



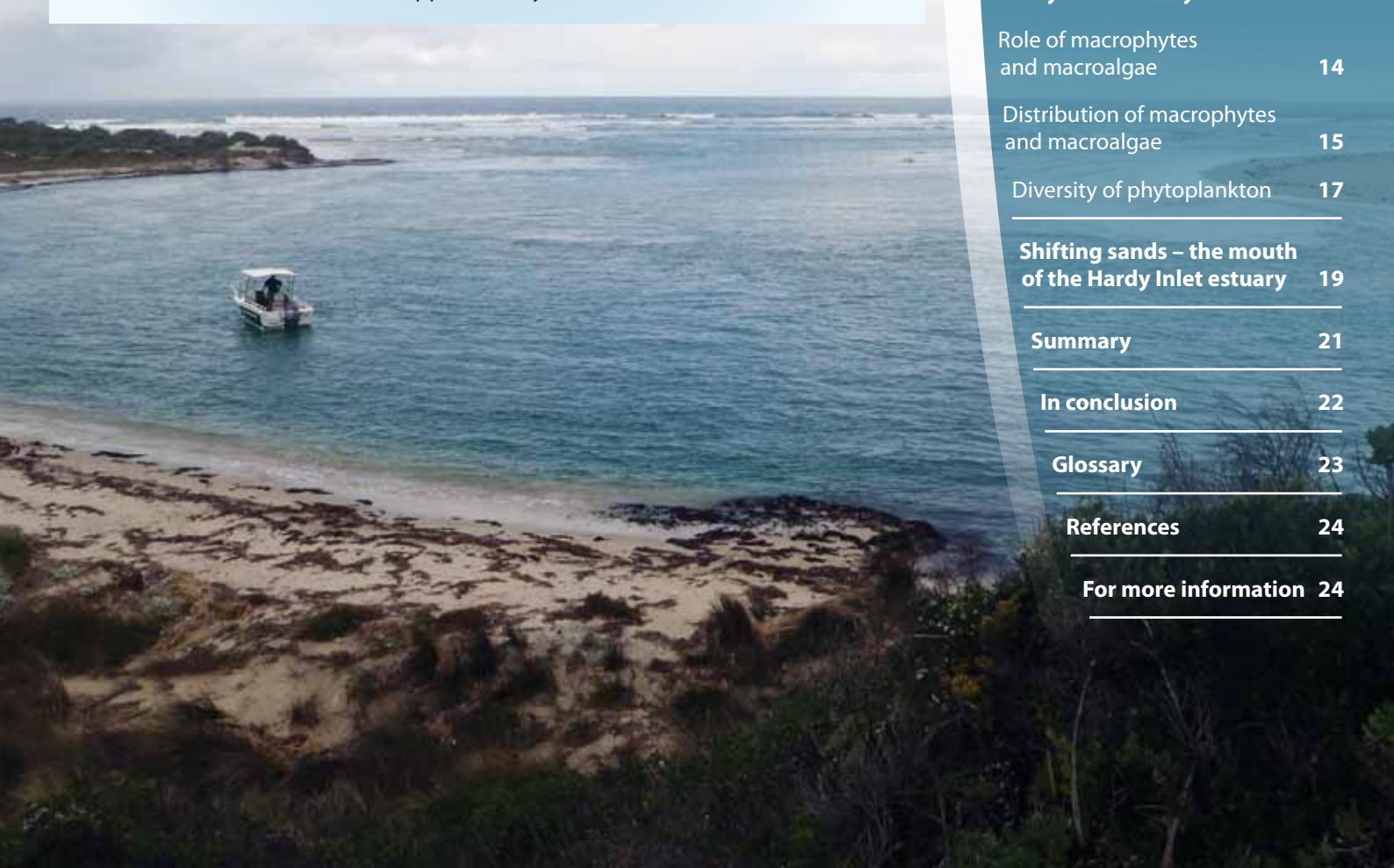
## Estuary condition report 1999 to 2010

A decade's worth of monitoring and scientific studies have been collated in this report for the Hardy Inlet estuary to provide a synopsis on the current state of its condition over that period. Key findings were:

- ❖ Water quality in the Hardy Inlet estuary deteriorated towards the upper estuary past Molloy Island.
- ❖ The condition of the lower estuary was 'moderate to good'. The water column was well-mixed and oxygenated, and nutrient concentrations were low (except after heavy rainfall and flow events). Aquatic plant life was dominated by seagrass – a favourable habitat for fish and invertebrates. Phytoplankton blooms were infrequent. Nutrients from urban drainage may contribute to the excessive macroalgal growth that has periodically impacted the Augusta foreshore.
- ❖ The condition of the upper estuary was poor. Dissolved oxygen concentrations in the water were low and nutrient concentrations were high. Nutrients from catchment run-off, and from sediment nutrient release in the deep channels have affected water quality. Phytoplankton blooms were a frequent symptom of nutrient-rich conditions in the upper estuary.

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# Introduction

The Hardy Inlet is located on the far south-west coast of Western Australia adjacent to the town of Augusta. It is a relatively small estuary – 9 km<sup>2</sup>, at the seaward end of the 42 km-long Blackwood River estuary. It is one of only two estuarine systems on the south coast that maintains a permanent and natural opening to the ocean. The natural setting of the estuary is an asset to the local community and popular for visitors. Fishing, boating and ecotourism activities are enjoyed on the estuary.

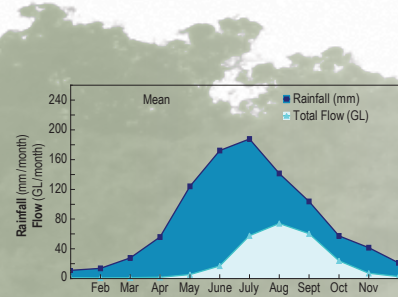
Two rivers enter the Hardy Inlet just north of Molloy Island. The Blackwood River, which gives the upper estuary its riverine appearance, drains a large agricultural catchment and carries substantial nitrogen to the estuary. The Scott River to the east is considerably smaller but delivers large loads of phosphorus, mainly due to the low phosphorus-binding capacity of soils in the Scott River catchment. Residential areas are also responsible for nutrient inputs: fertilised gardens, stormwater drains, and leaching from poorly sealed septic tanks contribute to the estuary’s nutrient load. The growth of the

residential community is likely to result in an increase of these inputs.

Estuary habitats are under increasing urban pressures worldwide, including nutrient and contaminant pollution, fishing and boating pressures, and increases in exotic species. As these pressures increase, ecosystem health is diminished and symptoms such as water column hypoxia, algal blooms and fish-kills increase. Sadly, amid the scenic backdrop of the Hardy Inlet estuary, there are clear signs of eutrophication. Estuary water quality has been negatively impacted by nuisance algae and hypoxia, a product of long-term nutrient and organic loading to the estuary from catchment and urban land uses. Increasing variability in natural drivers, such as river flows and oceanic exchange, has exacerbated the impact of nutrient and organic loading to the estuary.

The first issue of the *south-west estuaries* series focuses on providing an understanding of the condition of the Hardy Inlet and its rivers. The report is supported by a decade of comprehensive water quality monitoring data and numerous scientific studies in the estuary.

## What do we measure to assess estuary condition?



**Hydrology (rainfall and river flows)**

Meteorological and stream-flow gauging stations established in the catchment monitor rainfall and river flow volumes along the Blackwood River, Scott River and other major tributaries in the catchment. Freshwater inflows have a major influence on biophysical processes, such as salinity gradients, water quality and plant and animal distribution patterns in estuaries. The timing and volume of fresh water river flows is determined by the rainfall patterns in the catchment.

### Monitoring the catchment



**Water quality**

Physical water quality conditions (salinity, temperature and dissolved oxygen) and nutrient concentrations (nitrogen and phosphorus) were monitored fortnightly in the major tributaries of the Blackwood and Scott rivers. Natural and human pollutants (e.g. salt, nutrients, organic matter, sediments, toxicants and microbes) from the catchment can reduce the quality of water that reaches the estuary. This can disrupt estuary ecology and, for example, cause algal blooms.



### Estuary

### Land use and nutrient modelling

Land use data was collected, mapped and verified by the community and local agencies. When combined with information on soil types, agricultural practices (e.g. fertiliser use), water flow and nutrient concentrations, the loss of nutrient from the catchment to the estuary can be estimated. Appropriate management of the supply of nitrogen and phosphorus to the estuary is critical to mitigating the effects of eutrophication such as algal blooms, anoxia and fish kills.



# Water quality in the Hardy Inlet estuary

Our understanding of water quality conditions in the estuary is derived from a comprehensive monitoring program which was completed in 2011–12. Thirteen sites were regularly monitored for salinity, temperature, dissolved oxygen, nutrients, water clarity and phytoplankton abundance and composition (Figure 1).

## Understanding a 'salt-wedge' estuary

Hardy Inlet is permanently open to the ocean and influenced by the tides. Seawater has a greater density than the brackish estuary water so tides move into the estuary as a salty layer along the bottom. This layering or stratification phenomenon is called a 'salt-wedge'. Stratification can affect salinity and dissolved oxygen water column profiles in the estuary (see *Salt-wedge dynamics in the Hardy Inlet estuary*).

## What is an estuary and how do we measure condition?

Simply defined, an estuary is a semi-enclosed body of water where river and sea water mix. The interaction of fresh and marine waters creates a naturally dynamic environment where:

- ❖ Water within the estuary can become stratified (layered) and mixing between the two layers is limited.
- ❖ River flows and ocean exchange alter both physical (e.g. salinity and temperature) and chemical conditions (e.g. nutrients) in the estuary.
- ❖ Diverse habitats (e.g. channels, tidal flats/deltas, saltmarshes and beaches) are created by sediments delivered from rivers and ocean tides. These habitats are important to plant and animal communities.

Estuaries are extremely vulnerable to human-induced impacts from catchment activities, recreation and settlement. Natural and anthropogenic influences need to be considered. The Department of Water – as the lead agency for river and estuary science – has implemented monitoring and research programs to collect relevant data. Integrated assessments of ecosystem health (see *What do we measure to assess estuary condition?*) build on our understanding of processes that impact on estuary health. The Water Science Branch has developed estuary health indicators, with the intention of developing estuary report cards to guide potential management actions to improve estuary health.

## Estuary water quality



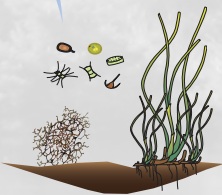
Physical water quality conditions (salinity, temperature and dissolved oxygen), and chemical water quality (total and dissolved nutrients of nitrogen and phosphorus, and chlorophyll) were measured fortnightly at several sites along the estuary. The results help us to monitor natural phenomena such as stratification and tidal flushing, as well as changes caused by human intervention such as pollution. A particular pollution problem for the Hardy Inlet is nutrient enrichment – from fertilizers and organic matter contributing to eutrophication of the estuary. This can cause nuisance algal growth, algal blooms and low oxygen conditions.

### Sediments



The physical properties (grain size and organic content), nutrient flux and metabolism of sediments are assessed every few years, or more often depending on hydrological conditions (e.g. during and after a flood). Sediment quality and dynamics (sedimentation, erosion and nutrient fluxes) influence the ecology of the estuary (e.g. provide habitat, nutrients and support and estuarine foodwebs). Changes in sediment quality often reflect changes in catchment loading (nutrients and sediment) and estuary dynamics.

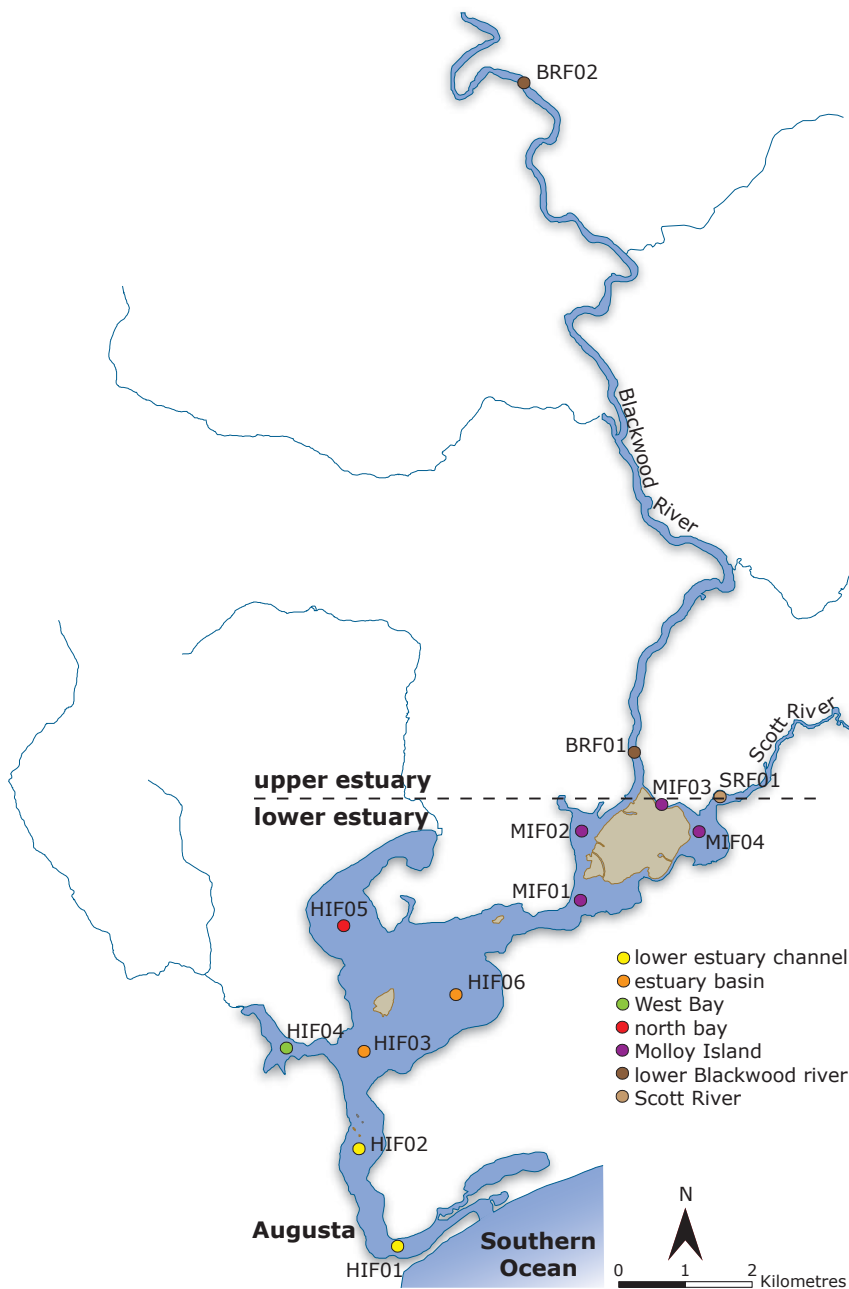
### Aquatic plants and algae



The extent and distribution of seagrass and accumulation of macroalgae was monitored every few years in the estuary. Phytoplankton was monitored fortnightly for density and composition, and the occurrence of harmful algal species. Shifts in species composition, the loss of seagrass habitat or excessive growth of nuisance macroalgae and phytoplankton blooms can result from direct disturbance or a deterioration in water quality.



