tbody>
</table>

The long summer flushing time (92 days) calculated with the freshwater fraction method was as expected, as summer river flows are low. Flushing times for estuaries are generally of the order of tens of days, and strongly depend on river flow (Dyer 1997). The estimate of 92 days is also of the same order as the flushing time of Wilson Inlet (~1 year), particularly since Wilson Inlet is a partially open estuary where tide is of minimal importance, whereas Hardy Inlet is permanently open (Ranasinghe & Pattiaratchi 1998).

The flushing time calculated for winter high flow conditions (8.5 hours) is unlikely to be correct, as it would require water to be flowing at velocities of at least 1.2 m/s downstream in the river. This velocity is at least 60 times any of the current velocities measured by Hunt (2003) in the tidal river in autumn, and double most of the velocities measured by Imberger et al. (1976) in the lower estuary in winter. In addition, Imberger et al. (1976) found that the whole volume of the estuary is exchanged on the scale of 2 days during winter high flow conditions. The flushing time estimated from the modeled high flow run was around 15 days. The freshwater fraction method used here therefore underestimated the flushing time. The method is limited in its ability to accurately predict flushing time because there is no consideration of the shape of the estuary, which affects flow and flushing time.

5.2 Tidal influence

5.2.1 Intratidal variation

The influence of the tide was evident in the model results. The salinity at the ocean edge decreased throughout the entire ebb tide, as fresh river water was advected down the estuary, reaching a minimum salinity at low tide. On the flood tide, the salinity at the ocean edge
increased until the salinity was the same as the ocean water, reaching a maximum salinity that remained stable. This was expected, because the model was initialized with less saline water in the estuary and saline water in the ocean, such that on the ebb tide, less saline water was transported seawards from the river. On the flood tide, once the salinity at the mouth of the estuary was close to the salinity of the ocean (35), the salinity could no longer increase (Pattiaratchi pers. comm.). The water in the river and estuary was fresher than the seawater, so salinity decreased throughout the whole ebb tide.

The model simulations show that stratification in the water column varied over the tidal cycle, suggesting that tidal straining was occurring. Tidal straining occurs because the surface water travels faster than the bottom water due to shear, and tidal straining can determine salinity in the estuary (Dyer 1997). The maximum stratification at late ebb tide and minimum stratification at late flood tide, and the isohalines sloped towards the ocean at ebb tide fit with expectations of tidal straining (Ranasinghe & Pattiaratchi 1999).

Intratidal salinity variation was also found in the field data. The long term sensor measured the highest salinity at late flood tide and the lowest salinity at late ebb tide. This was expected because the flooding tide pushed sea water upstream into the river and the ebb tide pushed freshwater downstream. River flow was low at the time of field sampling, so the tide could overcome stream flow and push seawater up to Alexandra Bridge. If river flow was higher, tidal variations would probably not be evident in the tidal river, as suggested from the model results, which showed high river flow prevented tidal variations in salinity in the tidal river at Warner Glen Bridge.

5.2.2  Tidal propagation

The model and field work both showed tidal propagation up the river. Hodgkin (1978) found that under high flow winter conditions in the Blackwood, water level increased in the tidal river and tides were not propagated within the estuary. The results of this study reflect this, with elevated water level in the tidal river under the modeled ‘average’ and ‘high’ river flows. Under high river flow, the model showed that there was no tidal variation in the tidal river, so tide was not propagated to the river. Strong barotropic forcing occurred under average and high winter flow
conditions, due to the steep longitudinal slope in water level between the ocean and the tidal river.

The long term sensor deployed at Alexandra Bridge showed the influence of the tides in the tidal river. The dominant tidal variation was diurnal, as expected from the form factor calculated in section 2.2.1 above. The average tidal range at Alexandra Bridge over the two week period was 0.28m. The tidal range at Albany was 0.66m, and it was assumed that the tidal range at Flinders Bay was the same. Imberger et al. (1976) found that the maximum tidal water level change in the basin of Hardy Inlet was 70cm, and that the tide was attenuated across the shallow basin, resulting in a relatively small tidal range in the river. The decrease in tidal range found here as the tide propagated upstream was therefore as expected. A longer time series of water level elevation, covering at least one month, would be required to determine the tidal range at Alexandra Bridge more accurately, and to distinguish between spring and neap tide.

