Wilson Inlet 10
Report to the community

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Government of Western Australia
Department of Water

Role of sediments in nutrient cycling

CONTENTS

Figure 1. Deploying a benthic chamber in Wilson Inlet to measure sediment nutrient fluxes. Photo: C.Tindall

This newsletter is the 10th in a series of community reports on Wilson Inlet produced by the Department of Water, formerly the Water and Rivers Commission (WRC). This newsletter summarises the results of Geoscience Australia's sediment geochemistry investigations in Wilson Inlet. The investigations focused on exploring the role of sediment processes in the nutrient cycles in Wilson Inlet. The work was carried out by Geoscience Australia (GA) and the WRC, with additional funding support from the National Eutrophication Management Program (NEMP). More recent sediment assessment work was undertaken in 2008 and will be reported in a subsequent newsletter

Introduction

Wilson Inlet is a seasonally closed estuary on the south coast of Western Australia. The major part of the inlet comprises a broad, shallow, flat-bottomed lagoon that lies behind coastal dunes. The lagoon has a surface area of 48 km^2. The lagoon opens to the Southern Ocean through a sandy flood-tide delta that breaks through the coastal dunes adjacent to a granitic headland. A sand bar isolates the estuary from the ocean for about half of the year (usually February to July). To prevent the flooding of land adjacent to the inlet as it fills with winter runoff, the sand bar is artificially breached each year once the water level reaches about 1 m above mean sea level (msl). The inlet floor has an average depth of 1.8 m below msl, and a maximum depth of 4 m below msl.

There is concern that as a consequence of land use changes in its catchment since European settlement, the inlet is becoming increasingly nutrient enriched – a process called 'eutrophication'. Without adequate management the eutrophication of the inlet could lead to the runaway growth of plants and algae, the constant recycling of nutrients, and a collapse of the present ecosystem.

Studies in other estuaries have demonstrated that sediments play a major role in recycling nutrients. Sediments accumulate organic matter over time and consequently have a large store of nutrients. Depending on the processes occurring, these nutrients may be locked up in

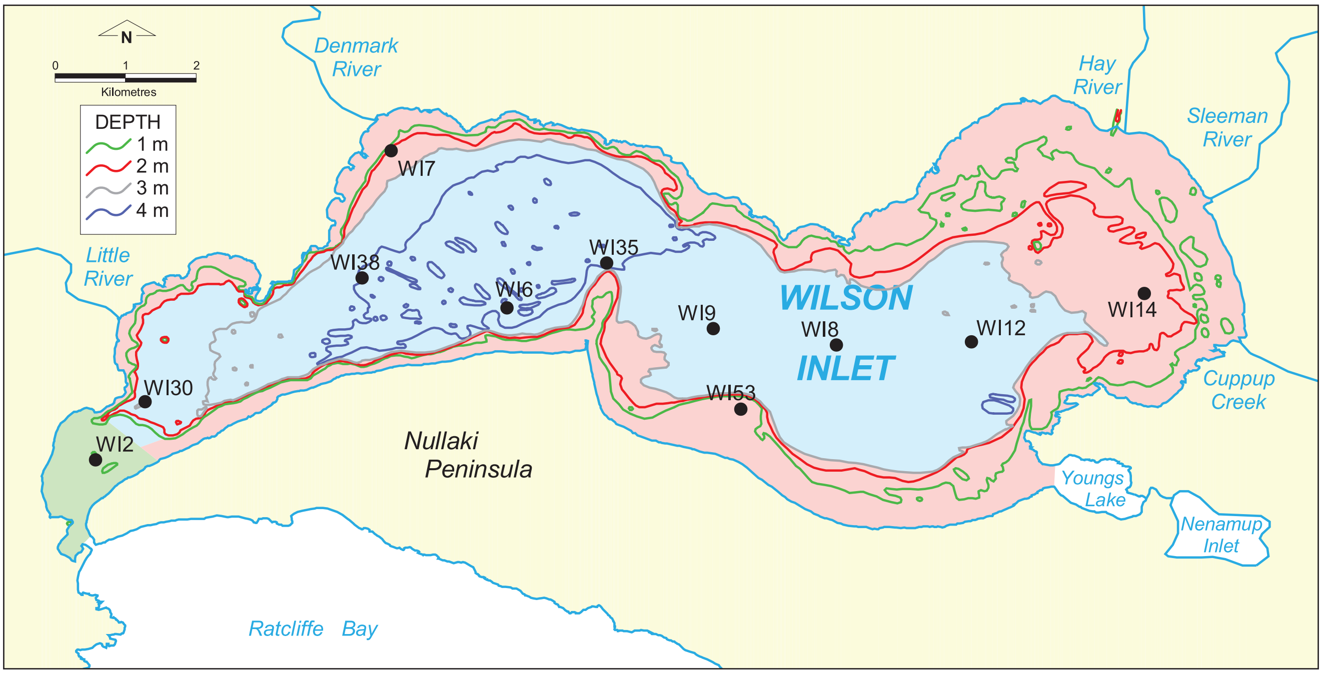


Figure 2. Map of Wilson Inlet indicating the depth contours below mean sea level, the main benthic chamber deployment sites and the rough distribution of sediment facies (green = marine facies, blue = mud facies, red = sand facies).

the sediments, converted into biologically unavailable forms, or recycled back into the water column in a form that supports ongoing plant and algal growth. Shallow saucer-shape estuaries like Wilson Inlet also have a high ratio of sediment area to water volume, which magnifies the importance of sediments. As such, an understanding of sediment nutrient processes was considered critical to understanding the nutrient status of Wilson Inlet.

GA was commissioned to investigate whether sediment processes in Wilson Inlet were a source or sink of nutrients for the inlet, and to determine what controlled sediment nutrient cycling processes.

GA and WRC staff undertook a preliminary survey of Wilson Inlet in August 1997 followed by four intensive two-week field investigations at times of the year representing different states of the inlet's behaviour. These investigations took place in November 1997, May 1998, September 1998 and February 1999. The data from these investigations were analysed with data from the Department of Water's regular water quality monitoring program and previous sediment geochemistry investigations in the inlet.

Evolution of Wilson Inlet

The Holocene is the most recent geologic time period, which started with a global sea level rise about 12 000 years ago. The period preceding the Holocene was an ice age and sea level was lower than today. At these times calcareous beach dunes built up between the granitic headlands along the coast, isolating the river valleys lying between them from the ocean. These dunes solidified over time to form the limestone cliffs and nearshore reefs that lie along the south coast today, the Nullaki Peninsula being an example.

With the melting of ice sheets at the end of the last ice age, sea levels rose rapidly until today's sea level was reached about 6000 to 8000 years ago. As sea levels rose, seawater flooded into the river valley – forming today's inlet. Initially the inlet was permanently open to the sea, had a smaller lagoon and was several metres deeper. At this time tides exchanged seawater and estuary water very rapidly.

Wave action washed sand from the ocean onto the coastline and began to build a sandbar across the mouth of the inlet, slowly forming a lagoon that was partially isolated from the ocean. The residence time for water in the inlet became much longer.

Sediments began accumulating in the inlet even as it was being formed. Sand was washed in from the ocean, while the rivers washed in clays, sands and other sediments. The area of the lagoon and tidal flats expanded as tides and waves eroded the shorelines, redistributing shoreline sediments into the lagoon. Organic matter derived from plants and animals living within the inlet accumulated on the lagoon floor. These processes have resulted in the infilling, widening and shallowing of the inlet over the past 8000 years.

Sediments of Wilson Inlet

Estuarine sediments are materials deposited and consolidated on the floor of an estuary. In Wilson Inlet sediments have been accumulating on the floor of the inlet ever since it was formed 6000 to 8000 years ago (to a depth of several metres in some locations). Deposited sediments consist of a combination of inorganic minerals and organic matter. Depending on the location in the inlet, the sediments may contain 1% to 30% organic matter and 20% to 80% inorganic matter. The remainder of the sediment, 25% to 80%, consists of water trapped in the 'pore spaces' between the sediment particles. This water is referred to as 'pore-water'.

The inorganic minerals in Wilson Inlet's sediments consist mostly of quartz sand and clays eroded from the shoreline or transported from the catchment by river flow, although

Figure 3. Aerial view of Wilson Inlet. The 600-million-year-old granitic headland of Wilson Head lies at the bottom of the photo. The 0.1-to 1-million-year-old lithified limestone dunes of the Nullaki Peninsula intrude towards the inlet (centre of the photo). The 6000- to 8000-year-old lagoon of the inlet itself lies to the north of the peninsula. It is worth remembering when looking at this photo that the lagoon is in fact a very shallow 'saucer' of water, an average of 1.8 m deep. Photo: S.Neville

the delta at the mouth of the inlet consists mainly of quartz sand of marine origin washed in from the ocean. Some mineral material may also be formed within the sediments after they have been deposited. The most important of these minerals are iron and manganese sulfides. Shells made of calcium carbonate are also found in the sediments, particularly in the marine sands at the inlet mouth.

