

Wilson Inlet 5



Report to the Community

WATER AND RIVERS COMMISSION

AUGUST 2002

Water Quality in Wilson Inlet from 1995 to 2002



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Figure 1: Aerial photo of Wilson Inlet looking in a north easterly direction.

Photo S. Neville

This newsletter is the fifth in the series of community reports on Wilson Inlet produced by the Water and Rivers Commission. It summarises the results of the Water and Rivers Commission's estuarine data collection and monitoring program in Wilson Inlet from January 1995 to March 2002. The program has focused on quantifying nutrient enrichment and its consequences, and therefore the following water quality parameters have been investigated and are reported on here: salinity, temperature, dissolved oxygen, nutrients and phytoplankton algae.

The second Wilson Inlet Report to the Community described the data from 1995 to 1998 and also described many of the important elements and processes of the Wilson Inlet system. This report touches on those elements and processes again when describing the events of the past seven years in Wilson Inlet.

Introduction

Wilson Inlet is a seasonally closed estuary on the south coast of Western Australia. The Inlet has a surface area of 48 km², is 14 km long from east to west, and is about 4 km

wide. A sand bar isolates the estuary from the Southern Ocean for about half of the year (usually about February to July). The bar is artificially breached each year to prevent flooding of land next to the estuary. The Inlet has an average depth of 1.8 m below mean sea level, and a maximum depth of about 4 m below mean sea level. Note that when the sand bar across the Inlet mouth is breached the water level is usually about 1 m above mean sea level.

The Inlet's partially cleared catchment covers some 2300 km². The average rainfall at the coast is approximately 1100 mm and at the inland boundary of the catchment is about 600 mm. About 10% of the rain that falls on the catchment reaches the Inlet itself, delivered largely by the Inlet's five major tributaries: the Hay, Denmark, Sleeman, Little and Cuppup.

There is ongoing concern that as a consequence of land use changes in its catchment since the 1950s Wilson Inlet is becoming increasingly eutrophied¹. An increase in benthic vegetation, mainly the seagrass *Ruppia megacarpa*, its epiphytes and various macroalgae, has to date been the

¹ Eutrophication means nutrient enriched.



Figure 2. Series of aerial photos of the Wilson Inlet delta, dated March 1946, January 1971 and December 1992 respectively. The series illustrates the increase in benthic vegetation in the Inlet over time. The clean sands present in the 1946 photo in the back of the delta (centre of photos), next to Poddyshot Point (top right of photos) and on the southern shore of the Inlet (bottom right of photos) have become increasingly vegetated in the 1971 and 1992 photos compared to 1946.

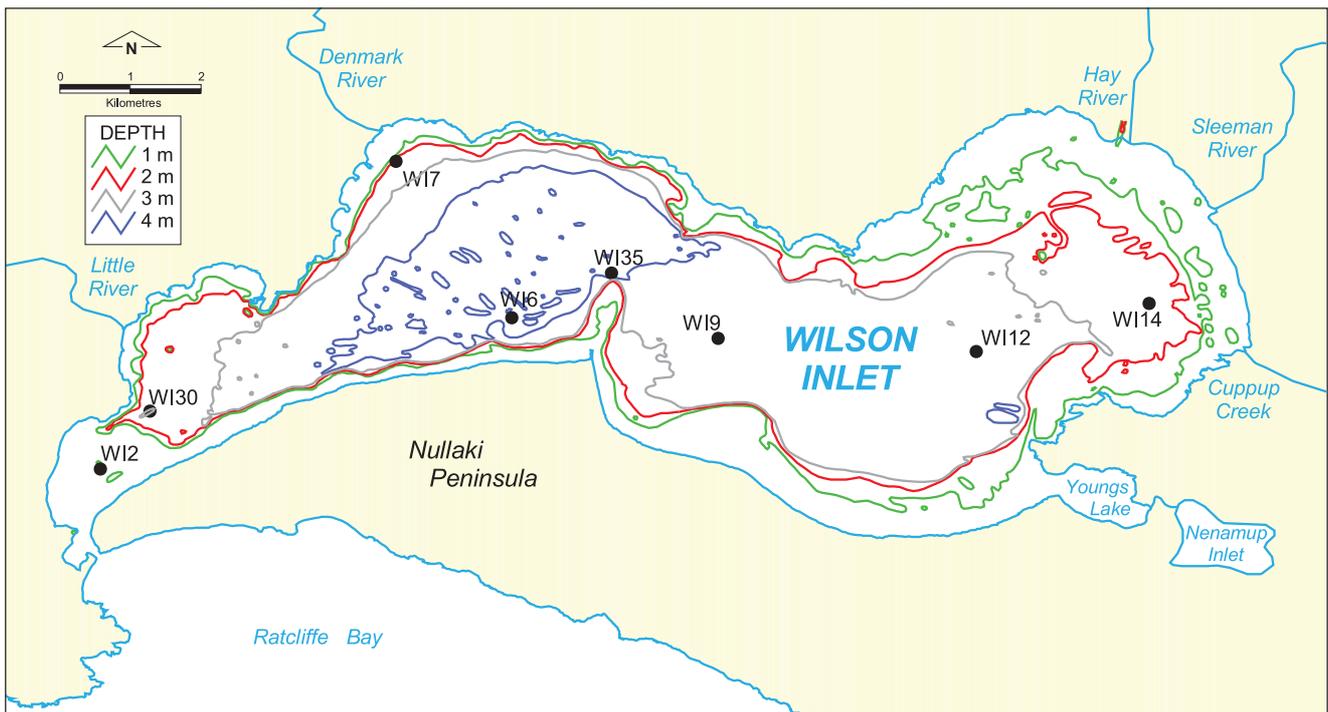


Figure 3. Map of Wilson Inlet showing water depths below mean sea level and the location of the eight commonly used water quality monitoring sites: WI2, WI30, WI6, WI7, WI9, WI35, WI12 and WI14.

major symptom of eutrophication in the Inlet (see Figure 2). There is also evidence suggesting that there have been concurrent increases in estuarine fish numbers over this period. The community is concerned that without adequate management the eutrophication of the Inlet will increase and eventually the runaway growth of plants and algae and the internal recycling of nutrients will lead to the collapse of the present ecosystem, similar to the case of the Peel-Harvey estuary in the 1980s.

To understand the nutrient status of the Inlet and the processes controlling it the Water and Rivers Commission has regularly monitored the water quality in Wilson Inlet at a number of sites since 1995. The locations of the monitoring sites are shown in Figure 3. At these sites measurements of the water temperature, salinity and dissolved oxygen concentration, are made from the surface down to the bottom using Hydrolab datasonde instruments. Water samples are collected from the surface and the bottom at a number of these sites and are analysed for nutrients (nitrogen, phosphorus, and silica) and the composition and concentration of phytoplankton.

Depending on the season and the year monitoring has taken place from weekly to monthly. During periods of stratification loggers have been placed on the bottom of the Inlet recording oxygen, temperature and salinity at 15 minute intervals.

Water quality monitoring has been a part of a broader investigation into the nutrient status of Wilson Inlet. The Water and Rivers Commission has also undertaken extensive catchment nutrient monitoring (discussed in the third Wilson Inlet report to the community). While the National Eutrophication Management Program (NEMP) and the Water and Rivers Commission have jointly funded investigations into the seagrass dynamics, sediment geochemistry, and phytoplankton of the Inlet. The Commission has also funded studies into coastal processes and the bar, and the fisheries of the Inlet. The NEMP projects are summarised in the fourth Wilson Inlet report to the community. Future community reports (numbers six to ten) will discuss the findings of each of these projects individually.

Why are nutrients a focus of study?

Nutrients are the essential chemical elements required by plants, algae, bacteria and animals for growth. In Wilson Inlet it has been found that the nutrients whose availability limits the growth of plants and algae are primarily nitrogen and phosphorus. Studies have found that the biomass of *Ruppia* is probably limited more by the availability of phosphorus and that phytoplankton algae biomass is probably more limited by the availability of nitrogen. In the same way that adding nutrients in the form of fertiliser to a paddock or a backyard improves plant growth, adding nitrogen and phosphorus to Wilson Inlet causes greater plant and algal growth. Nutrient cycles in the Inlet have therefore been studied to find out what processes they are governed by and how they can be managed.

A very simplified diagram of the nutrient cycle in Wilson Inlet is presented below in Figure 8. It is important to note that each of the required nutrients can be present in the water column in forms that the plants and algae are able to use and forms that they are not (Figure 7).

Nutrient	Form(s) available to plants and algae	Form(s) unavailable to plants and algae
phosphorus	orthophosphate, also called dissolved inorganic phosphorus (DIP) or filterable reactive phosphorus	dissolved organic phosphorus (DOP), and particulate phosphorus (PP)
nitrogen	ammonium and nitrate, together called dissolved inorganic nitrogen (DIN)	dissolved organic nitrogen (DON), particulate nitrogen (PN), and nitrogen gas (N ₂)

Figure 7: Forms of nutrients found in the water that are available for plants and algae to use, and forms that are not.

While it appears complicated, the major points to be derived from looking at the nutrient cycle are that: (1) different nutrient cycling pathways produce nutrients in different forms; (2) the sources of nutrients for the Inlet are the catchment and surface sediments; (3) the sinks for nutrients are the ocean and deep sediments, and also the atmosphere in the case of nitrogen only; (4) nutrients contribute not only to *Ruppia*, epiphyte, phytoplankton and macroalgal productivity, but also to the fishery productivity; and (5) there is the potential for the recycling of nutrients between the surface sediments, water column and the plants and algae, completely bypassing the other sources and sinks.