Monitoring the estuary



**Figure 1. Hardy Inlet estuary water quality monitoring sites**

### Changes in salinity

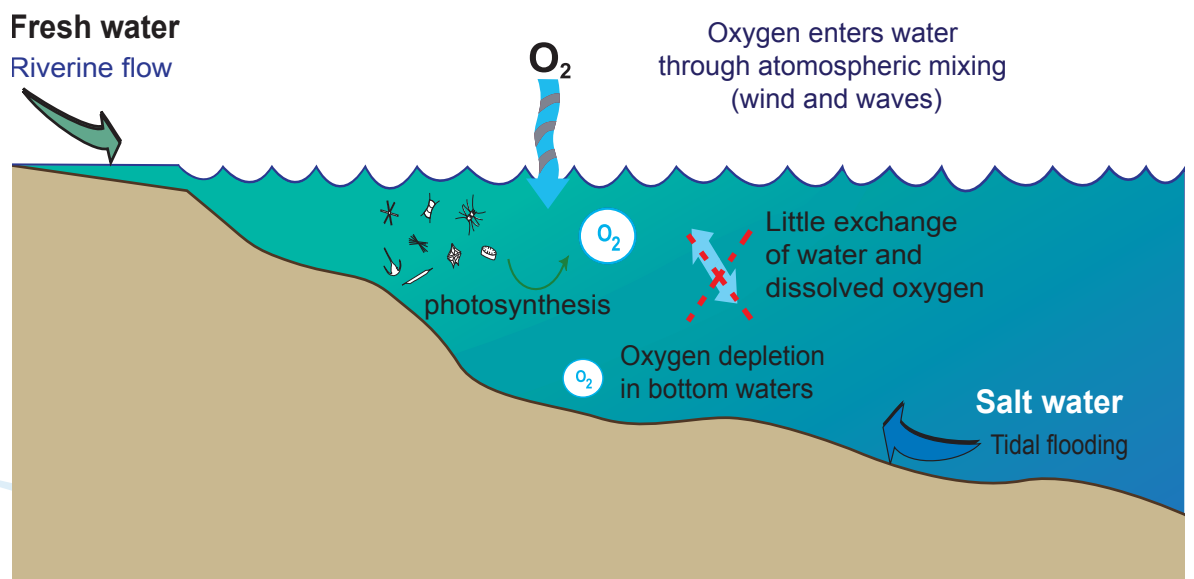
The salt-wedge in the Hardy Inlet estuary is dynamic. In the drier, warmer months when river flows were low, the salt-wedge moved a long way up the estuary (42 km). Salinities in Hardy Inlet estuary were generally high in these months and varied between 20 and 46 PSU (practical salinity units) depending on location – although the estuary was only occasionally more saline than the ocean (35 PSU). Stratification, due to the salt wedge, was less pronounced in the shallower parts of the lower estuary (which can be well mixed by the wind), compared to the lower reaches of the Blackwood River (Figure 2).

During winter, when river flows were usually higher, salt water was flushed from most of the estuary. Only the estuary mouth and the deepest sections of the lower Blackwood River remained saline in the bottom waters (20–30 PSU).

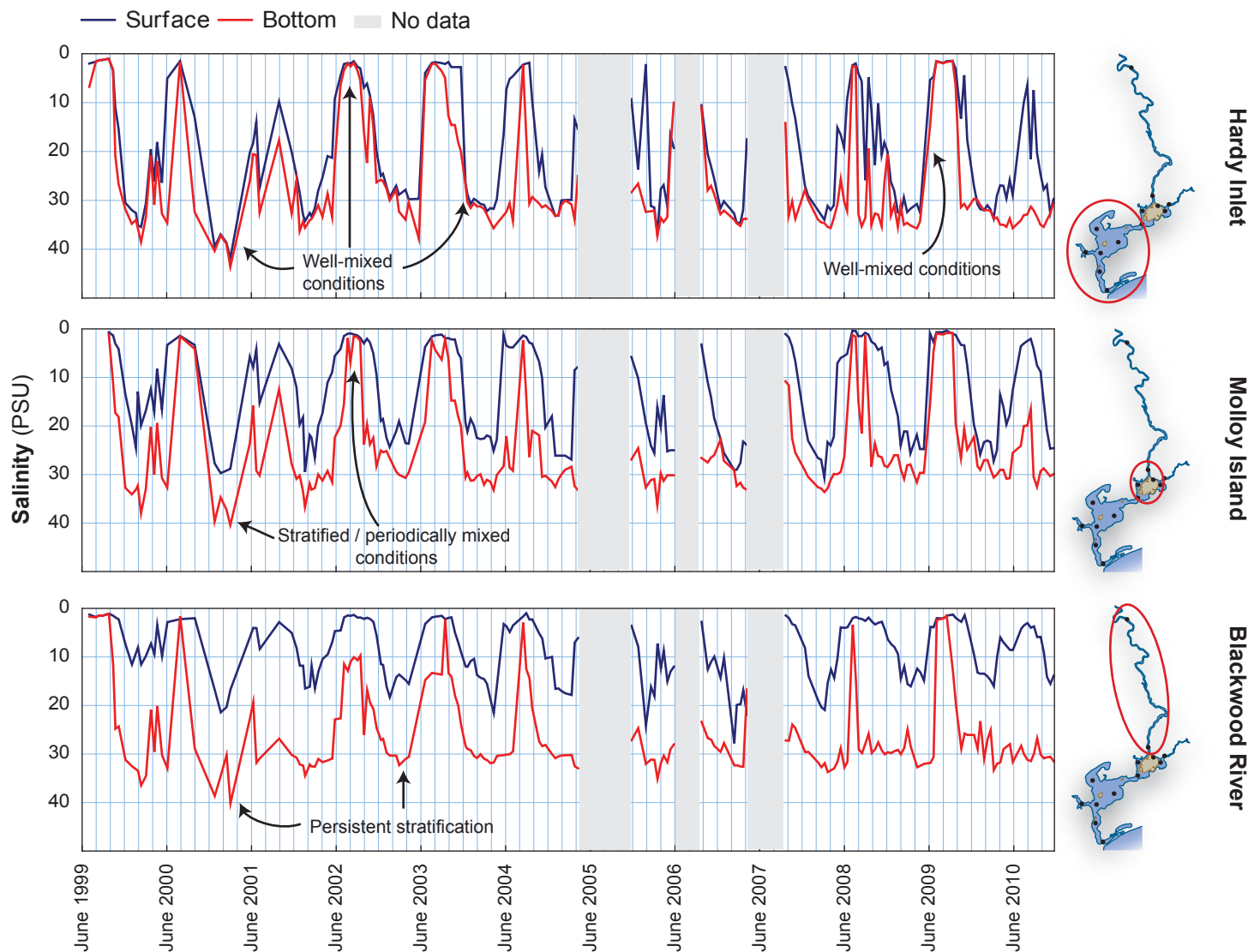
The deep holes (up to 12 m) in the lower Blackwood River had salinities as high as 20 PSU for many months at a time. Deeper waters were only flushed out during very high flows (in excess of 12 GL/day for several consecutive days). During the last 11 years of monitoring, we observed this phenomenon only three times; in the winters of 1999, 2000 and 2009 (Figure 2).

### Changes in dissolved oxygen concentrations

The decomposition of organic matter within sediment by aerobic bacteria consumes oxygen. Aquatic plants and phytoplankton also consume oxygen during dark respiration (during non-photosynthetic periods overnight). These processes deplete water column oxygen concentrations – particularly when the water column is stratified – and bottom waters can become anoxic.



**Salt-wedge dynamics in the Hardy Inlet estuary**



**Figure 2. Median surface and bottom salinities at sites in the estuary basin, Molloy Island and the estuarine reaches of the Blackwood River**

Increased organic matter loading exacerbates the depletion of oxygen in the estuarine waters. Organic matter may be derived either directly from the catchment or from plant and animal production within the estuary – see *Sediment organic matter*.

In the lower estuary, with the exception of the channels around Molloy Island, oxygen concentrations were high (greater than 6 mg/L). These good oxygen conditions were due to a well-mixed shallow water column and the low organic content of the sediments, which were mostly marine in origin (Figure 3). Oxygen concentrations were also high in the shallow estuarine parts of the Scott River. These high oxygen conditions are favourable for aquatic life.

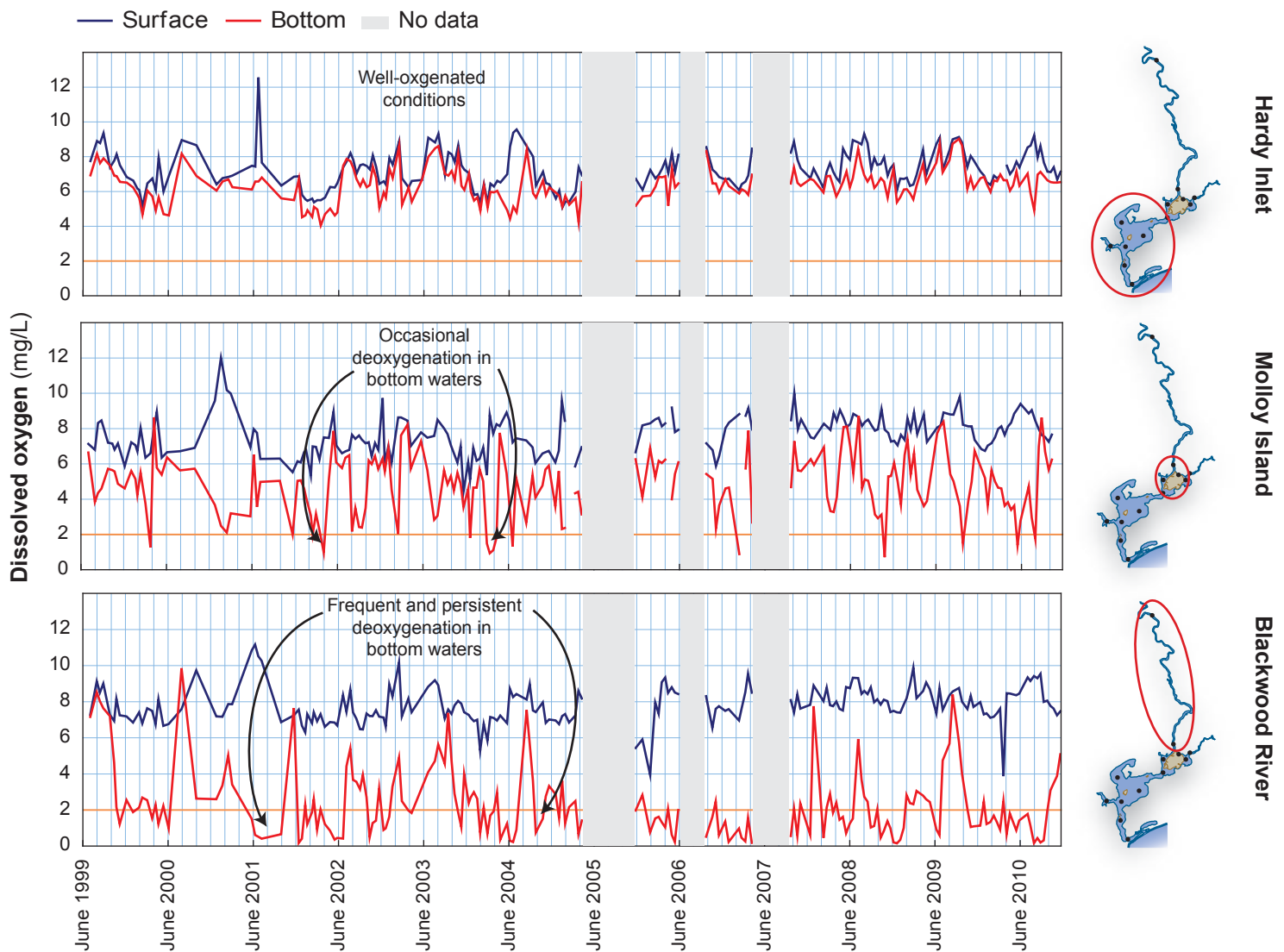
Unfortunately, less favourable oxygen conditions were present in the channels around Molloy Island and in the estuarine reaches of the Blackwood River. Salinity stratification was more persistent in these deeper waters.

Stratification and poor oxygen conditions are exacerbated by low river flows and long term organic loading from the catchment. The minimum oxygen concentration required for aquatic life is considered to be 2 mg/L. Dissolved oxygen conditions were frequently less than 4 mg/L – at which larval fish become affected – and often below 2 mg/L for extended periods (Figure 3). These low oxygen conditions may provide some explanation for anecdotal reports of reduced fish catches in the Blackwood River estuary.

Oxygenated conditions were restored with high river flows – an important process for the deeper sections of the Blackwood River which can remain stratified for months at a time.