The organic matter in the sediments consists of carbon compounds formed by living organisms. Organic matter may be added to the inlet from the catchment (terrestrial organic matter) or formed within the inlet. Terrestrial organic matter ranges from fine soil and leaf material, to whole leaves and large pieces of woody debris (and may also include human and animal wastes). Organic matter formed within the inlet has a number of sources:

- Microscopically small algae (microalgae) growing on plants (epiphytic microalgae), floating freely in the water (phytoplankton), or growing directly on the sediments ('benthic microalgae'). Most of these microalgae in Wilson Inlet both now and in the past are from a class called diatoms that have a characteristic silica frustule (skeleton), as shown in Figure 5, and referred to as 'diatomaceous microalgae'.
- Large macroalgae floating freely in the water, attached to plants or on the sediment surface. Most of the macroalgae in Wilson Inlet are marine-derived species that range in size from several centimetres up to several metres in length.
- Plants rooted in the sediment in the shallows of the inlet: the seagrass *Ruppia megacarpa* is the sole species in Wilson Inlet.
- Bacteria and fungi living in and on the sediments.
- Animals living freely in the water, on plants, or in the sediments. These obviously include fish and birds, as well as invertebrates including microscopic zooplankton, small molluscs, crustaceans, and polychaete worms.

Sediment 'facies' in Wilson Inlet

There are several distinct sediment deposits or 'facies' in Wilson Inlet (Figure 2). The different sediment facies contain different combinations of minerals and organic matter, reflecting the relative contributions of different sources of sediment material. The different sediment facies have different nutrient recycling characteristics. The major facies are:

- The 16 km^2 of sandy beach margins and near-shore sediments where *Ruppia* grows (the 'sand facies').
- The 30 km^2 of highly organic muds and sandy muds deposited in the basin of the inlet (the 'mud facies').
- The 2 km^2 of marine sands deposited in a delta found at the mouth of the inlet (the 'marine facies')

Sediment nutrient inventory of Wilson Inlet

A large number of short sediment cores (Figure 4) were collected from different locations in Wilson Inlet, representing different facies, during each of the field investigations. These cores were extruded and sliced up into sections of 1 cm to 2 cm thickness. The nutrient and mineral contents of the solid material and pore-waters of each section were analysed. In addition to providing an understanding of the processes occurring in the sediments, the data were compiled to generate an inventory of nutrients stored in the sediments.

The results indicated that only the nutrients in approximately the upper 10 cm of the sediments have the potential to be recycled back into the water. Nonetheless, the upper 10 cm of sediment contains about 20 000 tonnes of nitrogen and 2500 tonnes of phosphorus. This is a very large store of nutrients compared with the other stores of nutrients in the inlet (Table 1).

Nutrient store	Nitrogen	Phosphorus
Sediment (solid)	20000	2500
Pore-water (dissolved)	2 to 5	0.2 to 1
Water (dissolved)	2 to 5	0.2 to 1
Live plants & algae	50–250	5–25
Fish	1–2	0.5–1
Invertebrates	10–20	5–10

Table 1. Rough estimates of Wilson Inlet nutrient inventory (tonnes).

Fortunately less than 0.1% of this sediment nutrient store is in a form that is immediately available for plant and algal growth at any one time. The remaining 99.9% is either locked up in the sediment, or temporarily stored as part of the organic material that has accumulated in the sediments. How much of the remaining 99.9% becomes available to plants and algae is dependent on the sediment processes that occur and the ease with which it is broken down by bacteria.

Source of the organic matter in the sediments

A large number of surface sediment samples were collected to establish the distribution and composition of organic matter in the sediments. The composition of the organic matter indicates where the accumulated nutrients are coming from and also determines some of the nutrient cycling processes that will take place (e.g. microalgae decompose much faster than *Ruppia* or terrestrial organic matter).

The composition of the organic matter was determined using a combination of techniques. These included measuring ratios of carbon to nitrogen, measuring ratios of different carbon and nitrogen isotopes, and measuring the concentrations of different 'lipid biomarkers' representing algal, terrestrial and seagrass sources of organic material, as well as sewage and animal waste.

The results indicate that most of the organic matter in the sediments (70%) is derived from diatomaceous microalgae (Figure 5), with small contributions from terrestrial sources (less than 20%) and *Ruppia* (less than 10%). While the large contribution of microalgae was expected, what was surprising was the absence of significant amounts of *Ruppia* from the organic matter in the sediments. The reasons for this appear to be that the *Ruppia* breaks down and decomposes along the shorelines of the inlet rather than in the lagoon. The microalgae have a higher 'turnover rate' (see Figure 13) which means they grow many more generations in the same time period.

Sediment composition has changed over time

In addition to the short sediment cores collected throughout the inlet, a number of long sediment cores were collected from the centre of the inlet. The cores were collected to determine whether there had been major changes in the type or amount of organic matter that has been accumulating following European settlement. Each of these cores was 2.5 m to 3 m in length; the average depth of accumulated sediment in the inlet.

The cores showed that black, organic-rich mud, of similar composition to today's sediments, has been accumulating in the inlet for thousands of years. Radiocarbon dating indicated that the oldest sediments were about 8000 years old, roughly the age of the inlet. The upper 20 cm had accumulated since significant European settlement of the catchment.

It was found that because of different consolidation and mixing processes at different depths, each 10 cm of sediment could represent between 100 and almost 1000 years of sediment accumulation. However, based on measured accumulation rates, suspended-solid measurements in near-pristine tributaries (i.e. Mitchell River) and models from the eastern states, it is believed that the sediment load to the inlet has increased 10 to 40 fold since European settlement.

The black colour of the sediments is produced by the presence of iron sulfides. Iron sulfides are formed under 'anoxic' (completely oxygen-less) conditions when plenty of sulfate is available (from seawater). The occurrence of this black colour throughout the cores indicates that the sediments are naturally anoxic and that sulfate reduction is a natural component of the sediment decomposition. This is an important observation because sulfate reduction is often a consequence of eutrophication. In this case it indicates that the sediments are naturally rich in organic material and have been for thousands of years.

The ratios of nitrogen isotopes accumulated in the sediments indicate that since European settlement there has either been an increase in the amount of nitrogen derived from animals and fertiliser, or that the amount of sediment nutrient recycling in the inlet has increased. In all likelihood both have occurred and both represent a significant change to the nitrogen budget of the inlet that is detrimental to its 'health'.

A comparison of nutrient concentrations in the surface sediments collected in 1946–50, 1982–83, 1994 and 1997–99 shows there has been no significant change over this period in the total nutrient concentrations of the surface sediments. While this appears to be a good sign it should be remembered that the sediment accumulation

Figure 4. Sediment cores being collected and then extruded under nitrogen gas (so that the sediments and pore-waters are not exposed to atmospheric oxygen). Note the difference between dark muddy sediments and light-coloured sandy sediments. Photos: B. Boardman

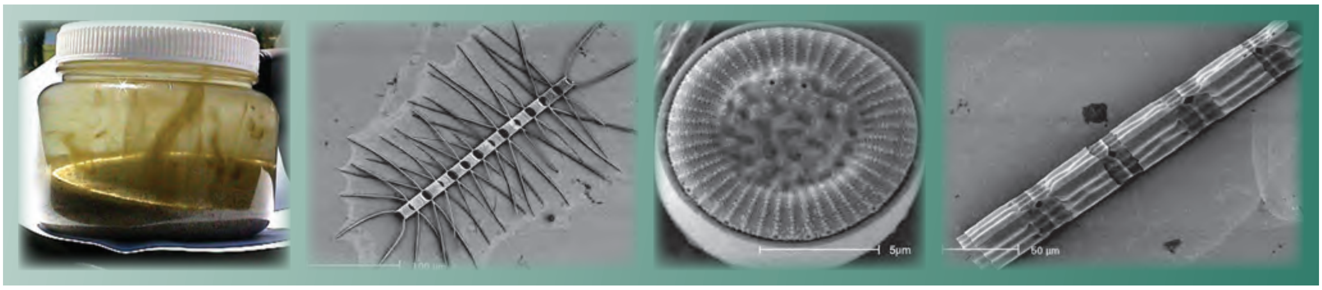


Figure 5. Some of the microalgae that contribute the bulk of the organic matter to Wilson Inlet sediments. L–R. a jar showing microalgae wafting in the water above a sediment sample from Wilson Inlet, and electron microscope images of the diatoms, Chaetoceros*,* Cyclotella *and* Lithodesmium*.* Photos: W. Hosja and L. Twomey

rate has also changed, at least since 1946–1950, and the increased sediment load will be 'diluting' any increased nutrient concentrations.