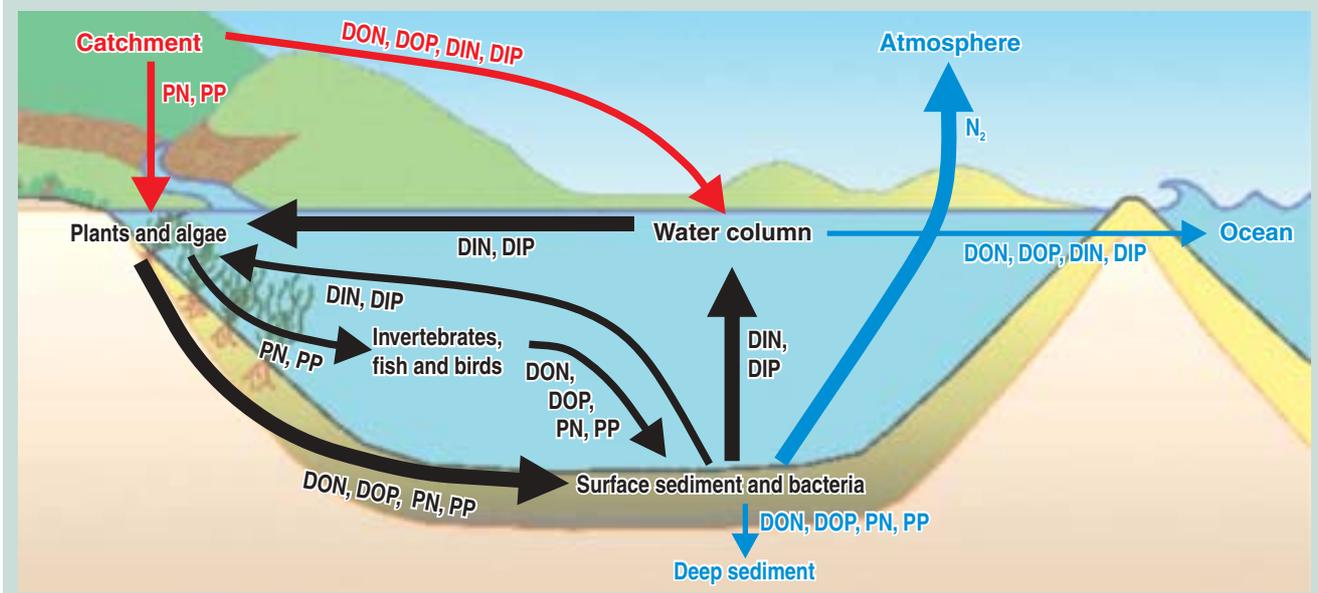


Figures 4, 5 and 6 (top to bottom): Analysing nutrient samples in a laboratory and sampling from the boat in Wilson Inlet with a Hydrolab instrument.

Photos B. Boardman and K Parker.

Figure 8 (below):

Simplified nitrogen and phosphorus cycle showing sources and sinks. The sizes of the arrows are intended to give a very rough idea of the relative scales of the different nutrient flow paths. The nutrient sinks are drawn in blue, the catchment source in red and the internal recycling in black.



The annual water quality cycle

Each year there is a regular, relatively predictable, annual sequence of events in the water quality of Wilson Inlet. This sequence reflects the annual cycles in the major drivers of the water quality. The external forces that drive the annual water quality cycle in Wilson Inlet and their effects on the Inlet are described below. Data for some of the drivers of the Inlet's water quality and the water quality data itself for the 1996/1997 period are presented so as to illustrate major elements of the annual water quality cycle in the Inlet (the data are for site WI6 in the centre of the Inlet).

Rainfall and river flow

In concert with landuse practice in the catchment, the rainfall and runoff determine the timing and load of nutrients delivered from the catchment to the Inlet, the salinity of the Inlet, the water colour and the water level in the Inlet. The availability of nutrients in turn contributes to plant and algal growth, whilst the salinity of the Inlet determines the species of plants, algae and animals present, and plays a role in determining the occurrence of salinity stratification, finally the water level determines the bar opening date. As can be seen in Figures 9 and 11 both rainfall and runoff (and hence nutrient delivery) have a clear seasonal pattern with some 80% of flow and 60% to 70% of rainfall occurring between June and October. The river flow and nutrient delivery characteristics of the catchment are described in detail in Wilson Inlet report to the community number three.

Ocean water levels

(including astronomic tides and barometric tides)

When the bar is open the ocean water levels (along with the bar channel dimensions) are the major determinant of the volume of marine exchange between the ocean and the Inlet. The subsequent marine exchange plays a role in determining the Inlet salinity, water colour, salinity stratification, and the export of nutrients to the ocean. The most important seasonal difference in the ocean water levels is that there are larger, more frequent, shifts from high to low water levels, due to the passage of low pressure systems, (and hence the potential for more pumping of water into and out of the Inlet) during the winter and spring periods than the summer. The ocean water levels and the marine exchange are plotted in Figures 12 and 15. For comparison the Inlet water level is also plotted in Figure 16.

Winds

(speed, direction, and duration)

Winds govern the vertical mixing in the Inlet (and hence play a role in determining stratification) and also affect the rate of evaporation and hence water level. Salinity stratification in turn effects bottom water oxygen status and nutrient recycling which has an impact on the availability of nutrients for plants and algae. The major seasonal

variation in the winds is the shift in the predominant wind direction. As shown in Figure 13, usually in about April the predominant wind direction shifts from south easterly to north westerly and then in October shifts back again. These shifts in direction are periods when the average wind speeds, and hence mixing activity in the Inlet, are at a minimum for the year as shown in Figure 14.

Ocean wave conditions

Ocean wave conditions largely affect the sand transport on Ocean Beach, this in turn affects the infill of the delta and the date of bar closure, which also have implications for the dimensions of future bar channels and marine exchange. The ocean wave climate is more intense over the winter months.

Solar radiation

(day length, angle of the sun, and cloudiness)

Solar radiation plays a major role in determining the water temperature which in turn effects growth rates of plants, algae and bacteria and hence the rates of nutrient uptake and recycling. Solar radiation also provides the energy for plants and algae to grow in the first place and therefore is of critical importance to nutrient cycles. Solar radiation has a strong seasonal response with a summer peak and a winter minimum. The number of daylight hours are presented in Figure 10 which gives some idea of the seasonality of solar radiation.

Air temperature, pressure, and humidity

These atmospheric parameters largely affect evaporation, water temperature, and in the case of the air pressure the ocean water level. No data for these are plotted here, in summary though air temperature is at a maximum in summer and minimum in winter whilst the reverse is the case for humidity. The air pressure has already been mentioned in the context of ocean water levels.

Water temperature

The water temperature in the Inlet, plotted in Figure 18, reaches a maximum of about 24°C in January and a minimum of about 12°C in July. The shallows may get slightly warmer and cooler than this in summer and winter respectively. The surface to bottom temperature difference is usually no more than a couple of degrees, and often the difference is negligible.

Water colour and clarity

The water colour, Figure 17, which reflects the varying contributions of marine and catchment water, only deviates significantly above its baseline during the period of river flow from the catchment when the Inlet is flooded with brown tannin stained waters. The clarity drops at this time in response to the particulate material carried into the Inlet by flows and by subsequent blooms of phytoplankton algae clouding the water.

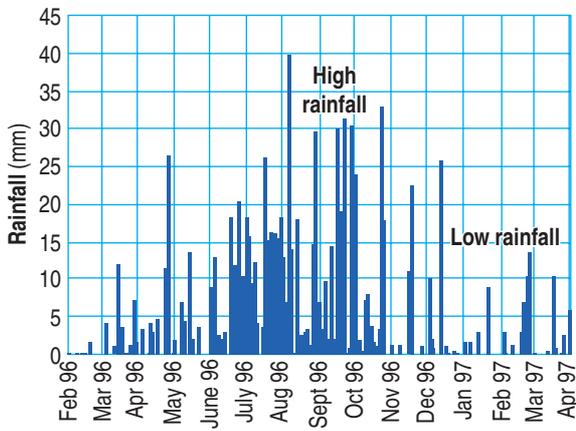


Figure 9: Daily rainfall at Denmark (mm)

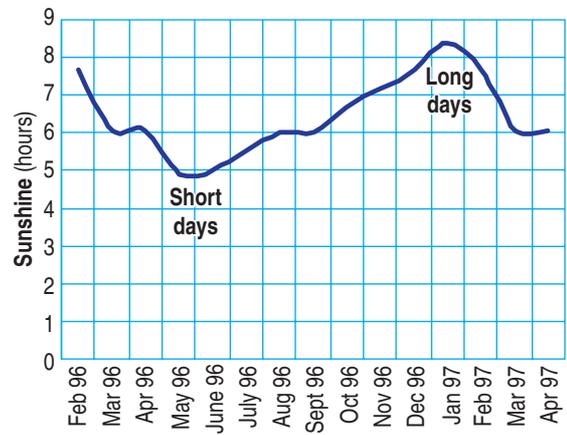


Figure 10: Daily sunshine (hours)

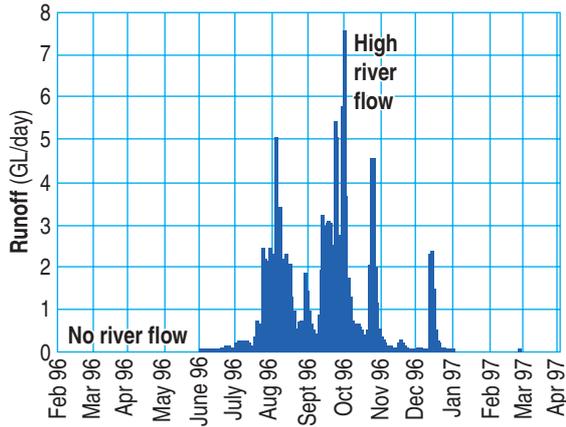


Figure 11: Daily runoff (GL/day) to the Inlet

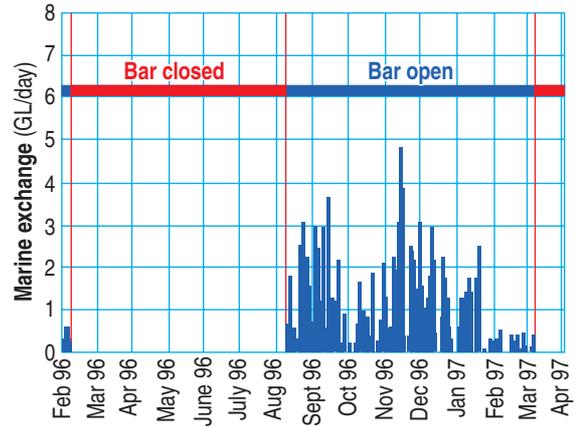


Figure 12: Marine exchange (GL/day) to the Inlet



Figure 13: Average daily wind direction in degrees

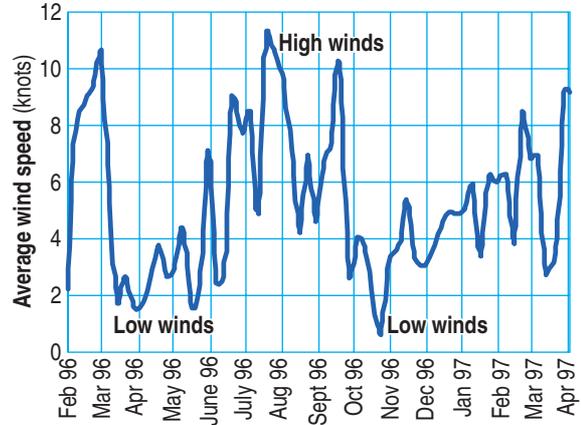


Figure 14: Average daily wind speed in knots

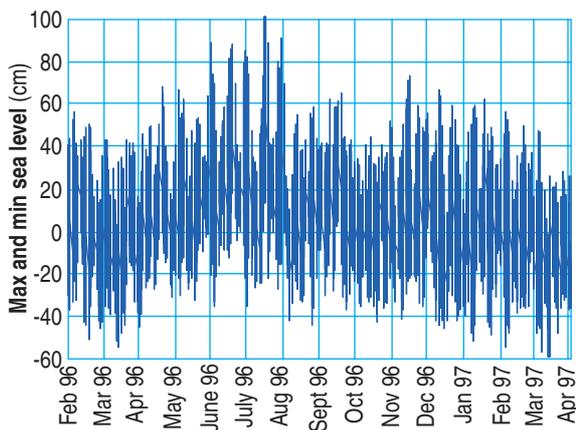


Figure 15: Daily max and min sea level (cm)