### Nutrients – our focus on nitrogen and phosphorus

Nitrogen (N) and phosphorus (P) are nutrients critical for phytoplankton and higher plant growth, and thus routinely monitored in many



**Figure 3. Median surface and bottom dissolved oxygen concentrations at sites in the estuary basin, Molloy Island and the estuarine reaches of the Blackwood River**

estuaries. Nutrient enrichment ('eutrophication') can lead to excessive and unfavourable plant growth, e.g. macroalgal accumulations and phytoplankton blooms.

Nitrogen and phosphorus both occur in either dissolved or particulate forms and may be inorganic or organic in nature (i.e. bound to carbon). Total nitrogen (TN) and total phosphorus (TP) includes all forms (inorganic and organic, dissolved and particulate) of nitrogen and phosphorus in the water column and are measured to determine the total nutrients in the estuary. Other nutrient measurements are fractions of this total and include dissolved nutrients such as ammonium ( $\text{NH}_4^+$ ), nitrate/nitrite ( $\text{NO}_3^-/\text{NO}_2^-$ ) and soluble phosphate or filterable/soluble reactive phosphorus ( $\text{PO}_4^{3-}$ ).

The inorganic fraction (e.g. phosphate, nitrate or ammonium) is considered the most available nutrient fraction to plants for growth. Organic nutrients and compounds may also influence plant and algal growth but are measured less

frequently. Dissolved organic nitrogen and phosphorus are released from decaying plant and animal material. Degrading plant-derived organic matter also releases tannins, and fulvic and humic acids.

#### *Nutrient sources – the influence of human activities on N and P*

The quantity and quality of river flow from the Hardy Inlet catchment has been altered by clearing and land-use activities. Approximately 75% of the catchment has been cleared. The catchment of the Hardy Inlet estuary (which includes the catchments for the Blackwood and the Scott rivers) extends 310 km from Augusta to just east of Kukerin and Nyabing and covers an area of 22 500 km<sup>2</sup>.

In the Blackwood River, catchment activities range from broadacre wheat and sheep farming in the east to more intensive land uses such as horticulture, viticulture, beef farming and dairying in the west. In the Scott River catchment (Scott Coastal Plain), plantation

forestry, horticulture, dry land grazing and irrigated dairy farming are the primary land uses.

There is increasing urbanisation pressure on the Hardy Inlet estuary. Augusta has historically been a popular summer destination for visitors, but many more people now also live in Augusta and around the Hardy Inlet estuary. From 2001 to 2009, the population has increased by 20%. Nutrients from septic tanks and run-off from fertilised lawns and gardens are thought to be causing abundant algal growth along the foreshore. However, the impact of urban nutrient inputs are yet to be quantified.

### Nutrient loads – how much N and P is leaving the catchment?

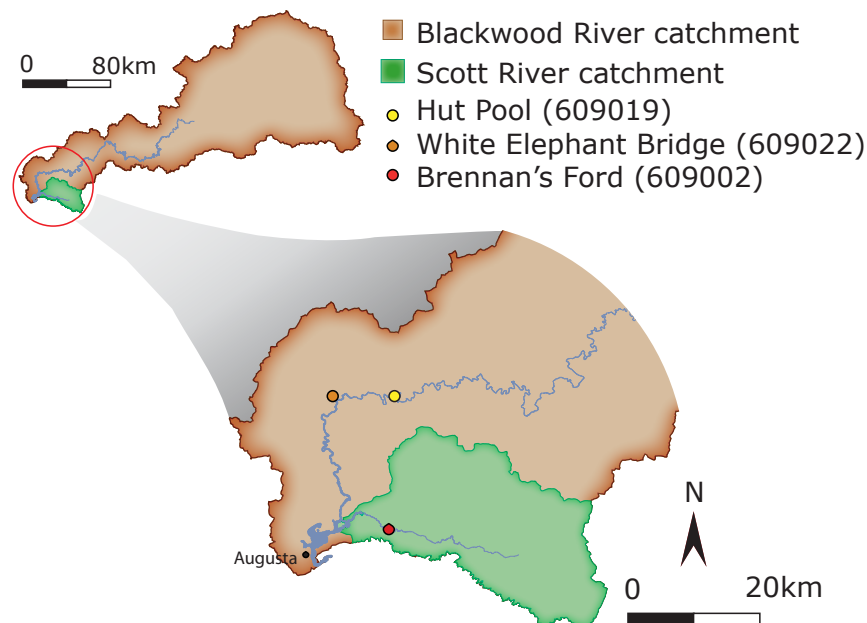
‘Nutrient loads’ tell us the amount of nutrients (in kilograms or tonnes) that are leaving the catchment over time and the relative contribution that each catchment supplies to the estuary. The Department of Water calculates nutrient loads from flow volume and nutrient concentration data collected at gauging sites on the Blackwood River (609019) and Scott River (609002) (Figure 4).

Annual nutrient load results for the Blackwood and Scott River catchments show that inter-annual variation in nutrient loads leaving the catchments was high, and that this variation was related to river flow. In other words, nutrient loads were higher for both TN and TP in years of high flow e.g. 2000, 2005 and 2009.

The relative contribution of TN and TP from each of the catchments was different (Table 1). Annual nitrogen loads were much higher from the Blackwood River catchment, because this catchment had significantly greater river flows. Phosphorus loads were larger from the Scott River catchment. The sandy soils in the Scott River catchment are unable to retain phosphorus. Consequently, phosphorus is easily lost as run-off and leached from the soils into groundwater. However, we expect nutrient loads were underestimated for the Blackwood River catchment because the monitoring site was located upstream of an agricultural sector. The high TP loads from the Scott River catchment were nevertheless significant given the smaller catchment (only 3% of the total area of both catchments) and lower river flow volumes (10 to 14% of the total).

Nutrient loading to the estuary fluctuates within any given year because of seasonal changes in rainfall and the effect this has on river flow (Table 2). In this region, June to September are typically wet with higher river flows. At these times, TN loads were up to 240 times higher in the Blackwood River catchment, and 30 times higher in the Scott River catchment than during the hot, dry months of November to February.

Similarly, TP loads were 143 times higher in the Blackwood River catchment and 27 times higher in the Scott River catchment during the wet months than the dry months.



**Figure 4. Map of Hardy Inlet and the Blackwood and Scott River catchments showing the location of stream flow gauging sites.**

**Table 1. Annual loads (tonnes) of total nitrogen (TN) and total phosphorus (TP) calculated for the Blackwood River and Scott River catchments (flow in GL)**

	Blackwood River			Scott River		
	TN	TP	Flow	TN	TP	Flow
2000	647	12	566	124	18	116
2001	49	1	124	27	4	25
2002	239	5	347	55	8	51
2003	370	7	435	59	9	54
2004	290	6	343	65	10	59
2005	974	19	842	90	13	82
2006	99	2	165	37	6	33
2007	324	6	360	50	7	44
2008	474	9	429	80	12	73
2009	846	15	650	134	20	123
2010	23	1	69	19	3	17

**Table 2. Summer (December to February) and winter (June to August) nutrient loads (tonnes) of total nitrogen (TN) and total phosphorus (TP) calculated for the Blackwood River and Scott River catchments in 2008–2009.**

	Blackwood River		Scott River	
	TN	TP	TN	TP
Summer 2008–09	3.3	0.1	3.7	0.6
Winter 2009	794.0	14.3	113.0	16.4

### Evaluating estuary nutrients – ecological guidelines for estuaries

Nutrient concentration data collected in the south-west estuaries are compared against the ANZECC & ARMCANZ water quality guidelines developed for south-west Australian estuaries (2000) (Table 3). These guidelines provide a framework for protecting ecological and recreation values in estuaries. Concentrations in the estuary should remain lower than the recommended guideline value for each of the total nutrients and nutrient fractions. Similar guidelines are also provided for different types of water bodies (e.g. rivers) and regions by the ANZECC & ARMCANZ.

**Table 3. ANZECC & ARMCANZ water quality guidelines for nutrients in south-west Australian estuaries (2000)**

Nutrient parameter	Guideline value (mg/L)
Total nitrogen (TN)	0.75
Ammonium (NH <sub>4</sub> <sup>+</sup> )	0.04
Nitrate (NO <sub>3</sub> <sup>-</sup> )/nitrite (NO <sub>2</sub> <sup>-</sup> )	0.045
Total phosphorus (TP)	0.03
Soluble phosphate (PO <sub>4</sub> <sup>3-</sup> )	0.005

### Estuary nutrient concentrations

Measuring catchment nutrient loads alone is not a good indicator of nutrient availability within the estuary for several reasons. Nutrients may be recycled or utilised within the rivers on the way to the estuary, and estuarine sediments can also release substantial amounts of nutrients. So, measuring nutrients in the estuarine water column provides the best indication of the nutrients available for primary production.

Nutrient concentrations in the estuary change with variations in river flow, and with processes that either recycle nutrients (e.g. sediment processes) or use nutrients (e.g. plants and algae). The Department of Water collected nutrient samples from 13 monitoring sites in the Hardy Inlet estuary. Samples were collected from the surface and bottom waters to help us

understand seasonal variation in concentrations as a result of changing river flows, stratification and nutrient cycling processes in the inlet.

### Patterns of nutrient enrichment – the link between catchment and estuary

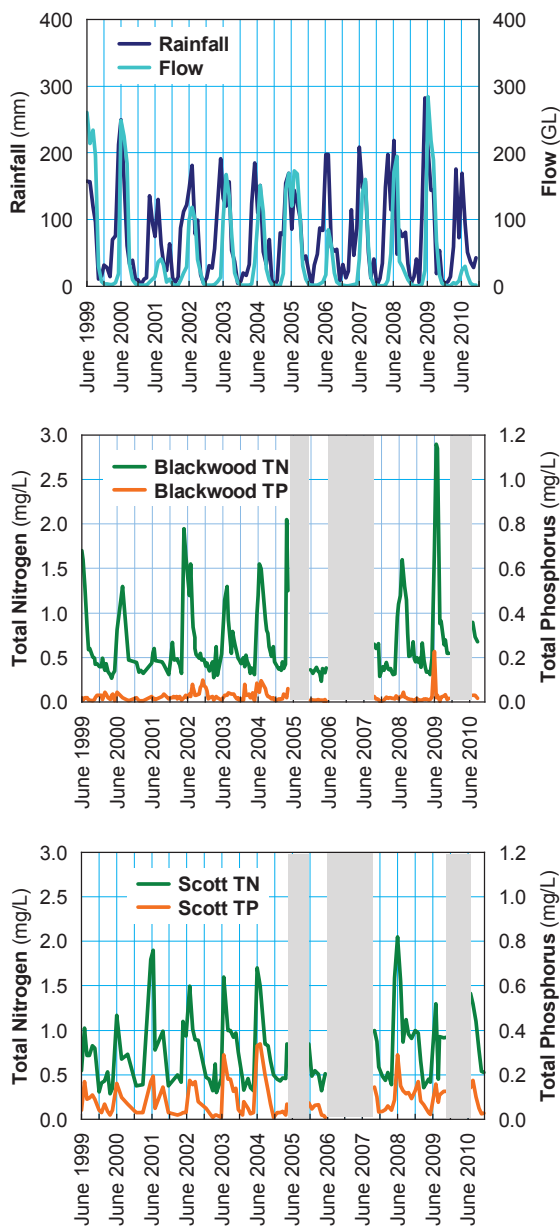
There was a critical relationship between nutrient losses (see *Nutrient loads*) from the catchment and nutrient concentrations in the estuary.

In the upper estuarine reaches of the Blackwood and Scott Rivers, nutrient concentrations in the surface waters (a useful measure of nutrient transport in river flows) increased significantly – exceeding ANZECC guideline concentrations – in the months between June and September. River flows (and nutrient losses) from the catchment were the greatest over this period (Table 2, Figure 5).

Patterns which emerged from the long-term monitoring data for the upper estuarine reaches of the Blackwood and Scott Rivers were:

- ❖ TN concentration ranges in both rivers were similar (0.13 to 2.9 mg/L).
- ❖ TP concentrations in the Scott River (0.005 to 0.38 mg/L) were higher than the Blackwood River (0.003 to 0.23 mg/L).
- ❖ TN concentrations in the Blackwood and Scott Rivers were strongly seasonal.
- ❖ TP concentrations in the Scott River were seasonal, but TP concentrations in the Blackwood River showed no clear pattern.
- ❖ winter TN concentrations in the Blackwood River fluctuated inter-annually.
- ❖ winter TN and TP concentrations in the Scott River were more consistent from year to year.
- ❖ TN concentrations increased considerably throughout the estuary between June and September (or during months of higher river flows), with median TN concentrations exceeding 0.75 mg/L at most sites (Figure 6).
- ❖ TP concentrations only increased around Molloy Island and in the estuarine reaches of the Scott River (exceeding 0.03 mg/L) (Figure 7).
- ❖ Fewer sites were affected by nutrient enrichment between November and February (or during months of lower flow).
- ❖ TN concentrations were low (below 0.75 mg/L) at all sites in the inlet (Figure 6).
- ❖ TP concentrations were below 0.03 mg/L at sites in the lower estuary only (Figure 7).
- ❖ TP concentrations in the estuarine Scott River were high and exceeded 0.03 mg/L (Figure 7).