In addition to radiocarbon and lead dating, the types of pollen in the sediments were used as an indicator to determine which sediments had accumulated before European settlement and which after. Exotic pollens, such as those from pine trees, introduced pasture and weed species, were only found in the top 10 cm to 20 cm of the sediment, indicating that only the top 10 cm to 20 cm of the sediment has been formed since European settlement. Interestingly, significant amounts of *Ruppia* pollen could only be found in sediments accumulated in recent decades, suggesting that the recent proliferation of *Ruppia* in the inlet is unprecedented in the past 8000 years.

Nutrient cycling processes

Before looking at the sediment nutrient cycles in detail, it is worth re-iterating which nutrients we are interested in. The growth of aquatic plants in Wilson Inlet is limited by nitrogen and phosphorus.

It is important to note that nitrogen and phosphorus can be present in forms that plants and algae are able to use and forms that they are not (Table 2). Only the dissolved inorganic nutrients, such as ammonium, nitrate and phosphate, are immediately available for plants and algae to use. Other nutrients, the organic or particulate forms, are not immediately available to plants and algae – they have to be remineralised first.

Nutrient cycling processes follow different pathways depending on whether or not the bottom waters and upper sediment are oxygenated.

In oxygenated waters

Firstly, let's consider the circumstances where oxygen is present in bottom waters and how sediments are oxygenated. A well-mixed water column receives oxygen from the surface through wind mixing and **photosynthesis** (by phytoplankton, seagrasses and macroalgae). There are several mechanisms which transport oxygen from the water column to the sediment layer. Burrowing by invertebrates (**bioturbation**) creates sediment complexity, greatly increasing the sediment surface area and enabling bio-irrigation; benthic phytoplankton create a photosynthetic layer which allows for the diffusion of oxygen to the sediment; seagrasses have been shown to

Preferred nutrient forms	Least preferred nutrient forms
Nitrogen	
Dissolved inorganic nitrogen – ammonia (NH_4^+) – nitrate (NO_3^-)	Dissolved organic nitrogen Particulate organic nitrogen Nitrogen gas (N_2)
Phosphorus	
Dissolved inorganic phosphorus – phosphate (PO_4^{3-})	Dissolved organic phosphorus Particulate organic phosphorus Particulate inorganic phosphorus

Table 2. Major forms of the nutrients nitrogen and phosphorus found in the water.

actively transport oxygen from their leaves to roots and to surrounding sediments – called **radial oxygen loss**. These sediment oxygenating mechanisms are summarised in Figure 6a.

Now let's look at the nutrient cycling which occurs in oxygenated sediments (Figure 6b). Organic matter from seagrass, phytoplankton, zooplankton etc. falls to the inlet floor and the nutrients bound up in this organic matter are released by a process called remineralisation. Microbes, mostly bacteria and fungi living in the sediments, feed on the organic matter for energy. In a process called 'decomposition' they digest and break down the large organic molecules into smaller inorganic ones, releasing ('remineralising') the nutrients as they do so. The nitrogen that was bound up in organic molecules is remineralised back into ammonium (ammonification), while the organic phosphorus is remineralised back into phosphate. The decomposition of organic matter directly consumes oxygen, a process called aerobic respiration.

The availability of dissolved oxygen in the sediment pore-waters and at the sediment-water interface is critical to maintaining the health of the inlet for several reasons:

1. oxygen is a prerequisite for denitrification
2. oxygen is essential for trapping phosphorus
3. oxygen allows bio-irrigators (invertebrate animals) to live in the sediment, an important process to bring oxygen to the top layer of the sediment (approximately the top 10 cm).

With oxygen present, a critical microbial process takes place whereby ammonia is converted to nitrate (nitrification) and subsequently to nitrogen gas (denitrification). The importance of denitrification is that ammonium, which is the preferred source of essential nitrogen for plants and algae, is converted into nitrogen gas (N_2) – a compound that most plants and algae are unable to use. Therefore, denitrification restricts the amount of plant and algal growth that can occur in an estuary and in fact exports nitrogen from estuary waters. Denitrification has been found to be one of the most important mechanisms for maintaining the health of estuaries throughout Australia. In the absence of oxygen the nitrification step cannot take place and consequently ammonium concentrations increase, supporting algal growth.

There is a small group of specially adapted bacteria and cyanobacteria (blue-green algae) that are capable of using nitrogen gas (N_2) for growth thereby converting nitrogen gas into organic nitrogen – a process called **nitrogen fixation**. The surface of the sediments of Wilson Inlet is an ideal environment for these organisms. This is therefore another way for nitrogen to enter the estuary.

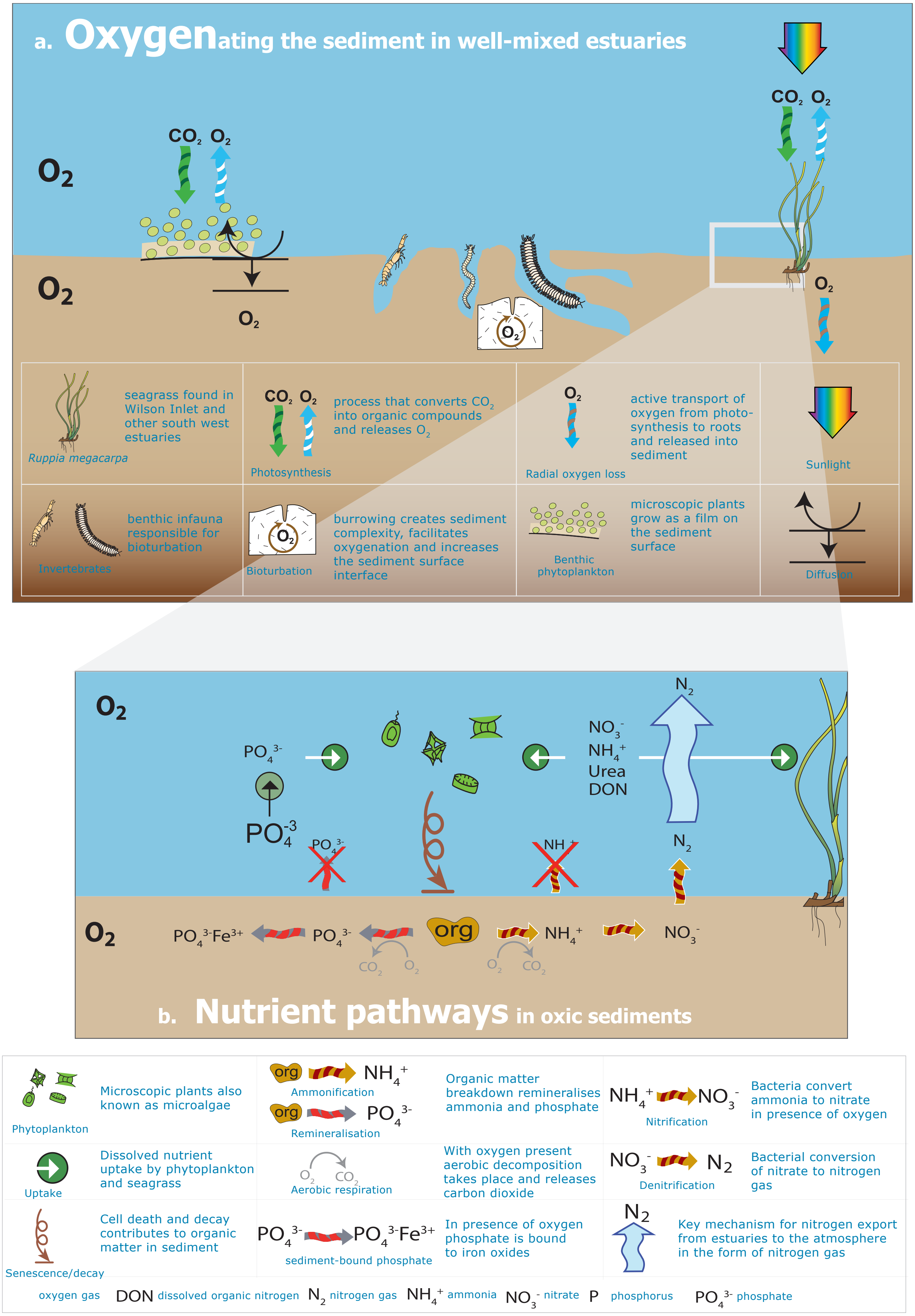
The phosphate that has been remineralised and accumulates in the pore-waters may be trapped by chemical processes (for ease of reference, referred to here as 'phosphorus trapping'). Again, in the presence of dissolved oxygen, iron in the sediments forms iron (III) oxyhydroxides: these compounds capture and hold onto the phosphate that is also present in the pore-waters, trapping it in a form that plants and algae are unable to use.