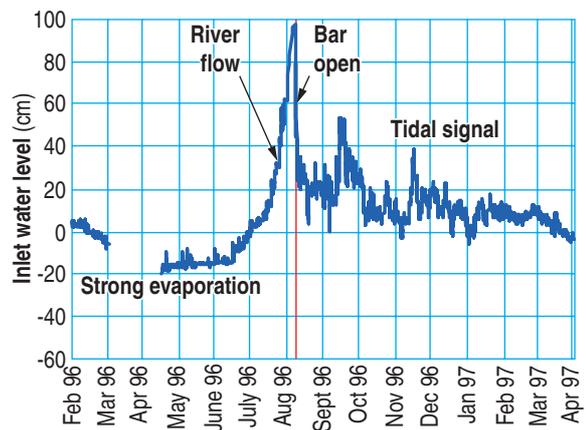


Figure 16: Inlet water level (cm above mean sea level)

Salinity

At the start of the year the Inlet is fully mixed with a salinity about two thirds that of seawater (Figure 19). Over late summer and autumn the Inlet remains mixed but the salinity increases, due to evaporation, reaching a peak in May. Over the same period the Inlet water level may drop between 10 cm and 80 cm due to evaporation. From early June until bar opening the water level rises and the salinity falls as freshwater flows into the Inlet from the catchment. In a typical year, by the time of bar opening the salinity has fallen to less than half that of seawater. Shortly after bar opening marine water intrudes into the Inlet causing a sharp rise in bottom water salinities, however surface water salinities continue to fall until about October.

This phenomenon whereby the bottom waters may be significantly saltier than surface waters is called salinity stratification (see boxed aside). Periods of salinity stratification may last from days to weeks depending on wind mixing. When mixing does occur stratification is usually re-established shortly afterwards. Episodes of salinity stratification persist until about December, during which time the marine intrusions are mixed into the surface and the overall salinity of the Inlet again reaches about two thirds that of seawater.

Dissolved oxygen

At the start of the year the dissolved oxygen concentration in surface waters is saturated at about 8 mg/L (Figure 20). From late summer until mid winter the concentration increases because colder, fresher water holds more oxygen than warmer, saltier water. By mid-winter the surface waters may hold something like 10 mg/L of oxygen. The spring period typically sees dissolved oxygen concentrations in surface waters rise above 10 mg/L due to the activity of phytoplankton. By the end of the year surface dissolved oxygen concentrations have fallen back to about 8 mg/L.

Bottom waters in the Inlet display very different seasonal behaviour. Bottom water concentrations may be lower than surface waters because there is more organic material and bacterial activity at the bottom of the Inlet and it is more difficult to mix oxygen into deeper bottom waters than it is into shallow surface waters. Bottom water concentrations in January are usually about 8 mg/L, increasing through winter to about 10 mg/L as the water cools. Following bar opening, and the establishment of stratification, deoxygenation of bottom waters may occur with dissolved oxygen concentrations falling below 2 mg/L (see pages 8 and 9). Episodes of deoxygenation in bottom waters, lasting days to weeks, persist through spring and summer while stratification is present. Concentrations in bottom waters rise to about 8 mg/L once mixing is again effective.

Nutrients

Nutrient concentrations in the Inlet are generally low through most of the year. Orthophosphate, ammonium and nitrate concentrations are often very close to or below their

respective analytical detection limits of 0.003 mg/L, 0.005 mg/L and 0.005 mg/L (Figures 21 to 23). These low concentrations are attributed to the rapid biological uptake of the nutrients in the Inlet by plants and algae. In fact the only occasions when dissolved nutrients are detectable in the water is at times when their rate of delivery to the Inlet outstrips their rate of biological uptake. The two annual events that lead to measurable nutrients in the water column are the winter runoff from the catchment and the recycling of nutrients from the sediment under low dissolved oxygen conditions.

While river flow is an obvious source of nutrients, the nutrients that are actually biologically available to plants and algae only make up a part of the total catchment nutrient load. About half of the phosphorus and more than 80% of the nitrogen from the catchment are bound up in nutrient forms that plants and algae are unable to directly utilise, these accumulate in the water over winter and most are lost to sea with marine exchange. The majority of catchment derived nutrients that are biologically available to plants and algae are trapped by the *Ruppia*, its epiphytes and macroalgae and are only briefly detected in the water.

Nitrate is usually only detectable in the Inlet after significant river flow, around about July. Nitrate is primarily detected in surface waters. After the flow subsides, around about October, nitrate is no longer detected in the Inlet; it has either been taken up by biota or denitrified². Both ammonium and orthophosphate are usually only detectable in the Inlet during periods of bottom water stratification as they are mainly regenerated from the sediments (see pages 8 and 9). They are usually detected in bottom waters between October and January before they are taken up by plants and algae. Ammonium and orthophosphate concentrations may also increase following the breakdown of algal bloom material.

Phytoplankton algae

The annual cycle of phytoplankton events in Wilson Inlet is usually dominated by the spring bloom (see Figure 24). It has been demonstrated that all of the major spring phytoplankton blooms have been related to a chain of events beginning with bar opening and marine exchange leading to stratification and nutrient release. As discussed in the boxed aside, stratification precipitates the deoxygenation of bottom waters and the subsequent increase in the recycling of nutrients into the water column from the sediment. With warming water temperatures and increasing day lengths these pulses of sediment derived nutrients lead to blooms of diatoms and dinoflagellates. Late summer bloom events have occurred in some years also, these also appear to be a result of nutrient recycling, in this case related to the senescence³ of *Ruppia*, its epiphytes and macroalgae. On occasion summer blooms have been related to wind mixing stirring up bottom sediments.

² The process of converting biologically available nitrogen in the water into biologically unavailable nitrogen gas.

³ The annual 'die back' at the end of the peak growth season.

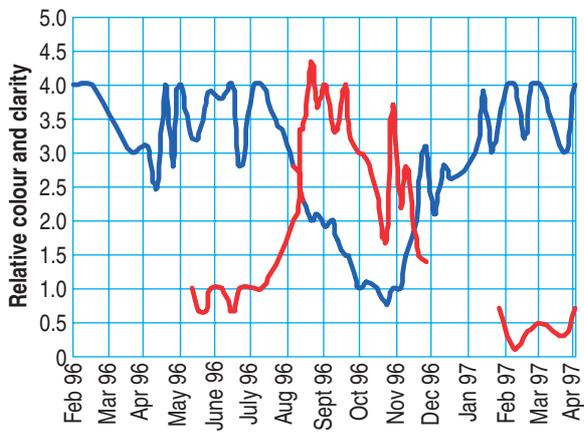


Figure 17: Relative water colour (red line) and clarity (blue line)

