Department of **Water and Environmental Regulation**

Department of **Primary Industries and Regional Development**

GOVERNMENT OF WESTERN AUSTRALIA

Bindjareb Djilba

Peel-Harvey estuary

HEALTHY ESTUARIES WA

Condition of the estuary 2016–19

#WAestuaries

Acknowledgements

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The department acknowledges the Bindjareb Noongar people as the Traditional Owners of the Djilba (Peel-Harvey estuary), the Bilya (rivers) and the lakes, and pays respect to their Elders past, present and emerging.

Most photos are by Ash Ramsay, Department of Water and Environmental Regulation. Others: p. 8 Traditional fishing: photographer Daniel Wilkins, courtesy of the City of Mandurah, p. 9 Building the Harvey River diversion scheme, State Library of Western Australia (5297B/13), p. 22: photographer Andrew McKenzie courtesy of Peel-Harvey Catchment Council, p. 25 seagrass *Halophila ruppia*: photographer Caitlyn O'Dea, Department of Water and Environmental Regulation, p. 39 microalgae under the microscope: photographer Amanda Charles, Department of Water and Environmental Regulation, p. 43 Murray River fish kill, courtesy of Healthy Rivers program, Department of Water and Environmental Regulation.

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About estuaries

Estuaries are unique and dynamic environments where freshwater and seawater meet. They provide safe harbours and places of beauty for recreation and quiet reflection. They connect people to the natural environment, act as nurseries for recreational and commercial fisheries, provide sanctuaries for birds, and are highly productive and biodiverse ecosystems.

Estuaries face numerous pressures, primarily from excessive nutrient inputs from catchment land uses, and climate-related changes (reduced river inflows, increased temperatures, ocean acidification, and rising sea levels). These pressures can diminish estuary health and, consequently, the social, economic, and environmental values they hold.

Our vision of healthy estuaries requires collaboration with landowners, farmers, non-profit catchment and conservation groups, government agencies, and local communities. The Healthy Estuaries WA program (2020–24) aims to build on the collaborative model we started through the Regional Estuaries Initiative (2016–20).

The Regional Estuaries Initiative extended scientific monitoring programs in six estuaries in Western Australia's (WA) south-west. This provides foundational knowledge on current ecosystem health, seasonal variation in water quality, and key drivers of estuary dynamics (e.g. river flow, catchment nutrient inputs, and marine exchange). This information helps us assess whether estuarine health is changing over time.

Insight into the condition of our estuaries enables more effective management. It allows, for example, for the development of targeted fertiliser practices; pinpointing of high-priority stream restoration sites; identification of public health risks and notification of the public if needed; and understanding of where more research is needed.

Report at a glance

This report summarises three years of Peel-Harvey estuary water quality monitoring (2016–19) and compares the results with historical data. We report on the main drivers of estuary health – climate, flow, and catchment nutrients; and the estuary response – water quality indicators such as salinity, oxygen, nutrients, and microalgal activity.

The Bindjareb Djilba (Peel-Harvey estuary) is the largest and most diverse estuarine complex in south-western Australia. It is valued for its natural beauty and a destination for waterside living, tourism and recreation.

The Bindjareb Djilba suffered ecological collapse during 1970–80 because of nutrient enrichment. The engineering solution of the Dawesville Channel (or Dawesville Cut) constructed in 1994 reduced persistent algal blooms in the estuary basins, but not the estuarine river reaches. A Water Quality Improvement Plan (WQIP)[1] was developed in 2008 to address drivers of severe water quality problems; however, implementation was insufficient to improve the health of the estuarine river reaches.

Renewed State Government focus on long-term protection of the estuary's values delivered *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020).[2] This plan and *Gabi Warlang Bidi – Water Quality Improvement Plan for the Peel-Harvey estuary system* (in prep)[3] provide the key strategic framework guiding the protection of the estuary over the next decade and detail management actions to improve water quality in the estuary and its catchment.

The water quality data summarised in this report provides foundational knowledge on estuary health to support scientific understanding of how it is tracking over time and assessment of water quality objectives. Outcomes from 2019–23 will be assessed in a subsequent report.

Actions to reduce nutrient losses and organic matter from catchments need to be implemented at scale and sustained for at least a generation to achieve measurable improvements in water quality.

Key points:

- The Peel Inlet has good water quality free from persistent symptoms of nutrient enrichment; the Harvey Estuary is poorly flushed and shows poor water quality with summer hypersalinity, high nutrient concentrations and, at times, elevated microalgal densities.
- The estuarine river reaches are in poor health. The Waangaamaap Bilya (Serpentine River) has very high nutrient concentrations that fuel microalgal activity year-round with frequent blooms of potentially harmful microalgae. Oxygen in the bottom waters of the Bilya Maadjit (Murray River) is persistently low and occasional microalgal blooms and fish kills occur.
- Unseasonal flows in summer 2017 delivered excessive organic material and nutrient enriched poor-quality waters to the estuary, leading to fish kills and subsequently an autumn bloom of potentially harmful microalgae in the Murray River.
- Excessive nutrients and climate change impacts are key threats to the health of the Bindjareb Djilba ecosystem. Reducing nutrient losses from the catchments is essential to build resilience and allow the estuary to adapt, especially considering climate change pressures are projected to increase.

1 Environmental Protection Authority 2008, *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system* – phosphorus management, Environmental Protection Authority, Perth.

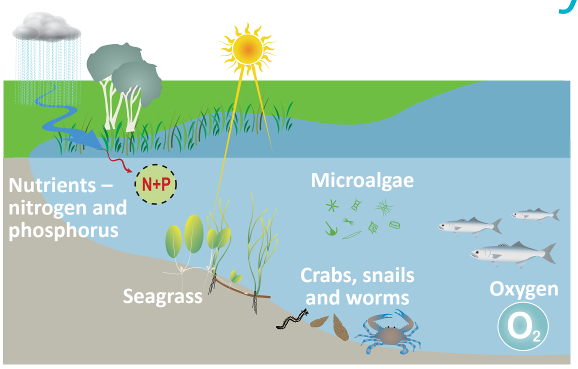
2 Department of Water and Environmental Regulation 2020, *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary*, Perth, Western Australia.

3 Department of Water and Environmental Regulation (in prep), *Gabi Warlang Bidi Water Quality Improvement Plan for the Peel-Harvey estuary system. Where to from here?* Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

Estuary health refers to the ecological integrity of an estuary. Many things can compromise the ecology of an estuary: overfishing, contamination from industrial waste or the invasion of foreign species. However, for estuaries in WA's south-west, eutrophication is the main threat.

Eutrophication is the overgrowth of aquatic plants (usually micro- or macroalgae) caused by excessive nutrients: nitrogen and phosphorus. High algal growth (or algal blooms) and organic matter loading from the catchment leads to high organic matter decomposition rates which deplete oxygen in the water. Eutrophication can also cause fish and other fauna deaths and even lead to an ecosystem shift from a healthy seagrass-dominated system to the less desirable microalgae-dominated system.

What is estuary health?

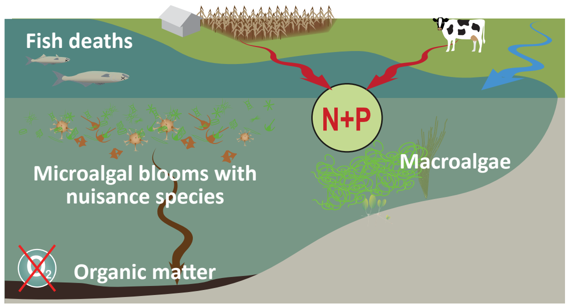


Healthy estuaries

Estuary waters are clear, free from algal blooms, litter, and turbidity. Fish are diverse and abundant. Estuary and river foreshores have healthy native trees and sedges.

Small amounts of nutrients are naturally transported to the estuary by rivers and groundwater. Low concentrations of microalgae support the base of the food web. Bottom waters and sediments are well-oxygenated.

Seagrasses thrive in well-lit, low-nutrient waters. Seagrasses also stabilise sediments, shelter fish, provide food for birds such as swans, and oxygenate bottom waters.



Unhealthy estuaries

Catchments and foreshores are extensively cleared for agriculture, urban and/or industrial land uses, leading to excessive nutrient concentrations. High nutrients fuel microalgal growth and favour macroalgae over seagrasses.

Both decomposing micro- and macroalgae contribute to high levels of organic matter and oxygen consumption, while also reducing the light available to bottom-rooted seagrass, which cannot thrive in low-light environments.

Microalgal communities change from healthy species to less desirable nuisance or potentially harmful species. Low oxygen and toxins from microalgae can lead to fish and fauna deaths.

What we measure

In the catchment

Flow: The volume of water per unit of time determined at hydrological gauging sites.

Temperature, dissolved oxygen, salinity, pH: Measured by an in situ probe, about mid-channel.

Nitrogen and phosphorus: In river concentrations, when multiplied by flow volume is an estimate of the load that enters the estuary.

In the estuary

Temperature, dissolved oxygen, salinity, pH: Measured by an in situ probe at 0.5–1 m depth intervals.

Water clarity: Measured as Secchi depth

Nitrogen and phosphorus: Concentrations measured in surface and bottom water samples. Analyses includes totals and dissolved nutrients (nitrate, ammonium and phosphate).

Microalgae: Chlorophyll *a* concentration in surface samples, and species identification and cell density in depth-integrated samples.

About Peel-Harvey estuary and its catchment

The Bindjareb Djilba (Peel-Harvey estuary) is located on the south-west coast of Australia, 75 km south of Perth. The estuary's catchment covers an area close to 9,400 km^2, extending from the coastal city of Mandurah, 150 km east up onto the Darling Scarp to the farming communities of Williams and Popanyinning ('waterhole' in Noongar language).

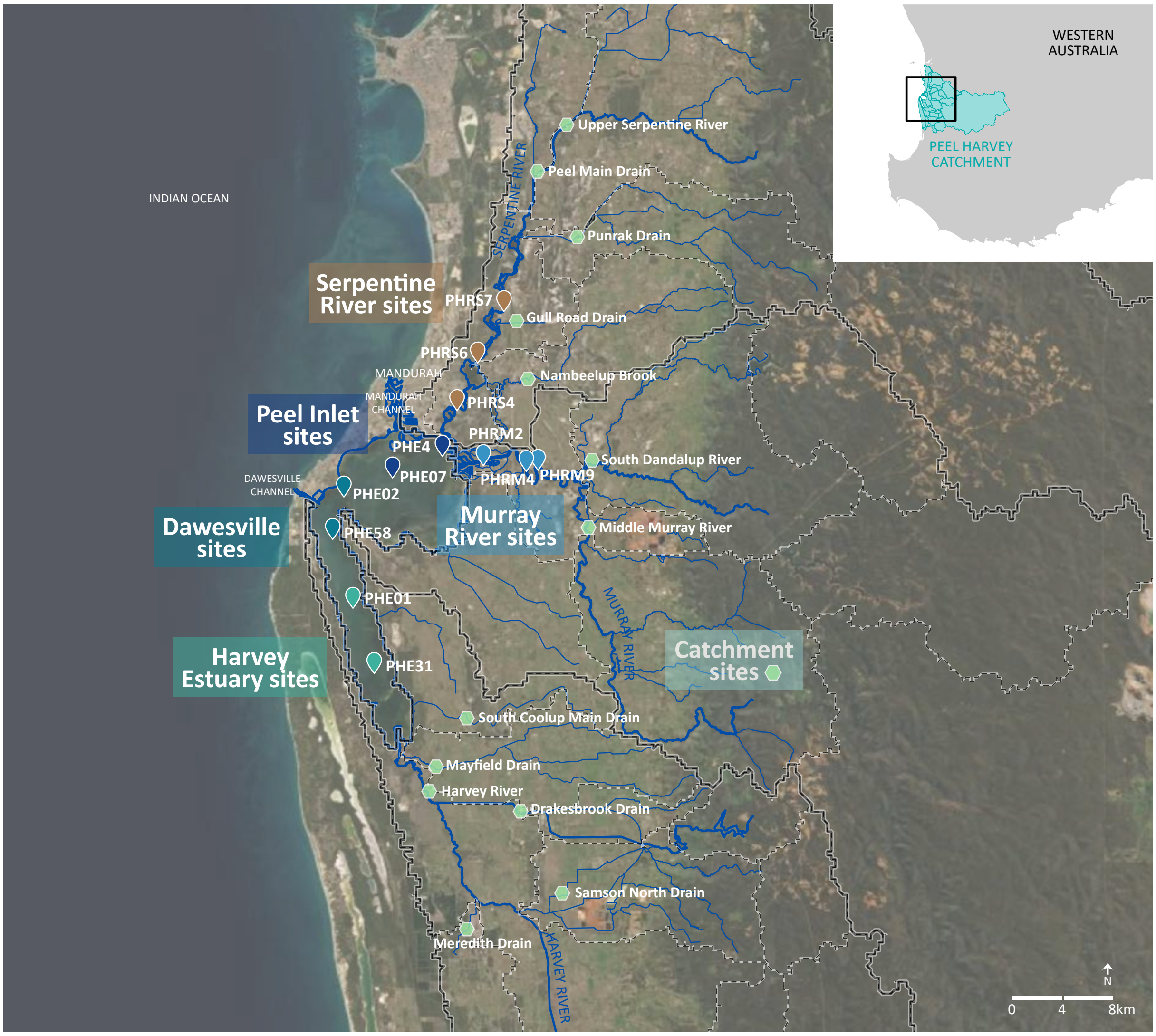
The Peel-Harvey estuary is the largest inland waterbody in south-west WA, with an area of 134 km^2. It consists of two shallow basins less than 2 m deep: the long and narrow Harvey Estuary and circular Peel Inlet. Three rivers connect the catchment to the Peel-Harvey estuary. The Serpentine and Murray rivers flow from the north and east into the Peel Inlet and the Harvey River flows from the south-east into the Harvey Estuary.

The estuary is permanently connected to the ocean via the Mandurah Channel, in the north of the Peel Inlet, and the engineered Dawesville Channel (Dawesville Cut), located between the two basins. The tidal range is around 0.5 m. Marine water intrudes into the Serpentine and Murray rivers, so lower river reaches are considered part of the estuarine ecosystem.

Soils are sandy within the coastal plain portion of the Serpentine and Harvey catchments, while the Murray catchment comprises sand and clays. These soils differ in their ability to retain phosphorus, and consequently the export of nutrients into streams and drains differs between the catchments.[4]

The estuary is part of the Ramsar[5] listed Peel-Yalgorup wetland system, its wetlands providing for diverse and unique bird populations, both international and Australian, with different habitat and food resources. The system supports a regionally important commercial finfish[6] and commercial crab fishery[7] and is used extensively for recreational and tourism purposes, particularly boating, fishing and crabbing. It holds very special cultural and spiritual value for Noongar people.

Water quality monitoring is undertaken fortnightly at 12 estuary and 13 catchment sites. Ten of the 13 catchment sites are also monitored for flow.



4 Hennig K et al. 2021, *Hydrological and nutrient modelling of the Peel-Harvey catchment*, Water Science Technical Series, report no. 84, Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

5 The Convention on Wetlands, signed in Ramsar, Iran in 1971 (commonly known as the Ramsar Convention). The agreement covers all aspects of wetland conservation and wise use, recognising wetlands as ecosystems that are extremely important for biodiversity conservation and for the wellbeing of human communities.

6 Department of Fisheries 2015, *Finfish Resources of the Peel-Harvey Estuary Harvest Strategy 2015–2020*, Fisheries Management Paper No. 274, Department of Fisheries, Perth.

7 Department of Fisheries 2020, *Draft Blue Swimmer Crab Resource of South-West Western Australia Harvest Strategy 2020–2025*, Fisheries Management Paper No. 273, Department of Primary Industries and Regional Development, Perth.

Historical context

The Bindjareb Djilba (Peel-Harvey estuary) sits inside the boodjar (Country) of the Bindjareb (Pinjarup) Noongar people. The Bindjareb people refer to the Peel-Harvey estuary as Djilba.[8] This is the ancient name used for thousands of years. Djilba is also a name for one of the Noongar people's six seasons from August to September, straddling the western European seasons of spring and winter. Djilba is also a name for the fish, bream.

According to the local Noongar people, the Peel-Harvey estuary, and all the rivers and lakes that are connected to it, were formed in the Dreamtime, when there was a drought on the land and the freshwater sources were drying up.

The Noongar creator being, the Woggaal, is associated with the creation of freshwater places in the Dreamtime. The Peel Inlet was created by the female aspect of the Woggaal, known as Maadjit, when she went inland from the sea to give birth to her children.

Other parts of the Peel-Harvey's surrounding rivers, streams, lakes, waterholes, wetlands, and springs were formed by Maadjit's children or koolaangka as they left the estuary and travelled throughout the country leaving their own marks and trails.

Finally, the remainder of the waterways were formed by Maadjit as she searched for what became of her children.

Djilba's values are associated with renewal and re-birth, or what we would refer to as spring values. Djilba's values are also specifically referred to by some Noongar groups as incorporating the 'second rains' that 'fill lakes and waterholes'.

Djilba is also one of the Noongar names for bream, which live and are abundant in the south-west waterways, including the Peel-Harvey, and which start to spawn in the estuary around spring time each year.

In cultural knowledge, the relationship between the environmental values of Djilba and the Dreamtime story of the creation of the Peel-Harvey estuary system are clear. The birth of the spirit children of Maadjit comes at a time of drought, and through the birth and subsequent life of the children, new freshwater rivers and waterholes are created, and the fertility of the land is re-set.

The values of bream are also elegantly embodied by Djilba. Bream were, and remain, a major food source of Noongar people. They start to spawn during the sixth Noongar season, and unlike many species that give birth in estuaries only to move to ocean, the bream spend their entire lives in the estuary, where the ebb and flow of saltier and fresher water plays a key role in the timing of its movement and life cycles.

In respect to the Maadjit, the Murray River is called Bilya (River) Maadjit (Female Creator) therefore the bridge where the Kwinana Freeway ends and where Forrest Highway begins is named Bilya Maadjit.[8]

[8] Information courtesy of cultural informants George Walley, Cultural Knowledge Holder, and Joseph Walley, Senior Elder and Cultural Knowledge Holder (RIP) Peel-Harvey estuary, Prepared for the Regional Estuaries Initiative website, Department of Water and Environmental Regulation, Western Australia.