The remineralised nutrients accumulate in the sediment pore-waters. Depending on which physical and microbial processes occur, the nutrients that have accumulated in the sediment pore-waters may remain trapped in the sediments, may be processed further, or may be transported back into the overlying water.

The rate of organic material decomposition is controlled by temperature, the amount of organic matter accumulating (sometimes referred to as the carbon rain rate), and by the type of organic matter. This process of decomposition and the release of carbon dioxide is also referred to as sediment respiration. The more organic matter that accumulates, the more nutrients can be recycled and the more dissolved oxygen consumed. However, some forms of organic matter are easier to digest and therefore have a higher decomposition rate; for example, a fallen tree branch is much slower to rot than a piece of fruit. A higher decomposition rate means faster turnover, faster recycling of nutrients and more plant and algal growth. In Wilson Inlet the terrestrial organic matter (leaf litter, branches etc.) has the slowest decomposition rate, followed by *Ruppia*, then macroalgae, with diatomaceous microalgae the fastest.

Bio-irrigation

Bio-irrigation refers to the pumping of water into and out of the sediments by animals. Animals live or burrow into the sediment and pump water for a variety of reasons; for example to filter out food. Bio-irrigation oxygenates the sediments when the water that is being pumped into the sediments from the water column contains dissolved oxygen. When this is the case bio-irrigation is a major mechanism for oxygenating the upper 10 cm of sediment, where most of the bio-irrigating animals live. The animals involved in bio-irrigation in Wilson Inlet include polychaete worms (60%), gastropod molluscs (15%), bivalve molluscs (10%) and crustaceans (10%).

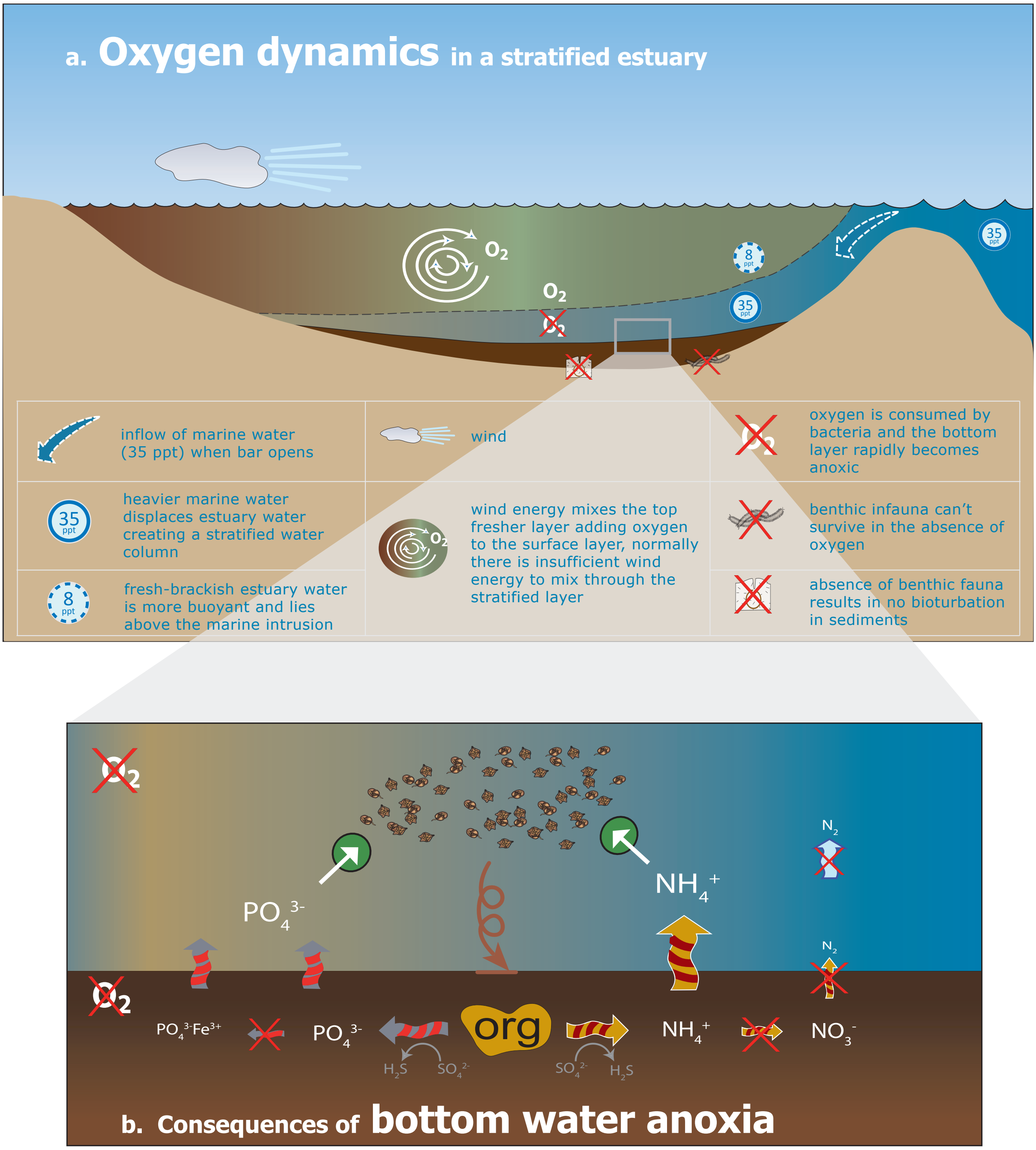


Ruppia megacarpa	seagrass found in Wilson Inlet and other south west estuaries
Photosynthesis (CO_2 O_2)	process that converts CO_2 into organic compounds and releases O_2
Radial oxygen loss (O_2)	active transport of oxygen from photosynthesis to roots and released into sediment
Sunlight	
Invertebrates	benthic infauna responsible for bioturbation
Bioturbation (O_2)	burrowing creates sediment complexity, facilitates oxygenation and increases the sediment surface interface
Benthic phytoplankton	microscopic plants grow as a film on the sediment surface
Diffusion	

Phytoplankton	Microscopic plants also known as microalgae
org → NH_4^+ Ammonification org → PO_4^{3-} Remineralisation	Organic matter breakdown remineralises ammonia and phosphate
NH_4^+ → NO_3^- Nitrification	Bacteria convert ammonia to nitrate in presence of oxygen
Uptake	Dissolved nutrient uptake by phytoplankton and seagrass
O_2 CO_2 Aerobic respiration	With oxygen present aerobic decomposition takes place and releases carbon dioxide
NO_3^- → N_2 Denitrification	Bacterial conversion of nitrate to nitrogen gas
Senescence/decay	Cell death and decay contributes to organic matter in sediment
PO_4^{3-} → $PO_4^{3-}Fe^{3+}$ sediment-bound phosphate	In presence of oxygen phosphate is bound to iron oxides
N_2	Key mechanism for nitrogen export from estuaries to the atmosphere in the form of nitrogen gas

oxygen gas DON dissolved organic nitrogen N_2 nitrogen gas NH_4^+ ammonia NO_3^- nitrate P phosphorus PO_4^{3-} phosphate

Figure 6. Oxygenated sediments, (a) key processes and (b) nutrient pathways.



a. Oxygen dynamics in a stratified estuary

inflow of marine water (35 ppt) when bar opens	wind	oxygen is consumed by bacteria and the bottom layer rapidly becomes anoxic
35 ppt: heavier marine water displaces estuary water creating a stratified water column	O_2: wind energy mixes the top fresher layer adding oxygen to the surface layer, normally there is insufficient wind energy to mix through the stratified layer	benthic infauna can't survive in the absence of oxygen
8 ppt: fresh-brackish estuary water is more buoyant and lies above the marine intrusion		absence of benthic fauna results in no bioturbation in sediments

b. Consequences of bottom water anoxia

Dinoflagellates	a group of phyto-plankton which flourish in eutrophic conditions	$PO_4^{3-}Fe^{3+}$ → 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
Senescence/ decay	cell death and decay contributes to organic matter in sediments	org → NH_4^+ Ammonification	organic matter breakdown releases ammonia	SO_4^{2-} → H_2S Sulfate reduction	decomposition without oxygen uses sulfate-producing hydrogen sulfide (rotten egg gas)
org → PO_4^{3-} Mineralisation	organic matter breakdown releases phosphate	NH_4^+ NO_3^- Nitrification NO_3^- N_2 Denitrification	anoxia inhibits the nitrification/denitrification process resulting in ammonia buildup	Dinoflagellate bloom	bottom water nutrient build-up favours dinoflagellate blooms and the cycle continues

Figure 7. Anoxic sediments, (a) oxygen dynamics in a stratified estuary and (b) consequences of bottom water anoxia.