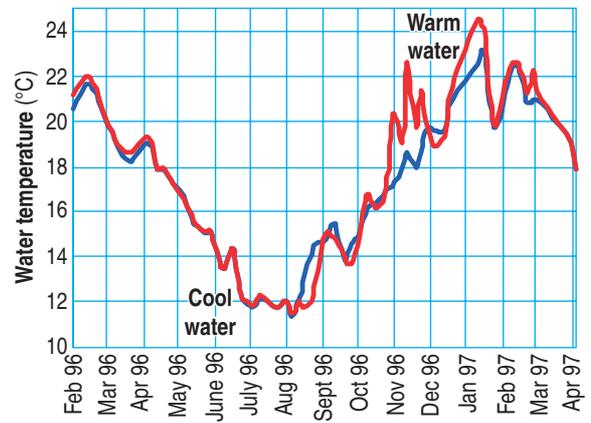


Figure 18: Temperature (°C), red line is surface and blue bottom water

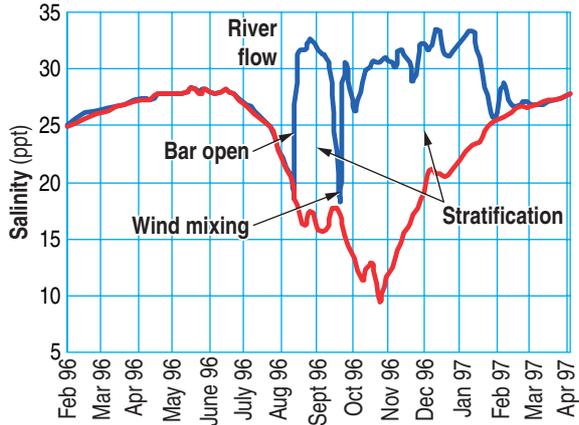


Figure 19: Salinity (ppt), red line is surface and blue bottom water

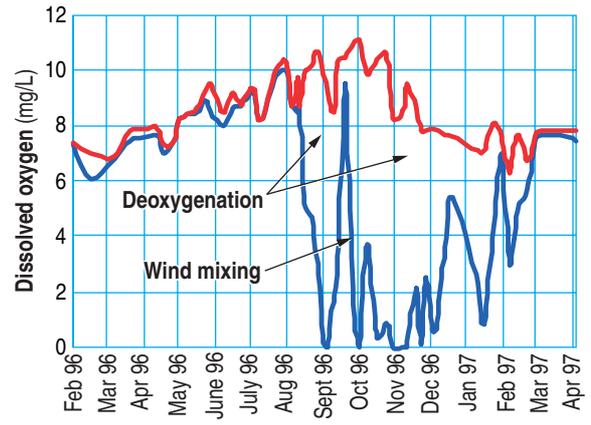


Figure 20: Dissolved oxygen (mg/L), red is surface and blue bottom

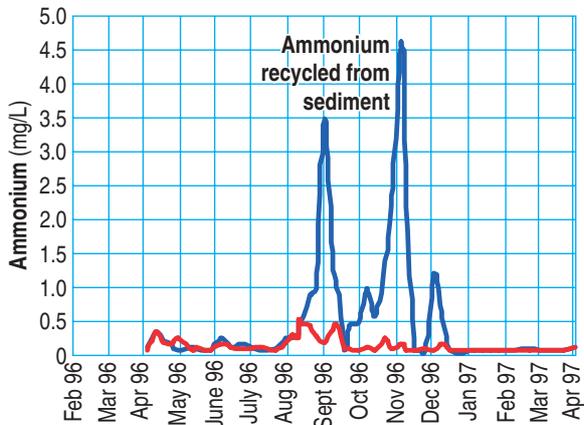


Figure 21: Ammonium (mg/L), red is surface and blue bottom water

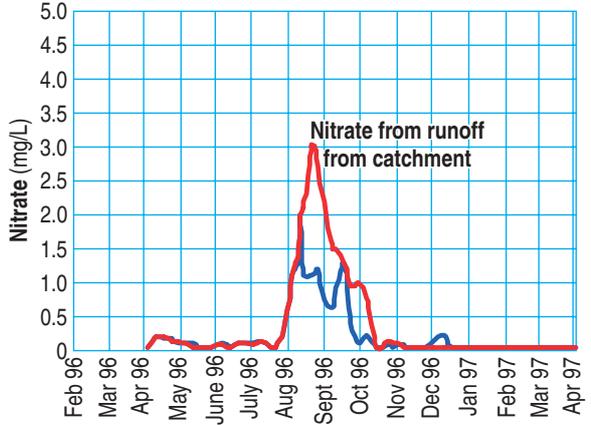


Figure 22: Nitrate (mg/L), red line is surface and blue bottom water

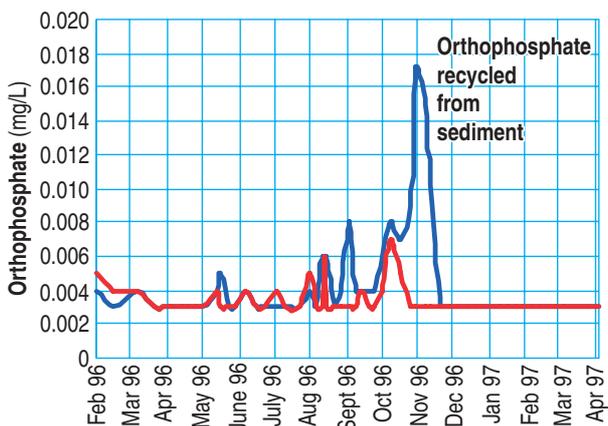


Figure 23: Orthophosphate (mg/L), red is surface and blue bottom

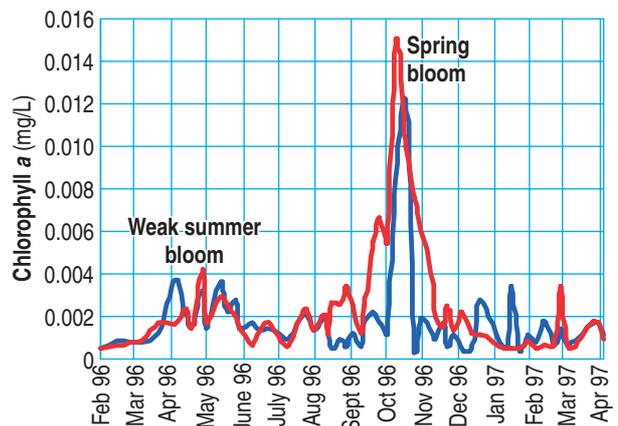


Figure 24: Chlorophyll a (mg/L), red is surface and blue bottom

Stratification and nutrient cycles

The cycling of phosphorus and nitrogen in Wilson Inlet is intimately linked to the availability of dissolved oxygen at the sediment water interface; when dissolved oxygen is low the concentrations of nutrients in forms available to plants and algae greatly increases. Salinity stratification is a process that potentially reduces the availability of dissolved oxygen at the sediment water interface and therefore may change the nutrient cycling in the Inlet.

Salinity stratification refers to the situation where there are layers of water of different salinity sitting on top of one another. Salinity stratification occurs because the density of water in the Inlet depends on its salinity. When a layer of fresher water overlies a layer of saltier water a situation that resists mixing exists. The stratification resists mixing because the saltier water is heavier than the fresh and therefore it takes a lot more energy to mix the two layers together than it would if they were the same density. Winds over the Inlet provide the major source of energy for mixing, and when salinity stratification occurs it can take days or even weeks to mix the water column if winds are light.

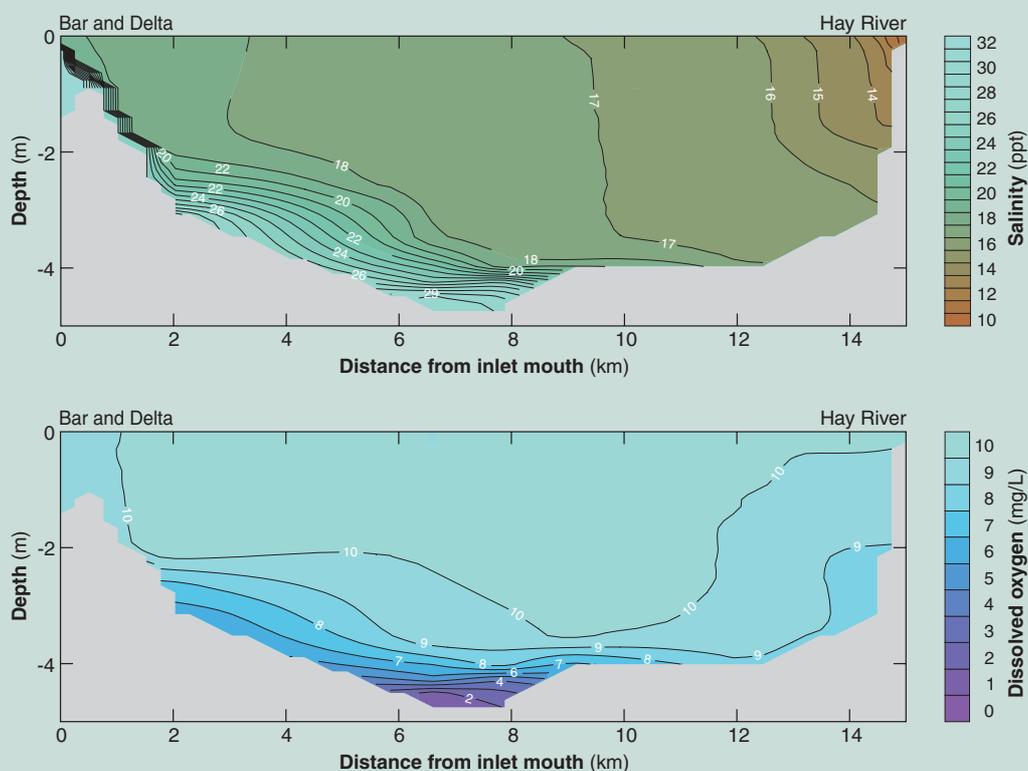
Dissolved oxygen in the Inlet can come from two sources. It dissolves into the Inlet from the atmosphere, and plants and algae may photosynthesize and produce oxygen themselves; but only during the day when there is sunlight present. As a result there is usually plenty of oxygen in the water at the surface of the Inlet and around the shore of the Inlet (except where there are accumulations of rotting biomass around the shoreline). However the oxygen can easily be used up at the bottom of the Inlet, especially in the deeper areas.

The major cause of deoxygenation in Wilson Inlet is reduced mixing during periods of salinity stratification

and light winds. The most prolonged periods of light winds during the year usually occur in October and April (see Figure 14) while the period most prone to stratification is the first few months following bar opening; roughly August to November. Dissolved oxygen loggers placed on the floor of the Inlet demonstrate that deoxygenation occurs within one to four days of stratification being achieved (Figure 27). This data also demonstrates that decreases and increases in dissolved oxygen concentrations at the sediment water interface may occur on timescales shorter than our weekly to monthly water profile sampling. However it shows that the weekly sampling runs have roughly approximated the major features of the pattern of deoxygenation, and that deoxygenation events occur when our weekly data shows salinity stratification to be occurring.

When deoxygenation occurs, the animals and bacteria that require oxygen are unable to survive in the deoxygenated waters. Many of these animals and bacteria regulate the nutrient cycling at the sediment water interface. Without them, and with a low dissolved oxygen concentration, nutrient cycling at the sediment water interface changes. Nutrients that were previously trapped by chemical processes in the sediments or were recycled in forms that plants and algae were unable to use are released into the water column in forms that plants and algae can use.

The key processes controlling nitrogen and phosphorus availability at the sediment water interface are denitrification and the trapping of orthophosphate by iron-oxhydroxide compounds respectively. Denitrification is a two stage process that results in the conversion of ammonium (readily available to plants and algae) into nitrogen gas (not readily available to plants and algae). The first stage of this process requires oxygen,



Figures 25 (top) and 26 (bottom). These transects of salinity (Figure 25) and dissolved oxygen (Figure 26) through the Inlet in September 1996 illustrate the effects of stratification. Marine water is entering the Inlet at the left of each figure and freshwater from the right. A lens of saltier, marine derived, severely deoxygenated water lies in the deeper parts of the Inlet. Although in this case the depth of deoxygenated water is no more than 0.5 m it is commonly as much as 1 m.