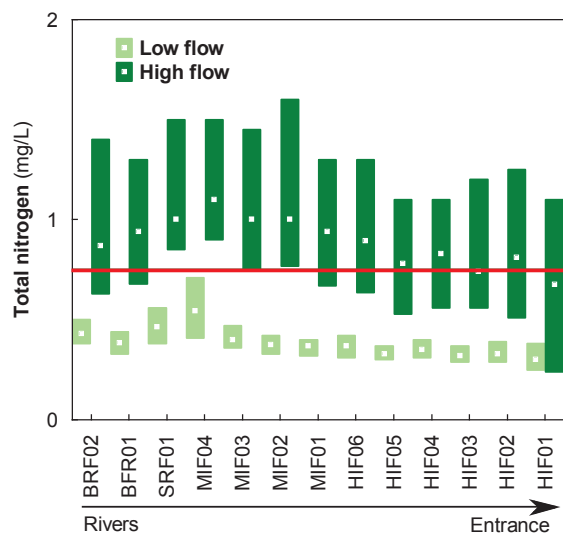




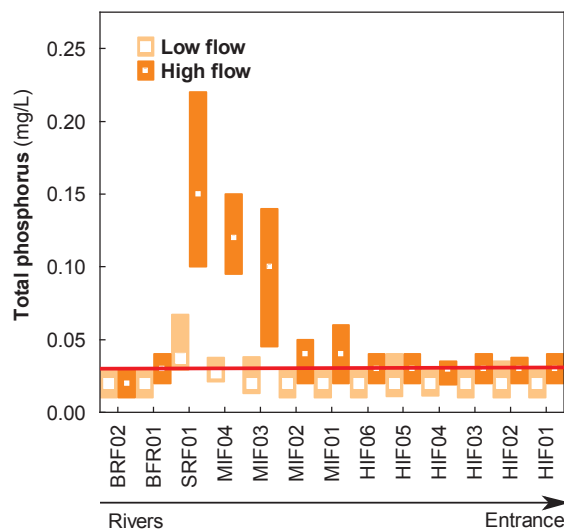
**Figure 5. Monthly rainfall and river flow recorded in the Hardy Inlet catchment and corresponding total nitrogen and total phosphorus concentrations – for surface waters – in estuarine reaches of the Blackwood and Scott Rivers.**

Consistently higher nutrient concentrations, in particular TP, were measured around the Scott River confluence in both the summer and winter months. This highlighted the influence of high nutrient loads leaving the Scott River catchment, but also suggested that these nutrients were not well-diluted or flushed seaward from this region.

The geomorphology of the region near the Scott River confluence influences flow and dilution of nutrients. The Scott River flows into the inlet via a wide shallow basin. Molloy Island and the narrow surrounding channels further restrict flows and



**Figure 6. Surface total nitrogen (TN) concentrations during high and low flow periods at monitored sites collected between 1999 and 2010.** The data represents the median (white square), and the 80<sup>th</sup> and 20<sup>th</sup> percentile data range. The red line represents the ANZECC & ARMCANZ guideline value.



**Figure 7. Surface total phosphorus (TP) concentrations during high and low flow periods at monitored sites collected between 1999 and 2010.** The data represents the median (white square), and the 80<sup>th</sup> and 20<sup>th</sup> percentile data range. The red line represents the ANZECC & ARMCANZ guideline value.

increase the residence time of nutrient-rich water in the region. This had an accumulating affect on nutrient concentrations and a huge impact on aquatic plant life. Blooms of the potentially toxic cyanobacteria species *Lyngbya aestuarii* have frequently affected the waters around Molloy Island.

## Sediment quality and nutrient cycling in the Hardy Inlet estuary

Sediments in estuaries accumulate large stores of nutrients (often as organic matter). Depending on the nature of the sediments, organic matter and nutrient cycling process, nutrients may either remain stored within the sediments (when sediments act as a 'nutrient sink'), be processed further, or be released into the overlying water column (when sediments act as a 'nutrient source'). Estuary 'health' is decreased when there is an increase in organic loading and nutrient availability to sediments and overlying water column.

The Department of Water, in collaboration with Geoscience Australia, undertook detailed sediment studies to better understand nutrient cycling processes in the Hardy Inlet estuary.



*Sediment cores being collected for porosity and pore water nutrient analysis*  
(Geoscience Australia 2008)

Measures of sediments included:

- ❖ *Physical features of the sediments* – different sediment types have different nutrient cycling characteristics.
- ❖ *Sedimentation and organic matter* – the amount of sediment and organic matter depends upon how much material from various sources is reaching the estuary. The organic matter composition can inform on where the accumulated nutrients originate.
- ❖ *Sediment nutrient pools* – provides an inventory of dissolved nutrients stored in the pore waters (water between sediment particles).
- ❖ *Sediment nutrient fluxes* – provides a measure of the rate of nutrient transport across the sediment-water interface. These fluxes are influenced by the availability of oxygen in the bottom waters and surface sediments.

### Physical characteristics of sediments in the Hardy Inlet estuary

The physical characteristics of sediments, such as grain size, porosity and organic content give an account of the sediment and hydrodynamic conditions in the estuary. Fluvial and ocean transport bring sediment into the estuary, and currents – created by flows, wind and shear forces – influence the movement and deposition of sediment in the estuary.

Analysis of sediment samples from the Hardy Inlet estuary showed that there were three main sediment environments present:

- ❖ *Lower estuary channel and basin* – characterised by coarse marine sediment permanently deposited in the shallow environment. Fine sediments were kept in suspension by wind-driven wave energy. Sediments contained very little organic matter.
- ❖ *East and west channels of Molloy Island* – transit areas for river flows and were affected by scouring periodically. Surface sediments were highly variable from year to year.
- ❖ *West Bay and deep river channels* – sediments in these regions were very fine and rich in organic matter. The effects of wind and wave energy were diminished and deposition of fine sediment was favoured.

### *Sediment organic matter – how much is there and where is it from?*

Sediment organic matter is derived from within the estuary or natural or anthropogenic sources from outside the estuary. Within estuary sources can include plant and animal detritus from

bacteria, fungi, benthic, planktonic or pelagic fauna and flora, and water birds. The amount of organic matter within sediments depends on the organic matter reaching the sediment surface, and its subsequent burial.

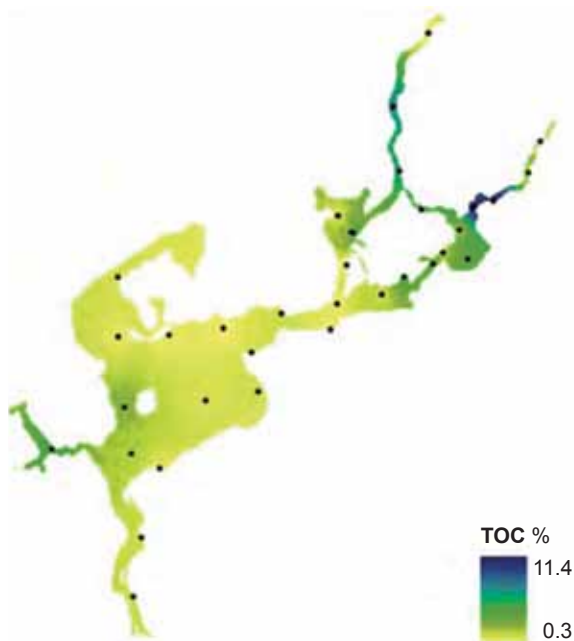
Sediment delivered from the catchment was found to still impact the estuary, but at a slower rate than at the time of initial land clearing in the 1920s.

Organic matter content is generally much higher in fine-grained sediments. The fine grained and muddy sediments in the deep lower Blackwood River, around Molloy Island and in West Bay were much higher in organic carbon content compared to the coarser sandy sediments in the estuary basin and lower channel (Figure 8).

Stable isotope analysis of sediment organic matter (used to indicate carbon source) found that organic matter was from a mixture of marine and terrestrial sources, but that terrestrial sources were the primary source of organic carbon in the deep lower Blackwood River, around Molloy Island and in West Bay.

### Sediment nutrient pools – where are the largest stores of nutrients in the inlet?

When organic matter decomposes it releases bio-available nutrients (nitrate, ammonium and phosphate) or less-available dissolved or particulate organic nutrients and nitrogen gas. Nutrients may either remain stored within the sediments, and pore waters, or released into the overlying water column. Dissolved inorganic nutrients are rapidly used by phytoplankton.



**Figure 8. Interpolated total organic carbon concentration in sediment in the Hardy Inlet (sampling sites shown as black dots).**

Pore waters were extracted from samples in the Hardy Inlet estuary to determine the size of the dissolved nutrient pools stored within the estuary sediments. Sediment cores collected at sites throughout in the Hardy Inlet estuary showed that:

- ❖ ammonium, phosphate and silicate were stored as nutrient pools within sediment
- ❖ very little nitrate was stored in the sediments of the Hardy Inlet estuary.
- ❖ fine-grained sediments in the deeper sections of the estuary generally contained a greater store of nutrients.
- ❖ the largest nutrient pools were located in the channel to the west of Molloy Island where nutrient pools of ammonium and phosphate were up to seven times greater than at other sites.

### Sediment nutrient cycling

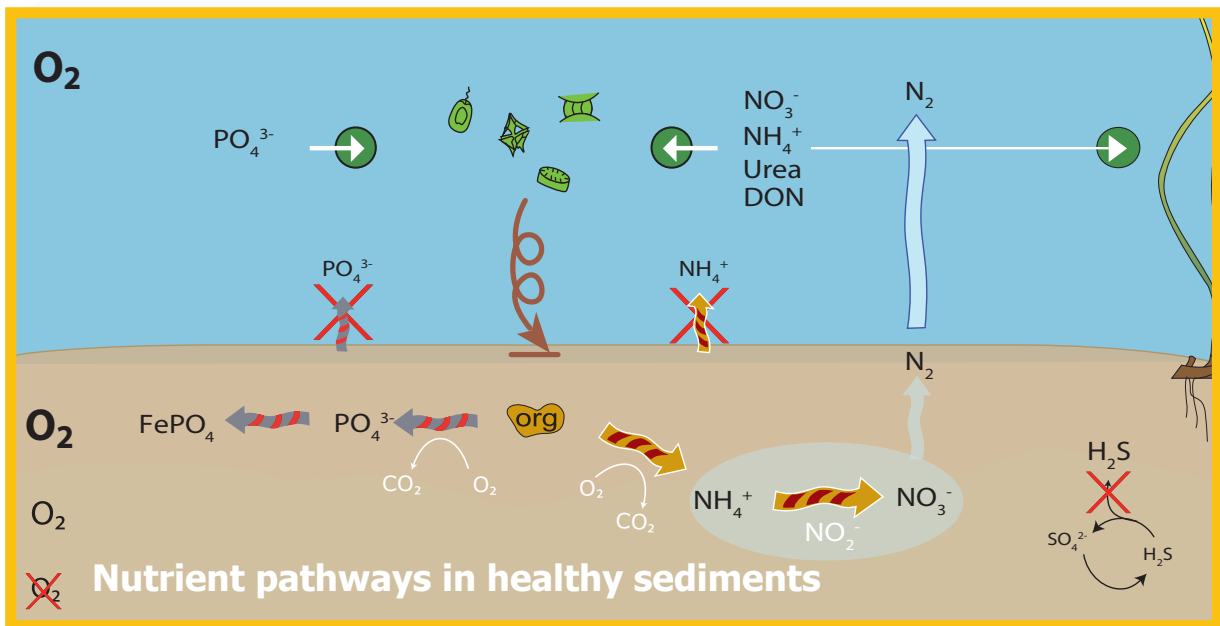
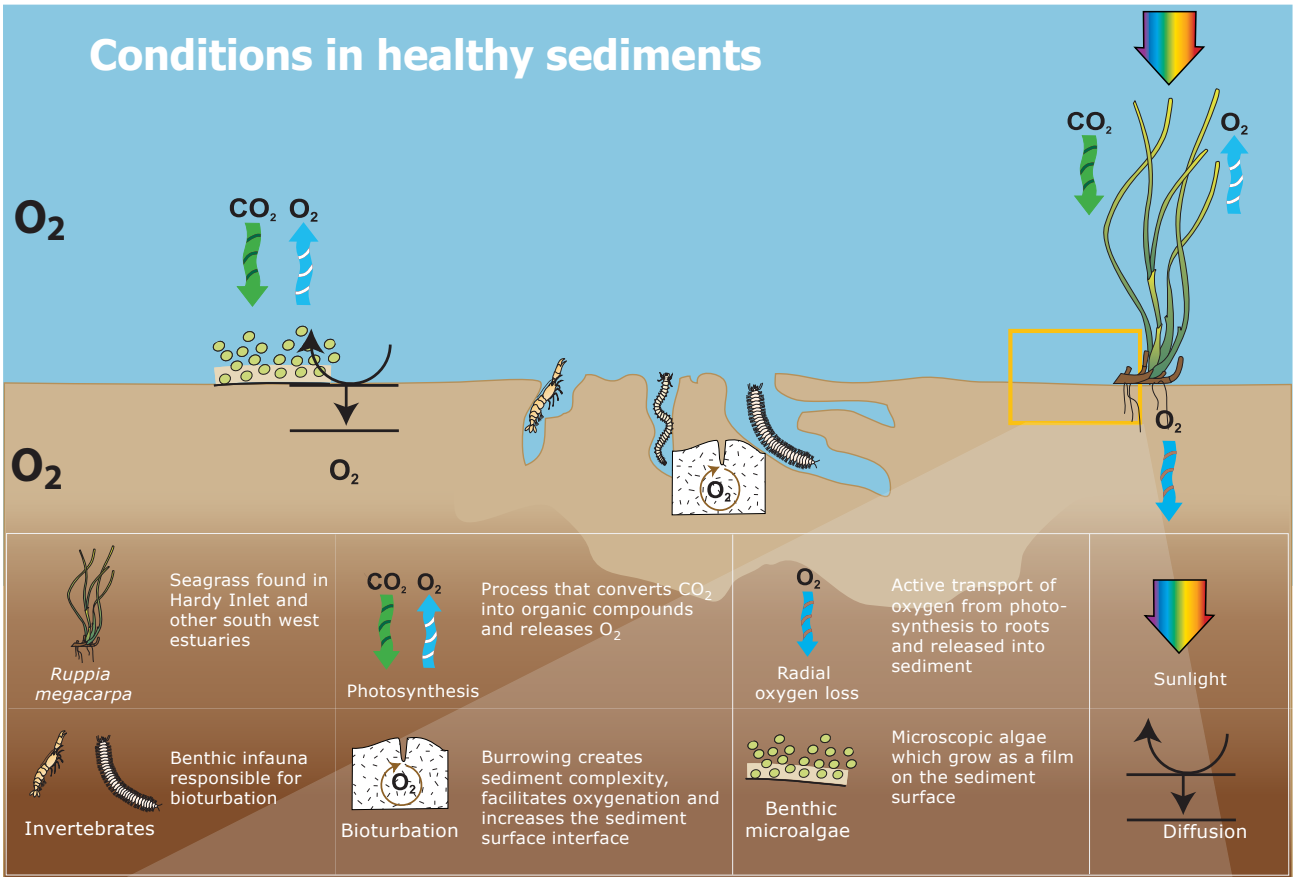
Nutrient cycling processes follow different pathways depending on sediment type, whether or not the bottom water and surface sediments are oxygenated, the origin of organic material, and the type of bacteria present which can facilitate the decomposition reactions. These factors create an assortment of niches in which different nutrient cycling pathways can co-occur.