When oxygen is absent

Now let's have a look at how estuary bottom waters become low in dissolved oxygen (hypoxic) or completely without oxygen (anoxic). Wind and wave action oxygenate surface waters and the wind and water movements mix estuarine waters so that the oxygen is distributed throughout the water column. When waters become stratified a major impediment to wind mixing occurs. In south coast estuaries such as Wilson Inlet, when the bar opens marine water enters the inlet and, being heavier than brackish estuarine waters, intrudes along the bottom and displaces the lighter water above. Although oxygenated, when it enters the estuary, the bottom layer quickly becomes hypoxic and/or anoxic due to sediment respiration processes. Often the wind energy is insufficiently strong to break down the stratification and the oxygen in the bottom layer is not replenished (Figure 7a). Benthic invertebrates cannot survive without oxygen and therefore the bioturbation mechanism for oxygenated sediments is also lost.

Hypoxia and anoxia also have profound consequences for the nutrient cycling within estuaries – with adverse affects on estuary 'health' and public amenity. As previously discussed, nutrients are remineralised by microbial decomposition of organic matter. Without oxygen this decomposition (anoxic decomposition) takes place with other oxidants, such as sulfate which transforms into hydrogen sulfide. In all types of decomposition processes carbon dioxide is produced.

Microbes carrying out the decomposition of organic matter prefer to consume dissolved oxygen. However, in the mud facies the oxic layer is only a few millimetres deep while in the sand facies it is no more than 10 cm. Where there is no dissolved oxygen for microbes to use, they use other oxygen-containing molecules that are present in the sediments. These include nitrate, iron and manganese oxides and especially sulfate (resulting in 'sulfate reduction'). Sediment respiration processes that use these molecules are collectively known as 'anoxic respiration' or 'anoxic decomposition'.

Among the potential negative consequences are the production of foul-smelling hydrogen sulfide gas (rotten egg gas), the formation of sulfides in the sediments, and changes in the way sediments bind and/or release nutrients (Figure 7b).

In the case of phosphorus, when dissolved oxygen is absent, iron (III) oxyhydroxides are unable to form. In addition, iron (III) oxyhydroxides that were previously formed in the presence of oxygen break down as the iron (III) is converted to iron (II) and release their phosphate. Sulfide, which is only present when there is no dissolved oxygen, binds with the iron (II) forming iron sulfides and preventing phosphate from forming iron phosphates. The net result of a lack of dissolved oxygen is a build-up of phosphate.

Transport of nutrients into the water column

As we have seen, nutrients remineralised from organic matter may accumulate in sediment pore-waters. There are a number of subsequent mechanisms responsible for transporting these nutrients into the overlying water. These include diffusion and a variety of 'advective' mechanisms in which pore-waters and the overlying water are mixed. When materials are transported from the sediments to the water we usually call this a 'flux'.

Diffusion occurs because the concentrations of nutrients in the pore-waters accumulate to higher levels than in the overlying water. This concentration gradient drives the movement or diffusion of dissolved species from the high concentration to the low. Diffusion moves the dissolved species alone, not the pore-water, so is a slow process compared with the others below (consider how effectively the sugar in a cup of tea dissolves if it sits at the bottom of the cup compared with stirring it).

Wave-pumping and sediment resuspension

The movement of water by tidal currents and wave action can pump water from the overlying water column into and out of the sediments. As it does so, it also displaces pore-waters and their associated nutrients into the overlying water column. Wave action also stirs and 'resuspends' the surface sediments in shallow areas (especially the fine siltier sediments), mixing their pore-waters into the water column. Resuspension can be especially effective where there are no plants (e.g. *Ruppia*) to anchor the sediments and dissipate the wave energy.

Bio-irrigation

As we have seen above, bio-irrigation is an important mechanism for transporting oxygen into the sediments; it is also an important mechanism for transporting nutrients out. As bio-irrigating animals pump overlying water into the sediments, they pump out the pore-waters and their own excreta, with the associated nutrients, into the overlying water column. The oxygenated burrows and tubes effectively enhance the oxygenated surface area of the sediment.

Sediment nutrient fluxes in Wilson Inlet

The fluxes of nitrogen, phosphorus, silica, carbon dioxide and oxygen into and out of the sediments were measured using devices called 'benthic chambers' (Figure 8).

Benthic chambers consist of perspex containers, not unlike a very large drinking glass, placed upside down on the sediments. The chambers trap a known volume of water over a known area of sediment. The rate at which nutrients and carbon dioxide are released and oxygen is consumed by the sediments are then determined by measuring the change in their concentrations in the trapped volume of water. Several types of chambers were used. These included 'light' chambers that would allow photosynthesis to continue and 'dark' chambers that would prevent photosynthesis.

Chambers were deployed in the field for 8 to 48 hours, and between 30 and 60 deployments were made throughout the inlet during each field trip. The locations of the main field sites are shown in Figure 2.

Figure 8. Manual and automatic benthic chambers, underwater and being deployed. Photos C. Tindall.

Inside and outside of each chamber the water's dissolved oxygen, conductivity, temperature, pH and ambient light were measured at intervals of a few minutes. Every 1 to 6 hours water samples from the chambers were analysed for concentrations of carbon dioxide, nutrients and inert 'tracers'. These tracers were used to compare the effects of groundwater, bio-irrigation and diffusion. Inlet-wide estimates of the sediment fluxes are tabulated in Table 3.

Oxygen consumption rate and deoxygenation

The sediment respiration rates varied considerably throughout the inlet and through the year. The average sediment respiration rate was found to be in the range of 1000 to 2000 mg of dissolved oxygen/m^2/day. These are quite high sediment respiration rates and indicate that the sediments of the inlet consume about 50 to 100 tonnes of oxygen per day. Oxygen is consumed by bacteria in breaking down organic matter and also by chemical reactions; for example the oxidation of reduced compounds such as dissolved Fe, FeS, dissolved Mn, and H_2S.

This respiration rate is quite significant when it is considered that on average the water in the inlet contains about 700 tonnes of dissolved oxygen. If this oxygen were not being constantly replenished, then the inlet would become deoxygenated in one or two weeks due to the consumption of the sediments alone. This does not happen because the photosynthesis of plants and algae produces oxygen and because oxygen is mixed into the inlet from the atmosphere.

If, however, there is a layer of water in the bottom of the inlet that is not being replenished with oxygen – that layer can become anoxic relatively quickly. For a layer 0.5 m deep it takes 2 to 4 days to become anoxic, for a layer 1 m deep it takes 4 to 8 days. We regularly observe this deoxygenation when salinity stratification occurs.

Salinity stratification describes the situation where layers of water of different salinity lie over each other. Salinity stratification occurs because the density of water in the inlet is dependent on its salinity. When a layer of fresh water overlies a layer of salty water, a situation that resists mixing exists because the saltier water is heavier than the fresh and it takes a lot more energy to mix the two layers together than if they were the same density. (See report no. 5 in this series for more details.)

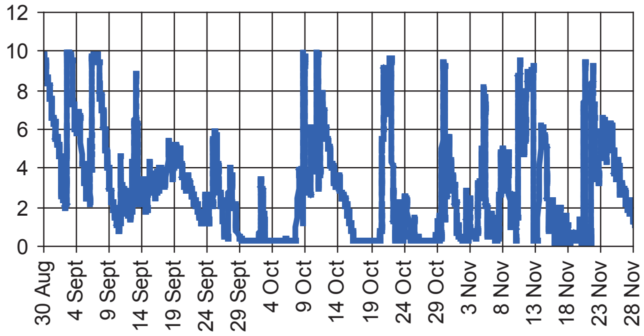
Figure 9 illustrates a three-month period following the bar opening in 1997 when repeated salinity stratification resulted in bottom water deoxygenation, the deoxygenation being relieved by either strong winds or new saltwater intrusions.

Based on regular water quality monitoring (see report no. 5 in this series) we believe that a measured dissolved oxygen concentration in bottom waters of 2 to 4 mg/L is the limit below which an increase in sediment nutrient release occurs.