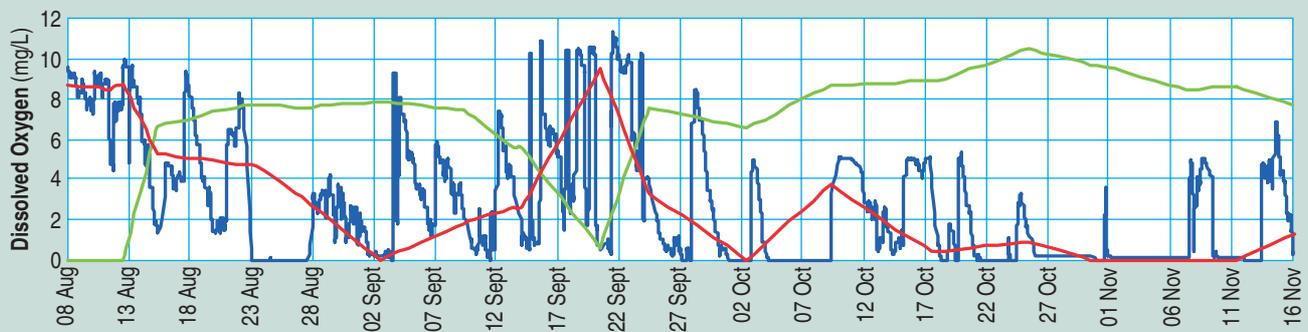


Figure 27. Bottom water deoxygenation for spring 1996 at site W16. The plot compares a time series trace of dissolved oxygen (mg/L) recorded at 15 minute intervals (blue line) from a logger placed on the floor of the Inlet, against the bottom water dissolved oxygen as measured by weekly profiles (red line) and the relative strength of stratification as measured by weekly profiles (green line).

therefore without oxygen ammonium is not denitrified and instead becomes available to plants and algae. In terms of phosphorus, iron-oxyhydroxide compounds become unstable in the absence of oxygen and therefore release their trapped orthophosphate back into the water, which is then available to plants and algae.

Sediment bio-geochemistry work undertaken by the Australian Geological Survey Organisation (AGSO), to be published in Wilson Inlet report to the community number eight, demonstrated the importance of these dissolved oxygen regulated nutrient cycling processes at the sediment water interface. Under the present incidence of bottom water deoxygenation, it was estimated that about 500 tonnes of nitrogen and 20 tonnes of phosphorus were delivered to the Inlet from the sediments lining the estuary (all of it available to plants and algae). Furthermore, it was also found that a further 500 tonnes of nitrogen per year and an unknown amount of

phosphorus could also be delivered to the Inlet from the sediments lining the estuary in the event of further deoxygenation of bottom waters in the Inlet.

As the nutrient cycle diagram in the previous boxed aside illustrated, nutrients are delivered to the Inlet from two main sources; the catchment and the sediments lining the floor of the estuary. The two main sinks for nutrients on the other hand are the ocean and the sediment processes (with subsequent loss to the atmosphere or burial). The estimated loads from these sources and exports to these sinks are tabulated below in Figure 28. This data demonstrates the relative importance of sediment processes compared to catchment inputs and losses to the ocean. Given the importance of sediment processes in nutrient cycles, and the reliance of these processes on the availability of oxygen, clearly the maintenance of dissolved oxygen concentrations at the sediment water interface must be a prime management concern.

Species	Inputs from the catchment	Inputs from the sediments	Losses to the ocean via export through the bar	Losses due to sediment processes
DON	160 tonnes	n/a	140 tonnes	at least 50 tonnes
DIN	30 tonnes	500 tonnes	20 tonnes	500 tonnes (as N ₂)
PP	6 tonnes	n/a	3 tonnes	at least 5 tonnes
DIP	4 tonnes	20 tonnes	1 tonne	?

Figure 28. Loads of nutrients, internal recycling, denitrification and exports for Wilson Inlet (average of 1995-1997 and AGSO data). This work will be expanded on in greater detail in Wilson Inlet report to the community number eight. The biologically available fraction is highlighted.



Figure 29 (left) and 30 (right): Two of the consequences of eutrophication in Wilson Inlet. Figure 29 shows short stands of Ruppia on the floor of Wilson Inlet, smothered with the macroalgae Spyridia and Polysiphonia (photo B. Dudley) while Figure 30 shows macroalgae (Cladophora in this case) growing on Ruppia in the shallows of the Inlet (photo W. Hosja).

Water quality for 1995 to 2002

The water quality that occurs in any year is a usually a rough approximation of the annual cycle described above. However interannual variations in the drivers of the system and the subsequent variations in the conditions at the start of a year (due to the summed effects of past interannual variations) result in some variability in the water quality between years.

Bar opening

In each of the years between 1995 and 2001 the sand bar was artificially breached at its western end once water levels within the Inlet reached approximately 1 m above mean sea level. The average period of bar opening in the past 50 years has been about 190 days. Therefore the duration of opening in 1995 and 1996 were average, 1998 and 1999 were above average, and 1997, 2000 and 2001 were below average. The duration of opening ranged from about 50 to 289 days. The sixth Wilson Inlet report to the community describes the sand bar in more detail. However the inter annual differences are largely attributed to variations in ocean water levels, ocean wave conditions, and rainfall and runoff.

Rainfall and runoff

Considerable variation in the runoff from year to year was a major factor driving interannual variations in the system. The highest volumes of river flow in the monitoring period occurred in 1996 and 1998, with the lowest volume, at less than half the highest, occurring in 2000. Notably, none of the years in the monitoring period had river flow to the Inlet above the long term average, which is estimated to be approximately 200 GL. Similarly the rainfall in each of the past six years at Denmark was below the long term average of 1120 mm.

Marine exchange

Despite similar opening regimes (western opening when the Inlet level reached approximately 1m above mean sea level) there were marked differences from year to year in the volume of marine exchange. The major drivers of this variation were differences in the rainfall and runoff between years, differences in ocean wave conditions, differences in bar channel dimensions and perhaps most

importantly differences in the ocean water levels, especially the timing of the passage of low pressure systems. (For example during the 1997/1998 season within the first four months after bar opening there had been only 50GL of marine exchange, whilst in 1998/1999 after four months there had been 140GL of exchange. The difference being due largely to variations in the ocean water levels driven by the passage of low pressure systems.)

Water colour and clarity

While it was not possible to determine any significant difference in water clarity between years, there was a clear difference in water colour between years. The difference in water colour was primarily a result of the different volumes of river flow (rather than marine exchange). In high runoff years the Inlet water was twice as dark as in low runoff years.

Salinity and stratification

Whilst the annual salinity cycles in the Inlet largely conformed to the typical pattern described above there were some notable exceptions (Figure 32). In particular salinities following the 1998 bar opening were much higher than previous years. Conversely the maximum salinities following the 2000 opening were low and, unusually, some salinity stratification persisted through the autumn of 2000.

As expected the rate of salinity decrease in any winter/spring was clearly correlated with the volume of inflow and rainfall in that period. Whilst the rate of salinity increase in any spring/summer was strongly influenced by the volume of marine exchange. There was a reasonable relationship between the final salinity in any year and the volumes of rainfall, inflow, and marine exchange, although it was complicated by the apparent variations in mixing between years. On the whole there was a reasonable correlation between the intensity of stratification and the marine exchange; the more marine exchange, the more strong stratification.

Overall the interannual variation in salinity (and stratification) in the Inlet was primarily due to variations in rainfall and runoff, the sea level (particularly barometric conditions), wind energised mixing, ocean wave conditions (effecting the bar closure and subsequent bar channel dimensions) and possibly the timing of bar opening.

Year	Breached	Shoaled	Duration open	Rainfall	River flow	Exchange
1995	19 August 95	26 February 96	191 days	950 mm	105 GL	105 GL
1996	5 August 96	23 February 97	202 days	970 mm	185 GL	165 GL
1997	18 August 97	19 January 98	154 days	830 mm	115 GL	60 GL
1998	7 August 98	23 May 99	289 days	1050 mm	185 GL	250 GL
1999	30 June 99	6 March 00	250 days	1000 mm	135 GL	110 GL to 25 October
2000	21 July 00	30 November 00	132 days	1030 mm	90 GL	Not available
2001	03 October 01	15 February 02	135 days	930 mm	Not available	Not available

Figure 31: Dates of bar opening and closing, duration of opening, the rainfall for the Denmark town site, the gauged flows from the catchment to the Inlet, and the volume of marine exchange (estimated using hydraulic modelling) for the 1995–2001 period (where available).

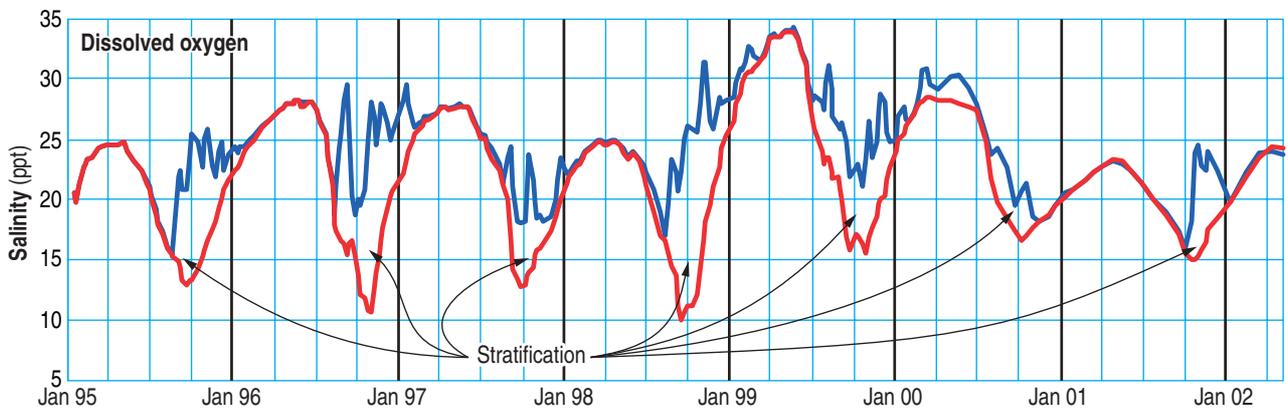


Figure 32: Surface and bottom salinities in ppt in Wilson Inlet. The red line is the average of surface data and blue line is the average of bottom data for sites: WI6, WI35, WI12, WI14 and WI9. Where the lines diverge stratification is occurring.