"Bindjareb Noongar people maintaining a very important relationship with the waterways today, as our ancestors have done in times past. When families visit the rivers it is with the same reasoning, to sit, look for foods, relax, swim, and to experience what their parent's generation have experienced. Every generation has maintained links in some form to what the waterways have kept that is sacred. The sacredness is that it is the same today as it has been since the Woggaal created all waterways"[9]

190 years since European settlement

Since European settlement in 1829, the catchment has been extensively cleared for agriculture and urban development. The natural river flows have been modified for 15 dams, flood mitigation and irrigation systems. An extensive drainage network (~3,000 km) constructed over an extended period from the 1890s to 1980s but with periods of intensification in the 1930s and 1970s, was designed to quickly clear water off the land during seasonal inundation. Rivers were de-snagged, deepened and straightened to accommodate the high flows resulting from the catchment modifications. The parallel expansion in agriculture resulted in high nutrient loads delivered to the estuary. By the 1980s, nutrient concentrations were well beyond the capacity of the estuary to process, resulting in smothering of seagrass beds by macroalgae. The extensive mats of macroalgae washed ashore and decayed on beaches to the point that it required mechanical harvesting to reduce smells and recover beach access. In time the macroalgae was itself replaced by persistent noxious cyanobacteria (also known as blue-green alga or cyanophyte).

In the 1990s, the annual blooms of the toxic cyanobacteria *Nodularia* were so prolific in the basins of the Peel-Harvey they could be seen by satellite imagery. Thick mats of macroalgae fouled fishing nets and continued to accumulate on the shore and decompose, releasing bad odours. Fish kills and invertebrate deaths were observed from 1910 onwards, with many events most likely a consequence of low dissolved oxygen associated with the blooms. Overall, the estuary suffered an ecological collapse because of nutrient enrichment – all its values were degraded.

The impact of the Dawesville Channel on water quality

The Dawesville Channel more than trebled the volume of seawater exchange into the estuary, reducing the residence time of nutrient-rich waters from the catchment and increasing the salinity. The net result was a significant reduction in algal blooms in the main basins. But problematic blooms have not been eliminated. Macroalgal blooms still occur, although not at the widespread scale of the 1990s. Nuisance and potentially harmful microalgal species frequently bloom in the lower estuarine reaches of the Murray and Serpentine rivers. The number and concentrations of potentially harmful microalgal species are greater in the Peel-Harvey estuary than most other estuaries in the south-west (see Microalgae: seasonal patterns).

[9] Walley, G & Nannup, F 2012, *Water quality improvement plans for selected subcatchments in Peel-Harvey as part of filtering the nutrient storm project – Bindjareb Noongar Perspective*, A report to the Peel-Harvey Catchment Council, Mandurah, WA.

Climate change in the south-west

Climate is a key driver of estuary health and it is changing

The south-west of WA has a Mediterranean climate pattern, with high winter rainfall and little summer rainfall.[10]

Rainfall plays a key role in estuary dynamics as it influences freshwater inflows. The interplay between freshwater inflows and ocean water exchange determines the salinity, flushing rate and stratification patterns in estuaries. Temperature is also important, as it strongly influences biological growth rates.

Changes in the key climate drivers in the south-west are already evident and predicted to continue. The region has become warmer and drier.

Between 1910 and 2013, the average annual air temperature in the south-west increased by 1.1°C, with the rate of warming higher since 1960. Average, maximum and minimum temperatures are projected to continue to rise. By 2030, the average annual warming under potential emission scenarios is projected to range from 0.5 to 1.1°C above the 1986–2005 baseline.[11]

The decline in rainfall in south-west WA has been larger than anywhere else in Australia with a marked drying trend in autumn and early winter. May to July rainfall since 1970 has been about 19 per cent less than the average from 1900–69, the decline worsening since 2000 to 27 per cent.[12] There is strong evidence to suggest that rainfall in the region will decline further in the future.[10, 13]

Reductions in rainfall, especially in winter, impact streamflow. Freshwater flows have decreased significantly by up to 70 per cent since the 1970s – a pattern which is expected to continue.[14]

Summer rainfall is typically associated with tropical lows and cyclone activity which are infrequent and highly variable.[13] Rainfall caused by such events affected the Peel-Harvey estuary in summer 2017 and 2018.

Against the drying trend, the intensity of short-duration heavy rainfall is expected to increase, as a warmer atmosphere can hold more moisture. Effects on streamflow are likely to be complex with associated flood and erosion risks.[12]

[10] Hope P et al. 2015, *Southern and south-western flatlands cluster report, Climate change in Australia projections for Australia's natural resource management regions: cluster reports*, ed Ekström M. et al., CSIRO and Bureau of Meteorology, Australia.

[11] Department of Water and Environmental Regulation 2021, *Western Australian climate projections, Summary*, Government of Western Australia, Perth. Available at: Western Australian climate projections summary (www.wa.gov.au)

[12] Bureau of Meteorology 2022, *State of the Climate 2022, Australia's changing climate*, Bureau of Meteorology website accessed 30 November 2022. Available at: www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml

[13] Department of Water 2015, *Selection of future climate projections for Western Australia*, Water Science Technical Series, report no. 72, Department of Water, Western Australia.

[14] Petrone K et al. 2010, 'Streamflow decline in southwestern Australia, 1950–2008', *Geophysical research letters, Hydrology and land surface studies, 37 (11)*. Available at: agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL043102

How will estuaries be affected?

Reductions in freshwater flows will lead to increased average salinity in most estuaries. Some areas will be prone to hypersalinity, where a lack of freshwater inflows and summer evaporation mean that salt concentrates in zones with restricted ocean exchange. Hypersalinity can already be seen in parts of the Peel-Harvey and Leschenault estuaries. Ecological consequences of hypersalinity are decreased microalgal diversity, reduced seagrass habitat and restricted habitat for brackish and freshwater fish species.

Water quality may improve in some areas. For example, the zones closest to permanent openings with good connection to the marine environment will most likely see an increase in marine biodiversity and a decrease in algal activity as they become less influenced by fresh, nutrient-rich catchment river flows. Conversely, intermittently closed estuaries (common on the south coast of WA) are likely to have longer periods of sandbar closure. This change in environmental conditions may reduce biodiversity and increase the effects of nutrient-rich catchment inflows.

Stratification patterns will change as low flows cannot fully flush estuarine waters in winter; rather, smaller freshwater flows sit as a layer above the saline bottom waters and may persist for longer periods of time. This can result in depleted oxygen (known as hypoxia) and the release of sediment-bound nutrients, which can fuel undesirable algal blooms (discussed in more detail later).

Nutrients from catchment inflows could become retained in the estuary rather than being flushed out to sea. This can lead to increased algal activity and low light conditions for seagrasses. The estuarine river reaches of many south-west estuaries already show these patterns of extended periods of low oxygen status because of high nutrient loads and persistent stratification.

Shallow estuaries will be particularly vulnerable to warming conditions. Higher temperatures favour microalgal growth and estuaries may have greater microalgal productivity as a result, which subsequently affects the overall food web. Extreme heatwaves also affect some fauna and flora, such as important seagrasses. Rising sea levels and more frequent summer storm events could increase the occurrence of coastal inundation events.

The synergistic impact of these various stressors is difficult to predict, and recent studies show that these effects are happening at rates faster than those predicted by climate change models.[15]

[15] Scanes E, Scanes PR & Ross PM (2020), 'Climate change rapidly warms and acidifies Australian estuaries', *Nature Communications 11* (1803), available from https://www.nature.com/articles/s41467-020-15550-z.

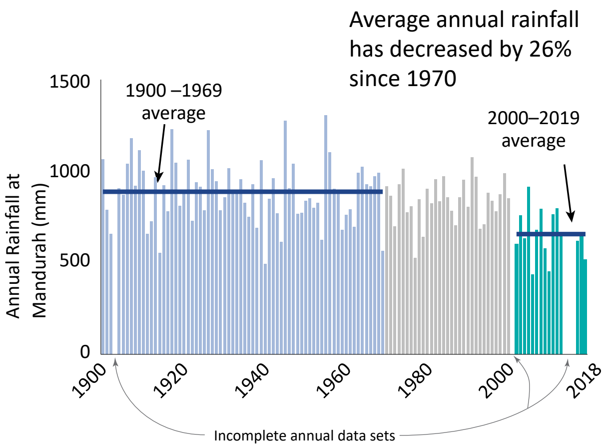
Rainfall and flow

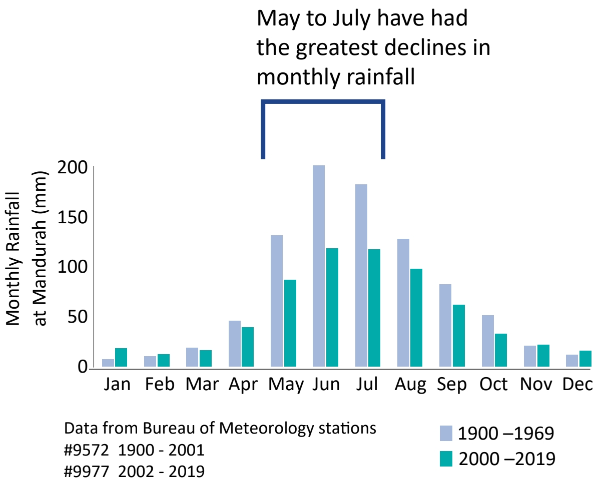
Across the Peel-Harvey estuary catchment a trend of declining annual rainfall has been observed. In Mandurah, average annual rainfall from 2000–19 was 657 mm – a 26 per cent decline since the 1900–69 average rainfall of 888 mm. Inland at Dwellingup, average annual rainfall is typically higher but has also shown a 17 per cent decline – 1,087 mm from 2000–19 compared with 1,311 mm from 1934–69.

Key points:

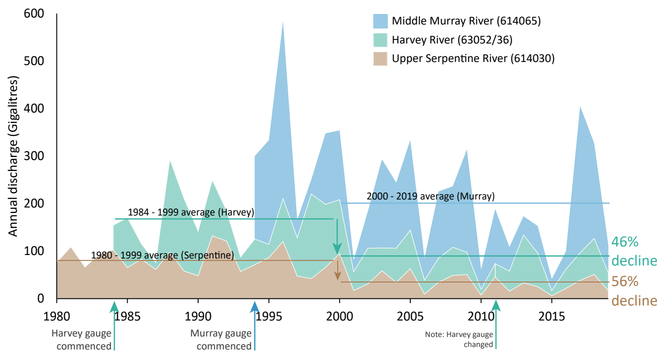
- Rainfall has decreased by 26 per cent in Mandurah and by 17 per cent in Dwellingup since 1970.
- The greatest monthly declines in rainfall were in May to July.

The monthly distribution of rainfall in this region revealed patterns consistent with the south-west WA regional climate trend of reduced rainfall from May to July; intensifying after 1999.[16]





Discharge volumes from the rivers of the Peel-Harvey estuary catchment have varied widely year to year, due in part to varying rainfall. The amount of rainfall influences the volume of water discharged to the estuary: years with high annual discharge are generally associated with higher rainfall, and vice versa for years with low annual rainfall (2001, 2006, 2010 and 2015). Over the longer-term, average annual discharge reflects the declining trend in regional rainfall.



[16] Bureau of Meteorology 2022, *State of the Climate 2022, Australia's changing climate*, Bureau of Meteorology website accessed 30 November 2022. Available at: www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml

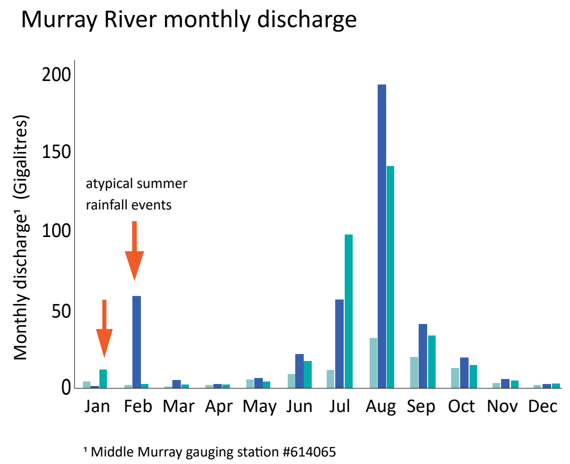
Since 2000, average annual discharge from the rivers has decreased. Average discharge dropped by 56 per cent from the Upper Serpentine River, from 80.3 GL before 1999 to 35.2 GL since 2000. For the similar period average discharge from the Harvey River dropped by 46 per cent, from 167 to 90 GL. Although the Murray River contributes the highest percentage of the total discharge to the estuary the data record is not long enough to compare with the historical average; however, the overall trend appears to be declining.

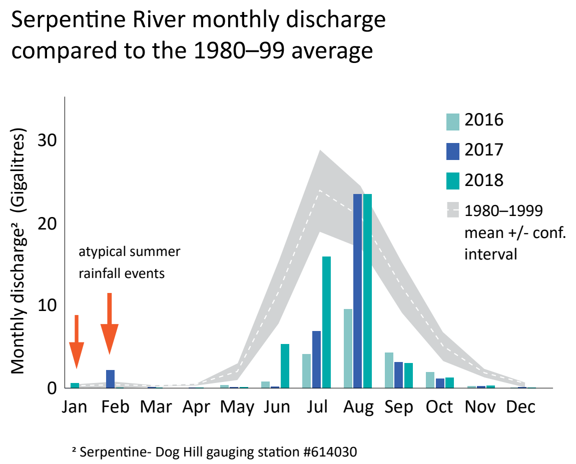
The Upper Serpentine's average rainfall decreased by nine per cent from 1984-99 to 2000-19, which is disproportionate to its decrease in discharge. Similar patterns have been observed throughout the south-west,[17][18] and projections to 2050 show the declines will continue.[19]

The relationship between rainfall and discharge is complex as other factors come into play, so that similar annual rainfall does not consistently yield comparable river flows. Catchment runoff is affected by characteristics of the rainfall event (e.g. intensity and duration) and the characteristics and condition of the receiving catchment (e.g. size, shape and elevation, soils, soil moisture, groundwater level, land-use, and evaporation rates). A series of dry years reduces soil moisture and ground water levels and results in a disproportionate decrease in runoff and discharge. This can cause a hydrological shift that will not be reversed without multiple years of high rainfall.

Peak monthly river discharge has shifted in response to the regional climate trend of reduced rainfall from May to July. Peak monthly discharge from the Upper Serpentine River occurred later during 2016–18: in August, rather than in July (compared with the 1980–99 averages). Monthly discharge between years was variable but generally below the historic averages in all months, the exceptions being above-average discharge in August of 2017 and 2018 – relatively wet years and following atypical summer rainfall in February 2017 and January 2018. Peak monthly discharge from the larger Middle Murray River followed a similar pattern, though comparable historic data is unavailable for 1980–99. The discharge of 57 GL from Middle Murray River in February 2017 was the subcatchment's highest for a summer month in 25 years (1994–2019), being of a magnitude more typically recorded in winter months.

The influence of seasonal patterns of discharge, and impact from atypical events on nutrient concentrations is discussed later in 'Nutrient and chlorophyll concentrations'.





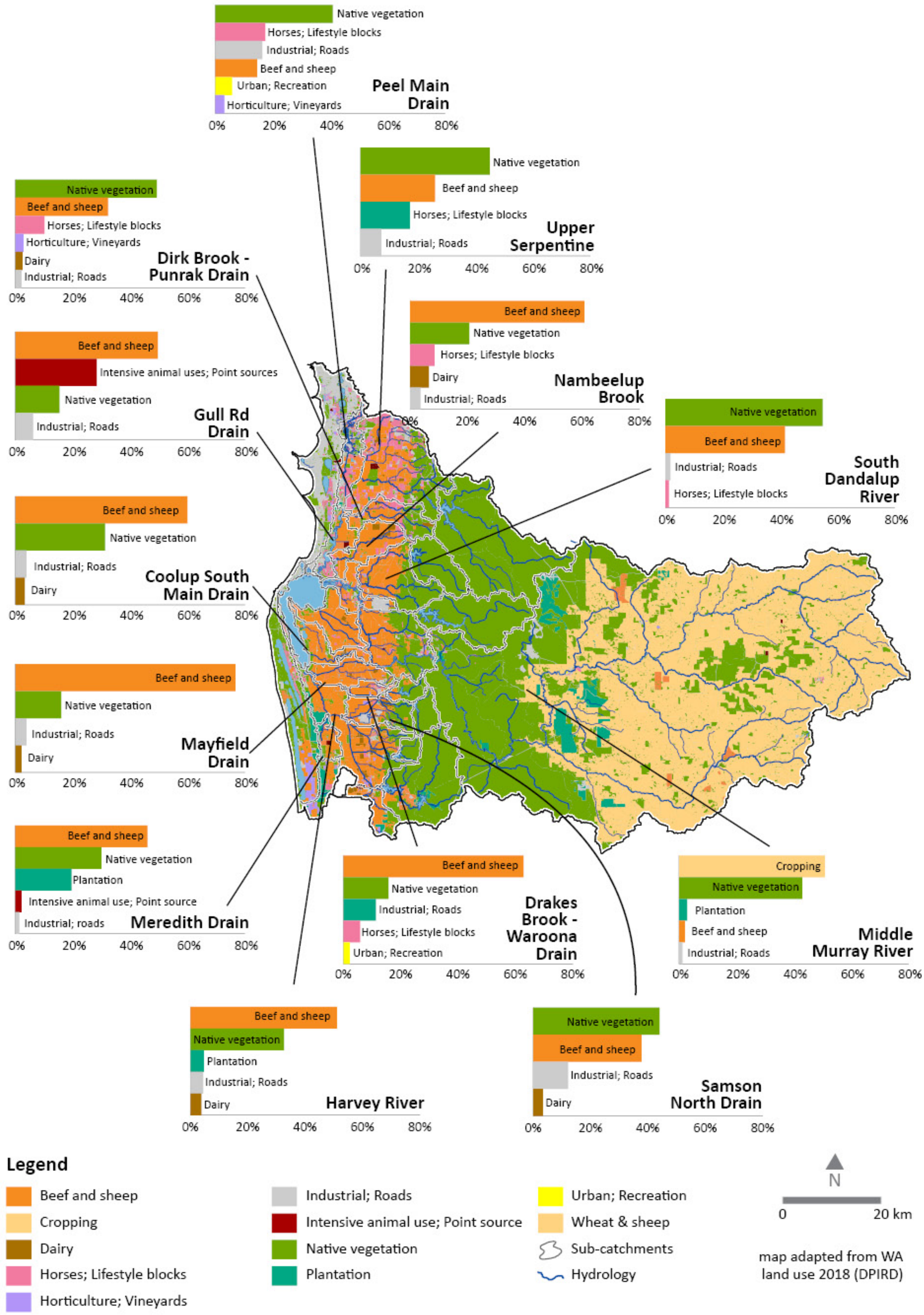
Note – insufficient time period for comparable historic Murray River mean and confidence interval, annual gauging commenced in 1994

17 Petrone, K et al 2010, 'Streamflow decline in southwestern Australia, 1950–2008', Geophysical Research Letters, *Hydrology and Land Surface Studies*, vol. 37, no. 11. Available at: agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL043102

18 Department of Water 2015, *Securing water resources for the South West*, DoW, Perth.

19 Department of Water 2010, *The effects of climate change on streamflow in south-west Western Australia: projections for 2050*, DoW, Perth.

