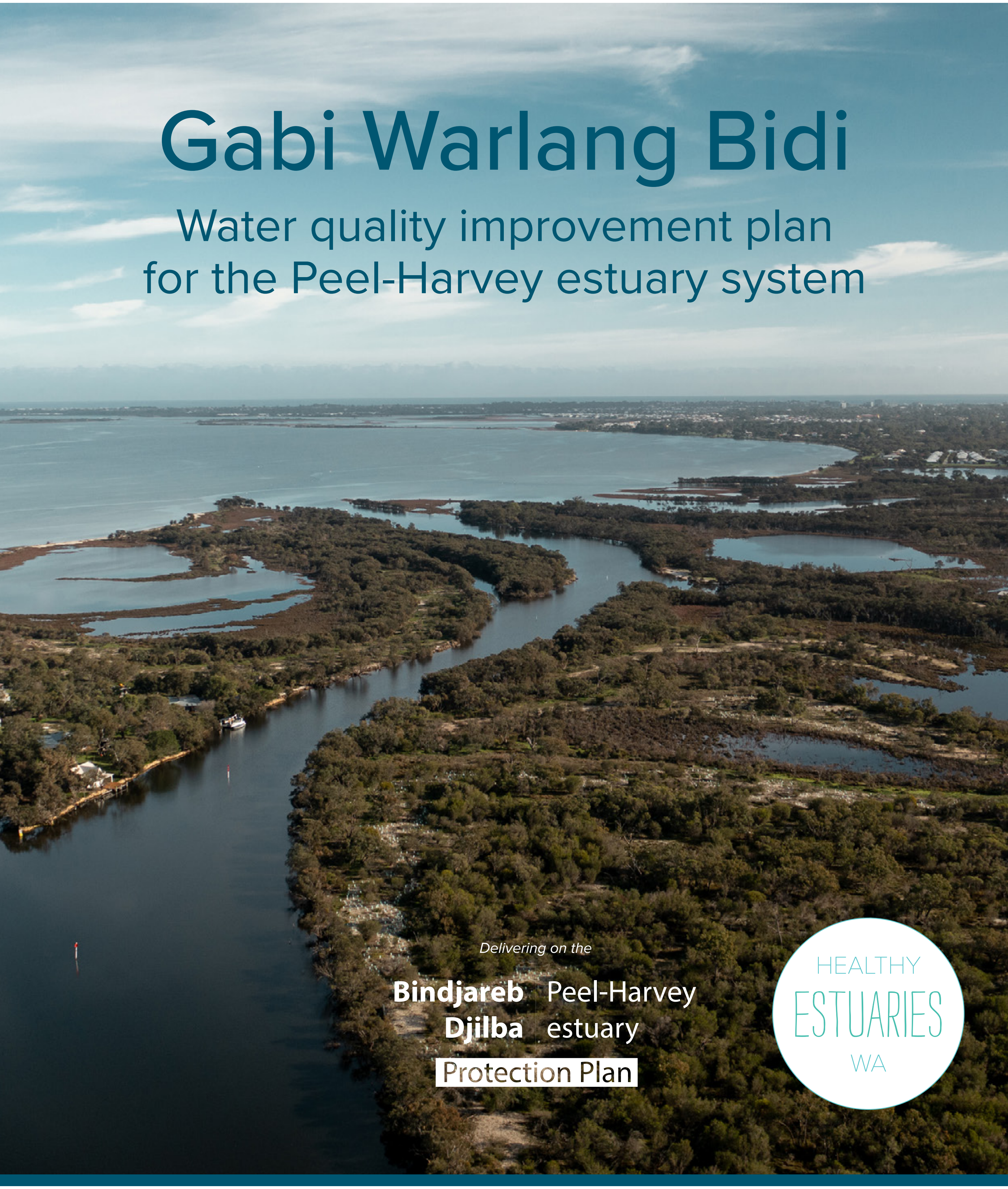
Government of **Western Australia**
Department of **Water and Environmental Regulation**

Gabi Warlang Bidi

Water quality improvement plan for the Peel-Harvey estuary system



Delivering on the

Bindjareb Djilba Peel-Harvey estuary Protection Plan

HEALTHY ESTUARIES WA

January 2025

#WAestuaries

Acknowledgement of Country

The Department of Water and Environmental Regulation acknowledges the Bindjareb people of the Noongar nation as the Traditional Owners of the lands and waters covered by this plan. We pay our respects to their Elders past and present, and we recognise the practice of intergenerational care for Country and its relevance to our work. The Bindjareb Noongar people have looked after the Djilba (estuary) for more than 50,000 years based on governance and lore. Bindjareb Noongar people have a continuing life commitment and cultural responsibility to the preservation of the Djilba (estuary) and Bilya (rivers).

Gabi Warlang Bidi

Gabi (all water) is important and connected in Bindjareb boodja (country): Gabi of the djilba (estuary), the three rivers (bilya), associated wetlands, and groundwater.

This plan provides a bidi (pathway) to improve the quality of gabi (all water) to warlang (heal) and protect the Bindjareb Djilba for our future. Gabi Warlang Bidi.

Bindjareb water story by Bindjareb Cultural Knowledge Holder George Walley

"Bindjareb Noongar baalap kaadadjan, Djilba Gabi ngalang Gabi Wonga. Nyitting yey, nidja yey, benang yey, ngalang Gabi Wonga boola moorditj. Nidja Wirrn Boodja Baalap kaadadjan, doyntj-doyntj koorl wer Noongar Dandjoo, ngalang kaaleepga. Ngalang Gabi waalang, ngalang wirrn waalang, ngalang Noongar waalang, ngalang koort waalang, ngalang kaaleepga waalang."

Bindjareb Noongar people's cultural knowledge about our estuary is our water story. From the creation time to the present time, to the future, our water story is a very amazing and important story. The interconnectedness of Spirit, Land, and People brings together our cosmology, our sense of place, our homeland. Our waterway health is connected with our own health and wellbeing.

Fish traps have been used by Noongar people for thousands of years.
Photo credit: Daniel Wilkins, City of Mandurah.

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Cover photograph: Peel Inlet and Yunderup Islands. Photo credit: Andrew McKenzie (Splendid Films) courtesy of the Peel-Harvey Catchment Council.

Uncredited photos throughout the plan are credited to the department – thanks to the Aquatic Science Branch and Communications Branch.

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Summary

The Peel-Harvey estuary (Bindjareb Djilba) and its tributaries, catchment and interconnected wetlands are highly valued for their diverse and unique ecology, aesthetic, recreational and tourism opportunities, abundant fisheries, and rich cultural and spiritual connections. It is the largest and most complex estuarine system in the South West, being part of the Peel-Yalgorup wetland that is recognised as an internationally significant habitat for waterbirds (Ramsar Convention 1971).

For many Western Australians the Peel-Harvey estuary is iconic. It is central to the Peel region, with its rapidly growing urban population and multiple surrounding agricultural land uses. Thousands of jobs and billions of dollars of investment depend on the estuary's health. It is the hub for educational and scientific activities, recreation and eco-tourism in the region. The relationship between Bindjareb Noongar people and the Djilba (estuary) and the depth of their cultural responsibility for its preservation cannot be overstated.

This water quality improvement plan (WQIP) brings together our current understanding of the health of the Peel-Harvey estuary. Insights and predictions from recent modelling show where we need to focus management actions and what strategies are likely to be most effective.

The Peel-Harvey estuary suffered ecosystem collapse in the 1970s. This was characterised by prolific blooms of macroalgae (which had to be physically removed with marine harvesters), loss of seagrass, fish kills and toxic cyanobacteria (*Nodularia spumigena*) coverage visible from space. The collapse was undeniably a result of massive modifications to the catchment and its hydrology. Extensive draining of wetlands and seasonally inundated lowlands, along with the widespread clearing of native vegetation for agriculture on poor-nutrient-retaining soils, led to very high nutrient loads going into the estuary.

Public pressure demanded a coordinated approach to restore the health of the estuary. The *Peel Inlet and Harvey Estuary management strategy* (EPA 1985) was approved in 1989 with two main components for action: construct an artificial opening to the sea and develop and implement an integrated catchment management plan to reduce the flow of nutrients to the estuary.

The resulting Dawesville Channel (or otherwise known as the Cut) was an engineered solution of mammoth scale. The channel was constructed between 1990 and 1994 and cost about $37 million. The 2.5 km long, 200 m wide artificial opening increased the exchange of water between the estuary and the ocean, flushing nutrients out to sea and increasing the estuary's salinity.

The Environmental Protection Authority (EPA) reviewed the management strategy in 2003. It found that the Dawesville Channel had successfully reduced nutrient concentrations in the estuary, but that the integrated catchment management plan aimed at addressing the cause of the problem had not progressed. Eventually the *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management* (EPA 2008b) (referred to as the 2008 WQIP) was

developed in a collaborative effort between State Government agencies, the Australian Government and the community. Importantly, it was informed by a process-based catchment model that identified sources of nutrients and enabled the effectiveness of catchment actions to be predicted and assessed. The 2008 WQIP outlined priority management actions for water quality improvement, emphasised the importance of linking land use planning decisions to water quality, and recommended modernisation of the *Environmental Protection (Peel Inlet and Harvey Estuary) Policy 1992* and the *Statement of Planning Policy 2.1: Peel-Harvey coastal plain catchment* (WAPC 1992) to make them more effective and easier to implement.

The concerted efforts of State Government departments, the Peel-Harvey Catchment Council, local governments, Water Corporation, the Peel Development Commission and community groups to implement the 2008 WQIP saw substantial shifts in behaviour and improvements to water quality – most notably in relation to agricultural and urban point sources of nutrients. Yet the lack of long-term funding and appropriate coordinating mechanisms has hindered progress. There is still much to do – particularly given the ever-increasing pressures of urban growth and agricultural intensification, and the effects of climate change.

The ambitious strategic assessment of Western Australia's Perth and Peel regions put a spotlight on the linkages between development and land use planning and environmental outcomes. Approvals under the *Environmental Protection and Biodiversity and Conservation Act 1999* required an assessment of estuary condition with respect to water quality and Ramsar values in negotiations between the Australian and State governments. The EPA provided comprehensive guidance to this process through *Perth and Peel @ 3.5 million: Environmental impacts, risks and remedies* (EPA 2015).

The Regional Estuaries Initiative (REI) was instigated in 2016, with a focus on improving water quality in six at-risk estuaries, including the Peel-Harvey estuary, through targeted management actions. Working with the benefit of scale and synergies across catchments, the REI provided consistent funding over four years to implement an array of nutrient reduction actions and evaluate their effectiveness. Healthy Estuaries WA continues the work of the REI, with ongoing funding to support the implementation of many of the proposed actions in this plan.

In 2020, the State Government launched *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020b) (referred to as the *Bindjareb Djilba Protection Plan).* This brought renewed attention to the specific challenges for the Peel-Harvey estuary and outlined a clear path to work together for its protection and management over 10 years. This WQIP documents in greater detail the data summarised in the *Bindjareb Djilba Protection Plan*, provides evidence to support the plan's actions and expands on how best to implement priority actions.

This WQIP builds on the lessons learnt since the 2008 WQIP. Since then, we (the Department of Water and Environmental Regulation) have developed a hydrological and nutrient model of the Peel-Harvey catchment which identifies nutrient sources by land use and estimates the effectiveness of various management actions in the catchment.

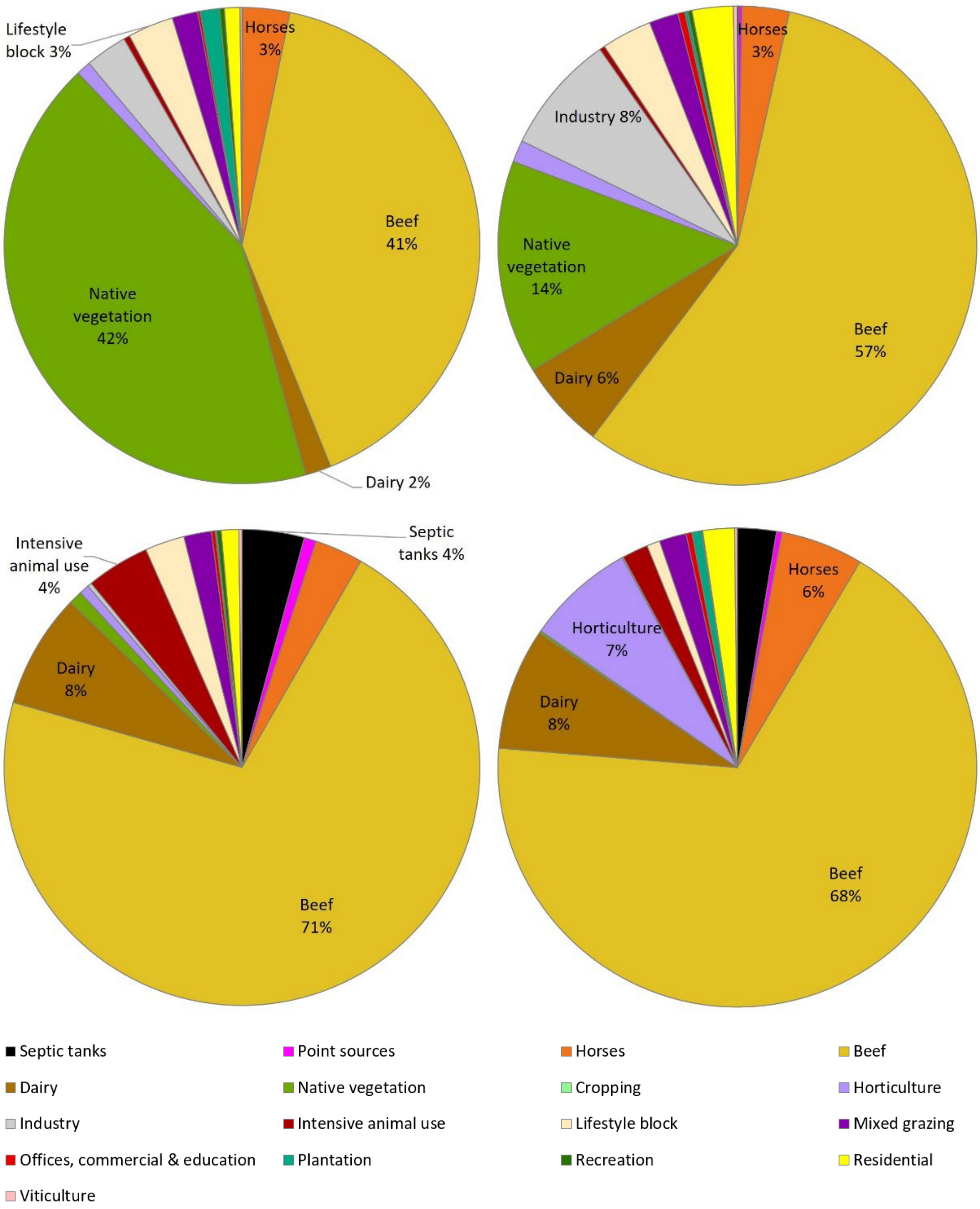
The first chapter of this WQIP summarises the history of changes in land use, management practices and water quality since European settlement began in the early 1800s. Chapters 2 and 3 describe the Peel-Harvey estuary, its tributaries and catchment area and summarise their water quality and ecological condition. Chapter 4 outlines our vision for the estuary, the community values, management goals and water quality objectives. Chapter 5 summarises the major pressures on the estuary. Chapter 6 discusses balancing the needs of water users and allowing for adequate environmental flows. Chapter 7 discusses the hydrological and nutrient model and estimates the nutrient concentrations and loads originating from each reporting catchment, guiding management action priorities and what land uses to focus on. The model also predicts how future pressures may affect nutrient loads, which are presented in Chapter 8. Chapter 9 brings together all the recommended actions and highlights where and how they could make a difference and quantifies nutrient load reductions where estimates are available from modelling. Chapter 10 identifies research needs and recommends how these may best be addressed.

The Peel-Harvey estuary has received plenty of research attention since the dramatic intervention of the Dawesville Channel, and the conclusions are disturbingly similar. Nutrients and organic matter continue to be lost from agricultural land to waterways, with very poor water quality in the riverine portions of the estuary – the Serpentine River as far as Lake Amarillo, the Murray River to Pinjarra, and the warm, shallow waters near the mouth of the Harvey River. Although the total amount of nutrients that end up in the estuary has reduced because flows are lower, nutrient concentrations remain high. Most of the nutrient load (calculated by multiplying concentration by flow) settles in the riverine portions where algal blooms and fish kill events remind us of the ecological implications of nutrient enrichment.

Elsewhere in the estuary, increasing amounts of macroalgae suggest a return to more eutrophic conditions. This is a cause for concern, especially for people who remember the macroalgal blooms of the 1970s and the subsequent collapse of the ecosystem. Murdoch University’s Fish Community Index shows poor fish community health in the shallower waters of the Peel Inlet and Mandurah Channel, the deeper waters of the eastern Peel Inlet, and the lower Serpentine and Murray rivers. In these areas, the fish communities have lower species diversity and are dominated by detritivores. These low scores are not entirely because of poor water quality and may reflect factors including the loss of nursery and feeding habitat (e.g. saltmarsh). On the other hand, there are positive signs in the distribution and density of seagrass meadows – these have responded well to the clearer waters brought about by the increased marine exchange from the Dawesville Channel.

The water quality and biotic indicators summarised in this WQIP remind us that the protection of the Peel-Harvey estuary depends not just on improving water quality but also on protecting and restoring river, estuary, and fringing habitats.

We used the hydrological and nutrient model (Hennig et al. 2021) to quantify nutrient export from the catchment to the estuary. Comparing land use areas with their contributions to nutrient load helps to identify what land uses should be prioritised for actions to reduce export (Summary figure 1-1).



Summary figure 1-1 The contribution of each land use to the area, flow and annual nutrient loads for all reporting catchments on the coastal plain that drain to the Peel-Harvey estuary

Grazing for beef contributes 393 tonnes (62 per cent) of the nitrogen (N) and 40 tonnes (67 per cent) of the phosphorus (P) load even though it only occupies 11 per cent of the catchment area. Cropping (12 per cent), dairy farming (7.8 per cent), intensive animal industries (3.8 per cent) and septic tanks (3.7 per cent) are the next largest contributors to the N load. Intensive animal uses export the largest N loads per unit area. After beef grazing, the main contributors to the P load are dairy farming (8.1 per cent), horticulture (7.3 per cent), horses (5.5 per cent) and septic tanks (2.6 per cent). In-ground horticulture is by far the largest exporter of P per unit area.

We also used the hydrological and nutrient model to estimate how nutrient loads would be affected by catchment management actions, modifications to land use and the impacts of climate change. The model predicts the most effective management actions for reducing the P and N loads reaching the estuary. It also points to what combinations of management actions would enable the water quality objectives (WQOs) for catchment nutrient concentrations to be met over time.

We used the model to calculate the load reductions required across all the reporting catchments to meet the WQOs for catchment nutrient concentrations of 1.2 mg/L of N and 0.1 mg/L of P – see Summary table 1-1.

Summary table 1-1 Current and acceptable nitrogen and phosphorus loads for the Peel-Harvey estuary from the coastal plain portion of the catchment

Nitrogen	
Current load (t/yr)	552
Acceptable load (t/yr)	293
Required reduction (t/yr)	259
Required reduction (%)	47%
Phosphorus	
Current load (t/yr)	59
Acceptable load (t/yr)	24
Required reduction (t/yr)	35
Required reduction (%)	59%

We modelled catchment management actions to estimate subsequent changes in nutrient loads to the estuary. No single management action is predicted to meet the WQOs for catchment nutrient concentrations, but there are combinations which get us very close. If the following actions were implemented on beef and dairy farms across the coastal plain of the Peel-Harvey estuary, we predict the average annual P load to the estuary would reduce to 25 t (58 per cent reduction) – very close to the target load of 24 t (59 per cent reduction):

- optimise fertiliser use matched to agronomic need and use slow-release P fertiliser on low P retention index (PRI) soils
- apply soil amendments to low PRI soils
- apply best-practice effluent management within all dairy operations (i.e. meet the *Code of practice for dairy farm effluent management WA* (2021)).

If we then add a suite of non-agricultural management actions for reducing N loads to the estuary, the average annual P and N loads to the estuary are estimated to reduce to 20 t (67 per cent reduction) and 358 t (35 per cent reduction) respectively, meeting the P load target and getting close the N load target (Summary figure 1-12).

These actions include:

- target revegetation of land used for grazing and replant with deep-rooted native species (24,770 ha, preferentially replacing beef/dairy farms on low PRI soils)
- build fences to exclude stock and revegetate riparian zones along 1,394 km of waterways and drains
- minimise discharge of point sources (including piggeries, feedlots and stockyards) to waterways and drains
- decommission septic tanks located in environmentally sensitive areas and connect those properties to reticulated sewerage (1,074 units)
- retrofit all urban areas using water sensitive urban design (WSUD) principles.

As the N load target is based on total nitrogen (TN), and much of that is dissolved organic nitrogen (DON), further work is needed to ascertain the bioavailability of DON and potentially identify alternative approaches to addressing N export to the estuary.

The management actions described above – such as revegetating the catchment with deep-rooted native species and fencing and revegetating riparian zones – also have significant ecological benefits, including increased biodiversity and resilience to climate change.

Numerous assumptions are associated with the scenarios modelled. For example, the mining by-products used for broadscale soil amendment have limited commercial availability at present. In addition, supporting farmers to modify the way they use and apply fertiliser will take time.

The model was also used to predict changes in nutrient load under indicative development scenarios, including the conversion of 3,000 ha of beef farming to conventional in-ground horticulture in the Nambeelup reporting catchment.

The Nambeelup catchment was at the centre of a study led by the Department of Primary Industries and Regional Development (DPIRD) to assess whether intensifying agricultural productivity in the Peel region was feasible, as part of the Transform Peel program (Peel Food Zone). The Nambeelup catchment requires the greatest load reductions of all the catchments that drain to the estuary (69 per cent reduction for N and 84 per cent for P). DPIRD's analysis of the land capability for the

Peel Food Zone, under the Peel Integrated Water Initiative (GHD 2017), confirmed that most soil types in the zone study area (around the Nambeelup catchment) were not suitable for irrigated in-ground agriculture because of high nutrient export risks.

The modelled scenario supported these conclusions. The conversion of 3,000 ha of beef farming to conventional in-ground horticulture was predicted to increase P loads from 7 t/yr to 29 t/yr from the Nambeelup reporting catchment – an overall increase of P load to the estuary of 38 per cent. The scenario highlights that the intensification of agriculture on the low P-binding soils of the estuary coastal plain are only feasible if innovative approaches that avoid nutrient losses, such as closed agricultural systems are applied (e.g. closed loop, fully autonomous, vertical smart farms).

Summary figure 1-2 Comparison of reducing nutrient export under selected management scenarios and the combined scenarios as described above (Hennig et al. (2021)

This WQIP outlines a range of management actions which, if taken together, have the potential to prevent a further decline in estuary health and improve water quality. The management actions have various aims; that is, to reduce nutrient losses from current practices, minimise future losses through new urban and agricultural developments, improve ecological health (which may improve water quality indirectly), and measure and report on changes to water quality and progress towards implementing this WQIP.

We make the following recommendations based on the collective knowledge gained from 25 years' experience, measures of effectiveness and a cost-benefit analysis to provide assurance that the actions are practical and feasible.

The recommended catchment actions that target nutrient reduction are already underway as part of the *Bindjareb Djilba Protection Plan* (DWER 2020b). This WQIP underpins the *Bindjareb Djilba Protection Plan*, providing a broader and more detailed description of the environmental issues at play in the estuary catchment and documenting the scientific evidence of the management actions. Funding provided for both Healthy Estuaries WA and the *Bindjareb Djilba Protection Plan* (DWER 2020b) will support implementation of this WQIP.

Improved management of diffuse agricultural nutrients

1. Reduce phosphorus fertiliser losses by optimising fertiliser use to agronomic requirements, as determined by soil testing, agronomic advice (or DPIRD's nutrient calculator) and demonstration trials.[1]
2. Continue to develop and use fertiliser products that meet the needs of farmers on sandy coastal soils, as indicated by soil and plant tissue testing, including slow-release phosphorus fertilisers.
3. Reduce losses of nitrogen by working with farmers to encourage best-practice application of nitrogen fertilisers.[2]
4. Improve phosphorus retention in sandy soils used for intensive and broadscale agriculture by using soil amendments.
5. Develop new best-management practices for broadscale agriculture to encourage holistic management and regenerative agriculture principles that improve soil health, use water efficiently, maintain soil cover and support the *State Soil Health Strategy, Western Australia* (DPIRD 2021).

   In conventional broadscale agriculture, reduce fertiliser losses and erosion through improved whole-of-farm management practices, including the use of perennial pastures to avoid bare soils.
6. Conserve water and reduce nutrient runoff from irrigated agriculture by requiring Nutrient Irrigation Management Plans (NIMPs) as part of planning approvals and water licensing processes and applying best management practice to irrigation design to achieve appropriate pressure, reach and uniform distribution. Irrigation scheduling should carefully consider soil moisture content and local evaporation rates.

[1] See DPIRD Phosphorus for high rainfall clover pastures in Western Australia; and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

[2] See DPIRD Nitrogen for high rainfall pastures in Western Australia; and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

7 Help farmers and other landholders exclude stock from waterways and drains to reduce erosion and the input of sediment and organic matter to the estuary and its tributaries.
Linked to recommended action 19.

Improved management of point source agricultural nutrients

8 Industry to consider integrating drainage networks with engineered, constructed wetlands to reduce the export of intensive, diffuse sources of nutrients, such as those from free-range chicken farms, rotational outdoor piggeries (free-range and outdoor bred), and irrigated horticulture.

9 Improve effluent management within dairy operations to minimise discharge and maximise reuse of water and nutrients to standards in the code of practice.
Linked to recommended action 28.

10 Manage effluent, stormwater and other sources of nutrients from intensive animal industries (e.g. piggeries, poultry sheds, feedlots and abattoirs) to national or international best-practice standards.
Linked to recommended actions 25–28.

11 Develop and implement intensive horticulture best-management practices suited to high-nutrient-leaching environments, including optimising fertiliser use to agronomic requirements, as determined by soil testing and agronomic advice, and investigating the feasibility of implementing closed agricultural systems (annual horticulture).[3]
Linked to recommended action 26.

Improved management of diffuse urban nutrients

12 Help householders improve water use efficiency in existing urban gardens and minimise nutrient export risk through the Waterwise Council Program and other waterwise education programs (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).

13 Public open space managers to reduce nutrient application (fertiliser and others) and export risk, and improve water efficiency in existing public open space (see Waterwise Council Program and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).

14 Developers of new urban land and public open space should evaluate and use soil amendments to reduce phosphorus losses in areas with sandy soils that have low phosphorus retention.

15 Target upgrades to existing stormwater systems in priority areas according to water sensitive urban design principles (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).
Linked to recommended actions 16, 31 and 32.

[3] See DPIRD Horticulture.

16 Increase training and development opportunities for local government and the stormwater management industry to adopt water sensitive urban design principles.
Linked to recommended actions 15, 31 and 32.

Improved management of point source urban nutrients

17 Increase the reuse of treated wastewater from wastewater treatment plants[4] on green spaces where there is a low risk of leaching into waterways and promote the reuse of wastewater within the industrial (e.g. mining) and agricultural sectors by identifying opportunities and addressing barriers.

18 Encourage the replacement of existing septic systems by way of connection to a reticulated sewerage network, where available. If reticulated sewerage is not available, a secondary treatment system with nutrient removal capability should be fitted.
Linked to recommended action 30.

Drainage works and in-stream management to improve water quality

19 Implement the 2017 Drainage Partnering Agreement between Water Corporation, the Department of Water and Environmental Regulation and the Peel-Harvey Catchment Council.
Linked to recommended action 7.

20 For all drains across the catchment, evaluate approaches (e.g. in-drain vegetation and sediment traps) to improve water quality in drains that discharge to the Peel-Harvey estuary and its tributaries. Implement approved approaches in prioritised drains.

21 Investigate, develop and evaluate the use of innovative materials for phosphorus removal in drains, including phosphorus-binding clays.

Other management actions to improve water quality and biodiversity

22 Reinstate the ecological function of key waterways through restoration works and revegetation of the riparian zone.

23 Undertake strategic revegetation of the catchment to improve biodiversity, mitigate climate change effects, and contribute to water quality improvement.

Planning and policy actions

24 Implement a contemporary statutory framework to achieve water quality improvements in the Peel-Harvey estuary by revising the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* or replacing it with an appropriate alternative.

[4] Also known as Water Resource Recovery Facilities.

25 Ensure land planning decisions are consistent with relevant State Government and local government policies for the health of the Peel-Harvey estuary.[5] New planning or development proposals – in particular, intensive land uses such as in-ground horticulture, poultry farms, piggeries and feedlots – should not be in areas prone to nutrient export unless they can demonstrate that nutrient inputs can be met to achieve the maximum acceptable nutrient loads to the estuary: 45 kg N/cleared ha/year and 6.5 kg P/cleared ha/year (Section 7.5), or updated nutrient input rates that the State Government may publish in the future.[6]

Existing industry should comply with all relevant local, state and national policies and guidelines that relate to their industry.

Linked to recommended action 10.

26 In areas prone to nutrient export, investigate and support the transition of intensive land uses to closed agricultural systems, with zero discharge of nutrient-rich liquid or solids to the immediate environment.

Linked to recommended actions 10 and 11.

27 Develop guidance material for agricultural and intensive animal industries to align and integrate with relevant state planning policies, the *Peel Regional Scheme – Priority agriculture and rural land use policy* (WAPC & DPLH 2017) and *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*.

Linked to recommended action 10.

28 Review regulation of point source discharges from agricultural activities (e.g. dairy sheds, piggeries, feedlots) to ensure treatment to national best-practice before discharge to the environment.

Linked to recommended actions 9 and 10.

29 Reduce or eliminate discharges to waterways through a review and update of licensing and works approval requirements for prescribed premises/activities.

30 Implement the sewerage and on-site wastewater management provisions in the *Government Sewerage Policy* (Government of Western Australia 2019a), *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b).[7]

Linked to recommended action 18.

31 Apply water sensitive urban design principles in new urban and industrial developments to ensure all changes in land use will reduce nutrients entering

[5] Including state planning policies, *Horticulture development local planning policy* (Shire of Murray 2018a), *Local Planning Policy 4.12: Horticulture* (Shire of Serpentine Jarrahdale 2018b), *P004 – Local Planning Policy 4 – Intensive agriculture* (Shire of Waroona 2021), the Peel Region Scheme and the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*, *Model Local Planning Policy – Horticultural development in the Peel-Harvey Coastal Plain Catchment* (PHCC 2023).

[6] 'Intensive land uses' are defined here as intensive animal industries, intensive horticulture, and premises with livestock numbers higher than recommended stocking rates.

[7] The *Government Sewerage Policy* (Government of Western Australia 2019a) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for Water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are published.

the estuary (aligned with *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).

Implement:

- relevant state planning policies
- *Better urban water management* (WAPC 2008)
- *Stormwater management manual for Western Australia* (DoW 2004–07)
- *Decision process for stormwater management in Western Australia* (DWER 2017a).

Use the UNDO (Urban Nutrient Decision Outcomes) tool when assessing new developments.

Linked to recommended actions 15, 16 and 32.

32 Update *Local planning policy for WSUD in the Peel-Harvey catchment* (Peel Development Commission 2006b) and *Peel-Harvey coastal catchment water sensitive urban design technical guidelines* (Peel Development Commission 2006a) to reflect current best practice.

Linked to recommended actions 15, 16 and 31.

33 Protect waterway vegetation:

- identify and map remnant waterway vegetation
- identify and protect waterway foreshore areas consistent with *Operational policy: Identifying and establishing waterway foreshore areas* (DoW 2012b) and *Determining foreshore reserves* (Water and Rivers Commission 2001a)
- protect water quality by providing an additional separation distance between potentially polluting intensive land uses and waterways, where required.

34 Protect wetlands, including their hydrology, water quality and habitats:

- identify and map wetlands
- develop and apply new wetland buffer guidelines to improve protection of wetlands identified as having ecological values
- apply wetland buffer guidelines that protect wetland values
- in addition to wetland buffers, provide further separation distance between potentially polluting land uses and wetlands to protect water quality.

35 Protect and conserve remnant vegetation in the catchment:

- develop and apply policy specific to the Peel-Harvey estuary to protect priority areas[8] of native vegetation and encourage revegetation with deep-rooted perennial species that improve water quality
- consider incorporating areas of remnant vegetation into regional parks and conservation reserves.

[8] The EPA has a mapping layer called 'Swan Bioplan – Peel Regionally Significant Natural Areas' (digital mapping, spatial dataset with explanatory notes) which identifies regionally significant areas of natural vegetation in the Peel, which helps to guide strategic land use and conservation planning.

Actions to partner with Bindjareb Noongar people to look after the estuary and rivers (from *Bindjareb Gabi Wonga:* Nannup et al. 2019)

36 Partner with Bindjareb Noongar people to arrive at a shared understanding and knowledge systems for improved catchment and estuary management:

- work with Elders to develop an agreement for Aboriginal participation and partnering in waterways planning and management of Bindjareb boodja (Bindjareb country) (*Bindjareb Gabi Wonga* action 1.1)
- develop a detailed implementation plan for the *Bindjareb Gabi Wonga* in partnership with key water stakeholders (*Bindjareb Gabi Wonga* action 1.2)
- embed Aboriginal values and Traditional Lore into water planning and management (*Bindjareb Gabi Wonga* action 1.3)
- review the legislative and policy framework, including State Government and local government policies, to implement measures to improve water quality and flows to preserve the cultural values of waterways (*Bindjareb Gabi Wonga* action 1.3.1)
- support the development of joint management responsibility opportunities for Traditional Owners to partner in the management of waterways (*Bindjareb Gabi Wonga* action 1.3.4)
- identify and consider water-dependent values of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.1)
- support initiatives that build capacity for Bindjareb Noongar partnerships in water planning and management including Aboriginal Ranger programs, Bindjareb Waterways Assessment Program, waterways protection and restoration projects (*Bindjareb Gabi Wonga* action 2.2)
- continue to undertake waterway health and scientific investigation programs to monitor the health of traditional sites and food places: the programs to include opportunities for Aboriginal participation, knowledge sharing, culture-embedded training and employment (*Bindjareb Gabi Wonga* action 2.4)
- continue to implement catchment management initiatives for water quality improvement of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.5)
- implement statutory and non-statutory mechanisms to protect traditional sites and food places (*Bindjareb Gabi Wonga* action 2.6).

Actions to assess water quality condition and measure progress

37 Continue to regularly (fortnightly to monthly) monitor the waterways and drains that flow into the Peel-Harvey estuary for assessment against the catchment water quality objectives in this WQIP, and for the calculation of nutrient status, trends and total loads.

Consider expanding the monitoring program to monitor flow and nutrient concentrations in waterways/drains in the WQIP’s reporting catchments that are currently unmonitored, ensuring alignment with the recommendations in this WQIP.

38 Continue to regularly (fortnightly to monthly) monitor water quality in the Peel-Harvey estuary including phytoplankton and nutrients and report on algal blooms. Use data to regularly track against the Water Quality Objectives in this WQIP. Use fixed instrument moorings in the Murray River to track oxygen levels and consider continuous monitoring at additional sites in the estuary.

39 Investigate the bioavailability, composition and sources of dissolved organic nitrogen and dissolved organic phosphorus across the catchment, to inform appropriate management actions.

40 Undertake seagrass and macroalgal surveys every three to five years, as a key component of ecological monitoring.

41 Undertake fish community surveys and report on changes using comparative tools such as the Fish Community Index (developed by Murdoch University)

42 Undertake periodic surveys of sediment condition and benthic invertebrate communities as indicators of changing environmental conditions.

43 Investigate the level of pesticide contamination in surface water, sediments and superficial groundwater across agricultural areas of the Peel-Harvey estuary coastal plain catchment, by monitoring pesticide chemicals across each season, over a year.

44 Periodically evaluate estuary condition (about every five years) and report to the community on observed changes, considering water and sediment quality and biotic indicators such as seagrass, macroalgae, fish community and benthic macroinvertebrate health. Annually report against the Water Quality Index (currently in draft) as a tool for communicating over-arching patterns through time and across the estuary.

45 Review recreational swimming sites within the Peel-Harvey estuary and estuarine reaches of the rivers. Consider more regular and widespread monitoring to determine if the water quality meets the standard required to protect community values associated with recreation and aesthetics.

Explore the possible efficiency gains if the departments of Health and Water and Environmental Regulation partnered to conduct microbiological water quality monitoring.

46 Use the Peel-Harvey coupled estuary-catchment model to integrate monitoring data, predict climate change implications, and guide management decisions.

47 Undertake studies to predict the impact of reduced river flows (under different climate change scenarios) on estuary water levels and estuary processes. Utilise the coupled estuary-catchment model to support such studies.

48 Update the hydrological and nutrient catchment model (Peel-Harvey Catchment Model) every five to 10 years to include changes in land use, land use practices and hydrology to help evaluate the effectiveness of nutrient reduction actions. Improve water quality model capabilities in eWater Source, so that dissolved nutrients and soil and groundwater stores of nutrients are incorporated.

49 Develop paddock-scale nutrient and water balance models to inform an understanding of nutrient losses at the local scale and to support the development of targets and guidelines.

A pre-cursor to this work is increased sampling at the outlets of paddocks to build our understanding of the relationships between water quality, land use, soil and drainage combinations.

50 Measure the effectiveness of management practices at an appropriate scale to improve hydrological and nutrient catchment model predictions and understand the response time between management actions and measurable improvements in water quality (i.e. lag time).

51 Support reporting against Ramsar Limits of Acceptable Change.

52 Report progress on implementing this WQIP to the community every five years.

53 Review and update this WQIP within 10 years.

Coordinating action

54 Establish a coordinating committee led by the Department of Water and Environmental Regulation to coordinate the policy and planning actions of the *Bindjareb Djilba – A plan for the protection Peel-Harvey Estuary* (DWER 2020b) and the aligned actions in this WQIP. This committee, supported by working groups, will share information on land development and planning proposals and collaborate with key stakeholders to support implementation of both plans.

There is a long history of inappropriate land use planning and development in the Peel-Harvey catchment, dating back to 1829. Land uses that are associated with high nutrient export have been established in areas that are at high risk of nutrient export (EPA 2015). As this WQIP's implementation requires a collaborative whole-of-government response, we need a mechanism to coordinate actions to improve water quality, especially to link planning and development decisions to water quality outcomes (see recommended action 54).

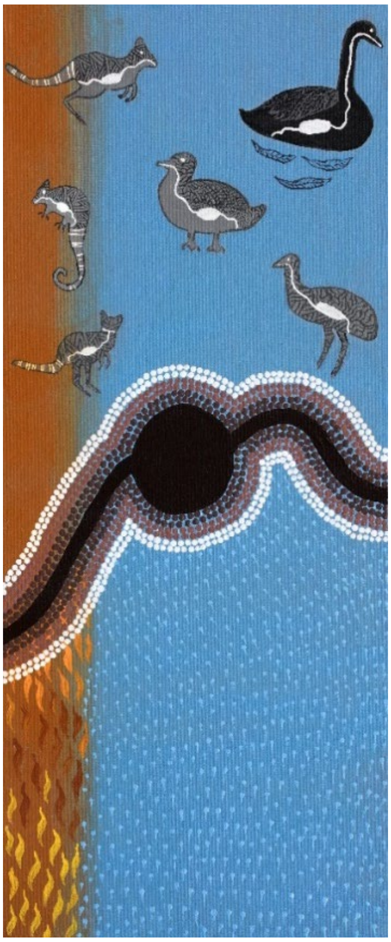
Now we are seeing a renewed focus on improving water quality in the Peel-Harvey estuary, building on the lessons of the past, while exploring new and innovative ways to manage the competing demands and pressures on this important system.

Good water quality and development are not mutually exclusive. The rebound of the local economy and increased development after construction of the Dawesville Channel show that good water quality and liveable environments underpin economic growth. As the effects of climate change worsen, it will be even more important to consider the environmental implications of new developments and look to innovative solutions to ensure future sustainability.

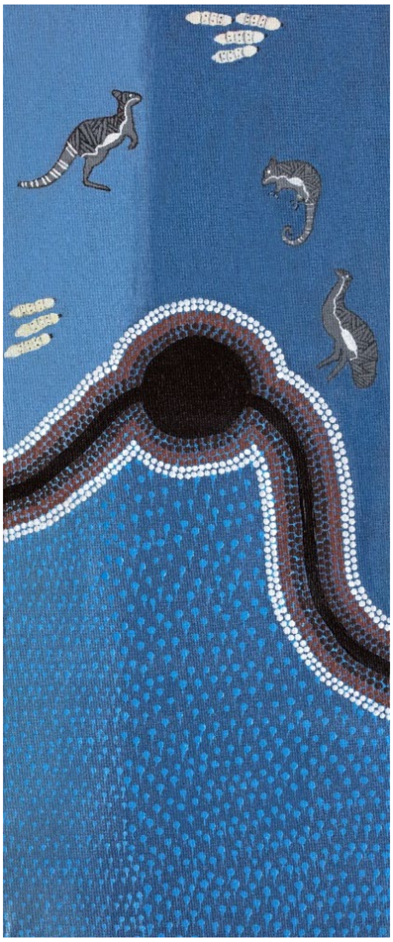
It is estimated that another ecosystem collapse would reduce the local economy by $2 to $3 billion and derail the aspirations of *Perth and Peel @ 3.5 million* (WAPC 2018a). This WQIP and the *Bindjareb Djilba Protection Plan* seek to prevent this.

The will to protect and improve the Peel-Harvey estuary's water quality is well demonstrated. However, meeting the challenges of climate change and urban and agricultural expansion will require coordinated action at a whole-of-catchment, whole-of-estuary and whole-of-government scale.

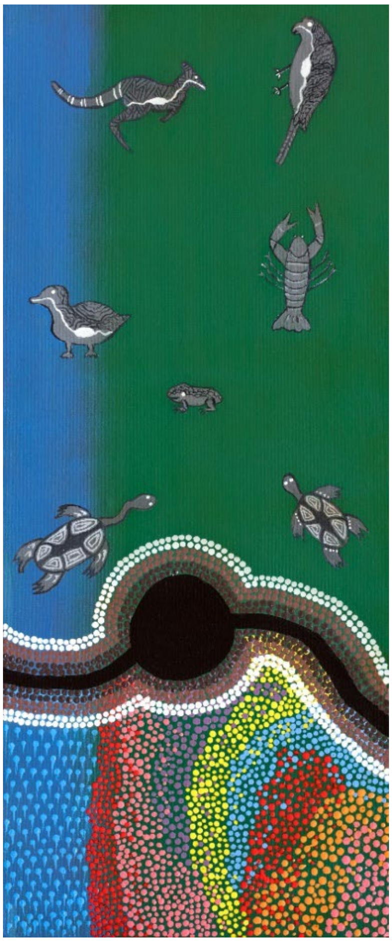
The increased attention on the Peel-Harvey estuary during the past four years offers an opportunity to consolidate the actions required over the next decade – not only to improve water quality but to enhance the community values of this extensive river, wetland and estuarine system. This WQIP provides direction but implementing the actions at scale and sustaining efforts over time is critical to protect this iconic estuarine system into the future.



Makaroo (June – July) is the time when the rain comes with the southerlies and some people stay on the (kwongan) plain and some families go to the Kaada Moornda (darkened hills known as the Darling Range). It is the time where the waterways become replenished and the coastal plain and hills are soaked which benefits plants and animals. It is time to take the bountiful supply of swan and duck eggs. After mating maali (swans) moult and become flightless for some weeks which make them vulnerable.



Djilba (August – September) is the second cold time with continued rains. The regeneration and new growth begin which continues into later seasons. It is a time where the land is refreshed and flowering plants begin to show their colours. People commence their coming back into the kwongan to experience a very wet coastal plain with rivers overflowing into the large swamp areas.



Kambarang (October – November) – the land is a visual explosion of colours from plants, and animal new births continues into the warmer seasons. The weather is warming up to have more drier days. People enjoy the abundance of plant regeneration and animal abundance. The consistent warmer weather turns the land grasses to a beige of dryness, but people take advantage of the warmer season and the bounty of bush foods and bush medicines.

Birak (December – January) is the warm time and getting hotter. The waterways have reached their peak and begin to subside through evaporation. The karil (blue manna crabs) are nearly at the right size and the kaarda (race horse goanna) have hatched and growing as they move away from their home. People enjoy the warmer weather around the waterways with marine foods and swimming.

Boonaroo (February – March) is the hottest time of the seasons. People stay close to the waterways to keep cool and for the marine foods. The karil are the right size and plentiful, the kaarda are hunted as well as the yongka (kangaroo) and wetj (emu).

Djeran (April – May) is still hot there are noticeable cooler changes in the weather and preparations are made to remake the winter shelters including the bibol (paper bark tree) bark for both the flooring and the roof. The salmon schools swim along the coast and people enjoy the beach, camping and reef spear fishing to feed families.

Noongar people’s six seasons. Artwork by Gloria Kearing, Bindjareb Noongar Elder, and account of seasons by George Walley, Bindjareb Noongar Kaadadjan Leader

1 Introduction

1.1 Setting the scene

The water quality in estuaries (where rivers discharge and meet the ocean) is closely linked to the ecological health of the whole estuary system and largely depends on conditions in the catchment (the land surrounding and draining to the estuary), as well as conditions in the water itself. The way we use and manage our estuaries affects how they function and their overall health.

Worldwide and Australia-wide, humans have modified estuary catchments for settlement, agriculture and industry, causing water quality to decline in most waterways and estuaries, and degrading their ecological health and social amenity.

The native vegetation in the Peel-Harvey estuary catchment on the Swan coastal plain has been extensively cleared to make way for agriculture, urban development and industry. The catchment hydrology has been heavily modified, and the sandy soils have an inherently high risk of phosphorus (P) export. These factors, combined with widespread agricultural activities (mostly beef/dairy farming) that require fertile soils and high fertiliser application rates, make the conditions extremely conducive to nutrients being lost to waterways, groundwater and ultimately the estuary.

Of all the estuaries in south-west Western Australia, the Peel-Harvey's eutrophication (nutrient-enrichment) problems have been the most extreme and extensive. As a result, it has been the target of the most State Government investment and effort to improve its health.

Large-scale remediation works were undertaken, including construction of the Dawesville Channel (locally known as the Cut) in the early 1990s, to increase the inflow of marine water and improve the oceanic flushing of nutrients from the estuary. These works were largely successful in reducing nuisance algae in the estuary's main basins. However, the proliferation of frequent, nuisance and toxic algal blooms, low oxygen levels in the water and mass fish deaths (known as fish kills) – all signs of an unhealthy system – are still occurring in several parts of the estuary system today. These are the responses of the ecosystem to environmental stress. Put simply, management actions to reduce excessive nutrients entering the estuary system from the catchment have never been adequately implemented.

With lower rainfall in the region since the 1970s, runoff and river flows have reduced, affecting the flushing of nutrients and other non-nutrient contaminants, and increasing water residence time in the estuary. Catchment and estuarine nutrient inputs accumulate in the basins and lower rivers, exacerbating eutrophication and creating the conditions for algal blooms and fish kills. In addition, reduced river flow because of climate change impacts (reduced rainfall) and rising sea levels mean the salt wedge can penetrate further upstream and increase stratification which – when dissolved oxygen levels are low – may result in even more nutrients being released from the sediments.

For many Western Australians, the Peel-Harvey estuary is iconic. It is the centre of the surrounding Peel region, which is seeing one of the fastest population growth rates in Australia. The estuary is highly valued by people who live, visit or work in the area, and supports the regional economy in a multitude of ways (e.g. recreational and commercial fisheries). Thousands of jobs and billions of dollars of investment depend on the health of the waterways and estuary. The estuary has high conservation value, is an internationally significant habitat for waterbirds (Ramsar Convention 1971) and provides important ecosystem services such as flood and pollution control. It is a hub for educational and scientific activities, recreation and eco-tourism and holds special cultural and spiritual value for Noongar people.

Taking effective, long-term action to protect and improve water quality in the estuary system is crucial to protect the community values into the future and balance social and economic development with conservation of the estuary environment.

The scientific research of the past 25 years has built a solid understanding of how the estuary has responded to reductions in river flow, catchment nutrient delivery and the dramatic changes in ocean connectivity brought about by the Dawesville Channel. This knowledge underpins the recommended actions of this water quality improvement plan (WQIP). Implementing the recommended actions will minimise export to the estuary of nutrients, organic matter and other contaminants originating from land use activities in the catchment.

This WQIP provides detailed data and other evidence to support the actions recommended for water quality improvement in *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020b) (referred to as the *Bindjareb Djilba Protection Plan*).

1.2 The history of declining water quality

Until the early 1800s, the Peel-Harvey estuary and waterways were in almost pristine condition. Bradby (1997) refers to the entire plain as a ‘wetland’ and describes the seasonal cycle of inundation across the Swan coastal plain:

> The plain would be flooded from the scarp through to the long ridge of tuart covered Spearwood dunes towards the coast, with only occasional sandhills remaining exposed… [and that] …the rivers, the wetlands and the flocks of waterbirds that we marvel at today are only a pale shadow of what once existed.
> (Bradby 1997, pages 48, 77)

During the wet winter months the rivers and streams would flow out onto extensive floodplains, inundating the coastal plain with fresh water and seasonally connecting one enormous complex of wetlands. Generally, only the Murray River remained in a clear stream channel for all of its length (Bradby 1997).

The Noongar communities used subsistence practices: only taking enough plants and animals to survive. They used fire to rejuvenate vegetation and flush out game, and traps to catch fish by hand. The estuary and waterways were healthy and resilient; the water was teeming with many species of fish and the shores were abundant with waterbirds.

Europeans began to settle in the Peel region in 1829, introducing European agricultural practices and commercial fishing operations. Economic growth was their focus and there was little or no thought for the consequences of their actions on the natural environment. Their agricultural practices neither suited the Peel-Harvey catchment’s soils nor the region’s climate and therefore settlement was initially confined to the river flats with their organic-rich soils and easier access.

The sheer volume and spread of fresh water across the coastal plain over the winter months initially proved a major obstacle to the spread of settlement and agriculture (e.g. fruit and vegetable production, wheat and cattle farming). The settlers made drastic changes to the catchment’s natural hydrology by constructing a network of artificial drains. They continually expanded the drainage network to clear the seemingly endless supply of fresh water off the land during seasonal inundation. In addition, they began large-scale clearing of native vegetation to make way for agriculture and settlement. In fact, clearing for agriculture was perceived as a cornerstone of regional and community development in the South West. As large trees were removed, groundwater rose and added to surface water – exacerbating the extent of flooding and in turn creating a perceived need for the construction of more drains. Rivers were dammed and wetlands were drained. Sections of rivers and streams were de-snagged, deepened and straightened to deal with the consequential increased flows. Much more water was reaching the estuary than ever before, but it was full of soil and silt washed out of bare paddocks and from the eroding banks of the drains. The water no longer ran clear but instead was heavy in organic matter (Bradby 1997). Any deep pools that remained in the rivers were choked with soil. By the 1920s, nutrients from the introduction of P fertilisers were also being washed into the streams, drains, rivers and inevitably the estuary (Bradby 1997).

By the 1940s, as a direct result of the extensive clearing and draining, the estuary was becoming eutrophic (nutrient enriched) because of large loads of sediment and nutrients being washed into it. Limited tidal exchange with marine waters caused high nutrient retention in the estuary. The health of the rivers and estuary was deteriorating every year and ‘floating pink slime’ and depleted fish stocks were affecting the once-lucrative commercial fishing industry (Bradby 1997). The aquatic ecosystems depending on adequate water quality suffered significantly and “the sparkling waters of the estuary” that had drawn such a large population “stopped sparkling” (Bradby 1997).

The widespread application of P fertilisers with high water solubility from the 1950s made agricultural activities more viable on the catchment’s infertile sandy soils. As well as increasing the nutrients being transported to the estuary, the practice accelerated land clearing across the coastal plain and led to the apparent need for the construction of more drains.

In the 1960s, beef prices boomed and farmers increased their rate of P fertiliser application (Bradby 1997). The estuary’s declining health became a matter of concern, particularly in summer and autumn, when the rapid growth and large accumulations of macroalgae in the Peel Inlet caused problems for everyone who used and valued the estuary. Persistent, unsightly algal blooms were leading to large quantities of rotting macroalgae piling up on the shores and decomposing into offensive-smelling black ooze, on what were once clean sandy beaches. Fringing plant communities which helped to stabilise the estuary banks were smothered and destroyed by algal accumulations (Lukatelich and McComb 1989, Brearley 2005).

> Sandy beaches were turned to black mush, people were nauseated, property values dropped, and tourism was affected.
> (Bradby 1997)

The accumulations of macroalgae were outcompeting the previously dominant macrophytes. This led to a substantial loss of the resident seagrasses (mainly *Halophila* and *Ruppia)* given they were confined to the shallows (Lukatelich and McComb 1989). *Cladophora montagneana* flourished in response to the nutrient-rich waters (Lukatelich and McComb 1989, McComb and Lukatelich 1995).

In 1970 the problems began to worsen: a blue-green ‘algae’ (*Nodularia spumigena* – which is actually a bacteria) that looked like a thick, green sludge covered more than 6 km of the Serpentine River and covered the Serpentine Lakes. *Nodularia* is a toxic cyanobacteria that can kill animals or make them sick after drinking infected water. In late spring and early summer there were also regular, massive blooms of *Nodularia* in the Harvey Estuary (Wilson et al. 1999) driven by nutrient-rich river inflows and sediment P sources (McComb and Lukatelich 1995).

The algal blooms in the 1970s and 80s were severe and persistent and became a serious public nuisance. Because rotting algae decreases dissolved oxygen levels in water, fish kills also became a regular occurrence in the estuary – continuing into the 1990s. Because of toxic phytoplankton blooms, people could not come in contact with the estuarine waters for extended periods of time. The Harvey Estuary was frequently the subject of human health warnings arising from toxic *Nodularia* blooms and closed to recreational use. The presence of a mosquito-borne virus also posed a serious health risk to people within 10 km of the estuarine waters (EPA 2008b).

Large banks of macroalgae were fouling and damaging fishing nets and outboard motors regularly became entangled in the Peel Inlet (Lukatelich and McComb 1989).