The long term sensor recorded an average tidal lag of 3.45 hours between high tide at Flinders Bay and high tide at Alexandra Bridge. The sensor deployment period covered low water and high water conditions and the lag ranged from 2.64 hours to 6.24 hours. Imberger et al. (1976) found the tidal phase lag from Seine Bay to Warner Glen Bridge was 2 hours at high water and 3 – 5 hours at low water, so the tidal lag found here is within the required range. The sea bar at the mouth of the estuary dampened the tide, reducing the amplitude of the tidal oscillation inside the estuary relative to the oceanic tidal range.

The tidal lag calculated from the model at Alexandra Bridge was approximately 8 hours, whereas the actual tidal lag measured in the field was 3.45 hours. This could be due to there being more friction in the model than actually existed in the estuary. Friction in the model at the sides and bottom of the estuary possibly slowed the tidal propagation relative to actual conditions. The model results for tidal lag are therefore inaccurate.

5.3 Non-tidal water level variation

5.3.1 Field data

The long term field data showed the response of the river to non-tidal water level variations. On 20 and 28 June, water level was subjected to two separate low pressure systems at Alexandra...
Bridge. The low pressure system on 20 June caused atmospheric pressure to drop by 15hPa, and disturbed the tidal water level variation. A decrease in pressure increases water level elevation due to the inverse barometric effect, so the water level over the period of the two storms was higher than it would have been due to only the tide.

The salinity and temperature at Alexandra Bridge also showed non-tidal variation on 20 and 28 June. Salinity and temperature patterns at other times showed tidal variation, but this pattern was disturbed during the storm events, suggesting that mixing occurred through the water column during the storm. These disturbances may also have been due to the disruption of the tidal cycle in the river, which may have changed the pattern of saline water advecting up the river.

5.3.2 Model results

A component of the modeling was comparing the effect of tides alone with the effect of tides combined with surge. The ‘tide and surge’ water level model runs showed that when surge was high, there was a net movement of seawater from the ocean into the estuary. Equally, when surge was low, there was a net movement of seawater from the estuary to the ocean. Surge can therefore influence the salt balance in the estuary. The combined effect of tides and high surge pushed more salt into the estuary than just tides alone, while low surge forced salt out of the estuary. The intratidal salinity variation in the estuary is therefore dependent on the ocean water level. This has implications for the ecology of the estuary, because an extended high or low surge will interrupt the usual salinity variation, which may impact on the diurnal habits of organisms in the estuary. Strong stratification induced by high surge can also create low oxygen conditions, as found in the field results.

Surge can have implications for estuarine beach geomorphology. Jackson et al. (2002) found a difference between tidal and surge features on the upper foreshore of estuarine beaches. Jackson et al. (2002) suggested that the effects of surge would be most prevalent in locations that are sheltered from the effects of waves and tides, such as near the head of estuaries. Point Irwin in the Blackwood River showed the effects of surge the most prevalently of all sites, as expected because it was closest to the ocean. The implications for any beaches between Point Irwin and the ocean may be that the beach morphology has distinct tidal and surge features, especially in the
upper foreshore area. Further investigation of beach profiles would be required to determine whether surge features were present.

5.4 Estuarine processes

The dominant estuarine processes in the Blackwood River estuary affect the dynamics of the estuary. The balance between stratification and mixing is crucial to estuarine dynamics, and the potential energy anomaly balance was a way of roughly quantifying each process. The estimates of the change in potential energy anomaly \( \frac{d\Phi}{dt} \) could only be approximated because direct measures of most of the parameters were not made. The results were on the same scale as calculations made by Gale et al. (2006) and Ranasinghe and Pattiaratchi (1999). Gravitational circulation influenced stratification more than tidal straining, and tidal mixing could not overcome stratification. This was as expected and fits with processes in other estuaries, with gravitational circulation often the most important stratification process (Pattiaratchi pers. comm.). Some tidal mixing was evident in the modeling results, with the ‘tide only’ runs resulting in the isohalines becoming slightly less distinct. Wind mixing should only influence vertical structure when winds are greater than 40 km/hr, which only occurs in the Hardy Inlet during storms and strong sea breezes in summer. No wind data were available upstream of Augusta, but the average wind speed is likely to decrease upstream as protection and distance from the ocean increases.