Catchment land use

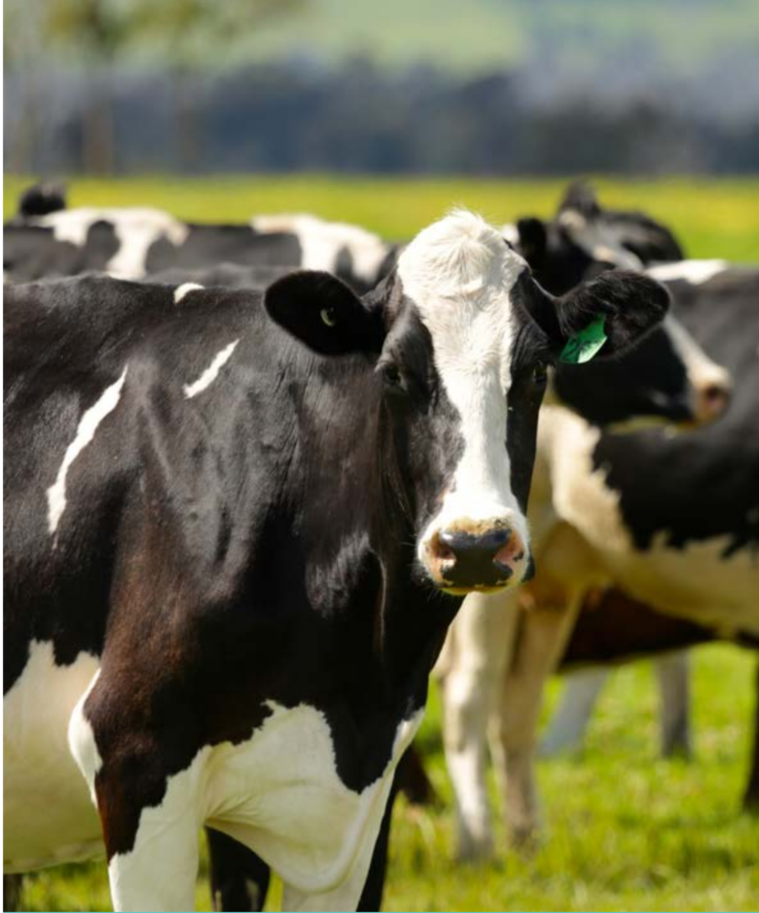


Catchment nutrient sources

Streams and drains with high nutrient concentrations are the primary cause of poor water quality in the Peel-Harvey estuary. Most of the nutrients entering the estuary originate in the coastal plain portion of the catchment and can generally be attributed to intensive land uses on poor nutrient-retaining soils and/or a high-water table that requires an extensive network of artificial drainage for agricultural and urban land uses.

Soils vary in their capacity to bind phosphorus. In south-west WA, areas on the coastal plains with grey sands tend to have poor phosphorus-binding capacity. Phosphorus applied as fertiliser can move relatively quickly to drains, streams and groundwater. Sustainable farming in the south-west can be achieved through improving soil structure, which will help reduce nutrient losses (mostly phosphorus) from farmland.

Land use mapping and knowledge of the nutrient concentration of the major flows within the catchment help us, via numerical modelling, to identify areas that currently have (or potentially may have) a negative impact on estuary health. This information is used to guide investment in mitigating land use impacts across large and diverse catchments.



Facts and figures

Catchment area	9,390 km^2 drains to estuary
Per cent cleared area (2018)	59% of 9,390 km^2
Inflows	Murray, Serpentine and Harvey rivers
Annual flow (2018)	583 GL (excluding South Dandalup River Samson North and Drakesbrook drains)
Main land use (2018)	Native vegetation, cropping, beef and sheep grazing

Different land use types vary in the amount of nitrogen and phosphorus they export to receiving waters such as estuaries.[20] Land covered by native vegetation exports the least. In catchments on the coastal plain draining to the estuary, beef grazing is the largest contributor to nitrogen and phosphorus loads (71 per cent and 68 per cent respectively), occupying 41 per cent of the land area. Other land uses contributing significant amounts of nitrogen to the streams and drains are dairy (8 per cent), intensive animal industries (4 per cent), septic tanks (4 per cent) and horses (3 per cent). After beef farming, the other main contributors of phosphorus load are dairy farming (8 per cent), horticulture (7 per cent), horses (6 per cent) and septic tanks (3 per cent). Horticulture exports a disproportionate amount of phosphorus relative to its total area comprising only 1 per cent of the catchment area.[21] Overuse of garden fertiliser and/or poor timing of its application can also be locally problematic in waterways adjacent to residential development.

While a decline in rainfall and streamflow has reduced annual nutrient loads, those nutrients that reach the estuary persist for longer (because of increased water residence time). In the past, water quality objectives have focused on reducing nutrient loads, but in a drying climate this approach will falsely suggest improvements to water quality. Concentration targets for coastal streams and drains of 1.2 mg L^{-1} for nitrogen[22] and 0.1 mg L^{-1} for phosphorus[23] are more appropriate water quality objectives; below these concentrations, the risk of nuisance algal blooms and declining ecological health is lessened. Under the current climate regime (based on 2006–2015 data), these concentrations translate into maximum annual loads of 293 tonnes for nitrogen and 24 tonnes for phosphorus (for catchments on the coastal plain targeted by the *Gabi Warlang Bidi – Water Quality Improvement Plan for the Peel-Harvey estuary system* (in prep) that excludes the Upper Murray River catchment); roughly half of the current inputs to the estuary.[21]

[20] Hennig K et al. 2021, *Hydrological and nutrient modelling of the Peel-Harvey catchment*, Water Science Technical Series, report no. 84, Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

[21] Department of Water and Environmental Regulation (in prep), *Gabi Warlang Bidi Water Quality Improvement Plan for the Peel-Harvey estuary system. Where to from here?* Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

[22] ANZECC & ARMCANZ 2000, *Australian and New Zealand guidelines for fresh and marine water quality*, vol 1: the guidelines. Available at: www.waterquality.gov.au/anz-guidelines/resources/previous-guidelines/anzecc-armcanz-2000 for slightly to moderately disturbed systems for lowland rivers.

[23] Environmental Protection Agency 2008, *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management,* Environmental Protection Authority. Available at: www.epa.wa.gov.au/policies-guidance/water-quality-improvement-plan-rivers-and-estuary-peel-harvey-system-–-phosphorus

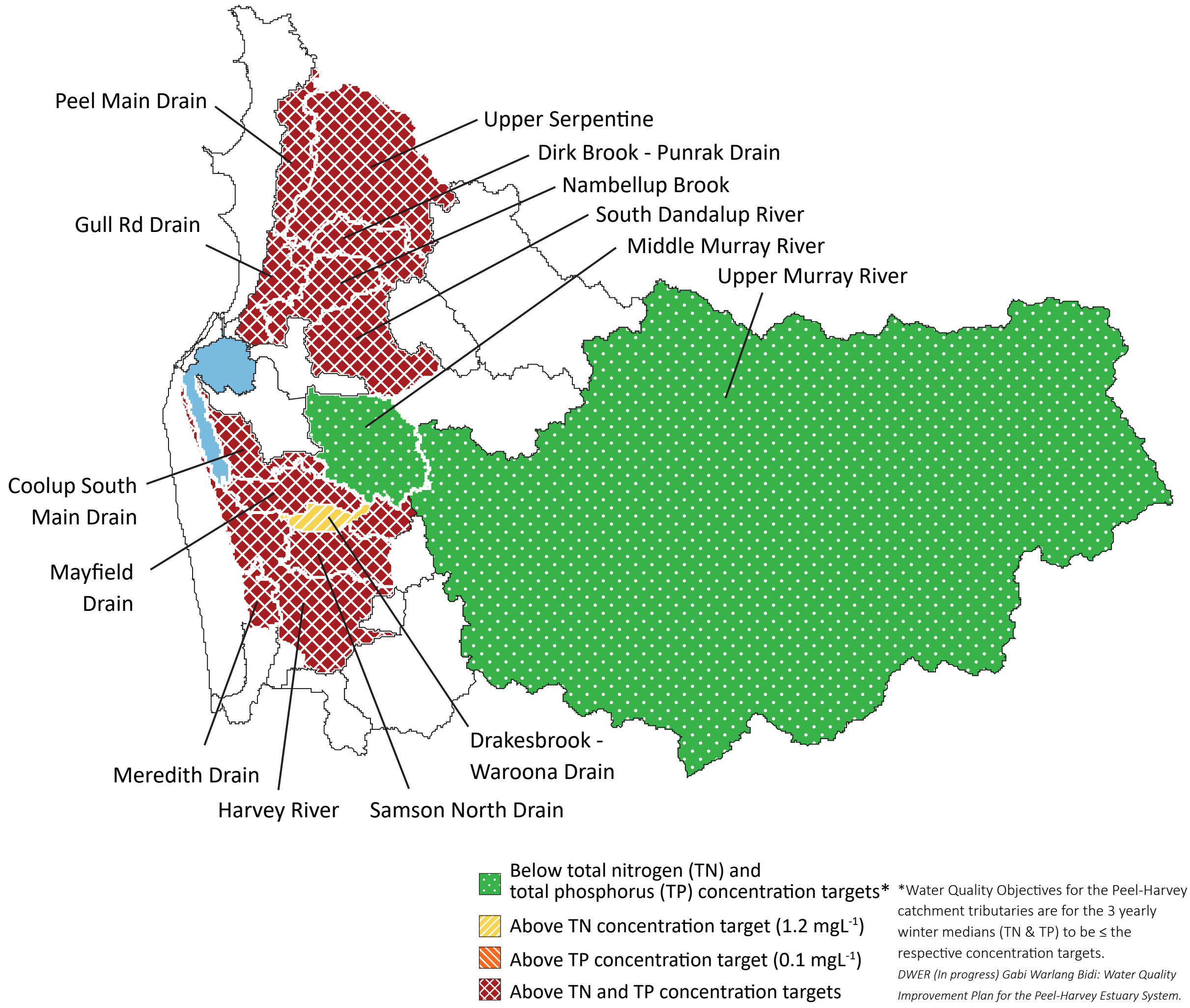
Catchment nutrient concentrations

Nutrient concentrations were measured fortnightly in the surface waters of 13 streams and drains in the Peel-Harvey catchment. Three-year winter median total nitrogen and total phosphorus concentrations were compared with concentration targets for total nitrogen (TN 1.2 mg L^{-1}) and total phosphorus (TP 0.1 mg L^{-1}). These concentration targets help determine what management actions need to be implemented and act as a value against which progress can be measured.

The map shows in which subcatchments 2016–18 winter median nutrient concentrations (measured in situ) were above concentration targets. Winter medians in the coastal subcatchments exceeded both the nitrogen and phosphorus concentration targets except for the Drakesbrook-Waroona subcatchment which only exceeded the nitrogen target (note that it is an upstream site, and its nutrient concentrations may not reflect those at the catchment outlet). The Middle Murray River subcatchment was an exception where winter medians were below both nutrient concentration targets.

This atypical result for the Middle Murray River subcatchment partly reflects that the Upper Murray River subcatchment drives better water quality at the monitoring site. The upper subcatchment has soils that tend to bind phosphorus, less nutrient-exporting land uses and a higher discharge owing to its larger area – which dilutes instream nutrient concentrations. Additionally, the location of the monitoring site must be considered. Most monitoring sites are located at the bottom of their subcatchment.

- Both dissolved and particulate nutrients in catchment waters were measured to understand the algal-growth potential of water draining to the estuary. These nutrient components are grouped as total nitrogen (TN) and total phosphorus (TP), and this information helps us understand nutrient losses from different subcatchments and know where to invest mitigation effort.
- The 2016–18 winter median nitrogen concentrations exceeded the TN concentration target in all subcatchments of the Serpentine and Harvey rivers.
- Winter median phosphorus concentrations also exceeded the TP concentration target in most of the coastal subcatchments.
- Both winter median nutrient concentrations in the Middle Murray River subcatchment were below concentration targets but nutrient losses especially from intensive agriculture and animal husbandry land uses situated downstream were not captured by in situ catchment measurement.
- Nutrients are highest in the subcatchments situated on the coastal plain with large areas of agricultural (beef and horticulture) and dairy farming.



However, for the Middle Murray River site, a large area of land lies downstream from the site with poor nutrient-retaining soils and nutrient-intensive land uses including beef and other grazing, a dairy shed, intensive animal uses and numerous septic tanks. These are likely to be exporting large amounts of nutrients that will not be detected by the catchment sampling. Numerical modelling is particularly useful here, where catchment land uses are combined with soil types and hydrology to estimate exported nutrients at the bottom of each subcatchment. Both modelled and monitored data should be considered when determining whether nutrient reductions within specific catchments are being achieved.[24]

Comparing all subcatchments, the Gull Road Drain that enters the Lower Serpentine River had the highest winter median concentrations of both nitrogen (4.22 mg L^{-1}) and phosphorus (0.8 mg L^{-1}), just over three and a half times the nitrogen concentration target and eight times the phosphorus concentration target. It was followed by Nambeelup Brook, also a subcatchment of the Serpentine River; its winter median concentration of nitrogen was 3.27 mg L^{-1} and phosphorus was 0.43 mg L^{-1}. The Meredith Drain had both highest nitrogen and phosphorus winter median concentrations of Harvey River subcatchments, being 2.6 mg L^{-1} and 0.44 mg L^{-1}, respectively.

These results confirm large reductions in nutrient concentrations are required. More detailed subcatchment results are available online.[25] These include assessment of short- and long-terms trends in nutrient concentrations from the catchment monitoring program for 2018.

[24] Department of Water and Environmental Regulation (in prep), *Gabi Warlang Bidi Water Quality Improvement Plan for the Peel-Harvey estuary system. Where to from here?* Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

[25] Catchment nutrient reports 2018– Healthy Estuaries (dwer.wa.gov.au). Available at: estuaries.dwer.wa.gov.au/nutrient-reports/

Flows and loads to the estuary

The total amount (or load) of nutrients entering the estuary from subcatchments is calculated by multiplying daily flow with daily nutrient concentration and aggregating over the year.[26] The pattern of high inter-annual variability in annual river discharge is therefore reflected in the annual nutrient loads.[27]

The annual discharge and nutrient loads over 2004–18 are presented for the Upper Serpentine, Middle Murray, and Harvey subcatchments.[28] TN and TP loads were closely related to discharge; years with high annual discharge had large nutrient loads and vice versa.

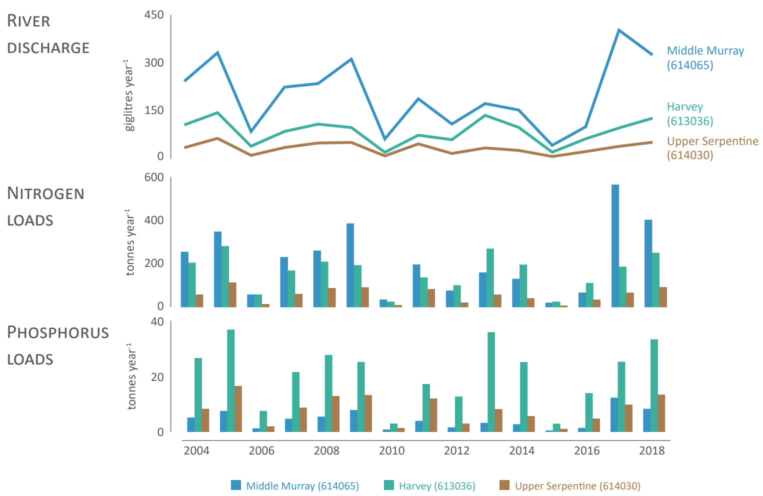
In the reporting period, the Middle Murray River discharged eight times as much nitrogen and phosphorus into the estuary in the high flow year of 2017, compared with the lower flow year 2016. The nutrient loads of 2017 were the Middle Murray River's highest in 15 years, reflecting flow from both atypical summer and winter rainfall. The nutrient loads in 2018 were similar to loads of the subcatchment's other higher flow years (2005 and 2009). While nutrient concentrations measured in situ from this subcatchment were below guideline values, the annual load from this subcatchment is driven by the larger flow volume, a consequence of its relatively large area.

In contrast, with respect to phosphorus, the Harvey River, followed by the Upper Serpentine River – subcatchments on the coastal plain, typically contribute larger annual loads to the estuary compared with the Middle Murray River.

In the reporting period, highest annual flow from both the Harvey and Upper Serpentine subcatchments occurred in 2018. Total nitrogen and total phosphorus loads from the Harvey River in its historic higher flow years of 2005 and 2013 were slightly more than in 2018. Nutrient loads from the Upper Serpentine River in the high flow years of 2005, 2008, 2009 and 2011 were equivalent or higher than to those in 2018.

Several very low-flow years occurred in 2006, 2010 and 2015 in which nutrient loads substantially decreased.

It may appear that low flows caused by a drying climate are beneficial for estuaries as nutrient loads are reduced but the issue is more complex. The timing and distribution of flows and nutrients during the year influence how an estuary responds in terms of its productivity. For instance, several small flows over the year or unseasonal storm events, especially in spring or summer, have greater potential to fuel undesirable algal growth in the estuary than a large winter flow, even when a lesser amount of nutrients is discharged.



26 Department of Water and Environmental Regulation, 2022 Data analysis–catchment nutrient reports, the department's website accessed 30 November 2022. Available at: estuaries.dwer.wa.gov.au/nutrient-reports/data-analysis/

27 These nutrient loads are derived from the in situ catchment monitoring data and not directly comparable loads generated by numerical modelling based on land use.

28 Annual nitrogen and phosphorus loads for other catchments not presented here (as their load data was not contiguous year to year) are reported in Catchment nutrient reports 2018, Healthy Estuaries (dwer.wa.gov.au). Available at: estuaries.dwer.wa.gov.au/nutrient-reports/

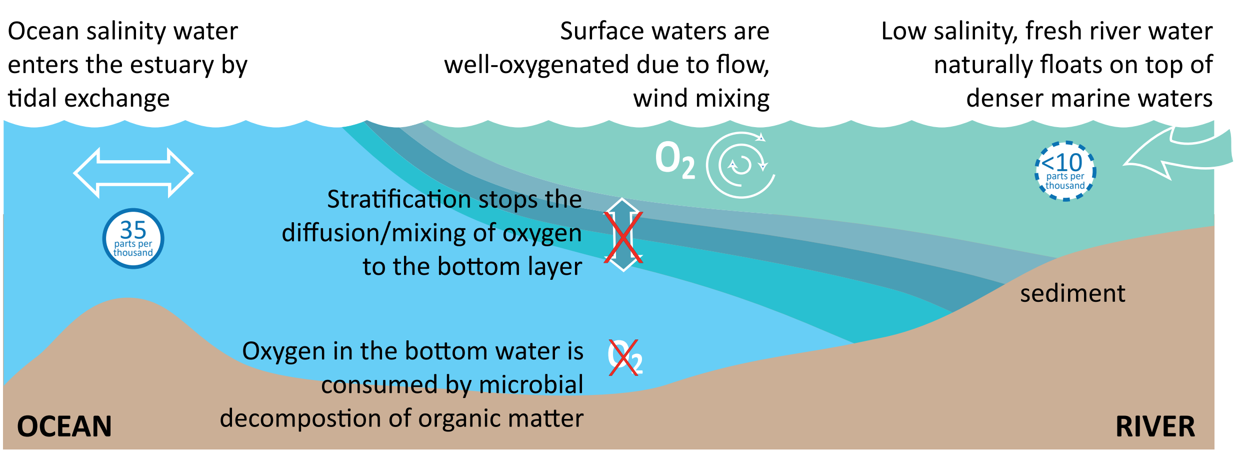
In the estuary:

the importance of stratification

Salinity stratification in water is an important feature of most estuaries. It relates to vertical differences in salinity: freshwater from the rivers tends to sit at the surface, while the denser marine water entering from the ocean makes up the bottom layers. These layers require energy to mix – either from wind, currents, or shear-driven mixing because of movement between the two layers. The strength and persistence of stratification varies seasonally and even daily within an estuary, affected by river flow, tidal conditions, and distance from the ocean entrance.