The land use pressures from clearing and drainage for agriculture continued and the use of superphosphate fertilisers began, resulting in tonnes of extra P entering the estuary. By the end of the 1970s there was confirmation that the use of phosphate fertiliser in the catchment was the main source of the nutrient enrichment causing the problems in the estuary and rivers. Since the mid-20th century, fertiliser had been widely used in the catchment with no understanding of the negative impacts it was causing or about how P was stored in soils.

The oversupply of nutrients to the Peel-Harvey estuary was recognised and in 1976, the Peel Management Area was gazetted under the *Waterways Conservation Act 1976*. This was to enable better planning, management and decision-making to protect the estuary and waterways for public amenity. However, water quality continued to decline and in the 1980s, the Peel-Harvey estuary had an ‘ecological collapse’, causing huge economic losses and social amenity impacts. The excessive algal growth had severely damaged the health of the ecosystem, made recreational use of the estuary unpleasant or impossible, and negatively affected the quality of life and health of people living around it. All users, including the fishing and tourism industry, were affected in some way.

Significant pressure from the public and industry about the ongoing algal blooms and fish kills forced the government to react and officially investigate the cause of the ecological collapse. Action was desperately needed for a coordinated cross-government approach to find a solution and restore the health of the estuary.

In 1988, Western Australia’s Environmental Protection Authority (EPA) created an environmental review and management program (ERMP) to improve the environmental conditions and excessive eutrophication occurring in the estuary. As part of this, the ambitious *Peel Inlet and Harvey Estuary management strategy* (Peel-Harvey Study Group 1985, Kinhill Engineers Pty. Ltd. 1988) (the strategy) was developed and subsequently approved by the Minister for Environment in January 1989. The strategy sought to address the massive algal growth problem attributed to the increase in nutrients (particularly P) from the estuary’s coastal catchment. Its objective was for the Peel-Harvey system to become “visibly clean and healthy and ecologically healthy and resilient” (EPA 1985) – an aim that is still relevant.

The strategy stated that three things needed to happen to improve the environmental conditions and excessive eutrophication occurring in the estuary:

- construction of the Dawesville Channel (a large-scale engineering intervention) to increase oceanic flushing of nutrients from the estuary and increase the inflow of marine water (which would inhibit the growth of salt-intolerant *Nodularia*)
- continued harvesting of macroalgae found rotting on estuary shores, drifting in navigation channels and growing in the shallows to prevent the smell and to maintain some level of recreational use of the estuary (although partially successful, the tractors caused severe erosion of the shorelines and destruction of rushes and other marginal vegetation in some locations)
- implementation of catchment management measures, including development of a catchment management program that would ‘cap’ rural P use.

It acknowledged that unless the sources of nutrient input were significantly reduced, the Dawesville Channel and macroalgae harvesting would provide little benefit other than to remove *Nodularia* blooms from the estuary and eliminate the smell of rotting algae.

In January 1989, a general moratorium on clearing and drainage proposed in the Stage 2 ERMP (Kinhill Engineers Pty. Ltd. 1988) was set as a Ministerial Condition to limit nutrient export to the estuary. The moratorium on drainage prevents the creation of new drains and cleaning of existing drains. These controls are to continue until the

Minister for Environment is satisfied that such activities are environmentally acceptable. However, some flexibility in the interpretation of these controls has been permitted – provided projects are designed to significantly reduce nutrient flows to the estuary.

In 1990, the Community Catchment Centre in Pinjarra was opened to bring together government staff and community members for river restoration, fertiliser use management, revegetation and other activities.

In 1992, the statutory *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* (the EPP) (formed under Part III of the *Environmental Protection Act 1986*) was gazetted to set environmental quality objectives for the Peel-Harvey system, aiming to prevent excessive growth of algae in the estuary. It requires all parties to contribute to water quality improvement towards reaching the environmental quality objectives.

In the same year, the EPA released the *Draft strategy for the elimination of faecal pollution of rivers* which foreshadowed actions to reduce the huge nutrient and organic matter loading from the Wandalup Piggery and from poorly regulated wastewater treatment plants. The piggery was the largest single point source of nutrients in the entire catchment at the time.

The Dawesville Channel was opened in 1994 and thus the tidal exchange between the estuary and the marine waters increased, helping to flush the river-delivered nutrients out to sea and thereby preventing algal blooms (*Nodularia*). On average the channel increased tidal range in the Peel Inlet and Harvey Estuary from 17 and 15 per cent respectively to 48 and 55 per cent of the ocean tides (EPA 2008b). Modelling estimated that, on average, the export of total nitrogen (TN) out to sea increased from 50 to 71 per cent, and the export of total phosphorus (TP) from 31 to 49 per cent of annual catchment loading (Hipsey et al. 2019). The nutrient export via the channel is estimated to be two to three times more than what goes through the Mandurah Channel (Hipsey et al. 2019). The resulting dramatic improvement in estuary water quality led to substantial investment in urban developments (including canal estates). The follow-on effect was that large sections of estuarine wetland habitat – important for the processing and removal of nutrients from the estuary – were lost.

The aspect of the strategy that was not adequately addressed and still requires significant action today is the nutrient pollution from human activities in the catchment entering the waterways and drains.

During the 1980s and 1990s the agricultural portion of the catchment was the subject of many rehabilitation projects which sought to:

- optimise fertiliser application on farms and minimise fertiliser losses to waterways
- rehabilitate drains, streams and wetlands
- trial alternative farming practices including the use of soil amendments to reduce P losses

- reduce nutrient pollution from point sources (e.g. wastewater treatment plants, intensive animal industries).

Water quality analyses of samples taken from the catchment's waterways during this period (Bussemaker et al. 2004) showed that despite the land management measures undertaken, there was very little change in catchment nutrient concentrations. Thus the gains made by the various management practices were either not of sufficient magnitude to make an improvement in water quality or, alternatively, were being masked by land use changes in the catchment that were increasing nutrient concentrations.

In 2000, the Peel-Harvey Catchment Council (PHCC) was formed. The PHCC is a non-profit community-based natural resource management (NRM) organisation that promotes an integrated approach to catchment management and protection and restoration of the environment within the Peel-Harvey catchment. It replaced the Pinjarra Community Catchment Centre and was designed to act as the community interface – in partnership with government – for work on catchment management activities to improve water quality in the estuary.

In 2003, the EPA found that components of the 1989 strategy had been successful, but the issue of poor water quality remained in the rivers and some lakes in the system (EPA 2003). Significant action was still required to reduce the P input to the waterways as this was known to be one of the key drivers of algal blooms.

In 2004, legislation was introduced (Environmental Protection (Clearing of Native Vegetation) Regulations 2004) to prohibit further clearing of native vegetation in Western Australia, providing stronger protection for the remnant native vegetation in the Peel-Harvey catchment – an important initiative for restoration of the catchment waterways and estuary.[9]

1.3 What is a water quality improvement plan?

A WQIP provides guidance on policy and catchment management actions to improve water quality within a defined area (such as the catchment of an estuary) to protect the community values of that system. The Australian Government's *Charter: National water quality management strategy* (2018) outlines the following key steps for a WQIP:

- consolidate current scientific understanding of the catchment and estuary
- identify pressures and stressors to water quality and their effects
- define appropriate management goals and water quality objectives (to compare with current water quality condition)
- recommend specific management actions to improve water quality
- regularly monitor water quality to evaluate progress.

[9] unless a clearing permit or exemption is granted by the Department of Water and Environmental Regulation.

WQIPs should be ambitious and include all management actions relevant to improving water quality in a plan area. They usually guide subsequent implementation plans, which tend to be narrower in scale and have greater detail around practical implementation and costing. Implementation of some actions may be catchment-wide (e.g. optimal fertiliser use on beef/dairy farms) while others may be for a smaller, reporting catchment scale (e.g. for strategic placement of stock-exclusion fencing and riparian-zone revegetation). WQIPs consider the relative costs of implementation and the effectiveness of various management actions and support targeted investment through implementation plans. Multiple implementation plans are expected to be produced over the life of a WQIP.

Implementing a WQIP is a shared responsibility among all stakeholders in a catchment. While the State Government has primary responsibility for water quality management, for WQIPs to be effective, strong cooperation and collaboration must exist between landholders, community groups, catchment groups, industry, regional management authorities and all levels of government.

Management actions may not manifest in improved water for many years. This lag effect (see 'Lag time' text box in Section 9.7) is because of the excessive nutrients that have infiltrated the soils and washed into the waterways, and are being stored in the catchment soils, and river, drain and stream sediments. It can take many years for these nutrients to deplete and discharge. For this reason, WQIPs are long-term plans – it may take up to 30 years to achieve their water quality objectives.

1.4 Implementing the 2008 WQIP

Although the Dawesville Channel improved water quality in the main body of the estuary from oceanic flushing of the nutrient-rich estuary waters, nutrient loadings remained largely unaltered. Water quality and environmental problems remained in the rivers and Serpentine Lakes, including algal blooms (EPA 2008b). Clearly, the third part of the 1989 strategy (implementation of catchment management measures) needed further action to measurably improve catchment and estuarine water quality.

In 2003, the Australian Government's Coastal Catchments Initiative (CCI) identified the Peel-Harvey system as a national water quality hotspot and priority for pollution reduction. This led to the development of the *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management* (EPA 2008b) (referred to as the 2008 WQIP), co-funded by the State Government and the Australian Government's CCI. The 2008 WQIP was one of the first in Australia; it was based on the knowledge of the time and the methodology given in the *Framework for marine and estuarine water quality protection* (Department of Environment Water Heritage and the Arts 2002).

In the 2008 WQIP (EPA 2008b), the EPA acknowledged that the Dawesville Channel had improved the flushing of nutrients from the main basins, but described the estuarine reaches of the Serpentine and Murray rivers as highly stressed and "degraded ecosystems (experiencing algal blooms, bacteriological scums, fish kills, unsightly episodic decomposition of alga producing offensive odours)".

The 2008 WQIP set water quality objectives in the form of a median load of TP flowing to the estuary of less than 70 tonnes per year (as measured by the ‘load measuring units’ at the gauging stations for each of the three rivers, not including the Upper Murray catchment). From the three rivers, the median loads of TP flowing into the estuary were set at:

- Serpentine River < 21 tonnes (as measured from the gauging station at the Upper Serpentine River site, AWRC 614030)
- Murray River < 11 tonnes (excludes Upper Murray catchment) (as measured from the gauging station at the Middle Murray River site, AWRC 614065)
- Harvey River < 38 tonnes (as measured from the gauging station at the Harvey River site, AWRC 613036. Note: pre-2017 the site was AWRC 613052).

The 2008 WQIP aimed to improve water quality in estuarine waters through recommending management actions to reduce P discharges from the various land uses in the Peel-Harvey catchment. These focused on changes to agricultural and urban practices and land use planning improvements. The management actions were for the coastal plain portion of the Peel-Harvey estuary catchment – some addressed existing activities while others sought to prevent and reduce discharges in the future.

The 2008 WQIP acknowledged other ecological problems in the system, including nitrogen (N) levels in estuarine waters, bacterial build-up from animal and human waste, acid soil drainage and estuarine and riverine habitat loss. However, it assumed that measures to reduce P would, in part, address many of these other issues.

In the 2008 WQIP, the recommendations to reduce P loading to the estuary included actions to better manage:

- agricultural land practices (fertiliser, soil amendment, perennial pastures, irrigation, livestock practices)
- urban land practices (fertiliser, soil amendment, water sensitive urban design)
- urban and rural effluent (upgrading septic tanks, sewerage infill)
- licensed agricultural nutrient discharges
- wetlands and waterways (riparian revegetation and stock exclusion)
- drainage management practices.

It also sought to:

- translate research into best-management practices (BMPs) for nutrient reduction in both rural and urban landscapes
- implement a monitoring and reporting program
- identify and address barriers to the uptake of BMPs
- foster community partnerships for better water quality.

The 2008 WQIP noted that because of decades of nutrient input into the catchment, large stores of P existed in the soils and sediments, but that if catchment management actions were implemented at scale, water quality improvements were possible in a decade. Yet it predicted decades more to reach the P load target for the estuary (EPA 2008b).

Unfortunately funding for the 2008 WQIP's implementation was minimal, limited in scope, inconsistent and discontinuous. At first, funding of $1 million was directed from state NRM programs for the period 2009–11 and then from the Australian Government's Caring for our Country program, with $1.5 million ending in 2013. Both programs focused on wetland, biofilter and stormwater management treatments and included development of subcatchment implementation plans. The Department of Water and Environmental Regulation (the department) engaged the PHCC to deliver projects through the Filtering the Nutrient Storm program which, to date (other than the Regional Estuaries Initiative), has been the biggest 2008 WQIP implementation effort, closely followed by the Department of Agriculture and Food's (DAFWA) Fertiliser Partnership programs (described below) and the work done by local governments.

Efforts to reduce nutrient losses from agriculture came through the *Fertiliser Action Plan* and the subsequent Fertiliser Partnership (Accord), which were applied across the Swan and Scott coastal plains. Recognising that the bulk of P fertiliser was applied in a highly soluble form, the *Fertiliser Action Plan* engaged the fertiliser industry in phasing out the use of high-water-soluble P fertiliser in favour of fertiliser with lower water solubility (slow-release P fertiliser) that was less likely to leach from the soil during autumn and winter rains. The *Fertiliser Action Plan* was recast as the Fertiliser Partnership, which saw the emphasis on phasing out high-water-soluble P fertiliser shift to overall best practice in fertiliser management delivered through the fertiliser industry's Fertcare® program.

Underpinning both programs, however, was the whole-farm nutrient mapping led by DAFWA (now DPIRD). This provided soil testing and agronomic advice to optimise fertiliser usage for agronomic need.

The 2008 WQIP recommended a review on progress after five years (i.e. 2013). New hydrological and nutrient modelling of the catchment (referred to as catchment modelling) completed in 2011 (Kelsey et al. 2011) provided the basis for a review of load reduction targets. These were found to have remained valid, while the more detailed modelling data was used for the subcatchment implementation plans developed by the PHCC (2012). The PHCC also reported on the first few years of 2008 WQIP's implementation, providing a short summary of achievements and how uptake of the recommended actions had progressed to 2011 (PHCC 2013).

The Regional Estuaries Initiative (REI – see Appendix A) was established in 2016 to implement the recommended WQIP actions in six estuaries of south-west Western Australia, one of them being the Peel-Harvey. The REI tackled catchment sources of nutrients through a partnership approach – from which much was learned to inform this next-generation WQIP.

1.5 Drivers for the next-generation WQIP (2024)

Many of the water quality issues documented in the 2008 WQIP are still relevant today, along with its management recommendations. However, as described above, implementation of the 2008 WQIP was limited, in part because of funding constraints and a lack of coordinated action.

We are now dealing with a fundamentally different climate; that is, reducing rainfall and river flow combined with rising sea levels and higher temperatures. Urban expansion is connecting Perth and the Peel as envisaged by the *Perth and Peel @ 3.5 million* (WAPC 2018a) and the *Perth and Peel @ 3.5 million South Metropolitan Peel sub-regional planning framework* (WAPC 2018b). At the same time, agriculture is becoming more diverse and intense as the region expands further into global markets. To help deal with these new pressures, we now have a bank of accumulated knowledge from the partial implementation of the 2008 WQIP and more than 20 years of monitoring and scientific studies of the estuary's response to the Dawesville Channel. Collectively, we have proven strategies to improve water quality and identified priority areas for further investigation.

In 2024, the Peel-Harvey estuary and its waterways are still showing warning signs of deteriorating water quality. With reduced river flows, saline water intrusion is extending the estuarine reaches of the rivers even further – leading to hypersalinity and loss of freshwater habitat. Parts of the main body of the estuary are in good condition because of the increased marine circulation. However, the Harvey Estuary's southern end and the estuarine reaches of the Serpentine, Murray and Harvey rivers are severely and regularly affected by algal blooms, the presence of toxic algal species, sulfur-rich sediments, deoxygenation events and fish kills (see Section 3.3).

1.6 Approach to the 2024 WQIP

The revised *Gabi Warlang Bidi – Water quality improvement plan for the Peel-Harvey estuary system* (this WQIP) builds on the 2008 WQIP, expanding coverage to a broader range of issues and providing additional evidence-based solutions. This WQIP is closely linked to the *Bindjareb Djilba Protection Plan* (DWER 2020b).

This WQIP is consistent with the Australian Government's *Charter: National water quality management strategy* (2018) and aims to improve the water quality and ecological health in the Peel-Harvey estuary and tributaries, thereby protecting the community values. To protect those values (Section 4.1) this WQIP:

- considers the current scientific understanding of catchment and estuary processes and water quality condition, as well as the effectiveness of past and current management strategies on the health of the system
- identifies key pressures and stressors to water quality

- identifies suitable management goals, developing appropriate water quality objectives (WQOs), and selects relevant guideline values for the chosen indicators
- compares current water quality condition against the chosen WQOs
- carefully considers the results from updated hydrological and nutrient modelling of the catchment which looks at changes in land use and climate since the last modelling was conducted 10 years ago
- recommends management actions relating to urban, industrial and agricultural activities supported by catchment modelling, along with cost-benefit considerations for implementation; new or updated policies to support water quality improvement; and actions to ensure review of the WQIP's progress
- provides general advice and discussion about implementation of the management actions
- identifies research needs to inform future investigative work.

This WQIP draws guidance from the EPA's advice provided in the *Perth and Peel @ 3.5 million – Environmental impacts, risks and remedies* (EPA 2015) and also complements and closely links with the *Bindjareb Boodja Landscapes – A strategy for natural resource management in the Peel-Harvey region, Western Australia* (2021).

This WQIP builds on knowledge gained from scores of previous and current projects in the Peel-Harvey catchment, including the REI and Healthy Estuaries WA.[10] Many of this WQIP's actions extend those successfully implemented through the REI or that are underway as part of Healthy Estuaries WA and implementing the *Bindjareb Djilba Protection Plan* (DWER 2020b).

Investigations associated with the Peel Integrated Water Initiative (PIWI) provide up-to-date assessments of future water availability and alternative supply options for a 42,000 ha investigation area straddling the Serpentine and Murray catchments. The PIWI also looked to minimise land use impacts on the environment by identifying strategies to reduce agricultural nutrients entering the Peel-Harvey estuary. Its key recommendations, such as the use of soil amendments and transitioning intensive horticulture to closed agricultural systems, are integrated into this WQIP.

It is critical to have a strong, consistent and coordinated approach through policy and regulatory mechanisms – for land use planning, waste and pollution management, urban design and water management, and agricultural practices – to reverse decades of estuary decline and secure the long-term health of an ecosystem that underpins the future of the Peel region.

The recommended actions in this WQIP are reflected in the *Bindjareb Djilba Protection Plan* (DWER 2020b). This WQIP offers an integrated approach to catchment management and asks many groups to work together to protect the

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[10] A State Government commitment to improve the health of seven estuaries across south-western Australia.

estuary system for future generations. Actions related to land use planning, location of industrial estates, regulation, agricultural intensification, waste and pollution management, urban design and water management are primarily a government responsibility. Other actions, such as substantial shifts in agricultural practice on the coastal plain, require partnerships between government, NRM groups, farmers and industry.

The State Government has invested and committed to the *Bindjareb Djilba Protection Plan* (DWER 2020b) which will require sustained investment at sufficient magnitude over time to protect community values. A policy and planning coordinating committee has been established as part of implementing the *Bindjareb Djilba Protection Plan* (DWER 2020b). This includes representatives from across government and the PHCC to link policy and planning to water quality outcomes and will provide an ideal forum to put this broader plan in place.

1.7 Scope and boundaries of this plan

This WQIP is supported by recent hydrological and nutrient modelling of the Peel-Harvey catchment (Hennig et al. 2021). The Peel-Harvey Catchment Model covers the entire catchment, including areas that drain to the ocean as well as the estuary. In this WQIP we focus on those parts of the catchment on the Swan coastal plain which drain to the Peel-Harvey estuary – referred to as the Peel-Harvey estuary coastal plain catchment or the plan area (2,636 km^2 – see Figure 1-1). This includes the river catchments of the Serpentine, Murray (excluding the Upper Murray catchment) and Harvey rivers.

We selected this area because it has the highest population density, the most intensive land uses and the greatest urban and agricultural development pressures in the Peel-Harvey catchment. The area has a high watertable, modified hydrology in the form of an extensive network of artificial drains, and generally poor sandy soils with a low capacity to retain nutrients.

The large upland area of the Murray River catchment – the Upper Murray reporting catchment in Hennig et al. (2021) – is not a priority area to manage for water quality improvement. The Upper Murray only exports 0.200 kg/ha of N each year and 0.002 kg/ha of P per year – the lowest nutrient loads per cleared area in the entire Peel-Harvey catchment (Hennig et al. 2021). The smaller nutrient loads are because of lower rainfall and flows, soils with higher P retention and cropping being the predominant land use – with its lower nutrient inputs and better nutrient-use efficiency than the predominant land uses on the coastal plain (e.g. beef and dairy farming).

Both on-ground management actions and planning and policy actions relate to this defined area and focus on improving water quality and ecological health in the estuary and its tributaries (waterways and drains). This WQIP does not include management actions for the estuary itself, or the lakes in the catchment. For reasons relating to how the catchment modelling was performed, the boundaries of some reporting catchments include some vegetated upland areas that are part of the

Darling Scarp, but these areas are outside of the scope of the management actions in this WQIP.

Figure 1-1 The Peel-Harvey estuary coastal plain catchment (plan area)

To be consistent with the work of Hennig et al. (2021), when we talk about modelling results and on-ground management actions in this WQIP, we refer to the subcatchments within the plan area as reporting catchments (Figure 1-2):

- Serpentine River catchment – Upper Serpentine, Peel Main Drain, Dirk Brook, Nambeelup, Lower Serpentine and Mandurah reporting catchments
- Murray River catchment – Lower Murray and Coolup (Peel) reporting catchments
- Harvey River catchment – Harvey, Meredith, Mayfield and the Coolup (Harvey) reporting catchments.

We refer to the area bounded by the above reporting catchments as the plan area.

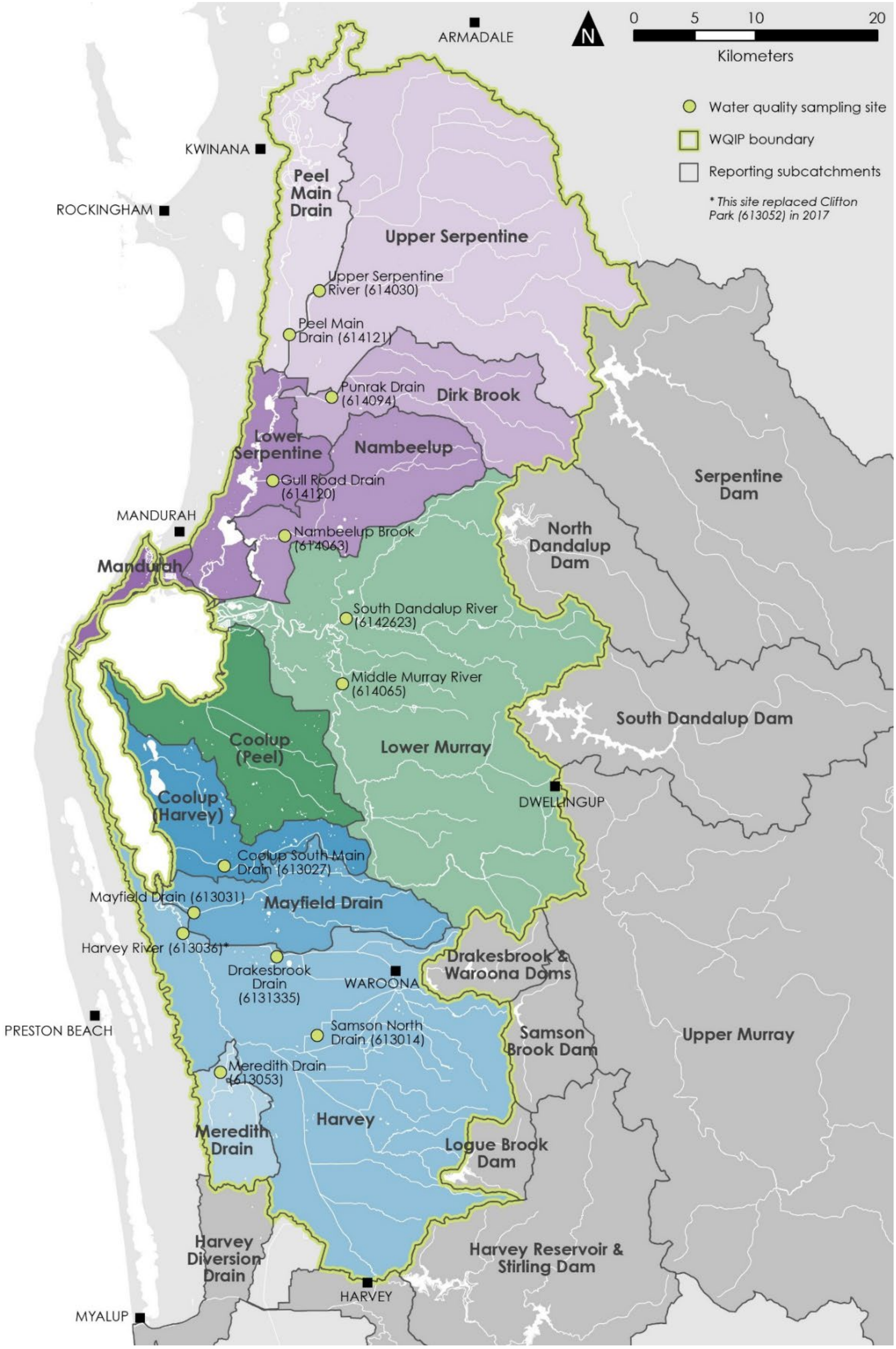

Figure 1-2 Reporting catchments and water quality monitoring sites within the plan area, as aligned with Hennig et al. (2021)

1.8 Relevant legislation, policies and plans

Below is a non-exhaustive list of current legislation and government policy and plans relevant to the water quality of the Peel-Harvey estuary.

Legislation

- *Waterways Conservation Act 1976* and Waterways Conservation Regulations 1981
- *Water Agencies (Powers) Act 1984*
- *Water Services Act 2012* and Water Services Regulations 2013
- *Environmental Protection Act 1986*, Environmental Protection Regulations 1987 and Environmental Protection (Clearing of Native Vegetation) Regulations 2004
- *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*
- *Rights in Water and Irrigation Act 1914* and Rights in Water and Irrigation Regulations 2000
- *Soil and Land Conservation Act 1945* and Soil and Land Conservation Regulations 1992
- *Biodiversity and Conservation Act 2016* and Biodiversity Conservation Regulations 2018
- *Aboriginal Heritage Act 1972* and Aboriginal Heritage Regulations 1974
- *Carbon Credits (Carbon Farming Initiative) Act 2011* (Australian Government)
- *Native Title Act 1993* (Australian Government)
- *Environment Protection and Biodiversity Conservation Act 1999* (Australian Government).

International conventions and agreements

- *The Ramsar Convention on Wetlands of international importance especially as waterfowl habitat 1971*
- *Convention on the conservation of migratory species of wild animals* (Bonn convention)
- *Convention on biological diversity* (Biodiversity convention)
- *Japan–Australia migratory bird agreement* (JAMBA), *China–Australia migratory bird agreement* (CAMBA) and *Republic of Korea–Australia migratory bird agreement* (ROKAMBA) are relevant.

State Government policies, frameworks and plans

- *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020b)
- *Statement of Planning Policy 2.0: Environment and natural resources* (WAPC 2003a)
- *Statement of Planning Policy No. 2.1: Peel Harvey coastal plain catchment* (WAPC 1992)
- *Statement of Planning Policy No. 2.7: Public drinking water source policy* (WAPC 2003b)
- *State Planning Policy 2.9: Water resources* (WAPC 2006)
- *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) (these will replace several state planning policies and guidelines, see Appendix B)
- *Government Sewerage Policy* (Government of Western Australia 2019a)
- *Perth and Peel @ 3.5 million* (WAPC (Western Australian Planning Commission) 2018a) and *Perth and Peel @ 3.5 million – South Metropolitan Peel sub-regional planning framework* (2018b)
- *Waterwise Perth – Two year action plan* (Government of Western Australia 2021a) and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2* (Government of Western Australia 2022a).
- *Peel Regional Scheme – Priority agriculture and rural land use policy* (WAPC & DPLH 2017)
- *Statewide Policy no. 5: Environmental water provisions policy for Western Australia* (Water and Rivers Commission 2000a)
- *Native vegetation policy for Western Australia* (DWER 2022c)
- *Operational Policy 4.3: Identifying and establishing waterway foreshore areas* (DoW 2012)
- *Better urban water management* (WAPC 2008)
- *Stormwater management manual for Western Australia* (DoW 2004–07)
- *Decision process for stormwater management in Western Australia* (DoW 2017a).

Relevant local government policies

- *Local Planning Policy: Horticultural Development* (Horticultural Development within Peel-Harvey Coastal Plain Catchment) (Shire of Murray 2018a)
- *Local Planning Policy 4.12: Horticulture* (Shire of Serpentine Jarrahdale 2018b)

- *P004 – Local Planning Policy 4 – Intensive agriculture* (Shire of Waroona 2021)
- *Model Local Planning Policy – Horticultural Development in the Peel-Harvey Coastal Plain Catchment*. Prepared by the Bindjareb Djilba (Peel-Harvey estuary) Protection Plan Policy and Planning Coordinating Committee (PHCC 2023)
- *Peel-Harvey WSUD local planning policy* (PDC 2006b) and *Peel-Harvey coastal catchment water sensitive urban design technical guidelines* (PDC 2006a)
- *Water sensitive urban design – local planning policy* (Shire of Murray 2018b)
- *Local Planning Policy 2.4: Water sensitive urban design guidelines* (Shire of Serpentine Jarrahdale 2018a)
- *Water sensitive urban design policy POL-RDS 07* (City of Mandurah 2019)
- *Town Planning Scheme No. 3 Local Planning Policy LPP15 Water sensitive urban design* (City of Mandurah 2009).

Other relevant guidance, plans and frameworks

- *Water quality improvement plan for the rivers and estuary of the Peel-Harvey System – Phosphorus management* (EPA 2008b)
- *Environmental factor guideline – Inland waters* (EPA 2018) and chapters B4 and B5 of *Guidance statement 33 – Environmental guidance for planning and development* (EPA 2008a), which is currently being reviewed
- *Perth and Peel @ 3.5 million, Environmental impacts, risks and remedies: Interim strategic advice of the Environmental Protection Authority to the Minister for Environment under section 16(e) of the Environmental Protection Act 1986* (EPA 2015)
- *Horticulture in the Peel-Harvey – A guide for investors and growers*. Revised guidelines prepared by the Bindjareb Djilba Planning and Policy Coordinating Committee, for the implementation of the Bindjareb Djilba (Peel-Harvey estuary) Protection Plan (PHCC 2024)
- *Bindjareb Boodja Landscapes, A strategy for natural resource management in the Peel-Harvey region, Western Australia* (PHCC 2021)
- *Wetlands and people plan for the Peel Yalgorup system – A CEPA action plan for Ramsar site 482* (PHCC 2017)
- *Aboriginal Heritage Act 1972 Guidelines (DPLH 2023)*
- *Bring Together Walk Together Aboriginal partnership engagement framework* (Walley and Grant 2021)
- *Bindjareb Gabi Wonga (Bindjareb Water Story)* (Nannup et al. 2019)

- *Our knowledge our way in caring for Country: Indigenous-led approaches to strengthening and sharing our knowledge for land and sea management, Best practice guidelines from Australian experiences* (Woodward et al. 2020).

1.9 Supporting projects

This WQIP has been supported by many projects and a body of important research – all of which has either directly or indirectly helped to improve water quality in the Peel-Harvey estuary system, including:

- monitoring of water quality by the department
- multiple projects as part of the REI (Royalties for Regions) and continuing under Healthy Estuaries WA
- various projects led by DPIRD such as soil testing of grazing farms/whole-farm nutrient mapping, soil amendment trials (including mining clays) and working to improve irrigation efficiency in agricultural areas
- the Australian Research Council (ARC) Linkage project *Balancing estuarine and societal health in a changing environment* (Valesini et al. 2019b), which developed a sophisticated coupled model of the Peel-Harvey estuary and catchment (Hipsey et al. 2019)
- environmental projects that have worked to improve the health of the catchment, waterways and estuary implemented by Alcoa, the PHCC, Greening Australia and The Nature Conservancy
- river restoration projects by the Harvey River Restoration Taskforce (HRRT)
- previous investigations by the department into non-nutrient contaminants being discharged from wastewater treatment plants in the catchment
- PIWI studies (Bainbridge et al. 2018, Hennig et al. 2018, Charles et al. 2019, Hipsey et al. 2019, Summers et al. 2020, DWER 2021b)
- Healthy Wetland Habitats administered by the Department of Biodiversity, Conservation and Attractions (2006–22)
- State Government's Carbon Farming and Land Restoration program (led by DPIRD) that funds activities such as revegetation on farms in the South West that sequester carbon in the landscape and deliver additional, positive outcomes referred to as 'co-benefits' (e.g. biodiversity and conservation).[11]

See Appendix A for further information about most of these projects.

1.10 Stakeholder engagement and partnerships

The water quality issues of the Peel-Harvey estuary system are the cumulative result of many actions over a long time (see Section 1.2) and they can only be successfully

[11] Western Australian Carbon Farming and Land Restoration Program

addressed through collaborative efforts across government and stakeholder groups. We consulted with regional stakeholders both for this WQIP and the *Bindjareb Djilba Protection Plan* (DWER 2020b) to develop and refine a list of management actions which – when implemented fully – will improve and protect water quality and ecological health in the estuary system.

Much of the thinking derived from the extensive consultations undertaken as part of the government's Strategic Assessment of the Perth and Peel regions provided the basis for subsequent development of the WQIP – especially in making the explicit links between water quality outcomes and planning and development decisions.

Meetings and regional workshops to discuss policy and catchment management actions were conducted in 2019 with the following government agencies and organisations:

- Peel Development Commission
- Peel-Harvey Catchment Council
- Shire of Murray
- Shire of Serpentine-Jarrahdale
- City of Mandurah
- Shire of Waroona
- Shire of Harvey
- City of Rockingham
- Department of Water and Environmental Regulation (Perth and regional Kwinana-Peel)
- Department of Primary Industries and Regional Development
- Department of Biodiversity Conservation and Attractions
- Department of Planning, Lands and Heritage
- Department of Parks and Wildlife.

We have also discussed with and presented to various stakeholders on topics including the historical and current condition of water quality in the Peel-Harvey estuary, the estuary's key environmental issues, and the results from the Peel-Harvey Catchment Model. Those stakeholders included the PHCC Board and the team from the ARC Linkage project *Balancing estuarine and societal health in a changing environment*) (Valesini et al. 2019b). We also presented to the Peel Yalgorup Ramsar site technical advisory group in 2019.

In addition, we also fed key learnings and feedback from stakeholders on the REI into development of the recommended management actions in this WQIP.

We circulated the draft WQIP among key stakeholders before consideration by government and its release.

Partnering with Bindjareb Noongar people to look after the Peel-Harvey estuary and rivers

Consistent with the *Charter: National water quality management strategy* (Australian Government 2018), we recognise the importance of embedding the cultural and spiritual values of the Bindjareb Djilba (Peel-Harvey estuary) and the three Bilya (rivers) into water planning.

We meaningfully engaged the Traditional Owners of the waterways, Bindjareb Noongar people, to develop the *Bindjareb Djilba Protection Plan* (DWER 2020b) – which is closely linked and shares objectives with this WQIP.

We partnered with Bindjareb Noongar Elders to co-produce the Bindjareb Noongar Water Perspectives project to empower Aboriginal people, identifying opportunities to look after Aboriginal land and water. Through yarning for Bindjareb Noongar Water Perspectives, Bindjareb Noongar people have led the development of their own plan to look after the Djilba (estuary) and Bilya (rivers): the *Bindjareb Gabi Wonga* (Nannup et al. 2019). The *Bindjareb Gabi Wonga,* or Bindjareb Water Story, communicates Bindjareb people's vision, management goals and priority actions for the planning and management of the Bindjareb Djilba (Peel-Harvey estuary) and Bilya (rivers). The *Bindjareb Gabi Wonga* is informing this WQIP.

Bindjareb Noongar people encourage strong partnerships with key water stakeholders to look after their waterways, actively partnering with the PHCC, local government authorities and the State Government.

1.11 Impacts of eutrophication on estuary ecology

Estuaries are complex and dynamic waterbodies with unique characteristics of shape, size, depth, level of freshwater input, and level of saltwater flushing via ocean connectivity. Estuaries support an important array of plants and animals (biota) that in a healthy estuary are in a state of balance. The biological and chemical processes in estuaries, and the intricate links with the biota that these processes involve, respond to environmental changes in flow, temperature, salinity and nutrient input. A healthy estuary has stable biological and chemical processes, maintains its biodiversity and is resilient to change.

N and P are nutrients that play a critical role in plant nutrition: they contribute to a wide array of physiological and biochemical processes and are essential to the effective functioning of the ecosystem. Estuarine nutrients can originate from internal sources such as from organic matter decomposition and sediment release, especially under hypoxic (low oxygen) or anoxic (no oxygen) conditions, as well as from external sources such as natural ecological events (e.g. leaf litter fall, weathering) and human activities in the catchment (e.g. agricultural activities such as fertiliser application). Healthy estuaries receive relatively small amounts of nutrients in their inflow and there is a limit to the amount of nutrients they can assimilate before showing signs of stress, as described below.

Macroalgae and phytoplankton (microscopic single-celled algae or cyanobacteria that float freely in water) are natural components of estuarine ecosystems that form the foundation of aquatic food webs. However, the excessive input of nutrients in a waterbody can result in deterioration of water quality (known as eutrophication), which in turn stimulates rapid and widespread growth of phytoplankton, macroalgae and/or plants to nuisance proportions. Rapid and widespread growth of phytoplankton cells (a ‘bloom’) can result in discoloured water or scum that can accumulate at the surface (Figure 1-3). These blooms of phytoplankton are often followed by mass death of the cells as nutrients and other resources needed for growth are depleted. The dead cells contribute to organic matter, which is decomposed by bacteria that consume oxygen in the water, causing hypoxic conditions. Hypoxic conditions can lead to mass mortalities of aquatic fauna (e.g. fish kills, see Figure 1-4) and negatively affect habitat quality and species diversity.

Figure 1-3 Toxic algal bloom in the Lower Serpentine River in summer 2019 (aerial photo credit: Eduardo Perotti, City of Rockingham)

When oxygen concentrations approach zero (anoxia) at the sediment–water interface, there is generally an increased release of bioavailable nutrients from the sediment, which fuels further plant and algal growth.[12]

Eutrophic conditions may also enable growth of species of algae and cyanobacteria (blue-green bacteria) which have the potential to release toxins that are harmful to aquatic biota, humans and animals.

Figure 1-4 Fish kill event in the Serpentine River near Keralup in February 2013

[12] Bioavailable means nutrients or compounds that are readily accessible for uptake or absorption by algae and plants.

Seagrasses (flowering aquatic plants) are an important part of estuarine ecosystems, providing habitat and food for aquatic life. They also contribute to good water and sediment quality by absorbing nutrients, oxygenating bottom waters and stabilising sediments. Excessive growth of some algae can smother seagrass and reduce light availability, making it difficult for the seagrass to photosynthesise. This can cause a shift from a healthy macrophyte/seagrass-dominated system to a less healthy, nuisance macroalgae/phytoplankton-dominated system.

In addition to the negative ecological impacts, symptoms of eutrophication, such as large accumulations of rotting algae, have significant impacts on recreational and visual amenity. Dense algal growth has also been known to impede boat navigation and cause problems for commercial fishers (Bradby 1997).

South West estuaries

Waterways and estuaries in the South West have evolved under naturally low-nutrient (oligotrophic) conditions and are therefore particularly vulnerable to excessive nutrients and to becoming eutrophic (Brearley 2005). South West estuaries can rapidly recover from natural disturbances that have been part of their evolutionary history, but they are vulnerable to disturbances such as ongoing nutrient pollution caused by human activities in their catchments (EPA 2003). Long-term exposure to excessive nutrients has drastically degraded many of our South West waterways and estuaries, reducing their ecological health and limiting the many benefits and uses for which they are so highly valued.

The largest of the nutrient inputs to South West estuaries is from diffuse runoff from agricultural areas, with nutrients originating from the use of fertiliser and from liquid and solid waste from farm animals. Nutrient-rich water infiltrates and pollutes groundwater or is washed into waterways and drains with runoff from rainfall, transporting nutrients to the receiving estuary.

2 About the Peel-Harvey estuary, its rivers and catchment

2.1 Location and description

Noongar people's words for estuary and river

Bindjareb people refer to the Peel-Harvey estuary as Djilba. This is the ancient name used for thousands of years. Djilba is also a name for one of the Noongar people's six seasons and runs between August and September, straddling the western European seasons of winter and spring. Djilba is also a name for the fish, bream.

The Noongar word for river is bilya. The word bilya begins in the bily, meaning navel or belly button, becoming the bilya the cord of life, the umbilical cord and Noongar people have a deep cultural connection to rivers in this way.

(Walley 2018)

The Peel-Harvey estuary (Bindjareb Djilba) is 75 km south of Perth and is the largest inland waterbody in south-western Australia (Brearley 2005). The estuary (djilba) comprises two broad interconnected shallow basins: the Peel Inlet and the Harvey Estuary (Figure 1-1), in addition to the lower reaches of its three rivers (bilyas) which are strongly influenced by marine waters that move upstream with the tide. The estuary is classified as microtidal, with tides less than 1 m.

The Serpentine River (Waangaamaap Bilya) and Murray River (Bilya Maadjit) discharge into the Peel Inlet, while the Harvey River (Yoordinggaap Bilya) discharges into the Harvey Estuary (Figure 1-1). The three rivers and about 15 major drains deliver seasonal flows (with 80 per cent of the flow arriving between May and October) into the estuary. Peak flows are in August in all three rivers with the greatest flow occurring in the Murray River followed by the Harvey River and then the Serpentine River. Lowest flows occur in February or March each year. See Section 3.1 for more information on historical and recent river flows.

The Peel-Harvey estuary has an area of about 133 km^2 and is connected to the Indian Ocean by the natural and narrow 5-km-long Mandurah Channel (connecting the northern end of the Peel Inlet to the sea) and the artificially constructed Dawesville Channel (connecting the southern end of the Peel Inlet and the northern end of the Harvey Estuary to the sea), both of which are artificially maintained and permanently open to the Indian Ocean (see Figure 1-1). The channel (2.5 km long and 200 m wide) was completed in 1994 and was designed to increase marine flushing of the estuary.

The basins have very shallow margins up to 0.5 m which fringe the estuary shoreline and are often exposed during low tides. The central depth of the basins is about 1.5 m with a maximum depth of about 3 m in the Harvey Estuary and 3.5 m in the Peel Inlet. Shallow depths and the south-westerly winds mean the basins are mostly well mixed. The estuarine parts of the Serpentine River are also up to 3.5 m in the reach closest to the basins but become shallower (about 1 m) near, and in, the Serpentine Lakes, which are well mixed. In the lower Serpentine River, downstream of Lake Amarillo, a series of deep pools (4–8 m) are seasonally stratified, with a fresher surface layer and a more saline bottom layer (Tulipani et al. 2020). The Murray River reaches a depth of up to 5.5 m and is also subject to salinity stratification.

The entire catchment of the Peel-Harvey estuary covers 11,920 km^2 with cropping areas in the wheatbelt to the east, forests along the Darling Range in the middle and agricultural land on the Swan coastal plain to the west. The northern and western boundaries of the catchment are characterised by concentrated residential developments. About 870 km^2 of the catchment drains directly to the Indian Ocean: the catchment of the Harvey Diversion Drain flows to the ocean at Myalup and the lands on the western side of the Spearwood dune system drain to the ocean or to local wetlands (from Fremantle to Myalup). A further 1,662 km^2 drains to the dams and the remaining catchment drains to the Peel-Harvey estuary with an area of about 9,390 km^2 (Figure 2-1). The coastal plain portion of the Peel-Harvey estuary catchment (the plan area) is 2,636 km^2, and includes areas within the cities of Mandurah, Rockingham, Kwinana, Cockburn and Armadale and the shires of Murray, Waroona, Harvey and Serpentine-Jarrahdale.

The major dams in the estuary catchment are used for potable water (Serpentine Main and Pipehead, North Dandalup, South Dandalup, Samson, Conjurunup Pipehead and Stirling) and agricultural water supply (the Waroona, Drakesbrook, Logue, Wokalup dams and Harvey Reservoir). All dams are managed by Water Corporation or Harvey Water, the latter being responsible for delivering agricultural water through its network of pipe and channel infrastructure.

During winter, inundation is common because of the flat landscape, high groundwater table, and short, relatively wet rainfall season (May to October). Water enters the estuary and river system from rainfall, runoff, tidal movement and groundwater, and is lost via flows that drain directly to the ocean, through tidal movement and evaporation (Hodgkin and Lenanton 1981, Brearley 2005).

The shallow depths to groundwater in many areas of the catchment mean that many intact ecosystems are potentially reliant on groundwater to meet their water requirements (Bainbridge et al. 2018).

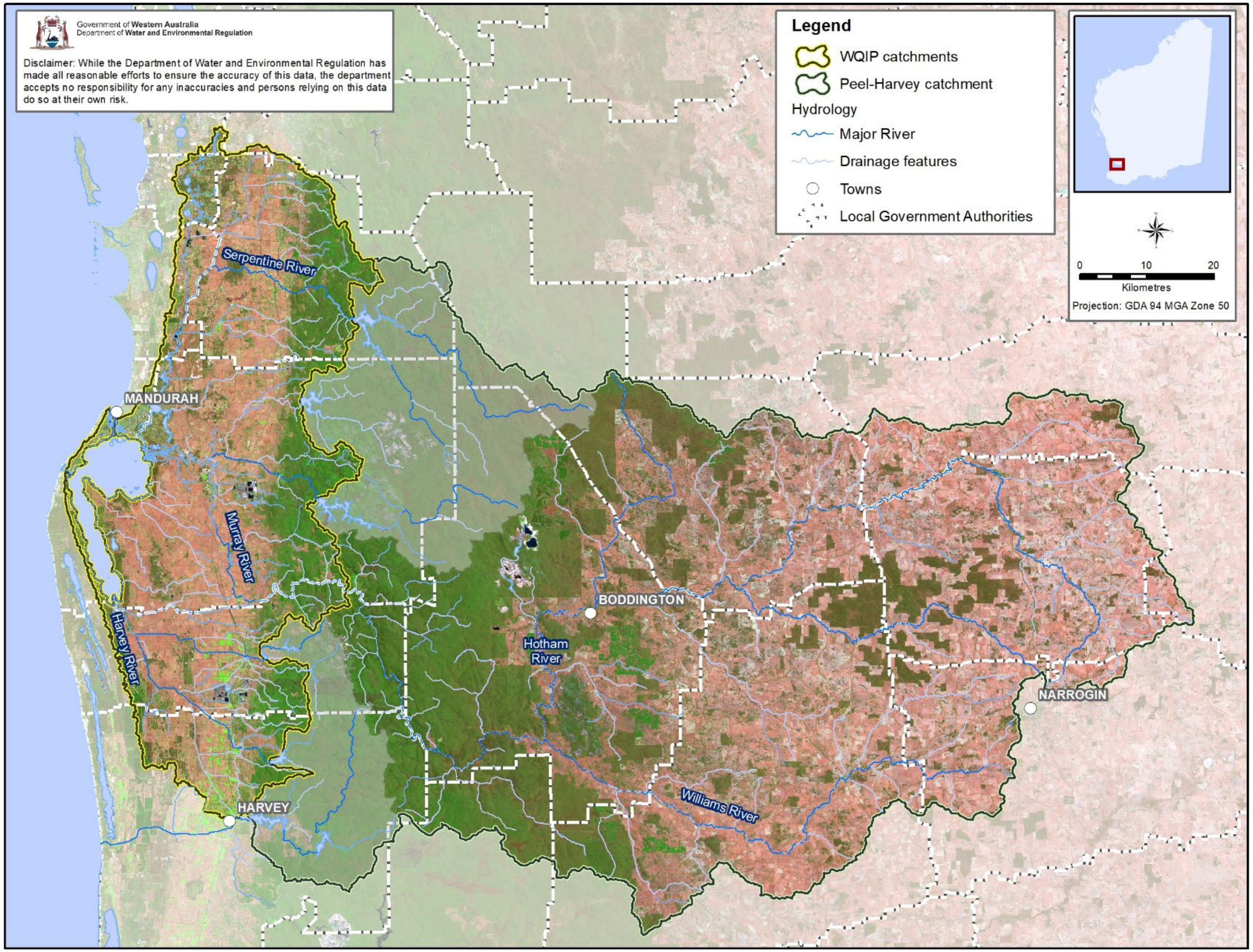

Figure 2-1 The entire Peel-Harvey estuary catchment showing the portion on the coastal plain (the plan area)

2.2 Climate

The Peel-Harvey catchment has a Mediterranean climate with cool, wet winters and hot, dry summers. Average annual rainfall (from 1975 to 2003) increases from about 750 mm on the coast to 1,050 mm on the Darling Scarp, and then decreases east of the scarp to about 400 mm at the catchment's eastern boundary (Figure 2-3). The highest average rainfall occurs in the winter months (June–August) and the lowest in the summer months (December–March) with about 80 per cent of rainfall occurring from May to October each year.

South-western Australia has experienced a marked drying trend since 1970, particularly in autumn and early winter. The decline in this region has been larger than anywhere else in Australia (Government of Western Australia 2021b). Further decreases in annual, winter and spring rainfall are projected with high confidence (Government of Western Australia 2021b).

At Pinjarra, just east of the Peel-Harvey estuary, the average annual rainfall from 1900–75 was 950 mm, which reduced to 860 mm from 1975–99, and further to 730 mm from 2000–19 (Figure 2-3). With climate change, the rainfall season has become shorter with a delayed onset of winter rains and a reduction in the intensity, frequency and persistence of rain events (Charles et al. 2019).

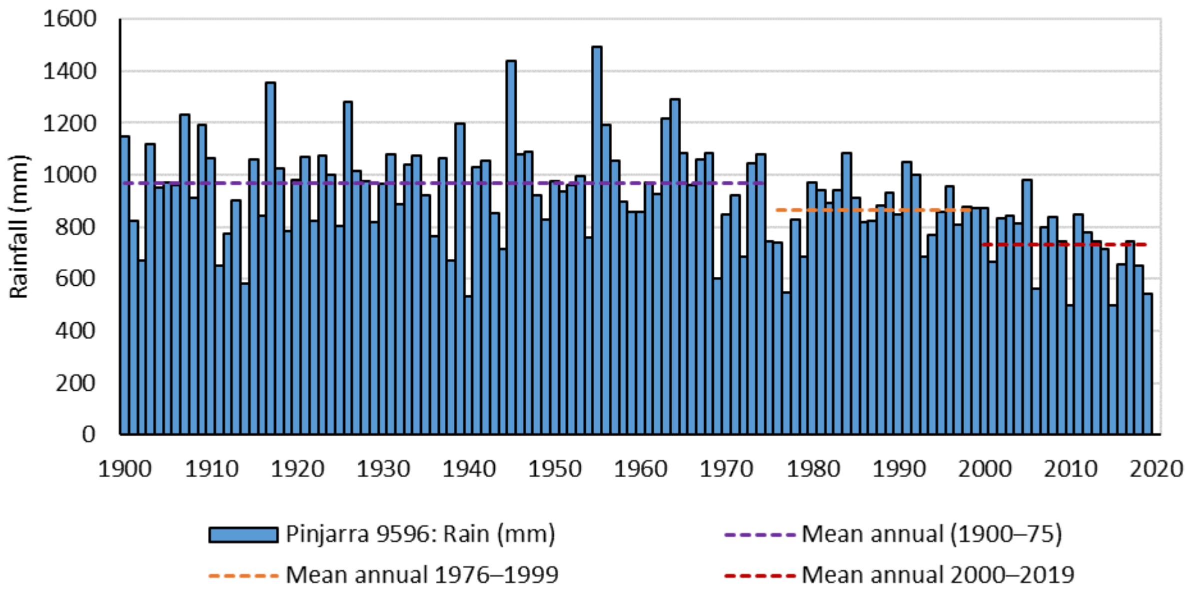

Figure 2-2 Average annual rainfall recorded at Pinjarra, near the Peel-Harvey estuary, from 1900 to 2020

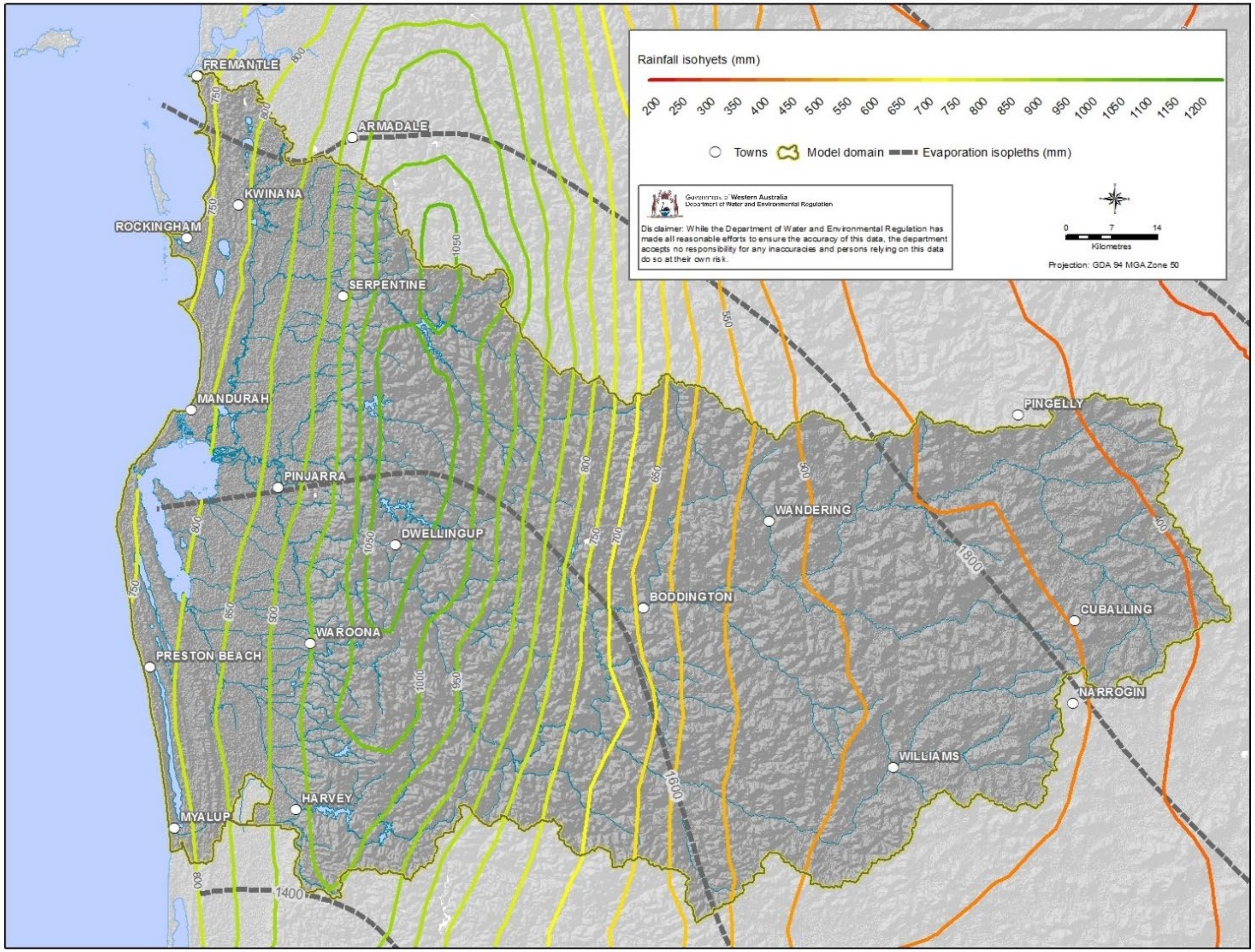

Figure 2-3 Rainfall isohyets and evaporation isopleths for the entire Peel-Harvey catchment area (averages for 1975–2003)

2.3 Physiography, hydrogeology and soils

The Peel-Harvey catchment is made up of two physiographic units – the Swan coastal plain and the Darling plateau. The Darling Scarp, which marks the plateau's western edge, is aligned parallel to the coast. The coastal plain is about 30 km wide and slopes gently upwards from the coast to an elevation of about 40 m at the base of the scarp, with low undulations of up to 3 m, except for the Tamala Dunes which have much higher undulations.