The gravitational forcing in any estuary is a combination of baroclinic and barotropic forcing. The modeled water level in the tidal river was higher than the water level in the rest of the estuary when the river was flowing, resulting in strong barotropic forcing. Baroclinic forcing was also operating because of the longitudinal salinity gradient up the river. During periods of low flow, baroclinic forcing was more important than barotropic forcing. These findings support the conclusion of Hunt (2003) that tidal mixing is the dominant mixing process in low flow summer conditions. During high flow, barotropic forcing was more important.

The potential energy anomaly calculations did not account for streamflow. There were significant differences between the modeled zero flow, average flow and high flow conditions. Tidal exchange resulted in very limited mixing over the simulation period when the river was not flowing, so streamflow had a more significant impact on flushing than tidal exchange. This fits with the conclusions of Ranasinghe and Pattiaratchi (1998), who found that the major influence
on flushing in Wilson Inlet was streamflow, with tidal exchange having only a minimal effect. The results found here also fit with the findings of Kurup et al. (1998), who found that freshwater inflow was the most important mechanism affecting the salt wedge position in the Swan River estuary.

5.5 Ecological implications

The flow characteristics of the Blackwood River Estuary influence the biological communities in the estuary. The oxygen content of the freshwater in the river was high, as expected, because as water is transported through the catchment into the river, it has a long period of contact with the atmosphere, increasing the saturation and dissolved oxygen content (CENRM 2005). Although the model could not model dissolved oxygen concentrations, predictions about ecology could be made from the model results by assuming that freshwater has high oxygen content. Under average and high flow conditions, almost the entire estuary was therefore flushed with freshwater and would have had high oxygen content and saturation by the end of the 24 day modeling period. Freshwater flowing from the river has high oxygen content and saturation, and is an important source of oxygen to the organisms living downstream in the estuary.

The low oxygen, high salinity patches measured on the river bed in the field work were as expected. The salty water was most likely pushed upstream by tides from the ocean over the summer. In the absence of any significant river flow in the previous six months, the salty water was isolated at the bottom by stratification and gradually became oxygen depleted, due to the aerobic activity of bacteria and other organisms in the water and sediment (Brearley 2005). The patches of low oxygen, high salinity water decreased in size by the second field sampling day, most likely due to freshwater moving down the river displacing the saline water.

Dissolved oxygen concentrations of less than 2.0 mg/L and oxygen saturation of less than 40% make respiration difficult for most fish species and are detrimental to fish over long periods of time (CENRM 2005). Brearley (2005) suggests that levels of at least 5.0 mg/L are required in south west Australian estuaries to maintain healthy freshwater systems. Dissolved oxygen concentration at the river bed at many sites on 17 June was below 2.0 mg/L with saturation levels of less than 30%, suggesting unhealthy levels of oxygen for ecological activity. Freshwater flow is therefore important in the Blackwood River, because it is responsible for flushing saline,
oxygen depleted water, and replacing the water with oxygenated water. More vigorous flushing of the tidal river usually occurs earlier in the year on average, but would not have occurred at the time of field work due to the very low rainfall in the catchment over the preceding six months.

The presence of deep holes, such as the 10 m deep hole at site 14, was documented in the 1974 study of the estuary, but Imberger et al. (1976) did not collect oxygen data, so the ecological implications of these holes could not be considered. When many other sites were flushed from surface to river bed with freshwater on 1 July in response to increasing river flow, there was still high salinity, low oxygen water remaining in the deep holes. Kurup and Hamilton (2002) found that deep holes in the Swan River estuary were hypoxic during low flow conditions, with adequate freshwater flows required to maintain suitable oxygen levels in these holes. Strong, constant river flow would be likely to be required to completely flush the deep holes in the Blackwood River. The model results indicate that river flows of 4.8 GL/day would be sufficient to flush deep holes.