Stratification greatly influences estuarine chemistry and biology, especially the oxygen status of bottom waters. Strong stratification causes a physical barrier to the diffusion of oxygen from the atmosphere to the bottom waters.

In estuaries with poor sediment condition and/or significant microalgal productivity, the bottom layer also has a large amount of organic matter which is decomposed by microbes who will consume oxygen in the process if it is available. Oxygen can be depleted rapidly and when stratification persists, low oxygen (hypoxic) or no oxygen (anoxic) conditions emerge. These conditions are inhospitable to bottom-dwelling animals. When oxygen is absent in the bottom waters, rotten-egg-smelling hydrogen sulfide gas is generated by microbes, which is also toxic. Sediment chemistry is also altered by anoxia, releasing sediment-bound nutrients, further adding to eutrophication problems.



Salinity and oxygen concentrations

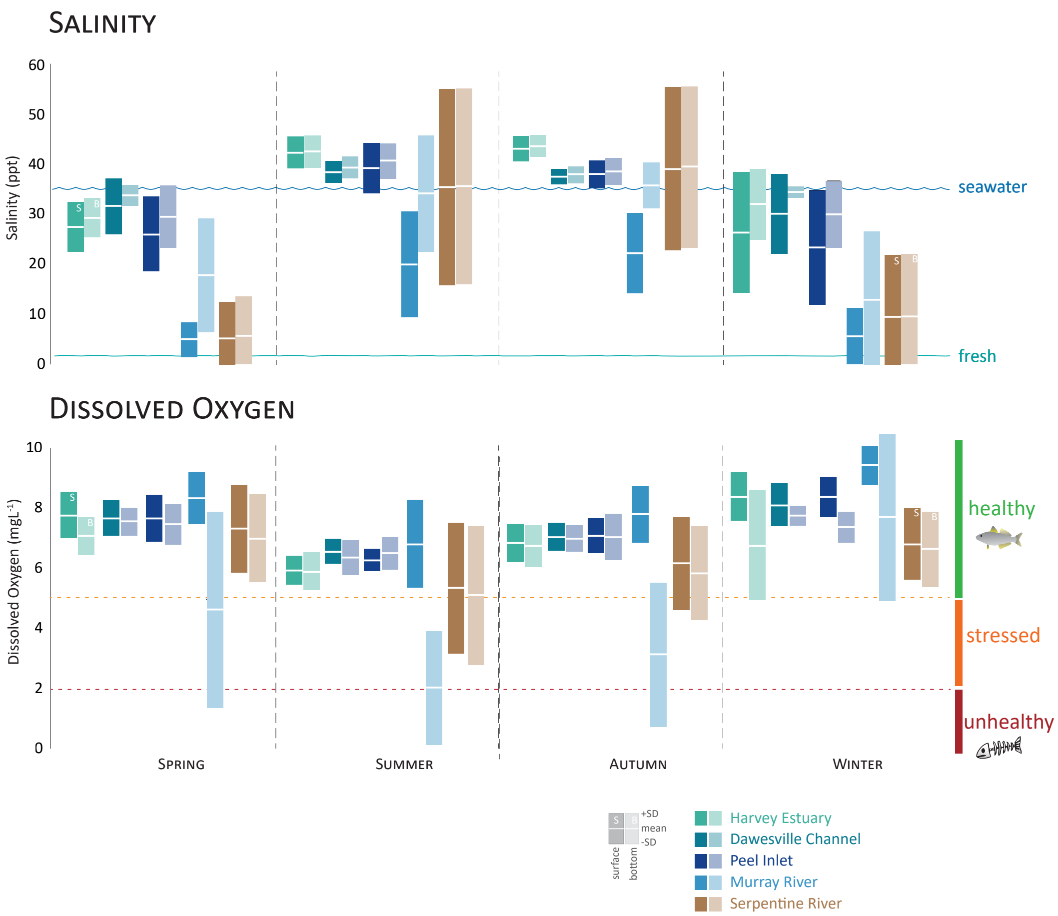
Estuary basins

Salinity in the estuary basins is driven by freshwater discharge from the rivers, tidal exchange of marine water through the Dawesville and Mandurah channels, evaporation at the water surface and wind forces across the large water surface.

Average seasonal salinities ranged from near marine to hypersaline, indicating the greater influence of tidal exchange and evaporation over freshwater discharge. The Harvey Estuary was hypersaline during summer and autumn because of evaporation and low flows from the Harvey River. The Peel Inlet salinities were lower than those of the Harvey Estuary because of the greater volume of freshwater from the Murray River.

From summer through autumn, water in the estuary basins was typically well mixed from surface to bottom. In contrast, stratification developed because of winter freshwater inflows, when brackish water overlayed marine water; this persisted into spring but weakened as discharge declined.

Average oxygen concentrations of the estuary basins were in the healthy range year-round. In winter, in bottom waters of the Harvey Estuary, there was larger variation around the average. This indicates that oxygen concentrations sometimes declined towards the stressful range for fish.



Estuarine rivers

Stratification was a persistent feature of the Murray River – fresher water overlaid brackish water from winter to spring. When river discharge declined, tidal exchange became the dominant hydrodynamic influence resulting in brackish water overlaying marine water through summer into autumn, known as a 'salt wedge'. The salt wedge was displaced from the estuarine reaches of the river during peak winter discharge, and by freshwater discharge following atypical summer rainfall events; these contributed to the larger variation in salinities than expected during summer.

Stratification influenced oxygen status in the water of the Murray River. At the surface, average dissolved oxygen concentrations were in the healthy range year-round. In contrast, except during winter, average oxygen concentrations at the bottom were stressful for fish. The variation around the average was large and at times below 2 mg L^{-1}, indicating unhealthy conditions of severe hypoxia and near anoxia.

At individual sites in the Serpentine River the water was generally of uniform salinity from surface to bottom, but along its course large differences in salinities occurred. The shallow middle and upper sites were hypersaline in summer and autumn (maxima 75 parts per thousand (ppt)), hence the considerable variation in salinity around the average. Average salinities were near fresh in spring, marine through summer shifting towards hypersalinity in autumn, then mildly brackish in winter.

For the Serpentine River, average dissolved oxygen concentrations were in the healthy range. However, the large variation around the average during summer and autumn indicates that concentrations at the surface and bottom could be stressful to aquatic life, more so in summer.

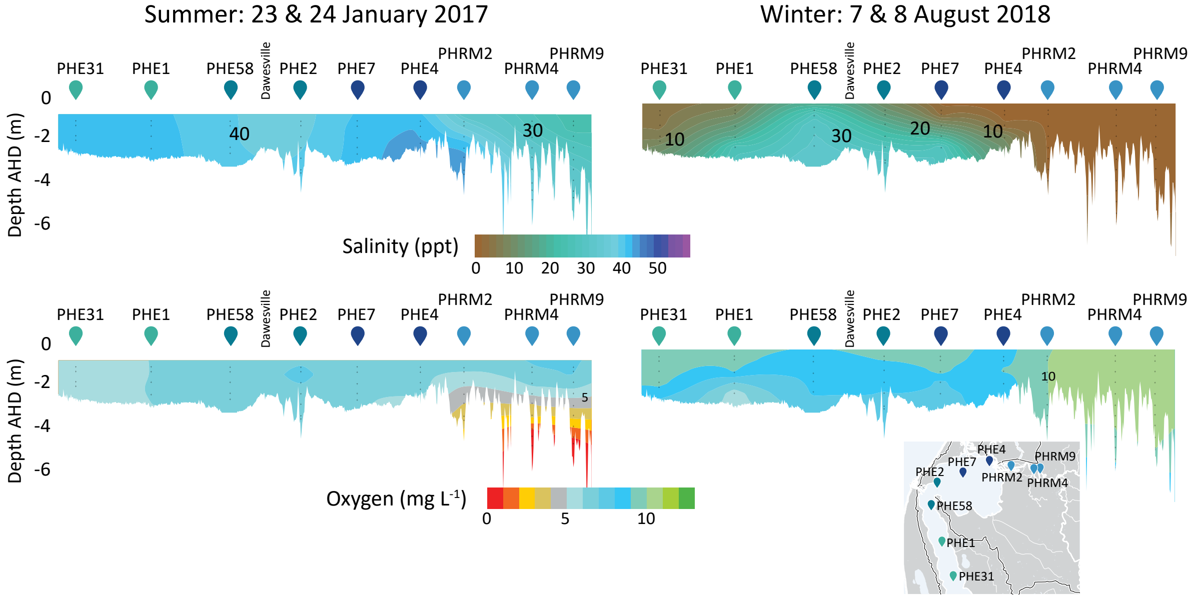
Average water temperatures (not shown) across the zones ranged from 13°C in winter to 27°C in summer – the summer maximum occurred in the Murray River and was about 4°C warmer in comparison to the other zones. The Murray River also had the warmest average surface and bottom waters from spring to autumn, which being the most biologically productive period likely exacerbates the stresses upon aquatic life (e.g. increased respiration rates, habitat squeeze or reduction owing to species specific and life-stage thermal tolerances). Higher temperatures also stimulate the rate of microbial decomposition of accumulated organic matter, and therefore oxygen consumption, again detrimental to estuary health.

Physical profiles

The physical profiles of salinity and oxygen (below) show a vertical slice through the estuary over two consecutive days; the Serpentine River sites were typically sampled the day after the main transect. Contours on the plot join points of equal concentration, so we can see differences in the physical characteristic between and within each zone. The main transect passes from the southern end of the Harvey Estuary (left side) up past the Dawesville Channel into the Peel Inlet, crossing the basin to enter the mouth of the Murray River. The transect continues for 11.3 km up the Murray River (right side). The minor transect shows the estuarine reaches of the Serpentine River from the upstream site (right side) downstream to where it enters the Peel Inlet (left). In both transects, variation in water depths reflects the sediment topography, with deeper holes present in the estuarine river reaches.

These plots illustrate a typical summer condition (23–24 January 2017) and a winter condition at the time of maximum freshwater inflow (7–8 August 2018).

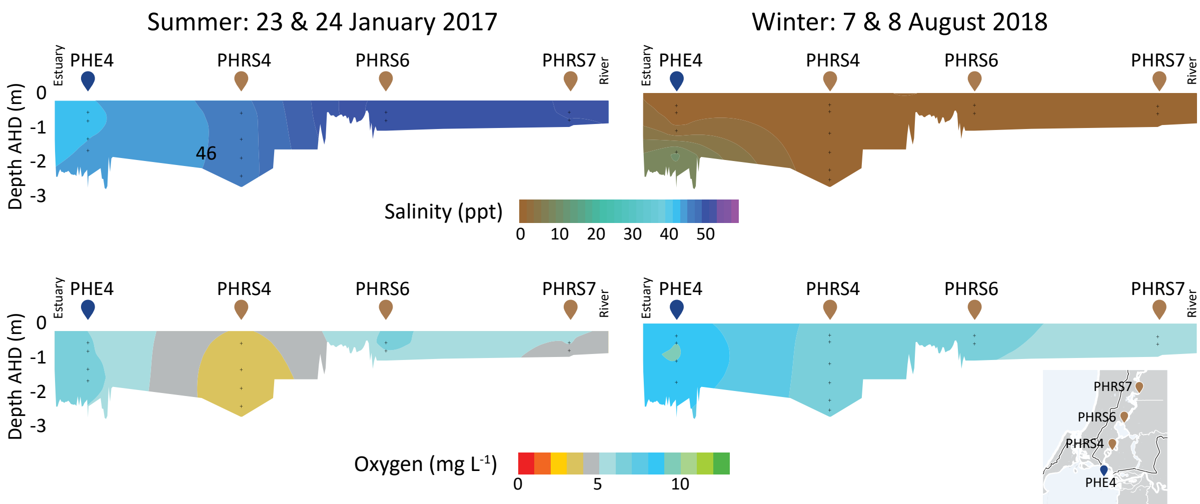
Estuary main basins and Murray River – hydrodynamics



In summer, with little freshwater discharge from the catchments, salinities within the main estuary basins were above marine salinity (35 ppt) and relatively uniform from the surface to the bottom. The Murray River was vertically stratified with brackish water overlaying bottom waters of marine salinity. Oxygen concentrations were healthy throughout the estuary basins. The negative influence of stratification on oxygen concentrations in the Murray River was clear; oxygen concentrations were depleted (less than 5 mg L^{-1}) below three meters depth throughout the zone as shown by the grey to red colour bands.

The winter physical profile from August 2018 captures the greatest freshwater discharge from all catchments measured during the 2016–19 period. The estuarine reaches of the rivers were flushed with fresher waters and a plume of less saline water created a surface layer over bottom waters of near marine salinities through the Harvey Estuary and Peel Inlet seawards to the Dawesville Channel. This instance of winter stratification did not have a widespread or long-lasting impact on healthy oxygen concentrations since water temperatures were cool which limits microalgal growth.

Serpentine River – hydrodynamics



In summer, estuarine reaches of the Serpentine River were hypersaline with highest salinities at the shallow upstream sites. In summer dissolved oxygen concentrations were stressful for aquatic life in parts of the Serpentine. The opposite conditions occurred in winter, when the Serpentine River was flushed with fresh, well-oxygenated waters.

Current and historic physical profiles are published online.[29]

[29] Peel-Harvey: Physical profiles–Healthy Estuaries (dwer.wa.gov.au). Available at: estuaries.dwer.wa.gov.au/estuary/peel-harvey-estuary/estuary/condition/physical-profiles/

Water clarity

Water clarity is the degree to which light penetrates the water column. Secchi depth is a universal and simple estimate of water clarity – the depth at which a Secchi disc is no longer visible from the surface. Poor water clarity has shallow Secchi depths and indicates either high turbidity from suspended sediments or high algal activity. In estuaries, both are undesirable as they can limit the light reaching the seabed that seagrasses need to thrive and because clear waters are preferred for recreational activities.

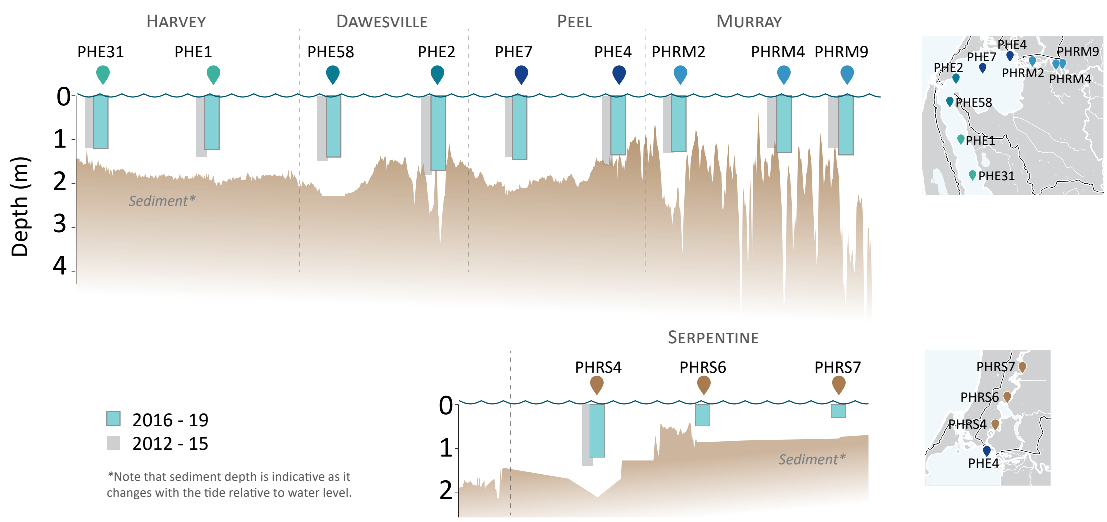
Median spring/summer Secchi depths ranged from 1.2–1.7 meters in the main basins. Sites closest to the Dawesville Channel had the best water clarity.

In the Murray River, median Secchi depths ranged from 1.3–1.4 m. The poorest water clarity occurred in the upper Serpentine River sites, with median Secchi depths of 0.5 m and 0.3 m. The poor water clarity of the Serpentine River reflects the high microalgal activity in this zone (see 'Microalgal dynamics').

Secchi depths for the 2016–19 period were like those measured in 2012–15, shown in grey in the following figure.

Median Secchi Depth - Spring and Summer

2016-19 and 2012-15



In the estuary:
nutrient and chlorophyll concentrations

Nitrogen and phosphorus are the most important nutrients for plant growth. They exist in many forms. The dissolved inorganic nutrients – such as ammonium, nitrate, and phosphate – are immediately available for plants and algae to use. Other nutrient forms (organic or particulate) are not immediately available.

As discussed earlier, catchment inflows are a key source of nutrients to most estuaries. Nutrient concentrations in eight monitored catchment inflows of the Peel-Harvey estuary demonstrate a typical seasonal pattern where increased nutrient concentrations are measured on commencement of, and during, winter discharge. The remaining five subcatchments[30] differ. In some their winter nutrient concentrations decrease with increased flow because of the stronger influence of nutrient-rich groundwater on nutrient concentrations – they are greater during dry months and are subsequently diluted by increased surface flow in winter.