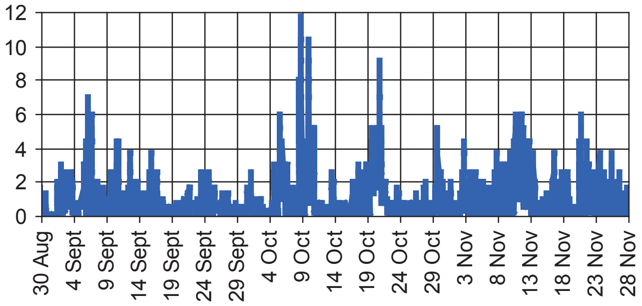
Carbon dioxide production and sulfate reduction

The carbon dioxide fluxes were found to vary considerably between sites and throughout the year; the inlet-wide average was about 2000 to 3000 mg/m^2/day. These fluxes are relatively high and are greater than the oxygen respiration rates allow, suggesting that either dissolution of carbonate minerals or sulfate reduction is occurring. While both may be occurring, the sulfide concentrations in the sediments suggest that sulfate reduction is certainly occurring.

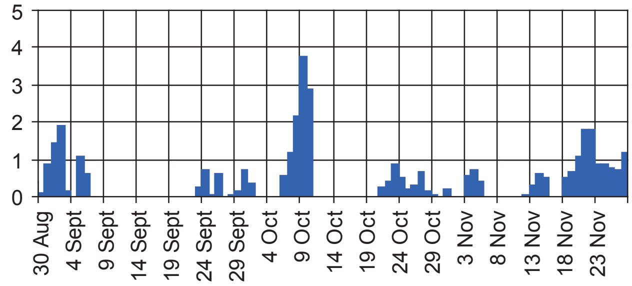
The occurrence of sulfate reduction is usually taken as an indicator of poor sediment 'health'. However, as noted earlier, sulfide concentrations in the sediments of Wilson Inlet are naturally high (in mud facies, not in sand facies), and sulfate reduction appears to have been occurring for thousands of years. So the occurrence of sulfate reduction in the mud facies needs to be read carefully. In the sand facies, the *Ruppia* and benthic microalgae are providing sufficient oxygen to the sediments to prevent nutrient



Dissolved oxygen (mg/L) at site WI6 (recorded 15 minutes).



Wind power (kW) available for mixing the inlet in 1997 (based on Albany airport data so not exactly correct for Wilson Inlet but closest available).



Daily marine exchange (GL) past Poddyshot in 1997. Bear in mind that the approx volume of the inlet at mean sea level is about 90 GL.

Figure 9. These plots compare the dissolved oxygen concentration for bottom waters in the centre of the inlet at the time of the 1997 bar opening with the wind power available to mix the inlet and the marine exchange occurring. The water should hold about 8 mg/L to 10 mg/L of dissolved oxygen when saturated. A concentration of about 4 mg/L is the level below which we start to see an increase in sediment nutrient release. Looking at the data plotted here and the complementary conductivity data, we can determine which peaks in the dissolved oxygen are due to wind, which are due to marine intrusions and which are a function of both. On the whole wind mixing appears to relieve deoxygenation more often than marine intrusions.

recycling via sulfate reduction. This limitation on at least some of the sulfate reduction that might occur is advantageous for the 'health' of the inlet.

Nitrogen fluxes and denitrification efficiency

The measured nitrogen fluxes were found to vary considerably throughout the inlet and throughout the year. The inlet-wide average ammonium flux rates were 20 to 120 mg/m^2/day (with a maximum of 220 mg/m^2/day). The inlet-wide average nitrate flux rates were less than 1 mg/m^2/day. The inlet-wide average nitrogen gas flux rates were estimated to range from 5 to 200 mg/m^2/day. Individually, none of these fluxes is remarkable; however, interpreted together they have enormous implications for the 'health' and management of the inlet.

As already noted, the availability of nitrogen is one of the major controls on plant and algal growth in Wilson Inlet, and, while ammonium and nitrate are available to plants and algae, nitrogen gas is not. The nitrogen flux data (see Table 3) indicate that more than half of the nitrogen released from the sediments is in the form of nitrogen gas. In other words, more than half of the nitrogen that has been recycled from the sediments has been denitrified – released as relatively inert nitrogen gas that cannot be used by most plants and algae.

A 'denitrification efficiency' can be estimated by considering how much of the recycled nitrogen has been denitrified and how much has been released into the water column as ammonium and nitrate. The average annual denitrification efficiency for Wilson Inlet is about 60% (with a range of 50% to 80%). This means that on average only about 40% of the nitrogen recycled to the water column is available to plants and algae and the remaining 60% is lost as nitrogen gas.

Again, as already discussed, the process of denitrification requires oxygen. If dissolved oxygen is not available, denitrification cannot occur. If the incidence of deoxygenation increased in Wilson Inlet, then instead of eliminating 60% of the nitrogen they process as nitrogen gas, the sediments would release this nitrogen into the water as ammonium and there would be a massive increase in algal abundance in the inlet. Notably, the flux data already indicate that the denitrification efficiency is much lower in the spring when stratification and deoxygenation occur, than in the summer and autumn when *Ruppia* and benthic microalgae are most actively oxygenating the sediments. Any management action must therefore consider the fact that denitrification is a key process,

	Oxygen gas (tonne O_2/yr)	**CO_2 gas** (tonne CO_2/yr)	**Ammonium** (tonne N /yr)	**Nitrate** (tonne N /yr)	**Nitrogen gas** (tonne N /yr)	**Phosphate** (tonne P /yr)	**Silicate** (tonne Si /yr)
Nov 97	-20 800	31 000	530	40	920	8	3 800
May 98	-7 300	10 300	380	30	100	11	1 700
Sept 98	-6 200	32 600	740	-60	870	10	800
Feb 99	-26 500	34 500	620	40	940	113	3 700
Average*	-15 000	23 000	500	10	500 to 620	20 to 50	2 400

*Table 3. Annual sediment fluxes of major metabolites (positive fluxes are production from sediments, negative fluxes are consumption by sediments). *Note that the average is a seasonally weighted average and that all fluxes are summation of fluxes from sand facies and mud facies.*

dependent on the availability of dissolved oxygen, which prevents the inlet's 'health' from rapidly deteriorating.

Based on computer modelling work and data from other estuaries, we believe that the critical denitrification efficiency, below which an estuary's health rapidly deteriorates, is an efficiency of roughly 40%.

Phosphorus fluxes

The measured fluxes of phosphate from the sediments were generally low and in almost all cases lower than what would be expected compared with the respiration rate and the nitrogen fluxes. The inlet-wide average was about 1 mg/m^2/day.

Several hypotheses may explain this. However, the most likely explanation for these low phosphate fluxes is that the sediments are trapping the phosphate very efficiently for much of the year.

Interestingly, a few very much higher fluxes were recorded: up to 40 mg/m^2/day (with regular water column monitoring providing evidence that fluxes to a maximum of 90 mg/m^2/day occur). These fluxes are higher than the respiration rate, nitrogen fluxes and silicate fluxes would suggest is possible from decomposition of organic matter. The implication is that for these few high fluxes the phosphate must be coming from another source. Interestingly these high fluxes only occurred when dissolved oxygen concentrations had fallen very low (negative oxygen flux as shown in Figure 11). Under low dissolved oxygen conditions the sediments are releasing the phosphate that had previously been trapped.

Importance of Ruppia *and benthic microalgae*

Data for light and dark chambers indicated that the benthic microalgae were a very active oxygen source for the sediments during summer and autumn. The importance of oxygen availability in regulating phosphate fluxes and denitrification efficiency has already been discussed above. Data from chambers containing *Ruppia* demonstrate that they are a significant source of oxygen from late spring to autumn. Experiments clearly showed that much more sulfate reduction occurred in muddy rather than sandy sediments with *Ruppia*.

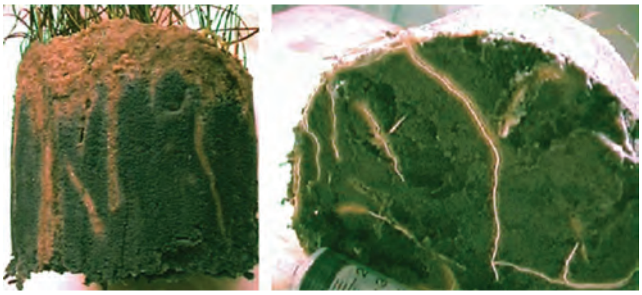


Figure 10. Surface sediment core samples illustrated the role of Ruppia *and benthic microalgae in oxygenating sediments. In this case oxygenation is seen around* Ruppia *roots (lighter area oxygenated, darker area unoxygenated).*

It also appears that the benthic microalgae intercept much of the nutrient flux from the sediments, preventing it from fuelling phytoplankton blooms. While the *Ruppia* trap catchment-derived nutrients, preventing them from being used by phytoplankton (see report no. 7 in this series), the *Ruppia* only occupy the shallows and are remote from much of the sediment flux. Instead it is the diatomaceous benthic microalgae that trap sediment nutrient fluxes though summer and autumn. In fact one of the reasons the spring phytoplankton blooms occur is that coming out of winter with its low temperatures and coloured, turbid fresh water, the benthic microalgae are not yet able to compete with the phytoplankton for nutrients when sediment nutrient fluxes occur as a result of stratification-related deoxygenation.