The Swan coastal plain has considerable groundwater resources because of its sedimentary geology. There are four main aquifers: the unconfined, largely fresh superficial and Rockingham aquifers and the regional, mainly confined Leederville and Yarragadee aquifers. These aquifers are comprised of many different geological formations which were laid down from the Jurassic to Quaternary geological ages (Deeney 1989, Davidson 1995), as summarised in appendices C and D. See section 6.3 for information on the use of groundwater in the Peel-Harvey catchment and how the department manages its allocation.

The Peel-Harvey estuary coastal plain catchment has sandy soils that are low in natural clays and loams. Soils are mostly of alluvial depositions overlaid with deep, weathered sands forming low parallel dunes running north to south. Appendix E shows the main surface soils of the study area and a description of each is available in Hennig et al. (2021).

Most of the Swan coastal plain has soils with a low soil P retention index (PRI) (<7) (Figure 2-4). Soil PRI is a measure of a soil's capacity to retain P. Soils with a low PRI leach P easily with the passage of water through the soil profile and across the soil surface. The lower the PRI, the easier it is for P to move through the sandy soils. Soil with a PRI of zero would have no capacity to retain P.

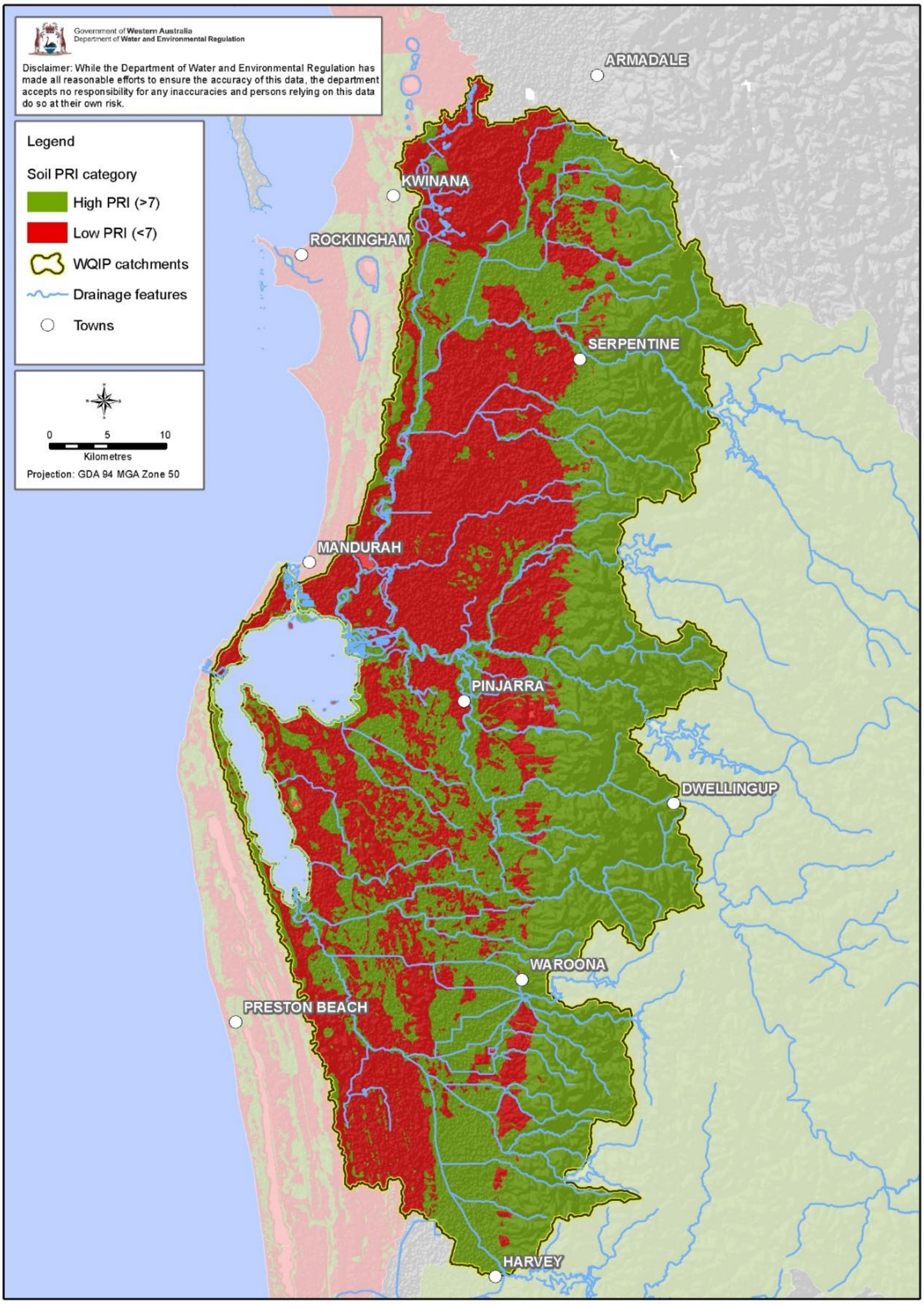

Figure 2-4 The plan area shows high (>7) and low (<7) soil phosphorus retention index (PRI) categories. Soil PRI mapping was taken from the DAFWA soil mapping and is the same data as used in Kelsey et al. (2011).

Figure 2-5 demonstrates the strong, positive relationship between PRI and the P concentration measured in waterways that drain that catchment. The higher the percentage of soils with a low PRI in a catchment, the more susceptible the catchment is to P export and hence, higher P concentrations are seen in the receiving waterways.

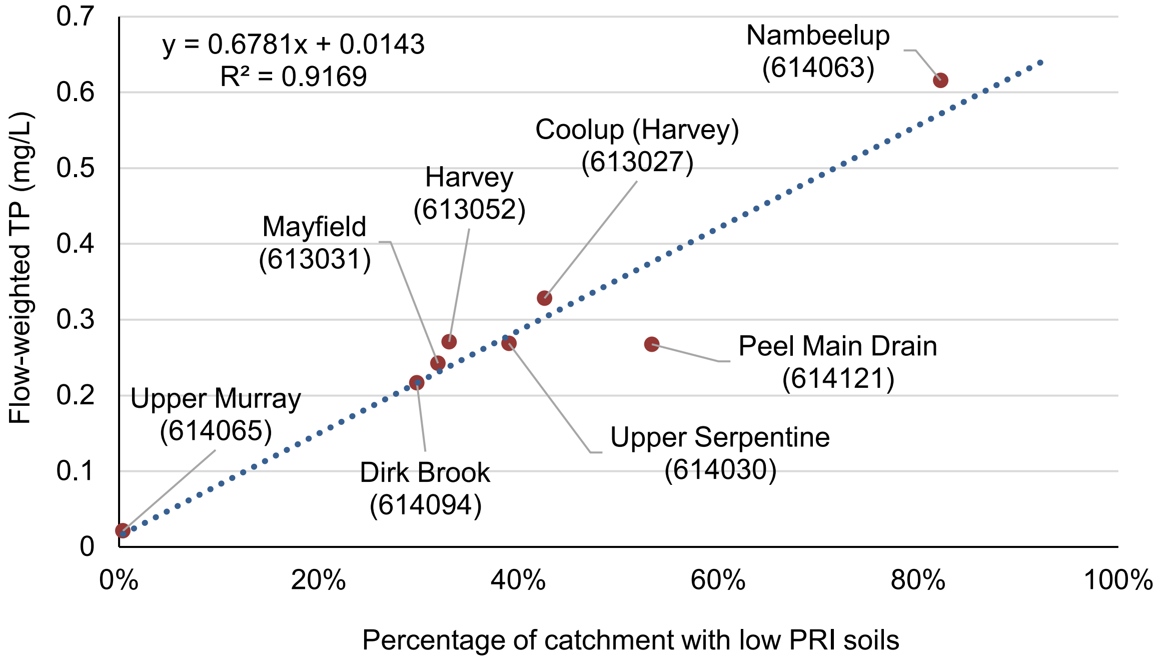

Figure 2-5 The positive linear relationship between per cent of catchment with PRI and average, annual (2011–15), locally estimated scatterplot smoothing (LOESS), flow-weighted, TP concentrations at eight sites in the Peel-Harvey estuary catchment. LOESS is used to estimate nutrient concentrations based on a derived flow-concentration relationship from measurements. Trend analyses is then performed on the flow-adjusted concentrations.

For more detailed information on the geology, geomorphic elements and vegetation of the Peel-Harvey catchment, see Kelsey et al. (2011).

2.4 Flora and fauna

Estuary

The Peel-Harvey estuary and its fringing environment provide a biologically diverse natural system that supports a variety of habitats including open water, mudflats, aquatic plants, samphire, paperbark community and freshwater sedgelands.

The estuary and fringing environment are internationally recognised for having a high ecological value with a diverse array of biota – including many native fish and bird species, aquatic invertebrates and dolphins – which depend on the estuary system for their survival (habitat, food, shelter) and/or reproduction (Figure 2-6). Because of the uniqueness of these flora and fauna and the severe pressure from human impacts they are under, the estuary now forms part of a Global Diversity Hotspot (South West Australia Ecoregion) (Myers et al. 2000).

Figure 2-6 Dolphins depend on the Peel-Harvey estuary for shelter, food and habitat

The estuary is a high-conservation-value aquatic ecosystem and is included in the *Directory of important wetlands in Australia* (Environment Australia 2001).[13] It is an internationally significant habitat for waterbirds and migratory wading birds and is also recognised as a 'wetland of international importance' (part of the Peel-Yalgorup wetland system – Ramsar Convention site 482) (Figure 2-9) under the Convention on Wetlands (Ramsar Convention 1971), currently meeting six of the nine criteria for a Ramsar listing (PHCC 2019). As a contracting party to the Ramsar Convention, the Australian Government has accepted several obligations relating to the management of listed wetlands, one of which is to manage listed wetlands in a manner that maintains their ecological character.

The Peel-Yalgorup Ramsar site is an important part of the East-Asian-Australasian Flyway and regularly supports six species of international migratory shorebirds that

[13] For more information including the criteria for determining nationally important wetlands in Australia, see Directory of Important Wetlands in Australia.

are considered threatened under the *Environmental Biodiversity and Conservation Act 1999* (EPBC Act), with four of the six critically endangered: bar-tailed godwit (*Limosa lapponica menzbieri)*, curlew sandpiper (*Calidris ferruginea*), eastern curlew (*Numenius madagascariensis)*, great knot (*Calidris tenuirostris*), greater sand plover (*Charadrius leschenaultia*) and red knot (*Calidris canutus*). The estuary also supports greater than 1 per cent of the population of the fairy tern (*Sterna nereis nereis*) which is threatened (vulnerable) under the EPBC Act (PHCC 2019). By supporting and protecting threatened bird species, the estuary helps to maintain the biological diversity of the biogeographic region.

Large populations (in the tens of thousands) of waterbirds use the estuary and lakes each year as a drought refuge, as well as for feeding, breeding and nursery grounds (Figure 2-7 and Figure 2-8).

Since the 1980s, 104 species of waterbirds have been sited on the Peel-Harvey estuary (Table 2-1), including 38 species listed under international migratory agreements: *Bonn convention on migratory species* (28), *China–Australia migratory bird agreement* (CAMBA*)* (33), *Japan–Australia migratory bird agreement* (JAMBA) (34) and *Republic of Korea–Australia migratory bird agreement* (ROKAMBA*)* (31), as well as an additional 35 Australian species that are listed as marine under the EPBC Act (PHCC 2019).

Figure 2-7 Pelecanus conspicillatus (booladaalaang, Australian pelican) are common in the Peel-Harvey estuary and lakes. They feed on fish and use the fringing estuary environment for breeding and nesting colonies.

Figure 2-8 The snowy white Ardea alba (great egret) is found wading in the shallow waters of the Peel-Harvey estuary and lakes, feeding mainly on fish and other small aquatic animals (Hale and Butcher 2007)

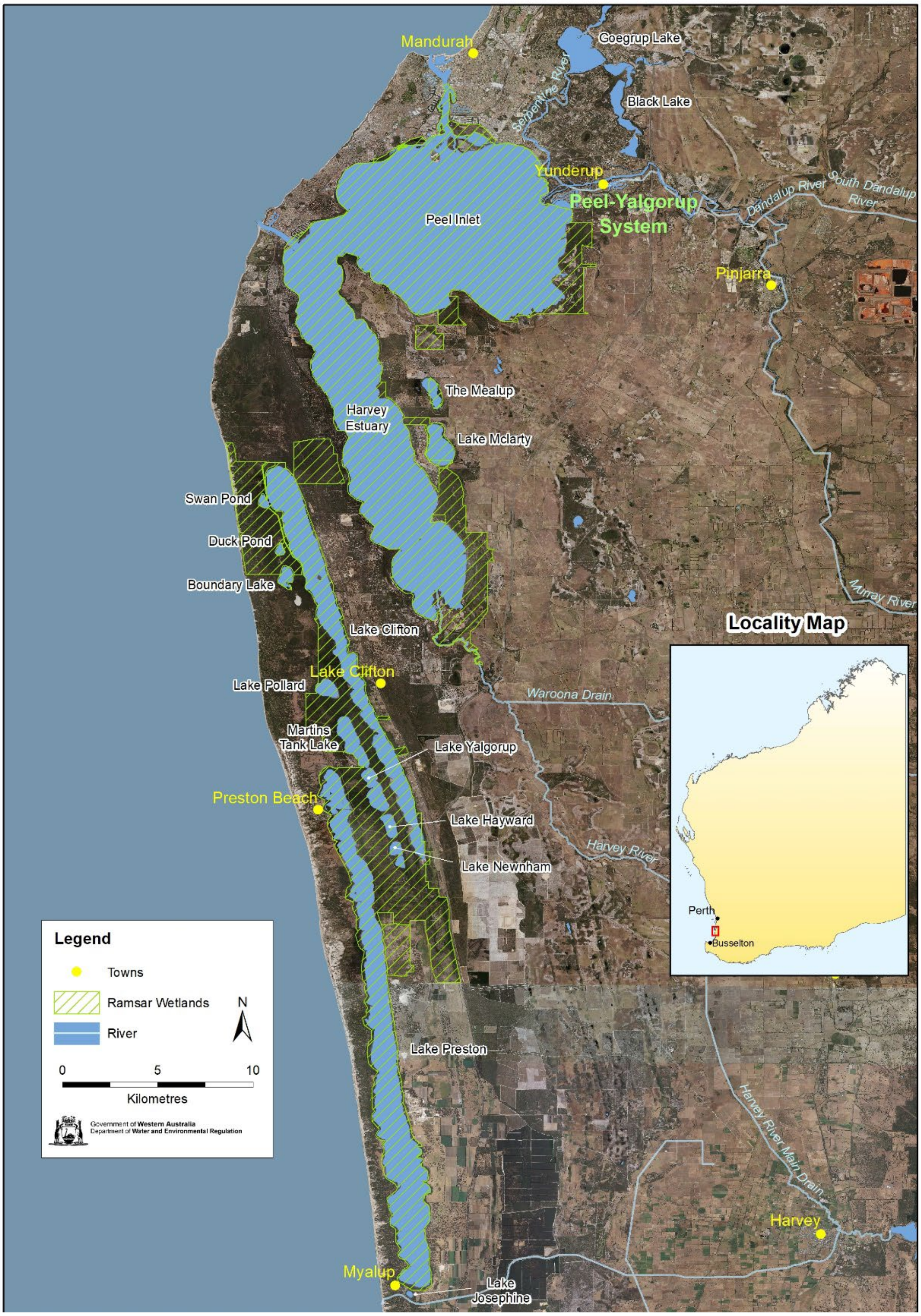

Figure 2-9 The Peel-Harvey estuary forms part of the internationally recognised Peel-Yalgorup wetland system, recognised as a 'wetland of international importance' under the Ramsar Convention on Wetlands (Ramsar site no. 482)

Table 2-1 The seven types of birds found in the Peel-Harvey estuary system

	Bird Group	Description	Number of species
	Ducks and small grebes	Ducks (yerderap)and small grebes that typically are omnivorous and shallow or open- water foragers.	14
	Macrophyte-eating (herbivores)	Black swans (maali), hens (kwiyaloom)and coots (kidjibroon) that have a vegetation diet.	6
	Fish-eating species	Gulls, terns (kaldirkang), cormorants, petrels (nekayit), shearwaters and grebes with a diet mainly of fish	20
	Australian shorebirds	Australian resident shorebird species that feed in shallow inland waters or mud and sand flats mainly on invertebrates.	12
	International shorebirds	Palaearctic shorebird species that breed in the northern hemisphere and migrate to the southern hemisphere to feed.	31
	Large wading birds	Long-legged wading birds with large bills, feeding mainly in shallow water and mudflats.	14
	Other wetland-dependent birds	Other birds that are wetland dependent such as birds of prey (white-bellied sea eagle, swamp harrier), reed warblers and the orange-bellied parrot	7
Total	**Total**		**104**

Djilba (Peel-Harvey estuary) Gabi (water) djerap (birds)

For thousands of years, local Bindjareb Noongar families have observed the diverse and unique djerap populations of the Djilba Gabi. Observation was an important part of how Bindjareb people in Mandjoogoordap (Mandurah) survived and lived successfully according to the six Noongar seasons. Looking at the activities of the birds was part of a very complex threading and wider knowledge base. The waterbirds were given Noongar names and became part of culture and language.

The estuary environment is a nursery, breeding and feeding ground for *Portunus armatus* (blue swimmer crab) (Figure 2-10) and *Penaeus latisulcatus* (western king prawn). It also supports populations of about 70 fish species (Potter et al. 2016), including marine species such as *Sillaginodes punctatus* (King George whiting), *Mugil cephalus* (sea mullet), *Pomatomus saltatrix* (tailor) and *Hyperlophus vittatus* (whitebait), and estuarine species such as *Acanthopagrus butcheri* (black bream) and *Cnidoglanis macrocephalus* (estuary cobbler). In addition, the estuary provides an important migratory route for *Geotria australis* (pouched lamprey).

Figure 2-10 The estuary provides important habitat for Portunus armatus (blue manna crab) to live in and reproduce

There is a high diversity of benthic macroinvertebrate species (e.g. shrimp, worms and bivalves living on or in the sediment) in several areas of the Peel-Harvey estuary. These species play an essential role in the functioning of the estuarine ecosystem by decomposing organic matter and recycling nutrients, and are a major food source for the birds and fish (Cronin-Reilly et al. 2019). Cronin-Reilly et al. (2019) found that the benthic macroinvertebrate species present in the estuary belong to environmentally tolerant taxa, which typically reflect ongoing stressful environmental conditions. Areas of the estuary associated with high nutrients and organic matter showed very poor macroinvertebrate health or were completely devoid of any invertebrate fauna (Cronin-Reilly et al. 2019).

A variety of unique plant communities fringe the Peel-Harvey estuary depending on the local salinity, water levels and other environmental conditions. These fringing vegetated areas act as buffers and protect the margins of the estuary during flooding (Brearley 2005).

Salt-tolerant plants including grasses, sedges, rushes and shrubs form fringing saltmarsh communities on the low-lying flats around the estuary. Saltmarsh communities are an important component of the fringing vegetation and are nationally recognised under the EPBC Act as a threatened (vulnerable) ecological community. The extent of saltmarsh communities appears to have declined since 1994, with no substantial change in extent occurring after 2007 (Hale and Kobryn 2017). There has, however, been a change in community composition: more salt-tolerant species have taken over at the expense of species better suited to brackish conditions. This may be ongoing change because of the increases in salinity since the opening of the Dawesville Channel, or may be in response to changing conditions because of climate change (Hale and Kobryn 2017).

Samphires, rushes and salt-tolerant trees such as *Casuarina obesa* (salt sheoaks) and *Melaleuca cuticularis* (saltwater paperbarks) are more commonly found higher up the banks where inundation occurs less regularly (Brearley 2005). Many paperbark communities are currently in poor condition (with dead trees and/or branches plus a high cover of weeds) with some areas, such as the Harvey delta and Yalgorup lakes, showing a decline in extent as well (Hale and Kobryn 2017).

The fringing vegetation provides waterbirds with an important refuge from predators, as well as foraging grounds, nesting habitat and roosting sites. Fringing vegetation buffers estuary margins from flooding and when flooded, provides important nursery and feeding grounds for fish and aquatic invertebrates.

The shallow, well-mixed waters of the Peel-Harvey estuary basins support the growth of macroalgae (e.g. *Willeella brachyclados, Chaetomorpha linum*) and seagrasses (*Ruppia megacarpa, Halophila ovalis* and *Zostera muelleri*). These plants, along with microphytobenthos (microscopic photosynthetic organisms that live in the sediment) and phytoplankton (microscopic photosynthetic organisms that float freely in water), play a vital role in the ecosystems of the estuary. They are the foundation of the food chain supporting large populations of invertebrate animals (e.g. zooplankton, benthic invertebrates) which provide food for the fish, birds and mammals in the estuary.

Catchment waterways

Much of the native vegetation on the Swan coastal plain has been cleared or heavily modified, with the remaining areas of intact native vegetation and wetlands considered to be of high conservation value (Del Marco et al. 2004).

Despite the degraded condition of much of the riparian zone, some reaches of waterways and drains in the Peel-Harvey estuary coastal plain catchment provide sufficient riparian and aquatic habitat quality to support diverse native fauna. These include the following freshwater and freshwater-estuarine species that are endemic to the South West: *Afurcagobius suppositus* (south-western goby), *Leptatherina wallacei* (western hardyhead), *Bostockia porosa* (nightfish), *Galaxias occidentalis* (western minnow), *Nannoperca vittata* (western pygmy perch), *Tandanus bostocki* (freshwater cobbler), *Cherax cainii* (smooth marron), *Cherax quinquecarinatus* (gilgie), *Cherax preissii* (koonac) and *Cherax crassimanus* (restricted gilgie). The catchment waterways are also home to native species including *Pseudogobius olorum* (blue-spot goby), *Galaxias maculatus* (common jollytail), *Geotria australis* (pouched lamprey), *Acanthopagrus butcheri* (southern black bream) and *Mugil cephalus* (sea mullet).[14]

[14] Based on data collected by the department, DPIRD, universities and other research groups (DPIRD 2018, DWER 2020a).

Figure 2-11 Nannoperca vittata (western pygmy perch; left) and Tandanus bostocki (freshwater cobbler; right)

Several species in the coastal estuary catchment have conservation significance: *Geotria australis* (pouched lamprey) (priority listed species under the *Biodiversity Conservation Act 2016*), *Westralunio carterii* (Carter's freshwater mussel) (listed as vulnerable (EPBC Act 1999 and *Biodiversity Conservation Act 2016)* and *Hydromys chrysogaster* (rakali) (a reclusive semi-aquatic native rodent (classed as near threatened in Western Australia under the *Biodiversity Conservation Act 2016*).

Figure 2-12 maps the total number of freshwater native fish and crayfish species, plus estuarine-freshwater native fish species that you could expect to find in the catchments of the plan area. The largest diversity in native species is expected in the middle catchments of the Serpentine River (within the Upper Serpentine reporting catchment) and Murray River (within the Lower Murray reporting catchment), as well as in Logue Brook, just upstream of the Harvey Main Drain (within the Harvey reporting catchment in this WQIP).[15] All the rivers have areas with a high diversity of native fish and crayfish (7–8 species), with the Murray having the longest length of river with high species richness (Figure 2-12).

See Appendix F for further information on the native and non-native fish and crayfish species that are likely to be found in the plan area.

[15] Freshwater Fish Distribution in Western Australia

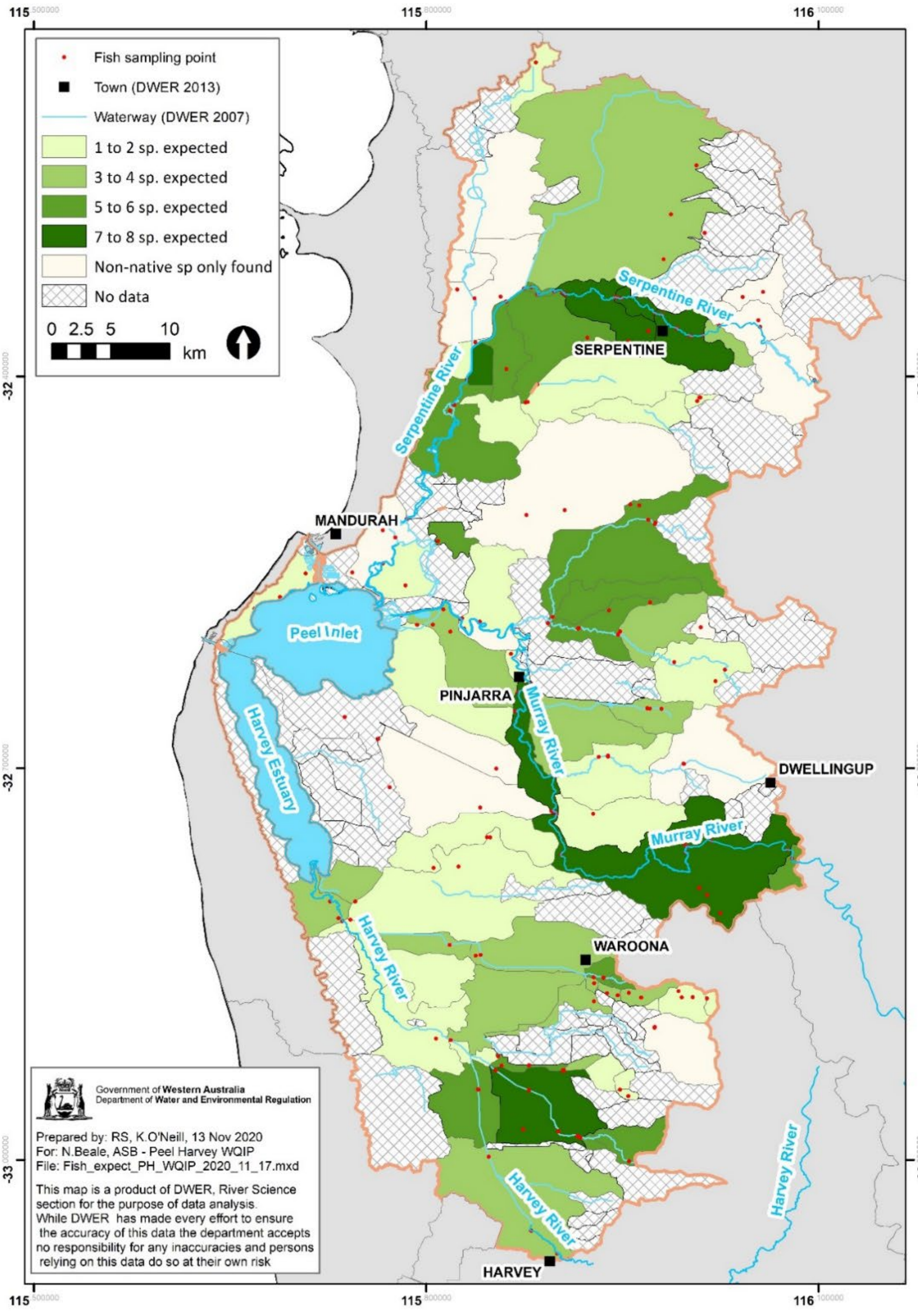

Figure 2-12 The total number of native freshwater-estuarine fish and freshwater crayfish species expected in each reporting catchment based on actual and interpolated data collected by the department, DPIRD, universities and other research groups (DPIRD 2018, DWER 2020a)[16]

[16] Data can be accessed online: Freshwater Fish Distribution in Western Australia.

3 Condition of the Peel-Harvey estuary and catchment

3.1 River flow

Flow is monitored at 10 of the 13 monitoring sites (Figure 3-3) in the estuary coastal plain catchment. The rivers below the three primary gauging stations (Middle Murray River, AWRC ref. 614065; Harvey River, AWRC ref. 613052/613036; Upper Serpentine River, AWRC ref. 614030) are dominated by tidal flows, especially since construction of the Dawesville Channel.

River flows closely follow the seasonal pattern in rainfall (Figure 3-1; see also Section 2.2), with most of the flow occurring in the five months from May to October, with the peak median flow in August (Figure 3-1). The highest flows from 2006–19 were observed at the Murray River site (AWRC ref. 614065) with peak median flows of about 40 GL/month. The highest median flows for the Harvey River (AWRC ref. 613052/613036) are half this volume (20 GL/month), while the peak median flow at the Upper Serpentine River (AWRC ref. 614030) is 9 GL/month (Figure 3-1).

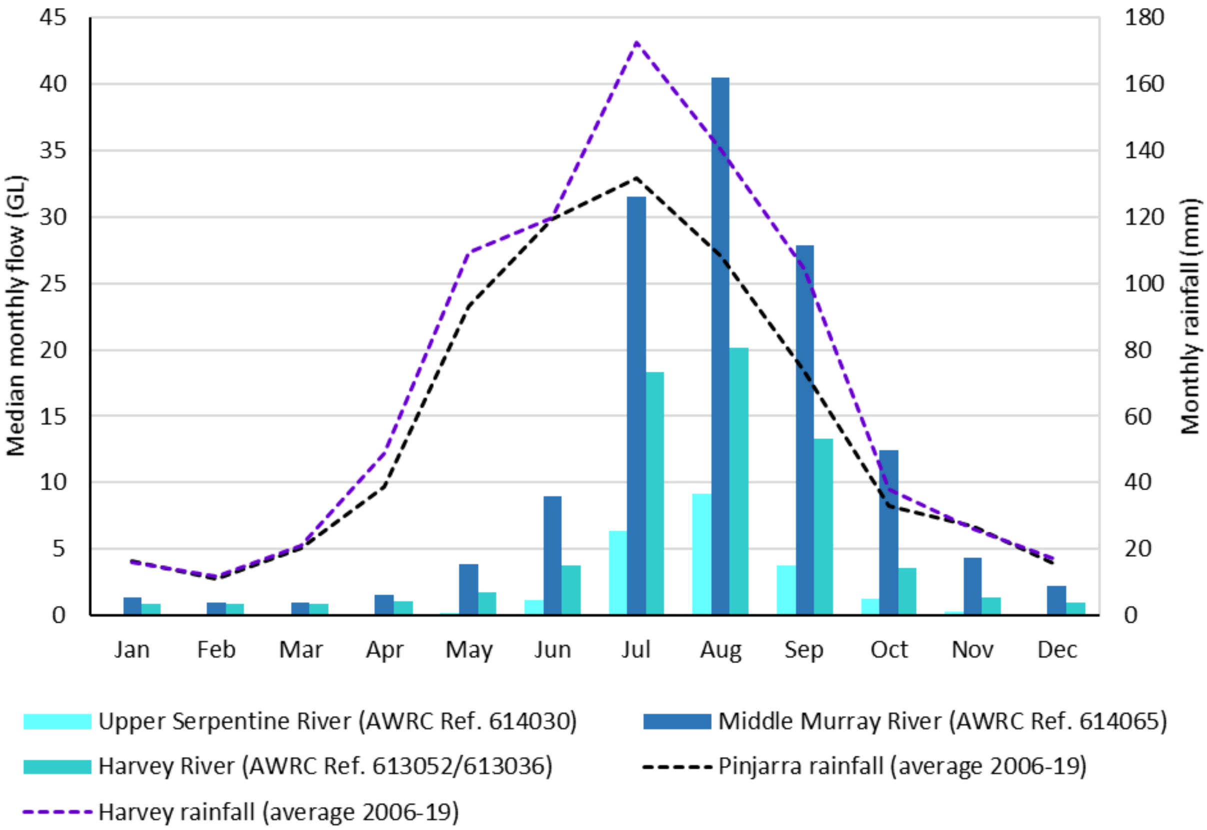

Figure 3-1 Median river flows at the three primary gauging stations – Upper Serpentine River (AWRC ref. 614030), Middle Murray River (AWRC ref. 614035) and Harvey River (AWRC ref. 613036/613052) from 2006–2019

All gauging stations in the catchment (2000–2019, where data was available) record highly variable flows (Table 3-1, Figure 3-2). The three primary gauging stations are no exception, with the highest variability seen at the Upper Serpentine River site (AWRC ref. 614030), which ranged from 132 GL in 1991 to 6 GL in 2015 (Figure 3-2).

Total annual flows in all three rivers have declined during the past 25 to 35 years and this is evident at each monitoring site (Figure 3-2).

At the Harvey River site (AWRC ref. 613036/613052), average flows between 1984–99 and 2000–19 decreased by 46 per cent; at the Upper Serpentine River site, average flows between 1980–99 and 2000–19 decreased by 56 per cent (Figure 3-2).

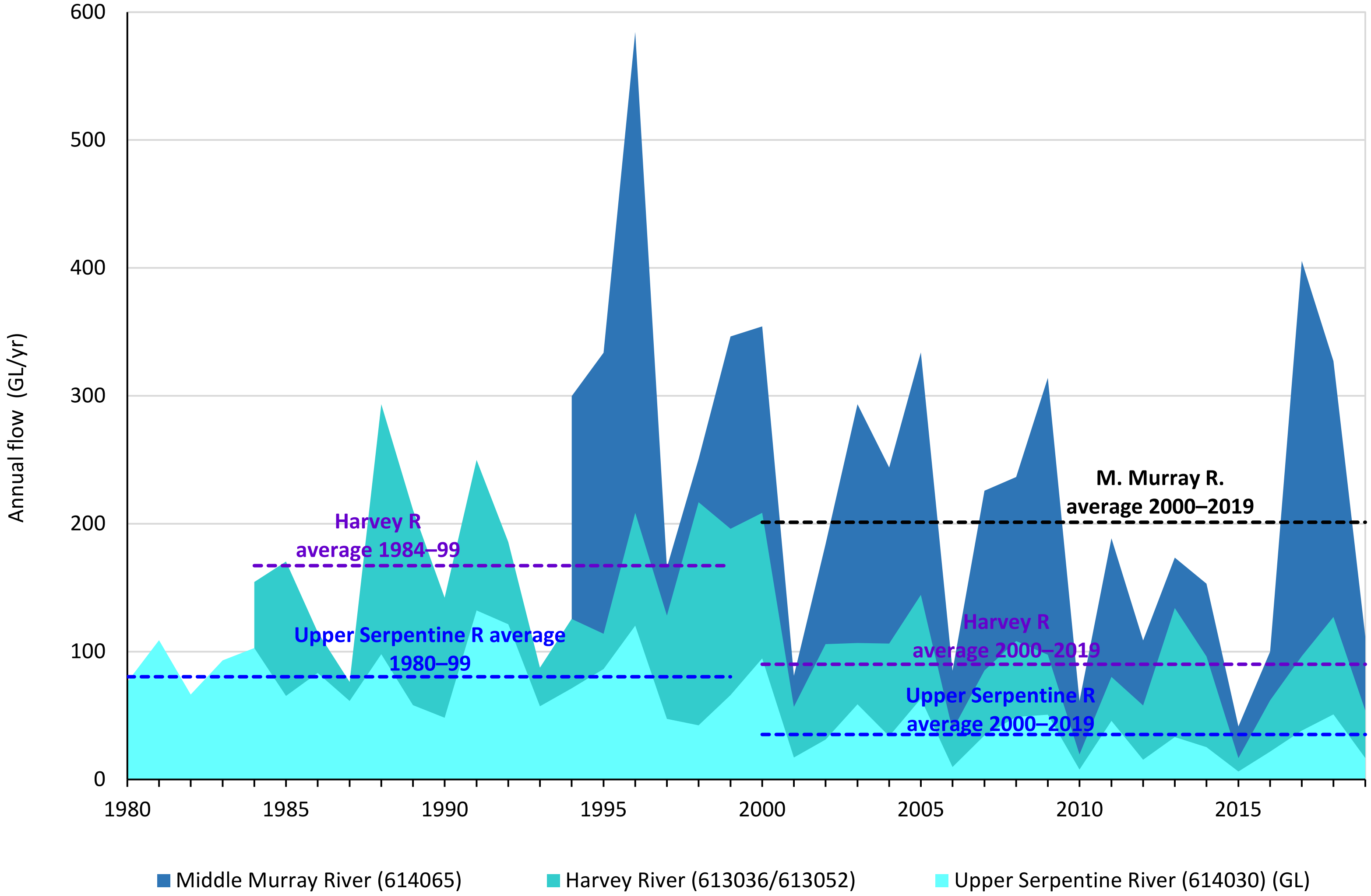

Figure 3-2 Total annual flow (GL/yr) for the Upper Serpentine River (AWRC ref. 614030) (1980–2019), Middle Murray River (AWRC ref. 614035) (1994–2019) and Harvey River (AWRC ref. 613036/613052) (1984–2019) showing how average flows have declined over time

Table 3-1 Total annual flows (GL) from 2000–2019, as monitored at gauging stations in the Peel-Harvey estuary coastal plain catchment

Monitoring site	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Serpentine R. catchment																				
Upper Serpentine River (AWRC ref. 614030)	95	17	31	59	34	63	9.7	35	49	51	7.7	46	16	33	25	6.2	22	38	51	17
Peel Main Drain (AWRC ref. 614121)							2.7	6.0	12	7.3	1.8	6.7	3.9	7.5	5.0	2.2	4.1	9.0	12	5.6
Punrak Drain (AWRC ref. 614094)	21	4.3	15	42				15	15	18	6.8	12	5.5	11	9.6	2.0	6.3	13	17	4.8
Gull Rd Drain (AWRC ref. 614120)						0.9	0.03	0.3											0.3	0.1
Nambeelup Brook (AWRC ref. 614063)							3.4	11	13	15	1.5	9.2	6.1	9.8	9.7	1.7	4.8	14	16	3.1
Murray R. catchment																				
Middle Murray River (AWRC ref. 614065)	354	81	184	293	244	334	85	226	237	314	61	189	109	173	153	41	100	405	327	112
Harvey R. catchment																				
Coolup Sth Main Drain (AWRC ref. 613027)							0.3	3.0	4.5	2.7	0.4	2.1	1.5	3.6	2.1	0.2	1.6	2.8	5.1	1.5
Mayfield Drain (AWRC ref. 613031)	36	3.7					3.4					11	9.8	22	13	1.9	12	17	24	8.5
Harvey River (AWRC ref. 613052/613036)	208	57	106	107	106	144	39	85	108	98	20	73	59	136	98	20	62	96	127	54
Meredith Drain (AWRC ref. 613053)	4.0		2.1	0.9	3.5	6.2	0.8	2.2	3.5	1.4									4.3	1.4

3.2 Catchment condition

Water quality

Nutrients

As nutrient concentrations drive eutrophic processes in the estuary, it is important to understand the sources of nutrients, what form they are present in and where concentrations are high. The department monitors nutrients fortnightly to monthly at 13 waterways and drains in the Peel-Harvey estuary coastal plain catchment (Figure 3-3). The monitoring sites are usually located at flow gauging stations upstream of the tidal influence where flow can be measured accurately.

Nutrient forms

To effectively manage water quality, it is important to understand what species of nitrogen (N) and phosphorus (P) are present and how and when they are transported from the catchment to the estuary.

Measures of total nitrogen (TN) and total phosphorus (TP) include particulate and dissolved forms and can be organic or inorganic species. Understanding the proportions of these forms, their bioavailability and how easily they break down can help us determine appropriate catchment management actions.

The dissolved inorganic species we measure are nitrate (combined concentrations of both forms of oxidised inorganic nitrogen are reported in this WQIP: $NO_3^- + NO_2^-$), total ammonia ($NH_3 + NH_4^+$) and filterable reactive phosphorus (FRP), which is mainly phosphate species (PO_4^{3-}).[17] These forms are readily bioavailable to phytoplankton, macroalgae and plants and will be removed from the water as they are taken up by algae and plants or converted into gaseous forms (e.g. N_2O and N_2). When plants and algae die, they generally decompose in the sediment, which may act as a sink for nutrients; they can also become a source as particulate nutrients are remineralised and returned to the overlying waters, potentially fuelling further growth of phytoplankton, macroalgae and plants.

The dissolved organic species are dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP). DON is a large portion of TN in many catchments in the South West. DON originates from both natural and anthropogenic sources and is made up of a mixture of compounds. Some, such as urea, which may be derived from fertiliser, are potentially bioavailable to algae. Others are complex organic compounds, like proteins and humic acids, which generally originate from broken-down pasture and manure (as well as natural vegetation) that has leached to

[17] The term nitrate is used for simplicity in this plan, as the vast majority (>99%) of oxidised inorganic nitrogen will generally be in the form of nitrate, as nitrite is highly reactive and tends to transition quickly to either nitrate (NO_3) or ammonium (NH^{4+}). When water samples are analysed by standard laboratory methods, nitrate is converted to nitrite, and the total concentration of nitrite is reported and represents the concentration of oxidised inorganic nitrogen.

groundwater and wetlands and have very little bioavailability. DON, along with dissolved organic carbon (DOC), are dominant components of the tea-brown colour of natural waters in the South West, which can limit light transmission through the water column, slowing down algal growth and thereby mitigating eutrophication. DOP is currently not monitored in the catchment.

Particulate N and P tend to be deposited as sediment or organic matter in the estuarine reaches of the rivers and drains, but in high flows may be delivered directly to the main estuary basins. Organic matter, in forms such as animal manure, can be a major source of nutrients to the estuary. Although organic matter concentrations in the water can be estimated from measurements of total organic carbon and DOC, these estimates miss the larger quantities of organic matter (e.g. solid waste from cattle) which settle to the sediment. Both particulate N and particulate P generally need to be broken down to be bioavailable to phytoplankton, macroalgae and plants.

Nutrient forms in the Peel-Harvey estuary coastal plain catchment

In the subcatchments of the Peel-Harvey estuary, a large portion of winter TN is attributed to DON (38–92 per cent, Table 3-2); however, we have limited understanding of the bioavailability of this fraction. Wells et al. (2019) also found that DON dominated the N pool in farm dams, feeder drains, main drains, rivers and the estuary basins. They found that DON concentrations progressively became more diluted downstream, indicating that the source of the DON was likely to be terrestrial (Raymond et al. 2016).

It is strongly recommended that further work is done to measure the bioavailability of DON across the reporting catchments, identify the composition of DON and its sources, and consider the influence of source on bioavailability (i.e. urban versus agricultural land uses). See Section 10.2 and recommended action 39.

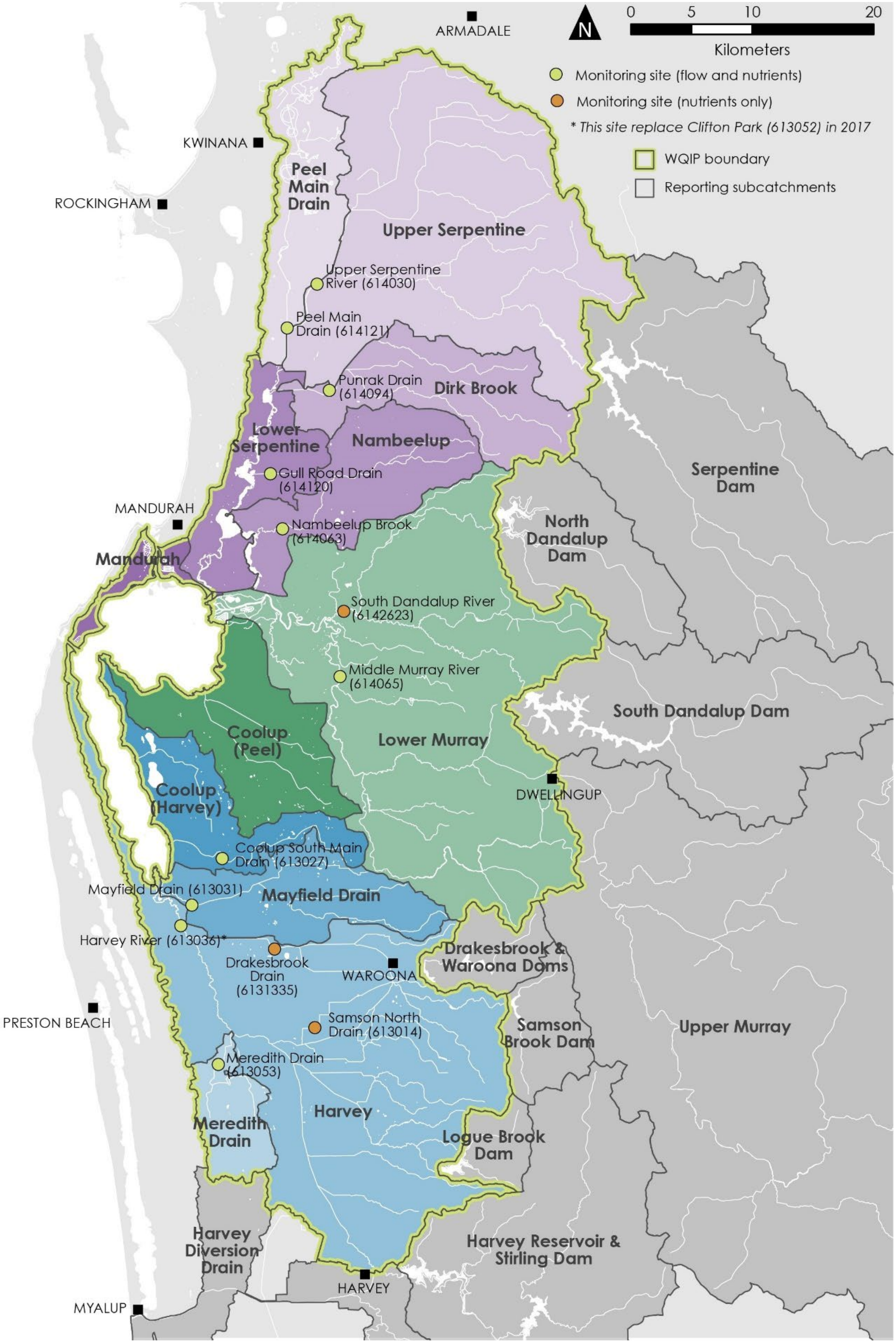

Figure 3-3 Location of sites monitored fortnightly (AWRC number in brackets)

Nutrient concentrations

Table 3-2 and Table 3-3 show the three-year (2016–18) winter median concentrations of N and P species calculated from fortnightly observations at the monitoring sites. Winter medians are used for comparison as most of the flows occur during winter and many streams do not flow at all in summer, which may skew comparisons when using annual medians.

In the absence of location-specific guideline values for N species (TN, NO3-+ NO2-, NH3 and NH4+) and also FRP, we refer to the ANZECC guideline values for slightly disturbed lowland rivers (ANZECC & ARMCANZ 2000b) as a point of reference and to allow for easier comparisons between sites. We have also compared TP concentrations with the locally specific guideline value used in previous WQIPs for estuary systems on the Swan coastal plain (TP of 0.1 mg/L). Concentrations that are above these guideline values are identified in Table 3-2 and

Table 3-3.

Both TN and TP winter median concentrations (2016–18) are above the guideline values in the Serpentine and Harvey rivers for all sites sampled, except for TP in Drakesbrook Drain in the Harvey River catchment (Table 3-2 and Table 3-3). By contrast, all monitoring sites in the Murray River catchment had TN and TP winter median concentrations (2016–18) below guideline values.

The highest TN winter median concentrations (2016–18) were observed in the Serpentine River catchment at Nambeelup Brook and Gull Road Drain, where the 2016–18 medians were about 2.5 and 3.5 times higher than the ANZECC guideline value respectively.

Nitrate (NO_3^-+ NO_2^-) winter median concentrations (2016–18) varied greatly across the catchment, with three sites in both the Serpentine and Harvey river catchments above the ANZECC guideline value (Table 3-2). Drakesbrook Drain and Samson North Drain showed particularly high nitrate winter median concentrations (2016–18) of about 1 mg/L, almost seven times the guideline value.

Extremely high TP winter median concentrations (2016–18) were also observed in the Serpentine River catchment at Nambeelup Brook and Gull Road Drain, where the TP concentrations were four to eight times more than the locally specific guideline value. In the Harvey catchment, the TP winter median concentrations (2016–18) at Meredith Drain were also high, about four times the locally specific guideline value.

The FRP winter median concentrations (2016–18) were above the ANZECC guideline value at almost all the same sites showing above-guideline TP concentrations (i.e. most Serpentine and Harvey river catchment sites). The high concentrations of FRP observed generally reflect the large losses of nutrients from the surrounding agricultural land on the coastal plain, with their mostly poor nutrient-retaining soils (low PRI).

*Table 3-2 Three-year winter median N concentrations for the period of 2016–18, calculated from fortnightly monitoring. * indicates medians above the ANZECC guideline value for lowland rivers (TN: 1.2 mg/L, nitrate ($NO_3^- + NO_2^-$): 0.15 mg/L of N, total ammonia ($NH_3 + NH_4^+$): 0.08 mg/L of N). Note no guideline value is available to use for DON. DIN is dissolved inorganic nitrogen (nitrate and total ammonia). n is number of TN samples.*

River catchment	Site name	AWRC ref. no.	TN (2016–18) winter median (mg/L)	DON (2016–18) winter median (mg/L)	NO_3^- + NO_2^- (2016–18) winter median (mg/L of N)	NH_3 + NH_4^+ (2016–18) winter median (mg/L of N)	% DIN (2016–18) winter median %	% DON (2016–18) winter median %	No. of samples n
Serpentine	Upper Serpentine River	614030	1.40*	1.10	0.16*	0.04	14%	79%	32
Serpentine	Peel Main Drain	614121	1.51*	1.20	0.20*	0.05	17%	79%	32
Serpentine	Punrak Drain	614094	1.75*	1.00	0.40*	0.06	26%	57%	34
Serpentine	Gull Rd Drain	614120	4.22*	3.89	0.06	0.16*	5%	92%	23
Serpentine	Nambeelup Brook	614063	3.27*	2.80	0.09	0.07	5%	86%	31
Murray	South Dandalup River	6142623	0.96	0.62	0.14	0.06	21%	65%	32
Murray	Middle Murray River	614065	0.70	0.49	0.15	0.02	24%	70%	32
Harvey	Coolup South Main Drain	613027	1.99*	1.80	0.04	0.05	5%	90%	29
Harvey	Mayfield Drain	613031	1.59*	1.31	0.04	0.02	4%	82%	32
Harvey	Harvey River	613036	2.00*	1.14	0.53*	0.05	29%	57%	32
Harvey	Drakesbrook Drain	6131335	1.96*	0.74	1.02*	0.06	55%	38%	33
Harvey	Samson North Drain	613014	2.46*	1.19	1.00*	0.04	42%	48%	32
Harvey	Meredith Drain	613053	2.60*	2.17	0.05	0.14*	7%	83%	32

*Table 3-3 Three-year winter median P concentrations for the period of 2016–2018, calculated from fortnightly monitoring. * indicates medians above the ANZECC guideline value for FRP in lowland rivers (0.04 mg/L) and over the locally specific guideline value for TP (0.1 mg/L). n is number of samples of TN which closely relates to the number of samples of TP (may vary by one or two).*

River catchment	Site name	AWRC ref. no.	TP (2016–18) winter median (mg/L)	FRP (2016–18) winter median (mg/L)	No. of samples n
Serpentine	Upper Serpentine River	614030	0.21*	0.10*	32
Serpentine	Peel Main Drain	614121	0.18*	0.09*	32
Serpentine	Punrak Drain	614094	0.18*	0.11*	34
Serpentine	Gull Rd Drain	614120	0.80*	0.65*	23
Serpentine	Nambeelup Brook	614063	0.43*	0.22*	31
Murray	South Dandalup River	6142623	0.09	0.02	32
Murray	Middle Murray River	614065	0.01	0.01	32
Harvey	Coolup South Main Drain	613027	0.27*	0.10*	29
Harvey	Mayfield Drain	613031	0.16*	0.05*	32
Harvey	Harvey River	613036	0.21*	0.10*	32
Harvey	Drakesbrook Drain	6131335	0.07	0.02	33
Harvey	Samson North Drain	613014	0.14*	0.04	32
Harvey	Meredith Drain	613053	0.44*	0.31*	32

Seasonal patterns

First flush

Nutrient concentrations in waterways and drains are closely related to flow, with higher loads transported in higher flows and maximum loads transported during flood events.

The first rainfall after an extended dry period (usually the start of the wet season) which results in flow to the tributaries is referred to as the ‘first flush’. Runoff from the sandy soils of the Swan coastal plain generally takes several rainfall events to start, and the rainfall needs to be substantial. These first rainfall-runoff events tend to entrain relatively high loads of sediments, particulates and pollutants that have built up during the preceding dry period.