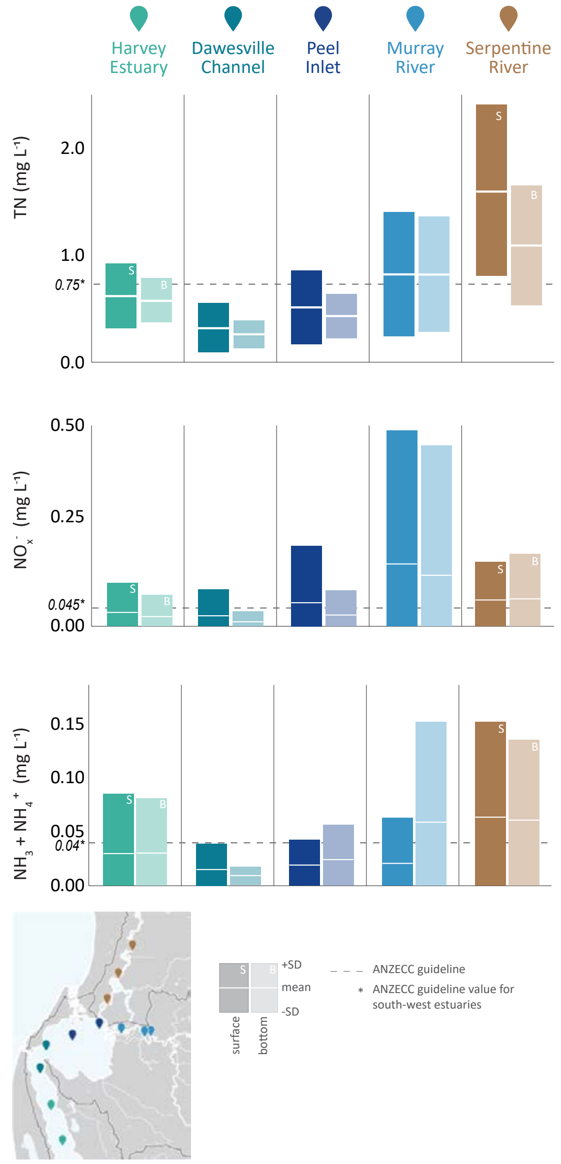
Sediments can also be a significant source of dissolved nutrients from accumulated organic matter. By measuring the seasonal pattern of nutrient concentrations in surface and bottom water samples, we can infer whether these nutrients are likely to come from catchment and/or groundwater inflows, sediments, or a combination.

The first response of an estuary to higher nutrient concentrations is usually increased microalgal activity. We monitor this by measuring the concentration of chlorophyll *a*, a plant pigment, in water.

[30] Dirk Brook–Punrak Drain, Gull Road Drain, Nambeelup Brook, Coolup South Main Drain and Samson North Drain.

Spatial nutrient patterns 2016–19

Here, the 2016–19 average surface and bottom nutrient concentrations and surface chlorophyll *a* concentrations for each zone are compared with ANZECC and ARMCANZ water quality guidelines for estuaries in south-west Australia.[31] These guideline values provide a concentration above which there may be a risk of an adverse impact on water quality.



Total Nitrogen (TN)

In the main estuary basins, average surface and bottom TN concentrations were below the guideline and lowest in the most marine-influenced Dawesville Channel zone. Both surface and bottom[32] average concentrations were above the guideline in the estuarine reaches of the Murray and Serpentine rivers – over twice the value in Serpentine River surface waters (1.6 mg L^{-1}).

Nitrate (NOx-)

Average concentrations of nitrate[33] were generally below the guideline value in the main basins but above it in surface waters of the Peel Inlet. The Serpentine River average concentrations were above the guideline and Murray River values were well above with a high degree of variability as indicated by the large standard deviation. Despite measured concentrations in the Middle Murray River subcatchment meeting nutrient concentration targets, these results show a large input of nitrate from the catchment. As stated earlier, land uses with high nutrient export factors are situated downstream of the catchment monitoring site and are likely to be contributing nutrients to the Murray River and surface waters of the Peel Inlet.

Total Ammonia (NH_3 + NH_4 +)

Average concentrations of ammonium[34] in the estuary basins were below the guideline. In the Murray River, average concentration of ammonium in bottom water was substantially higher than in the surface water and above the guideline value. This zone experiences persistent salinity stratification with oxygen-depleted bottom waters. These results suggest the sediment is a key source of ammonium to the bottom waters of the Murray River. The Serpentine River averages were equally high. Since the Serpentine system is shallow and well-mixed it is difficult to differentiate the nutrient source.

[31] ANZECC & ARMCANZ 2000, Australian and New Zealand guidelines for fresh and marine water quality, vol 1: the guidelines. Available at: www.waterquality.gov.au/anz-guidelines/resources/previous-guidelines/anzecc-armcanz-2000.

[32] Note in the Serpentine River zone, nutrient concentrations in bottom water are from one site PHRS-4, as the other sites are shallow.

[33] The measurement for the nutrient nitrate actually measures both nitrate (NO_3-) and nitrite (NO_2-), which is reported as NO_x-. We still refer to this as nitrate as in most surface waters nitrite is present in very low concentrations.

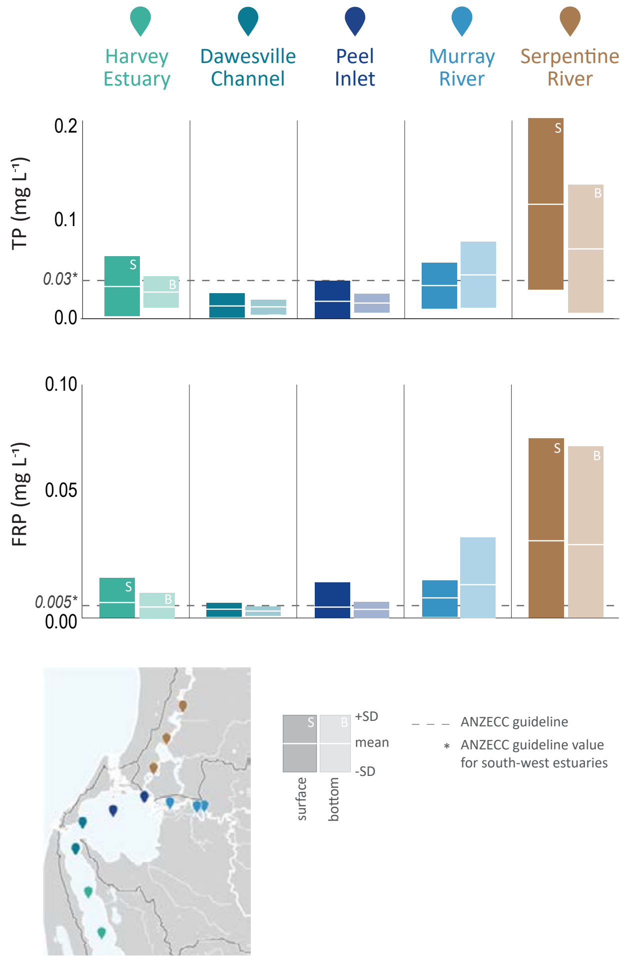
[34] Ammonia (NH_3) and ammonium (NH_4 +) are present in natural waters in a pH dependent equilibrium. During analysis, the pH of the sample is adjusted to 'force' all of it to be present as NH_3. For most fresh and marine waters (pH < 8) there is negligible NH_3 in the sampled waters, so it is technically correct to discuss this as 'ammonium'.

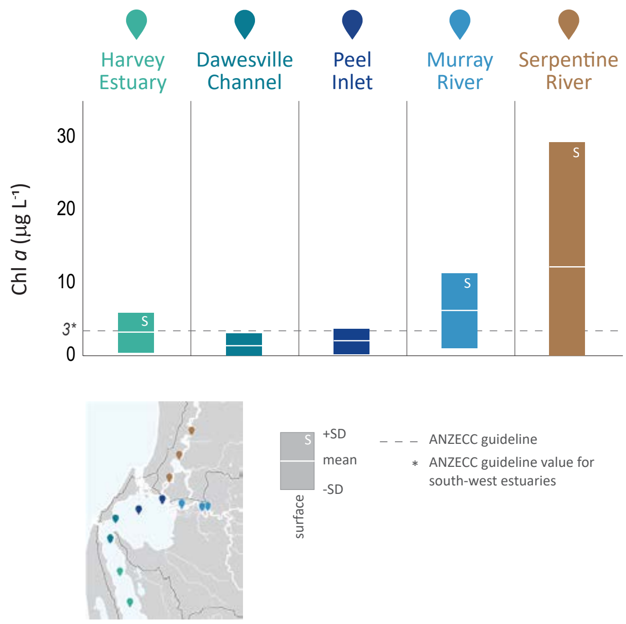
Total Phosphorus (TP)

The Serpentine River had the highest average TP concentrations of all zones, in surface and bottom waters. Average concentration of TP in surface water was 0.12 mg L^{-1}, nearly four times the guideline value.

Filterable Reactive Phosphorus (FRP) or Phosphate[35]

In the main basins, the Harvey Estuary had the highest average phosphate concentrations in surface and bottom waters, the surface concentration slightly above the guideline. In the Murray River, the average phosphate concentration in bottom waters was above that of the surface, again indicating the sediment release of nutrients under oxygen-depleted conditions. Average phosphate concentrations in the Serpentine River were well above the guideline with a high degree of variability.





Chlorophyll *a*

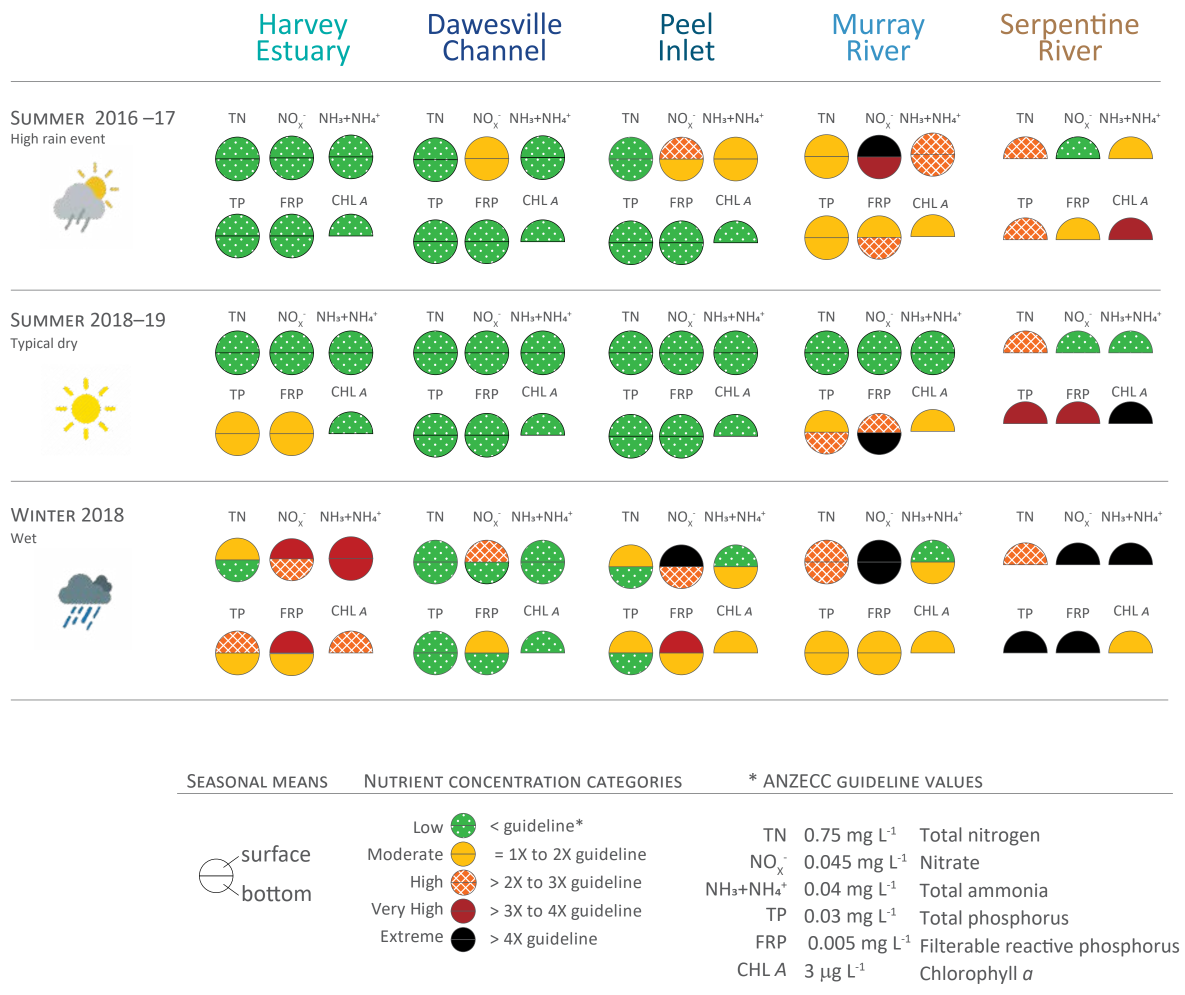
Average surface chlorophyll *a* concentrations in the main estuary basins ranged from 1.1 to 2.9 µgL^{-1} – all below the guideline. Average chlorophyll *a* concentrations in the estuarine reaches of the rivers exceeded the guideline, being 5.8 µg L^{-1} in the Murray River and 11.8 µg L^{-1} in the Serpentine River. That was nearly twice and four times the guideline concentration respectively, demonstrating the ecological response by microalgae to excess nutrient concentrations. The Serpentine River was the most productive zone overall, the large variation owing to both seasonal and site differences in microalgal activity within the zone (see 'Potentially harmful microalgal blooms').

[35] The nutrient phosphate is measured as filterable reactive phosphorus (FRP), in surface waters this is mainly present as phosphate (PO_4^{3-}) species.

Seasonal patterns: summer and winter

Seasonal patterns in nutrient concentrations in both the surface and bottom water samples can indicate whether nutrients are coming from the catchment, groundwater or from the sediments. Two high rainfall events – an unusual summer rainfall event in February 2017 and a wet winter in 2018, clearly demonstrate the rainfall-runoff delivery of high nutrient concentrations from the catchment to the estuary.

The average concentration of nutrients in surface and bottom waters during summer (Dec-Feb) and winter (Jun-Aug) along with average surface chlorophyll *a* concentrations are categorised (by colour code) relative to the ANZECC and ARMCANZ[36] guideline values. This categorisation broadly demonstrates the spatial and temporal patterns in nutrient concentrations.



[36] ANZECC & ARMCANZ 2000, *Australian and New Zealand guidelines for fresh and marine water quality*, vol 1: the guidelines. Available at: www.waterquality.gov.au/anz-guidelines/resources/previous-guidelines/anzecc-armcanz-2000.

Summer 2016–17 (high rain event):

The February 2017 rainfall event over the Serpentine and Murray river catchments caused significant and atypical river flow, especially from the Murray River that discharged into the Peel Inlet. Six days after the peak in rainfall, an extensive fish kill event occurred in the Murray, Peel and Serpentine estuarine zones and organic matter in the form of a 10 cm-thick layer of organic-rich silt and cow faeces was observed being washed downstream through the Murray River into the Peel Inlet.[37] Average nutrient concentrations in the Murray River during this flow event were substantially higher than in the typical summer of 2018–19. Nitrate, in the extreme concentration category, was transported downstream leading to moderate to high concentrations in the Peel Inlet and Dawesville Channel sites. Sources of bioavailable nutrient forms – nitrate, ammonia, and phosphate – include animal wastes and fertilisers. The high to extreme average concentrations of these nutrients plus the fact that animal waste was visible as a thick surface layer on the water surface highlights the importance of active catchment management to prevent nutrients from agricultural land uses entering the estuary.

Despite an increase in chlorophyll concentrations, the averages remained in the low category in the Peel and Dawesville zones because of the flow event being short-lived. Microalgal activity as indicated by microalgal cell density data did however show an increase (refer to later section ‘Microalgae: seasonal patterns’).

Also, it is worth noting that, while not shown here, the autumn Murray River average chlorophyll *a* was in the extreme category, 12.6 µg L^{-1}, the highest in the Murray River during the three-year monitoring period. Once the flow had subsided the high nutrient concentrations in the water fuelled high microalgal growth (also described in the ‘Microalgae’ section).

Owing to nutrients being sampled monthly at this time[38] the peak in nutrient concentrations was unlikely to have been measured and the nutrient concentrations would therefore be under-represented. Nevertheless, evidence of the catchment as a source of nutrients was clear and impact of unseasonal rainfall or storm events upon estuary health observed. More frequent summer rainfall events as predicted by climate change projections have the potential to degrade estuary health overall.

We also note the low nutrient concentrations of all measured nutrients in the Harvey Estuary – this is because despite the rainfall, flows from the Harvey River system are highly regulated by dams, drains, and irrigation schemes.[39] During this summer, the Harvey Estuary was marine to hypersaline, indicating strong evaporation and absence of any significant freshwater inflows.

Summer 2018–19 (typical dry)

Under dry summer conditions, when discharge from streams and drains was minimal or they had ceased to flow there was a distinct contrast in nutrient and chlorophyll patterns compared with the previous wet summer. Dawesville and Peel averages were all low which indicates there were not significant nutrient sources to these zones or, alternatively, that any inputs were rapidly used by macroalgae and/or seagrass for growth.

[37] Hallet C et al. 2019, *Assessing the health of the Peel-Harvey Estuary through its fish communities.* Balancing estuarine and societal health in a changing environment. ARC Linkage Project LP150100451, November 2019. Centre for Sustainable Aquatic Ecosystems, Murdoch University, Perth, WA.

[38] Note: Frequency of nutrient sampling changed from monthly to fortnightly matching measurement of physical parameters in May 2018 to better inform modelling and condition reporting.

[39] Department of Water and Environmental Regulation 2022, *Harvey River*, the department’s website, accessed 22 August 2022. Available at: rivers.dwer.wa.gov.au/basin/harvey-river/

In the Harvey Estuary the phosphorus averages in the bottom waters were moderate which could indicate a groundwater source. Other studies have demonstrated high nutrient concentrations in groundwater.

Bottom waters of the Murray had significantly higher concentrations of phosphate (FRP) than the surface. Stratification and bottom water anoxia (absence of oxygen) is a characteristic of the Murray River in typical summer conditions. These conditions lead to sediment release of nutrients as described in detail in the next section ‘Low oxygen and nutrient release in Murray River’.

The Serpentine River results show us a different pattern again; the extreme category chlorophyll *a* concentration highlights significant microalgal growth over the summer. The bloom and decay of microalgae can contribute to an active cycle of nutrient release from decay of cells and uptake to fuel more microalgal growth. Nutrient monitoring in several Serpentine subcatchments also indicates high nutrient concentrations in summer, under no flow conditions, which could also indicate a strong groundwater signal, particularly in the case of phosphate (FRP).

The greater concentration of phosphate relative to bioavailable nitrogen, as was the case in the Serpentine River, can influence the microalgal groups that dominate. Such situations, combined with favourable physical environmental conditions, may favour the growth of certain cyanophytes (blue-green algae) – organisms which can supplement their nitrogen supply by ‘fixing’ atmospheric nitrogen. Cyanophytes were the dominant group in the estuarine reaches of the Serpentine River in summer 2018–19 and, in turn, average concentration of chlorophyll *a* was extreme.