#### Nutrient cycling pathways

Three basic sediment environments exist (separated by dissolved oxygen characteristics) in which different nutrient cycling pathways operate:

- ❖ *Oxic sediments* – in the presence of dissolved oxygen, nitrogen and phosphorus compounds (as organic material) are mineralised to ammonium (*ammonification*) and phosphate by aerobic bacteria. Ammonium is further processed to nitrate, via nitrite (nitrification). Nitrate may be released from the sediments and utilised by plants for growth. Phosphate (in the Hardy Inlet) usually remains bound in oxic sediments particularly those rich in iron.
- ❖ *Hypoxic sediments* – in low oxygen sediments, nitrogen gas ( $N_2$ ) can be formed by denitrifying bacteria which convert nitrate and nitrite to  $N_2$  (denitrification). The process 'anammox' functions in a similar way converting ammonium and nitrite to  $N_2$  gas. In most cases,  $N_2$  is not able to be used by plants so is lost to the atmosphere. Denitrification and anammox are important nutrient cycling pathways as they reduce the impact of eutrophication of the estuary.

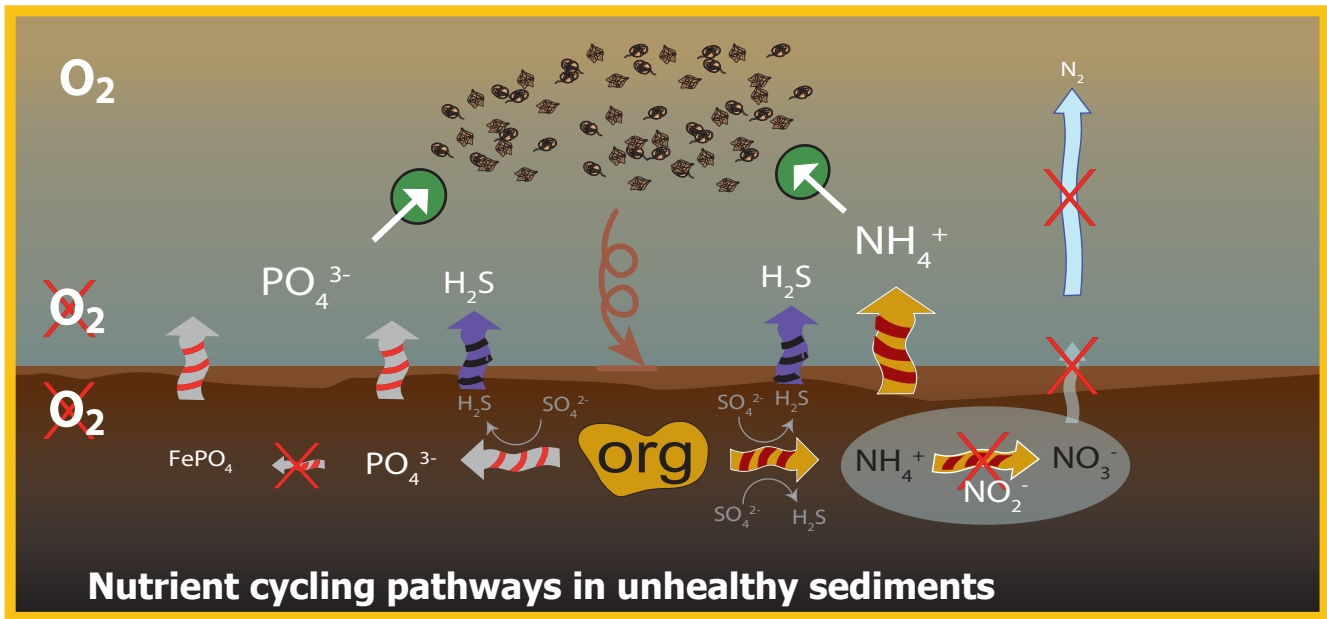
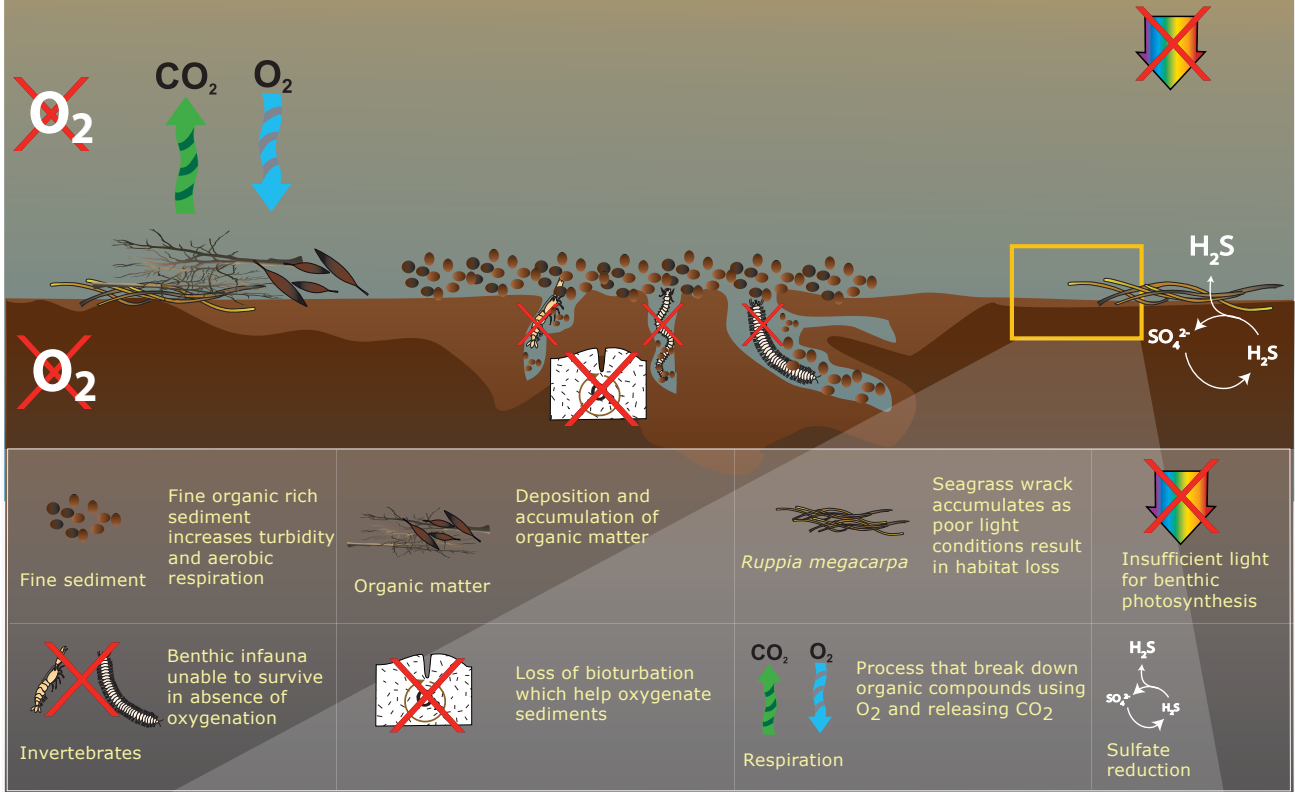
# Conditions in healthy sediments



## Nutrient pathways in healthy sediments

	Microscopic algae which drift in the water		Organic matter breakdown releases phosphate		Bacteria convert ammonia to nitrate in the presence of oxygen			
	Dissolved nutrient uptake by phytoplankton and seagrass		In the presence of oxygen phosphate is bound to iron oxides		Bacterial conversion of nitrate to nitrogen gas (denitrification and anammox)			
	Cell death and decay contributes to organic matter in sediment		Organic matter breakdown releases ammonia		Hydrogen sulfide is contained in the deeper sediments by re-oxidising to sulfate			
	Sediment oxygen conditions		Organic matter breakdown by anaerobic bacteria in anoxic organic-rich sediments					
O <sub>2</sub> oxygen	DON dissolved organic nitrogen	N <sub>2</sub> nitrogen gas	NH <sub>4</sub> <sup>+</sup> ammonia	NO <sub>3</sub> <sup>-</sup> nitrate	PO <sub>4</sub> <sup>3-</sup> phosphate	Fe <sup>3+</sup> ferric iron	H <sub>2</sub> S hydrogen sulfide	SO <sub>4</sub> <sup>2-</sup> sulfate

# Conditions which make sediments 'unhealthy'



	A group of phytoplankton which flourish in eutrophic conditions	$FePO_4 \rightarrow PO_4^{3-}$	Sediment-bound phosphate release	In the absence of oxygen sediment-bound phosphate is released to the sediment pore-water and diffuses into the water column	$PO_4^{3-}$ $NH_4^+$	Substantial fluxes of inorganic nutrients (phosphate and ammonia) from sediment to the water column	
	Cell death and decay contributes to organic matter in sediments		Ammonification	Organic matter breakdown releases ammonia	$SO_4^{2-} \rightarrow H_2S$	Sulfate reduction	Decomposition without oxygen uses sulfate-producing hydrogen sulfide (rotten egg gas)
	Organic matter breakdown releases phosphate	$NH_4^+ \rightarrow NO_3^-$	Nitrification	Anoxia inhibits the nitrification/denitrification process resulting in ammonia buildup	$NO_3^- \rightarrow N_2$	Denitrification	Bottom water nutrient build-up favours dinoflagellate blooms and the cycle continues

- ❖ *Anoxic sediments* – anoxia may result from prolonged deoxygenation of bottom water or from an excess of easily degradable organic matter. Under anoxic conditions, organic matter decomposition is dominated by sulfate reduction. This process also produces hydrogen sulfide gas (H<sub>2</sub>S) and the associated ‘bad egg’ smell often experienced when disturbing the soft black mud. In the complete absence of oxygen, nitrification and denitrification are unable to take place leading to a build-up of ammonium in the pore waters. Phosphate binds readily to iron in sediments, but under anoxic conditions, changes in the oxidation state of iron results in the release of the bound phosphate. Phosphate and ammonium, released from these anoxic sediments, may be rapidly used by phytoplankton.



*A benthic chamber being deployed in the Hardy Inlet estuary*  
(Geoscience Australia 2008)

Under ‘healthy’ conditions, sediments have a well-oxygenated surface layer (see *Conditions in healthy sediments*). Nutrient cycling processes that take place in hypoxic and low oxygen conditions still occur, but happen deeper into the sediment profile. Nutrients released and recycled in the deeper sediments therefore have little influence on water column nutrients. Sediment oxygenation is facilitated and maintained by oxygenated conditions in the water column at the sediment-water interface, bioturbation by benthic fauna (which require oxygen to survive), and oxygenation by roots e.g. *Ruppia*. In the Hardy Inlet estuary, these healthy conditions best described the sediments in the lower estuary basin.

Sediment conditions become ‘unhealthy’ when the oxygenated surface sediment layer is lost (see *Conditions in unhealthy sediments*). This is most persistent when excessive organic loading puts the system under stress. Under

these conditions, anaerobic processes such as sulfate-reduction dominate, and nutrient release from the sediment enriches the bottom waters. Bottom waters are also likely to experience ongoing deoxygenation as the anoxic sediments strip oxygen from the water column. Sediments which lack oxygen inhibit the establishment of benthic fauna and submerged plants. These ‘unhealthy’ conditions were typical of the sediments in the upper estuary (Blackwood River estuary), which have been subject to years of organic loading and accumulation.

### *Nutrient fluxes in the Hardy Inlet estuary*

Benthic chambers were used to measure the change in nutrient concentration (nutrient flux) at the sediment-water interface. Nutrient fluxes inform us of the rate of nutrient release from the sediment into the overlying water column. Measurable ammonium fluxes, related to low oxygen conditions, were detected in the benthic chambers at sites in West Bay and in the deeper estuarine reaches of the Blackwood River. Measurable phosphate fluxes, also related to low oxygen conditions, were only detected in the estuarine reaches of the Blackwood River.

## **Aquatic plants in the Hardy Inlet estuary**

Macrophytes (seagrasses), macroalgae (seaweeds) and microalgae (phytoplankton) are the dominant primary producers in estuaries. Macrophytes and macroalgae typically occur in shallower waters where light is adequate. Macrophytes require suitable sandy substrates for their roots to establish, while macroalgae generally rely on woody debris or rocks for attachment. Some macroalgae attach to other plants (called ‘epiphytes’). Phytoplankton generally float with the currents, with the exception of a few specialised groups that have ‘flagella’ (dinoflagellates) and propel themselves through the water. Dinoflagellates are typically associated with harmful algal blooms.

### **Role of macrophytes and macroalgae in estuaries**

Macrophytes and macroalgae are an essential part of the ecosystem. They provide critical habitats for invertebrates and fish and support complex food webs – providing food for small and large organisms, including water birds. The roots and rhizomes (below-ground stems) of macrophytes stabilise sediments and reduce erosion, while the leaves and stems reduce turbidity by slowing down water flow and the re-suspension of sediment. Macrophytes also take up nutrients and play a vital role in reducing the availability of those nutrients to

less favourable macroalgae and potentially toxin-producing phytoplankton (see *Ruppia ecology in the Hardy Inlet*).