It is important to consider the seasonality of nutrient concentrations, and the relative contributions of surface water runoff and groundwater inflows to flow in a waterway, when determining suitable water treatment options or actions to manage the source. In 2018 many monitoring sites in the Peel-Harvey estuary coastal plain catchment showed a seasonal pattern in N concentration while others showed none.[18] There are large differences between waterways that have a strong influence from groundwater and those with more influence from surface flows. Data from the Harvey River and Punrak Drain are compared below to illustrate this variability.

The Harvey River site is an example of one with strong seasonal patterns in all forms of N in 2018, noting total ammonia (NH_3 + NH_4^+) was less evident than the other forms (Figure 3-4). The peak in June reflects the ‘first flush effect’ where N is mobilised by the first heavy rainfall for the year. Much of this N was probably the result of organic N in soils, waterways and drains that mineralised during summer to become dissolved, inorganic forms (that are bioavailable), plus runoff from grazing land (a mixture of dissolved and particulate N) which had built up with animal waste and fertiliser during the dry summer period.[19] Concentrations of TN, DON and nitrate (NO_3^- + NO_2^-) remain high during July and August, but decline near the end of August as rainfall and runoff ease. This suggests that during winter, most of the N at this site is coming from surface flows whereas shallow groundwater is contributing the bulk of the N in the drier months.

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[18] Not all monitoring sites had flow year-round.

[19] Nitrogen mineralisation is the microbial conversion of organically bound nitrogen in soil organic matter, crop residues, manure, and other organic amendments into inorganic forms of ammonium and nitrate.

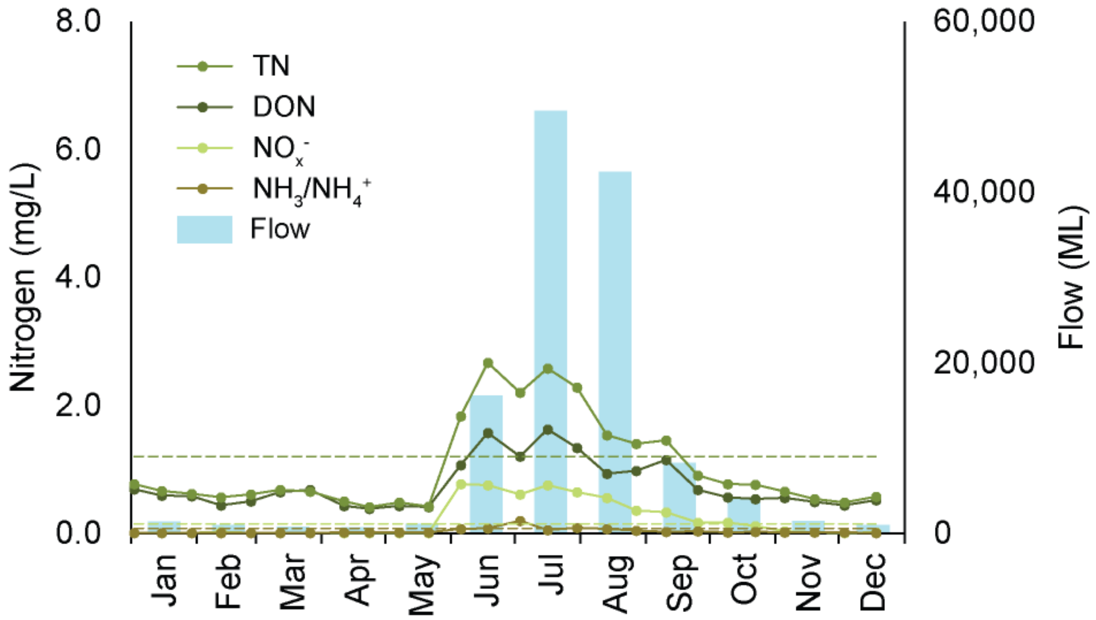


Figure 3-4 Nitrogen concentrations and monthly discharge at Harvey River (AWRC ref. 613036) in 2018. The dashed lines are the ANZECC guideline values for lowland rivers for the different nitrogen species.

Punrak Drain is an example of a site that did not show the typical seasonal response in TN and DON concentrations; these nutrients were higher in the drier months when flow was at its lowest (Figure 3-5). Sources of DON were likely shallow groundwater (which would be contributing most of the flow at this time of year) and decaying plant and algal matter in the drain. Evapo-concentration (increasing concentrations because of evaporation) may also have contributed to the high DON concentrations. The origin of nutrients found in shallow groundwater that feeds waterways in the drier months is most likely the land uses surrounding the waterways.

Nitrate (NO_3^- + NO_2^-) concentrations did show a seasonal response at Punrak Drain; the highest concentrations were observed in early June with N mobilised by heavy rainfall.

TP and FRP concentrations at the Harvey River site increased in June and remained high while flows were elevated. The alignment of seasonal patterns in P concentrations and flow suggests that most of the P at this site is washed in with surface flows (first-flush effect), and that groundwater contributions are likely to be minor (Figure 3-6). In-stream sources such as bank erosion and sediment fluxes may also be contributing to P concentrations.

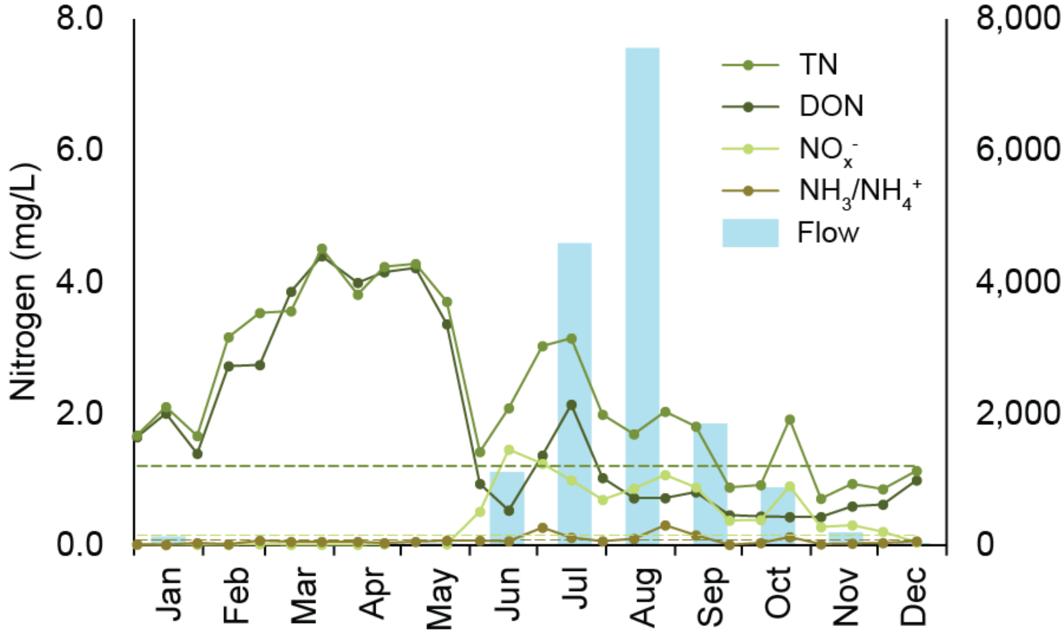


Figure 3-5 *Nitrogen concentrations and monthly discharge at Punrak Drain (AWRC ref. 614094) in 2018. The dashed lines are the ANZECC guideline values for lowland rivers for the different nitrogen species.*

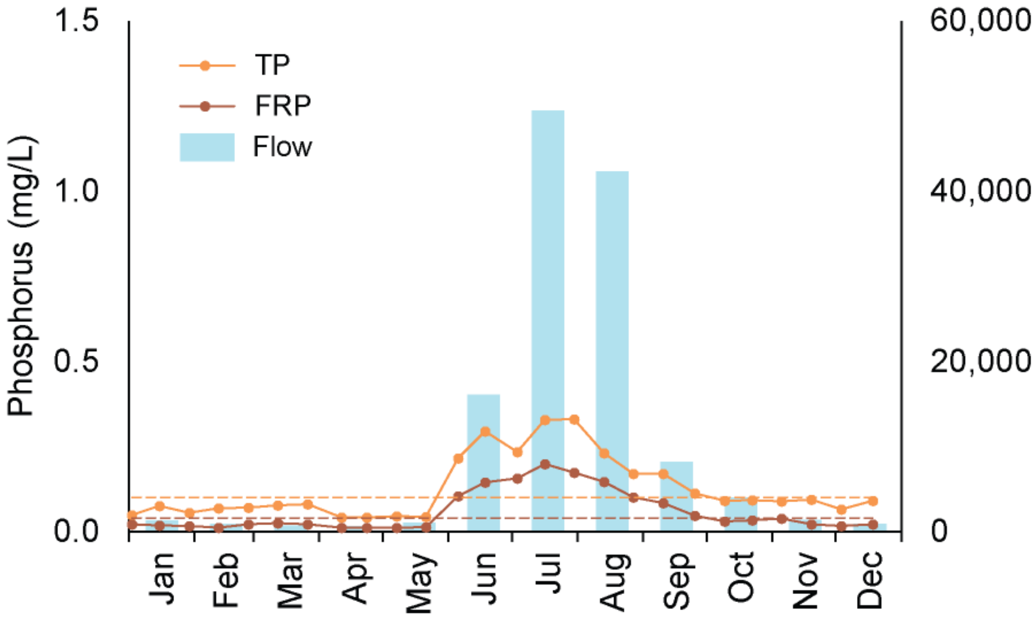


Figure 3-6 *Phosphorus concentrations and monthly discharge at Harvey River (AWRC ref. 613036) in 2018. The paler dashed line is the locally specific guideline value for TP; the darker dashed line is the FRP ANZECC guideline value for lowland rivers.*

In contrast, TP and FRP concentrations were highest at Punrak Drain in the first part of the year, when there was little or no surface flow and the relative proportion of groundwater in the drain was largest (Figure 3-7). This suggests that FRP is entering the drain from high-concentration shallow groundwater. The source of P in groundwater is likely to be a land use activity close to the measurement site, as FRP tends to be rapidly taken up by algae in slow-flowing waters. After the onset of winter rain, the concentrations of both TP and FRP declined rapidly, suggesting the P-rich groundwater is being diluted by lower-concentration surface flows.

Salinity showed a similar seasonal pattern to TP and FRP (Figure 3-8), also reflecting the increased influence of groundwater in the drier months.

We recommend further research to characterise nutrient concentrations in shallow groundwater across the coastal estuary catchment and the interaction of this with waterways, drains and the estuary (see Section 10.4).

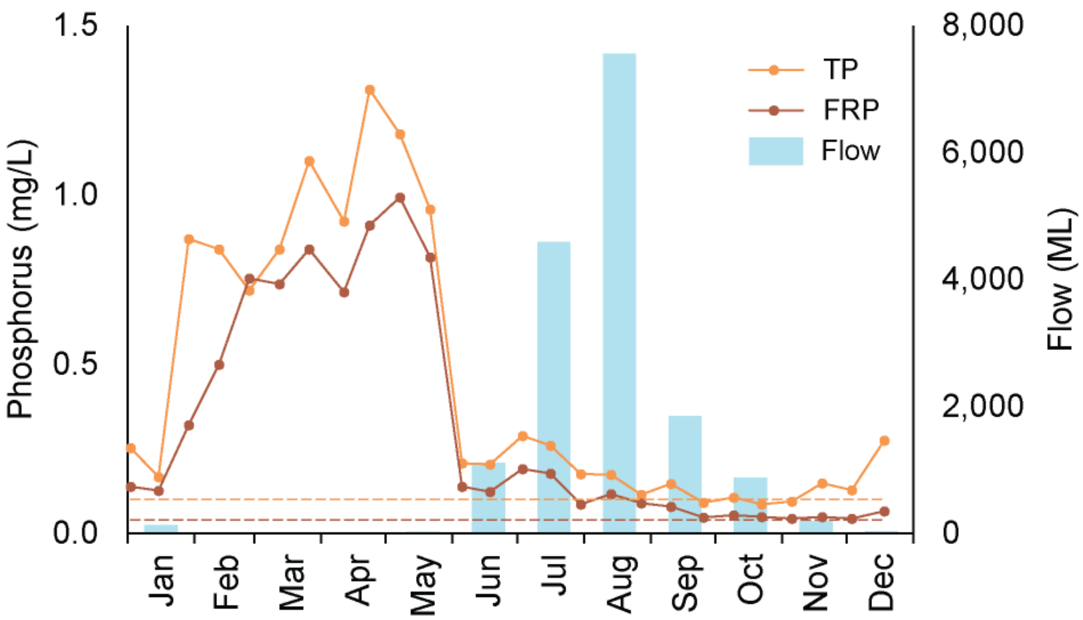


Figure 3-7 Phosphorus concentrations and monthly discharge at Punrak Drain (AWRC ref. 614094) in 2018. The pale dashed line is the Peel-Harvey locally specific guideline value for TP; the dark dashed line is the FRP ANZECC guideline value for lowland rivers.

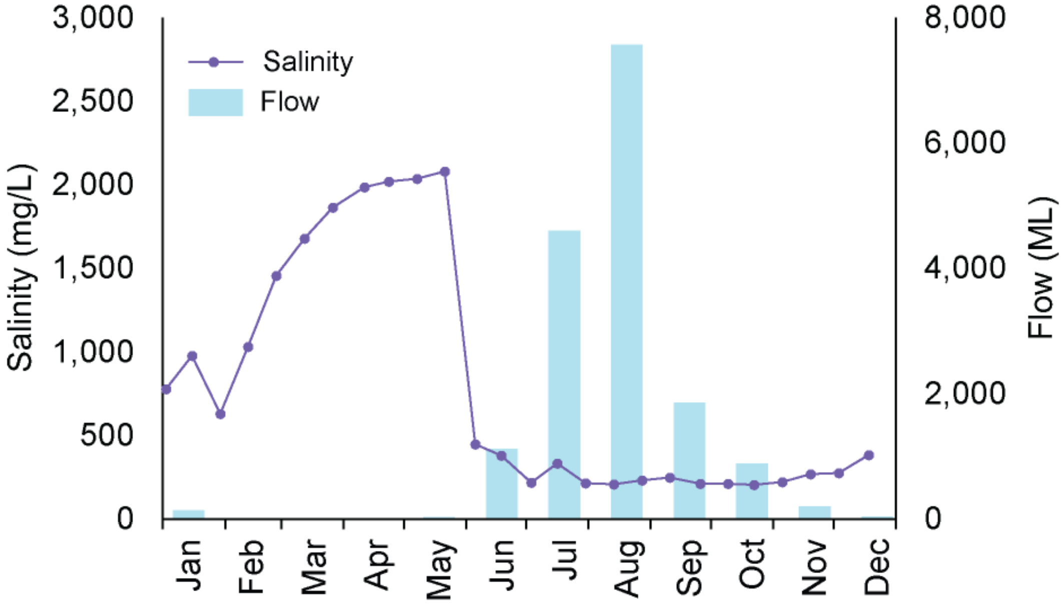


Figure 3-8 Salinity concentrations and monthly discharge at Punrak Drain (AWRC ref. 614094) in 2018

Below are the sites in the catchment that showed a typical seasonal pattern in their nutrient concentrations in 2018, and those that did not.

Sites that showed a seasonal pattern in TN and TP concentrations:

- Drakesbrook Drain (AWRC ref. 6131335)
- Harvey River (AWRC ref. 613036)
- Mayfield Drain (AWRC ref. 613031)
- Meredith Drain (AWRC ref. 613053)
- Middle Murray River (AWRC ref. 614065)
- Peel Main Drain (AWRC ref. 614121)
- South Dandalup River (AWRC ref. 6142623)
- Upper Serpentine River (AWRC ref. 614030)

Sites that did not show a typical seasonal pattern in TN and TP concentrations:

- Coolup South Main Drain (AWRC ref. 613027) (note this site did not flow year-round)
- Punrak Drain (AWRC ref. 614094)
- Gull Rd Drain (AWRC ref. 614120) (note this site did not flow year-round)
- Nambeelup Brook (AWRC ref. 614063)
- Samson North Drain (AWRC ref. 613014)

See Appendix G for the complete set of graphs for 2018 data of N species, P species, salinity, DON and total monthly flow for each site monitored in the catchment (where flow data was available for a site). See also the Peel-Harvey estuary catchment nutrient reports (DWER 2021a) for a detailed discussion of the water quality monitoring results for 2018. Both this and the older nutrient reports (2015–17) can be accessed online.[20]

Ecological health assessments

As part of the Regional Estuaries Initiative (REI), the department conducted ecological health assessments at 10 sites in the Peel-Harvey catchment between 2017 and 2020. We assessed a further 16 sites before 2017 with rapid field assessments that assigned ecological health values.

The ecological health assessments provide a baseline condition for each site, helping us to evaluate catchment management activities aimed at improving the ecological health of the waterways. The ecological assessments also support various management decisions, particularly when determining ecological water requirements. See Figure 3-9 for the 10 sites, with the results summarised below.

[20] For 2018 catchment nutrient reports, see Catchment nutrient reports 2018 and for the older nutrient reports, see Catchment nutrient reports 2012-2017.

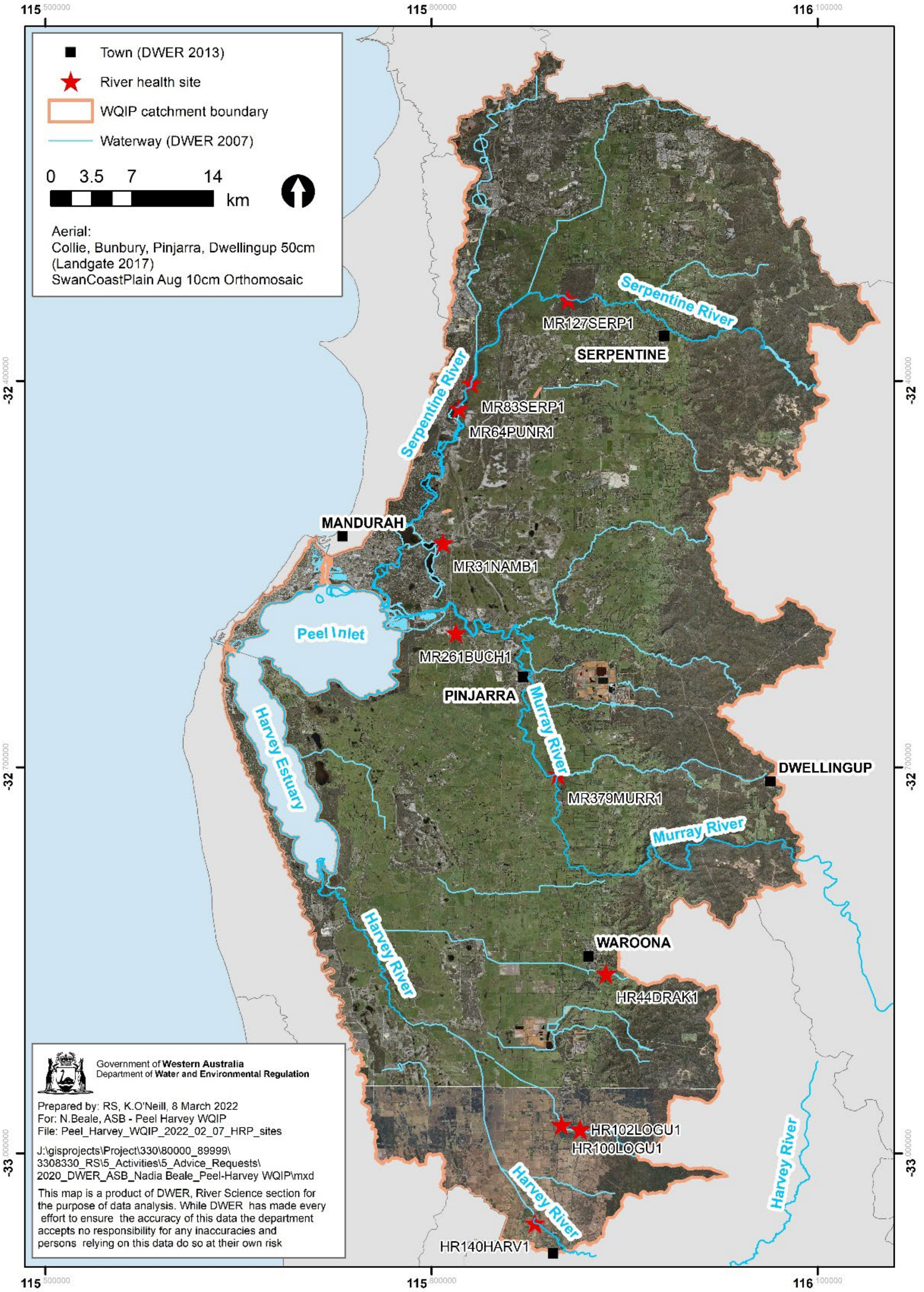


Figure 3-9 The sites of the department's 10 ecological health assessments in the Peel-Harvey estuary coastal plain catchment from 2017–20

Riparian vegetation

Intact riparian vegetation is essential for the health of our waterways: it stabilises the banks, slows surface erosion and runoff, contributes to water quality improvement and helps to improve the overall ecological function of the waterway.

Historical clearing of the Peel-Harvey estuary coastal plain catchment has led to significant losses of riparian vegetation. What remains is often in a degraded condition and generally reflects the impacts of surrounding land uses on the river. The ecological health assessments identified that many sites across the plan area had a sparse riparian overstory (tree layer) with a minimal understory (shrubs and groundcover layers). These sites were often degraded and dominated by exotic weed species that did not adequately stabilise riverbanks or provide sufficient shading of the waterway.

A few sites within each river catchment were an exception, such as Lowlands Nature Reserve (DWER site MR127SERP1, Figure 3-9) in the Serpentine River's upper reaches. This site lies at the western edge of about 1,300 ha of remnant native vegetation. It has near-pristine riparian vegetation (extending 40–50 m on either bank), with broad and healthy native trees (mainly *Eucalyptus rudis* – flooded gum). The shrubs are mainly *Melaleuca* spp. and the groundcover layers are rushes, sedges and the native fern *Pteridium esculentum* (Austral bracken); there is a complete absence of exotic weeds. The aquatic habitat is supporting a healthy community of fauna with strong recruitment (juveniles recorded for all observed native species).

Figure 3-10 Lowlands Nature Reserve, upper to mid Serpentine River, demonstrates near-pristine riparian vegetation

In a stark contrast, only a few kilometres downstream below the confluence with the Peel Main Drain (DWER site MR83SERP1, Figure 3-9), the Serpentine River is a straightened floodway channel with levees on either side. The site has severely degraded riparian vegetation, no shady trees or shrubs, and only a grassy groundcover. The in-stream aquatic habitat is uniform, and lacks substrate diversity, woody debris and aquatic macrophytes.

Figure 3-11 The Serpentine River, downstream of the confluence with the Peel Main Drain (DWER site MR83SERP1), showing the degraded state of the riparian vegetation

The loose, sandy soils of the Swan coastal plain are easily eroded if not supported by adequate riparian vegetation. Reaches of rivers with cleared catchments are prone to sedimentation because of increased erosion. Effects can include smothered benthic habitats, reduced diversity of aquatic fauna, loss of riparian vegetation (and associated shading) plus damage to land and fencing.

Aquatic fauna

Aquatic fauna are dependent on good water quality. Adequate riparian shading, natural flow regimes (or artificial water releases to mimic natural flows) and low nutrient concentrations are all important factors that help maintain optimal water quality for native aquatic fauna. Aquatic fauna also need appropriate habitat and maintenance of summer refuges (e.g. in ephemeral systems).

Our 10 ecological health assessments showed that several locations throughout the plan area provided sufficient habitat and water quality to support native aquatic fauna. Nine native freshwater and freshwater-estuarine fish and crayfish species were present in the Peel-Harvey estuary coastal plain catchment waterways and drains (note: * = endemic to the South West):

- *Tandanus bostocki* (freshwater cobbler) *
- *Nannoperca vittata* (western pygmy perch) *
- *Galaxias occidentalis* (western minnow) *
- *Bostockia porosa* (nightfish) *
- *Pseudogobius olorum* (Swan River goby or blue-spot goby)
- *Leptatherina wallacei* (western hardyhead) *
- *Mugil cephalus* (sea mullet)
- *Cherax quinquecarinatus* (gilgie) *
- *Cherax cainii* (smooth marron) * (Figure 3-12).

Figure 3-12 Cherax cainii (smooth marron)

Some species that are not as common were recorded, including the *Westralunio carterii* (Carter’s freshwater mussel) and *Hydromys chrysogaster* (rakali).

Non-native species have a competitive advantage in their behavioural plasticity and tolerance of conditions that are suboptimal for South West native and endemic fish and crayfish. Five non-native species were recorded:

- *Phalloceros caudimaculatus* (one spot livebearer)
- *Gambusia holbrooki* (eastern gambusia)
- *Carassius auratus* (goldfish)
- *Cherax destructor* (yabby)
- *Caridina indistincta* (indistinct river shrimp) (a recently discovered exotic invertebrate pest).

Locations in the plan area with riparian vegetation of good extent and quality (e.g. Lowlands reserve, DWER site MR127SERP1, Figure 3-9) generally had better and more varied aquatic habitat, higher species richness and numbers of native aquatic fauna, and lower numbers of non-native species than sites where the riparian vegetation was severely degraded. Endemic species dominated the aquatic fauna at Lowlands reserve, including *Cherax quinquecarinatus* (gilgie), *Galaxias occidentalis* (western minnow), *Nannoperca vittata* (western pygmy perch) and *Bostockia porosa* (nightfish), as well as the native estuarine-opportunistic species *Pseudogobius olorum* (Swan River goby or blue-spot goby) with evidence of recruitment (juveniles observed). Only two exotic species were recorded at Lowlands reserve – *Gambusia holbrooki* (eastern gambusia), which was abundant with some juveniles present, along with a single *Cherax destructor* (yabby).

Channelised and cleared reaches of the Serpentine River (e.g. DWER site MR83SERP1, Figure 3-9), where the riparian vegetation was limited to grass, generally displayed little diversity in aquatic habitat. The aquatic fauna at site MR83SERP1 was dominated by non-native species such as *Gambusia holbrooki* (eastern gambusia), *Cherax destructor* (yabby) and *Carassius auratus* (goldfish). Four native species were present but only in relatively low numbers with poor recruitment (i.e. few juveniles): *Bostockia porosa* (nightfish), *Galaxias occidentalis* (western minnow), *Nannoperca vittata* (western pygmy perch) and *Cherax quinquecarinatus* (gilgie). Large numbers of two native estuarine-opportunistic species – *Pseudogobius olorum* (blue-spot goby) and *Leptatherina wallacei* (western hardyhead) – were also recorded. However, most of these fish were moving downstream (i.e. intercepted in the upstream-facing net), most likely to escape poor water quality conditions and access better quality habitat downstream.

Sites with limited riparian shading, limited aquatic habitat and elevated nutrients routinely exhibited poor water quality that exceeded the tolerance thresholds for native fish. Non-native species, on the other hand, can often survive such conditions.

The contrast of two sites relatively close together on the Serpentine River highlight the role of healthy native riparian vegetation in supporting the ecology of in-stream habitat and a community of aquatic fauna rich in native species. This WQIP aims to improve the extent and quality of riparian vegetation through programs targeting revegetation and stock-exclusion fencing along waterways and drains, as well as other river restoration activities. These, along with management actions that reduce nutrient (and non-nutrient) export from the catchment, will improve the ecological health of the waterways – which should be reflected in future river health assessments.

For further information about the ecological assessments and aquatic fauna species present in the catchment, see Healthy Rivers.

3.3 Estuary condition

The department has regularly monitored water quality in the estuary since 2000, with an increase in frequency from 2016 (to a fortnightly–monthly regime) to better assess condition and the estuary's response to reducing river flows and changes in catchment land use (see Figure 3-13 for the location of the monitoring sites).[21] The following variables are measured either in situ or by laboratory analysis: salinity, dissolved oxygen, temperature, pH, water clarity, nutrients (various chemical forms of N and P), chlorophyll *a* and phytoplankton densities.

In this section, we look at historical data (2002–2017) to understand changes in estuary condition over time and make inferences about future condition. This data has also been used to develop a coupled catchment-estuary model (Hipsey et al. 2019) to enable more extensive predictions of future responses to change.

Water quality

Nutrients

N and P concentrations indicate the eutrophic status of a waterbody and have historically been measured at the surface and bottom. Surface water nutrients typically originate from agricultural and urban runoff in the wet season or via mixing of bottom waters with surface waters, whilst bottom water nutrients are more likely to come from degradation of organic matter in sediment, or from groundwater. TN and TP are measures of both particulate and dissolved forms, which include both organic and inorganic species, with each fraction having a different bioavailability (see page 47 for a discussion about nutrient forms).

Figure 3-14 and Figure 3-15 illustrate the influence of river flow and show the residence time of nutrients in the Peel-Harvey estuary. They also compare wet and dry seasonal concentrations (see Figure 3-13 for monitoring site locations).

[21] Between the 1970s and 2000, the frequency of estuary water quality monitoring varied.

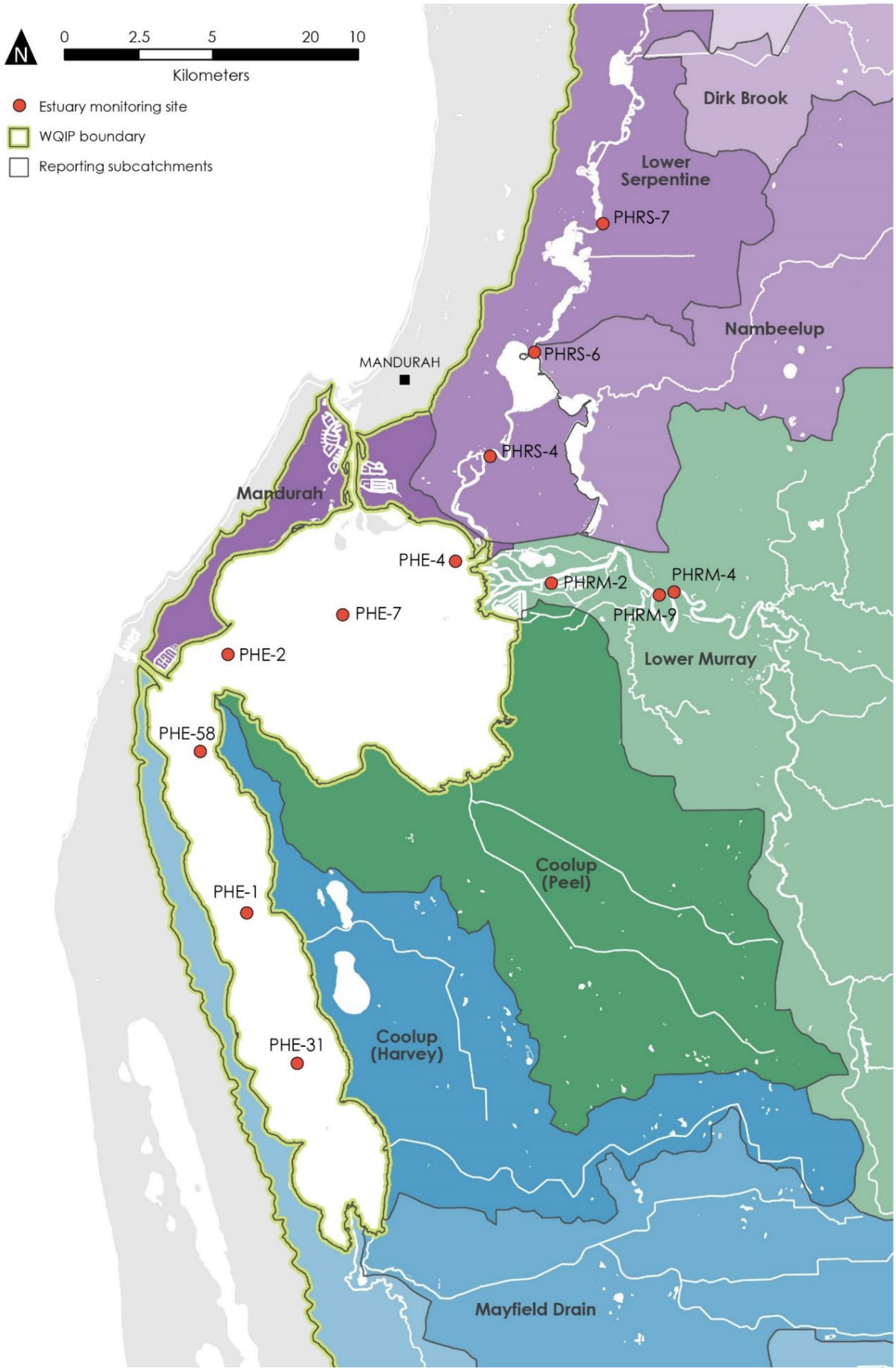


Figure 3-13 Estuary map showing water quality monitoring sites

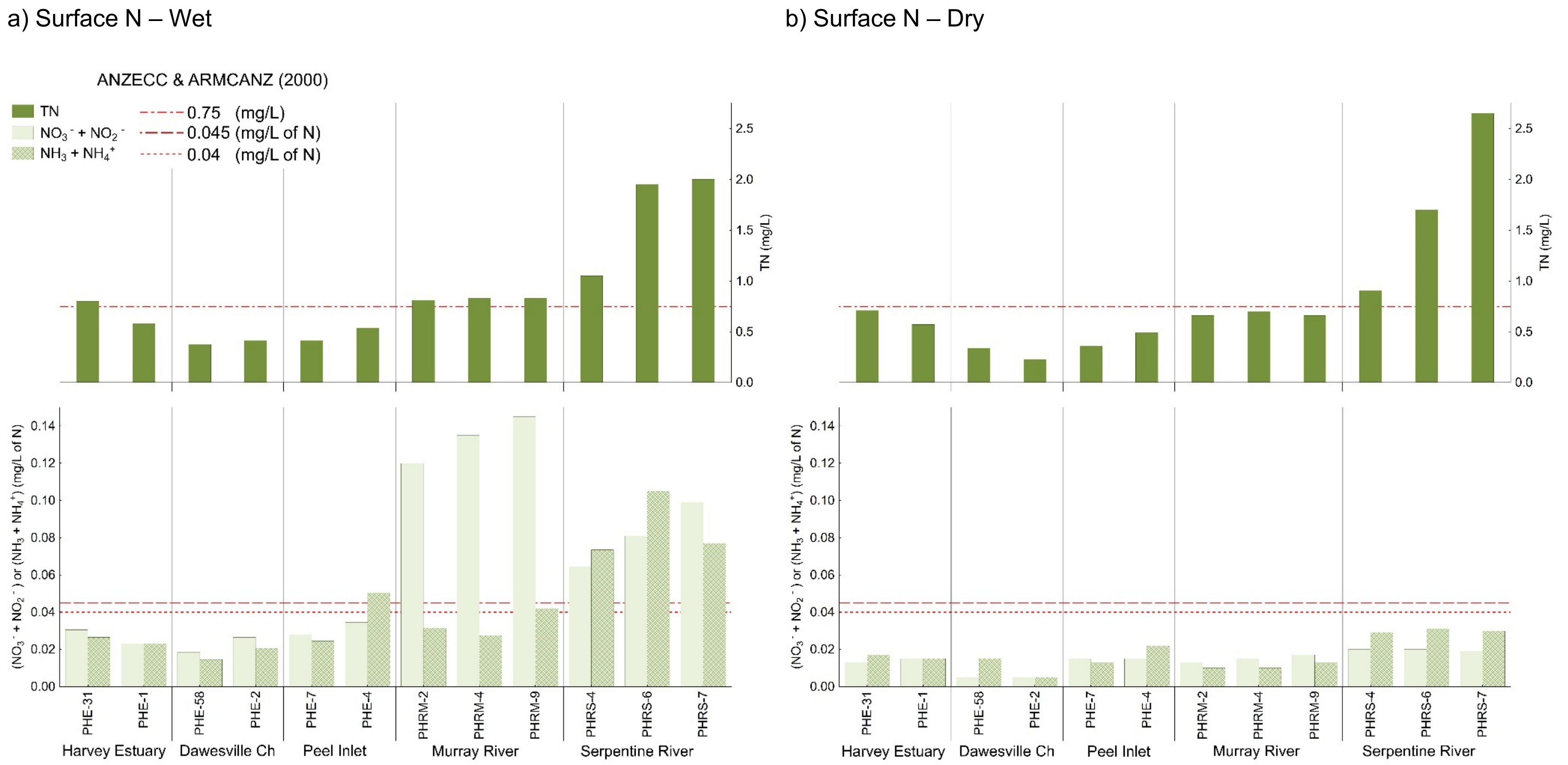


Figure 3-14 Total nitrogen (TN) (mg/L), nitrate (NO_3^- + NO_2^-) (mg/L of N), total ammonia (NH_3 + NH_4^+) (mg/L of N), in the wet June to October and dry seasons November to May (2007/08–2012/13, 2016/17; except PHE-58, PHE-2 2016/17 only). Default guideline values for estuaries in south-west Australia (slightly disturbed ecosystems) are shown as dotted red lines (ANZECC & ARMCANZ 2000b).

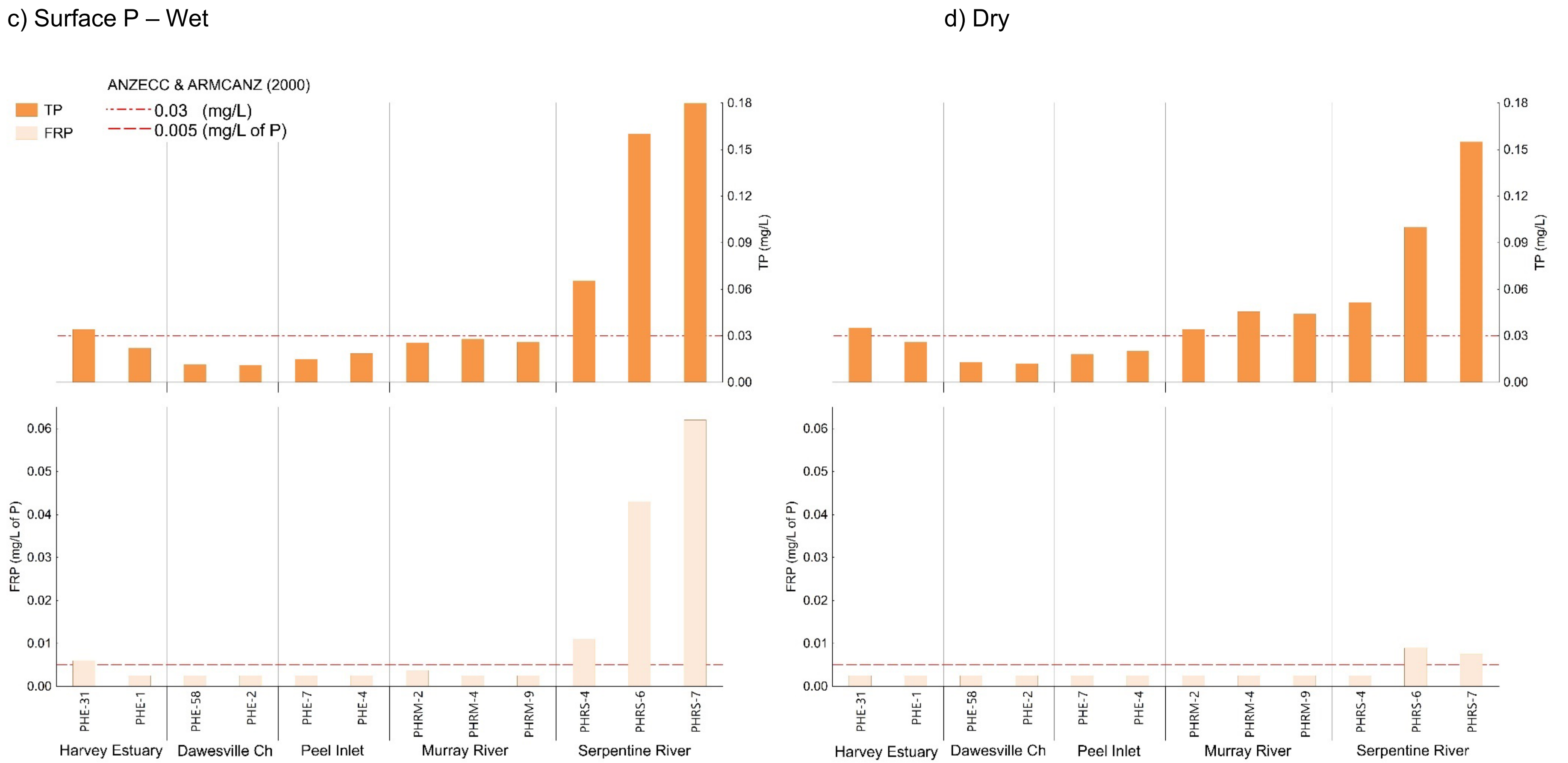


Figure 3-15 Total phosphorus (TP) and filterable reactive phosphorus (FRP) concentrations (mg/L) (median surface) in the wet (June to October) and dry seasons (November to May) (2007/08–2012/13, 2016/17; except PHE-58, PHE-2 2016/17 only). Default guideline values for estuaries in south-west Australia (slightly disturbed ecosystems) are shown as dotted red lines.

In both the wet and dry seasons, the estuarine reaches of the Serpentine River have much higher TN concentrations than those of the Murray River. Most high TN concentrations in the dry season can be attributed to N assimilated by the high density of phytoplankton present. In the wet season, nitrate concentrations are the dominant form of dissolved N in the estuarine reaches of the Murray River, reflecting catchment-derived inputs. In contrast, in the Serpentine River, nitrate and total ammonia concentrations are similar.

TP concentrations are high in the estuarine reaches of the Serpentine River year-round. In the wet season, a much larger portion of TP is in dissolved form, originating from surface and groundwater flows, and possibly from the sediment. In the dry season, a larger portion of TP is present in particulate form, much of which is assimilated in the high density of phytoplankton.

Salinity

Estuary salinities are influenced by connectivity and distance to the ocean, freshwater flows, tides, wind and currents, and evaporation. Salinity levels typically decline in winter and spring when rainfall and runoff increase and rise during the summer and autumn when these inputs subside. During summer and autumn, the salt wedge penetrates further upstream into the lower rivers and higher temperatures increase the rate of evaporation, particularly in shallow waters – often resulting in hypersalinity (salinities greater than sea water) in these regions.

The salinity data shown in Figure 3-16 shows relatively stable marine salinity near the Dawesville Channel, and highly variable salinity in the estuarine reaches of the Murray and Serpentine rivers where it fluctuates from fresh to hypersaline (>35 parts per thousand). Salinity stratification is evident in the Murray River with fresher water overlying the saltier and more dense bottom waters.

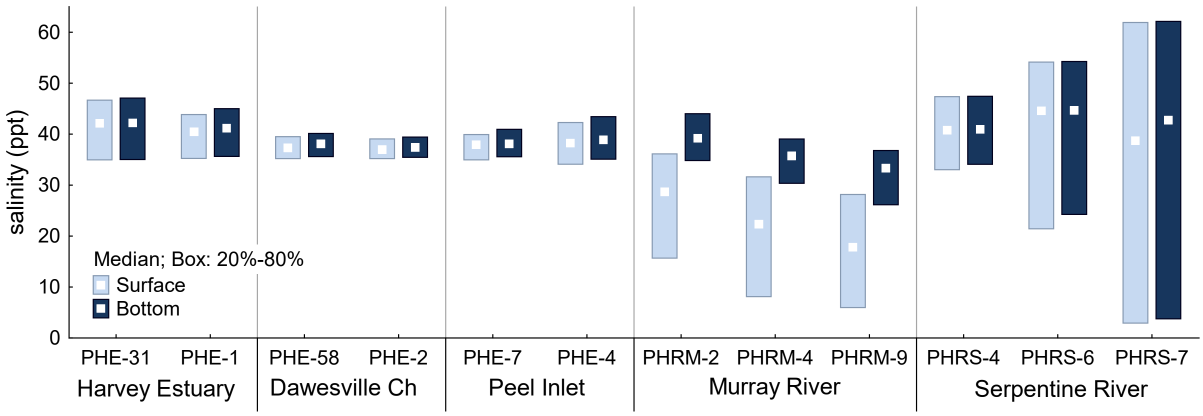


Figure 3-16 Salinity (ppt) showing the median and 20–80th percentiles from samples at the surface and bottom in the dry season, November to May (2002/03–2016/17), in the basins and estuarine reaches of the rivers

Dissolved oxygen

Dissolved oxygen (DO) concentrations in a waterbody reflect the balance between processes that add oxygen (e.g. diffusion from the atmosphere and photosynthesis by aquatic plants) and those that consume oxygen (e.g. respiration by aquatic plants). As described in Section 1.11, when an algal bloom dies, the organic material sinks to the sediment and decomposes (facilitated by oxygen-consuming bacteria). This can deplete the oxygen in the water column and lead to anoxic conditions.

The survival of aquatic life depends on adequate dissolved oxygen (DO) concentrations. Below DO concentrations of about 5 mg/L, the ability of fish and other aquatic fauna to grow and reproduce is reduced (USEPA 2000). Concentrations below 2 mg/L may lead to extreme physiological stress or death. DO tolerances vary between species and depend on the length and frequency of exposure.

When DO concentrations in the bottom waters approach zero, anoxic biogeochemical processes at the sediment/water interface can release toxic chemicals and gases (e.g. zinc, lead, copper, ammonia, hydrogen sulfide).

Low-oxygen conditions are created by several factors including:

- **stratification**, where differences in salinity and/or temperature of the water form distinct layers which prevent oxygen exchange
- **aerobic decomposition** of organic matter washed in from the catchments and/or dead algae or aquatic plants
- **respiration**, where algae or aquatic plants use oxygen at night to break down sugars for growth
- **low solubility** at high temperatures and salinities.

Salinity stratification often leads to low bottom oxygen if there is high sediment oxygen demand because of the bacterial degradation of organic matter. Figure 3-17 shows the difference between the well-mixed waters of the Peel Inlet and Harvey Estuary and the stratified waters of the estuarine reaches of the Murray River, where long-term hypoxia (oxygen less than 2 mg/L) and occasional anoxia (0 mg/L) in the bottom waters is primarily because of organic-rich sediments.

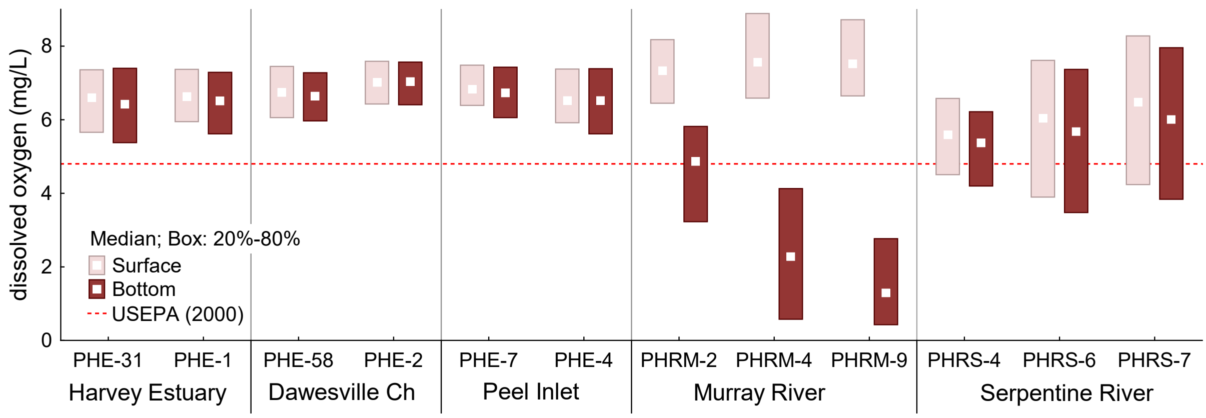


Figure 3-17 Dissolved oxygen concentrations (mg/L) showing the median and 20–80th percentiles of samples at the surface and bottom in the dry season, November to May (2002/03–2016/17), in the basins and estuarine reaches of the rivers. Guideline value of 4.8 mg/L (USEPA 2000) shown as a dotted red line.

Phytoplankton and chlorophyll a

Phytoplankton are single-celled algae or cyanobacteria – microscopic organisms that are an essential component of any estuarine ecosystem. To grow, they need specific nutrients and adequate light and temperature. When optimal conditions occur, phytoplankton (algal) blooms are stimulated. Even though they are microscopic, at very high numbers they are visible as discolouration, or a scum on the water surface. Occasional and short-duration algal blooms are a normal part of an estuarine ecosystem, but when blooms occur regularly, persist or are directly or indirectly harmful (toxic) to humans and other fauna, they are an indication of poor water quality.

Concentration of chlorophyll *a*, a pigment found in plants and algae, is often used as an indicator of phytoplankton activity and to indicate the trophic status (level of pollution) of a waterbody (ANZECC & ARMCANZ 2000a), as increased nutrient input can lead to increased phytoplankton in the water column. However, variation in chlorophyll *a* does not always reflect changes in estuary nutrient loading (Cloern 2001).

Before the Dawesville Channel was opened in 1994, chlorophyll *a* concentrations in the estuary basins were very high at >50 ug/L (Pearce et al. 2000), reflecting extreme eutrophic conditions. In fact, the blue-green cyanobacteria *Nodularia* were so prolific they could be seen in satellite imagery (Hodgkin and Lenanton 1981, Hale and Butcher 2007).

The rationale for the channel's construction and the focus of the 2008 WQIP was to reduce the intensity and frequency of algal blooms, especially phytoplankton blooms, by enabling marine conditions in the estuary and increasing the flushing of P out to sea. Dramatic reductions in chlorophyll *a* were observed in the early post-construction years, but although the *Nodularia* no longer blooms in the estuary basins, nuisance blooms still occur primarily in the estuarine reaches of the rivers.

Figure 3-18 shows that for all seasons in the estuarine reaches of the rivers, the chlorophyll *a* concentrations are at or above ANZECC guideline values (ANZECC & ARMCANZ 2000b) and are especially high during summer and autumn. The variability in the concentrations over the 10-year period, particularly in the Murray and Serpentine rivers, reflects annual differences in river flow, temperature and nutrients among others. In the Harvey Estuary, chlorophyll *a* concentrations are higher in winter, most likely because of nutrient delivery from the Harvey River.

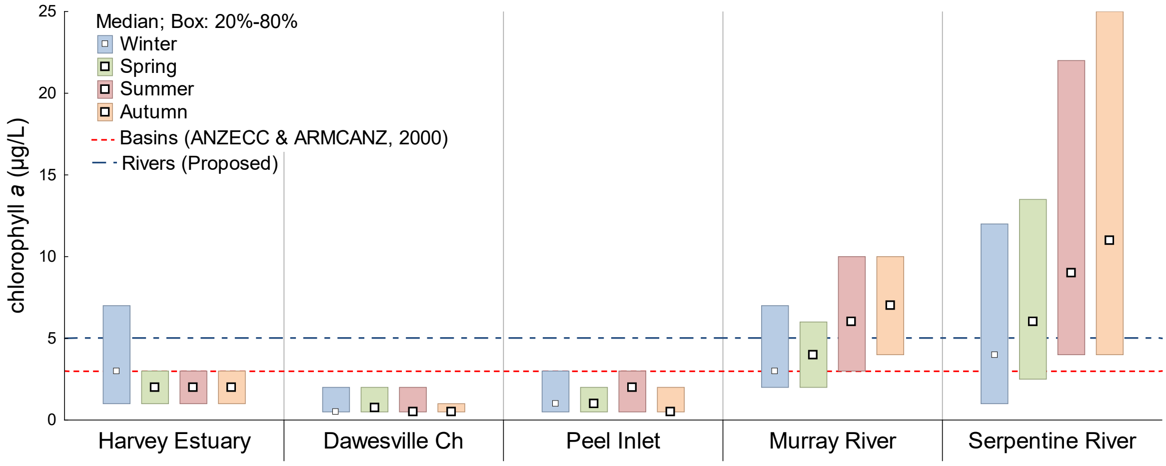


Figure 3-18 Chlorophyll a concentration (µg/L) showing the median and 20–80th percentiles from samples at the surface (2007–2017), in the basins and estuarine reaches of the rivers. Guideline for basins in red (ANZECC & ARMCANZ 2000b) and proposed guideline for the rivers in blue.

While some species of phytoplankton produce toxins that may be harmful to humans and wildlife at low cell densities, most species are only problematic at very high cell densities. The department monitors the density and composition of phytoplankton across the Peel-Harvey estuary and reports on the number of exceedences that occur, as measured against nationally established or local interim guidelines which may suggest a risk to human health, fish health or a decline in aesthetics.

The phytoplankton population in the Peel-Harvey estuary is comprised of eight key groups: the Chlorophyta, Diatoms (Bacillariophyta), Cyanophyta, Dinophyta, Cryptophyta, Haptophyta, Chrysophyta and Raphidophyta (Figure 3-18). Five of these groups – Cyanophyta, Dinophyta, Haptophyta, Diatoms and Raphidophyta – contain species that may be directly harmful to humans and fish.

The high chlorophyll *a* concentration in the estuarine reaches of the Serpentine River is historically and currently dominated by chlorophytes, diatoms and cyanophytes. Densities of cyanophytes are periodically so high that the waters resemble pea soup.