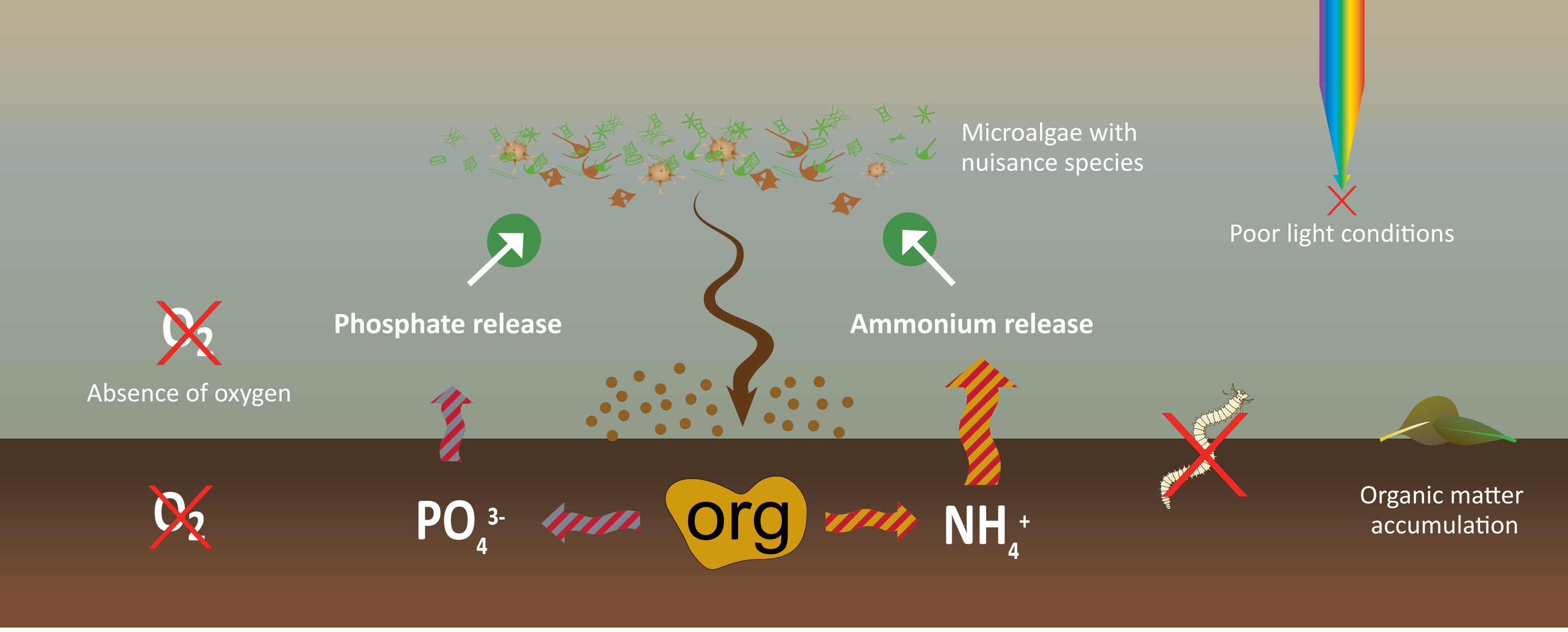
Winter 2018 (wet)

Winter 2018 was very wet, yielding above-average discharge (compared with winter months since 1994) from all three rivers, especially during July and August.

The physical profile for winter in the earlier section ‘Salinity and oxygen concentrations – Estuary main basins and Murray River – hydrodynamics’ shows that the estuary basins were stratified; fresh surface water formed a surface layer spreading out across the Harvey Estuary and Peel Inlet seawards to the Dawesville Channel over bottom waters of near-marine salinities. During winter, the source of moderate to extreme average concentrations of nutrients in surface waters could be identified as primarily from the catchments. But nutrient concentrations in bottom waters in the estuary basins were also elevated by release from the sediments. For example, very high and moderate ammonium in the bottom waters of the Harvey Estuary and Peel Inlet respectively were released during the brief episode of stratification, with reduced oxygen concentrations in those bottom zones.

In the Harvey Estuary, moderate to very high average concentrations of TN and TP and their bioavailable forms were the zones’ highest for the monitoring period, the export of excess nutrients from its catchments not observed in prior wet seasons of this monitoring period. The nutrients fuelled the winter microalgal bloom in the Harvey Estuary; a normal ecological response to winter inflow in estuaries, the high average concentration of chlorophyll *a* at 7.4 µg L^{-1} reflecting this.

In the Serpentine River, chlorophyll *a* concentration was lower than during the two summers, but nutrient averages were in the extreme category. This shows that microalgal growth was limited by factors other than nutrients (N and P), such as low water temperature, shorter day length and/or water movement (flow and turbulence).



Low oxygen and nutrient release in Murray River

Stratification of the water column can lead to low-oxygen bottom waters that make it difficult for organisms to thrive. It is important to note that, under such conditions, nutrients are often released from the sediment.

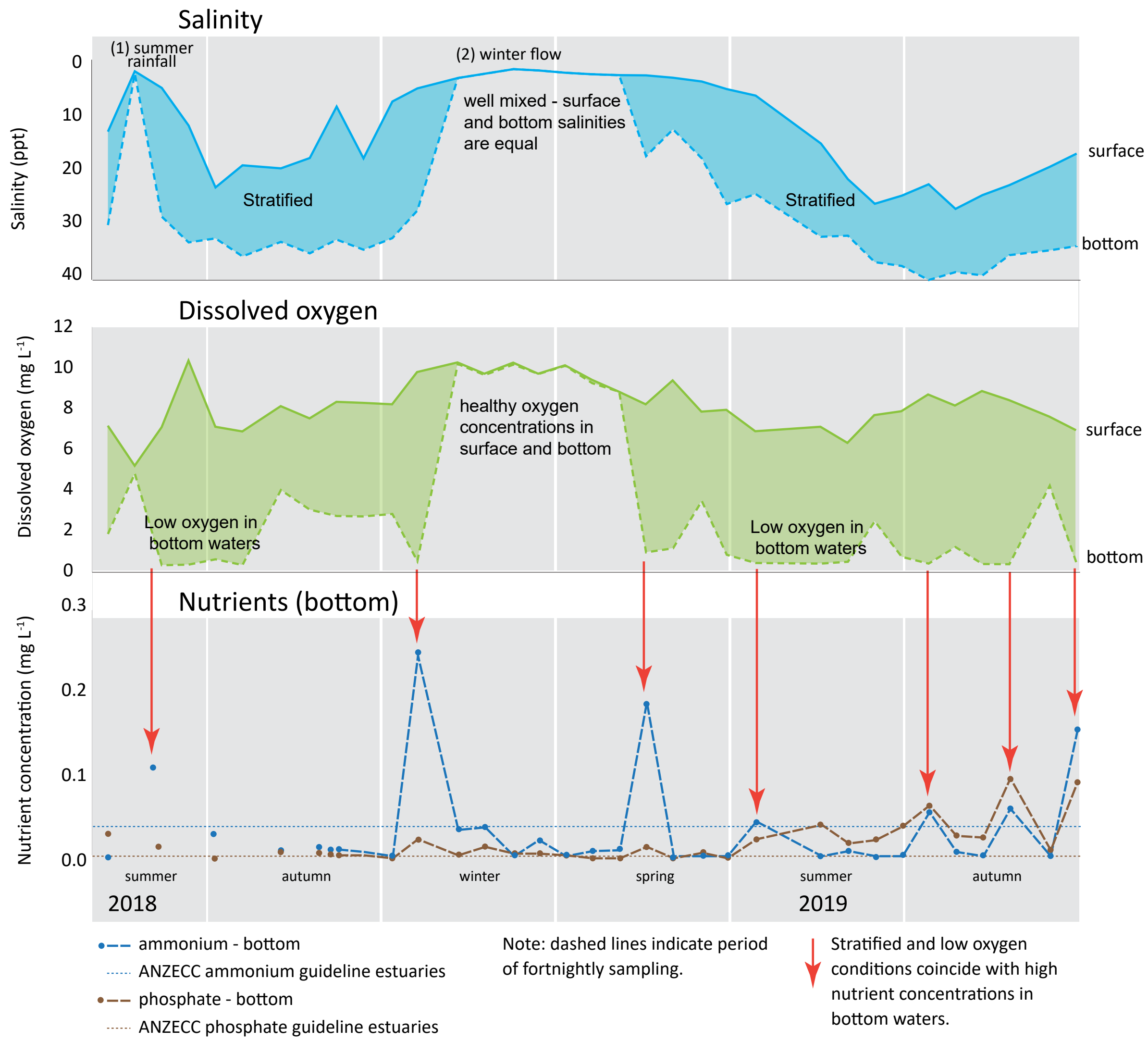
Nutrient concentrations in the bottom water at the Murray River's upper site (PHRM-9) between January 2018 and May 2019 inferred release from sediments when stratification re-established after two contrasting rainfall events:

1. The first was an intense but short-lived summer rain event (January 2018) which flushed the Murray River with fresh water. Stratified conditions were re-established within two weeks, by the next sampling period.
2. The winter event caused by seasonal winter rain flushed the Murray River for four months. During this event bottom oxygen concentrations were at their highest before flow reduced and stratification established.

Once stratified by salinity, oxygen in the bottom water was rapidly consumed by the breakdown of organic material by microbes and could not be replenished through mixing with oxygenated surface water. During these periods, oxygen concentrations became hypoxic (less than 2 mg L^{-1}) to near anoxic at the sediment surface, changing the chemical processes. In oxygenated waters, ammonium is converted to nitrogen gas by microbial processes. In the absence of oxygen this pathway is suppressed, resulting in an increase in ammonium measured in bottom waters.

When oxygen is not limited, phosphorus is largely unavailable for algal growth being adsorbed to clay and silt particles or precipitated as iron phosphates. However, changes in dissolved oxygen concentration, salinity, and pH, can alter this balance. As phosphorus becomes more soluble it is released from the sediments as phosphate into the water.

Murray River – site 9
January 2018 – May 2019



At PHRM-9, increased ammonium concentrations in bottom water were observed each time dissolved oxygen concentrations decreased. The largest ammonium releases seen were when the relative change in dissolved oxygen was greatest from the preceding concentration. Similarly, concentrations of phosphate in the bottom water fluctuated in relation to changes in dissolved oxygen. Note that during summer to late autumn in 2018 nutrient sampling was monthly, and fortnightly thereafter. As monitoring is not continuous, even a fortnight between sampling means that the pulses of nutrients released from sediments were mostly likely under-represented.

These results show that persistent stratification is not only threatening to aquatic organisms, who require oxygen to survive, but also contributes to further increases in nutrient concentrations in the water.

Comparison with historical data

Historically, there has been variation in the water quality monitoring of the Peel-Harvey estuary in terms of sampling frequency and spatial extent. Here three-year periods, each nine years apart which span pre- and post-Dawesville Channel eras, are presented with the 2016–19 period.[40] Average surface and bottom nutrient concentrations for TN and phosphate and surface chlorophyll *a* are presented for the zones where data was available.

Before 1994 the Peel-Harvey estuary was hypereutrophic, a status characterised by excessive nutrients and high microalgal productivity, as evidenced by chlorophyll *a* concentration. The Dawesville Channel was a highly successful engineered intervention – reducing nutrient and chlorophyll *a* concentrations in the main estuary basins. For example, average chlorophyll *a* concentration in the Dawesville zone declined by a factor of 19 between the 1989–92 (pre-channel) and 1998–2001 (post-channel) periods. Reductions continued – average chlorophyll *a* concentrations in both Dawesville and Peel Inlet zones had roughly halved in 2007–10 being below the guideline of 3 µg L^{-1} – with equivalent low average concentrations maintained nine years later in 2016–19. The Harvey Estuary remained a more productive zone for longer when compared with Dawesville and Peel Inlet; average chlorophyll *a* concentration below the guideline was measured in the recent period. It is positive that microalgal productivity (as measured by chlorophyll *a*) has substantially reduced throughout the estuary basins and it is essential for ongoing estuary health that this is maintained.

Data was unavailable for the estuarine reaches of the Murray and Serpentine rivers in the pre-channel period (and partial for 1988–2001 so has been excluded). Earlier sections have described the nutrient-enriched status of these zones in the current period, and comparison of TN and phosphate concentrations between 2016–19 and 2007–10 confirm nutrient enrichment to be an enduring issue in the estuarine reaches of the rivers, and in the case of phosphate of concerning magnitude.

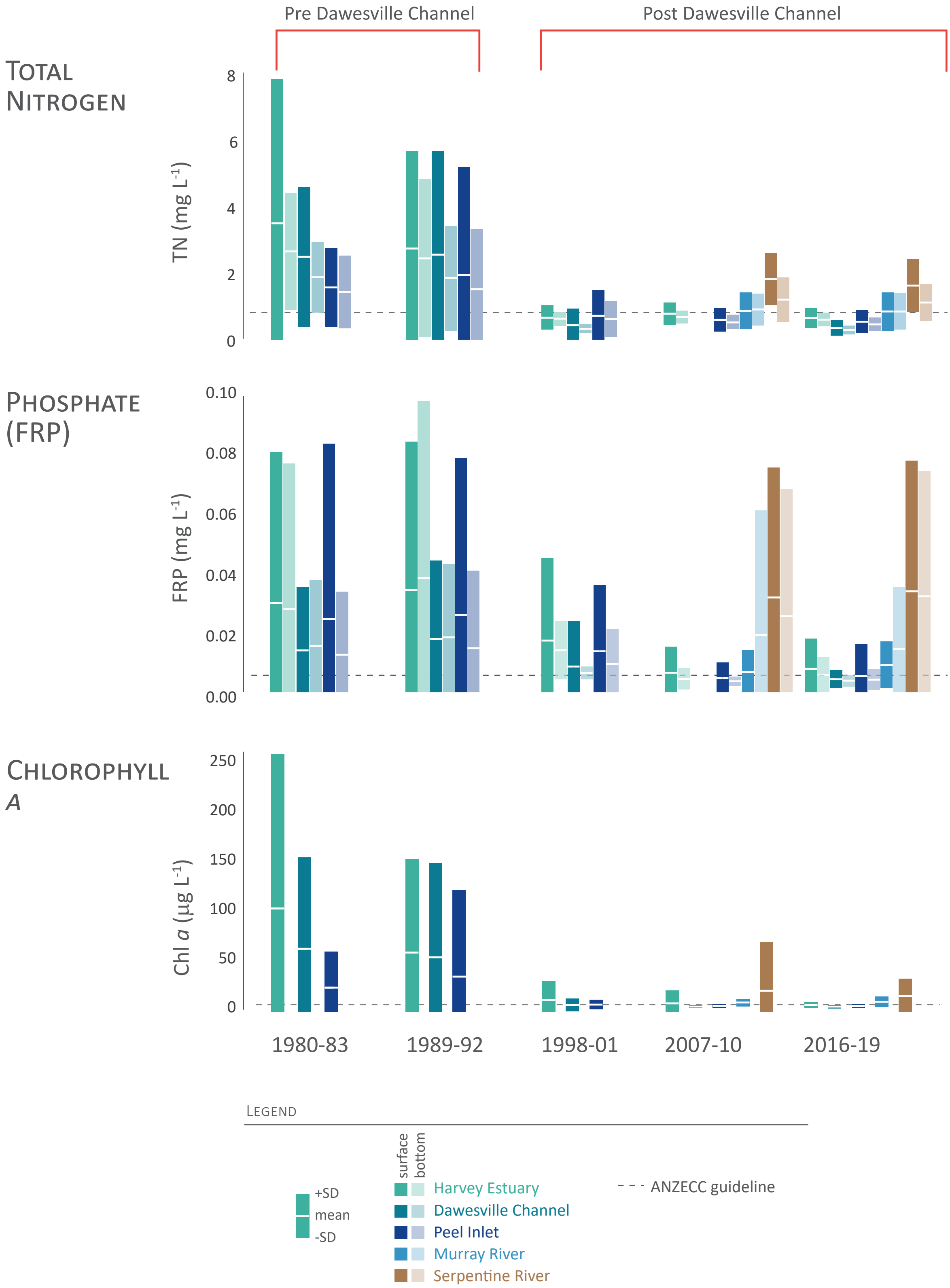
Average surface concentrations of phosphate in the estuarine portions of the Serpentine and Murray rivers post-Dawesville was equivalent to pre-Dawesville phosphate concentrations in the areas of the estuary for which data are available, such as the Harvey Estuary.

These data support the necessity of coordinated and enduring management actions to reduce nutrient losses from the catchments to reduce nutrients in the estuarine reaches of the rivers. However, there will be a 'lag time' – this being the period between a management change and a related improvement in water quality in the receiving system. Lag time is site and system dependent and can be long.[41]

In systems with excessive phosphorus in agricultural soils, such as the coastal plain of the Peel-Harvey catchment, the lag time is likely to range from years to decades. This is particularly relevant for diffuse sources of nutrients, as a residual store may be present in soils from historic land use practices that will continue to leach out, even if no further nutrients are applied.

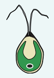
[40] Historic data for period 1980–2001 sourced from Marine and Freshwater Research Laboratory, (MAFRL) Perth and 2007–2019 sourced from Department of Water and Environmental Regulation, Government of Western Australia.

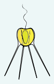
[41] Meals DW et al. 2010, 'Lag time in water quality response to best management practices: a review', *Journal of Environmental Quality*, vol. 39, pp. 85–96



Pre Dawesville Channel
Post Dawesville Channel
TOTAL NITROGEN
TN (mg L-1)
8
6
4
2
0
PHOSPHATE (FRP)
FRP (mg L-1)
0.10
0.08
0.06
0.04
0.02
0.00
CHLOROPHYLL A
Chl a (µg L-1)
250
200
150
100
50
0
1980-83
1989-92
1998-01
2007-10
2016-19
LEGEND
surface
bottom
+SD
mean
-SD
Harvey Estuary
Dawesville Channel
Peel Inlet
Murray River
Serpentine River
ANZECC guideline

Phytoplankon groups


Chlorophytes are a large and diverse group of green algae, with more than 7,000 species. Like land plants, green algae contain chlorophylls *a* and *b*.


Chrysophytes, are known as golden-brown algae due to their pigment. In the Peel-Harvey, this group is represented predominantly by the genus *Pseudopedinella*.


Cryptophytes are algae which occur in freshwater and marine habitats. Their unique characteristic is the presence of ejectosomes, two coiled springs which release under stress and propel the cells in a zig-zag fashion.


Cyanophytes, also known as cyanobacteria, are primitive, single-celled organisms, often blue-green in colour. Cyanobacteria in estuaries indicate poor water quality, when abundant.


Diatoms are single-celled or chain-forming microalgae and generally indicate healthy aquatic flora.


Dinophytes use their flagella to move through the water column, and many are also mixotrophic, meaning they can photosynthesise and/or ingest prey for growth.