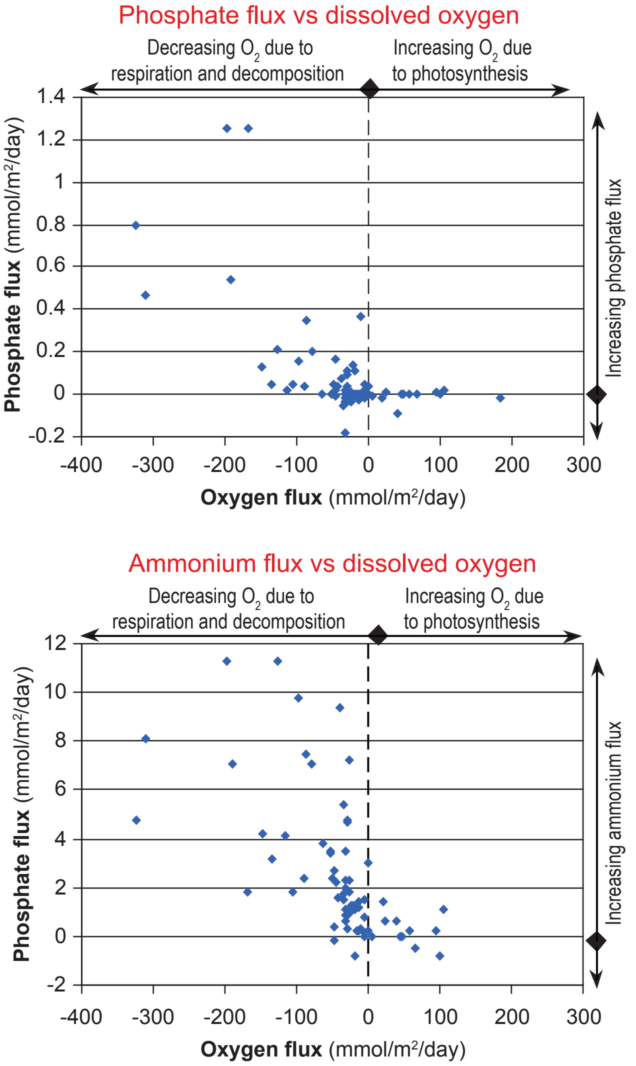


Figure 11. Flux data from chambers show a strong correlation of increasing nutrient fluxes with decreasing oxygen.

Importance of bio-irrigation

Tracer experiments and models of diffusive flux versus measured flux determined that there was significant advective transport. The transport of dissolved oxygen into the sediments (and pore-waters out) was typically several times greater at muddy sites and up to 10 times greater at sandy sites than could be expected by diffusion alone.

Density displacement was ruled out by measuring the distribution of tracers down the depth of sediment cores.

Groundwater movement was measured with piezometers and by tracking the movement of naturally occurring

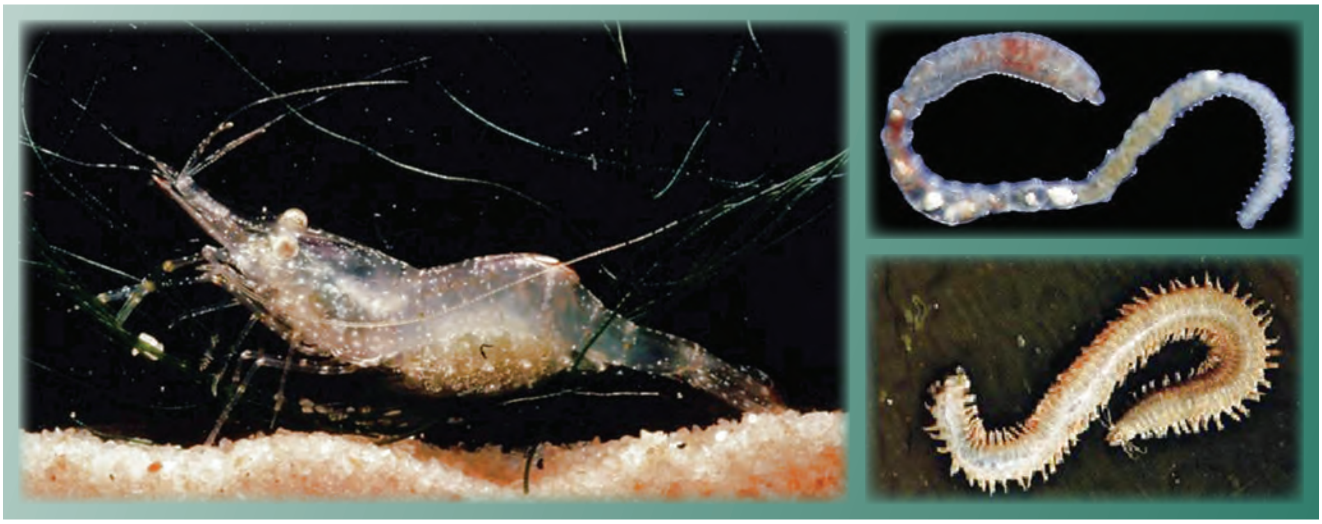


Figure 12. Some examples of bio-irrigating invertebrate organisms, including shrimp and polychaete worms.

radioactive isotopes generated deep in the sediments. The flow of groundwater was found to be small and confined to shallow, shoreline areas, however such flows may be locally important.

Wave action and re-suspension were not directly measured. It was expected they could be important in shallower areas but would be less important in deeper waters. It was also believed that *Ruppia* would mitigate the effects in many shallow areas by stabilising the sediments and dissipating wave energy.

Further experiments involving sterilised chambers determined that the measured advective flux was almost exclusively due to bio-irrigation. The volume of bio-irrigation suggested by chamber data was 500 to 1000 GL/yr. This seemed high so was cross checked against the known numbers of bio-irrigating organisms in the sediment and literature values of their bio-irrigation rates, resulting in an estimate of 1000 to 2000 GL/yr. These rates are comparable with other estuaries around the globe.

Volumes for comparison	Volume in GL
Due to groundwater flow/year	< 0.5
Due to density displacement/year	< 1 (to maximum 5)
Due to wave action/year	unknown (guess < 100)
Due to bio-irrigation/year	500 to 2000
Volume of inlet (at msl)	85
Pore-water in top 10 cm sediment	3 to 5
Annual rainfall on inlet	50
Annual river flow into inlet	150 to 250

Table 4. Volumes pore-water exchanged and/or transported into water column

While they transport pore-waters and nutrients out of the sediments, bio-irrigating organisms only live in oxygenated waters, and probably transport 5000–10 000 tonnes/yr of oxygen into the sediment (of the average 15 000 tonnes/yr used; the balance from *Ruppia* and benthic microalgae). The high bio-irrigation rates also suggest that these organisms probably play an important role in filtering and clearing the inlet's waters.

Estuarine response to nutrient loads

Nutrients entering from the catchment are rapidly taken up into plant matter or lost directly to sediments in the particulate form. Nutrients are used and recycled at different rates by microalgae and *Ruppia,* which is why microalgae contribute the bulk of the organic matter to the sediment. Nutrients are used and recycled at different rates by microalgae and *Ruppia*. The lifecycle of microalgae is much shorter than *Ruppia* – therefore the recycling of N and P molecules is more rapid for microalgae which enhances the rate of organic matter build-up in sediments (see Figure 13).

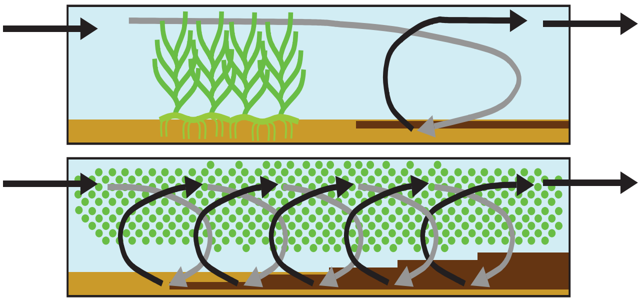


Figure 13. Each molecule enters and exits only once but can be recycled more than once. The high turnover rate of microalgae compared with Ruppia *magnifies the recycling further, and results in more organic matter.*

The 'health' of an estuary does not respond linearly to increases and decreases in catchment nutrient loads. For decades an estuary can absorb an increasing load with only slow deterioration, then once a critical point is reached, the deterioration can be rapid. When loads are decreasing, especially if a critical point has been passed, improvement in an estuary's condition may be slow despite years of successful effort in reducing loads. One of the key critical points is the shutdown of denitrification (others include loss of seagrass and benthic microalgae and loss of fish communities).