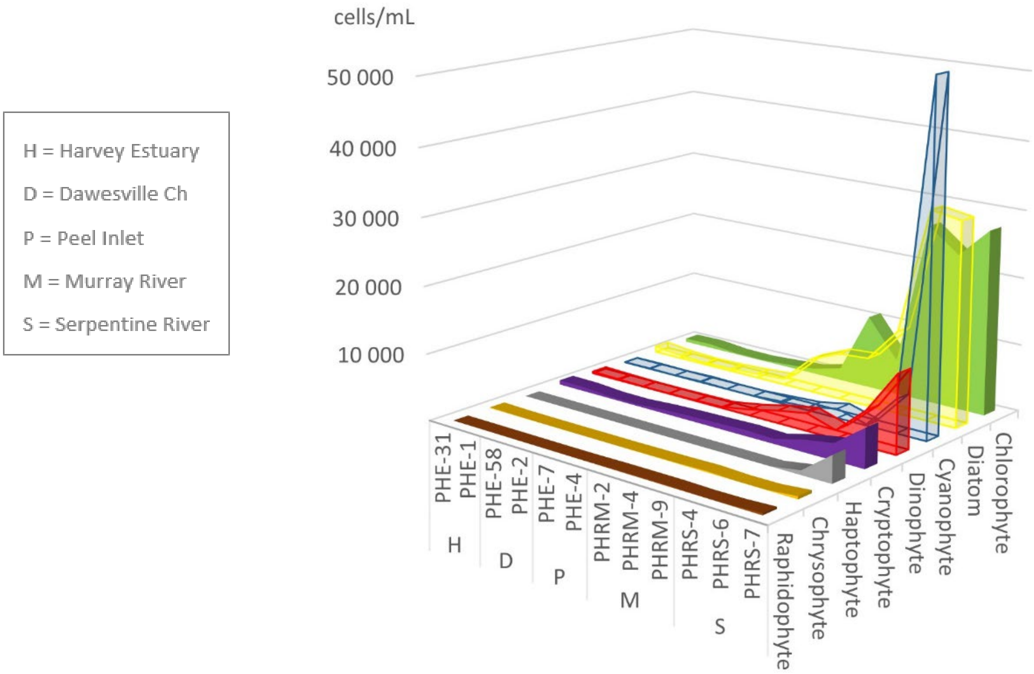


Figure 3-19 Phytoplankton groups cells/mL (mean annual) in the five zones of the Peel-Harvey estuary (May 2002 – June 2017, except for PHRM-9, May 2007 – June 2017) depth integrated samples

Besides chlorophytes and diatoms, the estuarine reaches of the Murray River can also have high densities of dinophytes. The class Dinophyta includes dinoflagellates, which are characteristic of stratified waters. They move from the surface to the bottom waters to take up nutrients released from breakdown of organic matter in sediments and then back to the surface to photosynthesise.

The warm and shallow nutrient-rich waters of the Serpentine River favour Cyanophyta (blue-green bacteria), many of which can produce toxins. The occurrence of high phytoplankton concentrations in the estuarine reaches of the rivers has been a feature of the Peel-Harvey system post Dawesville Channel, reflecting the combination of saltwater penetration further up the rivers, nutrient leaching, organic matter deposition in the estuarine reaches of the rivers, and reduced river flows.

See *Bindjareb Djilba (Peel-Harvey estuary): Condition of the estuary 2016–2019* (DWER 2023a) for the current (2016–19) number of exceedences of harmful and nuisance algae/cyanobacteria.

Water clarity

Water clarity measures the extent to which light can travel through the water and how much light is available for the growth of photosynthetic organisms such as phytoplankton, microphytobenthos (bottom-dwelling microalgae), seagrass and macroalgae.

As discussed in Section 1.11, seagrasses are an important part of estuarine ecosystems, and require sufficient light to thrive. Excessive growth of some algae can smother seagrass by creating low-light conditions and making it difficult for seagrass to photosynthesise.

Secchi depth is a measure of water clarity where the deeper the secchi depth, the higher the water clarity. Secchi depth was measured at 10 of the 12 sites in the Peel-Harvey estuary (Figure 3-20). Sites show a median secchi depth that varies from 1.2–2.4 m and a bottom depth that varies from 1.8–4.5 m. The water clarity is lowest in the deepest sites in the estuary, located in the estuarine reaches of the Murray River. Water clarity at these sites is likely to be influenced by suspension of fine particles of clay eroded from the catchment, emphasising the need to manage erosion of soils from these areas. In contrast, the highest water clarity was observed in the ocean-influenced Dawesville Channel sites.

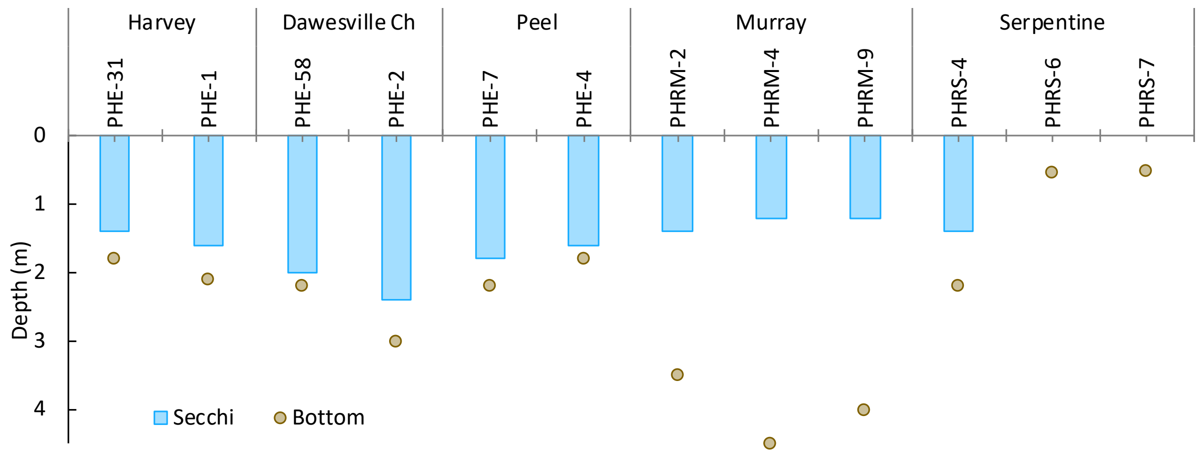


Figure 3-20 Median secchi depth (m) and bottom depth for each of the five zones monitored in the Peel-Harvey estuary (2002–17)

Water Quality Index

Water quality indices have been developed for many aquatic ecosystems around the world; they are designed to synthesise measures of key water quality indicators to create a relatively simple expression of water quality status. An interim Water Quality Index (WQI) for the Peel-Harvey estuary (Thomson 2021) has been developed which uses a methodology similar to those in other Australian states. The interim WQI scores each of the 12 monitoring sites in the Peel-Harvey estuary and the estuarine reaches of the Serpentine and Murray rivers based on phytoplankton (measured as chlorophyll *a*), DO, and TN and TP concentrations. The interim WQI for 2017–18 highlighted the spatial differences in condition across the estuary – ranging from very good near the Dawesville Channel sites to very poor in the lower reaches of the Serpentine and Murray rivers (Appendix H). See Thomson (2021) for details of the methodology for the interim WQI. Once the methodology is refined, the WQI can be calculated annually and/or seasonally to track the condition of the estuary and compare pressures and stressors such as flow, marine exchange and nutrient loads.

Sediment

Sediment health influences the plant and animal communities that live in or around them. Sediment condition is dependent on a range of measures: phosphorus binding efficiency, denitrification efficiency, sediment nutrient stores, sediment composition (grain size and organic matter content), and sediment oxygen demand. The organic matter that has accumulated in the sediment, such as dead plant material (including algae) or animal waste, is decomposed by microbes. The decomposition of large amounts of organic matter can create low-oxygen (hypoxic) or even no-oxygen (anoxic) conditions (see 'Dissolved oxygen', page 70). Enriched, hypoxic sediments can become sources of nutrients to the water column, and potentially fuel harmful algal blooms (Conley et al. 2007). Even worse are the anoxic organic-rich muds known as monosulfidic black oozes, which can occur in parts of the Peel-Harvey estuary (Kraal et al. 2013).

The proportions of total organic carbon (a measure of organic matter) in the sediments of the Peel-Harvey estuary were measured in 2016 (Figure 3-21) (Hallett et al. 2019b). Values greater than 5 per cent are considered high in estuaries of the South West (Radke et al. 2004). Accumulations of organic carbon of this magnitude occur where the rivers discharge into the Peel Inlet and along the central channel of the Harvey Estuary. The organic carbon also accumulates in several areas in the Murray River and at the bottom of Lake Goegrup. Measurements in 2019 also showed very high proportions (~9 per cent) of organic carbon in the Serpentine River upstream of Lake Goegrup (Tulipani et al. 2019). Because of the accumulation and degradation of organic matter, sediments in depositional zones have a high oxygen demand which may lead to deoxygenation of the overlying water. The accumulation of organic matter in the lower Serpentine is likely to be contributing to low DO conditions in this area despite it being relatively shallow and well mixed. Decreasing freshwater flows means organic matter is rarely scoured downstream.

In estuaries, the organic carbon in sediments comes from a mixture of land-based (terrestrial) and aquatic plants, macroalgae and phytoplankton. Sources of organic matter can be determined by measuring the ratios of naturally occurring forms (isotopes) of common nutrients like carbon and N (Lamb et al. 2006). Application of this technique found that more of the organic carbon in the lower and upper Murray came from terrestrial plants; in the lower Serpentine, more came from phytoplankton; and in the Peel Inlet and Harvey Estuary, more came from phytoplankton and/or macroalgae.

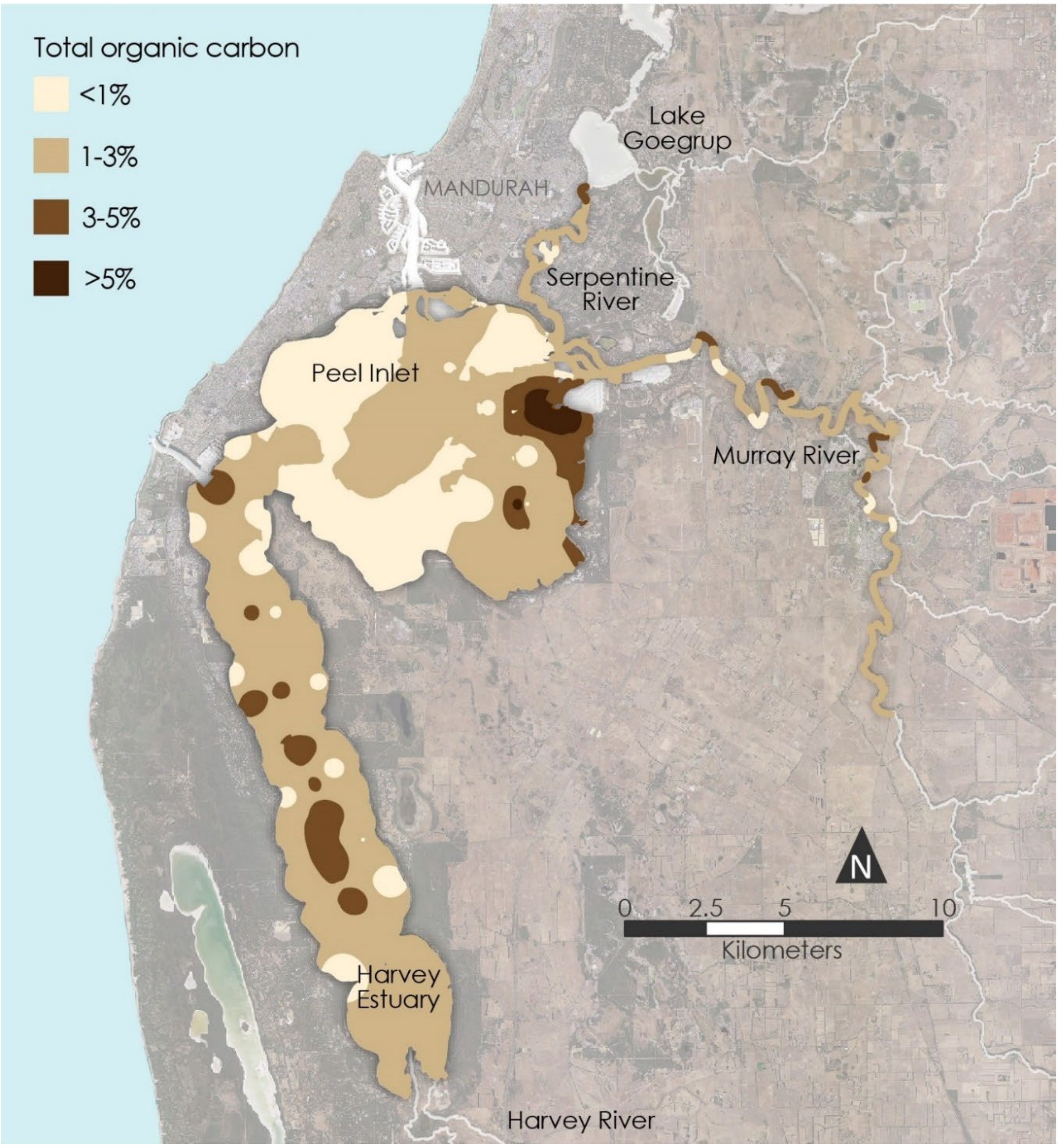


Figure 3-21 Organic carbon (per cent) distribution in the Peel-Harvey estuary, from a snapshot survey in November/December 2016. For details of sites and collection methods, see Hallett et al. (2019b).

Seagrass and macroalgae

Key differences in the physiology and growth patterns of seagrasses and macroalgae mean they respond differently to changes in water quality. As seagrasses are rooted in the sediment, they need good water quality and sediment conditions to thrive. By contrast, the macroalgae in the Peel-Harvey estuary tend to be free-floating, taking up nutrients directly from the water with minimal dependence on sediment quality. While both seagrasses and macroalgae are important parts of the ecosystem, in the Peel-Harvey estuary the presence of seagrass is generally considered to indicate healthy conditions, while an overabundance of macroalgae indicates poor conditions.

As discussed in Section 1.2, the proliferation of nuisance algae in the 1970s and 1980s led to construction of the Dawesville Channel. Post channel, macroalgae decreased from about 15,000 t in spring 1994 (Water and Rivers Commission 1998) to a spring average of about 4,000 t in 1995–1999 (Figure 3-22), being most abundant in the lower Harvey Estuary and eastern Peel Inlet, where *Chaetomorpha* species dominate (Marine and Freshwater Research Laboratory 2019). A general increase in seagrass was observed post channel and about 1,800 t (spring average) was present in 1995–2000 (Marine and Freshwater Research Laboratory 2019) (Figure 3-23). The most common species was *Halophila ovalis* (paddleweed), which was most abundant in the main basin of the Peel Inlet.

Seagrass and macroalgae were far more abundant in 2017 than 1995–2000, with more than five times more seagrass (about 10,300 t) and 65 per cent more macroalgae (about 6,500 t) (Marine and Freshwater Research Laboratory 2019). The increase in biomass may reflect the environmental conditions of that year (rainfall, temperature, sunshine), with the historical data showing annual variability of this magnitude. The most dominant seagrass species was *Ruppia megacarpa,* favoured by the unusually large inflows of fresh water over the preceding summers (2016, 2017). Note that its growth form tends to lead to greater measures of biomass. The relatively high abundance of macroalgae in 2017 is concerning and may suggest a shift back towards a more eutrophic state. The species most prevalent was *Willeella brachyclados*, a nuisance green macroalgae that proliferated in large free-floating mats pre channel. It collects in the southern Harvey Estuary and eastern Peel Inlet, where it makes use of the high concentrations of nutrients coming in from the rivers.

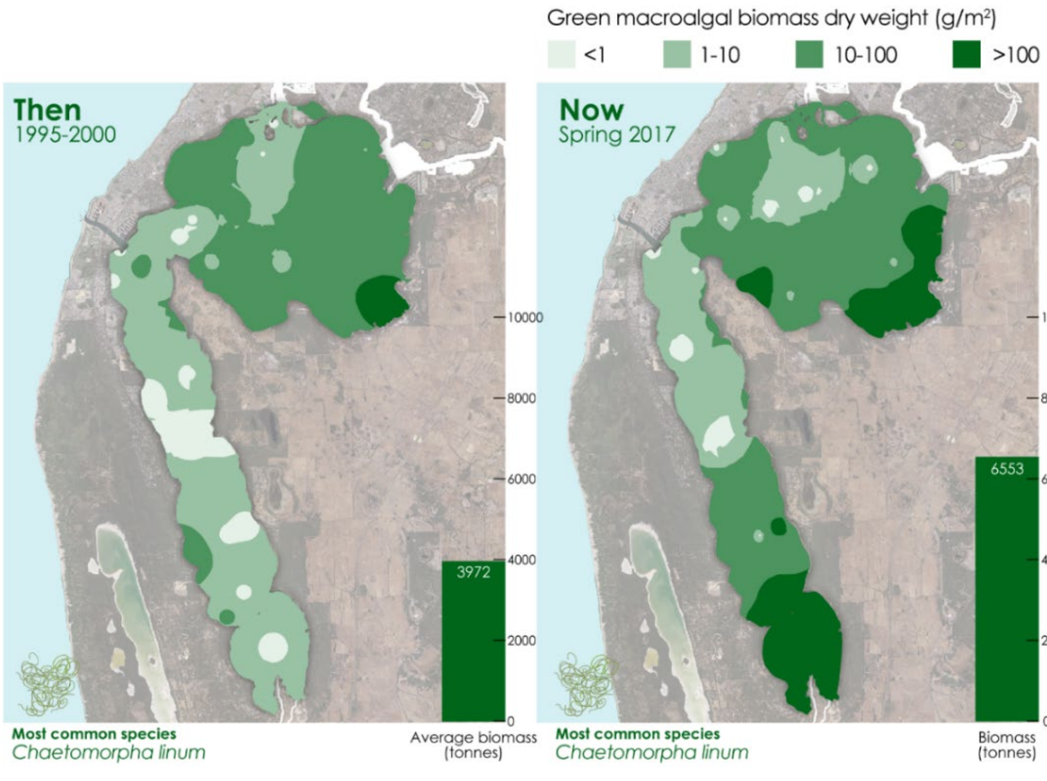


Figure 3-22 Distribution and density (g/m²) of macroalgal biomass in 1995–2000 (average, left pane) and spring 2017 (right pane)

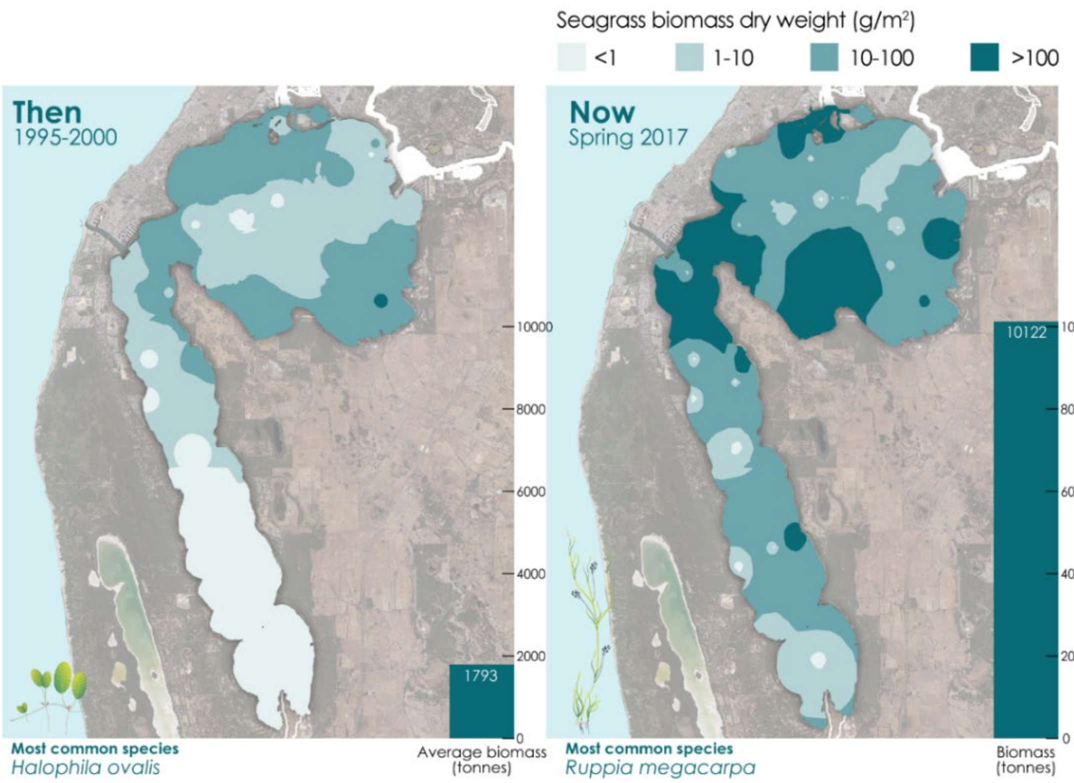


Figure 3-23 Distribution and density (g/m2) of seagrass biomass in 1995–2000 (average, left pane) and spring 2017 (right pane)

Fish

For fish communities to be healthy, diverse and productive they need good water quality, appropriate habitat and adequate connectivity between marine, estuarine and freshwater environments (Hallett et al. 2019a).

Some of the key pressures on the Peel-Harvey estuary, such as reduced rainfall and fertiliser runoff from beef/dairy farming (see Section 5), directly affect its ecological health, including that of its fish communities. As estuary health declines, fish community abundance and composition are impacted. Sensitive species such as those that cannot tolerate lower levels of oxygen, or that have specialised breeding habits that require freshwater inflows, are usually lost first (Hallett et al. 2019a).

Murdoch University has developed a Fish Community Index which scores key characteristics of the fish community and integrates these into an overall measure of fish community health (Hallett et al. 2019a). The key characteristics of a healthy estuarine fish community are a balance of specialist and generalised feeders and benthic and estuarine breeding species. Those indicative of an unhealthy community are higher proportions of detritivores (feeding on decaying plant and animal matter), non-specialist feeders, and an indicator species (blue-spot goby) that can tolerate poor conditions like low oxygen.

When applying the index to data collected from the Peel-Harvey estuary in 2017–18, the estuary generally performed poorly (Figure 3-24). Fish community condition was worst in the shallower waters of the Peel Inlet, the Mandurah Channel and the deeper waters of the eastern Peel Inlet, and the Serpentine and Murray rivers (scoring a D). The condition was slightly better in the Harvey Estuary and shallower regions of the Serpentine and lower Murray rivers (scoring a C). The deeper regions of the western Peel Inlet, the northern Harvey Estuary and the shallow waters of the upper Murray River performed the best (scoring a B).

Unless the water quality improves, fish community condition will remain poor in the deeper parts of the lower rivers. And while water quality in the basins is relatively good, the mostly poor Fish Community Index scores suggest that other factors may be limiting fish community condition, such as the loss of nursery and feeding habitat (e.g. saltmarsh) (Hale and Kobryn 2017).

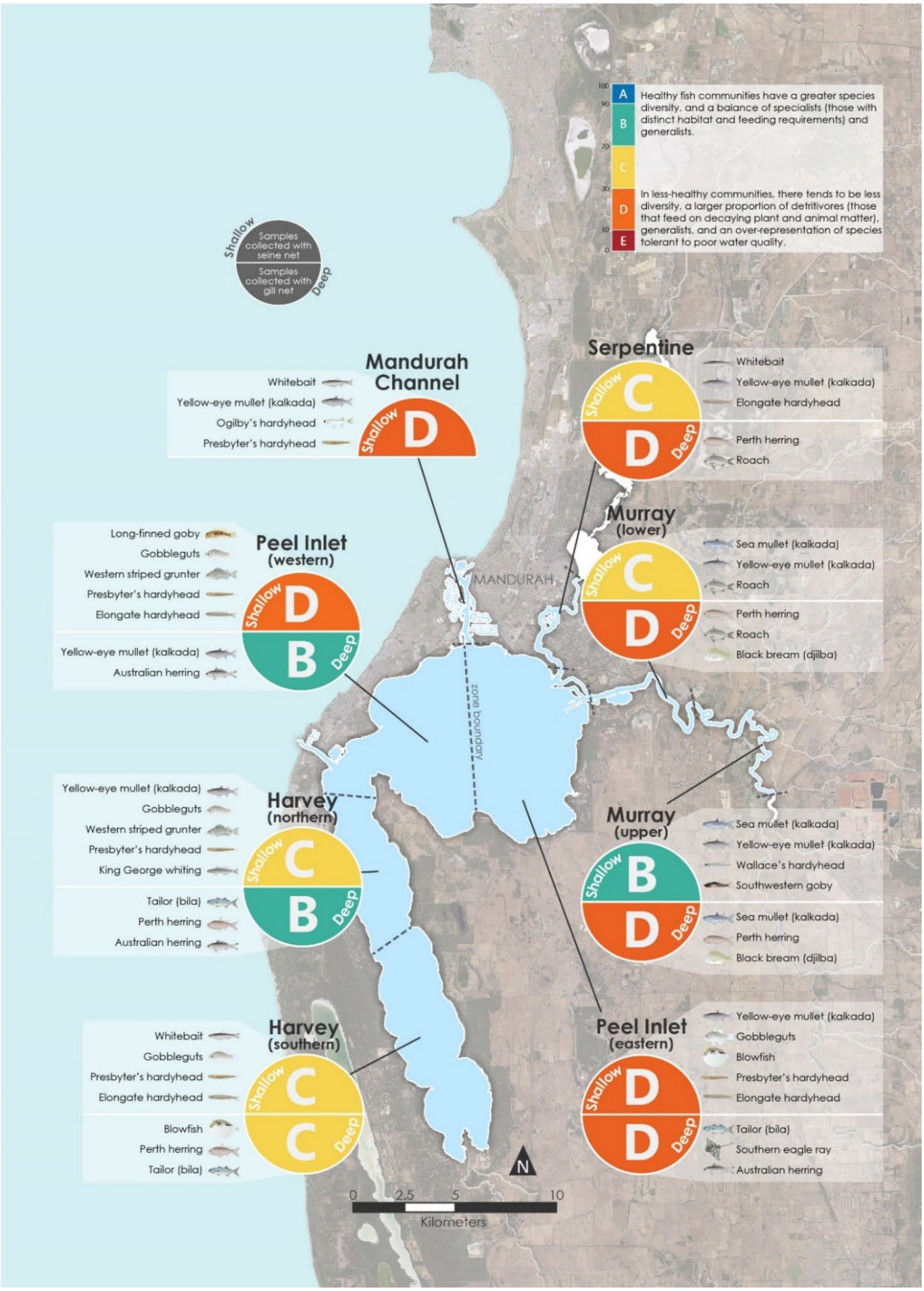


Figure 3-24 The Fish Community Index, developed by Murdoch University, scores key characteristics of the fish community from 2017–18 and integrates these into an overall measure of fish community health

Fish kills

Fish kill events are another symptom of eutrophic conditions in aquatic ecosystems (see Section 1.11). Fish kills are generally reported through the Fish Watch alert line. The department and DPIRD staff respond based on the established protocols, and the information is stored at the department.

The Peel-Harvey estuary has seen at least one fish kill event every year during the past 19 years, with seven occurring in 2017 alone (Figure 3-25). Poor water quality and phytoplankton blooms are associated with fish kills in the estuarine reaches of the rivers; 20 events have been recorded for the Murray River and 17 for the Serpentine. The numbers of fish deaths in each of these events has often exceeded 1,000, particularly in the Serpentine River (Figure 3-25). Only six fish kills have been noted for the Peel Inlet, where water quality is better and phytoplankton blooms are rare. The Peel Inlet fish kills may have originated in the lower parts of the two rivers and then been transported by tides and winds.

Of the fish kills reported to the department between April 2016 and September 2020 in the REI catchments, more than half (13 of 21) were in the Peel-Harvey catchment, predominantly in the lower reaches of the Serpentine and Murray rivers (generally because of poor water quality and low DO). There were no fish kills recorded in the Harvey Estuary during this time. This may be because of the limited tidal influence into the narrow and shallow Harvey River, resulting in less frequent stratification and low-DO events. Alternatively, fish kills may be occurring, but because of the relative remoteness of this part of the estuary, are not being reported.

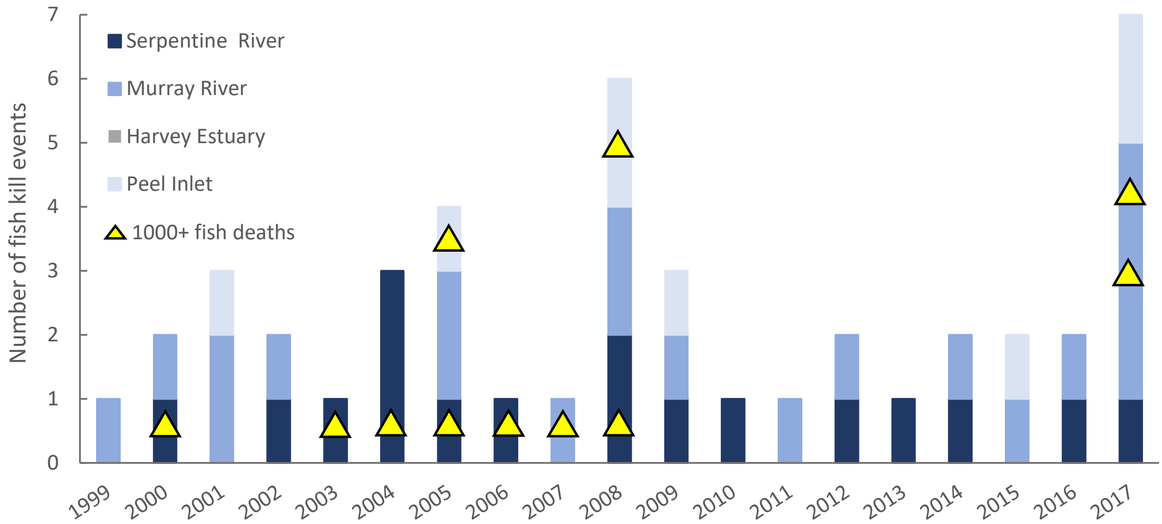


Figure 3-25 Fish kill events reported (1999–2017) in the Peel Inlet and in the estuarine parts of the Serpentine and Murray rivers. 1000+ fish deaths shown with yellow triangles. No fish kill events have been reported in the Harvey Estuary.

Summary

The estuarine reaches of the Serpentine and Murray rivers show significant eutrophic symptoms. These include high algal activity, harmful algal blooms, low DO concentrations and periodic fish kills. The poorest water quality and greatest density of potentially harmful phytoplankton species were observed in the estuarine reaches of the Serpentine River. In comparison, the main estuary basins have reasonable water quality and low numbers of potentially harmful algal species. The basins are, however, showing increasing concentrations of available N and – at the sites of riverine discharge – high proportions of organic matter and proliferating nuisance macroalgae.

The results of extensive monitoring of the water quality, sediments, macrophytes (seagrass and macroalgae), benthic invertebrates and fish communities of the Peel-Harvey estuary as part of the ARC Linkage project (Valesini et al. 2019b) are consistent with the analysis of the department’s monitoring data (described above), both concluding that the estuary is a sensitive system with high levels of organic matter, nutrient-enriched water and poor ecological health.

The estuary’s current condition can be summarised in conceptual diagrams for each estuary zone, as well as for each season (wet: winter/spring, dry: summer/autumn) for the estuarine reaches of the rivers.

Murray River (estuarine reaches)

In the wet season, the condition of the Murray River’s estuarine reaches is influenced predominantly by nutrient inputs from surrounding land uses via surface runoff, erosion from poorly vegetated banks, salinity stratification in the deep waters and accumulations of monosulfidic black oozes in the sediment (Figure 3-26). The organic matter from freshwater river flows, and phytoplankton and macroalgae that grow because of the nutrient inputs, accumulate in the sediments. The high oxygen demand of the sediment and salinity stratification contributes to low DO in the bottom waters, which may increase the release of biologically available nutrients to the water (phosphate and ammonia), as well as ‘rotten egg’ gas (hydrogen sulfide).

In the dry season, the waters become warmer and more saline, oxygen levels decline even further (with the bottom waters often becoming anoxic) and released nutrients contribute to dinoflagellate blooms. Fish kills may also occur (Figure 3-26). Nutrient-rich groundwater has a greater influence in the dry season. Light penetration is poor all year round because of the suspension of fine clay particles in the water column, which favours dinoflagellates as they move from the nutrient-rich bottom waters to the surface to photosynthesise. A surface scum, like the froth on a cappuccino, also appears in the wake of boats as propellers stir up the water.

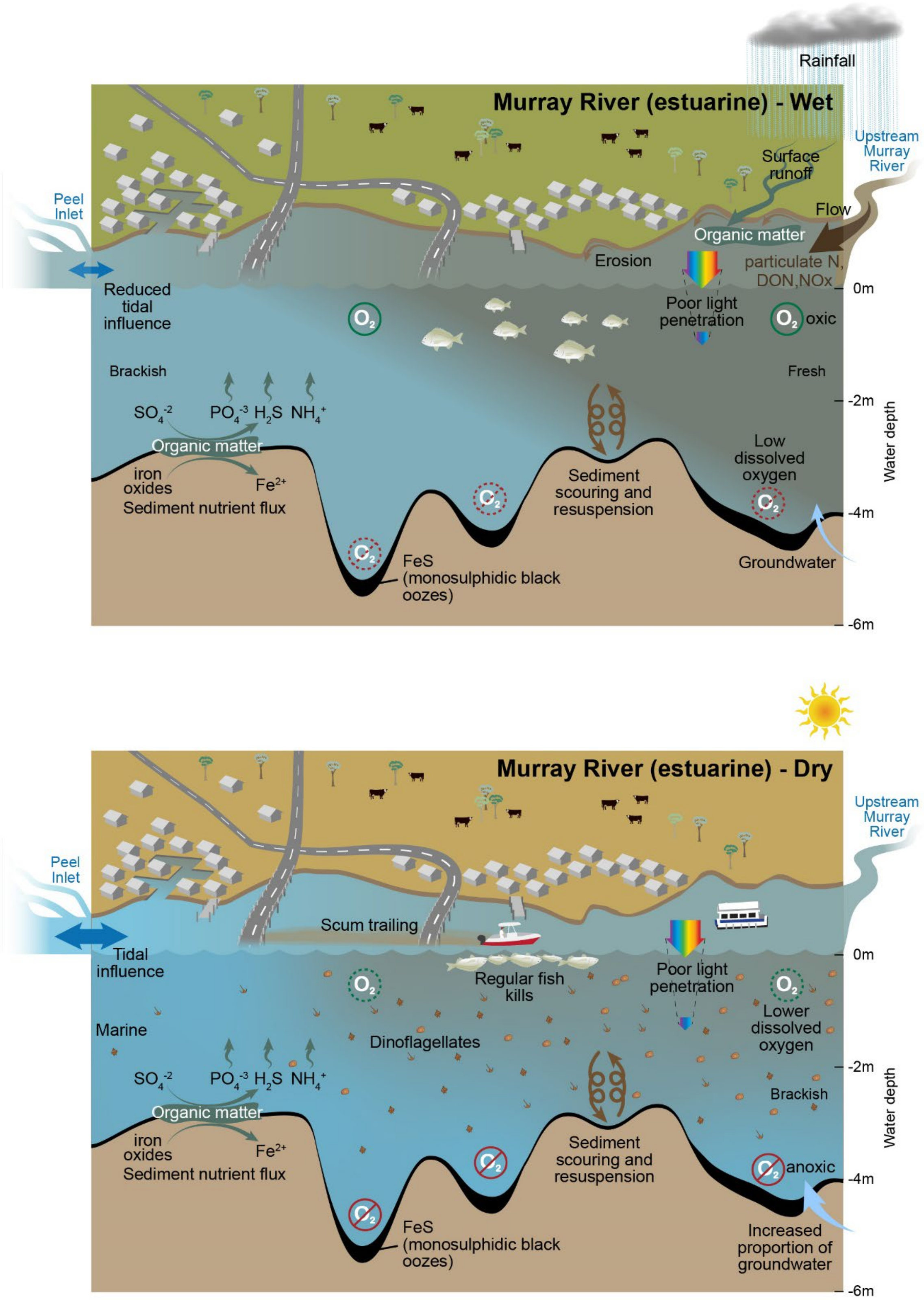


Figure 3-26 Conceptual model of the key pressures and stressors relevant to the estuarine reaches of the Murray River with some of the ecological responses that occur in the wet (top) and dry (bottom) seasons

Serpentine River (estuarine reaches)

The condition of the Serpentine River's estuarine reaches in the wet season is influenced by nutrient inputs from the surrounding land uses (e.g. beef farms, poultry, and horse agistment) (Figure 3-27). The impact of these land uses is intensified by the network of drains, many of which flow continuously, discharging organic matter and nutrient-rich surface and groundwater to the river. Erosion of unvegetated banks contributes to poor light penetration, as does the particulate matter in river flows and resuspended sediments. Monosulfidic black oozes accumulate in the upper reaches of this zone and contribute to nutrient releases, low oxygen and the production of hydrogen sulfide gas.

In the dry season, in the very shallow upstream areas, light penetration and temperatures increase. Nutrients released from the sediment, together with favourable conditions, drive cyanobacteria blooms that blanket the surface in green scums (Figure 3-27). This can cause oxygen concentrations to become very high during the day, and to go very low overnight because of respiration, and fish kills can occur. The shallow waters are mixed well by wind and thus do not exhibit the vertical salinity stratification that persists in the Murray River's estuarine reaches. Instead, the stratification is horizontal, with tidal fluctuations seasonally pushing hypersaline waters from Lake Goegrup, and other shallow lakes, upstream to Lake Amarillo.

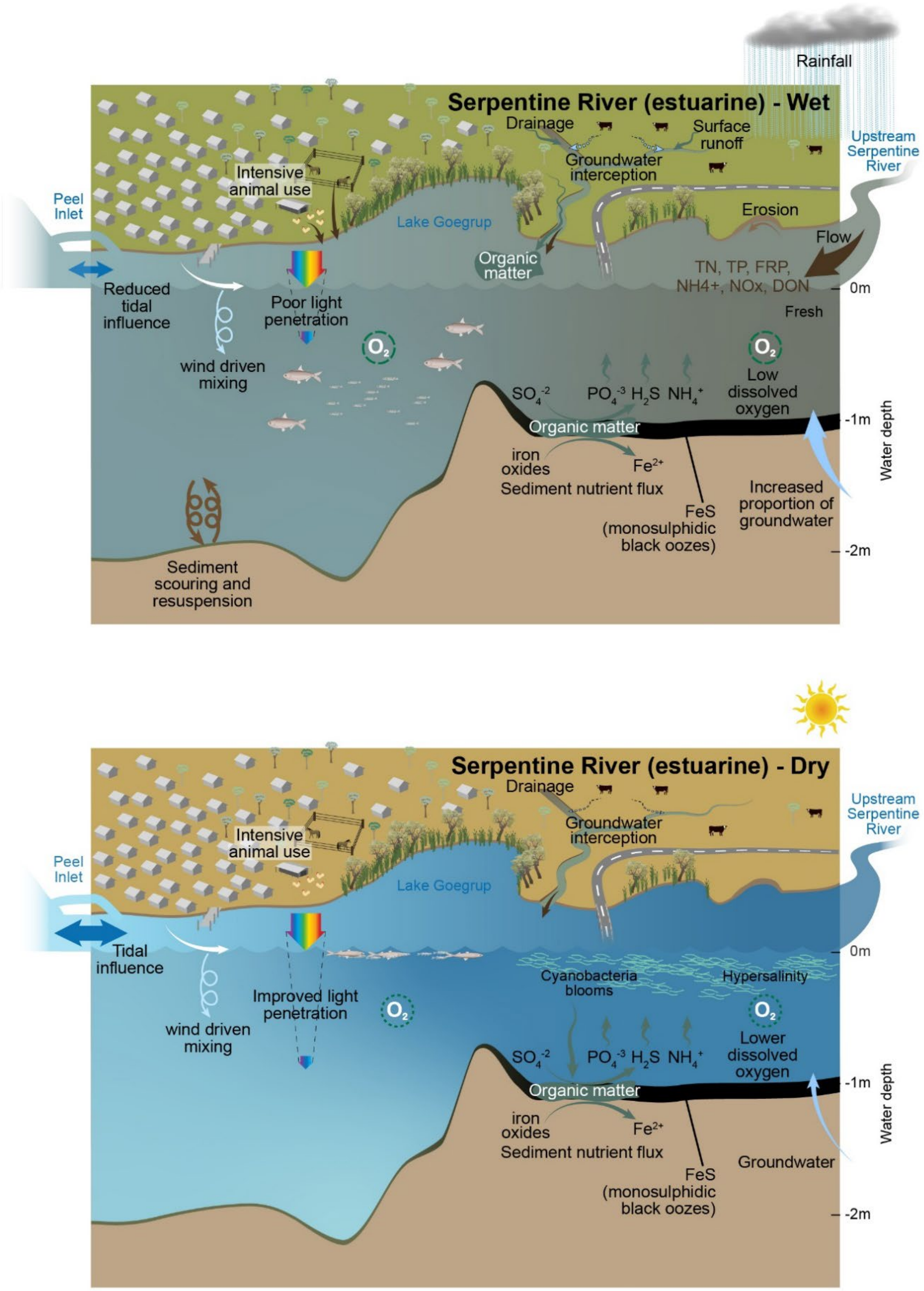


Figure 3-27 Conceptual model of the key pressures and stressors relevant to the estuarine reaches of the Serpentine River with some of the ecological responses that occur in the wet (top) and dry (bottom) seasons

Peel Inlet

The Peel Inlet is surrounded by dense urban development on its northern and western sides and its shallow waters receive nutrients from both the Serpentine and Murray rivers (Figure 3-28). Although high concentrations of nutrients are generally not measured in the water column in this zone, there are frequent blooms of macroalgae that are most likely fuelled by these inputs. The breakdown of these blooms along with organic matter delivered from the catchment are likely contributing to the poor diversity of fish species near the river mouths (Hallett et al. 2019a).

Nearer the high-density residential areas, localised inputs of nutrients occur from surface runoff and leaching from septic systems into groundwater, also contributing to macroalgal blooms in the basin. The frequency of dredging for vessel navigation is increasing because sediments are being retained within the inlet, instead of being scoured with historical heavy river flows. Otherwise, the shallow marine waters of the inlet have good light penetration, are well oxygenated and mixed, and support seagrass and non-nuisance species of macroalgae. All these aspects support community values such as commercial and recreational fishing, crabbing and boating, as well migratory shorebirds.

Harvey Estuary

The impact of surrounding land uses (e.g. beef and dairy farms) on the Harvey Estuary is intensified by the drainage network: most of the drains continually discharge organic matter and nutrients to the Harvey River, plus one goes directly to the estuary. Monosulfidic black oozes accumulate at the delta of the Harvey River mouth and are likely to be releasing nutrients that feed macroalgal blooms in the region. Harmful dinoflagellates also persist nearer the river confluence. In the dry season, the marine waters become hypersaline, only supporting plants and animals that have high salinity tolerances. Commercial fishing, crabbing, migratory shorebirds, and seagrass beds closer to the Dawesville Channel are recognised as community values.

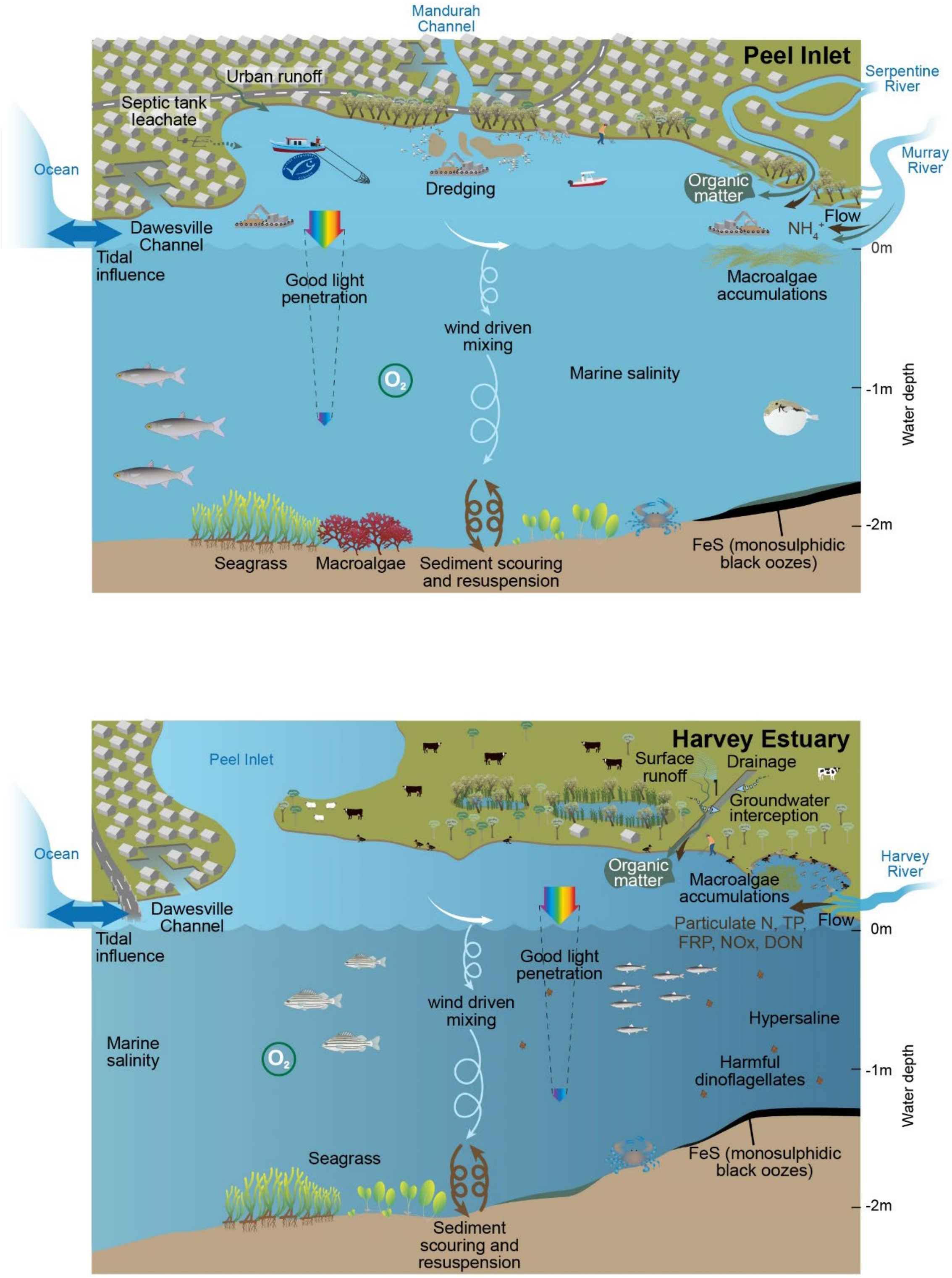


Figure 3-28 Conceptual model of the key pressures and stressors, with some of the ecological responses that occur in the Peel Inlet (top) and the Harvey Estuary (bottom)

4 Our vision for the estuary

The Peel-Harvey estuary and its tributaries are highly valued by the community, although the values themselves will vary between people, as will the priorities for management. This WQIP uses the approach of the *Charter: National water quality management strategy* (Australian Government 2018) to identify key community values, management goals and water quality objectives (WQOs). The community values selected from the charter are essentially high-level groupings, with the management goals that sit underneath being more tangible statements of what the community would like to protect. Community values can have social, economic and environmental elements. In addition to the key concepts from the charter, we have written value statements that aim to capture the intent of the suite of management goals for each community value.

Economic and social benefits from land uses in the catchment can impact on the community values associated with the estuary. It is important that decision-makers and the community appreciate these trade-offs when coming to a consensus on the management goals.

Community values are specific characteristics or uses of the environment that are important for a healthy ecosystem or public benefit, welfare, safety or health. Community values are often interdependent and at times it may be necessary to prioritise the protection of one value over another. Ideally this would be done through community consensus. Community values have also been defined as ‘environmental values’ or ‘beneficial uses’.

Management goals are measures or statements used to assess whether the community values are being protected. They should be unambiguous, measurable and achievable and reflect the desired level of protection values. Management goals are underpinned by appropriate water quality.

Indicators are variables that can be measured and changes in their value are related to a change in overall condition of the waterbody. We can think of a desired condition for the Peel-Harvey estuary – clean water, productive fisheries, diverse communities of biota and high ecological value. We describe these things in terms of indicators that contribute to an understanding of condition.

Water quality objectives (WQOs) are guideline values (a measurable quantity, such as a concentration) for relevant indicators or are narrative statements which, if met, support the management goals and the protection (or recovery) of community values. WQOs need to be achievable and easily monitored to assess whether implemented management actions are achieving the management goals.

4.1 Community values and management goals

The many and varied community consultation activities of recent decades have helped identify the community values and management goals for the Peel-Harvey estuary and its waterways. This WQIP draws on the following sources:

- the values and benefits identified in the *Wetlands and people plan for the Peel Yalgorup system – A CEPA action plan for Ramsar site 482* (PHCC 2017)
- community priorities identified through consultation in the *Binjareb Boodja Landscapes 2025, A strategy for natural resource management in the Peel-Harvey region* (PHCC 2015)
- the environmental values for the Peel-Harvey estuary identified in the 2008 WQIP (EPA 2008b)
- the cultural, economic and social services and benefits identified in the *Ecological character description for the Peel-Yalgorup Ramsar site* (Hale and Butcher 2007).

The community values from the *Charter: National water quality management strategy* (Australian Government 2018) that we have prioritised for protection in this WQIP are: aquatic ecosystems; fishing; recreational and aesthetics; and cultural and spiritual.

Aquatic ecosystems

The Peel-Harvey estuary is recognised for its high conservation value and unique biodiversity. Section 2.4 summarises the diverse array of biota that depend on the estuary system for their survival (habitat, food, shelter) and/or reproduction. The estuary:

- forms part of a Global Diversity Hotspot (South West Australia Ecoregion)
- is included in the *Directory of important wetlands in Australia* (Environment Australia 2001)
- is a 'wetland of international importance' (part of the Peel-Yalgorup wetland system) under the Convention on Wetlands (Ramsar Convention 1971)
- supports seven species of waterbirds that are considered threatened under the *Environmental Biodiversity and Conservation Act 1999* (EPBC Act), and 38 species listed under international migratory agreements
- supports saltmarsh communities that are recognised as threatened under the EPBC Act.

This community value considers the preservation of biodiversity; ecological processes and functions; wetland, fringing and riparian vegetation; aquatic invertebrates; and vertebrates (e.g. fish, waterbirds, dolphins). Aquatic ecosystems support research and education endeavours and eco-tourism industries. The aquatic ecosystems value is considered particularly important as it underpins the other community values.

Pelicans (booladaalaang) are common inhabitants of the estuary.

Management goals:

- Water quality is improved, with fewer harmful or nuisance algal blooms and fewer low-oxygen events and fish kills.
- Sediment condition is maintained and improved and when sediment is disturbed (e.g. by dredging), harm is minimised.
- Key habitat types and food sources of local and migratory birds are preserved and Ramsar status is maintained.
- Endemic fish populations and their habitats are protected.
- Seagrass meadows are resilient with stable or increasing areal coverage.

Fishing

The Peel-Harvey estuary supports recreational, commercial and cultural fisheries, which underpin several important regional economies.

At present there are 11 commercial fishing licences (of which 10 are also permitted to take crabs). A voluntary buy-back scheme is underway to reduce the number of licences (down to six to eight), to reallocate a greater share of the catch to the recreational sector. Licensed commercial fishers catch a mix of temperate estuarine finfish species with a total annual catch ranging from about 100 to 130 t (Department of Fisheries 2015b), all of which are sold in Western Australia. Sea mullet (*Mugil cephalus*) (certified as sustainable by the Marine Stewardship Council since 2016) and yelloweye mullet (*Aldrichetta forsteri*) have been targeted historically and sold as bait fish, but more recently there has been a shift to species that are more valuable for human consumption. This includes cobbler (*Cnidoglanis macrocephalus*), yellowfin whiting (*Sillago schomburgkii*) and Australian herring (*Arripis georgianus*) (Department of Fisheries 2015b).

Finfish targeted by recreational anglers include Australian herring (*Arripis georgianus*), whiting (*Sillago* spp.), tailor (*Pomatomus saltatrix*), silver trevally (*Pseudocaranx georgianus*), King George whiting (*Sillaginodes punctata*) and black bream (*Acanthopagrus butcheri*). The quantity of finfish caught by recreational fishers is unknown, but it is considered minor compared with the commercial sector. It is estimated that the commercial and recreational fishing operations in the estuary are worth more than $1.8 million a year (Economic Consulting Services 2019).

The Peel-Harvey estuary supports the largest commercial blue swimmer crab (*Portunus armatus*) fishery in the South West, certified as sustainable by the Marine Stewardship Council since 2016. The commercial crab fishery currently has 10 commercial fishers catching between 45 and 105 t/year from haul net and gill net fishing (Department of Fisheries 2015a). It is also one of the most popular places in the South West for recreational crab fishing, with an estimated total catch of 80 t in 2011–12 (Department of Fisheries 2015a).

The finfish resources of the Peel-Harvey estuary have provided sustenance to the Bindjareb Noongar people for thousands of years. For example, wooden fish traps were traditionally used for harvesting sea mullet (*Mugil cephalus*) and Australian salmon (*Arripis truttaceus*) in the Serpentine River (Gibbs 2011).

Bream remains a food source for Noongar people. Bream complete their life cycle in the estuary and therefore depend on the estuary to provide suitable water quality, habitat and food.

Value statement: The estuary will support sustainable fisheries for recreational, commercial and cultural fishers.

Commercial fisher, Damien Bell. Photo credit: Marine Stewardship Council ©.

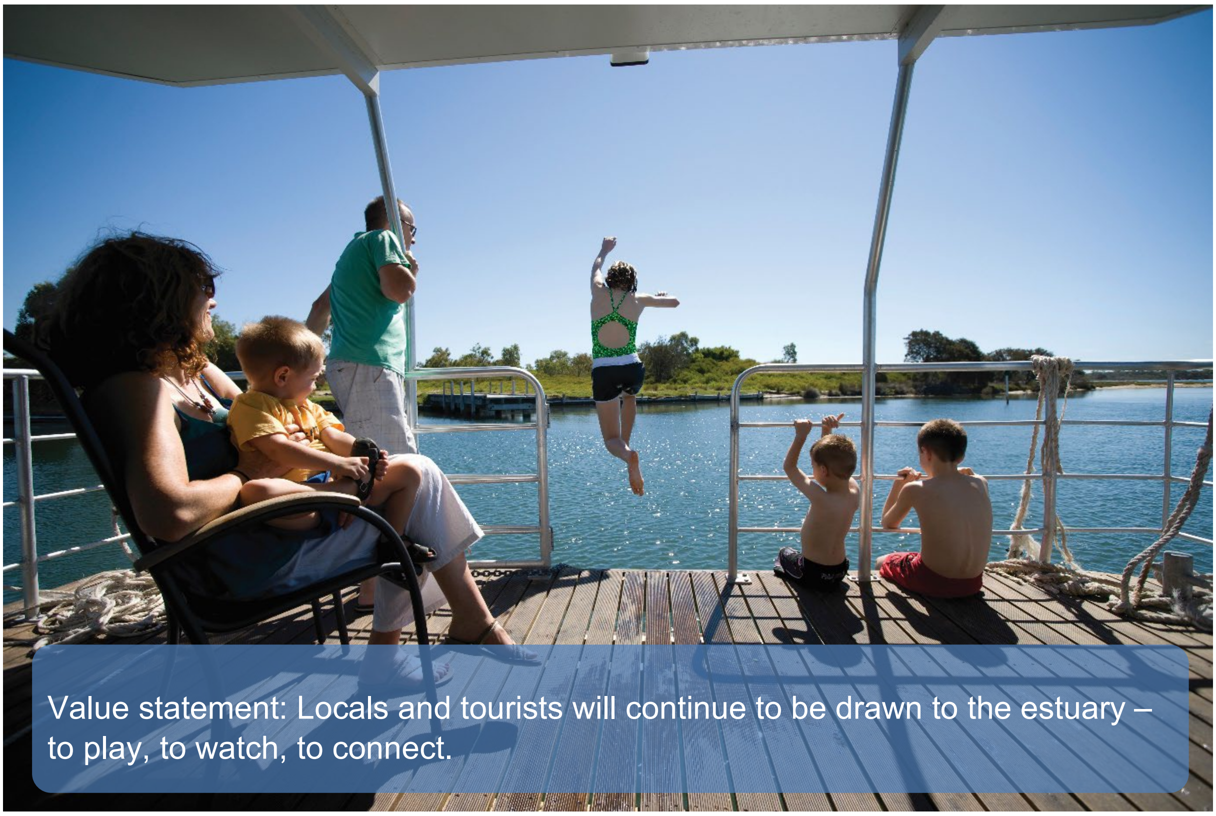
Management goals:

- The blue swimmer crab and sea mullet retain their Marine Stewardship Council certification.
- No health warnings are issued on the consumption of finfish and crabs.
- Licensed fishers maintain their livelihoods within the constraints of ecological sustainability.
- Recreational fishers can continue to catch crabs and finfish.
- Traditional fishing practices remain viable.