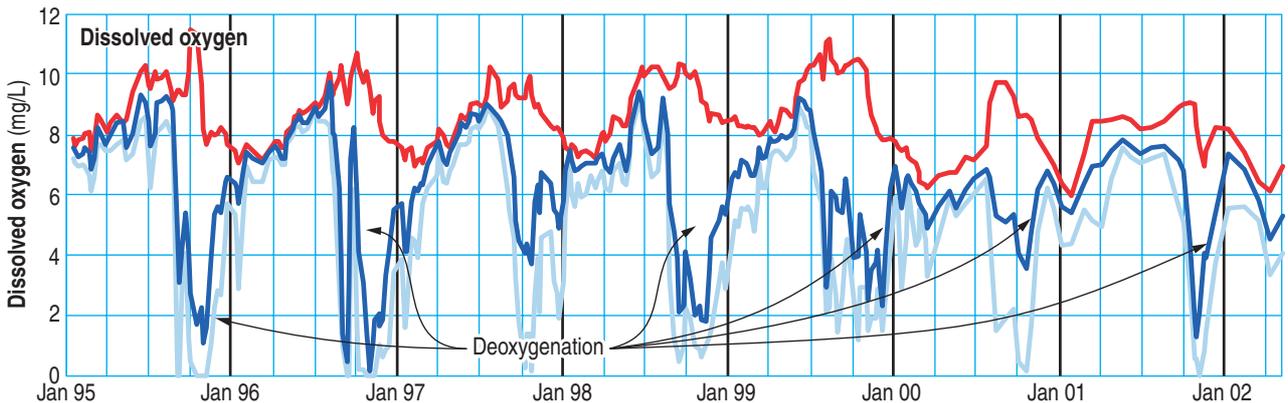


Figure 33: Dissolved oxygen in Wilson Inlet in mg/L. The red line is the surface average, the dark blue line the bottom average and the light blue line the bottom minimum from sites: WI6, WI35, WI12, WI14 and WI9. From 2000 onwards the frequency of sampling was reduced and therefore fewer low dissolved oxygen events may have been recorded. Where the surface and bottom concentrations diverge, in most cases deoxygenation is occurring.

Dissolved oxygen

The annual dissolved oxygen cycles in the Inlet largely conformed to the typical pattern described above (Figure 33). Periods of super-saturation (eg October 1995 or August 1999) due to high phytoplankton productivity were often recorded post bar opening. Deoxygenation of bottom waters clearly tracked the stratification (there was a reasonable correlation between deoxygenation and stratification in the water profile data; a correlation coefficient of 0.7 when filtered for stratification due to marine intrusions). While complete anoxia was rarely recorded in water profiles, it was commonly recorded in bottom logger data (as in Figure 27) indicating perhaps a shortcoming of weekly to monthly profiling.

The number of bottom water samples that were severely deoxygenated (below 10%) ranged from about 10% of bottom water samples in 1996 to 1% in 1999. Like the stratification, there was no single clear relationship between the frequency of deoxygenation in any year and the volume of river flow, marine exchange or wind strengths; all three factors play an interacting role in the occurrence of deoxygenation. The apparent lack of very low dissolved oxygen events from 2000 onwards is probably an artefact of the sampling frequency being reduced from weekly to monthly, and possibly also reflects weaker stratification due to poor bar openings and poor river flow. An apparent downward trend in dissolved

oxygen concentrations over this period may be an artefact of a change of monitoring instrument on 25 February 2000 or may be a real, but as yet unexplained feature of the water quality data.

Nutrients

The annual nutrient cycles in the Inlet largely conformed to the typical patterns described above (Figures 34 to 38).

The peaks in ammonium concentrations (Figure 34) strongly tracked the occurrence of stratification and deoxygenation (as discussed in the boxed aside this is due to the lack of dissolved oxygen preventing denitrification). Elevated ammonium concentrations began to be detected once dissolved oxygen fell below about 4 mg/L; in other words measurements of anoxia in the profile data were not a good gauge of the extent of sediment nutrient cycling. There was a 7-fold variation in maximum and a 5-fold variation in average ammonium concentrations between years. Higher ammonium concentrations were generally measured in years where more deoxygenation was also measured.

The measured nitrate concentrations (Figure 35) reflected the strength of river flow. Nitrate concentrations were generally lower than ammonium. There was a 30-fold variation in maximum and a 3-fold variation in average nitrate concentrations between years.

The peaks of orthophosphate (Figure 36) tracked stratification and deoxygenation (as discussed in the boxed aside, this is due to changes in the binding of phosphorus to sediment in the absence of oxygen) and the recycling of algal bloom material. The relatively high concentrations (compared to the normal background) through 1999 and the first half of 2000 appears uncharacteristic. The phenomenon has not been adequately explained as yet but may be related to the high salinities following the bar opening of 1998/1999. There was a 5-fold variation in maximum and a 2-fold variation in average orthophosphate concentrations between years.

In Figures 37 and 38 the total nutrient concentrations are compared to the ANZECC guidelines for water quality in south west Australian estuaries. The total nitrogen and phosphorus concentrations have largely (85% and 70% of sample period respectively) been below the guideline trigger values of concern for eutrophication impacts in slightly disturbed estuaries.

Phytoplankton algae

Spring blooms are evident in the first four years of the data set and in 2001, as are weaker late summer blooms in most

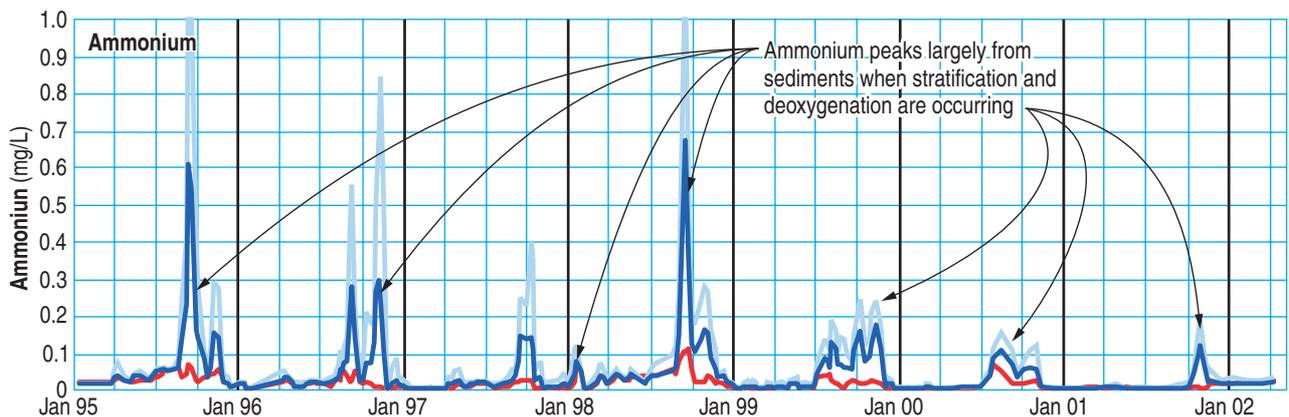


Figure 34: Ammonium concentrations in Wilson Inlet in mg/L. The dark blue line is the average and the light blue line the maximum for bottom waters and the red line the average for surface waters of sites: WI6, WI35, WI12, WI14 and WI9.

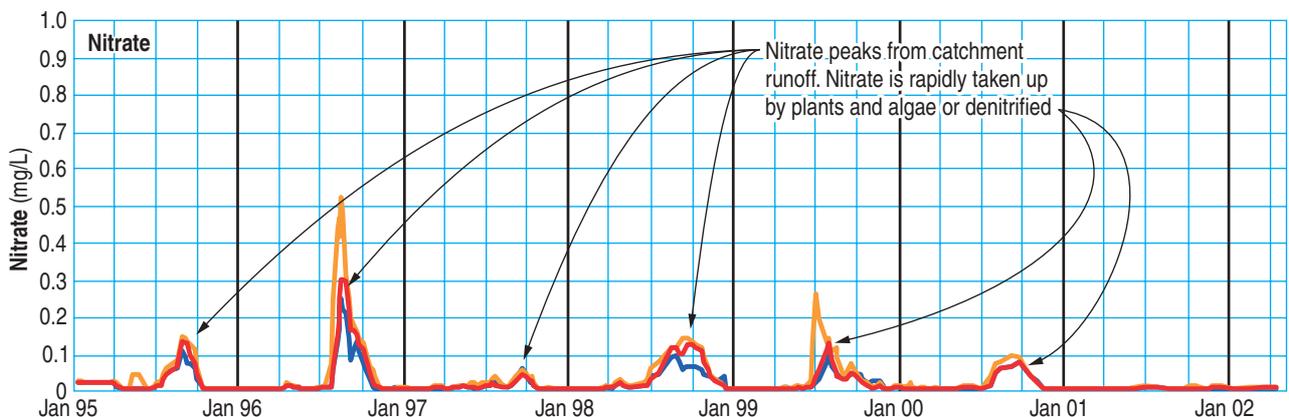


Figure 35: Nitrate concentrations in Wilson Inlet in mg/L. The red line is the average and the light orange line the maximum for surface waters and the blue line the average for bottom waters of sites: WI6, WI35, WI12, WI14 and WI9.

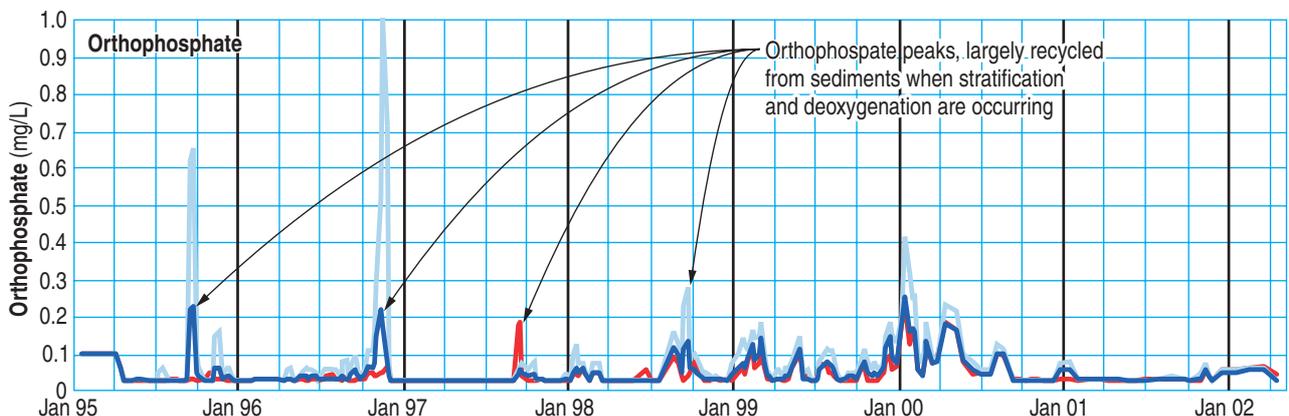


Figure 36: Orthophosphate concentrations in Wilson Inlet in mg/L. The dark blue line is the average and the light blue line the maximum for bottom waters and the red line the average for surface waters of sites: WI6, WI35, WI12, WI14 and WI9.