Hunt (2003) presented dissolved oxygen data for sites downstream of Alexandra Bridge during summer, and concluded that the closer a site was to the estuary mouth, the higher the dissolved oxygen concentration due to tidal mixing. The data found here show the opposite trend, as expected, because the current study measured dissolved oxygen in winter when freshwater was bringing oxygen into the river at the head of the estuary. Investigations for the Water Corporation’s Yarragadee extractions measured dissolved oxygen concentrations at Hut Pool similar to the results found here, with surface dissolved oxygen concentrations of 9 mg/L, decreasing to around 2 mg/L at the river bed (CENRM 2005). Oxygen saturation was not reported for the Hut Pool site in the Water Corporation’s investigations.

5.6 Dryland salinity

Dryland salinity represents a major environmental issue throughout the Blackwood River catchment. The impact of dryland salinity on river flow salinity is currently minimized by fresh groundwater flowing into the river from the forested areas of the river around Nannup, 25 km upstream from Warner Glen Bridge (Brearley 2005). Water is fresher after flowing through Nannup and the water entering the estuary is fresher than the water upstream of Nannup. If dryland salinity continues to affect more land in the catchment, the salinity of the river may
eventually be affected (Mayer et al. 2005). The modeling results suggest that a small increase in salinity (around 5) is unlikely to affect the dynamics of the estuary, because the salinity gradient between the ocean and the river would be relatively unchanged. If salinity increased by more than 5, the saltier river flow would be less buoyant and would decrease the stratification in the water column in the tidal river. This would also decrease the longitudinal density gradient in the estuary, which would affect gravitational circulation and could decrease vertical mixing of the entire estuary. The tidal river may then become saline year round and freshwater species would be excluded.

Little is known about how salinity interacts with nutrient and carbon processing in Australian ecosystems (Nielsen et al. 2003). Elevated salinities have already caused substantial changes to the biological communities of aquatic ecosystems in south west Australia (Halse et al. 2003). Current studies suggest that increasing salinity and changes to hydrology in freshwater rivers could affect germination of aquatic plants and hatching of zooplankton, which would decrease biodiversity (Brock et al. 2005). This could impact on the entire food web in the Blackwood River estuary and alter species composition and distribution. Further research is required to understand the ecosystem dynamics of the estuary under increasing salinity conditions.

5.7 Climate change

As described above, streamflow determines flushing in the Blackwood River estuary. Climate models predict that rainfall will decrease in the catchment of the Blackwood in the future, decreasing river flow. Reduced flow is likely to result in limited flushing occurring later in the year, and complete flushing of the estuary rarely occurring. Anoxic hypersaline bottom patches could increase in size due to incomplete and infrequent flushing. Dissolved oxygen that is normally transported to the estuary in river flow would decrease, which could have detrimental effects on fish and other organisms living in the river (CENRM 2005).

Reduced flows associated with climate change could also have decreased velocities and decreased sediment carrying ability, which would decrease the amount of sediment suspended in the water column. Imberger et al. (1976) found that Hardy Inlet channels were eroded in winter when stream flows were high, and that sediment transport was negligible in summer when water was very clear. Reduced river flow may decrease erosion and give the water a clearer appearance.
5.8 Limitations and assumptions

Predictions about climate change and dryland salinity were limited by the amount of available information on long term trends in the south west. Climate change and dryland salinity are complex processes and some positive impacts for the estuary are possible. The analyses here were based only on two generally accepted views: (1) dryland salinity may increase streamflow salinity, and (2) climate change will most likely decrease rainfall in the south west (see Mayer et al. (2005), Natural Heritage Trust (2002), DEH (2003)). For simplicity, other impacts of climate change and dryland salinity were not considered here.

There were two main assumptions in the modeling (1) wind mixing was assumed to be negligible and (2) temperature was assumed to be constant throughout the estuary. The potential energy anomaly calculations suggest that wind mixing should only be important when winds are greater than 40 km/hr. Average wind speed at the exposed Cape Leeuwin is 25 km/hr, and winds in the majority of the estuary are likely to be less than 25 km/hr. Neglecting wind mixing was therefore justified, although wind could be important in vertical mixing in the lagoon during storm events and seabreezes.