Recreational and aesthetics

The Peel-Harvey estuary system is an iconic natural environment for Western Australians. It is a place of natural beauty and offers a range of recreational and lifestyle opportunities. The region’s population is growing at one of the fastest rates in Australia (Economic Consulting Services 2019). Waterfront living around the estuary is highly valued with the premium people pay to live near the water estimated to be about $1.4 billion (Economic Consulting Services 2019).

The estuary is the focus of many recreational activities and tourism operations, with an average of 2.9 million people (mostly day trippers) visiting every year (Tourism Research Australia 2021). Some of the most popular activities are boat and shorebased fishing (with about 11,500 registered recreational boats in Mandurah), other boating activities (including water skiing), bushwalking, crabbing, dolphin and birdwatching, camping, four-wheel driving, canoeing, swimming and picnicking.



Boating is a popular recreational activity in the estuary. Photo credit: Mandurah and Peel Tourism Organisation (now Visit Mandurah).

Management goals:

- Water is safe for swimming, water skiing, and other primary contact activities.
- Water is safe for boating, fishing and other secondary contact activities.
- Visual amenity is maintained, algal blooms are minimised, there are no fish kills, water is free from floating debris and scums, and odour and colour are acceptable.

Cultural and spiritual values

Many people have personal connections to the Bindjareb Djilba (Peel-Harvey estuary) and its Bilya (rivers), which are entwined in their beliefs, traditions and memories.

Noongar people are acknowledged and respected as the Traditional Owners of lands within south-west Western Australia. For more than 45,000 years, Bindjareb Noongar people have lived in the Peel region, looked after the land and been sustained by its natural resources (PHCC 2015). The Bindjareb Djilba (Peel-Harvey estuary), its Bilya (rivers) and catchment are culturally and spiritually significant to Bindjareb Noongar people who hold a deep sense of respect and kinship towards the Djilba (estuary), the Bilya (rivers) and adjacent country.

Bindjareb Noongar people have a strong spiritual and cultural connection to their waterways and have an ongoing cultural responsibility to their preservation.

> Bindjareb Noongar people maintain 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 food, relax, swim, and to experience what their parents' 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.
> (Walley and Nannup 2012)

There are more than 356 sites of Aboriginal significance in the Peel-Harvey catchment, which include sites of artefact scatter, camp sites, ceremonial sites, fish traps, skeletal remains and sites of mythological significance (Hale and Butcher 2007). It is important that the traditional sites, custodial responsibilities, spiritual and cultural knowledge, and food places for hunting and gathering are preserved and respected now and in the future.

Value statement: The unique and precious link between people, spirit and the estuary will be preserved for future generations.

Bindjareb Noongar people are acknowledged and respected as the Traditional Owners of lands within south-west Western Australia. Photo credit: Daniel Wilkins.

Management goals:

- Custodial responsibilities and spiritual and cultural knowledge are preserved.
- Traditional sites and food places for hunting and gathering are preserved.

- Symbolism, special places, and icons are respected and preserved.

Many of the diverse community values identified for the Peel-Harvey estuary system (particularly those relating to its recreational and commercial use) are ecosystem-based and impact on water quality. But they also depend on good water quality to uphold their value. Having good water quality in the estuary system is, therefore, a key factor in protecting the community values into the future.

4.2 Water quality objectives

The WQOs for this WQIP are based on long-term monitoring and our understanding of the water quality patterns in the Peel-Harvey estuary. The WQOs underpin the management goals and link to protecting the community values. We have selected indicators that are easily monitored, enabling progress towards the WQOs to be tracked over time as the actions in this WQIP are implemented.

It is difficult to set timeframes to achieve each WQO, as improvements in water quality depend on the extent to which the recommended actions are implemented across the catchment. In addition, lag time – the period between a management change and a related improvement in water quality in a downstream waterbody – is site and system dependent (see ‘Lag time’ box in Section 9.7). For example, it will take years to decades for changes in land use practices to run down excessive P levels in the agricultural soils on the coastal plain.

We recommend that the WQOs be assessed every five years and that the sensitivity and suitability of the selected WQOs be reviewed during this process.

Setting the water quality objectives

Previous WQIPs have tended to set WQOs using catchment nutrient concentrations in the tributaries as the only indicators for change. The 2008 WQIP focused solely on TP concentrations. Reduced river flows have increased the significance of internal cycling of nutrients in the estuary, especially at the sediment/water interface. This WQIP introduces WQOs for the estuary itself, in addition to the usual WQOs for nutrient concentrations in the tributaries.

We considered a broad suite of indicators and guideline values to select the WQOs, most of which are described below. See Table 4-1 for a summary of the selected WQOs. It is important to note that while the WQOs will indicate whether we are heading in the right direction, they will only tell part of the water quality story. More detailed analysis of water quality data is available in the *Bindjareb Djilba (Peel-Harvey estuary): Condition of the estuary 2016–2019* (DWER 2023a), which should also be considered when assessing estuary health.

Each of the WQOs support multiple management goals, thereby protecting several community values. The WQOs are all closely related; for example, if the concentrations of nutrients entering the estuary are reduced, the indicators of the other WQOs are likely to improve as well.

Nutrients

Catchment nutrient concentrations are a key indicator of a waterbody's eutrophic status. WQOs for TN and TP concentrations have been used previously in other WQIPs for South West estuaries, such as the Leschenault Estuary (Hugues-dit-Ciles et al. 2012), Vasse-Wonnerup wetlands and Geographe Bay (Government of Western Australia 2010) and Swan-Canning (Swan River Trust 2009).

The locally specific guideline value of 0.1 mg/L TP is an appropriate WQO for the tributaries of the Peel-Harvey estuary and is consistent with the 2008 WQIP (EPA 2008b) and those of other South West estuaries.

The default guideline value of 1.2 mg/L TN for slightly to moderately disturbed lowland rivers of south-western Australia (ANZECC & ARMCANZ, 2000a) is considered an appropriate WQO for the tributaries of the Peel-Harvey estuary.

The need to assess the bioavailability of dissolved organic nitrogen (DON) has been identified: this will determine the effort required to meet WQO 2 which relates to TN concentrations. In the interim, the default TN guideline value will apply until a better understanding of N fractionation and sources allows consideration of a more specific value for the Peel-Harvey estuary system.

Below these guideline values, the risk of nuisance algal blooms is considered low. Nutrient concentrations above these levels may lead to declining water quality and ecological health in the Peel-Harvey estuary system.

WQO 1 Total phosphorus (TP) concentrations in waterways and drains entering the estuary to be ≤ 0.1 mg/L, determined from winter medians over a three-year period at the subcatchment outflows (Figure 3-3) (three-year rolling dataset).

WQO 2 Total nitrogen (TN) concentrations in waterways and drains entering the estuary to be ≤ 1.2 mg/L, determined from winter medians over a three-year period at the subcatchment outflows (Figure 3-3) (three-year rolling dataset).

Dissolved oxygen

Dissolved oxygen (DO) is an essential requirement of a healthy ecosystem. Low oxygen concentrations occur when oxygen is consumed (e.g. by decomposing organic matter, respiration and oxidation of reduced chemical species) faster than it is replenished (e.g. via air-water oxygen transfer, photosynthesis and mixing). Stratification (where surface and bottom water mixing is inhibited because of density differences), which occurs seasonally in the estuarine reaches of the Serpentine and Murray rivers, makes the waterbody more prone to low oxygen concentrations. Conditions are exacerbated by organic-rich sediments, common in estuarine environments.

Low oxygen concentrations have a detrimental effect on aquatic fauna and vegetation, and severe events can deplete the benthic invertebrate community (Tweedley et al. 2016) and result in fish kills. Very low concentrations at the sediment/water interface promotes the release of reduced chemical species, which may be toxic to biota (e.g. ammonia and hydrogen sulfide) or stimulate algal growth by increasing bioavailable nutrients (Howarth et al. 2011).

The WQO for DO considers a guideline value for both surface and bottom waters. In surface waters the objective aims to ensure there is a refuge for fish. While different species have different tolerances, above a concentration of 5 mg/L there is generally minimal impact on fish physiology or behaviour. In bottom waters the objective aims to maintain aerobic biogeochemical processes at the sediment/water interface, promoting internal processing of nutrients and limiting the release of reduced chemical species from the sediment. A guideline of 2 mg/L in bottom waters has been selected to avoid anoxic conditions (DO concentrations = 0 mg/L) at the sediment/water interface.

WQO 3
(a) Dissolved oxygen in surface waters of monitoring sites in the estuary and estuarine reaches of the rivers (Section 3.3) to be ≥ 5 mg/L in 95 per cent, or more, of samples over a three-year period (three-year rolling dataset).

(b) Dissolved oxygen in bottom waters (0.2 m above the sediment) of monitoring sites in the estuary and estuarine reaches of the rivers (Section 3.3) to be ≥ 2 mg/L in 95 per cent, or more, of samples over a three-year period (three-year rolling dataset).

Algal activity

The persistent phytoplankton (microscopic algae or cyanobacteria) blooms in parts of the estuary – particularly the lower Serpentine and Murray rivers – are a highly visible sign of nutrient enrichment and poor water quality. While phytoplankton are an essential component of the aquatic ecosystem, large blooms are associated with surface scums (such as ‘cappuccino scum’ on the Murray River), bad odours, large fluctuations in oxygen concentrations, and anoxia.

Chlorophyll *a* is the green pigment found in plants which is essential for photosynthesis. The concentration of chlorophyll *a* in the water is a measure of the density of phytoplankton and tends to be high in nutrient-enriched systems.

The ANZECC guideline value (ANZECC & ARMCANZ 2000b) of 3 µg/L for chlorophyll *a* in estuaries in the South West is considered an appropriate target concentration for the Peel-Harvey estuary basins, consistent with the 2008 WQIP (EPA 2008b). The guideline value selected for the estuarine reaches of the Serpentine and Murray rivers is a seasonal median measurement of 5 µg/L, with a longer-term goal to achieve 3 µg/L.

WQO 4 Summer and autumn chlorophyll *a* concentration in surface waters to be ≤ 3 µg/L in the Peel and Harvey estuarine basins and ≤ 5 µg/L in the estuarine reaches of Serpentine and Murray rivers (Section 3.3), determined from combined seasonal (summer and autumn) medians over a three-year period (three-year rolling dataset).

In addition to reducing overall phytoplankton density, this WQIP aims to reduce the density of potentially harmful or nuisance species in the Peel-Harvey estuary basins and estuarine reaches of the rivers. While some species of phytoplankton can be harmful to humans or wildlife through toxin production, most species are only problematic at high densities.

The department monitors phytoplankton composition and density across the Peel-Harvey estuary and reports against species-specific (national or local) interim guidelines. When the guidelines are exceeded, this points to a risk of aesthetic decline (e.g. substantial surface scums or clogging of waterways), the presence of algae harmful to humans (via consumption or contact) and/or a threat to fish health. Further investigation or a management response may be warranted. If guidelines for harmful species are regularly exceeded (as identified by routine monitoring) then further toxicity research should be undertaken, and local management guidelines developed. The WQO for harmful or nuisance phytoplankton species is based on a reduction in exceedences over time.

WQO 5 Reduction in the density of nuisance or potentially harmful algae/cyanobacteria (phytoplankton) in the estuary and estuarine reaches of the rivers (Section 3.3), as determined by a reduction in exceedences against established trigger values for individual species over a three-year period (three-year rolling dataset).

Water clarity

Good water clarity supports seagrass growth and reproduction in areas where other conditions (e.g. salinity) are also favourable, such as in the Peel Inlet and Harvey Estuary. In addition, water clarity impacts on the aesthetic and recreational community values. The WQO for water clarity is based on maintaining or improving current measures.

WQO 6 Water clarity maintained or improved, as measured by the spring and summer (combined) median secchi depth (rolling three-year dataset) at each of the following selected ‘sentinel’ sites within the estuary basins and estuarine reaches of the rivers: Harvey Estuary (PHE-1), Peel Inlet (PHE-7), Dawesville Channel (PHE-58), estuarine reaches of the Murray River (PHRM-2) and estuarine reaches of the Serpentine River (PHRS-4) (Section 3.3).

Sediment health

The sediments in estuaries are crucial to the health of the plants and animals that live in or around them. A reduction in the load of organic matter and sediment coming from the catchment into the estuary would significantly improve the sediment and water quality condition in the estuary. However, the levels of total suspended solids (TSS) and dissolved organic carbon (DOC) measured regularly at the catchment monitoring sites are highly variable and the source of DOC is not well understood. Hence these measures were not selected for use as water quality indicators in this WQIP. The composition of sediments is closely linked to bottom water DO concentrations and, as such, some inference of sediment health can be drawn from performance against WQO 3b (bottom water DO ≥ 2 mg/L).

Recreational use of the estuary

In areas where the community values the estuary for primary contact (swimming, diving, water skiing) and secondary contact (wading, kayaking) recreation, the water quality must not pose an unacceptable risk to human health. The National Health and Medical Research Council (NHMRC) provides guidelines for managing risks in recreational waters (NHMRC 2006) based on *Enterococci* concentrations (faecal contamination as an indicator for recreational water safety). In Western Australia, the Department of Health (DoH) oversees and coordinates the monitoring of recreational water quality. The DoH has developed locally appropriate guidelines for *Enterococci* concentrations for primary and secondary contact recreation.

The Shire of Murray conducts fortnightly sampling across the recreational 'season' from November to April, monitoring *Enterococci* concentrations at nine sites along the Murray River (Baden Powell, Dwellingup Bridge, Coolup Bridge, Murray Bend, Pinjarra Boat Ramp, Ravenswood Hotel, Delta Drive, Tatham Road Jetty and Lucie Hunter Park) and one at Herron Point in the Harvey Estuary. In addition, several sites in the estuary basins are irregularly monitored by the City of Mandurah, including sites near the Dawesville and Mandurah channels. Sites are selected based on those that may pose risks to public health because of recreational water use. DoH reviews the samples and if they exceed their *Enterococci* guidelines, additional sampling may be required, and health warnings and temporary signage may be necessary.

The DoH also reviews the findings of fortnightly sampling of phytoplankton (algal and cyanobacteria) produced by the department's Phytoplankton Ecology Unit. This analysis compares species densities to interim guidelines for harmful and nuisance species. Exceedences of the density triggers may also lead to a health warning and temporary signage.

DoH undertook a large-scale study from 2014–2017 across Western Australia to grade popular sites for their suitability for recreational swimming, including many sites in the Peel-Harvey estuary and Murray River.[22] Each site was graded annually by combining two assessments: a microbial category based on *Enterococci* concentrations (from samples collected over the recreational 'season', as described above) and a sanitary inspection and risk assessment of potential sources of faecal contamination (reviewed annually). DoH updates gradings for sites in the Peel-Harvey each year.[23]

Swimming sites in the Peel Inlet are consistently graded as good or very good, with the water considered satisfactory for swimming most of the time or all the time. However, swimming sites along the Murray River have sometimes received a poor or very poor grading which suggests that conditions were 'often or consistently

[22] Annual Site Status Update - Yearly Comparison - 2017 – Regional

[23] Beach grades for Peel Recreational Waters

unsatisfactory for swimming because of elevated bacteria levels' (generally after rainfall events). These gradings are concerning, particularly considering that recreational use of the estuary is a community value. It is positive to note that the sites with the poorest ratings along the Murray River – Pinjarra Boat Ramp and Baden Powell – have both improved in recent years and are currently graded as fair and good (safe for swimming most of the time) respectively.

As the DoH is responsible for overseeing the monitoring of microbiological recreational water safety in the Peel-Harvey estuary, we have not included a WQO for recreational water safety in this WQIP. Nevertheless, we recommend that recreational swimming sites within the Peel-Harvey estuary and estuarine reaches of the rivers are considered for more regular and widespread monitoring to ensure that water quality aligns with the community values for specific areas. If the water quality is inadequate, work needs to be done to help adjust the community's expectations until the water quality can be improved by the actions in this WQIP.

With appropriate funding, the department and DoH could potentially partner to conduct microbiological water quality monitoring at popular recreational sites in the Peel-Harvey estuary system, building on the department's existing estuary monitoring program.

Aesthetics

While the NHMRC does not have guidelines for the aesthetic qualities of waterbodies, it recognises their importance for maximising the benefits of recreational water use (NHMRC 2006). Recreational waterbodies should be aesthetically pleasing to their users. The water should be free from visible materials that may settle to form objectionable deposits; floating debris, oil, scum and other matter; substances producing objectionable colour, odour, taste or turbidity; and substances that produce undesirable aquatic life. While it is difficult to set an easily measurable WQO for aesthetics, it is strongly related to the achievement of the other WQOs, particularly good water clarity and concentrations of chlorophyll *a*.

Table 4-1 Summary of all WQOs set in this WQIP to achieve the management goals and help protect the community values. We suggest that the indicators for these WQOs are monitored on a fortnightly basis.

WQO #	**WQO**
WQO 1 – Total phosphorus	Total phosphorus (TP) concentrations in waterways and drains entering the estuary to be ≤ 0.1 mg/L, determined from winter medians over a three-year period at the subcatchment outflows (Figure 3-3) (three-year rolling dataset).
WQO 2 – Total nitrogen	Total nitrogen (TN) concentrations in waterways and drains entering the estuary to be ≤ 1.2 mg/L, determined from winter medians over a three-year period at the subcatchment outflows (Figure 3-3) (three-year rolling dataset).
WQO 3 – Dissolved oxygen	(a) Dissolved oxygen in surface waters of monitoring sites in the estuary and estuarine reaches of the rivers (Figure 3-13) to be ≥ 5 mg/L in 95 per cent, or more, of samples over a three-year period (three-year rolling dataset). (b) Dissolved oxygen in bottom waters (0.2 m above the sediment) of monitoring sites in the estuary and estuarine reaches of the rivers (Figure 3-13) to be ≥ 2 mg/L in 95 per cent, or more, of samples over a three-year period (three-year rolling dataset).
WQO 4 – Chlorophyll *a*	Summer and autumn chlorophyll *a* concentrations in surface waters to be ≤ 3 µg/L in the Peel and Harvey estuarine basins and ≤5 µg/L in the estuarine reaches of Serpentine and Murray rivers (Figure 3-13), determined from seasonal (summer and autumn) medians over a three-year period (three-year rolling dataset).
WQO 5 – Harmful algae/cyanobacteria	Reduction in the density of nuisance or potentially harmful algae/cyanobacteria (phytoplankton) in the estuary and estuarine reaches of the rivers (Figure 3-13), as determined by a reduction in exceedences against established trigger values for individual species over a three-year period (three-year rolling dataset).
WQO 6 – Water clarity	Water clarity maintained or improved, as measured by the spring and summer (combined) median secchi depth (rolling three-year dataset) at each of the following selected 'sentinel' sites within the estuary basins and estuarine reaches of the rivers: Harvey Estuary (PHE-1), Peel Inlet (PHE-7), Dawesville Channel (PHE-58), estuarine reaches of the Murray River (PHRM-2) and estuarine reaches of the Serpentine River (PHRS-4) (Figure 3-13).

Using the water quality objectives

Comparing the current water quality in the estuary and its rivers to the WQOs, as well as considering the modelling results in Section 7, helps to highlight problem areas for management to protect the community values. Tracking and reporting on water quality monitoring data against the WQOs over time will identify improvements in estuary system health or highlight where additional focus or a revised management approach is required – an important part of an adaptive management strategy.

Table 4-2 summarises whether water quality monitoring data shows achievement of the WQOs, grouped by river catchment and estuary zone. See Appendix I for a more detailed table of the WQOs by individual catchment/estuary monitoring site.

Each WQO has or will be assessed against suitable water quality data:

- WQO 1 (TP) and WQO 2 (TN) are assessed from catchment water quality data provided in Section 3.2 (winter medians for TN and TP, 2016–2018).
- WQO 3 and WQO 4 are assessed using data on DO and chlorophyll *a* contained in the *Bindjareb Djilba (Peel-Harvey estuary): Condition of the estuary 2016–2019* (DWER 2023a).
- WQO 5 and WQO 6 are measures of comparative change and will be assessed during the first review of this WQIP, comparing current data (2016–19) on nuisance or potentially harmful algae/cyanobacteria (phytoplankton) species and secchi depth respectively, with data collected from 2019–23.\

Table 4-2 Summary of whether WQOs are currently being achieved in each zone of the estuary system (2016–2018/19). Note: n/a means this WQO will be assessed during the first review of this WQIP. See Appendix I for more details on which individual catchments and estuary monitoring sites currently meet the WQOs.

		Water quality objective #						
		1	**2**	**3 (a)**	**3 (b)**	**4**	**5***	**6***
		TP	TN	Surface DO	Bottom DO	Chlorophyll *a*	Nuisance harmful phytoplankton	Water clarity
Catchment	Serpentine River	X	X					
	Murray River	✓	✓					
	Harvey River	in part[ǂ]	X					
Estuary zone	Harvey Estuary			✓	✓	✓	n/a	n/a
	Dawesville Channel			✓	✓	✓	n/a	n/a
	Peel Inlet			✓	✓	✓	n/a	n/a
	Estuarine reach Serpentine River			X	✓	in part	n/a	n/a
	Estuarine reach Murray River			✓	X	✓	n/a	n/a

* WQO 5 and WQO 6 measure comparative change and will be assessed during the first review of this WQIP.

ǂ Drakesbrook Drain (AWRC ref. 6131335) is the only site in the Harvey River catchment that met WQO 1, but it is an upstream site and not reflective of nutrient concentrations at the catchment outlet.

Monitoring data represents a snapshot in time and space

Monitoring programs provide us with measured data that enables us to understand current conditions and patterns through time. However, it is important to remember that data represents a snapshot in time at a specific location. Catchment water quality monitoring generally occurs at gauging stations, which are usually located at the bottom of a catchment (Figure 4-1). But some catchments in the Peel-Harvey have large areas of land that lie below the most-downstream monitoring sites (e.g. the land identified in Figure 4-1). When these areas have soils with low PRI and nutrient-intensive land uses, as is the case in the Lower Murray (Figure 4-1), they are likely to be exporting large loads of nutrients that will not be detected by the water quality monitoring. By considering both the monitored data and outputs from the Peel-Harvey Catchment Model (which does include these downstream areas), we are able to build a more comprehensive understanding of where water quality improvement is required.

WQOs 1 and 2 are assessed using the monitoring data, which can be done regularly and simply. However, to determine which reporting catchments in the plan area should be targeted and to aid in setting the scale and type of management interventions, we have used the Peel-Harvey Catchment Model (Section 7). The model considers all land uses across each reporting catchment and their contribution to nutrient export to the estuary.

In some catchments, differences in monitored and modelled TN and TP concentrations have led to differences in whether WQOs 1 and 2 are currently being achieved. The likely reasons for these discrepancies are outlined in Section 7.2 and are primarily a result of monitoring sites only reflecting the gauged portion of the catchment.

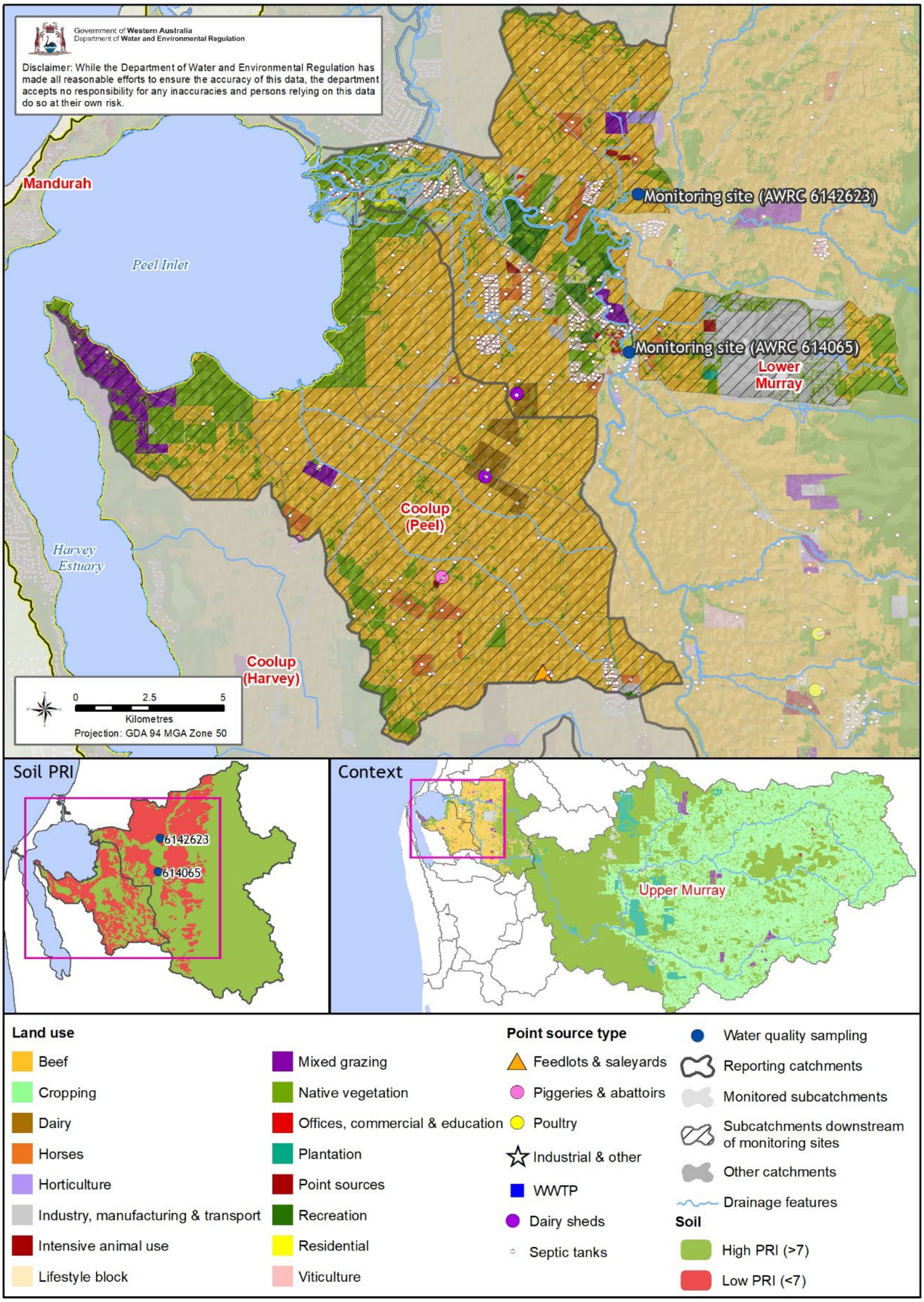


Figure 4-1 Maps of the soil PRI and land uses in the Lower Murray reporting catchment showing the location of water quality monitoring sites, highlighting that a large portion of the reporting catchment is ungauged

5 Pressures on the estuary

Identifying the links between pressures, stressors and responses can illustrate the potential causal relationships between human activities and ecological responses in the estuary.

Pressures are the driving forces behind the changes observed in waterways. Pressures result in changes in physical, chemical and/or biological conditions (known as **stressors**) which can reduce water quality and cause an adverse ecological **response** (Australian Government 2018).

In this WQIP we focus management recommendations on pressures resulting from human activity and land uses in the catchment.

The catchment of the Peel-Harvey estuary has been extensively modified since European settlement in 1829. This has enabled the development of a large agricultural sector with wide-reaching economic benefits to the region. In addition, urban growth has dramatically changed the landscape (Figure 5-1). Yet the social and economic benefits of past and present land use changes have come at a high environmental cost, culminating in ecological collapse of the Peel-Harvey estuary in the 1970s and 1980s (see Section 1.2).

Figure 5-1 Urban growth in the centres around the estuary and waterways and includes many canal estates

Most past and present land uses act as pressures on the estuary, which manifest as stressors in the system; for example, declining water quality and increased bank erosion. Stressors often lead to environmental responses that impact on community values, such as losses in recreational amenity or changes in ecological character that may weaken the criteria for which the site was Ramsar-listed.

A clear example of the links between pressure, stressor and response in coastal plain catchments involves fertiliser runoff from beef farming (pressure), which increases concentrations of dissolved nutrients in the receiving waterways (a stressor that drives eutrophication), which in turn reduces dissolved oxygen in the water column (also a stressor). These stressors may cause ecological responses such as algal blooms or fish kills (the response) which negatively affect community values. The enrichment of water and sediments with nutrients and organic matter is a key stressor on the health of the Peel-Harvey estuary.

See Table 5-1 and the summary below for the key pressures impacting on the Peel-Harvey estuary, many of which export nutrients to the estuary, increasing eutrophication and its associated negative ecological impacts and resulting in unpleasant odours and reduced recreational amenity.

- Agricultural activities (beef and dairy farming, horses, mixed grazing, intensive animal industries, cropping, horticulture, viticulture). Diffuse runoff and point source discharge of high-nutrient-concentrated wastes and organic matter from agricultural activities are a significant ongoing source of nutrients to the estuary.
- Clearing or degradation of riparian vegetation (e.g. by stock access) destabilises riverbeds and banks, leading to erosion and increased levels of organic matter, sedimentation, and turbidity in the estuary system. This can lead to reduced water depths and the smothering of benthic plant and animal communities. Loss of riparian vegetation also reduces habitat for fish and other fauna.
- Urban and industrial activities/development:
  - Increased stormwater runoff (because of increased impervious surfaces) from urban and industrial areas may contain elevated concentrations of nutrients and other pollutants such as heavy metals and pesticides.
  - During land development, if acid sulfate soils (ASS) are disturbed (via excavation or artificial drainage), toxic quantities of heavy metals may be released into the estuary system, and this can impact on the health and diversity of aquatic biota. ASS disturbance can also lead to the acidification of groundwater and waterways, deoxygenation of the water column (anoxic conditions) and formation of sulfidic black ooze.
- Clearing of native vegetation:
  - Land clearing associated with agricultural, urban or industrial development may involve clearing of native vegetation, leading to a raised groundwater table and losses of water and nutrients from the landscape to the estuary system.
- Discharge from wastewater treatment plants:
  - Discharge of treated wastewater via infiltration or directly to waterways and drains adds nutrients and toxicants to the estuary system.
- Leaching from septic tanks:
  - Sewerage contains nutrients, metals, salts, persistent organic pollutants including hormone-disrupting chemicals, bacteria, viruses and other pathogens. These may leach from septic tanks into groundwater and waterways.

- Diversion or abstraction of water:
  - Intensifying agriculture, urban development and industrial expansion (including mining) is likely to increase water demand, which if met by further abstraction of groundwater or diversion from drains, will reduce river flow. Reducing freshwater flushing of the estuary increases residence times and can negatively affect water quality, sediment condition and distribution of resident seagrasses (e.g. *Ruppia* that needs fresh water for germination).

Climate change imposes an additional suite of pressures including:

- Reduced rainfall:
  - Declining rainfall (less winter rainfall plus a shorter rainfall season) leads to lower river flows and reduced flushing of the estuary. Less runoff from the catchment is generally associated with reduced loads of nutrients and organic matter to the estuary. Yet concentrations remain excessive. The increased residence time means nutrients are more available for algal growth.
  - In addition, the estuary will be saltier for longer than under the current climate regime and the salt wedge will penetrate further upstream, extending the periods and degree of salinity stratification. This will further exacerbate low-oxygen events and lead to greater release of sediment nutrients, which increases eutrophication and can lead to algal blooms and fish kills.
- Increasing temperature:
  - Increasing air temperatures warm surface waters and increase evaporation, which can impact on the distribution and diversity of aquatic species (e.g. favouring species tolerant of higher temperatures/salinity) and key biological activities, such as fish spawning.
- Sea-level rise:
  - Altered salinity regimes and increased water levels increase pressure on freshwater species and fringing habitats. Freshwater and intertidal habitats shrink in area and aquatic species that are tolerant of marine conditions are favoured. Non-salt-tolerant fringing vegetation (e.g. paperbark communities) may decline further.
  - Inundation of low-lying areas of private and public land has the potential to have significant detrimental consequences.
- Changing frequency of summer storm events:
  - Longer, drier periods are predicted but with more variability and a change in the frequency and intensity of storm events, flooding and storm surges. Large floods have the potential to deliver bigger pulses of nutrients and organic matter to the estuary, bringing what has accumulated in the catchment during the longer, drier periods.
  - Storm surges are likely to inundate low-lying areas and impact on ecological communities, public infrastructure and assets.

It is recognised that catchment land uses and climate change are not the only pressures; others exist within the estuary itself such as dredging, construction of jetties, canal development, boat wash, and recreational and commercial fishing. These other pressures are included in the conceptual model in Figure 5-3, but are not further addressed in this WQIP. See the *Bindjareb Djilba Protection Plan* (DWER 2020b) for the recommended management actions that relate to these estuary pressures.

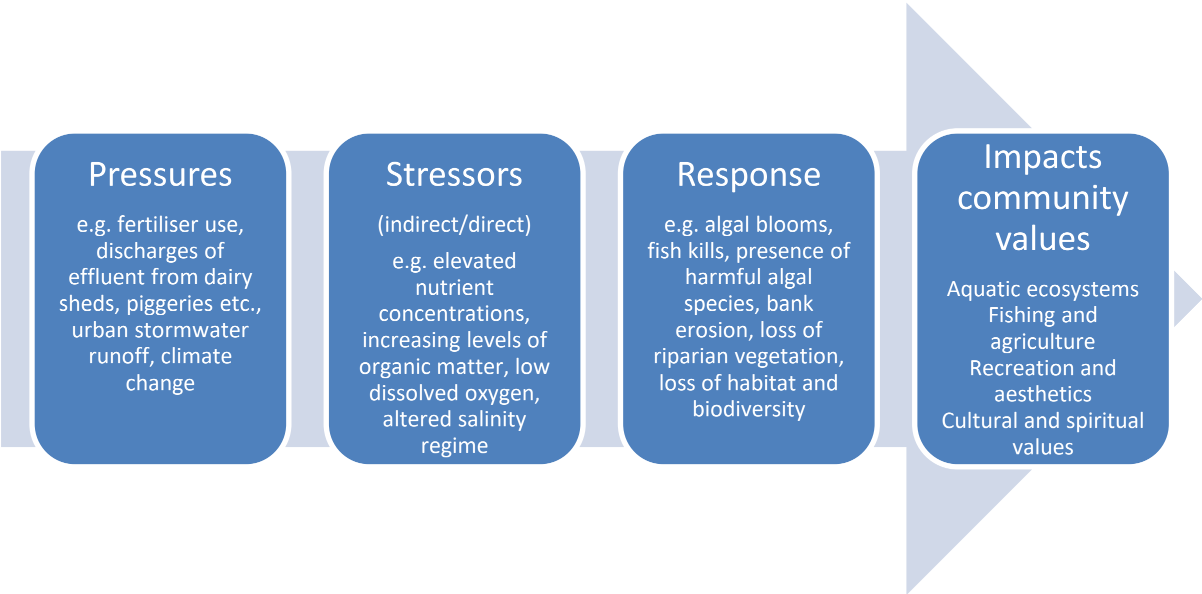


Figure 5-2 The relationship between pressures in a catchment, the resulting physical, chemical or biological changes (stressors) in the receiving waterbody and the system's ecological response to those stressors, which in turn impacts on the community values (modified from the National Water Quality Management Strategy Charter, Australian Government 2018)

The South Metropolitan Peel sub-region is expected to grow substantially to a population of 1.26 million by 2050 (WAPC 2018b). Urban expansion (i.e. increasing numbers of residential and lifestyle blocks) and agricultural intensification (i.e. higher animal stocking densities) and sector expansion (e.g. intensive horticulture) will increase the magnitude of the pressures and stressors on the estuary. Recreational boating, fishing and tourism will also intensify with the potential to further degrade the fringing environment (e.g. increased disturbance and erosion of the shoreline from foot traffic and boat wash).

Climate change is likely to compound existing stressors from land use pressures and the combined impact of multiple pressures is often greater than the sum of their parts (Thomson et al. 2017). Section 8.1 discusses modelled changes to nutrient loads because of climate change (to 2050). To provide estuary systems with the best chance to adapt to climate change, the goal is to increase the resilience of the system (State of NSW 2015). Implementing the recommended policy and catchment management actions (Section 9) will mitigate the impact of pressures and stressors and support the Peel-Harvey estuary's ability to adapt to change.

Table 5-1 Key pressures that exist in the estuary coastal plain catchment showing the related stressors and the impacts or potential impacts on the ecological health and water quality of the estuary system (the response)

Pressure	Stressors	Response
Human activities		
Agricultural development and activities: Application of fertilisers (diffuse source nutrients) Application of pesticides Discharge of effluent from dairies, piggeries and poultry sheds etc. (point source nutrients) Stock access to riparian zones (bank and soil erosion) Clearing of native vegetation	Increased nutrient concentrations Increased levels of organic matter Increased sediment loads and sedimentation Increased turbidity Increased levels of other toxicants (e.g. pesticides and metals) Reduced light penetration Reduced dissolved oxygen (anoxic/hypoxic conditions) Increased groundwater table	Nuisance algal blooms (visually displeasing and can inhibit navigation/fishing). Some algae/cyanobacteria release toxins that are potentially harmful and can make water unsafe for use or shellfish/fish unsafe for consumption. Fish kills (because of oxygen deficiency, algal toxins or other toxins) Unpleasant odours and reduced recreational amenity Smothering of aquatic plants Reduced distribution of seagrass beds Loss of habitat for fish and other fauna Loss of aquatic biodiversity Reduced fish stocks (and fisheries productivity) Increased acidification of groundwater and waterways Toxicity effects in aquatic organisms and potential impacts on human health Formation of sulfidic black ooze
Urban/industrial development and activities: Clearing of native vegetation Increasing areas of impervious surfaces Runoff and discharges from urban and industrial sites (including mine sites) Disturbance of acid sulfate soils Application of fertilisers and pesticides Leaching of septic tanks Discharge of effluent from WWTPs Illegal dumping of rubbish		
Diversion and increased use of groundwater and surface water	Reduced river flow Reduced groundwater levels Changing hydrodynamics Increased salinity Increased period of salinity stratification	Reduced freshwater flushing of the estuary Inflows have longer residence time in the estuary, making nutrients more available for algal growth Loss of biodiversity

Pressure	Stressors	Response
	Increased nutrient concentrations Increased levels of organic matter Reduced dissolved oxygen (hypoxic/anoxic conditions)	Increasing salinity may render waterways unsuitable for stock watering
Climate change		
Reduced rainfall/shorter wet season	Reduced river flow Reduced groundwater levels Changing hydrodynamics Increased salinity Increased period of salinity stratification Reduced dissolved oxygen (hypoxic/anoxic conditions) Increased nutrient concentrations Increased levels of organic matter	Reduced freshwater flushing of the estuary. Inflows have longer residence time in the estuary, making nutrients more available for algal growth; however, total nutrient loads to the estuary may reduce. Increased marine influence and tidal reach. Nuisance algal blooms (visually displeasing and can inhibit navigation/fishing). Some algae/cyanobacteria release toxins that are potentially harmful and can make water unsafe for use or shellfish/fish unsafe for consumption. Fish kills (because of oxygen deficiency, algal toxins or other toxins) Unpleasant odours and reduced recreational amenity Loss of freshwater habitat and aquatic biodiversity Reduced fisheries productivity Increasing salinity may render waterways unsuitable for stock watering
Increase in temperature	Increased water temperatures Increased evaporation Low dissolved oxygen (anoxic/hypoxic conditions) Increased salinity	Loss of habitat Changes in the distribution and diversity of aquatic species Impacts on key biological activities such as fish spawning

Pressure	Stressors	Response
Sea-level rise	Increased water level Altered tidal regime Altered salinity Altered area and period of saline stratification	Increasing pressure on freshwater species and fringing habitats Decline in non-salt-tolerant fringing vegetation Loss of habitat Changes in the distribution and diversity of biota dependent on intertidal zones Inundation of low-lying areas impacts on public infrastructure and assets Increased marine influence and tidal reach
Changing frequency/intensity of summer storm events	Temporarily increased river flows Temporarily increased water levels Increased nutrient concentrations Increased sediment loads Increased levels of organic matter Increased turbidity Reduced dissolved oxygen (anoxic/hypoxic conditions)	Erosion of river banks and degradation of riparian zones Nuisance algal blooms (visually displeasing and can inhibit navigation/fishing). Some algae/cyanobacteria release toxins that are potentially harmful and can make water unsafe for use or shellfish/fish unsafe for consumption. Fish kills Unpleasant odours and reduced recreational amenity Smothering of aquatic plants Reduced distribution of seagrass beds Loss of habitat for fish and other fauna, loss of aquatic biodiversity Reduced fish stocks (and fisheries productivity) Inundation of low-lying areas impacts on ecological communities, public infrastructure and assets Periodic increased freshwater flushing of the estuary

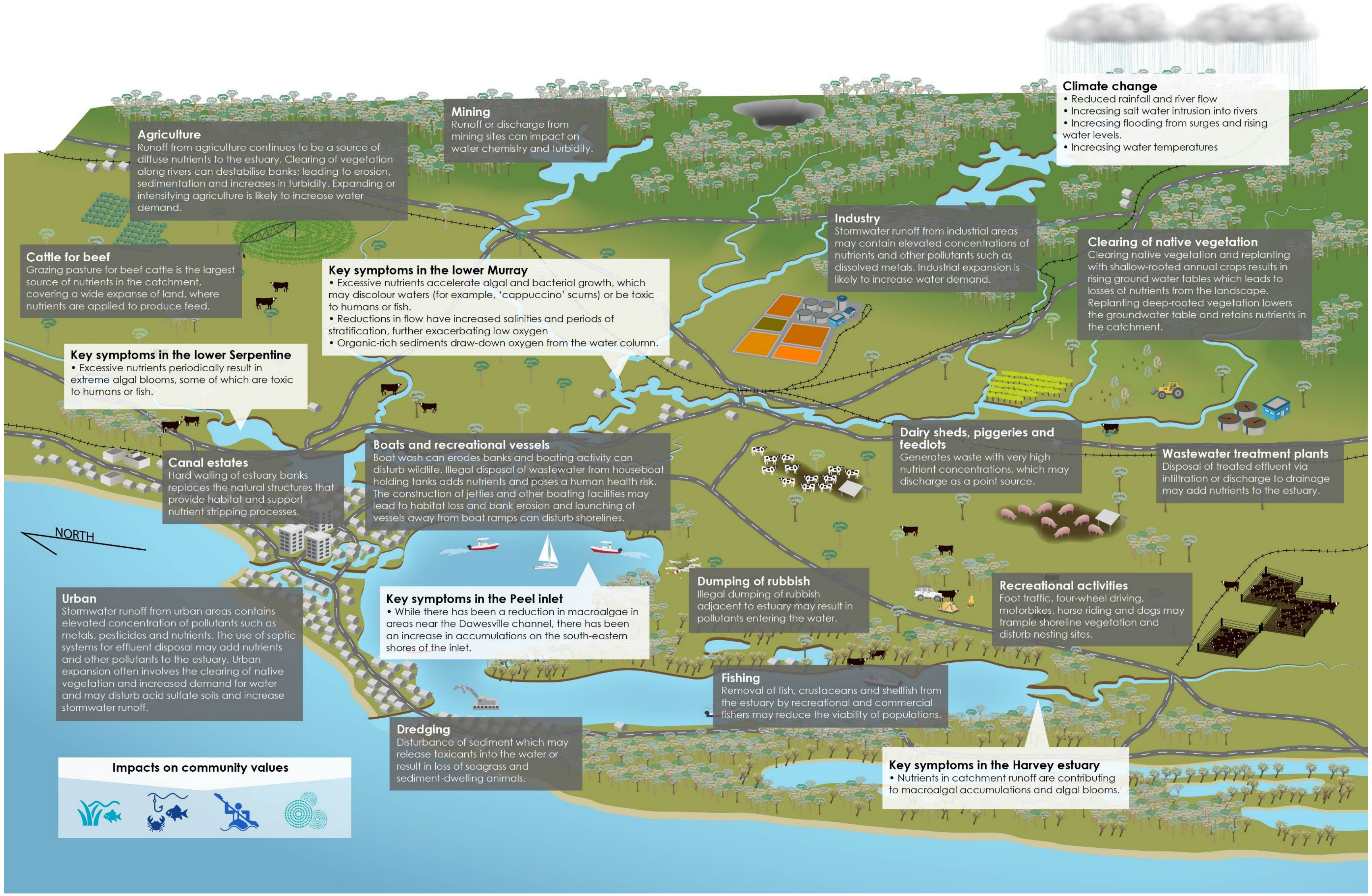


Figure 5-3 Conceptual model of the Peel-Harvey estuary system showing the pressures that exist in the catchment from land use activities and climate change

6 Water allocation and environmental flows

There are surface water and groundwater resources of variable quantity and quality in the plan area. Only limited water is available for further allocation from groundwater and there is a low likelihood that further surface water will become available. Alternative water sources, such as treated wastewater and drain water, will need to be investigated and developed for long-term water security and future development in the plan area.

The allocation of surface water and groundwater resources and the use of water in the catchment can impact on flows and water quality. The major water supply dams intercept all upstream winter inflow with some water released seasonally or annually to achieve downstream objectives, including maintaining water-dependent ecological values in river reaches below the dams.

This chapter describes the allocation and water supply status of traditional and alternative water sources, what licensees are required to do to avoid negative impacts to water quality and how water is released from major dams to provide for environmental flows.

6.1 Allocation and use of surface water resources

Climate change and a decline in rainfall has dramatically reduced streamflow (see sections 2.2 and 8.1) and the reliability of supply for existing users who are unable to access their full licensed entitlements. Surface water resources are a diminishing and unsecure source of water and there is a low likelihood that further water will become available for allocation from waterways or drains in both proclaimed and unproclaimed areas in the plan area.

Any future proposed abstraction of surface water from proclaimed or unproclaimed areas will need to demonstrate that the values (e.g. ecological and cultural values) of the drain, receiving waterway and estuary will be maintained or restored. Given reduced flows because of climate change, proponents must carefully consider the viability of surface water resources into the future (see Section 6.4).

Because the Serpentine, Dandalup and Murray river systems are proclaimed under the *Rights in Water and Irrigation Act 1914*, this means the take of most surface water resources in the plan area are subject to licensing under the Act. While there are some unproclaimed portions, this does not pose an increased risk of unsustainable abstraction or threaten to diminish future flows to the estuary. The department will continue to work with proponents to investigate the potential take of surface water from drains in unproclaimed areas, and apply the same hydrogeological, assessment and policy advice as the proclaimed areas.

The main licensed surface water users are Water Corporation, Harvey Water and Alcoa, which together hold entitlements to take 99 per cent of the allocated surface water in the plan area. Figure 6-1 shows all licences to divert surface water, identifies the main licensed users and pinpoints the ecological monitoring sites used to assess river condition and evaluate management strategies. How licensees harvest and supply surface water and manage the impacts on environmental flows is described below.

Water Corporation

Water Corporation is licensed to divert surface water from the Serpentine, Murray and Harvey river systems into eight major public water supply dams including: Serpentine Main, Serpentine Pipehead, North Dandalup, Conjurunup, South Dandalup, Samson Brook, Samson Pipehead and Stirling dams (Figure 6-1). These dams are critical storages and sources of water for the Integrated Water Supply Scheme (IWSS) which supplies Perth, the Goldfields and some parts of the South West.

For many years, Water Corporation has been unable to access its full entitlement. This is because the volume of water flowing into the dams each year has fallen, on average, by about 80 per cent since the 1970s. Note that the water in these dams is no longer just made up of inflows from rain. Groundwater and desalinated water are added to and stored in the dams during periods of low demand, so it is available for the IWSS when it is most needed, in the hotter months.

Water Corporation’s licences include conditions to release water from most of its dams to maintain downstream water-dependent values (Section 6.2). These include the Serpentine Pipehead,[24] North Dandalup, Conjurunup Pipehead, Samson Brook and Stirling dams.

Water Corporation must also completes river health assessments every three to five years to evaluate the effectiveness of the release regimes (Section 6.2).

In 2017, the department revised when and how much water is released from the IWSS dams. The approach aims to balance supply from the dams and protect downstream water users and water-dependent values in the river reaches below the dams. For more information see *Managing releases for the Serpentine River: Serpentine River allocation statement* (DWER 2017b) and *Managing releases from the North Dandalup Dam: North Dandalup allocation statement* (DWER 2017c).

Harvey Water

Across the plan area, Harvey Water holds five surface water licences and is entitled to about 66 GL per year. However, the effects of climate change have meant that Harvey Water was unable to access its full entitlement. Surface water is captured in several irrigation dams constructed on the Harvey River system including the Waroona, Drake, Logue and Wokalup Pipehead dams.

Harvey Water delivers non-potable water to customers through a network of channels and pipes across the Waroona and Harvey irrigation districts (Figure 6-1).

[24] Delivered via downstream release points in trunk mains.

This water is primarily used for dairy farming, beef grazing, horticulture and industrial operations.

Harvey Water's licences include conditions to release water from its dams to maintain downstream water-dependent values. Harvey Water releases water to river reaches below the Drakes Brook, Logue Brook and Harvey dams.

Harvey Water are also required to complete three- to five-yearly river health assessments to evaluate the effectiveness of the release regimes.

Alcoa

Across the plan area, Alcoa holds 11 surface water licences (Figure 6-1) and is entitled to about 19 GL per year. Climate change has impacted on Alcoa's ability to access its full entitlement. Surface water is diverted and stored in off-stream dams and/or pumped directly from the Dandalup, Murray and Harvey river systems.

Alcoa uses surface water at the Huntly and Willowdale bauxite mines and the Pinjarra and Wagerup alumina refineries. It is investigating a long-term and more secure alternative source of water.

Other licensed users of surface water

Across the plan area there are 46 privately held licences. The amount of surface water these users take (about 2 GL per year in total) is relatively small – collectively less than 1 per cent of the total water allocated across the plan area. They self-supply their own water by diverting or pumping directly from the Serpentine, Murray and Harvey river systems (Figure 6-1).

Licensees on the Serpentine River rely partly on water released by Water Corporation from the Serpentine Pipehead Dam. As the climate continues to dry, more low-flow years are expected. This means 100 per cent reliability of supply may not always be possible during the summer months. See *Managing releases for the Serpentine River* (DWER 2017b) for more information.

The department encourages licensees to adapt to climate change and a future with less natural available water by reducing demand, improving water efficiency, and developing alternative water sources to meet future needs.

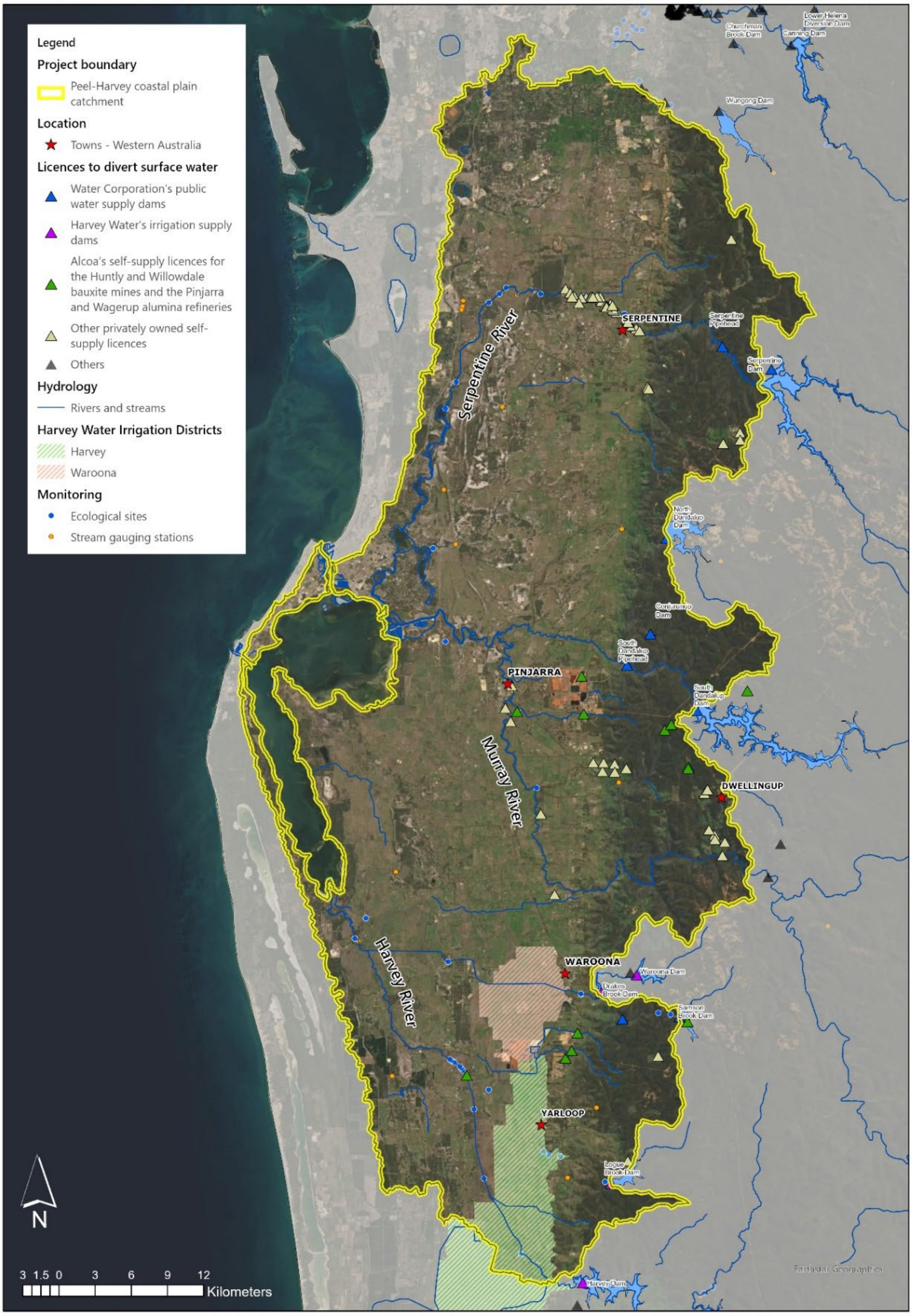


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Figure 6-1 Licences to divert surface water showing the main licensed users and the ecological monitoring sites used to assess river condition and evaluate management strategies

6.2 Environmental flows

Most of the flows in the Peel-Harvey catchment are modified by large dams. The main tools for managing environmental flows are releasing water from dams to the river below (known as river releases) and maintaining flows from undammed tributaries. Undammed tributaries and natural runoff below the catchment dams provide variation in streamflow, while river releases from dams help to maintain stream connectivity and water quality, thus supporting important refuge areas for aquatic and semi-aquatic species.