Haptophyte algae are a dominant marine microalgal group in the oceans.

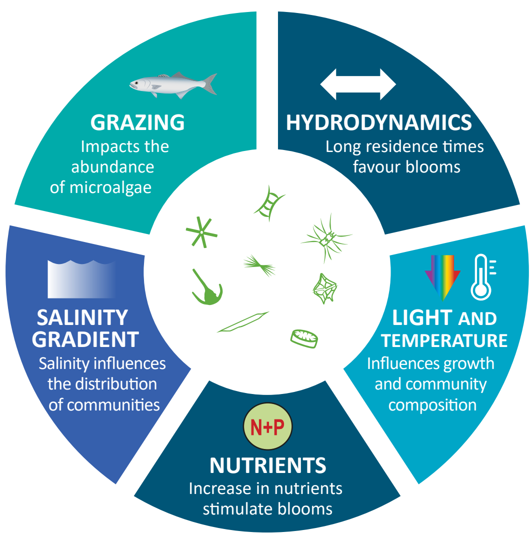

Raphidophytes encompass marine and freshwater species of algae. Their cells tend to be large with two flagella. *Heterosigma akashiwo* is the most notorious of this group and can form toxic algal blooms.

Microalgae dynamics

Microalgae, also known as phytoplankton, are tiny photosynthetic organisms which play a huge role in removing carbon dioxide from the atmosphere and generating the oxygen we breathe. As key components of healthy ecosystems, they provide food for invertebrates and fish. During the day they photosynthesise, which oxygenates the water. However, abundance of nutrients, warmer water temperatures and reduced water movement can lead to a rapid increase in the cell numbers of microalgae, promoting the occurrence of blooms. These blooms can be detrimental to aquatic ecosystems: they can reduce light availability to seagrasses; rapidly remove oxygen from the water when they decompose, causing fauna deaths; and certain species can produce toxins, which can be harmful to fauna such as fish, crabs, birds, and dolphins, as well as humans.

Chlorophyll *a*, as mentioned, is a universal indicator of microalgal activity. However, to further understand microalgal dynamics in estuaries, we also identify and assess the density of each type of microalgae.

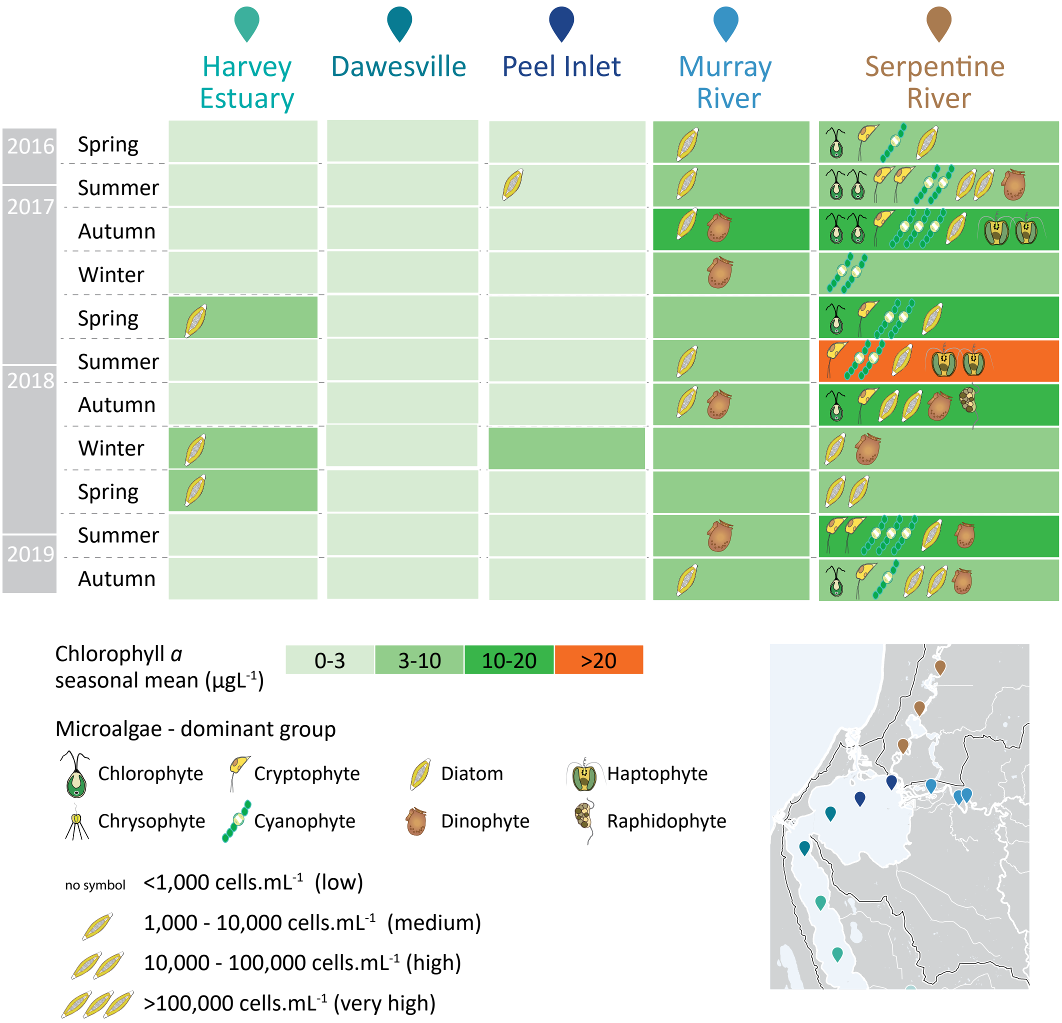
Analogous to studying plant communities on land, we investigate whether there is a community of desirable and diverse species, or whether it is dominated by undesirable plants such as weeds. This can tell us if the microalgal community composition is healthy or unhealthy. The composition of microalgal communities depends on a combination of factors which affect the algae's distribution. In estuaries, these factors include hydrodynamics, grazing, light availability, salinity gradient and nutrient availability. The groups listed in the table above are just some varieties present in estuarine microalgal communities.



Microalgae:
seasonal patterns

Key points:

- Diatoms were the dominant group in the estuary basins at low, or occasionally medium densities.
- Microalgal group composition patterns in the Murray and Serpentine rivers were very different to the estuary basins: diatoms and dinophytes were often co-dominant during autumn in the Murray River, while there was a greater diversity of groups in the Serpentine River with some occurring seasonally at high to very high average cell densities.



Harvey Estuary

Microalgal densities were low, occasionally medium (diatom-dominated) in winter and spring. Elevations in winter and spring diatoms is a typical pattern in estuaries with catchment-derived nutrient inputs from winter rainfall.

Dawesville

Seasonal average cell densities of all groups were low, and average seasonal chlorophyll *a* concentrations were consistently below 3 µg L^{-1}.

Peel Inlet

The medium diatom average density in summer 2016–17, in which the genus *Skeletonema* was dominant, was a response to the inflow of nutrient-enriched catchment discharge during the summer rainfall event.

Murray River

Diatoms and dinophytes were dominant, particularly in summer and autumn.

Karlodinium spp., which can potentially be harmful to fish, was the dominant dinophyte. Through autumn 2017, it formed an extensive bloom throughout the estuarine reach of the Murray River, attaining cell densities from 11,000 to 19,000 cells mL^{-1} in individual samples at the upper site. These dinophytes can swim using their flagella – so they can move down overnight towards nutrient-rich bottom waters inaccessible to other non-motile microalgae and return to the surface for maximum light for photosynthesis during the day.

In autumn 2018, *Karlodinium* spp. was co-dominant with another dinophyte potentially harmful to humans, *Prorocentrum minimum*, and later in summer 2018–19, the stable and strongly stratified conditions again favoured growth of *Karlodinium* spp. and its dominance of the dinophytes.

Serpentine River

Seven microalgae groups had medium to very high average cell densities, including five groups – chlorophytes, cryptophytes, cyanophytes, haptophytes and raphidophytes – that only occurred at low densities elsewhere in the estuary.

Diatoms were present nearly year-round, varying from medium to high average cell densities. Chlorophytes and cryptophytes occurred at medium to high average cell densities from spring through to autumn. Dinophytes occurred at medium average cell densities typically in summer and autumn, but in contrast to the Murray River the dinophytes were dominated by non-harmful species.

Chrysochromulina spp. and *Haptophyte* spp. were the dominant haptophytes contributing to high average cell densities during summer and autumn. *Heterosigma akashiwo* was a dominant species and almost solely contributed to the medium average cell density of raphidophytes during autumn 2018. All three species are potentially harmful to fish.

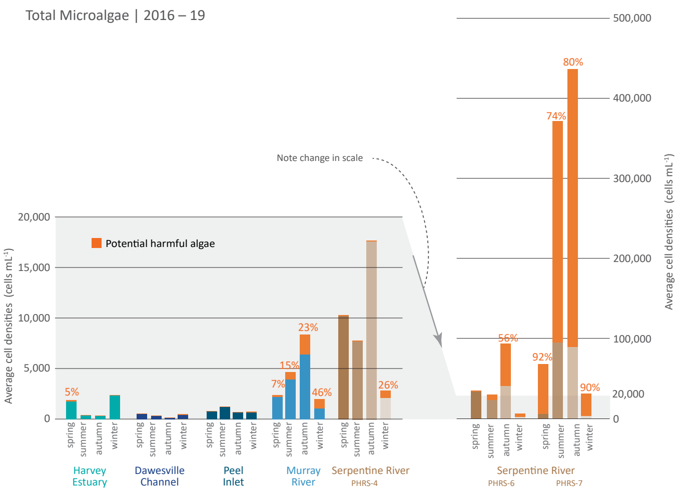
The Serpentine River was the only zone where cyanophytes exceeded dominance density thresholds. The occurrence of this phytoplankton group is characteristic of the zone and represented by both nitrogen fixing and non-nitrogen fixing species. Earlier we saw that the estuarine reaches of the Serpentine River had a highly variable salinity regime along its length and over time and salinity is an important factor controlling the growth and survival of cyanophytes. We anticipate that salinity in this zone influences cyanophyte densities and species. The nitrogen-fixing species, able to use atmospheric nitrogen when phosphorus was available but inorganic nitrogen limiting, contributed to the dominance of the group through the spring-summer-autumn periods.

The very high average density of cyanophytes in autumn 2017, compared with low-medium average densities in autumn 2018 and 2019, was likely a response to maintenance of salinities less than 40 parts per thousand through autumn to winter in 2017 caused by the atypical summer discharge. While microalga of several groups became abundant in response to the pulse of nutrients, once nitrogen became limiting, nitrogen fixing cyanophytes proliferated, especially *Planktolyngbya minor* and *Pseudoanabaena limnetica*.

Peak discharge occurred towards late winter 2017, so microalgae were not displaced earlier. In the subsequent autumns, declines in cyanophyte cell densities were concurrent with shifts to hypersaline conditions.

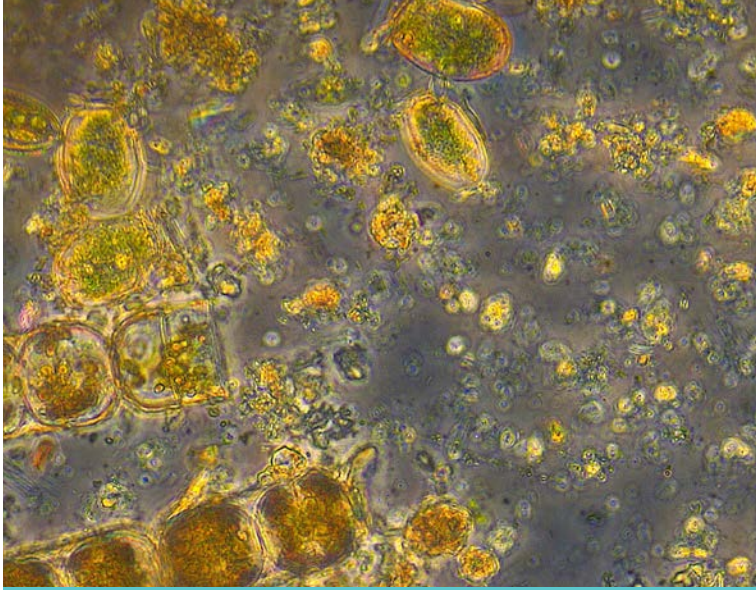
Potentially harmful microalgal blooms

Harmful microalgal bloom occurrence is linked to nutrient enrichment in coastal and inland waters worldwide. These blooms can be a threat to human health, fish, marine mammals, and birds via toxins and/or very high algal cell densities resulting in gill irritation. Our monitoring and analysis program includes the identification and enumeration of all microalgal species, including the potentially harmful ones.



In the Peel-Harvey estuary, 57 potentially harmful microalgal species were identified during 2016–19, from five major taxonomic groups – cyanophytes, diatoms, dinophytes, haptophytes and raphidophytes. This number of species was very high compared with the other estuaries in the south-west (Leschenault Estuary: 23, Hardy Inlet: 23, Oyster Harbour: 15, Wilson Inlet: 12).

Average total microalgae cell densities were lowest across the estuary basins. Within the estuary basins, the Harvey Estuary had the highest average densities during spring and winter (about 1,900–2,400 cells mL^{-1}). Potentially harmful species represented 2–12 per cent of the seasonal average total microalgae densities.



Key points:

- The Peel-Harvey estuary had 57 potentially harmful microalgal species – high compared with other estuaries in the south-west and they were present throughout all zones.
- Historic problems in the Harvey Estuary were with extensive blooms of *Nodularia spumigena* (a toxic cyanophyte). This no longer appears – its germination inhibited by increased salinity of the estuary following completion of the Dawesville Channel.
- Microalgal cell densities are now highest in the estuarine river reaches where cyanophytes and dinophytes may dominate blooms in the Serpentine and Murray, respectively.
- The environmental threat or impact of all potentially harmful microalgal species was gauged by counting instances when their cell density was greater than established guidelines categorised by risk to humans or fish and/or potential to cause aesthetic decline. Spatially exceedances of fish health and aesthetic decline guidelines were restricted to the estuarine river reaches, while some species exceeded human health guidelines in the Harvey Estuary, Peel Inlet and estuarine river reaches.

Average total microalgal densities in the estuarine parts of the Murray River peaked in autumn, where about a quarter of the cells were potentially harmful species. Microalgal activity was lower in winter, likely associated with freshwater flow flushing brackish and marine water, and lower temperatures.

Average total cell densities in the estuarine Serpentine River were orders of magnitude above the other zones (note the different scale used in the graph above). There are several reasons for this – this zone is highly nutrient enriched and the species involved are predominantly cyanophytes which are very small in cell size compared with most other microalgae. Two of the three Serpentine sites are also very shallow and therefore the sampling method tends to sample more of the surface scum than other sites. Even so, densities are at very high levels and the percentage of the total cells that are potentially harmful is more than 50 per cent in all seasons. There was also a wide variation between the Serpentine sites with cell densities extremely high in the uppermost site (PHRS-7). Average cell densities in PHRS-7 were about 400,000 in summer and autumn, with more than 70 per cent of these cells potentially harmful species.

Exceedances of microalgae guideline values

Potentially harmful microalgae are widespread and numerous in the Peel-Harvey estuary. Their potential environmental threat or impact are gauged by comparing species cell densities (cells mL^{-1}) and biovolume of cyanobacteria (mm^3 mL^{-1}) to the department's Phytoplankton Environmental Guideline values[42] which were derived from international and national guidelines[43], and expert local knowledge.

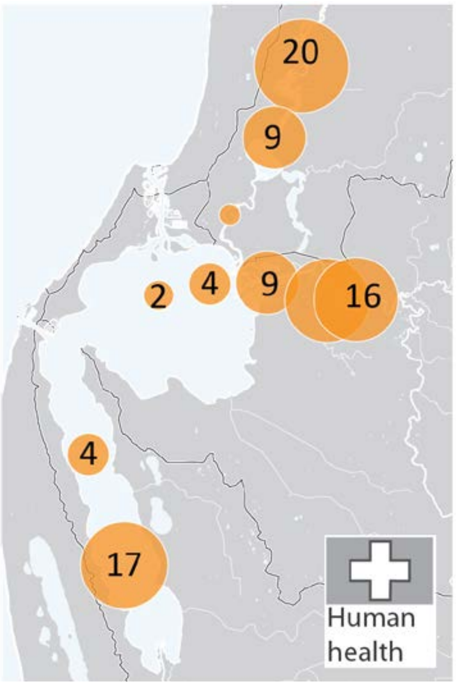
The number of exceedances by species of their specific guideline values in 2016–19 is presented by site[44] in the bubble plots below and are categorised based on their potential impact:

Human health

The human health category considers species that may cause illness or skin irritation through direct contact, and illness caused by the consumption of wild shellfish contaminated with microalgal toxins.

Exceedances of cyanobacteria guidelines, which pose a risk through direct contact, were restricted to the Serpentine River and were highest at the upper PHRS-7 site.

The only exceedances in the Harvey Estuary and Peel Inlet were in the human health category and these were caused by dinophyte species: *Karenia* spp., *Gonyaulax* spp., *Alexandrium* spp., *Alexandrium minutum* and *Dinophysis acuminata,* which may produce toxins and contaminate wild shellfish. These species plus *Karenia selliformis, Prorocentrum minimum* and a diatom of the *Pseudonitzchia seriata* group also caused multiple exceedances throughout the estuarine reaches of the rivers, particularly at Murray River sites.



[42] Department of Water and Environmental Regulation (in prep), *Phytoplankton Environmental Guidelines (PEGs) (2020)*, Phytoplankton Ecology Unit, Perth, Western Australia. PEGs formerly referred to as interim ecological trigger values.

[43] National Health Medical Research Council 2008, *Guidelines for managing risks in recreational waters*, National Health and Medical Research Council, Australian Government, Canberra.

[44] This data (AWARE 07/2019) will support assessment of a Water Quality Objective for potentially harmful and nuisance microalgae described in the *Gabi Warlang Bidi – Water Quality Improvement Plan for the Peel-Harvey estuary system* (in prep).

Dinophysis acuminata caused the most exceedances (13 out of 17) in the southern end of the Harvey Estuary where except for an isolated peak in cell density of 90–100 cells mL^{-1}, its density was below 25 cells mL^{-1}, similarly low cell densities occurred elsewhere. *D. acuminata* is associated with diarrhetic shellfish poisoning (DSP). The department's guideline value for *D. acuminata* is 10 cells mL^{-1}, higher than the WA Shellfish Quality Assurance Program guideline of 1 cell mL^{-1} applicable to commercial aquaculture operations.[45] The Peel-Harvey estuary is not a designated commercial aquaculture zone. Because of the exceedances of several potentially harmful species, the long-standing advice from the Department of Health not to eat wild shellfish from the Peel-Harvey estuary is still applicable to protect human health.