The drop sampling found that temperature variations were small along the transect, as expected because temperature variations of greater than 4°C are uncommon in the Blackwood River Estuary (Hodgkin 1978). During summer it is possible to see a vertical stratification in temperature in the water column, with bottom water several degrees hotter than surface water (Hodgkin 1978). This thermocline was not present between Alexandra Bridge and Warner Glen Bridge over the field sampling period so the underlying modeling assumption that the entire estuary was at a constant temperature was likely to be valid.

The influence of the Scott River, which discharges into the estuary close to Molloy Island was not modeled. The river contributes approximately 5 – 10% of the flow that the Blackwood contributes, so its influence on flow and salinity characteristics may be small (Imberger et al. 1976). Time constraints prevented the Scott River being included in the modeling in this study, so further work should focus on the contribution of the Scott River, as well as the nutrient loading in its water, which is high and could affect the whole estuary (Brearley 2005).
The field work was limited in its capacity to represent a true transect of the tidal river, because it was obviously not possible to sample every point in the river. There may therefore be significant variation in parameters between sampling sites, which would not be shown here. For example, the field sampling may have inadvertently sampled the deepest sites in the river, which would not accurately represent the average conditions in the river. The only way to improve this would be to increase the number of sampling sites between Alexandra and Warner Glen Bridges, which would increase sampling time in the field.
6.0 CONCLUSIONS

The methodology undertaken as part of this project provided information about flushing, stratification and mixing characteristics in the Blackwood River Estuary. Overall the methodology was successful and achieved the outlined objectives with few limitations.

Initial field results revealed that much of the tidal river was highly saline and deoxygenated, particularly in the deepest sections, most probably due to very low rainfall in the catchment in the first six months of 2006. The second field assessment, after two rainfall events had taken place throughout the catchment, showed that freshwater with high oxygen content had begun to flow in the tidal river, displacing the saltwater. Freshwater flow increased oxygen concentrations in the river, so freshwater flushing of the estuary is necessary to ensure that dissolved oxygen remains high enough to sustain life. Climate change may result in decreased runoff and infiltration to the river, and Yarragadee aquifer extractions could decrease groundwater flow to the river. The conditions observed in 2006, with low rainfall, low river flow and low oxygen bottom waters remaining in the tidal river until at least July, may be similar to the conditions created by climate change in the future. Fish and other organisms may be adversely affected by these conditions.

The hydrodynamic modeling successfully modeled the salinity and water level processes in the estuary. The modeling was verified by field work and some results were found to be similar. Surge influenced the salt flux in the estuary, with high surge increasing the volume of salt entering the estuary. Processes that affect water level, such as atmospheric pressure cells, seiches and continental shelf waves, therefore affected the salinity and stratification of the estuary, particularly at the ocean entrance and inlet.

The potential energy anomaly was a useful tool for quantifying stratification and mixing processes in the Blackwood River estuary. The results of the energy balance fit with expectations and observations of the estuary, indicating that the potential energy anomaly method, as described by Ranasinghe and Pattiaratchi (1999) and Gale et al. (2006), can be an accurate way of quantifying estuarine processes. This method could be applied to any estuary or water body where the required parameters were known.
Salinity varied in the estuary over the tidal cycle, with maximum stratification at late ebb tide and minimum stratification at late flood tide, which demonstrated tidal straining was present. However, the potential energy anomaly calculations revealed that gravitational circulation had a greater effect on stratification than tidal straining. Increases in river flow salinity that may be associated with dryland salinity will affect the longitudinal density gradient and gravitational circulation, which could decrease vertical mixing in the entire estuary.

The tide had limited influence on vertical mixing in the estuary and could not overcome the stratification under low flow conditions. Wind mixing probably only influences vertical mixing in the estuary during summer sea breezes and winter storm events. Streamflow had the largest impact on stratification, but significant rainfall is required throughout the catchment before the river flow increases and the estuary can be fully flushed. If rainfall and streamflow decreased in response to climate change, the estuary would probably remain saline and highly stratified with limited mixing for a greater proportion of the year, and full flushing would be rare.