River releases are agreed dam release volumes to meet downstream water-dependent objectives for river reaches below the dams; for example, to maintain ecological, social and cultural values and/or provide water for licensed users. A release reach is the area of river (longitudinal and lateral extent) known to be influenced by river releases. They typically include more natural sections of river with intact riparian vegetation and higher quality habitat than the highly channelised and cleared areas further west on the Swan coastal plain.

River releases are system dependent and can be adjusted: less water may be released following a low-inflow year, or more water may be released to combat a spell of hot weather. The release volumes and regimes consider a range of factors including:

- water-dependent ecological, social and cultural values
- licensed and unlicensed (riparian rights) water users in release reaches below the dams[25]
- current and projected future rainfall
- short-term local weather forecasts
- dam inflows and storage volumes
- water supply needs.

River releases are often designed to maintain:

- water quality (dissolved oxygen concentrations within the tolerance levels of native fish)
- important refuge pools at a certain depth
- stream connectivity.

The ecological needs of river release regimes are informed by ongoing monitoring of streamflow, water levels, water quality, aquatic biota and field observations.

In consultation with the department, Water Corporation and Harvey Water undertake three- to five-yearly river health assessments of targeted refuge areas in each

[25] Under the *Rights in Water and Irrigation Act 1914*, land owners or occupiers of land (not crown land) with a waterway running through their property can take a small volume of surface water for domestic use or watering of stock.

release reach. We use these river health assessments and any stakeholder feedback to evaluate whether the release regimes are effectively maintaining the water-dependent ecological values within a release reach. When necessary, river releases can be adjusted via an update or addendum to the dam operator's water resource management operating strategy.

See our Healthy Rivers program website to access the river health assessments.

River releases from major dams provide some water to the following waterways:

- Serpentine River (dry season only)
- North Dandalup River (dry season only)
- Conjurunup Brook (dry season only)
- Drakes Brook
- Samson Brook
- Logue Brook
- Harvey River.

While the river releases are not intended to reach the Peel-Harvey estuary, in some systems flow may be able to travel beyond the extent of a release reach during the dry season where groundwater connectivity exists, or where the reach joins a permanently flowing tributary.

6.3 Allocation and use of groundwater

As at June 2022, 52 GL of groundwater was allocated across 1,770 licences in the plan area (Figure 6-2). Groundwater supports mining, industry, construction, agriculture and some town water supplies, and makes up nearly all the water used to irrigate schools, public parks and recreational areas.

To avoid future impacts from the over-allocation of groundwater resources – both on river flow and community values – the department reviews allocation limits and adjusts them to reflect the impacts of climate change on rainfall recharge. Most groundwater resources are now fully allocated. The only groundwater left is not easily accessible (i.e. very deep or low yielding) or is of low quality (i.e. too salty).

The limited availability of natural groundwater should drive current users to optimise their water supply, decrease water demand, increase water efficiency and engage in water trading. Licence trades, transfers and agreements can allow new users to obtain an entitlement in fully allocated areas and existing licensees to expand their operations. Anyone seeking to trade water can find the details of current water licences using our online Water Register.

The Serpentine and Murray groundwater areas and portions of the Perth, Jandakot, Cockburn, Stakehill, South West Coastal and Karri groundwater areas are in the plan area. Except for the Karri, these groundwater areas are proclaimed under the *Rights in Water and Irrigation Act 1914*, which means proponents need a licence to construct or alter a well or to take groundwater from any aquifer, unless an exemption applies.[26]

Licensed water users have a legal responsibility to manage their water use according to the terms and conditions of their licence. To avoid water quality impacts and the contamination of groundwater, the licensee may require a more detailed operating strategy. Operating strategies outline prevention and mitigation measures that the licensee is required to follow.

Across a large portion of the plan area, intensive agricultural use (including in-ground horticulture) may be restricted, have special conditions attached, or not be permitted because of excessive nutrient contamination risk. Should intensive forms of agriculture be proposed, the proponent would need to secure planning approval from the local government before applying for a groundwater licence, and this might require development of a nutrient irrigation management plan (see *Water quality protection note 33: Nutrient and irrigation management plans* (DoW 2010b) and *Water quality protection information sheet 4: Nutrient and irrigation management plan checklist* (DoW 2010a). The proponent would need to demonstrate that nutrient input rates can be met to achieve the maximum acceptable nutrient loads to the estuary (see Section 7.5), and should adhere to other relevant state policy (including consistency with the *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a), *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b)) and local government policies.

For further information on how groundwater is allocated, see the:

- *Cockburn groundwater allocation plan* (DWER 2021)
- *Rockingham and Stakehill groundwater allocation plan* (DoW 2008a)
- *Peel Coastal groundwater allocation plan* (DoW 2015a)
- *South West groundwater allocation plan* (DoW 2009)
- *Murray groundwater allocation plan* (DoW 2012a)
- *Murray groundwater area allocation statement* (DWER, 2022)
- *Waangaamaap – Serpentine groundwater allocation statement* (DWER, 2024).

[26] The Karri groundwater area is largely fractured rock and so does not yield high volumes of groundwater like the aquifers in the other proclaimed groundwater areas.

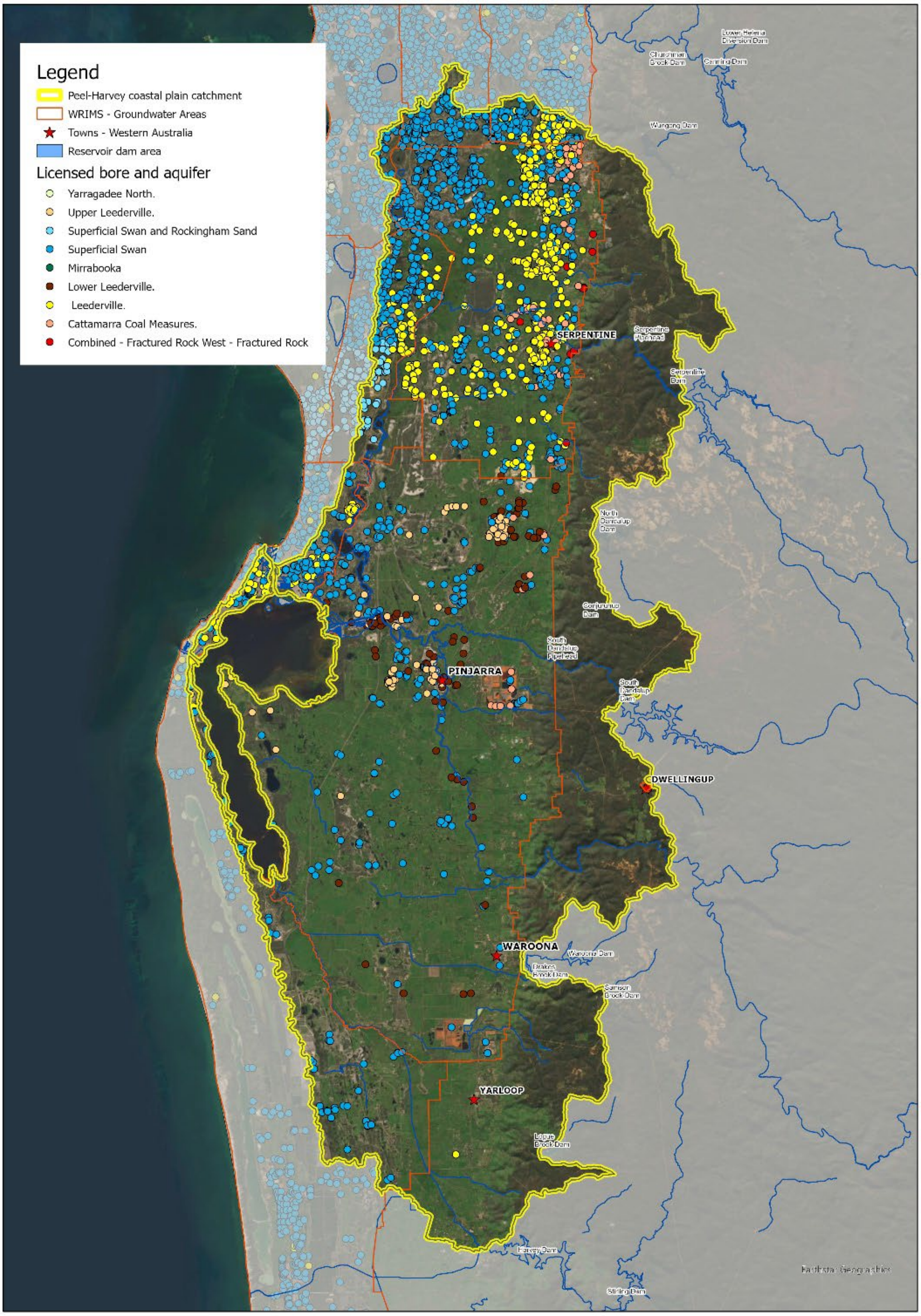


Figure 6-2 Licensed groundwater abstraction showing what aquifer they are drawn from

6.4 Meeting future water demand through alternative water sources

It is well recognised that alternative water sources are necessary to support long-term water security for future development in the plan area. Large water licensees, such as Water Corporation, Alcoa and Harvey Water, have already taken steps to boost water efficiency, and optimise and diversify their water supplies with alternative and climate-independent sources. However, more investment is needed to meet future demand, and all private self-supply licensees must prepare for a future with natural water being less available as the climate continues to dry. More efficient use and recycling of water is encouraged alongside a transition to land use practices with high water use efficiency.

The department collaborated with industry partners to complete preliminary investigations into a range of alternative water supply options as part of the *Transform Peel: Peel Integrated Water Initiative* (2021b). These included wastewater reuse, managed aquifer recharge in the Cattamarra aquifer using subsoil and surface drainage, and harvesting water from the drains for use in the agricultural sector.

Water harvesting from drains is unlikely to be a long-term viable option, as the flow in drains is diminishing over time because of climate change – making it a less reliable resource. However, this may provide a source in the short term until other water supply options are developed. We will work with proponents to help them investigate if and how drains could be harvested to help meet existing and future shortfalls in water supply without diminishing flows to natural waterways or the estuary.

Collaborative research and land planning are already underway to deliver Transform Peel's vision, with the Peel Development Commission and Peel Alliance. This includes working together to achieve industry growth and regional development objectives that are compatible with the sustainable use of the region's water resources and supplies under climate change. We will continue to support proponents to investigate potential options to develop alternative water sources for non-potable supply, including managed aquifer recharge and recycled treated wastewater from wastewater treatment plants (see recommended action 17, Section 9.1).

7 Nutrients coming from the catchment

Hydrological and nutrient models of estuary catchments are powerful tools for water quality management, planning and reporting. Catchment models are used worldwide to better understand the source, transformation and transport of nutrients in the catchment and their delivery to receiving waterbodies. Models support the development of water quality targets and enable us to predict the relative effectiveness of a range of catchment management actions and prioritise programs to improve water quality in the receiving waterbodies. Models are developed using real-world data collected by a wide range of stakeholders. These inputs include land use and drainage mapping, locations of point sources and septic tanks, fertiliser and feed inputs from surveys, soil testing, and climate data.

Why do we need models when we have monitored data available?

Quite simply, no monitoring program can measure everything everywhere. Numerical models are used to synthesise a wide range of spatial and quantitative data to estimate the effectiveness of actions and support management decisions. Models are used in conjunction with the monitoring program to understand current water quality and predict changes to water quality resulting from different management strategies under specified climate regimes. Numerical models are used to estimate flow in ungauged catchments from the relationship between rainfall and runoff: this is derived using a series of tried-and-tested algorithms and calibrated against gauged catchments.

By modelling the entire Peel-Harvey estuary catchment, all the land uses across each reporting catchment can be captured and their contribution to the nutrient export to the estuary considered. Monitored data, on the other hand, represents water quality at a specific time and sampling point on a waterway or drain and does not capture nutrients exported from land uses downstream.

7.1 eWater Source modelling and how it was used

The department’s hydrological and nutrient model of the Peel-Harvey catchment used the eWater Source framework (version 4.3), which is the national standard for catchment modelling and underpins the National Hydrological Modelling Platform program (Welsh 2013). The model determines how nutrients are generated by various land uses (diffuse and point sources), and how they are processed as they move through the catchment.

The model was calibrated to the observed water quality data, based on the five-year, winter median nutrient concentrations from 2011–2015. Flows generated from each of three sub-models (urban, vegetated, cleared) were added together to give the total flow for each reporting catchment. A detailed description of the model inputs, how it was constructed and calibrated, and a discussion of the recommended uses and limitations are provided in Hennig et al. (2021). The authors also discuss differences between the previous modelling performed by Kelsey et al. (2011) and the more recent modelling.

The model (Hennig et al. 2021) represents a current description of the Peel-Harvey catchment, with up-to-date land use mapping and additional and more accurate data (e.g. calibration, nutrient application and whole-farm nutrient mapping data) in a contemporary modelling framework.

In this WQIP we have used the model's outputs to determine:

- the relative proportion of N and P contributed by each land use type (at a catchment and reporting catchment scale)
- relative and absolute nutrient loads by land use and reporting catchment
- targets for nutrient-load reductions to meet maximum acceptable loads, based on meeting nutrient WQOs 1 and 2
- how nutrient loads are likely to be affected by catchment management actions, modifications to land use or climate change.

Most importantly, the model predicts the most effective management actions for reducing the P and N loads reaching the estuary and estimates whether combinations of management actions will enable WQOs relating to catchment nutrient concentrations to be met over time.

Catchment modelling results discussed in the proceeding chapters are from the Peel-Harvey Catchment Model (Hennig et al. 2021) that supports this WQIP.

7.2 Nutrient concentration by reporting catchment

Nutrient concentration versus nutrient load

Both nutrient concentrations and loads are used in this WQIP because they provide different information. Biological processes such as the rate of algal growth in a waterway will be influenced by nutrient concentrations, whereas loads are used to quantify the mass of a nutrient being discharged to, retained by, or leaving the estuary.

Nutrient concentration is the amount of a nutrient in a specified volume of water determined by laboratory analysis, which can be measured over time through a routine sampling program. Measured concentrations of nutrients are used to determine trends in water quality as described in Section 3.2 and 3.3, and to compare against a desired or target nutrient concentration such as the WQOs outlined in Section 4.2.

Nutrient load is the total mass of a nutrient delivered to a waterway over a given time (usually an annual average calculated over several years). Nutrient load is a function of both flow and concentration:

nutrient load = nutrient concentration x flow

As such, nutrient loads may be small under low-flow conditions, even when nutrient concentrations are high.

Annual loads are calculated by multiplying daily flow with daily nutrient concentration and aggregating over the year. In the Peel-Harvey catchment, annual nutrient loads are estimated from measured flow and fortnightly sampled nutrient concentrations using locally weighted scatterplot smoothing (LOESS) or by the hydrological and nutrient model.

Catchment nutrient reports (DWER 2021a) provide calculated nutrient loads for monitoring sites where both nutrient concentration and flow measurement data are monitored. Nutrient loads are highly variable from year to year and as such are poorly suited to use as a water quality target. In a drying climate, using loads as water quality targets can falsely suggest improvements in water quality.

When nutrients are applied to the land as part of agricultural activities (e.g. fertiliser) they are measured in mass (e.g. kg/ha), hence using loads when discussing management actions may be more relevant than nutrient concentrations to the land user.

Nutrient loads can be derived from the Peel-Harvey Catchment Model for all reporting catchments and land uses within the plan area, including areas below a gauging station. We can then use these loads to estimate the total flow and nutrient load entering the estuary.

As noted in Section 4.2, nutrient concentrations at monitoring sites do not always represent the whole reporting catchment. The model estimates nutrient concentrations in both the sampled and unsampled areas of the catchment and calculates daily flow and nutrient concentrations (2006–15) from all reporting catchments.

If we compare the modelled flow-weighted annual mean nutrient concentrations to WQOs 1 and 2 as we did in Section 4.2 with the monitored data, we generally draw the same conclusions. However, for some sites, the modelled flow-weighted annual mean concentrations are much higher than the monitored three-year winter median concentrations. While data from monitored sites in the Lower Murray and Harvey reporting catchments indicates that these are meeting one or both relevant WQOs in Section 4.2, modelled concentrations paint a different picture – suggesting nutrient management is required in all reporting catchments of the Peel-Harvey. This is because:

- A significant portion of the Lower Murray reporting catchment lies below the monitoring site and thus is not included in measured concentrations. Most of these unmeasured areas have poor soils, nutrient-intensive land uses and septic tanks, all of which are captured by the model and reflected in the modelled concentrations and loads (refer back to Figure 4-1).
- Monitoring data (three-year winter median) at the Middle Murray River site (AWRC ref. 614065) meets WQOs 1 and 2, but the Peel-Harvey Catchment Model shows this is because of dilution with low-nutrient flows from the Upper

Murray catchment. The model demonstrates that nutrients derived locally in the Lower Murray reporting catchment warrant management interventions.

- Flow is not measured at the monitoring sites of Drakesbrook Drain (Harvey River reporting catchment, AWRC ref. 613133) and South Dandalup River (Lower Murray catchment, AWRC ref. 6142623) but is accounted for in the model. The model estimates that these sites have a strong relationship between nutrient concentration and flow and because the model considers a much longer period (10 years), naturally large-flow and rarer events are captured. This results in the modelled flow-weighted annual mean concentrations at these reporting catchments being considerably higher than the three-year winter medians.

In addition, the model suggests that management interventions in the Coolup (Peel) reporting catchment are warranted but no monitoring sites exist there, so it is not possible to apply the WQOs to measured data in this location.

7.3 Annual nutrient loads

Comparing the modelled P and N load contributions for each reporting catchment helps to prioritise management actions and identify where they need to be implemented to meet the nutrient concentrations set as WQOs in this WQIP. To identify priority reporting catchments for N-targeting actions we considered where dissolved inorganic nitrogen (DIN) made up a high proportion of the TN – as we know that DIN (nitrate and total ammonia) is bioavailable and can contribute to algal blooms. By contrast, the bioavailability of dissolved organic nitrogen (DON), which makes up a large proportion of the TN in many reporting catchments, is not as well understood (Section 3.2).

We can prioritise reporting catchments based on total annual loads (t) or total annual loads per cleared area (kg/ha). Total annual loads indicate the relative contributions across reporting catchments and identify where broadscale management actions need to be applied. However, as vegetated areas generally contribute minimal nutrients and may dilute impacts from other land uses, loads per cleared area:

- highlight the relative impact of particular land uses
- identify nutrient hotspots
- emphasise smaller-scale remediation works; for example, those that target point sources of nutrients.

All three river catchments are contributing significant amounts of nutrients to the estuary every year (Figure 7-1, Table 7-1). The Harvey River catchment is the largest contributor of N (259 t, 47 per cent) and P (27 t, 45 per cent). The Serpentine River catchment contributes 169 t of N (31 per cent) and 23 t of P (40 per cent), while the Murray River catchment (excluding the Upper Murray reporting catchment) contributes 124 t of N (23 per cent) and 9 t of P (15 per cent) to the estuary annually.

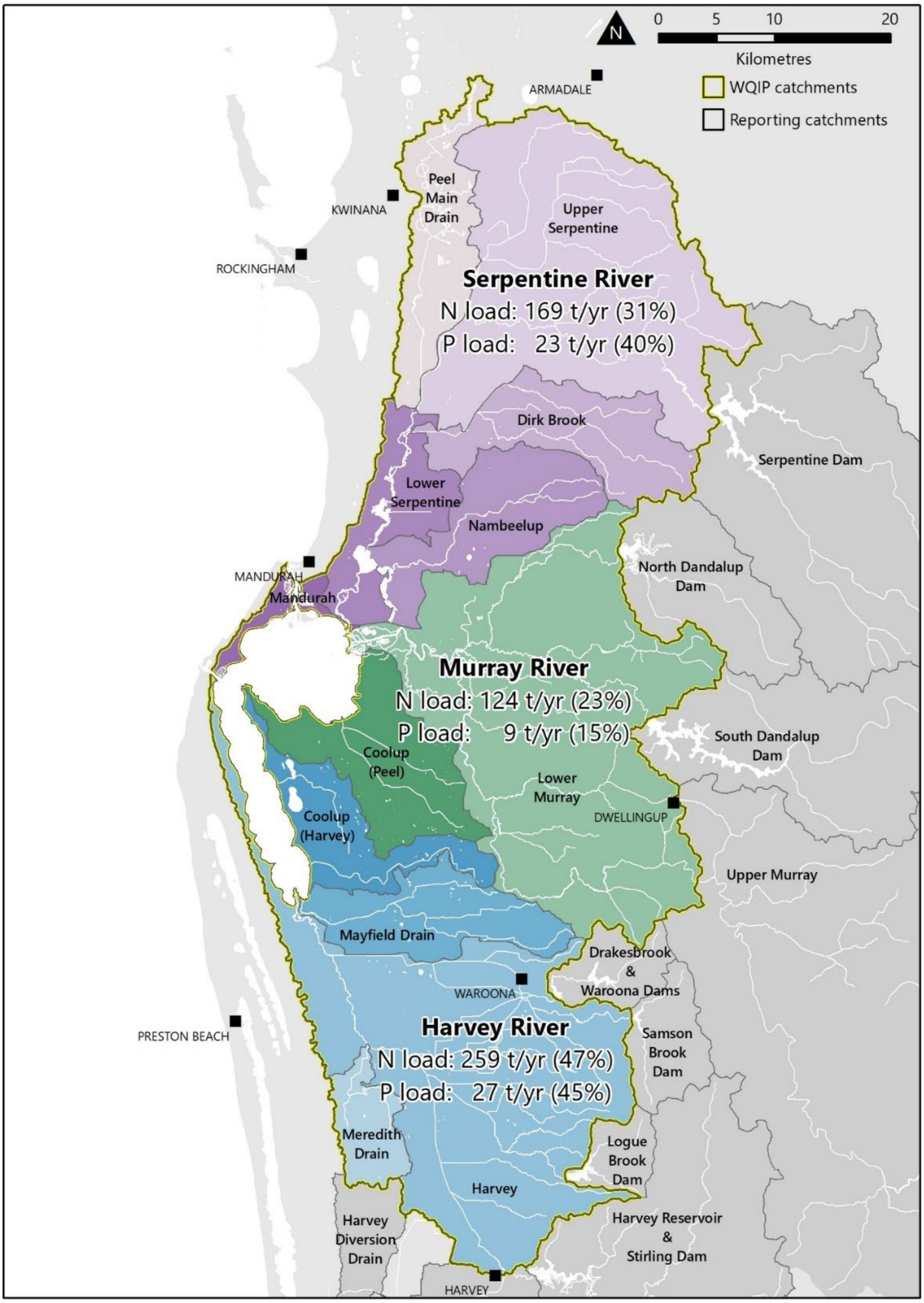


Figure 7-1 Modelled annual (2006–15) contributions to the nitrogen and phosphorus loads entering the Peel-Harvey estuary (excludes Upper Murray) from the major river catchments on the Swan coastal plain (Serpentine, Murray and Harvey rivers)

When these data are compared with total loads across the entire estuary catchment (which includes the Upper Murray catchment beyond the Darling Scarp), it is evident that most of the loads of N (552 of the 633 t, 87 per cent) and P (59 of the 60 t, 98 per cent) entering the estuary each year are originating from the Swan coastal plain.

The three largest reporting catchments in each river catchment – the Upper Serpentine, Lower Murray and Harvey (Figure 7-1) – are estimated to contribute the largest N loads to the estuary (Table 7-1) and combined are responsible for 69 per cent of the N load from the plan area. The Harvey reporting catchment alone contributes 205 t of N (37 per cent), followed by the Lower Murray (103 t, 19 per cent) and the Upper Serpentine (72 t, 13 per cent). However, we know that much of the TN measured in the Upper Serpentine and Lower Murray reporting catchments is DON (Section 3.2), the bioavailability of which is unknown.

The same three reporting catchments (Upper Serpentine, Lower Murray and Harvey), with the addition of Nambeelup, are estimated to contribute the largest P loads to the estuary (Table 7-1) and together contribute 72 per cent of the P load from the plan area. Like the N load, more than one third (34 per cent) of the P load reaching the estuary is attributable to the Harvey reporting catchment. This is followed by the Upper Serpentine (17 per cent), Nambeelup (11 per cent) and Lower Murray (10 per cent). Nambeelup contributes a disproportionate amount of P for its small size (139 km^2, Table 7-1).

Nutrient load per cleared area

The average annual (2006–15) nutrient loads per cleared area allow the comparison of nutrient export irrespective of catchment size, highlighting those reporting catchments that are exporting high loads on cleared land and could be targeted for management action (Table 7-1).

Table 7-1 Total and cleared area of each reporting catchment showing modelled average annual (2006–15) nutrient loads and nutrient loads per cleared area

Reporting catchment	**Total area**	**Cleared area**	**% Cleared**	**N load**	**N load per cleared area**	**P load**	**P load per cleared area**
	(km^2)	(km^2)	(%)	(t)	(kg/ha)	(t)	(kg/ha)
Peel Main Drain	125	67	54%	12	1.7	1.4	0.21
Upper Serpentine	490	250	51%	72	2.9	10	0.40
Dirk Brook	139	70	50%	29	4.1	2.8	0.40
Nambeelup	139	109	78%	40	3.7	6.7	0.61
Mandurah	24	15	61%	5	3.4	0.5	0.35
Lower Serpentine	100	51	51%	12	2.3	2.1	0.42
Lower Murray	636	294	46%	103	3.5	6.2	0.21
Coolup (Peel)	150	121	80%	21	1.7	2.7	0.23
Coolup (Harvey)	103	70	68%	13	1.9	2.1	0.29
Mayfield	122	100	82%	33	3.3	3.6	0.36
Harvey	553	339	61%	205	6.1	20	0.59
Meredith	53	37	69%	6.7	1.8	1.0	0.28
Serpentine River	1 018	562	55%	169	3.0	23	0.42
Murray River	786	415	53%	124	3.0	9	0.22
Harvey River	832	546	66%	259	4.7	27	0.49
Coastal estuary catchment (plan area)	**2 636**	**1 523**	**58%**	**552**	**3.6**	**59**	**0.39**

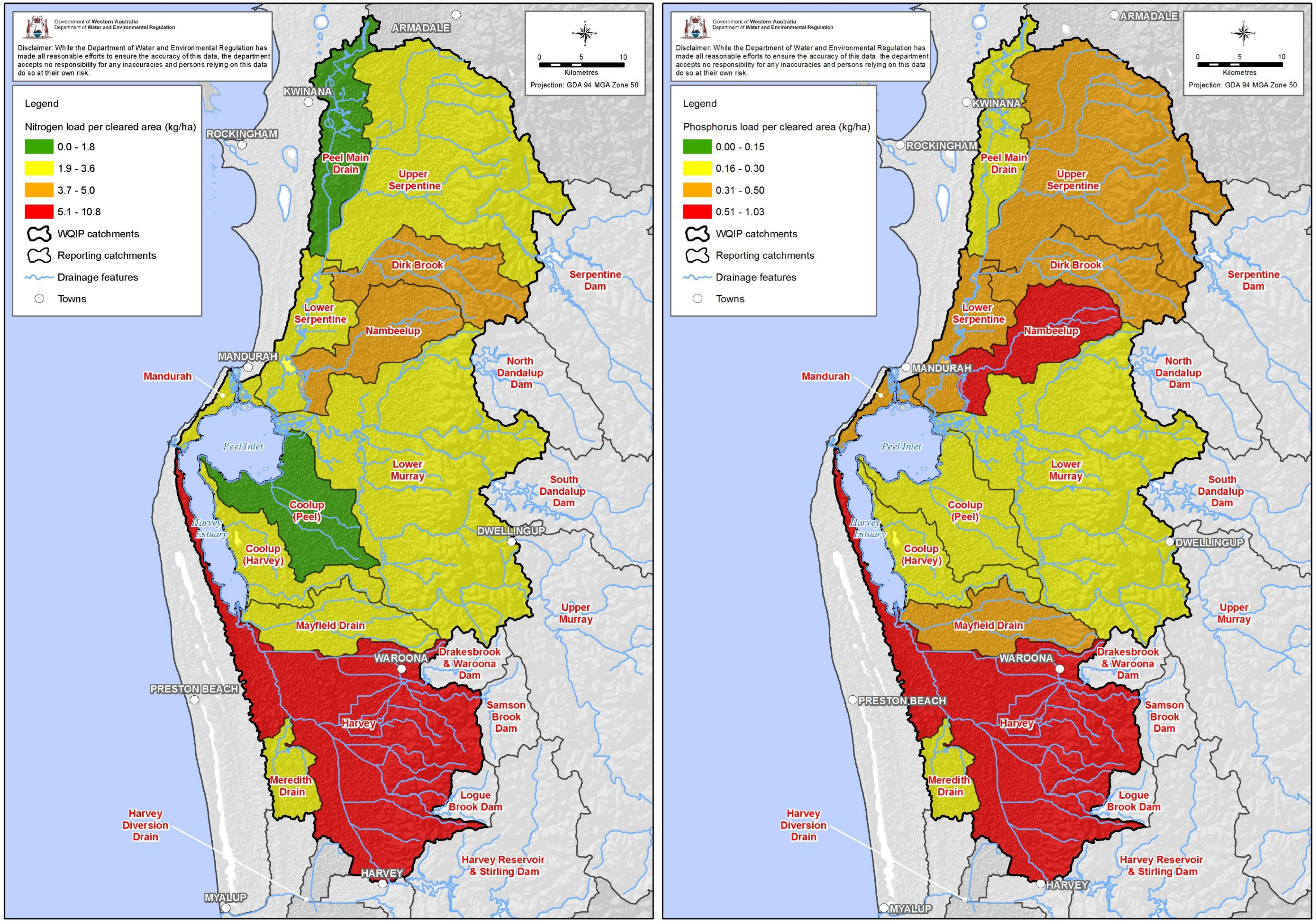
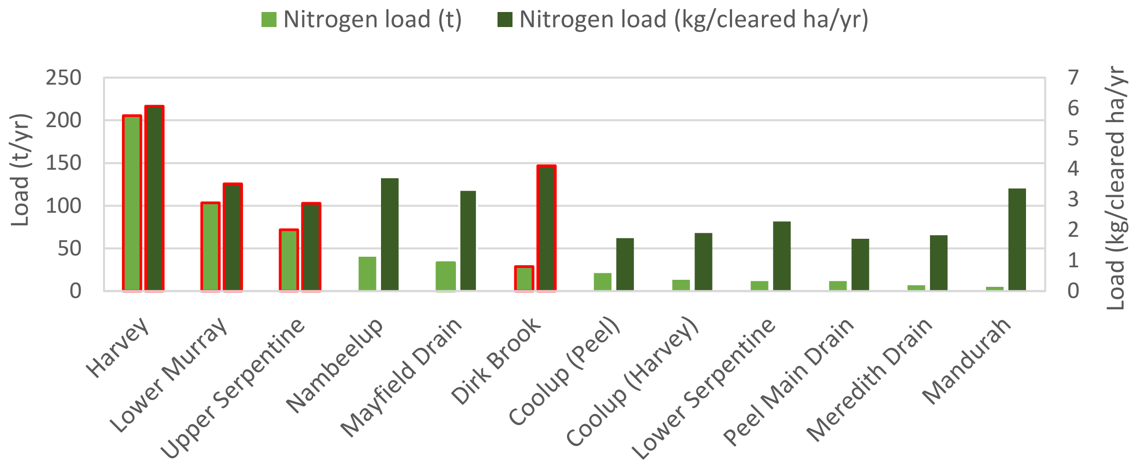


Figure 7-2 Reporting catchment categories based on N and P load exported per cleared area, highlighting the reporting catchments that are disproportionally exporting nutrients



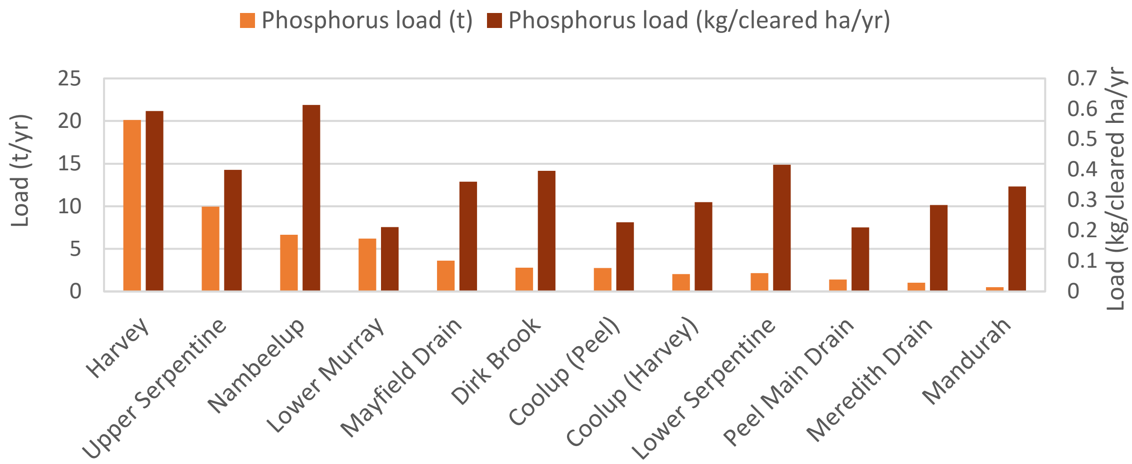


Figure 7-3 A comparison of the average annual (2006–15) nutrient loads and loads per cleared area for each reporting catchment. The red-outlined columns highlight catchments with high measured DIN concentrations (≥14 per cent of TN) and high modelled N loads.

Priority reporting catchments for action

We have prioritised the following reporting catchments for management actions targeting reduction in P export given they have the highest annual P loads, and high P loads per cleared area:

- Harvey
- Upper Serpentine
- Nambeelup
- Lower Murray.

The majority of TN in most reporting catchments is DON (see Section 3.2), the bioavailability of which is unknown (see recommended action 39), and most N-targeting actions are more effective at removing DIN. As a result, we have prioritised reporting catchments that have high modelled N loads and characteristically high measured DIN concentrations, with the Harvey reporting catchment being a clear focus for management actions. Other reporting catchments that have particularly high N loads and high DIN concentrations include Dirk Brook, Upper Serpentine and Lower Murray.

As Harvey is identified as a priority reporting catchment for both P and N reduction, it is an obvious focus for catchment management actions that target both TP and DIN reduction.

Some reporting catchments have very low annual nutrient loads but high loads per cleared area. An example is the Mandurah reporting catchment with its loads predominantly because of septic tanks. While the loads exported from Mandurah are only a small proportion of total loads to the estuary, converting septic tanks to reticulated sewerage would result in an immediate, reliable and ongoing reduction in nutrient loads and a localised improvement in water quality.

Seasonality of nutrient loads

Figure 7-4 shows the average monthly flow and nutrient loads from the Serpentine, Murray and Harvey rivers. All reporting catchments have most (greater than ~90 per cent) of their flow and nutrient load discharged from late autumn to early spring (May–October). Note that the Harvey catchment receives irrigation excess and so has persistent (although small) flows and nutrient loads during the summer months.

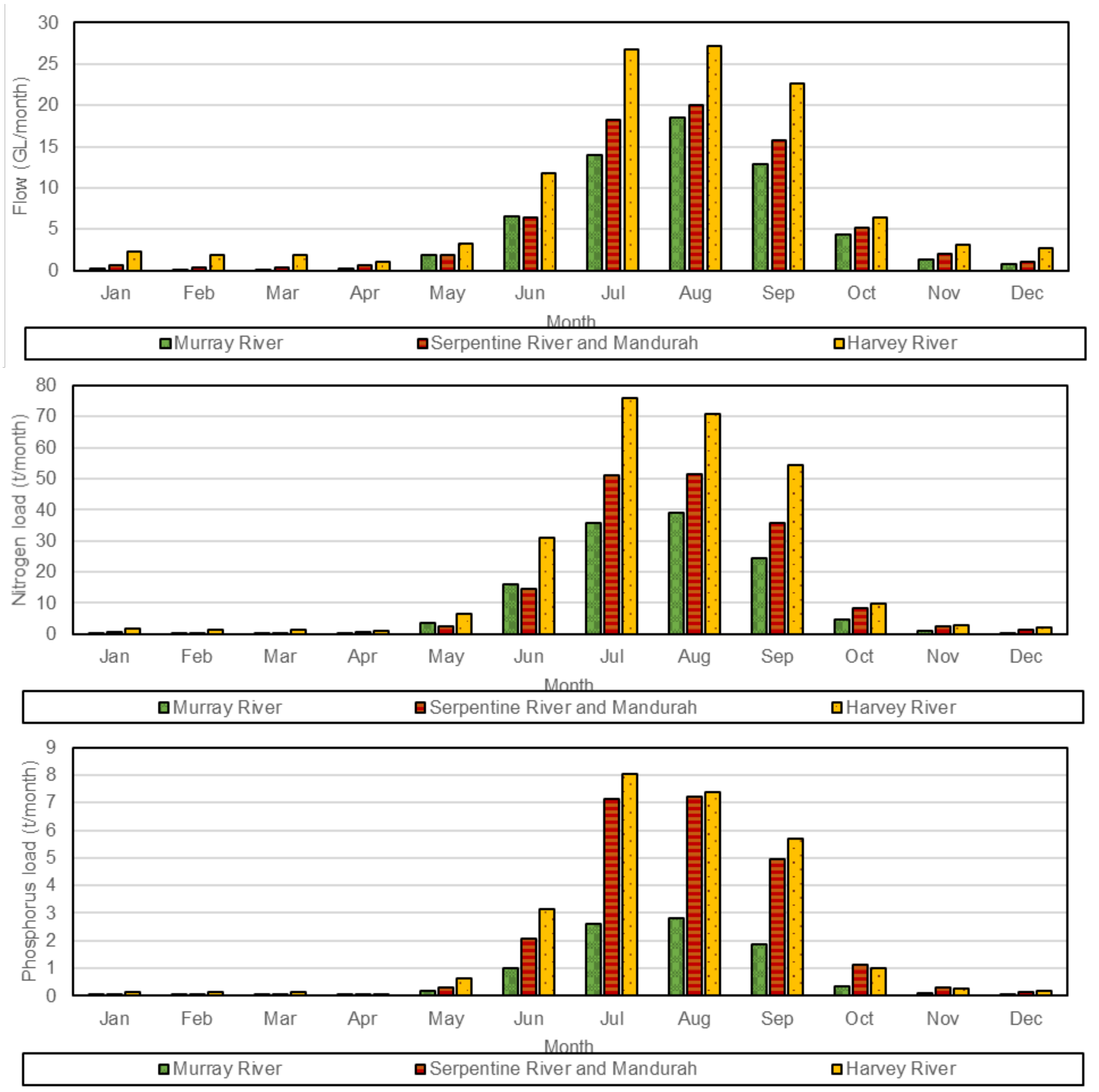


Figure 7-4 Average monthly modelled (2006–15) flow and N and P loads from the major river catchments to the Peel-Harvey estuary (excludes Upper Murray catchment)

7.4 What is the maximum acceptable load?

We calculate the maximum acceptable load for each reporting catchment by multiplying the nutrient concentration defined by WQOs 1 and 2 (Section 4.2) by the average annual flow (2006–2015). The maximum acceptable load to the Peel-Harvey estuary is calculated by summing the maximum acceptable loads across reporting catchments.

maximum acceptable load = target nutrient concentration x annual flow

The reduction in nutrient load required for P and N for each reporting catchment (referred to as the load reduction target) is determined from:

load reduction target = current annual load – maximum acceptable load

Maximum acceptable loads and load reduction targets indicate the scale of intervention required in each reporting catchment to meet the WQOs.

The maximum acceptable nutrient loads across the plan area are 293 t for N and 24 t for P. To achieve these targets, current loads need to be reduced by 259 t for N (47 per cent reduction) and 35 t for P (59 per cent reduction) (Table 7-2). Hence, to achieve the nutrient concentration targets set in the WQOs, the nutrient loads to the estuary need to be roughly halved.

Table 7-2 A comparison of current and acceptable N and P loads for the plan area showing the required reduction (in tonnes and per cent) to meet the maximum acceptable loads

Loads and targets	**Coastal estuary catchment (plan area)**
Nitrogen	
Current load (t/yr)	552
Maximum acceptable load (t/yr)	293
Required load reduction (t/yr)	259
Required load reduction (%)	47%
Phosphorus	
Current load (t/yr)	59
Maximum acceptable load (t/yr)	24
Required load reduction (t/yr)	35
Required load reduction (%)	59%

Table 7-3 shows the current (2006–15) average annual nutrient loads, plus the nutrient reduction required (per cent reduction) to meet the maximum acceptable loads for each reporting catchment. The largest N and P load reductions required are in the Meredith (60 per cent reduction for N, 78 per cent reduction for P) and Nambeelup (69 per cent reduction for N, 84 per cent reduction for P) reporting catchments, but all require large reductions to meet the maximum acceptable N and/or P loads (Table 7-3).

Table 7-3 Average annual flow, nutrient load, flow-weighted nutrient concentrations and nutrient reduction required to meet the maximum acceptable loads for each reporting catchment in the plan area (2006–15)

Reporting catchment	Average annual flow (2006–15) (GL/yr)	Average annual nutrient load (2006–15) (t/yr)	Nutrient reduction required to meet target (%)	Maximum acceptable load (2006–15) (t/yr)
Nitrogen				
Peel Main Drain	6.9	12	29%	8.3
Upper Serpentine	34	72	43%	41
Dirk Brook	13	29	48%	15
Nambeelup	11	40	69%	13
Mandurah	3.2	5.0	23%	3.9
Lower Serpentine	5.3	12	46%	6.3
Lower Murray	51	103	41%	61
Coolup (Peel)	9.5	21	46%	11
Coolup (Harvey)	6.3	13	43%	7.6
Mayfield	15	33	46%	18
Harvey	87	205	49%	105
Meredith	2.3	6.7	60%	2.7
Estuary coastal plain	244	552	47%	293
Phosphorus				
Peel Main Drain	6.9	1.4	51%	0.7
Upper Serpentine	34	10	66%	3.4
Dirk Brook	13	2.8	55%	1.3
Nambeelup	11	6.7	84%	1.1
Mandurah	3.2	0.5	37%	0.3
Lower Serpentine	5.3	2.1	75%	0.5
Lower Murray	51	6.2	18%	5.1
Coolup (Peel)	9.5	2.7	65%	1.0
Coolup (Harvey)	6.3	2.1	69%	0.6
Mayfield	15	3.6	59%	1.5
Harvey	87	20	57%	8.7
Meredith	2.3	1.0	78%	0.2
Coastal estuary catchment (plan area)	**244**	**59**	**59%**	**24**

7.5 Acceptable nutrient input

The statutory *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* requires all government and private activities in the catchment to contribute to reaching water quality targets for the Peel-Harvey estuary system. The purpose of the policy is still relevant after more than 30 years; that is, to “rehabilitate the Estuary and protect the Estuary from further degradation”.

Broadscale hydrological and nutrient modelling of the catchment (Hennig et al. 2021; Kelsey et al. 2011) showed that to achieve acceptable N and P export rates, on average the amount of N and P applied (including fertiliser, animal feed, imported livestock, N fixation) to cleared land across the plan area should be no greater than:

- 45 kg N/cleared ha/year
- 6.5 kg P/cleared ha/year.

Proponents should demonstrate adherence to the above interim input nutrient rates in planning proposals and development applications which involve the application of nutrients. These input nutrient rates are considered restrictive to many traditional forms of intensive animal industries or horticulture. Appropriate siting of such land uses within the catchment should be carefully considered.

We are currently undertaking finer-resolution modelling to accurately determine appropriate nutrient input and export rates for individual lots with different land uses, soils and locations.

7.6 Sources of nutrients in the catchment

After native vegetation, the primary land use within the plan area is beef farming (41 per cent) followed by a mixture of dairy, mixed grazing, horses, intensive animal use, lifestyle blocks, industry/manufacturing/transport, viticulture, residential, recreational and offices (Figure 7-5). These broadscale land uses are diffuse sources of nutrients, with nutrients entrained in runoff from the catchment, or infiltrated to groundwater. See Appendix J for further information on the spatial coverage of each land use category and corresponding estimates of nutrient exports from each of the three major river catchments.

In addition to diffuse sources, point sources of nutrients in the plan area need to be considered (Figure 7-6). Point sources are concentrated discharges at a single location from land uses such as feedlots/stockyards, piggeries, abattoirs, poultry farms, industry, wastewater treatment plants (WWTPs) and dairy sheds. Although point sources make up a negligible portion of the plan area, the nutrient loads they export can be significant. Point sources can also have significant localised impacts on water quality which may not be identified when looking at total loads across a reporting subcatchment.

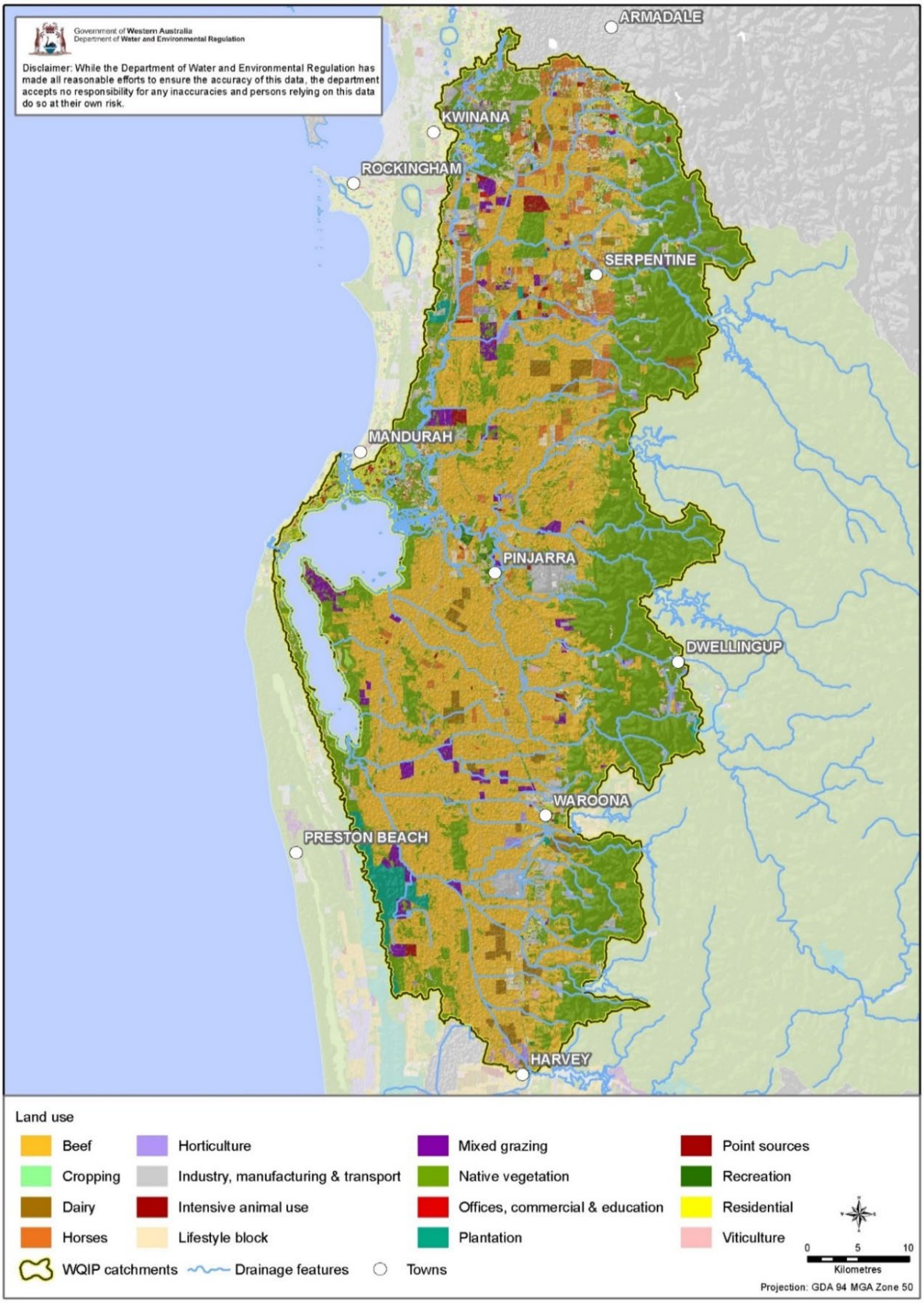


Figure 7-5 Land uses in the plan area (excludes point sources)

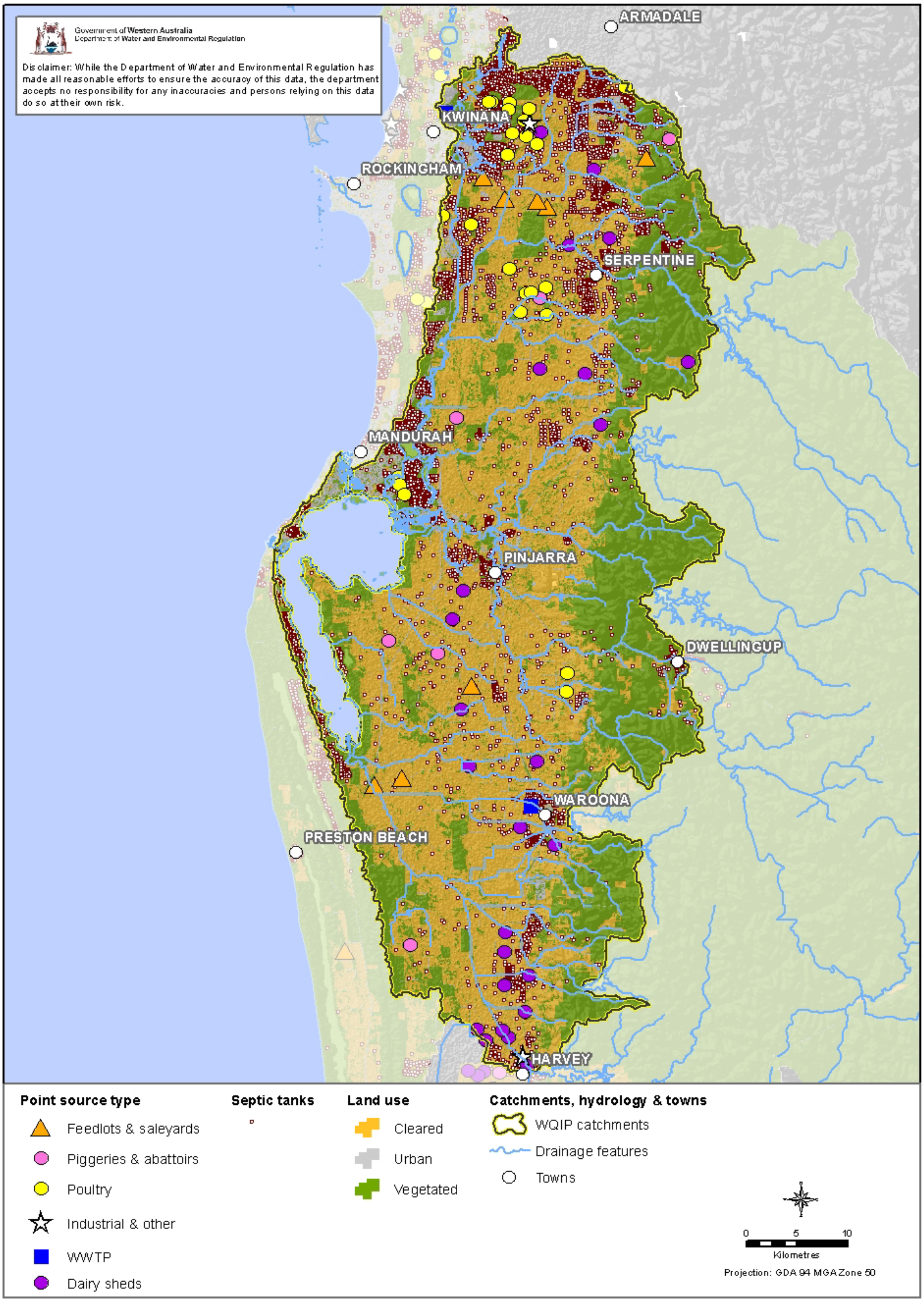


Figure 7-6 Point sources of nutrient export in the plan area

An isotope study (Wells et al. 2019) conducted as part of the ARC Linkage project *Balancing estuarine and societal health in a changing environment* (Valesini et al. 2019b) found that the key sources of N were diverse and included leaching from agricultural soils, effluent from WWTPs, urban storm drains and industrial sources. Earlier work established that the main origin of P to the Peel-Harvey estuary was fertiliser that had accumulated in soils and manures (from grazed plants) which was washed off or leached to surface waters (Gerritse and Schofield 1989, Ruprecht and George 1993). These results support the findings of Hennig et al. (2021), discussed below.

Land uses in the plan area that are contributing to the nutrient loads in the Peel-Harvey estuary are shown in Figure 7-7. See Appendix K for a breakdown of land uses in each reporting catchment (which will be useful for implementation planning at that smaller scale).