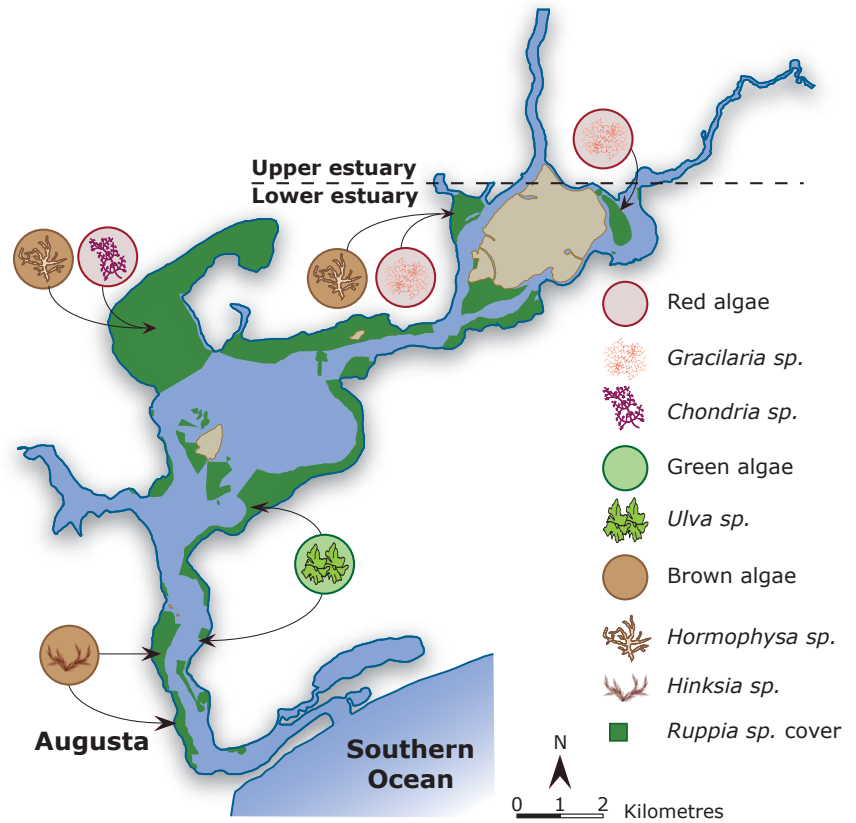
### Factors affecting the growth of macrophytes and macroalgae

The type of plants and algae, their distribution, and growth rates vary due to:

- ❖ **Light** – Essential for photosynthesis but is highly variable. Light is attenuated with depth, turbidity and stratification. Seagrasses require at least 10 per cent of the surface irradiance. Macroalgae require much less light and utilise different photosynthetic pigments (depending on the type of algae) with varying light harnessing abilities.
- ❖ **Salinity** – The survival and growth of a species may be influenced by salt concentration. Salinities in estuaries are generally variable and the species found in estuaries are tolerant of a wide range in salinity.
- ❖ **Temperature** – Community structure, seagrass physiology, growth rate, respiration, photosynthesis, and reproduction are all influenced by temperature.
- ❖ **Hydrodynamic conditions** – Seagrass plants and habitat structure are affected by current velocity, circulation flow patterns, and flow duration.
- ❖ **Nutrients** – although important for growth, when in excess can result in unnaturally high rates of primary production and organic matter accumulation. Excessive growth and subsequent decay is undesirable.
- ❖ **Substratum** – The establishment of macrophytes and macroalgal communities may be influenced by substratum type. Macrophytes typically require sandy substrates, whereas macroalgae mostly require solid structures for attachment.

### Distribution of macrophytes and macroalgae in the Hardy Inlet estuary

The distribution of macrophytes and macroalgae was surveyed in the Hardy Inlet estuary in 2000 and 2008 (see Figure 9 and Table 4). Large areas of seagrass were present in the lower estuary in the north bay, the inlet basin and around Molloy Island. Since the 2000 survey, seagrass also established in the lower estuary channel. These sandy shallow areas (less than 1.5 m deep) provided a good light environment for growth.



**Figure 9. Distribution *Ruppia megacarpa* and areas of major macroalgal growth in the Hardy Inlet estuary.**

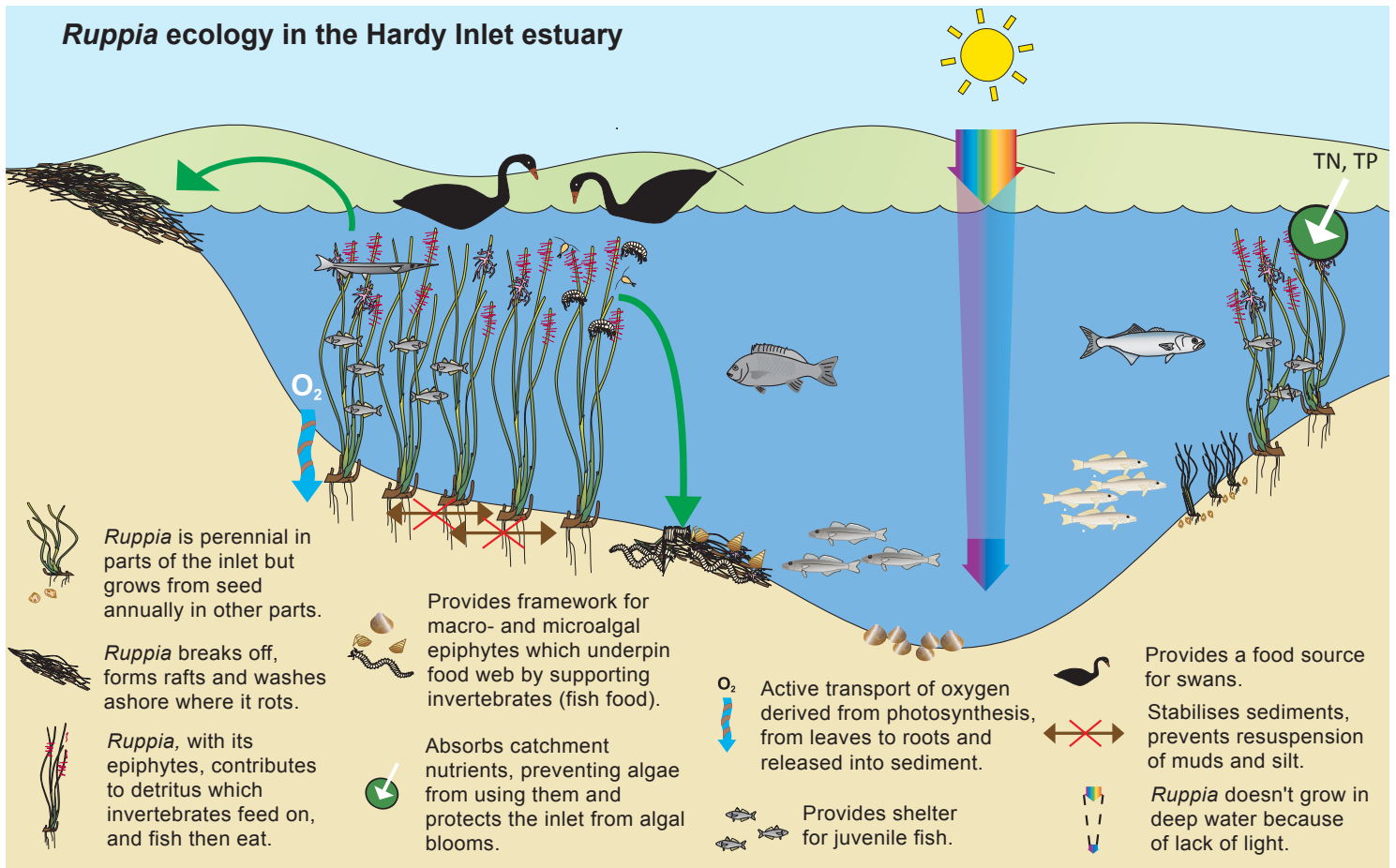
Depth-related light climates determine where species are most productive.

Conditions for the growth of seagrass in the lower Blackwood were not favourable. The channel of the Blackwood River was subject to scouring, the margins steep and water depth is much greater than in the lower estuary. Conditions were more turbid with suspended sediment being transported in the river flows. Both water depth and turbidity limited the light available for photosynthesis in this zone.

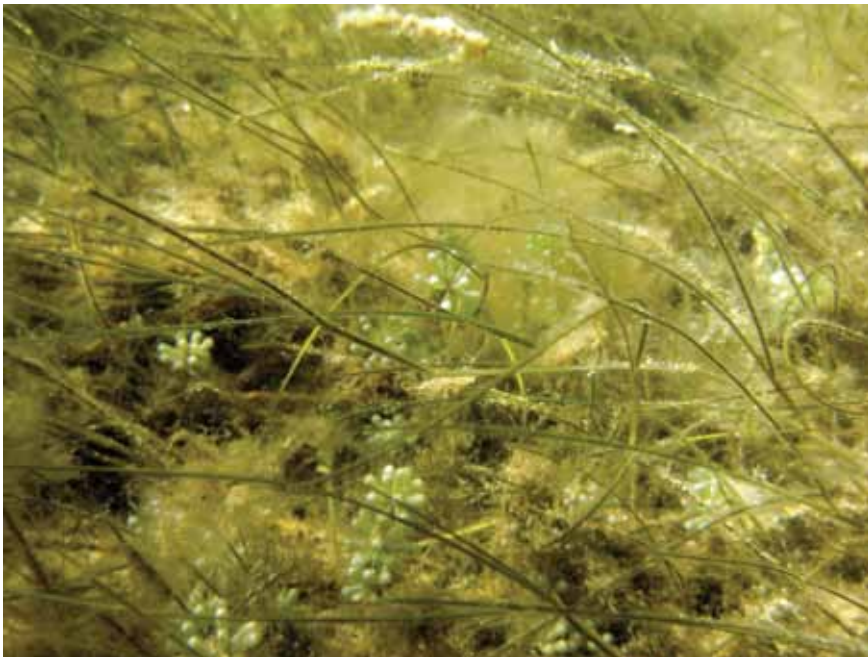
**Table 4. Common macrophytes and macroalgal species in the Hardy Inlet Estuary (February 2008)**

Macrophyte	
Seagrass	<i>Ruppia megacarpa</i>
Macroalgae	
Red algae	<i>Gracilaria chilensis</i>
	<i>Chondria fusifolia</i>
	<i>Hinksia michellae</i>
Brown algae	<i>Hormophysa cuneiformis</i>
Green algae	<i>Ulva flexuosa</i>
	<i>Polyphysa peniculus</i>

## Ruppia ecology in the Hardy Inlet estuary



Despite sufficient light, only a few species of macroalgae are present in the lower Hardy Inlet compared to other south-west estuaries (possibly from the lack of hard substrate for attachment). Most macroalgae is associated with *Ruppia*, either as epiphytes or as free-floating forms of algae accumulated within the seagrass.



An underwater scene showing *Ruppia* (the long, dark green, strap-like leaves), *Polyphysa peniculus* (the daisy-shaped, green algae) and assorted epiphytic and free-floating macroalgae (cottonwool, fluff-like) amongst the *Ruppia* (photo: Anne Brearley 2008)

## The seagrass *Ruppia megacarpa*

*Ruppia megacarpa* is a seagrass occurring in many estuaries along the south-west coast, and was the most abundant species in the Hardy Inlet estuary. Seagrasses are flowering plants which grow underwater. Most seagrasses occur in the marine environment, but *Ruppia megacarpa* – which can tolerate a wide range of salinities – favours sheltered saline environments like estuaries. This species also requires fresh water for its seeds to germinate.

*Ruppia* grows from rhizomes which are like grass 'runners' (underground stems). These runners are buried just beneath the sediment surface. Fine roots grow downwards from the rhizome, into the soft substrate. Leaves grow upward and into the water column and remain submerged or may float on the surface when water levels are low. Yellow-green flowers can be seen floating on the surface in summer at the end of a long, coiled stalk.

*Ruppia* is an important store or 'sink' for inorganic nitrogen in estuaries like Wilson Inlet near the town of Denmark, Western Australia. *Ruppia* is likely to play a similar role in the Hardy Inlet estuary. The loss of *Ruppia* as a nutrient buffer (without substantial nutrient reduction from the catchment) would have dire consequences for the health of the estuary.



## Macroalgae can point to sources of nutrients

Certain types of macroalgae – in particular filamentous species and ‘lettuce leaf’ like species – can be indicators of nutrient enrichment, due to their rapid uptake of nutrients and fast growth rate (faster than *Ruppia*). Two such species identified in the Hardy Inlet estuary were the filamentous species *Hinksia michelliae* (filamentous red algae) and *Ulva flexuosa* subsp. *paradoxa* (green algae, ‘sea lettuce’).

These simple-structured species of algae were found to be most abundant in the shallows, adjacent to urbanised areas or near structures such as boat ramps, public toilets and jetties. Nutrient inputs from drains, septic tanks, and fertilisers (from lawns and gardens) are likely to enhance macroalgal growth in these areas.

## Diversity of phytoplankton in the Hardy Inlet estuary

Phytoplankton (or microalgae) are a natural part of an estuary’s ecology. In the Hardy Inlet estuary, the phytoplankton communities included diatoms, dinoflagellates, chlorophytes and chrysophytes, and the less-abundant cryptophytes and prasinophytes. Each of these groups is mainly distinguished by its photosynthetic pigments. Photosynthetic bacteria (cyanobacteria) were also found.

Diatoms were the most common type of phytoplankton in the Hardy Inlet estuary. They are easily distinguished microscopically by their ornate silica structure. Diatoms are autotrophs, which means they rely solely on photosynthesis for energy production. Diatoms are considered favourable because they provide a critical food source to invertebrates and fish. Many of the diatoms in the estuary were marine species that drift in with the tides, for example the commonly occurring *Chaetoceros minimus*, *Cyclotella* sp. and *Thalassiosira* sp.

Dinoflagellates were the second-most abundant group of phytoplankton. Dinoflagellates are photosynthetic grazers (mixotrophs) and have a competitive advantage over autotrophs as they are able to photosynthesise, as well as graze on other algae. They are also motile, using their flagella to move through the water column. Dinoflagellates are less favourable and are often associated with toxin-producing harmful algal blooms.