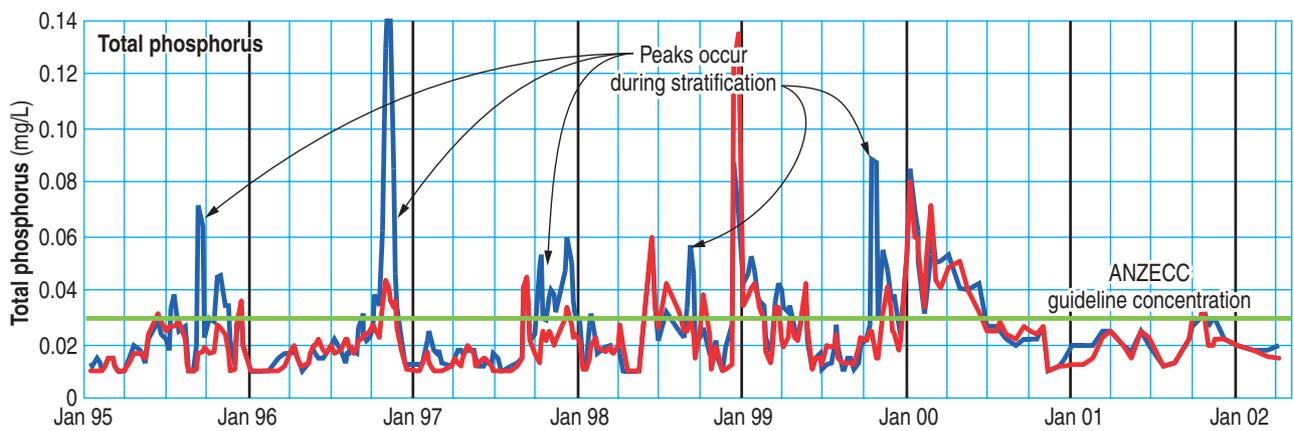


Figure 37: Surface and bottom water total phosphorus concentrations in Wilson Inlet in mg/L. The blue line is the average of bottom and the red line the average of surface concentrations for sites: WI6, WI35, WI12, WI14 and WI9. The green line is the ANZECC guideline for total phosphorus.

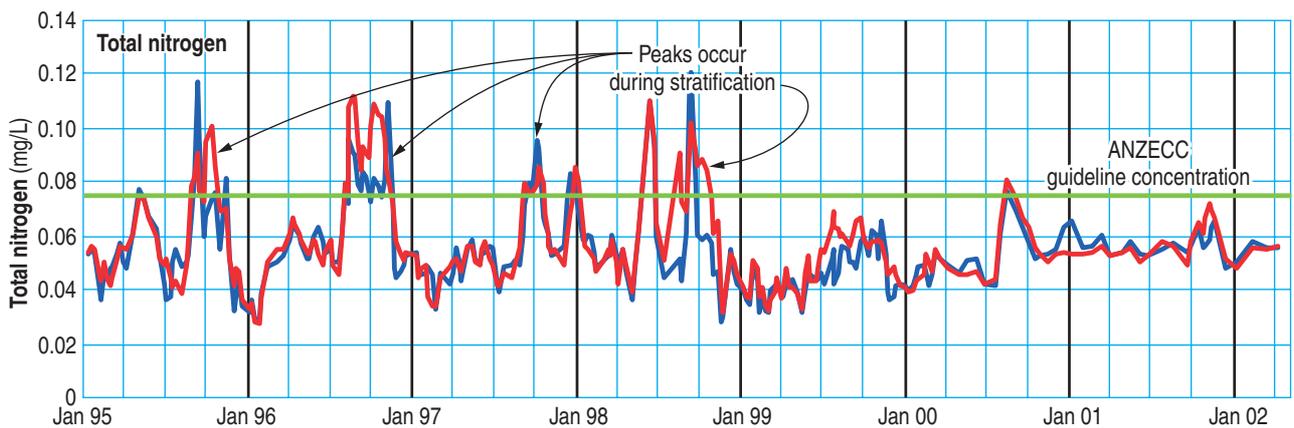


Figure 38: Surface and bottom water total nitrogen concentrations in Wilson Inlet in mg/L. The blue line is the average of bottom and the red line the average of surface concentrations for sites: WI6, WI35, WI12, WI14 and WI9. The green line is the ANZECC guideline for total nitrogen.

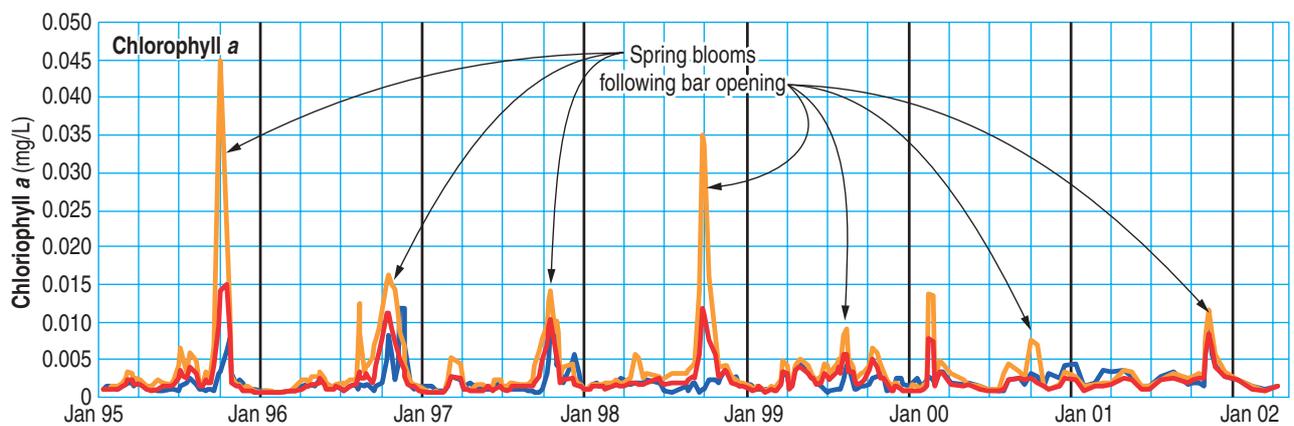


Figure 39: Surface water chlorophyll a concentrations in Wilson Inlet in mg/L. The red line is the average and the light orange line the maximum for surface waters and the blue line the average for bottom waters of sites: WI6, WI35, WI12, WI14 and WI9.

years. Spring blooms were also present, but much less intense in 1999 and 2000. All of the spring phytoplankton blooms were caused by the same regular chain of events, described above, that follows bar opening; stratification, deoxygenation, nutrient recycling increase and subsequent bloom. There was a 3-fold variation in maximum chlorophyll *a* concentrations between years and a 20-fold variation in maximum phytoplankton cell numbers between years. The phytoplankton algal flora was dominated by small diatoms of the genus *Chaetoceros* with important contributions, especially during blooms, from the dinoflagellate *Prorocentrum minimum*. Over the seven

years of data there is a decreasing proportion of flagellates to diatoms. The intensity of algal blooms between years was clearly affected by many changing interannual factors such as winds, the availability of nutrients, timing of bar opening etc. A detailed analysis has not been completed for all factors, however, summer bloom events appeared to be at a maximum in a period when above average orthophosphate concentrations were measured. Spring bloom intensity on the other hand correlated well with the availability of ammonium following deoxygenation and stratification.

Comparison to historical data

Given the scale of interannual variability within the water quality parameters measured in the Inlet over the 1995-2002 period it is difficult to determine any consistent trend, either up or down, over this period. In order to try and detect trends over a longer time frame than the seven years of 1995-2002 data, the current data set was compared to data collected in previous sampling programs. Because of the differences in methods, frequency of sampling, sampling sites and the availability of summary statistics only for some of the programs, the comparison between them and the 1995-2002 program is coarse.

The main observation is that there is no consistent pattern of increases or decreases over time represented by these data. Where there are small (albeit inconsistent) differences it is difficult to reconcile whether they are real or artefacts of the different frequencies, sites, biases in sampling period and number of samples in the project.