How 'healthy' are the sediments of Wilson Inlet?

The denitrification efficiency of sediments in Wilson Inlet measured in these studies averaged 50% to 70%. Other Australian studies and computer models have shown that the critical denitrification efficiency for maintaining a 'healthy' estuary is 40%. If the efficiency falls below 40% the recycling of nitrogen between the sediments, water column, and the plants or algae becomes self-sustaining, resulting in a large increase in plant and algal growth. Denitrification efficiencies in other Australian estuaries range from 30% to 90%. Based on denitrification efficiency the sediments of the inlet can be considered 'moderately healthy' and the estuary resilient.

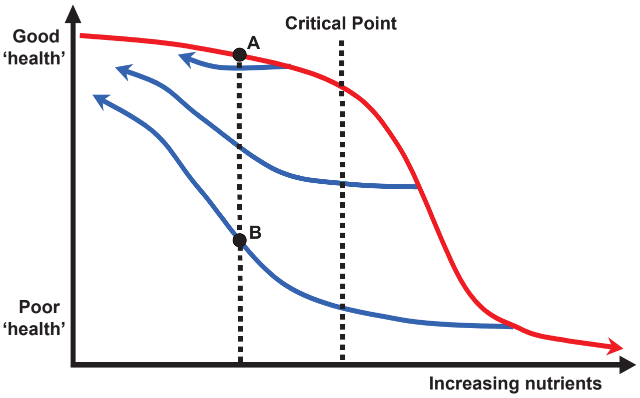


Figure 14. Red is response to increasing load, blue to decreasing. Once the critical point is passed deterioration is rapid and difficult to reverse. For example, a nutrient load that corresponds to a 'healthy' state if the critical point has not been reached (point A) will correspond to a 'poor' state if trying to return from beyond the critical point (point B); this phenomenon of non-linear response is called hysteresis. As a result more effort is required to improve estuarine 'health' if allowed to deteriorate beyond a critical point than if reversed before it passes the critical point.

Other factors that control sediment 'health' include the availability of dissolved oxygen at the sediments, the transport of oxygen into the sediments, the degree of sulfate reduction occurring and the oxygen consumption in the sediments.

The availability of dissolved oxygen at the sediments is 'moderate to good', however salinity stratification can disrupt this. The transport of oxygen into the sediments is 'good', with high bio-irrigation rates, however this too is vulnerable to disruption by anoxic events. The degree of sulfate reduction is high, with high levels of sulfides in the sediment. This is an indicator of 'low to moderate' sediment 'health', as the sulfides block crucial nutrient processing, but there is a long history of high sulfides in Wilson Inlet sediments. The oxygen consumption rate of the sediments is high: this is an indicator of 'low to moderate' sediment 'health' as higher consumption rates imply greater vulnerability to deoxygenation events.

An overall assessment based on denitrification efficiency and these other factors suggest that the inlet is currently processing the nutrients that enter it relatively efficiently. However, because of the high stores of nutrients in the sediments and the vulnerability of their processing to deoxygenation, deterioration will occur with any increase in deoxygenation events.

Management implications

The most significant observations for management were:

- Over time there has been an increase in sedimentation rate, an accumulation of nutrients, a change in nutrient sources, and an increase in nutrient recycling from the sediments.
- Although these changes reflect a deterioration in the inlet's condition, the inlet is currently processing the nutrients that enter it relatively efficiently (the historically unprecedented growth of *Ruppia* is one aspect of this).
- The availability of dissolved oxygen at the sediment-water interface is crucial to the efficient processing of nutrients, with benthic invertebrates being the most important transporters of oxygen into the sediments.
- The benthic microalgae grow with nutrients from the sediments, and with *Ruppia*, are also major sources of oxygen; however growth can be limited by poor water clarity.
- Denitrification coupled with nitrification, which is dependent on oxygen, removes half of the bio-available nitrogen from the inlet (this is many times more than is exported to the ocean).
- Phosphorus is effectively bound in the iron-rich sediments.
- The sediments will become a significant source of nutrients should dissolved oxygen availability at the sediment-water interface decrease.
- Consequently, the inlet's 'health' is likely to deteriorate in the event of increased incidences of deoxygenation.

The inlet is currently fairly resilient under catchment loading and so it makes sense to reduce catchment nutrient loads now – before the inlet's condition deteriorates beyond a critical point that leads to serious ecosystem decline. The *Wilson Inlet Action Plan* was developed and implemented to achieve these reductions and to maximise natural sediment nutrient processing by ensuring that any actions taken don't increase deoxygenation or cause loss of the benthic microalgae, benthic invertebrates and the *Ruppia* (say by increasing turbidity). As stratification can be a cause of deoxygenation, when assessing the viability of management actions such as permanent opening or altered bar opening regimes, careful consideration needs to be given to the potential for stratification.

Using sediment condition indicators

The work described in this newsletter was undertaken between 1997 and 2000 and greatly advanced our understanding of sediment nutrient dynamics. Since then these techniques have been applied along the south and south west coasts of WA using and improving the indicators developed in Wilson Inlet. Since sediments integrate all the processes that occur in the estuary, measurement of sediment indicators after a period of years will provide knowledge about changes in the ability of an estuary to process nutrients. For that reason Wilson Inlet was revisited in 2008 to measure changes in sediment indicators since the studies described here. The next Wilson Inlet report to the community will describe those changes.

A scuba diver's view of the floor of Wilson Inlet

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Glossary of terms

Ammonium – Along with nitrate a dissolved inorganic form of nitrogen (DIN); available to plants and algae to use.

Anoxic – Complete deoxygenation, i.e. no oxygen available.

Bacteria – Microscopic organisms that feed on organic carbon; while some need oxygen to survive many others don't.

Benthic microalgae – Also known as microphytobenthos; microalgae that live on the surface of the sediment.

Crustaceans – Includes crabs, prawns and similar animals millimetres in size, many may be mistaken for tiny insects.

Cyanobacteria – Sometimes called blue-green algae; bacteria that photosynthesise, require oxygen, and are capable of using or 'fixing' nitrogen gas as a nitrogen source.

Decomposition – Breakdown of organic material by bacteria.

Dissolved oxygen – Oxygen gas dissolved in the water.

Diatoms – Microalgae that have a shell-like silica 'frustule'.

Epiphytes – Animals and plants (usually algae) that grow on the leaves of seagrasses and macroalgae.

Eutrophication – Nutrient enrichment; a natural process that is greatly enhanced by human activity.

Macroalgae – Large multi-celled algae, such as *Cladophora*, that are often called seaweeds.

Microalgae – Tiny single-celled algae; these may be epiphytic, benthic or floating (phytoplankton).

Molluscs – Includes mussels, oysters, cockles, squid, octopus.

Nitrogen – A nutrient essential to plants and animals; nitrogen gas from the air can be ‘fixed’ into organic nitrogen by bacteria and then released as ammonium, nitrate or nitrogen gas during respiration or decomposition.

Nitrate – Along with ammonium a dissolved inorganic form of nitrogen (DIN); available to plants and algae to use.

Phosphorus – Nutrient essential to all plants and animals.

Phosphate – A dissolved inorganic form of phosphorus (DIP); available to plants and algae to use (also called FRP).

Photosynthesis – Process carried out by plants and algae that captures energy from the sun and stores it in organic carbon molecules, and produces oxygen gas.

Phytoplankton – Free-floating or weakly mobile photosynthetic organisms, usually single-celled or chain-forming (e.g. diatoms, dinoflagellates, chlorophytes, cyanobacteria).

Polychaete worms – Segmented worms, generally less than 10 cm in length. Each segment bears a pair of paddle-like and highly vascularised parapodia, which are used for movement and, in many species, act as the worm’s primary respiratory surfaces.

Respiration – Process of extracting energy from organic carbon molecules; produces carbon dioxide. Plants, animals and algae require oxygen for respiration, but some bacteria do and can perform anoxic respiration.

Ruppia – The dominant aquatic plant in Wilson Inlet.

Sulfate – Type of dissolved sulfur bound to oxygen; abundant in seawater; converted to sulfide during anoxic respiration.

Sulfide – Type of dissolved sulfur produced during anoxic respiration; forms hydrogen sulfide gas (rotten egg gas) and metal sulfides that colour sediments black.

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