Fish health

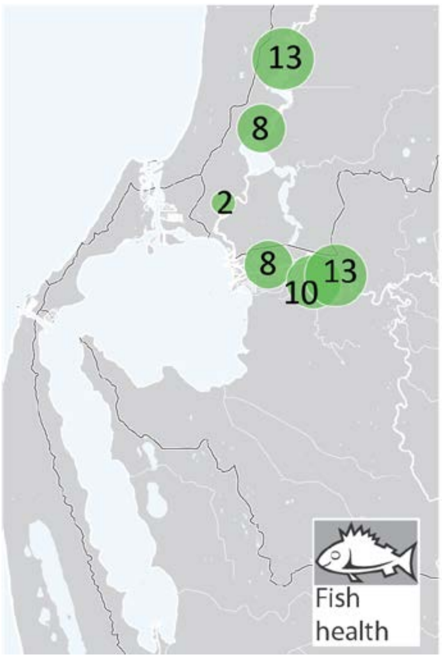
The fish health category considers species that pose a risk to fish health from microalgal toxins or a decline in gill function (e.g. clogging and/or irritation).

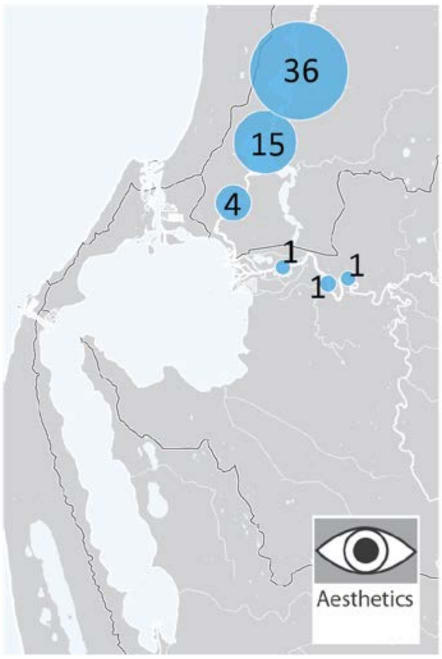
There were numerous fish health exceedances in the estuarine reaches of the rivers; caused by species of raphidophytes, dinophytes, haptophytes and diatoms. In the Murray River, the dinophyte *Karlodinium* spp. exceeded its guideline most often with densities typically in the thousands of cells per ml. However, densities notably peaked at 11,000 to 19,000 cells mL^{-1} in late autumn 2017 following the atypical summer rainfall, its growth spanning three months in which the Murray River had been strongly stratified with depleted oxygen in bottom waters with high concentrations of nitrogen and ammonium. A significant fish kill (see 'Fish kill reports' No.4) in the Murray River coincided with this period but without a pathology result microalgal toxins could not be implicated, rather observations suggested a deoxygenation event.

Aesthetics

The aesthetic category considers excessive cell densities of species that cause water discolouration and/or surface scums, and consistently diminish recreational values.

The Serpentine River zone had the highest algal activity of the estuary as measured by chlorophyll *a* concentration. Unsurprisingly it was also the zone in which aesthetic decline frequently occurred with multiple exceedances by many species primarily from the groups – cyanophytes, diatoms, chlorophytes and other passive flagellates.





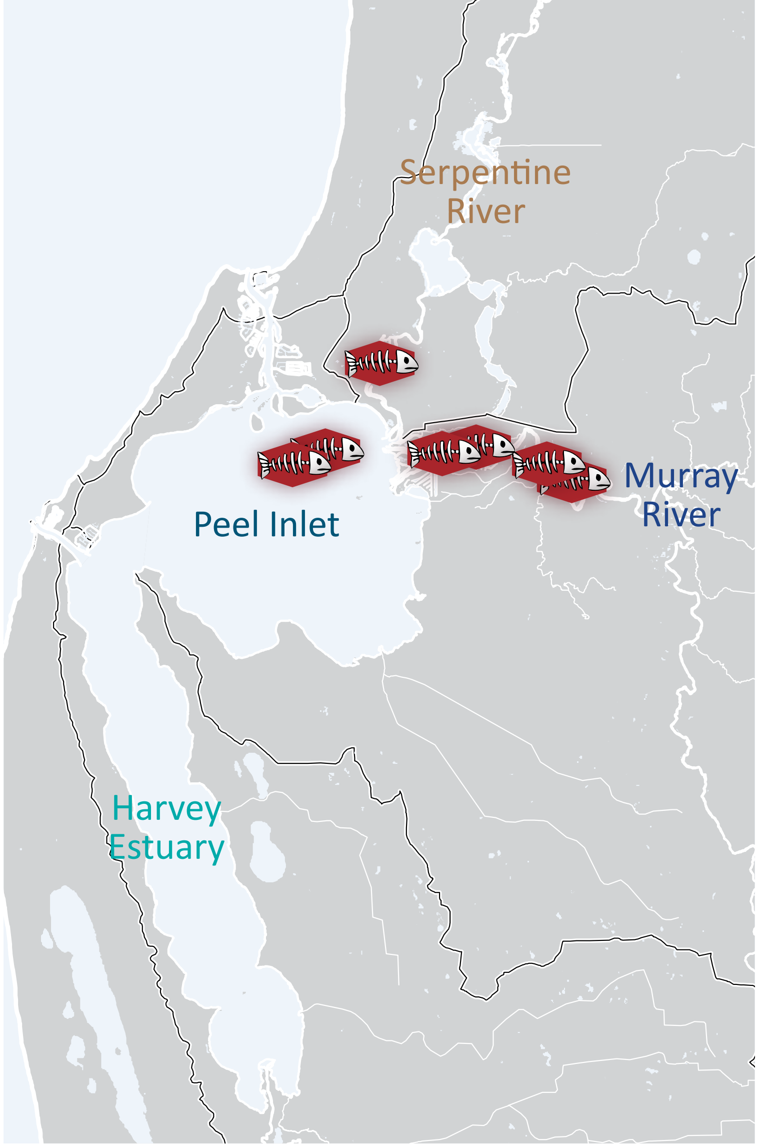
[45] Western Australian Shellfish Quality Assurance Program 2016, *Marine Biotoxin Monitoring and Management Plan 2016: Western Australia Shellfish Quality Assurance Program*, Department of Health, Perth.

Fish kill reports

In the Peel-Harvey estuary, fish kills are a highly visible symptom of poor water quality and are frequently associated with highly eutrophic conditions – high algal activity and/or low oxygen.

On average, one fish kill event has occurred every year in the Peel-Harvey estuary since 1999. These have occurred most frequently in the estuarine reaches of the Murray and Serpentine rivers.

During the October 2016 to May 2019 monitoring period, seven fish kills were reported in the Peel-Harvey estuary, all in 2017. In mid-February widespread kills were reported in the Serpentine, Murray, and Peel Inlet following the atypical February 2017 rainfall event. This was followed by three fish kills localised to the lower Murray River, and one in the Peel Inlet. No further fish kills were reported in the monitoring period up to May 2019, which was unusual. Details of these seven events are listed in the table on the next page.



2017 Fish Kill reports

Frequent and/or large-scale fish kill events can contribute to the decline in viable fish populations. Dead larger fish are a visible consequence of the stressors but there are less obvious impacts on smaller fish and earlier life stages during both these acute events and the environmental conditions preceding them. For example, scientists consider that the population status of the black bream (*Acanthopagurus butcheri*) is vulnerable within the estuarine river reaches of the Peel-Harvey estuary[46] because its Murray River habitat, characterised by near-persistent stratification and low dissolved oxygen concentrations at depth, overlaps with a spring-summer spawning period. Eggs and/or larvae may perish even before an adverse shift in environmental conditions gives rise to dead larger fish. The absence of additional fish kills in this monitoring period, especially from the Murray River, may be indicative of the scale of the detrimental effect the events of 2017 had on the fish populations – causing death and displacement of the spawning population and loss of recruits.

[46] Hallet C et al. 2019, *Assessing the health of the Peel-Harvey Estuary through its fish communities*. Balancing estuarine and societal health in a changing environment ARC Linkage Project LP150100451 Centre for Sustainable Aquatic Ecosystems, Murdoch University, Perth WA.

	Date	Event	Possible cause
1	13–19 February 2017	Murray River — black bream, yellowtail, mullet, and crabs (>>10,000s widely dispersed)	Atypical summer rainfall over region on 10 February, fish gasping, black-water event, high flow, low dissolved oxygen
2	13–19 February 2017	Serpentine River — as above	as above
3	13–19 February 2017	Peel Inlet — as above	as above
4	24–30 May 2017	Murray River — black bream, whiting, Perth herring, trumpeter (~30,000)	Low dissolved oxygen, turbid water, H_2S (hydrogen sulfide) and NH_3 (ammonia) odours
5	9–13 June 2017	Murray River — black bream (~300)	Followed rainfall and cooler temperatures (possible temperature inversion), H_2S (hydrogen sulfide) and NH_3 (ammonia) odours; low dissolved oxygen
6	25–26 June 2017	Murray River — black bream, Perth herring (~100)	Followed rainfall three days prior, strong ebbing tide, turbid water, low dissolved oxygen, some potentially harmful algae present
7	28 August 2017	Peel Inlet — primarily species living close to estuary sediment (~12)	Following rainfall, possibly rapid change in dissolved oxygen, salinity

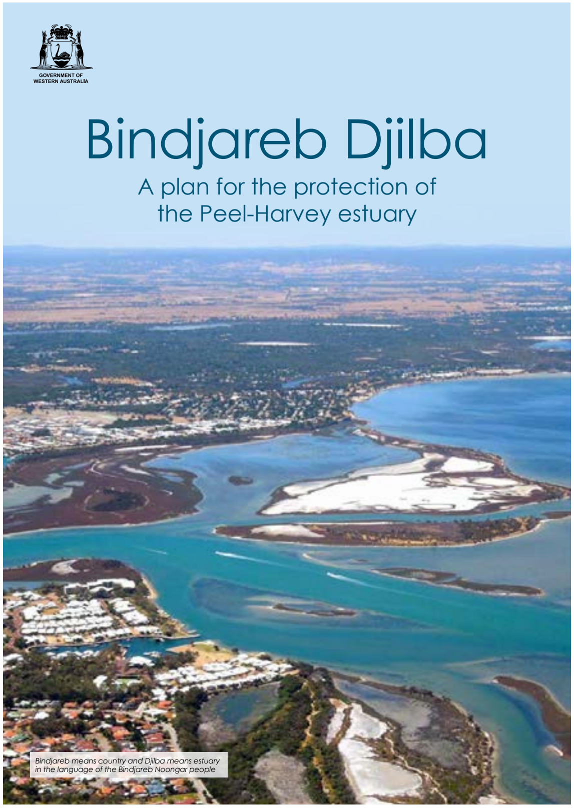
Bindjareb Djilba Protection Plan and Gabi Warlang Bidi Water Quality Improvement Plan

Despite the success of the Dawesville Channel in improving the water quality of the main basins of the Peel-Harvey estuary, monitoring results clearly demonstrate the persistent, poor water quality in the estuarine reaches of the Murray and Serpentine rivers that leads to algal blooms, fish kills and loss of amenity. Reduced river flows coupled with unchecked inflow of nutrients will lead to extension of poor water quality into the main basins.

For these reasons, the *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary (DWER 2020)*[47] was developed to protect the values of the Peel-Harvey estuary. The protection plan identifies practical actions to be delivered through a whole-of-government response incorporating more than 30 years of learnings. The main challenge is to link water quality outcomes to planning and development activity.

The protection plan is a 10-year plan of action to be implemented in phases and will have a strong focus on working with Traditional Owners.

The *Gabi Warlang Bidi – Water Quality Improvement Plan for the Peel-Harvey estuary system* (in prep)[48] is a much more detailed support document that describes the management actions required to improve the water quality of the Peel-Harvey estuary and its streams and drains, informed by our understanding of how the estuary responds to climate change and delivered nutrients.



[47] Department of Water and Environmental Regulation 2020, *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary*, Perth, Western Australia. Available at: www.wa.gov.au/government/publications/peel-harvey-estuary-protection-plan-bindjareb-djilba.

[48] Department of Water and Environmental Regulation (in prep), *Gabi Warlang Bidi Water Quality Improvement Plan for the Peel-Harvey estuary system. Where to from here?* Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

Outlook

Nutrient pollution and the future drying climate scenario threaten the health of estuaries along the south-west coast of WA.

Overall, the main basins of the Peel-Harvey estuary had good water quality free from persistent symptoms of nutrient enrichment. However, the southern Harvey Estuary is vulnerable with a decline in water quality evidenced by hypersalinity – reflective of reduced oceanic exchange and inflows, elevated nutrient concentrations in comparison to the other estuary zones, and occurrence of potentially harmful microalgae species at higher densities. The estuarine reaches of the Murray and Serpentine rivers are unhealthy with each river system displaying different but distinctive symptoms of nutrient enrichment which affect most of the estuary's values.

Over the past 20 years, river flows to the estuary reduced by a staggering 50 per cent – a pattern predicted to continue under a drying climate.[49] Nutrient loads will appear to decline, falsely suggesting an apparent improvement in water quality, but nutrients reaching the estuary will persist for longer, fuelling instability in the ecosystem. This coupled with warmer temperatures accelerating microalgal growth, salinisation through evaporation, intrusion of marine waters into fringing wetlands and further upstream in rivers owing to sea-level rise, will all drive changes to the region's flora and fauna.

Predictions for increased frequency of storm events[50 51] pose risk to sustaining the improved water quality conditions observed in the Peel and Harvey main basins post-Dawesville Channel construction. Witnessed in this monitoring period, unseasonal summer rainfall caused displacement of poor-quality water from the estuarine reaches of the Serpentine and Murray rivers, disrupting physical conditions and causing extensive fish kills of highly valued species.

Results of the estuary monitoring program underpin the importance of multi-scale integrated catchment management of nutrient inflows and continued commitment to actions already underway in the Peel-Harvey subcatchments for better water quality outcomes. Examples of this include use of soil amendments in agricultural catchments, clay trials for agricultural drains, stream restoration and stock exclusion fencing, improved dairy effluent management, and drainage works. Such actions have been informed by over 30 years of accumulated scientific understanding of influences upon and response of the estuary ecosystem. Practical on-ground action must be supported by planning processes, guiding appropriate siting of 'agricultural-intensive' and 'animal-husbandry – intensive' land uses, and innovations to transition agricultural systems to closed or zero discharge of nutrients.[52] Working to achieve the required nutrient reductions will support the resilience and adaptation of the ecosystem to other key stressors; the outlook for the estuarine reaches of the rivers remains especially poor otherwise.

Estuary health is essential to support the Peel region's ecological and conservation values, the lifestyle and wellbeing of its community including cultural and spiritual heritage, and for the sustainable growth of all sectors of its economy. A good scientific understanding of the fate and effect of delivered nutrients to the estuary over time is essential to informing beneficial management practice and adapting to climate change. Monitoring data integrated with coupled catchment-estuary modelling will provide the scientific base essential to achieving improved and stable water quality in the Peel-Harvey estuary.[53]

[49] Petrone K et al. 2010, 'Streamflow decline in southwestern Australia, 1950–2008', Geophysical research letters, *Hydrology and land surface studies*, 37(11). Available at: agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL043102

[50] Bureau of Meteorology 2022, *State of the Climate 2022–Australia's changing climate*, BOM website, accessed 30 November 2022. Available at: www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml

[51] Department of Water 2015, *Selection of future climate projections for Western Australia*, Water Science Technical Series, report no. 72, Department of Water, Western Australia

[52] Department of Water and Environmental Regulation 2020, *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary*, Perth, Western Australia. Available at: www.wa.gov.au/government/publications/peel-harvey-estuary-protection-plan-bindjareb-djilba

[53] Coupled catchment-estuary model developed by the Australian Research Council (ARC) Linkage project *Balancing estuarine and societal health in a changing environment* (Valesini et al. 2019, *Balancing estuarine and societal health in a changing environment*, [unpublished report], Murdoch University, Perth, Western Australia). The model is being further optimised by Department of Water and Environmental Regulation to support management decision making and to understand the range of climate change possibilities and adaptations.

More information

The long-term catchment and estuary monitoring reporting here started in 2016 with the Regional Estuaries Initiative and continues through the Healthy Estuaries WA program which also delivers a range of nutrient-reduction activities in the Peel-Harvey catchment. The scientific understanding, along with many decades of practical experience, underpins the recommended actions to improve estuary water quality in the *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary (2020)*[54] and the closely linked *Gabi Warlang Bidi – Water Quality Improvement Plan for the Peel-Harvey estuary system* (in prep)[55] which provides background information and catchment modelling results to support the actions.

Some key activities include:

- Working with farmers and the Peel-Harvey Catchment Council to restore stream function, moving stock away from waterways and implementing river action plans in partnership with the Peel-Harvey Catchment Council.
- Working in partnership with the Department of Primary Industries and Regional Development, industry, farmers, and the Peel-Harvey Catchment Council to reduce nutrient runoff from farmland through improved fertiliser management practices, while supporting farm productivity.
- Working in partnership with Western Dairy and industry to support dairy farmers to improve dairy effluent management practices and implement the revised *Code of Practice for Dairy Farm Effluent Management WA (2021).*[56]
- Trialling new materials to treat soil and water to bind phosphorus and reduce nutrient export to the estuary. For example, we trialled the application of a phosphorus-binding clay slurry on the Punrak Drain to reduce the phosphorus concentration of water flowing downstream to the estuary.
- Trialling new approaches to drain design in projects led by the Peel-Harvey Catchment Council that saw the construction of weirs on agricultural drains in the Mayfield catchment and diversion of water from the Peel Main Drain into six swales, seeking to slow the flows and reduce the flow of nutrients and organic matter to the estuary.

For more information on Healthy Estuaries WA and the Peel-Harvey Estuary visit estuaries.dwer.wa.gov.au/estuary/projects/

[54] Department of Water and Environmental Regulation 2020, *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary*, Perth, Western Australia. Available at: www.wa.gov.au/government/publications/peel-harvey-estuary-protection-plan-bindjareb-djilba

[55] Department of Water and Environmental Regulation (in prep), *Gabi Warlang Bidi Water Quality Improvement Plan for the Peel-Harvey estuary system. Where to from here?* Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.

[56] Western Dairy 2021, *Code of Practice for Dairy Farm Effluent Management Western Australia. Western Dairy, Western Australia*. Available at: www.dairyaustralia.com.au

What you can do

Farmers

Base fertiliser management decisions on soil test results.

Fence streams from livestock and restore native vegetation.

Homeowners

Adopt best fertiliser practice in your gardens.

Plant natives.

Local communities

Stay informed through the Healthy Estuaries website and community presentations.

Join your local catchment group.

Report algal blooms and unusual fish deaths.

Find out how at estuaries.dwer.wa.gov.au/participate

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HEALTHY ESTUARIES WA