## Phytoplankton blooms vs. harmful algal blooms?

A phytoplankton bloom occurs when there is a sharp increase in density of the phytoplankton population (usually of a particular group or species). Blooms can sometimes be recognised by discoloration of the water resulting from the

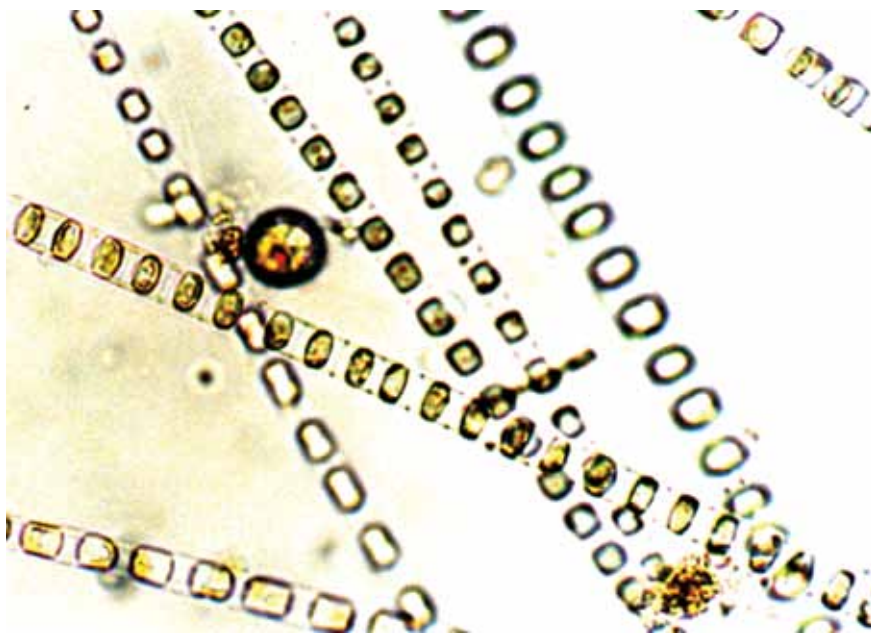


The filamentous green algae *Cladophora* growing on rocks near the boat ramp in the Lower Blackwood River (photo: Vanessa Forbes 2007).

high density of pigmented cells. Phytoplankton blooms usually occur in response to a sudden increase in nutrient availability.

In the Hardy Inlet, diatom blooms occurred erratically throughout the year, typically in response to an increase in dissolved nitrogen. The most significant diatom bloom in the estuary occurred in the spring of 1999, where cell numbers exceeded 120 000 cells/mL and *Skeletonema* cf. *potamo* was the dominant species.

While most phytoplankton species are favourable, some species are harmful because of the toxins they produce, or due to the mechanical damage they cause to other organisms (e.g. clogging up of fish gills). These

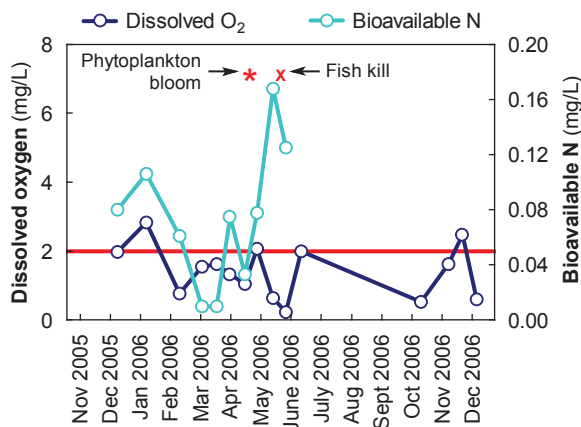


Micrograph of the diatom *Skeletonema* cf. *potamo* (photo: Wasela Hosja)

are referred to as 'harmful algal blooms' (HABs) and can damage ecological (fish and shellfish), and human health, even at low densities.

**Table 5. Potentially harmful phytoplankton species recorded in the Hardy Inlet estuary**

Type	Species	Toxin
Dinophyte	<i>Dinophysis acuminata</i>	DSP
	<i>Gymnodinium Karenia complex</i>	PSP
	<i>Prorocentrum minimum</i>	DSP
	<i>Karlodinium micrum</i>	Ichthyotoxin
Raphidophyte	<i>Heterosigma akashiwo</i>	Ichthyotoxin
Cyanobacteria	<i>Trichodesmium</i>	Respiratory problems
	<i>Lyngbya aestuarii</i>	Irritate skin



**Figure 10. Nitrogen concentrations that led to the 2006 phytoplankton bloom and the subsequent fish kill due to sudden anoxic conditions.**

Blooms of potentially toxic dinoflagellate and cyanobacteria (Table 5) have been occurring more frequently in the Hardy Inlet estuary. These unwelcome species were most common around Molloy Island and in the lower estuarine reaches of the Blackwood River.

Toxins affect humans through the consumption of contaminated shellfish. Shellfish filter these toxic species out of the water. Toxins include amnesic shellfish poisoning (ASP), paralytic

shellfish poisoning (PSP), neurotoxic shellfish poisoning (NSP), and diarrhetic shellfish poisoning (DSP). The Department of Health recommends that only commercially harvested shellfish be consumed. Contact with some cyanobacteria species can cause skin irritation.

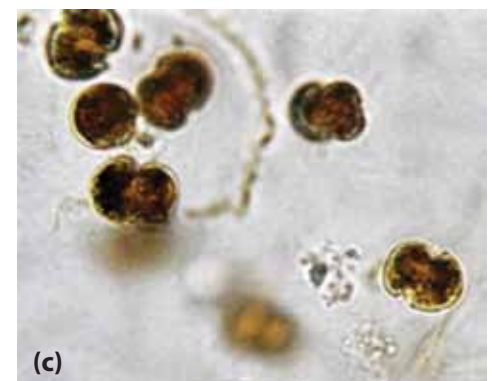
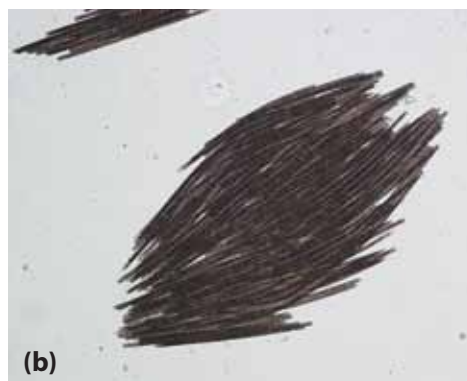
Phytoplankton blooms can also deplete oxygen concentrations in the water column. Phytoplankton cells are short-lived and the decomposition of these cells may strip the water column of oxygen (particularly when the phytoplankton population collapses en-mass). Hypoxic (low oxygen) or anoxic (no oxygen) conditions are unfavourable to aquatic plants and animals and can result in mass mortalities, such as fish kills. Thousands of black bream died in the upper estuary as a result of a sudden drop in oxygen in the water following the collapse of an algal bloom in 2006 (Figure 10).

### Red froth and green scum – cyanobacteria in the Hardy Inlet

Cyanobacteria blooms are less common than non-cyanobacterial blooms but can form large visible mats on the water surface.

In 2005, a noticeable oily red froth of a *Trichodesmium* bloom (a marine red tide species) in the lower estuary prompted the issuing of health warnings to recreational users. The *Trichodesmium* bloom was believed to have originated in the ocean and been blown into the estuary through the mouth and not triggered by estuary conditions. A similar and more recent event (December 2010) saw some residual scum from a *Trichodesmium* bloom near Granny Pools wash up in the estuary channel.

Of growing concern is the excessive growth of the cyanobacteria *Lyngbya aestuarii*, appearing as floating green scum, around Molloy Island. *L. aestuarii* blooms have consistently affected these parts of the estuary in the warmer months (December to February) since 2006, symptomatic of nutrient and organic loading from the Scott River catchment.



Micrographs of some common harmful algal bloom species from the Hardy Inlet: (a) *Dinophysis acuminata*; (b) *Trichodesmium* and; (c) *Gymnodinium Karenia complex* (photos: Vas Hosja)



*Residual Trichodesmium scum (reddish-brown froth) near Colourpatch following the bloom near Granny pools in December 2010 (photo: Tim Dyson)*



*Monitoring the Lyngbya aestuarii bloom in December 2006 (photo: Ashley Ramsay)*

Cyanobacteria, like *L. aestuarii*, are a specialised group which survive well in low-oxygen conditions and are able to fix nitrogen from the atmosphere. Cyanobacteria are also well known for their toxin-producing abilities which affect both animal and human health. However, in the case of *L. aestuarii*, the blooms in the Hardy Inlet were found to be non-toxic at the time of sampling. Genetic testing of *L. aestuarii* was unable to confirm whether this species would be able to produce toxins under different conditions. Given the unknown risk, caution is required at all times in affected areas.

## Shifting sands – the mouth of the Hardy Inlet estuary

The estuary mouth is naturally dynamic and has had various configurations over the decades. In fact, the current position of the natural entrance is quite similar to where it was between 1925 and 1935, and again in the early 1970s. Rainfall, river flows, ocean swells and currents are fundamental drivers of water and sand movement in and around the estuary mouth. Sand bars naturally build and erode depending on the balance between processes of deposition by ocean waves and currents (e.g. longshore drift) and scouring by large river flows.

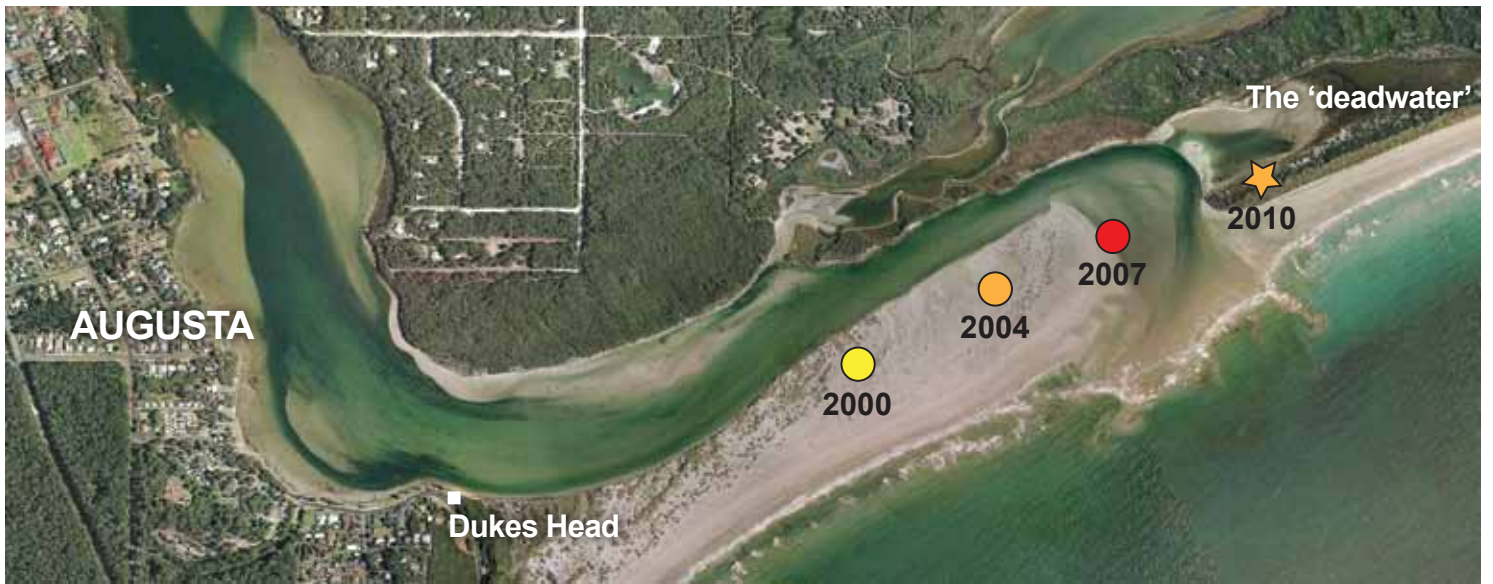
Years of low or average river flows to the Hardy Inlet estuary provides one explanation for the shift in this balance in favour of depositional forces. The estuary is located in a high rainfall zone (1000–1400 mm per annum) and large seasonal river flows have been an important mechanism for maintaining the permanent connection between the estuary and the ocean. In recent years, rainfall patterns have shifted the timing and volume of river flow to the estuary. The natural entrance does provides a good

connection with the marine environment, as shown by the good to moderate water quality observed in the lower estuary basin, and the sediment in this area – which is mainly of marine origin.

However, there is some concern that the shifting estuary entrance may influence tidal exchange and water quality in the inlet, particularly in the lower estuary. The mouth of the estuary has gradually migrated eastwards, (more than 1.1 km since 2000) and almost 2 km from its position in the 1970s near Dukes Head (Figure 11). Seine Bay west of Dukes head, which is remembered for its clear waters and fringing beaches, is now more estuarine in character. Waters are coloured and aquatic macrophytes and algae grow in the shallows.

This is also not the first time that the condition of the natural entrance has caused concern. In 1985, fears were raised about the entrance closing.

Recent changes in the character of the lower estuary (such as increased seagrass and algal growth) and concern that water quality was also declining, prompted the Shire of Augusta-Margaret River to propose a bar-opening strategy to create an alternative opening at the western end of the sand bar, adjacent to Colourpatch. This was approved in 2009 and implemented in August of that year. The success of this intervention relied on sufficient ‘head’ and river flow to scour and maintain the new opening. Despite some flow through this channel, low river flows in 2010 contributed to the channel silting up. Further excavation was required to reopen the channel. In years of high rainfall and river flow, channel maintenance may be reduced. Ultimately, the effect of two openings on the hydrodynamics of the estuary is not yet well understood.