The findings of this study were compared to the extensive field program undertaken by Imberger et al. (1976). The current study contributed valuable additional information to the findings of the original study, with dissolved oxygen data collected and hydrodynamic modeling undertaken for the first time in this system. The flow conditions in 1974 were very different from the conditions measured and modeled here, with river flow significantly lower in 2006 and flushing patterns different from those observed in 1974. Whether this was due to the unusually high flow in 1974 or due to recent climate change cannot be determined here. Further research into the flow patterns over the last 40 years at least would be required to confidently conclude that the 2006 low flow conditions were not merely part of the natural variation in the Blackwood River flow.

The methodology used here can be used to describe and study other estuarine systems. The results of this study have implications for the management of the Blackwood River estuary and its catchment, as well as for other estuarine systems in south west Australia. The results suggest that changes in the flow regime due to dryland salinity and climate change could adversely affect the dynamics and ecology of the estuary. The Blackwood River estuary system will be under increasing pressure from tourism, dryland salinity, aquifer extractions and reduced rainfall in the future, and effective management will rely on thorough estuarine understanding.
7.0 RECOMMENDATIONS

It is advised that future hydrodynamic models of the Blackwood River should vary initial salinity distributions and boundary salinities to investigate the impact of initial and boundary conditions on the model results. The current results suggest that under low flow conditions, the model final condition is highly dependent on initial salinity distribution. Warner et al. (2005) experienced the same issue with hydrodynamic modeling, with salinities in the modeled estuary highly dependent on initial and boundary conditions. Repeating the model with modified boundary and initial values would increase the validity of the conclusions made here. River flow should also be varied to find the critical flow between 0 and 4.8 GL/day that flushes the estuary.

The model was run for the maximum time allowable in HAMSOM, which was 24 days. However, the changes in the estuary under low conditions occur over a longer time scale than 24 days. If possible, it is recommended that the model be altered to run for longer than 24 days to more accurately represent the time scale over which salt is transported from the ocean to the river during low flow.

Temporal changes in the tidal river would be better understood if more extensive field measurements were taken regularly. Currently, no regular monitoring of the tidal river downstream of Warner Glen Bridge occurs. Field measurements in the tidal river implemented year round would provide an indication of the temporal changes in dissolved oxygen and salinity, and the potential for changes to the system in the future.

To more accurately predict changes to the estuary associated with salinity, climate change and aquifer extractions, longer data sets are required to study trends in the catchment. Only then can the combined effect of these threats on river flow and salinity be predicted. These potential changes in combination may have a profound influence on flow and dynamics in the estuary. For example, climate change may exacerbate inland salinity problems, so climate change and salinity problems need to be considered simultaneously.

The effects of increased salinity on common organisms in the river should be investigated. In general, little is known about Western Australian aquatic organisms and their response to
increased salt loading in the water. Studying the response and tolerance of seagrasses, fish and other organisms as a whole ecosystem would assist commercial and recreational fisheries in predicting the impact of climate change and dryland salinity on their catches.

More groundwater and surface water salinity data should be collected from throughout the Blackwood River catchment to determine trends in dryland salinity. A long term data set is required to distinguish between localised problems and larger scale patterns. Retaining forested areas throughout the catchment is an effective way of reducing salinity increases in river flow. Only when trends are understood can predictions for the river be made.

The low river flow in 2006 may have been part of the natural variability of the Blackwood River. However, it may also have been part of an overall trend in Western Australian rivers towards lower flow and later flushing. Analysis of all historical data in the Blackwood River would be required to determine whether the conditions observed in 2006 were consistent with the natural variation of the system. Climate change models predict decreasing rainfall in the south west so the dependence of river flow on rainfall, as opposed to groundwater discharge, should also be quantified.

It is suggested that the methodology used in this study be applied to other south west estuaries to determine the influence of estuarine processes. The potential energy anomaly calculated here could also be applied to other estuaries. All south west estuaries will be affected by climate change, but the response of each estuary is likely to be unique, depending on rainfall, exposure and geomorphic classification. Predictions about future estuarine condition in other estuaries can then be made.
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Appendix A – Frequency spectrums for long term temperature and salinity data at Alexandra Bridge (17.06.06 – 1.07.06)
Appendix B – Salinity plots for model runs 2 and 5 and runs 3 and 6