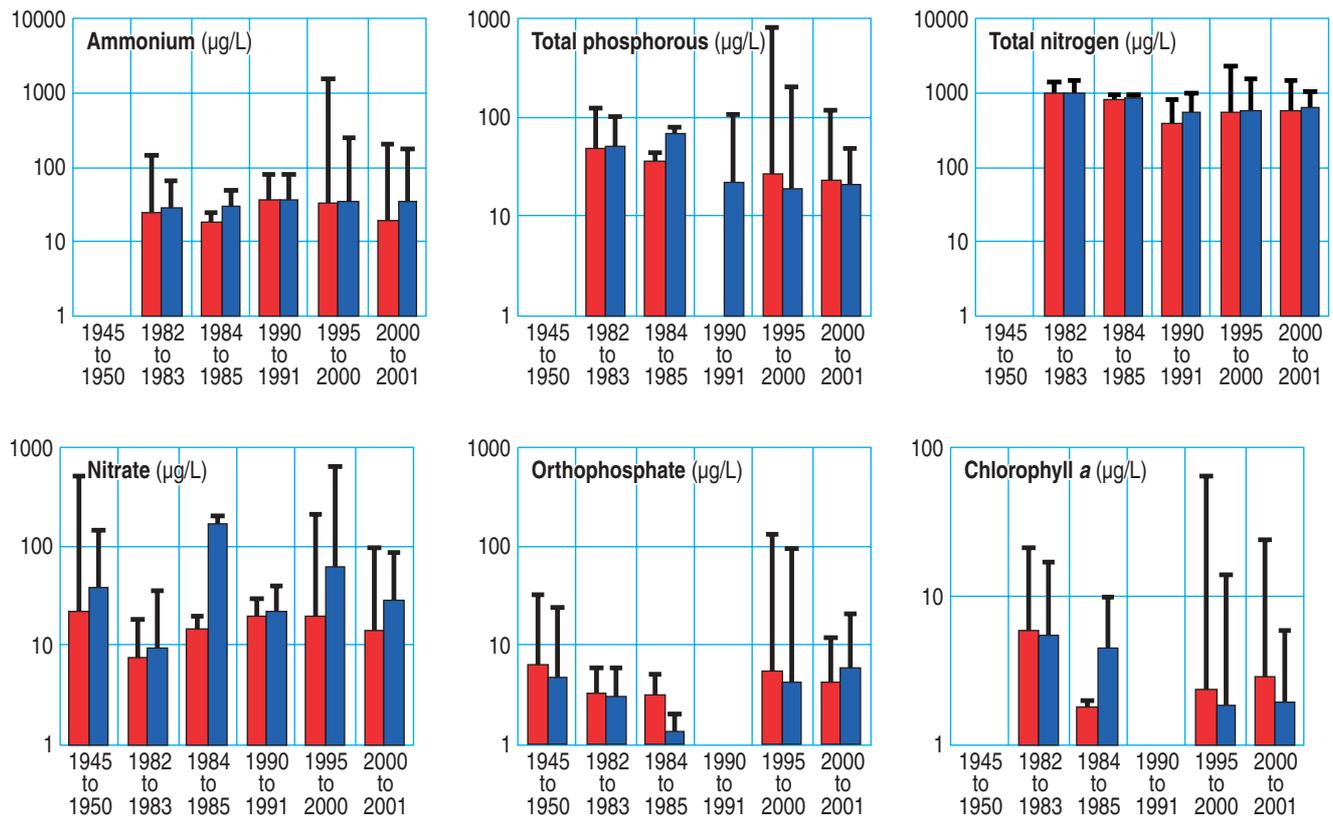
Comparison to other inlets

A comparison of the Wilson Inlet water quality data with other south western Australian estuaries has been made so as to gauge its relative condition compared to those other

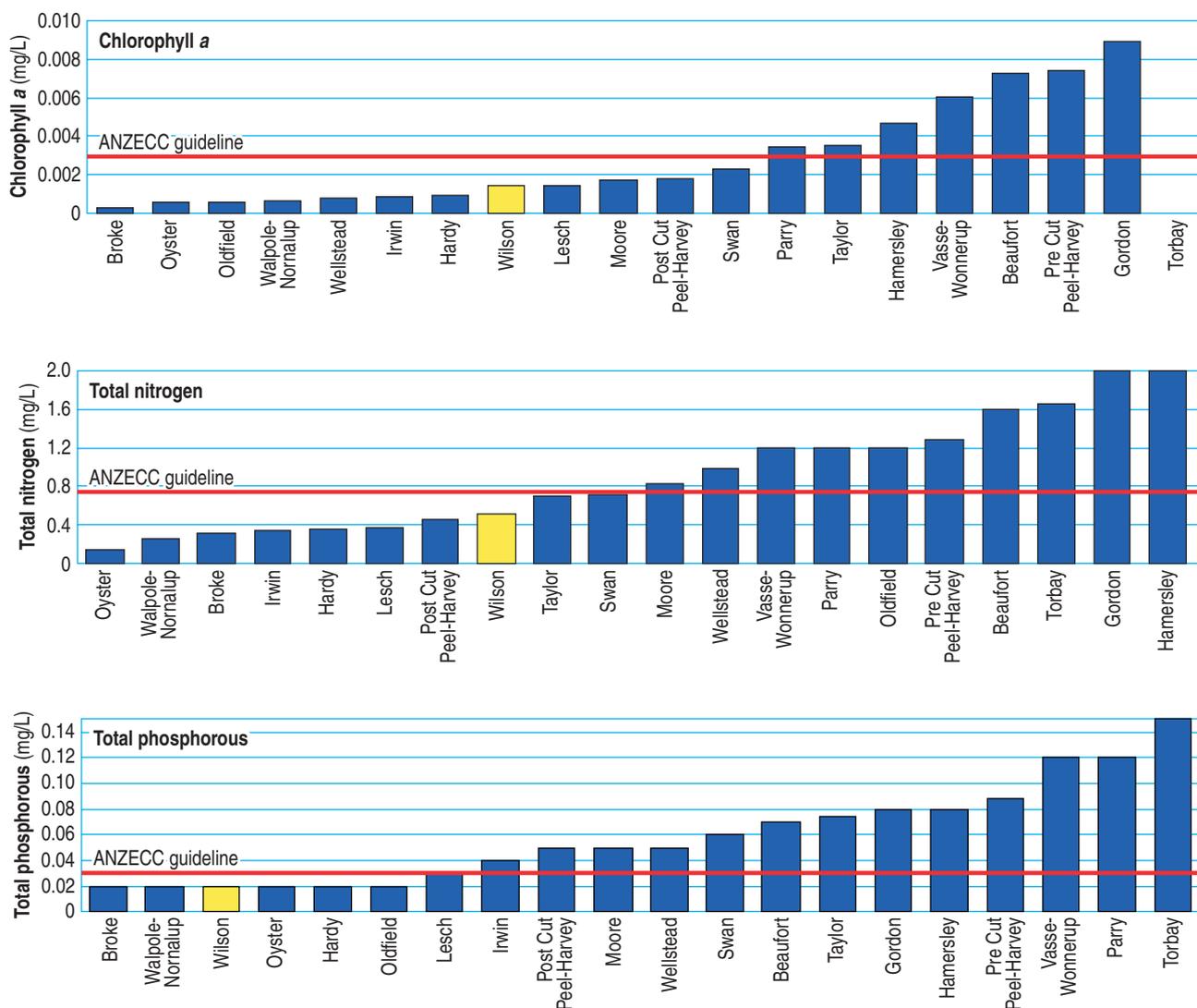
estuaries. The data presented below are medians of all of the data points for each estuary in the 1995-2001 period, except for the pre Dawesville Channel Peel-Harvey data which is for the period 1980 to 1993.

As with the above analysis, the limited number of samples for some estuaries makes the analysis fairly coarse, though instructive nonetheless.

In summary, water quality in Wilson Inlet is on average significantly better than the Peel-Harvey prior to the Dawesville Channel (and for the most part is still better than the Peel-Harvey post Dawesville Channel) and significantly better than in the adjacent Torbay and Parry systems, the Vasse-Wonnerup at Busselton, and the Hamersley, Gordon and Beaufort Inlets to the east. The Inlet's water quality is also better than the Moore River at Guilderton, the Swan River at Perth, the nearby Irwin and Taylors Inlets and the Wellstead Inlet at Bremer Bay. Wilson Inlet's water quality is comparable to the Hardy Inlet at Augusta and Leschenault Inlet at Bunbury, and on some parameters to the nearby Walpole-Nornalup Inlet and Oyster Harbour. The only Inlet that has substantially better water quality than Wilson Inlet is the near pristine Broke Inlet.



Figures 40 to 45: Comparison of the present data set to historical data collected in Wilson Inlet. Data are presented on a logarithmic scale. The solid columns represent the average concentration (combined surface and bottom) of each parameter in the data set of interest and the bars represents the maximum concentrations. Red columns are for the period September to May, blue are for the period June to August. The data analysed from each project are from basin sites (ie excludes river and ocean mouth sites). The treatment of the data in this way was an attempt to achieve comparability between data sets and reflects the limited information that was available for some of those data sets.



Figures 46 to 48: Comparisons of Wilson Inlet chlorophyll a (mg/L), total nitrogen (mg/L) and total phosphorous (mg/L) data to other Inlets in south west WA. Medians of all data.

Summary of findings

To date the major findings of the water quality monitoring program have been:

- Water quality in the Inlet is good for most of the year; compared both to other south west Australian systems and to Australian guidelines. However, there is no question that eutrophication has occurred post WWII given the increasing proliferation of *Ruppia*, its epiphytes and macroalgae.
- Unlike the benthic vegetation, based on the historical data we have, there appears to be little change apparent in the water quality over time. This suggests that to date the Inlet is buffering the nutrient input effectively, presumably in the form of the *Ruppia*, its epiphytes and macroalgal growth.
- Much of the nutrient that enters the Inlet from the catchment, and the great majority of what is exported to the ocean, is in forms that plants and algae are unable to readily utilise.
- Much of the nutrient that enters the Inlet from the catchment that is in forms that plants and algae can

utilise is taken up by *Ruppia*, its epiphytes and macroalgae before it is even measurable in the water column of the Inlet, let alone before it has a chance to be exported to the ocean.

- Given that only a small proportion of the nutrients are available to plants and algae, that their concentrations are unaffected by bar opening and that these nutrients are rapidly assimilated into *Ruppia*, epiphytes and macroalgae, it is believed that catchment management practices that target these available nutrients will rapidly translate into reduced *Ruppia* biomass and possible reduced macroalgal biomass.
- Major phytoplankton algal blooms to date have all been linked to a chain of events that is initiated by bar opening and proceeds through salinity stratification, deoxygenation and increases in sediment nutrient recycling.
- Sediment bio-geochemical studies (to be published in Wilson Inlet report to the community number eight) have demonstrated that under the present incidence of deoxygenation the sediments may recycle 15 times as much bioavailable nitrogen and 4 times as much

bioavailable phosphorus to the water column as the catchment. With more frequent deoxygenation events than present, these quantities could double with potentially disastrous results for the Inlet.

- Sediment bio-geochemical studies (to be published in Wilson Inlet report to the community eight) have demonstrated that under the present incidence of deoxygenation the sediments remove 25 times as much bioavailable nitrogen and significantly more bioavailable phosphorus from the water column as is exported to the ocean. With more frequent deoxygenation events than present, these quantities could be drastically reduced with potentially disastrous results for the Inlet.

We believe that while the Inlet is presently processing the nutrients that enter it effectively it is in a precarious balance based on the vulnerability of sediment nutrient recycling processes to adverse oxygen conditions. Maintaining adequate bottom water dissolved oxygen concentrations, and hence sediment nutrient processing is a major key to maintaining the health of the Inlet.

Until nutrient losses from the catchment are reduced, maintenance of the *Ruppia* as a buffer for the catchment derived nutrients is important to prevent the proliferation of macroalgae and an increased incidence of phytoplankton blooms.

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For more information contact



Water and Rivers Commission

Denmark Office

Suite 1, 55 Strickland Street
Denmark WA 6333
Telephone (08) 9848 1866
Facsimile (08) 9848 1733

Head Office

Aquatic Science Branch
3 Plain Street
East Perth WA 6004
Telephone (08) 9278 0300
Facsimile (08) 9278 0586
Web site <www.wrc.wa.gov.au>

Project manager Malcolm Robb

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