**Figure 11** The shifting channel entrance. Approximate distance from Dukes head: 860 m in 2000, 1200 m in 2004 and 1480 m in 2007. By 2010, the entrance has moved a further 500 m, almost to the end of the 'deadwater' (Source: Landgate 2006)



Bar opening looking south (a) and north (b) in the channel centre in August 2010 and looking south (c) and north (d) in October 2011

While an alternative opening at the western end of the sand bar may improve water exchange in this lower section of the estuary, factors which could be detrimental to estuary condition should also be considered. These include:

- ❖ *Increased deposition* of marine sand in the estuary channel. This may result as a consequence of altered flows and fewer scouring events.
- ❖ *Increased marine storm-surge exposure* potentially affecting low-lying town areas.
- ❖ *Stratification effects may be enhanced* with greater tidal exchange. Stratification together with organic and nutrient loading from the catchment puts the estuary under 'stress'. Organic decomposition reduces oxygen conditions and promotes nutrient release from the sediments.
- ❖ *Ruppia habitat in the channel may be lost* as *Ruppia* favours sheltered, calm conditions. Dense habitats which occupy the shallows adjacent to the town may be lost with changes to the hydrodynamics. *Ruppia* is an important habitat and food source for invertebrates, fish and birds and its loss would have a negative impact on estuary ecology.
- ❖ *The re-establishment of a nutrient-rich deadwater could occur.* Although noted as a productive habitat for juvenile fish, limited flushing would result in nutrient accumulating conditions leading to excessive algal growth and phytoplankton blooms.

The development of the water quality improvement plan for the Hardy Inlet estuary is an important step towards directing efforts to reduce nutrient inputs into the estuary.

## Summary

- ❖ The condition of the Hardy Inlet estuary was primarily driven by seasonality of rainfall and river flow, and connectivity with the ocean. These mechanisms influence the delivery, dilution and export of nutrients.
- ❖ The condition of the lower Hardy Inlet estuary channel and estuary basin was reasonably unaffected by nutrient inputs from the catchment, however nutrients from urban sources remain a concern.
- ❖ The flow of nutrients from the Blackwood River in winter was diluted in the wider estuary basin and exported from the estuary to the ocean. Nutrient uptake by the seagrass *Ruppia megacarpa* in the estuary basin buffers these nutrient inputs in the lower estuary. Without seagrass, unfavourable phytoplankton blooms may occur more frequently.

- ❖ Localised growth of filamentous macroalgae along the Augusta foreshore indicated potential nutrient enrichment from point sources such as drains, septic tanks and run-off from fertilised gardens and lawns. Nutrients from these sources need to be reduced in order to preserve the recreational and ecological value of these areas.
- ❖ The condition of the upper estuary was affected by rainfall, associated river flows and catchment nutrient inputs. The Blackwood River had much greater flows and provided higher nitrogen loads to the estuary than the Scott River. The Scott River, although only contributing 7% of the flow, had a greater phosphorus load. The differences in nutrient inputs to the estuary were related to land use, soils and physiography of the catchments. The relative proportions of nutrients may change in the future as a result of changing land use.
- ❖ Differences in nutrient inputs from the two catchments created environmentally distinct areas in the Hardy Inlet estuary. Phosphorus concentrations were highest in the estuary near the confluence of the Scott River, north of Molloy Island. The dilution of these nutrients from the Scott River was hydrodynamically restricted by Molloy Island. There was relatively more phosphorus than nitrogen available for plant growth at these sites. These conditions are favourable for organisms which can acquire their own nitrogen from the atmosphere, e.g. the cyanobacteria *Lyngbya* (common in the Scott Basin).
- ❖ The water column of the Blackwood River generally remained stratified. The decomposition of organic matter which had accumulated in the deeper channels and holes, stripped oxygen from the bottom waters. Low-oxygen conditions were also associated with rainfall. The resultant low-oxygen conditions in the bottom waters promoted the release of sediment-bound nutrients. Hypoxic conditions (and associated nutrient release) typically favour dinoflagellate blooms, and sometimes even harmful algal blooms.
- ❖ Low-oxygen conditions in the estuarine reaches of the Blackwood River and around Molloy Island were unfavourable to fish and invertebrate communities. Areas with permanent low or no dissolved oxygen in the bottom waters have resulted in 'dead zones' that are completely barren of invertebrate fauna. Individual reports also suggest that fish were being restricted to the surface waters. This is undesirable as both food and habitat are limited.

- ❖ Fish kills in the Hardy Inlet estuary have been infrequent. There was an anecdotal report of a fish kill in the 1970s, however since then the only reported fish kill occurred in 2006. This was linked to a cycle of events of rainfall, nutrient supply, phytoplankton blooms and the rapid depletion of dissolved oxygen.
- ❖ The estuary channel has a permanent connection to the ocean. There has been concern that due to the migration and shallowing of the entrance, it could close as a result of low flows from the catchment. This would be undesirable as the exchange of water between the estuary and the ocean provides resilience to the inlet, counteracting the large nutrient inputs from catchment and urban land use.

## In conclusion

The Hardy Inlet estuary is showing signs of deterioration related to human impact. In particular, the upper estuary is severely affected by nutrient and organic enrichment from the catchment. This enrichment is the main

driver of poor condition in the estuary causing widespread and persistent hypoxic and anoxic conditions in the bottom waters. This has put a squeeze on resident fauna for food and habitat and has ultimately resulted in dead zones where no benthic fauna exist and fish appear to be scarce. Due to the extent of the affected area, the impact of organic loading may become irreversible without a significant reduction in enrichment. Salinities in the lower Blackwood have also increased, affecting the natural breeding cycle of popular fish species, such as the black bream. This has been exacerbated by recent years of low river flows.

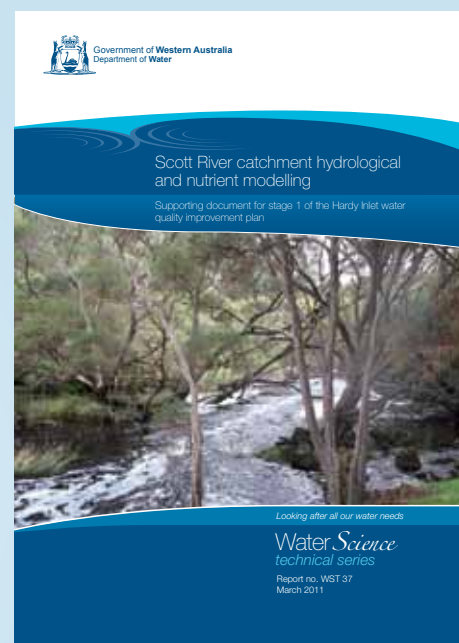
In the lower estuary, algal growth is a concern – most likely due to urban nutrient inputs along the Augusta foreshore.

Protection of the community values of the inlet can only be achieved by targeting and managing its nutrient sources. The Department of Water, in consultation with stakeholders, has prepared stage one of the *Water quality improvement plan (WQIP)* for the Hardy Inlet estuary. This plan focuses on the Scott River catchment, but managing the nutrient inputs

### Main actions of the *Hardy Inlet water quality improvement plan*

The purpose of the water quality improvement plan is to provide for the long-term improvement and protection of water quality in the Hardy Inlet. The first stage of the plan focuses on managing the largest source of phosphorus load to the Inlet: the Scott River. Water quality monitoring and modelling by the Department of Water has identified that phosphorus loads are mainly derived from diffuse agricultural sources while nutrients from septic tanks are likely to be minor. A phosphorus load reduction target of 28% (with a nil increase in N load) is required to alleviate water quality problems in the upper Hardy Inlet. Some management measures recommended to meet these reduction targets include:

- ❖ implement best-practice fertilizer management across the catchment
- ❖ investigate farm-scale nutrient hotspots in the catchment
- ❖ carefully evaluate proposals for further intensification of land uses in the catchment
- ❖ develop and implement a rural drainage management plan for the Scott River
- ❖ develop and implement a river action plan for the Scott River
- ❖ assess and upgrade effluent management at dairies in the catchment



- ❖ undertake paddock scale trials and soil amendment.

When the plan is funded, ongoing water quality monitoring in the catchment, rivers and estuary will gauge the effectiveness of these management actions.

from the Blackwood River catchment, Augusta and Molloy Island are also essential, and will be the focus of stage two of the WQIP.

Current efforts by the Department of Water are focused on the development of *estuary report cards*. Estuary report cards have been used with great success elsewhere in Australia and around the world to communicate to estuary managers, decision-makers and the wider community about estuary health. To date, the interpretation of estuary health in Western Australia has been underpinned by comprehensive water quality monitoring programs. Work is now underway to expand the list of indices to include seagrass and sediment health to provide a more robust description of estuary health.

## Glossary

**Aerobic:** living or occurring only in the presence of oxygen.

**Ammonium:** an important source of nitrogen to plants particularly in low-oxygen environments. Ammonium is a waste product of animals and enters waters either directly or as urea. It is an important source of nutrient to phytoplankton.

**Anaerobic:** an organism that can live in the absence of atmospheric oxygen.

**Anoxia:** absence of oxygen.

**Anthropogenic:** caused or influenced by humans.

**Aquatic macrophyte:** an aquatic plant (e.g. seagrass) that can be seen with the naked eye, and grow submerged, emergent or floating within marine, estuarine and riverine environments.

**Autotroph:** an organism capable of synthesising its own food from inorganic substances, using light or chemical energy.

**Benthic:** organisms living on or in sea or lake bottoms.

**Bioavailable:** a substance available for uptake/use by an organism.

**Cyanobacteria:** (also known as blue-green algae) are a photosynthetic bacteria that occur as single cells or as colonies (which can form filaments). Some species are nitrogen-fixing, converting nitrogen from the air to form ammonia and nitrates/nitrites.

**Detritus:** disintegrated or eroded organic matter.

**Estuary:** the river mouth where tidal effects are evident and where fresh water and sea water mix. Bar-built estuaries which can have a connection to the ocean that can be periodically (months to years) interrupted by the formation of a sand bar (similar to Victorian and South African estuaries).

**Eutrophication:** nutrient enrichment; a natural process that is greatly enhanced by human activity.

**Hypoxia:** low (<1 mg/L) oxygen conditions.

**Inorganic dissolved nutrients:** these include nitrate/nitrite, ammonium and soluble phosphate and are in forms most readily available to plants.

**Macroalgae:** photosynthetic plant-like organisms that can be seen with the naked eye. May be divided into the groupings: reds (rhodophytes); greens (chlorophytes); browns (phaeophytes); and blue-greens (cyanophytes). The divisions are primarily based on pigments in their tissues, usually evident in their appearance.

**Nitrate/nitrite:** dissolved inorganic forms of nitrogen. Found in fertilisers and a source of nutrients in catchment run-off. Also a by-product of septic systems which can leach into groundwater.

**Nutrient load:** the amount of nutrient being deposited into the estuary from the catchment.

**Organic loading:** the amount of organic matter or sediment being deposited into a specific area.

**Oxic:** presence of oxygen.

**Pelagic:** organisms living in open oceans or seas rather than waters adjacent to land or inland water.

**Photosynthesis:** the process where green plants and certain other organisms fix carbon using light as an energy source. Most forms of photosynthesis release oxygen as a by-product.

**Pore water:** water found in between sediment particles within the sediment column.

**PSU:** unit of measurement for salinity, roughly equivalent to parts per thousand.

**Primary producer:** see *autotroph*.

**Remineralisation:** microbial conversion of an organic form of a nutrient to an inorganic form.

**Soluble reactive phosphate (SRP):** a dissolved inorganic form of phosphorus. It is a form of nutrient readily available to plants. SRP binds readily to particulate matter, particularly those rich in iron. SRP is released from sediments in the absence of oxygen.

**Stratification:** the formation of water layers due to differences in water properties (e.g. salinity, temperature and/or oxygen) which act as a barrier to mixing.

**Total nitrogen:** is the sum of all forms of nitrogen found in the water column. This includes, particulate and dissolved forms, of inorganic and organic nature.

**Total phosphorus:** as above, but for phosphorus.

## References

ANZECC & ARMCANZ 2000. *Australian guidelines for water quality monitoring and reporting*. National Water Quality Management Strategy Paper No. 7, Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Brearley, A 2005. *Ernest Hodgkin's Swanland: Estuaries and Coastal Lagoons of South-Western Australia*, University of Western Australia Press, Crawley, Perth.

Carruthers, TJB, & Walker, DI, 1999. *Abundance of Ruppia megacarpa mason in a seasonally variable estuary*, Estuarine Coastal & Shelf Science, 48(4), 497–509.

Dudley, BJ, Gahnstrom, AME & Walker DI 2001. *The role of benthic vegetation as a sink for elevated inputs of ammonium and nitrate in a mesotrophic estuary*, Marine Ecology Progress Series, 219, 99–107.

Hale, J, Wilson, C & Paling, EI 2000. *Sediment quality and macrophytes survey of the Hardy Inlet*, Prepared by Marine and Freshwater Research Laboratory, Murdoch University, Perth.

Kelsey, P 2002. *Aggregated emissions of total nitrogen and total phosphorus to the Blackwood and Scott River catchments, Western Australia: A submission to the national pollutant Inventory*, Prepared by the Water and Rivers Commission, Perth.

Wilson, C & Paling, EI 2008. *Macrophyte survey of the Hardy Inlet 2008*, Prepared by Marine and Freshwater Research Laboratory, Murdoch University, Perth.

Haese, RR, Smith, CS, Forbes, VR, MacPhail, P & Hancock, G 2010. *Historic environmental changes and sediment based condition assessment for Hardy Inlet, Western Australia*, Prepared by Geoscience Australia, Canberra.

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## For more information

More information on estuaries and water quality can be found at: <[www.water.wa.gov.au](http://www.water.wa.gov.au)> understanding water > rivers and estuaries > monitoring and assessing waterways health > assessing estuary health.



RECYCLED CONTENT

## Department of Water

The Atrium, 168 St Georges Terrace, Perth  
PO Box K822 Perth Western Australia 6842

Telephone: 08 6364 7600

Facsimile: 08 6364 7601

Website: [www.water.wa.gov.au](http://www.water.wa.gov.au)

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