A large portion of plan area (41 per cent) is used for beef farming and this land use is responsible for a disproportionate amount of N (71 per cent) and P (68 per cent) entering the estuary. Beef farming has poor nutrient-use efficiency (~10 per cent of the nutrients applied to the land are converted into ‘product’) (Hennig et al. 2021) and a high nutrient surplus rate (a high proportion of the nutrients are stored in soil or plant material or lost from the land). In addition, farming is often undertaken in areas of the Swan coastal plain with low phosphorus retention index (PRI) soils that are frequently inundated in winter. These factors combine to make beef farming the largest exporter of nutrients to the Peel-Harvey estuary.

Other major contributors of P to the estuary are dairy (8 per cent) and horticulture (7 per cent). Land uses contributing significant amounts of N to the waterways are dairy (8 per cent), intensive animal use (4 per cent), septic tanks (4 per cent) and horses (3 per cent). Septic tanks only make up 4 per cent of the N load and 3 per cent of the P load reaching the estuary; however, on a reporting catchment scale, septic tanks are estimated to account for 32 per cent of the Lower Serpentine N load and 62 per cent of the Mandurah N load. Although dairy farms only take up about 2 per cent of the land area, they contribute an estimated 8 per cent of both N (43 t) and P loads (5 t) reaching the estuary.

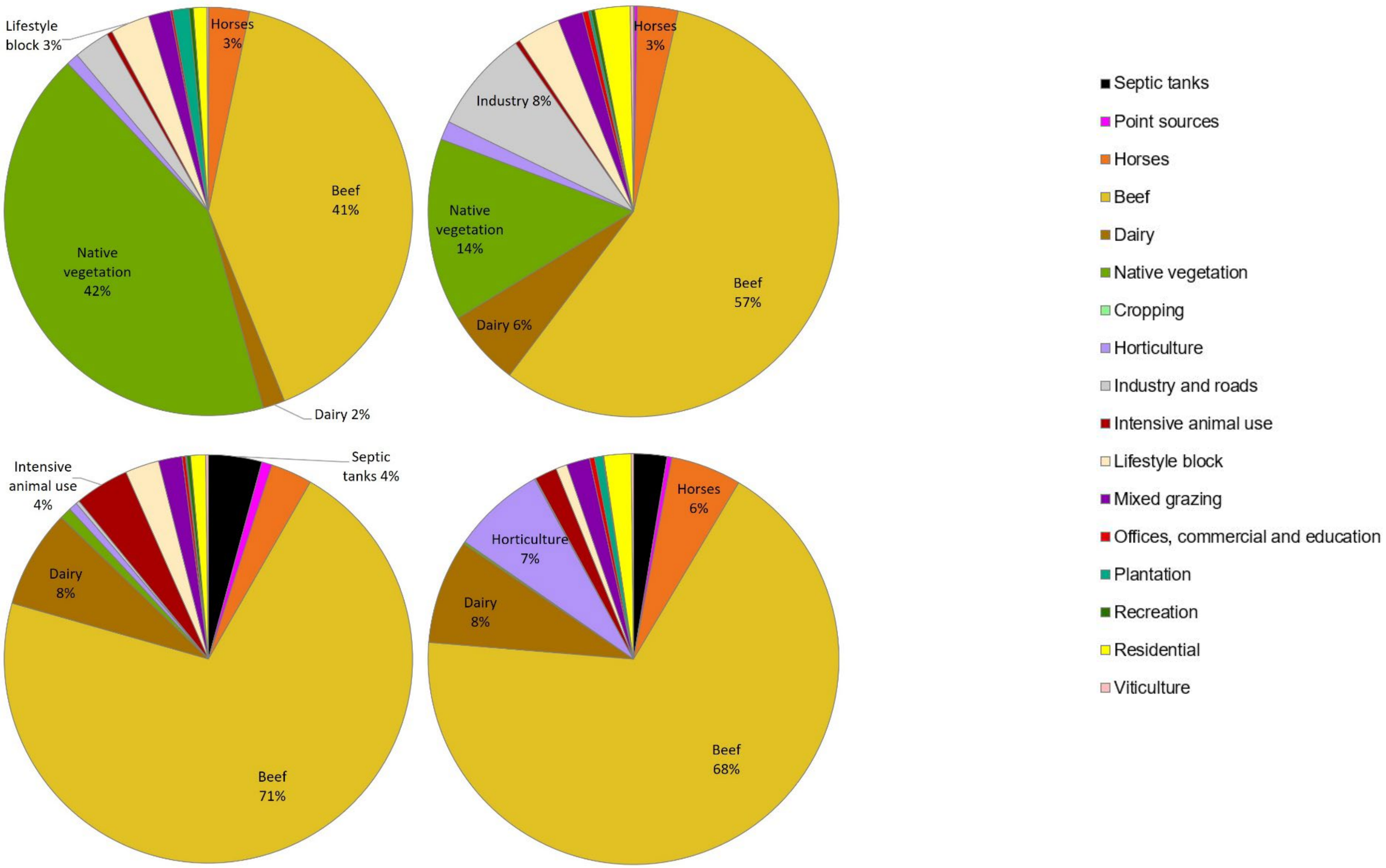


Figure 7-7 Relative contribution of each land use to the area, annual flow, and annual nutrient loads to the estuary for all reporting catchments in the plan area

Intensive animal industries (piggeries, abattoirs, poultry, feedlots and stockyards) are estimated to contribute less than 5 per cent of the P and N load across the plan area. However, in some reporting catchments, this land use makes up a much larger proportion of the load, which may lead to localised impacts. For instance, about 14 per cent of the N load and 17 per cent of the P load from the Meredith reporting catchment originates from a piggery. Working with this piggery to employ best-practice effluent management could result in a significant reduction in exported nutrients.

WWTPs and industrial and composting facilities are estimated to contribute less than 1 per cent of the P and N load reaching the estuary and are therefore low priority on a whole-of-catchment scale. However, best-practice management of nutrient discharges from these facilities is still important and encouraged.

For the priority catchments identified in Section 7.3, the major sources of N and P are shown in Table 7-4.

Table 7-4 Main sources of P in catchments that are prioritised for management action to address P export

Priority reporting catchment	Main sources of P
Harvey	beef (75 %), dairy (13 %), horticulture (4 %)
Upper Serpentine	beef (40%), horticulture (21%), horses (21%)
Nambeelup	beef (76 %), dairy (16 %), horses (5 %)
Lower Murray	beef (87%), horticulture (4%)

Table 7-5 Main sources of N in reporting catchments that are prioritised for management action to address N export

Priority reporting catchments	Main sources of N
Dirk Brook	beef (54 %), intensive animal use (15 %), horses (13%), dairy (10%)
Harvey	beef (78 %), dairy (14 %)

Beef farming and dairy farming are the largest contributors of nutrients to the estuary. Without substantial changes to fertiliser and land management in these industries, it will not be possible to significantly reduce the load of nutrients originating from the catchment. Other priority land uses include intensive animal use, horses, mixed grazing, horticulture and septic tanks (Table 7-4). See the recommendations for how this can be achieved in Section 9.

8 Predicted impact of future pressures on nutrient loads

The department used the Peel-Harvey Catchment Model to predict future nutrient loads to the estuary as a result of climate change (see Section 8.1) and urban and agricultural expansion (see Section 8.2) in the catchment.

The modelled scenarios are compared with the basecase period (2006–15) and either use the same or modified model inputs (e.g. land use, climate), depending on the scenario. Results are presented as the average annual nutrient loads that would eventuate once the full impact of the scenario is apparent.

8.1 Climate change

The climate in the south-west of Australia is drying. It is experiencing some of the most profound impacts of climate change not just in Australia (Government of Western Australia 2021b) but also the world (McFarlane 2005). Rainfall in the south-western Australia has declined since the 1970s, particularly during autumn and early winter. Further decreases in annual, winter and spring rainfall are projected with high confidence (Government of Western Australia 2021b).

By 2050, it is projected that annual rainfall in the plan area will reduce by up to 25 per cent and that annual potential evaporation will increase by 3 per cent, compared with the modelled basecase for 2006–15 (Hennig et al. 2021) using a dry scenario.[27] It is estimated that this will result in a 47 per cent decrease in river flow and a 53 and 55 per cent reduction in N and P annual loads respectively. The annual flow in the Meredith reporting catchment is predicted to be most affected by climate change, with the reduction in average annual flow a staggering 64 per cent (Hennig et al. 2021).

Compared with the climate period of 1961–90, the estuary post-2000 has less freshwater inflow (Charles et al. 2019), which has further increased marine influences on the estuary (Valesini et al. 2019a). The continuing increase in evaporation, plus reduction in freshwater inputs and nutrient loads, will lead to the estuary being more marine influenced and saltier for longer than under the current climate regime. Reduced runoff in winter may not allow for sufficient flushing of the river systems and will likely result in higher nutrient concentrations and longer residence times for nutrients in the waterways and estuary, which can lead to adverse impacts on the aquatic ecosystems.

[27] The Peel-Harvey Catchment Model was based on the dry scenario (Coupled Model Intercomparison Project Phase 5). Climate change projections were applied by using a 30-year monthly average per cent change to rainfall and potential evapotranspiration (relative to a baseline period of 1981 to 2010) – a suitable method to estimate the average impact of future climate change on the estuary. The National Hydrological Projections recently developed by the Bureau of Meteorology (BoM 2022) project similar declines in rainfall in the plan area (Australian Water Outlook).

Hipsey et al. (2019) found an increase in water residence time attributed to reduced flows associated with climate change in the Peel-Harvey estuary. Even though there will be less flow and nutrients being delivered to the estuary, the drying climate means warmer temperatures which – in combination with longer nutrient resident times – will likely lead to favourable conditions for algal blooms.

The coupled estuary-catchment model will be adapted to better understand the estuary response to climate change and to inform management decisions.

8.2 Future urban and agricultural development to 2050

The Peel region is continuing to grow rapidly: by 2050 the South Metropolitan Peel subregion is expected to rival the South West as one of the most populated regions outside of Perth, with a projected population of 1.26 million (WAPC 2018b).[28] The enormous urban growth predicted for the Peel region, together with the associated intensification of agricultural activities in the catchment, makes it vital that future nutrient loads to the Peel-Harvey estuary are managed carefully.

Impacts of future urban expansion

A 'future urban area' was modelled based on various planning spatial datasets from the Department of Planning, Lands and Heritage (2017 to 2018 datasets) and Department of Planning (2014 to 2015 datasets) – see Hennig et al. (2021) for full details. This future urban area comprised about 19,000 ha of currently undeveloped land zoned for urban, industrial, rural residential and nature reserves (termed zoned undeveloped), or land that may be rezoned to account for planned urban expansion to 2050. In modelling the 'future urban area', cleared farmland was replaced with urban, industrial, rural residential or public open space (Figure 8-1) with most of this land being in the Peel Main Drain, Upper Serpentine, Nambeelup, Lower Serpentine, Lower Murray and Harvey reporting catchments.

[28] Population prediction includes City of Gosnells but not Shire of Harvey, otherwise cities and shires overlap consistently with the plan area.

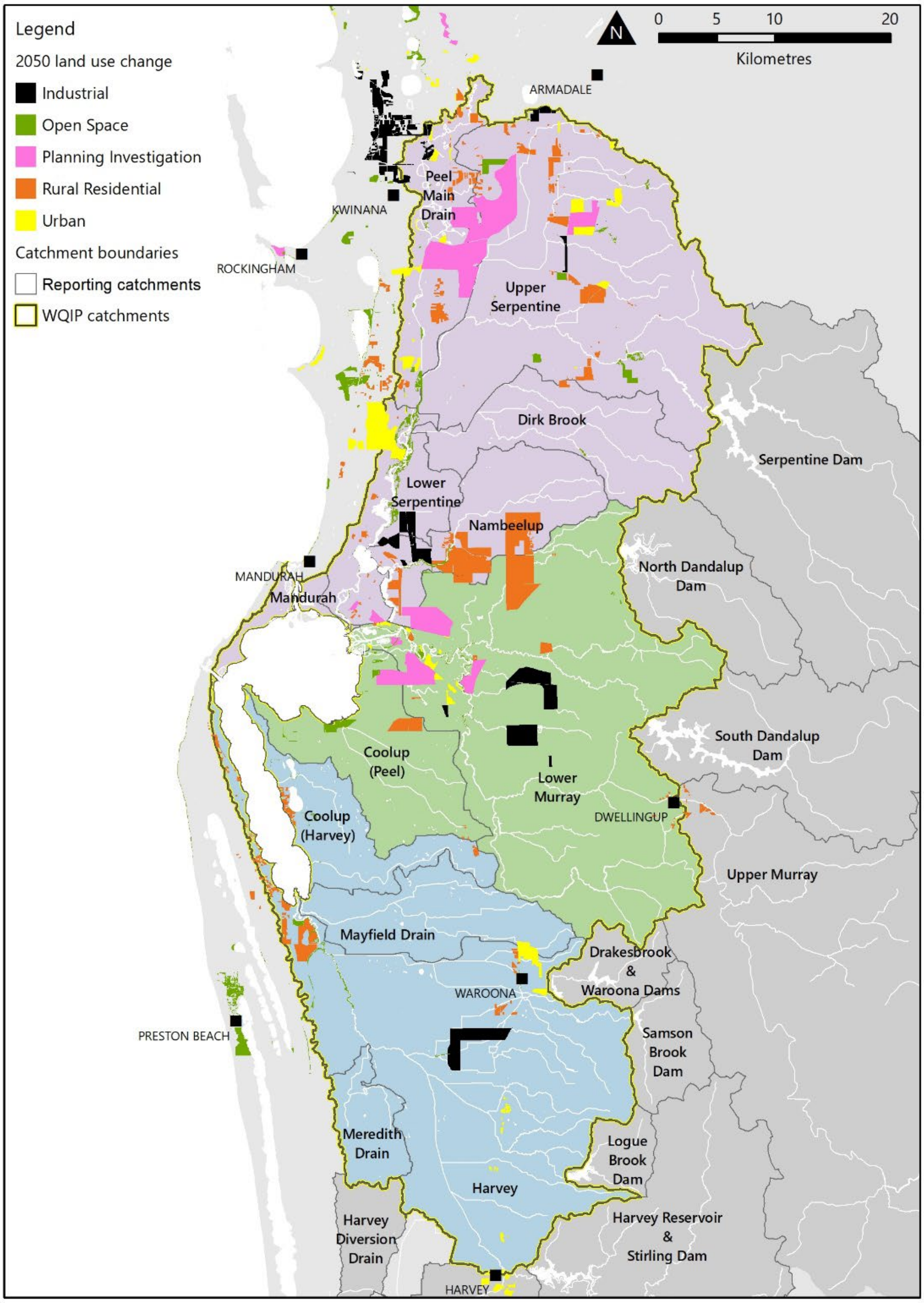


Figure 8-1 Areas identified and converted within the model as areas of future urban and industrial expansion to 2050

Urban development generally increases runoff because of the introduction of large areas of impervious surfaces and the removal of deep-rooted vegetation. This is demonstrated by modelling urban expansion with traditional drainage; that is, no water sensitive urban design (WSUD), which finds that average annual flow is predicted to increase by 7 per cent (to 16.6 GL/yr). Given that all new urban developments in the Peel-Harvey catchment now incorporate WSUD, this represents a worst-case scenario in which post-development hydrology is not managed to maintain pre-development hydrology.

It was predicted that average annual nutrient loads following urban expansion would be unchanged or decrease. P loads were estimated to decrease by 0.2 to 3.5 per cent per year and N loads by 0.4 to 3.1 per cent per year, depending on the extent of WSUD implemented during development. Nutrient reductions predicted in this scenario can be attributed to the associated reduction in beef farming area (and other agricultural land uses) which generally have higher nutrient exports than urban development with WSUD. However, in the summer months, small rain events will produce outflows in urban landscapes because of the higher area of impervious surfaces compared with rural areas. The contribution to nutrient load from urban areas because of rainfall events can, therefore, be significant during summer.

Impacts of future agricultural development

Annual horticulture has extremely high P input requirements (Figure 8-2), an order of magnitude higher than dairy inputs and 20 times higher than beef inputs, as recorded in surveys undertaken by DPIRD on the Swan coastal plain (Weaver et al. 2008). This land use, along with turf farms, has the largest rate of P surplus of the agricultural land uses. Where annual horticulture is a dominant land use in the South West, a high potential for environmental threat to waterways may exist (Ovens et al. 2008).

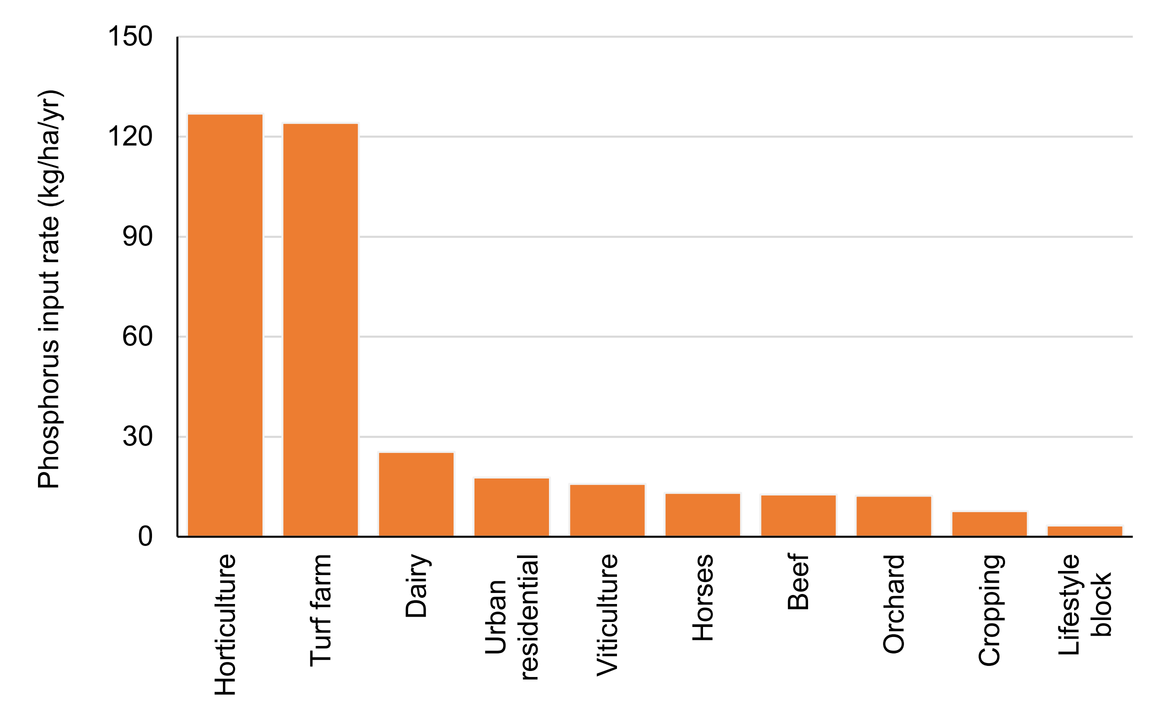


Figure 8-2 Phosphorus input rate for various land uses in the plan area

It is likely that agriculture will intensify in the Peel-Harvey catchment in the future. It is imperative that intensification only occurs in areas with suitable site and soil characteristics, where proponents can demonstrate that they can meet the nutrient input rates to achieve the maximum acceptable nutrient loads to the estuary (see Section 7.5). Proponents should also adhere to relevant state policy, including consistency with the *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a), *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) and local government policies.

The Nambeelup catchment was at the centre of a study led by DPIRD to assess the feasibility of intensifying agricultural productivity in the Peel region, as part of the Transform Peel program (Peel Food Zone).

Most of the soils in the Nambeelup catchment are low PRI with other landscape characteristics that promote offsite nutrient export. The Nambeelup catchment requires the greatest load reductions of all reporting catchments that drain to the estuary (69 per cent reduction for N and 84 per cent for P). Soil amendments including subsoil clays (where locally available) or suitable mining by-products (with consideration given to regulations) have been shown to improve P holding capacity and reduce nutrient losses from agriculture. However, some land uses, such as in-ground irrigated horticulture, require such large applications of P that the long-term risk of P export cannot be mitigated by soil amendment (Summers et al. 2020).

Analysis of land capability for the Peel Food Zone, conducted by DPIRD as part of the PIWI (GHD 2017), confirmed that most of the soil types in the Peel Food Zone study area (proposed around the Nambeelup catchment) were unsuitable for irrigated in-ground agriculture because of high nutrient export risks. In addition, it was determined that insufficient surface and groundwater was available to sustain long-term agricultural activities in that area. As a result of this study, intensification of agriculture in this area would need to involve substantial technological innovation to avoid nutrient loss to the rivers and estuary. An example of this type of innovation is the Eden Towers solar-powered vertical farm[29] – an Australian first, to be situated in the Peel Business Park as part of its Growing Bush Foods program.

Modelling demonstrates the impact of a conversion to in-ground horticulture in an area such as Nambeelup. It was predicted that if 3,000 ha of land were to change from beef farming to annual, in-ground horticulture, P loads from the Nambeelup reporting catchment to the estuary would increase from 7 t/yr to 29 t/yr – an increase of 336 per cent. Under this scenario, Nambeelup reporting catchment would become the second-largest contributor of P to the estuary and this would lead to an estimated total increase in P loading to the estuary of about 38 per cent. N loads from the Nambeelup reporting catchment were also predicted to increase from 40 t/yr to 154 t/yr – an increase of 282 per cent. This would lead to an estimated 114 t (21 per cent) increase in N load reaching the estuary.

[29] Media statement: Peel RED Grants diversifying regional economies

This modelled scenario illustrates how converting even small areas (about 1 per cent of the Peel-Harvey estuary coastal plain catchment) to high-nutrient-export land uses, such as in-ground horticulture, can have huge implications. Clearly, this type of agricultural intensification would not align with the objectives of the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*, or those of the 2008 WQIP (EPA 2008b) or this WQIP.

The PIWI found that if developers were to remove nutrient-rich drain water from the system, nutrient loads reaching the estuary would decrease by a maximum of about 1 per cent (Hennig et al. 2018).[30] Abstraction of high-nutrient drain water may have localised impacts on waterways and drains, but this needs further investigation. The potential exists for environmental benefits by reducing the nutrient load entering the Serpentine River. However, nutrient concentrations would remain high and continue to be an environmental stressor. In addition, reductions in flow must be considered both in the context of environmental water requirements and increased residence times for nutrients in the Serpentine River.

Planning proposals for agricultural developments or changes to agricultural land uses in the estuary coastal plain catchment should adhere to relevant state policies, including consistency with the *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a), *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b), and local government policies. Proposals will also need to demonstrate that they can meet the nutrient input rates so as to achieve the maximum acceptable nutrient loads to the estuary (see Section 7.5), with the risks of non-nutrient contamination of the surface water or groundwater appropriately managed.

[30] Abstracted high-nutrient water is likely to require treatment before use, and careful consideration would need to be given to the disposal of wastewater from this treatment process so as not to impact on the estuary.

Pesticide use in horticulture

Modern agricultural systems often rely heavily on chemical means of pest control (i.e. insecticides, herbicides, fungicides) to protect crops from pests, weeds and disease. If these chemicals, which can have high persistence, migrate offsite they may contaminate surface water, soils and/or superficial groundwater and can be toxic to aquatic organisms (Kookana et al. 1998, Nice et al. 2009, Allinson et al. 2014). Pesticide use in horticulture has been linked to impacts on water quality and aquatic biodiversity in receiving waterways (Mac Loughlin et al. 2022).

The best-practice use of pesticides will minimise export offsite and generally pose a minimal risk of adverse impacts on the environment. See the DPIRD and DoH websites (www.agric.wa.gov.au and www.health.wa.gov.au) for guidance on appropriate pesticide use in Western Australia.

In addition to encouraging best-practice use, this WQIP recommends that a short-term monitoring program be undertaken to identify pesticide contamination in the Peel-Harvey estuary coastal plain catchment. Data should be collected seasonally from representative surface water, superficial groundwater and sediment sites across the agricultural areas over a year.

Closed agricultural systems

Closed agricultural systems – such as fully autonomous, vertical smart farms where plants are grown in a closed and controlled environment (Figure 8-3) – may provide a viable alternative for the vast areas of the catchment unsuitable for conventional in-ground horticulture. It has been suggested that closed agricultural systems are capable of being engineered to have environmentally acceptable or zero nutrient emissions to the environment (Safstrom & Short 2012). However, to date no reviews of such case studies have been found in the scientific literature. The work by Haine et al. (2011) suggests that offsite nutrient losses may still occur, even when effluent recycling systems are used.

Innovative research and trials could investigate how closed agricultural systems might be engineered to ensure nutrient discharges are below acceptable nutrient input rates (Section 7.5) and to manage the risks of non-nutrient contamination of the surface water or groundwater in the coastal estuary catchment. Innovative agricultural systems will need to show economic viability (when rolled out at scale) and be compatible with the available water quantity and quality. Viable methods to dispose of solid and liquid wastes are needed to ensure that nutrient-rich wastewater and brine are not exported to the estuary. Strategic co-location or collaboration with other industries that have use for such by-products (i.e. brine or wastewater) may be advantageous and achievable through clever planning.

This is a future direction for agricultural intensification in the coastal estuary catchment that is worth exploring, and it could potentially lead the way for next-generation environmentally responsible agriculture in Western Australia. The establishment of the Western Australian Food Innovation Precinct within the Peel Business Park represents a unique opportunity to head in this direction.[31]

Figure 8-3 Vertical, automated smart farms may be a potential way to achieve closed agricultural systems on the Swan coastal plain. United States agri-tech startup company Iron Ox have developed a fully autonomous vertical farm in California. (Photo credit: 311 Institute)

[31] Food Innovation Precinct WA

9 Management actions to improve water quality

This chapter discusses the management actions that have strong potential to improve water quality in the plan area and makes recommendations for implementation based on good science, costs and benefits and many decades of practical experience. Management actions range from policy setting to on-ground works and may apply to lot to catchment scale. Where practical, we have modelled the management actions using the Peel-Harvey Catchment Model to quantify their predicted long-term impacts on nutrient export to the estuary. Many of the recommended actions reflect those in the *Bindjareb Djilba Protection Plan* (DWER 2020b), but this WQIP focuses more on catchment management, supporting evidence and guidance for implementation, and provides some additional actions.

Implementing the recommended actions will reduce the loss of nutrients, organic matter and sediments from the catchment and move us closer to achieving the WQOs and management goals, thereby protecting the defined community values into the future (Chapter 4).

The recommended actions aim to achieve this by seeking to minimise or prevent the export of nutrients and other contaminants from:

- existing urban and agricultural land uses – using on-ground catchment management actions
- future land use changes or developments – using measures to ensure State Government and local government policies effectively protect water quality.

The recommended actions are presented at the start of relevant discussions throughout Chapter 9, and are grouped into five key areas:

- catchment management actions (Section 9.1)
- planning and policy actions (Section 9.2)
- actions to partner with Bindjareb Noongar people to look after the estuary and rivers (Section 9.3)
- actions to assess water quality condition and measure progress (Section 9.4).
- coordinating action (Section 9.5).

See Table 9-5 towards the end of this chapter (Section 9.6) for a list of all the recommended actions.

9.1 Catchment management actions

Most of the nutrients we measure in the waterways and drains of the Peel-Harvey estuary system are a result of land management practices in the catchment. Land management practices that minimise degradation to the surrounding environment are known as best-management practices (BMPs). BMPs build on established knowledge with current science and technology and evolve over time. In an agricultural setting, implementing BMPs allows the farm to remain economically viable while minimising nutrient losses to the receiving environment.

Many management actions of the 2008 WQIP (EPA 2008b) are based on BMPs which remain relevant today and are common to other WQIPs developed for south-western Australian estuaries, such as the Leschenault Estuary WQIP (Hugues-dit-Ciles et al. 2012) and Vasse Wonnerup wetlands and Geographe Bay WQIP (Government of Western Australia 2010).

This section outlines the recommended catchment management actions (most based on BMPs) to reduce nutrient loads to the Peel-Harvey estuary. Many of the on-ground actions target the major land uses in the catchment. Some actions are aimed at working with farmers to improve management of agricultural nutrients from both diffuse and point sources, while others are aimed at reducing urban nutrient export. Larger-scale catchment actions aim to protect the natural environment and encourage revegetation and restoration.

Where possible, we estimated the potential effectiveness of a management action using the Peel-Harvey Catchment Model. However, not all management actions lend themselves to quantitative modelling of their effectiveness in reducing nutrient loads – whether because of insufficient data or additional benefits beyond nutrient reduction that would skew comparison. The unmodelled management actions that are important tools for improving water quality in the Peel-Harvey estuary are also discussed in this section but are not compared quantitively across reporting catchments.

We modelled 11 catchment management actions to provide quantitative comparison of potential reductions in estuary nutrient loads (Hennig et al. 2021). Modelling revealed that no single management action was sufficient to achieve the target nutrient load reductions for the estuary – thus a ‘treatment train’ is the best approach (Figure 9-1).

Modelled predictions are based on full implementation of the management actions, and so we consider them a best-case outcome. The results for each modelled action are reported as the average annual nutrient loads predicted to eventuate once the full impact of the management action is realised (post-lag period). These loads are presented at a reporting catchment scale and compared with the average annual nutrient loads for 2006–15 (Hennig et al. 2021).

See Appendix L for more information on most of the catchment management actions. See Hennig et al. (2021) for modelling methods, assumptions and further results, plus a compendium of relevant literature for each modelled management action.

The ‘treatment train’ approach

To address nutrient (and non-nutrient) pollution in a catchment, a ‘treatment train’ approach is often needed, where a combination of management actions are designed to work together to effectively achieve the water quality objectives (North

Carolina State University 2000). The management actions are implemented either concurrently (in parallel) or sequentially (one after another) in the catchment to:

- minimise generation of pollutants at source, including improvements to land use planning to minimise the impacts of polluting industries
- disconnect pollutant transport pathways (in transit)
- capture or treat pollutants before they reach the main drain or receiving waterbody (end-of-pipe).

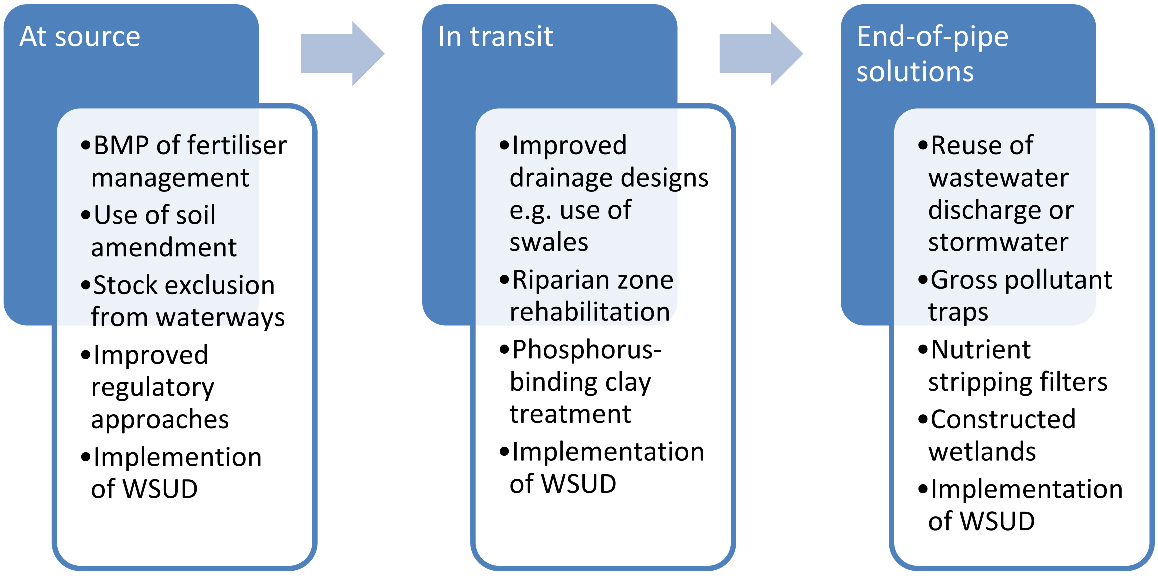


Figure 9-1 The 'treatment train' approach, with examples of at-source, in-transit and 'end of pipe' nutrient management actions, noting that some actions can be relevant to all three, such as implementation of WSUD

The Peel-Harvey Catchment Model also helped to identify which reporting catchments to target for management actions, as well as the extent of implementation required to adequately address nutrient loads. Where appropriate, we have identified reporting catchments for each catchment management action and indicated where to start.

We have divided the catchment management actions into those that target:

- diffuse nutrients from agricultural areas (page 154)
- point sources of nutrients from agricultural areas (page 173)
- diffuse nutrients from urban areas (page 179)
- point sources of nutrients from urban areas (page 183)
- nutrients and other contaminants within waterways and drains (as distinct from treatment at source, page 189)
- other water quality and biodiversity outcomes (page 192).

As most of the nutrient inputs to the estuary originate from diffuse agricultural sources (Section 7.6), the WQOs can only be met with broadscale changes to land management across the catchment's agricultural areas. While all actions are important both individually and cumulatively, investment in actions that reduce diffuse agricultural sources of nutrients are a priority.

Nutrient load reductions from diffuse sources are inherently difficult to measure and there is often a lag between the management change and the related improvement in water quality in the downstream waterbody. In the plan area's agricultural lands, this lag period may range from years to decades.

Across the plan area, point sources contribute proportionally less to nutrient loads than diffuse sources. However, water quality in local waterways can be highly impacted by point sources which, if mitigated, will result in noticeable improvements to local water quality and contribute to overall load reductions. In addition, management actions that address point sources result in an assured, immediate and sustained reduction of nutrients.

Determining 'where to start' for modelled management actions

As for previous WQIPs for estuary systems in the South West, the WQOs for nutrients are expressed in terms of total nitrogen (TN) and total phosphorus (TP). The department's hydrological and nutrient model is also based on TN and TP. While this approach gives broad information about the sources of nutrients and predicted outcomes of modelling scenarios, a finer resolution analysis that considers nutrient species would help to identify priority areas for management actions.

Much of the N in the tributaries of the Peel-Harvey estuary is in dissolved organic form (DON, see Section 3.2) and its bioavailability for algal growth is unknown. In contrast, dissolved inorganic nitrogen (DIN) species (nitrate and total ammonia) are highly bioavailable and strongly linked to eutrophication.

Until we have a better understanding of the bioavailability of DON across the catchment (recommended action 39, Section 9.4), we have focused on those catchments where large reductions in DIN concentrations are achievable. N-targeting management actions should be applied in catchments with high monitored concentrations of DIN, high modelled N loads and large predicted load reductions under that management scenario.

Filterable reactive phosphorus (FRP) is highly bioavailable and generally makes up a large proportion of the TP across the catchment (22–88 per cent, 2018 data) (DWER 2021a). Therefore, P-targeting catchment management actions should be applied to reporting catchments that have high TP concentrations and high predicted P load reductions under modelled scenarios.

Dissolved organic phosphorus (DOP) likely has low bioavailability for algal growth. This identified research need is also captured in recommended action 39.

Improved management of diffuse agricultural nutrients

Optimal fertiliser use in beef and dairy grazing

1. Recommended action

Reduce P fertiliser losses by optimising fertiliser use to agronomic requirements, as determined by soil testing, agronomic advice (or DPIRD's nutrient calculator) and demonstration trials.[32]

Where to implement? All reporting catchments except Mandurah.

Where to start? All areas with low PRI soil adjacent to drains, waterways and the estuary with a strong focus on Harvey and Nambeelup.

2. Recommended action

Continue to develop and use fertiliser products that meet the needs of farmers on sandy coastal soils, as indicated by soil and plant tissue testing, including slow-release phosphorus fertilisers.

Where to implement? All reporting catchments except Mandurah and Peel Main Drain.

Where to start? Harvey and Nambeelup.

3. Recommended action

Reduce losses of N by working with farmers to encourage best-practice application of N fertilisers.[33]

Where to implement? All reporting catchments except Mandurah and Peel Main Drain.

Where to start? Harvey and Dirk Brook.

Beef and dairy farms are the largest contributors of nutrients to the Peel-Harvey estuary. Cattle for beef contributes 68 per cent of P loads (40 t) and 71 per cent of N loads (393 t), while dairy contributes 8 per cent of both P (4.9 t) and N loads (43 t) to the estuary (Section 7.6). Much of the nutrient surplus from the fertiliser used is

[32] See DPIRD Phosphorus for high rainfall clover pastures in Western Australia; and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

[33] See DPIRD Nitrogen for high rainfall pastures in Western Australia and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

transported via surface runoff and groundwater leaching into waterways, drains and ultimately the estuary.

The use of fertiliser on beef and dairy farms is the largest source of nutrients entering the estuary from the catchment.

Best-practice fertiliser management involves ensuring that the soil pH is adjusted before fertiliser application and using the ‘four Rs’ of nutrient stewardship to reduce fertiliser wastage and nutrient export:

- Use the ‘**R**ight source’ of fertiliser to match the needs of the crop and the soil conditions. Undertake soil testing to determine the soil type and nutrient status; if P fertiliser is needed; for example, use a slow-release P fertiliser.[34]
- Apply fertiliser at the ‘**R**ight rate’, so that the amount matches the needs of the crop and the production targets of the enterprise. Undertake soil and plant tissue testing and consult an accredited agronomist; also use a calibrated variable-rate spreader.
- Apply fertiliser at the ‘**R**ight time’ so that nutrients are available when crops need them; nutrients should be applied to match the seasonal crop nutrient demand, in alignment with DPIRD’s advice.[35] Avoid fertilising on windy days or

[34] Slow-release P fertiliser is sometimes referred to as low-water-soluble P fertiliser.

[35] See DPIRD’s website: Phosphorus for high rainfall clover pastures in Western Australia and Nitrogen for high rainfall pastures in Western Australia.

when heavy rain is forecast; N fertiliser should be applied before light rain for incorporation into the soil, reducing the risk of losses to the atmosphere.

- Apply fertiliser in the '**R**ight place' where crops can use it, with a calibrated fertiliser spreader to ensure even and accurate application. Incorporate fertiliser-free buffer zones adjacent to waterways and drains, avoiding application on firebreaks and areas identified as high nutrient areas (e.g. soil P is in excess, where cattle congregate) or waterlogged soils.

We recommend farmers follow DPIRD's guidelines for P application in high-rainfall clover pastures in Western Australia. The *Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia* (Government of Western Australia 2022b) provides guidance and practical advice for farmers managing nutrients on-farm to optimise nutrient use efficiency and reduce nutrient loss (Government of Western Australia 2022b).

Hennig et al. (2021) modelled 100 per cent adoption of the '**R**ight rate' where farmers determine the P fertiliser requirements of their farm and apply only the appropriate amount to achieve optimal pasture production (farmers typically aim to achieve 85 per cent of maximum pasture production for beef farms and 95 per cent for dairy farms). This can be done by examining soil and tissue testing results and tailoring a fertiliser program for an individual farm.

The assumptions of this scenario align with the aims of best-practice fertiliser management programs:

- 100 per cent of farmers in the catchment are involved in the soil-testing program
- the farmers apply P at the recommended rate (derived from their soil-testing results)
- the farmers continue to soil-test and adjust fertiliser application each year, based on those results.

Transitioning farmers to using the '**R**ight rate' of fertiliser is a gradual process and so these model assumptions are a best-case scenario. Other components of fertiliser management such as liming of soils to reduce acidity and improve P uptake were not modelled in this scenario.

Modelling of fertiliser management using the principles of '**R**ight rate' on all beef and dairy farms in the plan area predicted a reduction in the P load to the Peel-Harvey estuary of 19 tonnes (33 per cent). While all reporting catchments (except Lower Murray) would still exceed their P load targets, those with significant coverage of beef and dairy farms showed reductions in P loads ranging from 0.3 to 7.4 t (20–41 per cent). The greatest reductions occurred in reporting catchments that had a large proportion of beef farms on low PRI soils, representing 74 per cent of the total estimated P reductions from implementing this action (Harvey, Nambeelup, Lower Murray and Upper Serpentine).

N was unaffected in this scenario as the majority of farm N input is from N-fixing pastures rather than fertiliser. For farms that do apply N fertiliser, we recommend that N be applied following DPIRD's guidelines on N management in high-rainfall pastures in Western Australia.[36] The *Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia* also provides guidance and practical advice for farmers managing N on their farms to optimise nutrient use efficiency and reduce nutrient loss (Government of Western Australia 2022b).

Significant progress has been made on recommended action 1 across south-western Australia through the Regional Estuaries Initiative (REI, 2016–2020) – Sustainable Agriculture Strategy, Revitalising Geographe Waterways (RGW, 2016–2020) and, before that, the Geocatch-led $mart soils program and the *Fertiliser Action Plan*. All these programs were underpinned by DPIRD's long-term whole-farm nutrient mapping program. The REI and RGW programs confirmed the popularity of subsidised soil testing combined with agronomic advice. These programs sustained high levels of uptake and involvement and were mainly limited by the availability of soil-testing contractors and accredited agronomists.

Of the beef and dairy farming area in the catchment, 10 per cent of farms by area were involved in the REI and 22 per cent were involved in farm soil-testing programs that ran from 2009 to 2020 (including those that were part of the REI). It is predicted that the Sustainable Agricultural Strategy of the REI reduced P loads to the Peel-Harvey estuary by an average of 2.2 t/yr (4 per cent). Farms that were part of all soil-testing programs from 2009 to 2020 were estimated to have reduced P loads by an average of 4.9 t/year (8 per cent), with 2 t/yr attributed to reductions in the Harvey reporting catchment alone.

The REI, RGW and whole-farm nutrient mapping programs showed that improved P fertiliser management could be achieved when soil testing was combined with workshops and sensible advice from soil agronomists familiar with the farmer and their needs. In addition, engaging and partnering with the fertiliser industry was critical.

Recommended action 1 is currently being implemented on beef and dairy farms through Healthy Estuaries WA (from 2021) and the Smart Farming Partnership (uPtake) by way of:

- subsidised soil testing to include both new and returning farmers through guided farmer sampling or through the project soil-testing teams
- workshops with farmers and Fertcare® accredited agronomists to translate soil-testing results into practical fertiliser decisions
- follow up one-on-one advice as required

[36] See DPIRD Nitrogen for high rainfall pastures in Western Australia.

- surveys to determine how effective the approach is and the program's rate of uptake
- additional broad surveys across catchments to better understand farmer needs and identify barriers to practice change
- trials of different fertiliser treatments
- effective communication of results
- farmer-to-farmer mentoring using principles derived from community-based social marketing.[37]

The benefits and measurable water quality improvements will accrue as the program extends across the catchment, moving towards the modelled best-case outcomes.

Implementation of this action at additional beef and/or dairy farms in the plan area forms part of the implementation of the *Bindjareb Djilba Protection Plan* (DWER 2020b).

Soil Wise is a new program (2022–24) funded by the National Landcare Program Smart Farms Small Grants – an Australian Government initiative that will also help to implement this action through development of extension activities.[38] It includes field days, workshops, webinars and the distribution of educational materials to raise the capacity of land managers and the adoption rates for best-practice sustainable agriculture.

In addition to the '**R**ight rate' principles*,* the continued development and evaluation of slow-release P and other alternative fertilisers ('**R**ight source') has the potential to improve crop and pasture production on the sandy soils of the estuary coastal plain catchment, while also reducing P loads to the estuary.

Previous government initiatives aimed to phase out the widespread use of high-water-soluble P fertilisers through the *Fertiliser Action Plan,* while the Fertiliser Partnership, which followed, aimed for a voluntary approach between the State Government, the fertiliser industry, user groups and the community.[39]

The combination of 100 per cent adoption of '**R**ight rate' on beef and dairy farms with the '**R**ight source' of slow-release P fertilisers on low PRI soils (instead of traditional high-water-soluble fertilisers) was also modelled. If the '**R**ight source' were used, it is estimated that P load could be reduced by an additional 6 per cent, or possibly more (an area of research associated with the uPtake program). The combined reduction of widespread use of slow-release P fertilisers and an optimal application rate based on agronomic need could reduce P loading to the estuary by 39 per cent – the largest reduction predicted of all the scenarios modelled.

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[37] See Appendix A and the Healthy Estuaries WA uPtake webpage for summary information on uPtake.

[38] Soil Wise is funded by the National Landcare Program Smart Farms Small Grants – an Australian Government initiative. It is supported by Healthy Estuaries WA. See Appendix A and the Healthy Estuaries WA Soil Wise webpage for more information.

[39] See DPIRD's Fertiliser Partnership FAQ webpage.

For more information on optimal fertiliser use, slow-release P fertilisers, and implementation of these management actions, see Appendix L.

Guidance for implementation

- Work with beef and dairy farmers, agronomists and the fertiliser industry to develop appropriate fertiliser products and to base fertiliser application rates and sources on agronomic requirements, as determined by soil and plant tissue testing.
- Prioritise work to optimise fertiliser use based on agronomic requirements in areas with low PRI soils or farms with high soil P reserves.
- Encourage farmers to create a farm map, showing paddock boundaries, waterways and environmentally sensitive areas, as well as infrastructure.
- Support farmers to develop a farm nutrient management plan based on soil-test results and production targets for each paddock, using an accredited agronomist or DPIRD’s nutrient calculator.
- To apply fertiliser according to the nutrient management plan, follow accredited advice and use the ‘four Rs’ of nutrient stewardship. Optimise nutrient use efficiency and reduce nutrient loss.
- Encourage farmers to keep accurate records of soil and plant tissue test results, and of fertiliser applications (product, rates timing) and pH adjustments (liming).
- Add lime to low pH soils and maintain soil pH at levels optimal for plant growth and nutrient availability. Seek advice from an accredited agronomist or use apps (e.g. iLime, Lime Comparison Calculator, Lime WA, Limemate) to determine a liming strategy for each paddock. Prioritise applications of lime over fertiliser if soil-test results indicate the need.
- Take plant tissue samples in spring to identify and address any plant nutrient imbalances.
- Continue to research how plant nutrition and crop production are affected by nutrient management, while considering individual farm needs and different soil types.
- Support the development and evaluation of alternative fertilisers (e.g. slow-release P fertilisers). Through extension programs and case studies, demonstrate their potential use for improved crop and pasture production and reduction in nutrient export from the land.
- Continue demonstration trials such as those funded by the Australian Government’s National Landcare Program – Smart Farming Partnerships, uPtake project (2019–2023) and the Smart Farms Small Grants’ Soil Wise program (2022–2024) (see Appendix A).
- Expand the scope of these trials to include N fertiliser management in relation to source (atmospheric, organic and inorganic), formulation, application rates and timing.

Soil amendment

4. Recommended action
Improve phosphorus retention in sandy soils used for intensive and broadscale agriculture by using soil amendments.
Where to implement? All reporting catchments, except Mandurah and the Peel Main Drain.
Where to start? Harvey, followed by Nambeelup, Upper Serpentine and Mayfield.

Much of the Peel-Harvey estuary coastal plain catchment consists of leached sandy soils that have little to no capacity to hold P. Soil amendments are materials that raise the P-retention capacity of soils and have the potential to significantly reduce P export to waterways from sandy soils. These include commercial amendments (e.g. bentonite), waste-derived products and local subsoil clays. Typically, commercial amendment products such as bentonite clays would only be used on intensive horticulture farms because of their high cost, while the latter two are more suited to the lower-cost broadscale application of soil amendments.

We modelled the use of soil amendments on all beef and dairy farms with low PRI soils in the plan area using the following scenario:

- 100 per cent of the beef and dairy farms treated with a soil amendment product (equating to 1,000,000 t) applied to 502 km^2 (50,200 ha)
- application rate of 20 t/ha
- 60 per cent efficiency in reducing P export (over the long term).[40]

P loads to the estuary were predicted to reduce by about 21 tonnes (35 per cent), with the largest reductions (2.2–6.7 t, 22–54 per cent) in the Harvey, Nambeelup, Lower Murray and Upper Serpentine reporting catchments. All other reporting catchments with significant areas of beef and dairy on low PRI soils were predicted to have reductions of 0.4–1.6 t (31–49 per cent). Again, while these reductions are large, all reporting catchments other than the Lower Murray would still exceed P targets, reinforcing the need for a suite of management actions to be applied across the catchment. In this scenario, N was assumed to be unaffected by soil amendments but research indicates that some amendments can reduce leaching of N from soils (Douglas et al. 2010, Chem Centre 2018).

Soil amendment application is predicted to be one of the most effective tools to reduce P loading to the estuary and could potentially have rapid and long-term positive impacts. Without widespread use of soil amendments it will not be possible to meet nutrient targets, even with best-practice fertiliser management across the

[40] During soil amendment trials of IronMan Gypsum (IMG) in the Peel-Harvey catchment, an application rate of 20 t/ha yielded the most immediate reductions in P losses for the lowest amount applied (Degens and Lam 2019, Degens et al. 2023). P export from paddocks treated with IMG is reduced by >80 per cent so modelling 60 per cent reduction is a conservative assumption (Douglas et al. 2010, Chem Centre 2018, Degens et al. 2023).

catchment. However, uncertainties and constraints make application to 100 per cent of beef and dairy farms in the estuary coastal plain catchment highly unlikely. Building trust with landholders and sharing the results of local and farm-based trials is particularly important when communicating the benefits. A shorter-term, more practical approach is to strategically apply soil amendments to specific paddocks of farms where soil testing shows levels of P exceed agronomic need. In these paddocks, there is an associated P runoff risk which can be mitigated using a soil amendment product to immediately minimise P losses from the production system.

New ways to produce and transport soil amendments need to be explored to make the cost of supply and application financially viable for the farmer. Government subsidies may be appropriate given the significant environmental benefit that can be realised from widespread application of soil amendments. Any subsidies would be offset by the future cost of environmental remediation works needed to address declining water quality in the estuary.

See Appendix L for more information on soil amendments and the implementation of this management action.

Environmental regulation of waste-derived materials

Existing legislation neither includes a framework for waste-derived materials nor prescribes when waste-derived materials will cease to trigger the licensing and waste levy regimes under the *Environmental Protection Act 1986* (EP Act), *Waste Avoidance and Resource Recovery Act 2007* (WARR Act), *Waste Avoidance and Resource Recovery Levy Act 2007* (WARR Levy Act) and the regulations made under these Acts. This creates uncertainty around whether a material is waste (and hence whether its storage or discharge onto land will attract licensing and waste levy requirements) and inhibits the market development for and uptake of recycled materials. Valuable non-virgin resources are being sent to landfill or stockpiled indefinitely, which is contrary to the circular economy approach encouraged by Western Australia's waste strategy 2030 (Government of Western Australia 2019b). This strategy advocates for most waste to be valued as a resource that can be reused or recycled for the benefit of the state's economy. These issues need to be resolved to encourage producers of soil amendments (e.g. mining by-products) to make them commercially available for broadscale agricultural use.

The department is working towards waste legislation reforms in Western Australia that aim to provide greater certainty about when waste-derived materials will trigger licensing and levy obligations. Issues and discussion papers outlining possible reforms to support and encourage the use of fit-for-purpose waste-derived materials were released in 2019 and 2020 respectively.[41] These papers are the first steps towards developing a legislative framework for waste-derived materials. Regulatory changes will make the use of mining by-products as soil amendments a

[41] Waste not, want not - Issues paper consultation

more feasible management action for wider adoption in the Peel-Harvey estuary coastal plain catchment.

This action is a component of Healthy Estuaries WA program (from 2021), and there is scope to expand trials as part of the implementation of the *Bindjareb Djilba Protection Plan* (DWER 2020b).

Guidance for implementation

- Investigate how changes to the regulation of waste-derived products can facilitate the wider use of soil amendments, including those around the definition and use of waste-derived products.
- Expand on-farm trials using mining by-products and other materials as soil amendments to determine the effectiveness of P retention, benefits to pasture productivity, and application methodology and rates. Seek to identify any limitations or undesirable environmental effects and make the results available to the industry.
- Promote the benefits of using soil amendments through paddock-scale trials to increase the adoption rate in the Peel-Harvey estuary coastal plain catchment.
- Provide support to farmers to apply soil amendments on their farms in a suitable way, focusing on paddocks with a high risk of losing excess P to waterways.
- Investigate opportunities and limitations around the commercial viability of soil amendments for farmers.
- Explore the potential of soil amendments to also retain bioavailable forms of N, including developing new formulations with other components such as organic carbon.

Regenerative agricultural practices

5. Recommended action

Develop new best-management practices for broadscale agriculture to encourage holistic management and regenerative agriculture principles that improve soil health, use water efficiently, maintain soil cover and support the *State Soil Health Strategy, Western Australia* (DPIRD 2021).

In conventional broadscale agriculture, reduce fertiliser losses and reduce erosion through improved whole-of-farm management practices, including the use of perennial pastures to avoid bare soils.

Where to implement? Rural land uses in all reporting catchments, except Mandurah.

Regenerative agriculture is a conservation and rehabilitation approach to food and farming systems. It focuses on topsoil regeneration, increasing biodiversity, improving the water cycle, enhancing ecosystem services, supporting biosequestration, increasing resilience to climate change, and strengthening the health and vitality of farm soil (SWCC 2020).

Holistic management is the foundation for regenerative agriculture. It is a decision-making framework that allows land managers to take a holistic approach to land management and make decisions that are environmentally, economically and socially sound.

The poor nutrient-retaining soils of the Swan coastal plain are not well suited to conventional farming practices where large amounts of nutrients are lost from the land and end up in the Peel-Harvey estuary. Climate change impacts will continue to dry the catchment, taking conventional farming practices further towards unsustainability.

The alternative approaches of regenerative agriculture and holistic management for nutrient poor soils aim to:

- improve soil health (including the soil moisture level and retention of nutrients and soil carbon)
- reduce soil erosion
- use water more efficiently
- extend the growing season and improve farm productivity
- reduce the dependence on inorganic fertilisers and pesticides
- reduce losses of nutrients and other contaminants from the land to downstream waterways.

The most common management practices associated with regenerative agriculture are:

- cover cropping to avoid bare soils (including the use of perennial pastures)
- diversification of crops and grasses for grazing
- reduced or no ploughing/tillage
- reduced chemical and fertiliser application
- rotational livestock grazing with the right density and mix of animals
- retention of water and natural wet areas on the farm.

A useful summary of transitioning to regenerative agriculture is provided by a South West Catchments Council (SWCC) report, *Supporting farmers to make the transition to regenerative agriculture* (2020). Regenerative farming practices have the potential to reduce fertiliser application and nutrient runoff, improve soil moisture retention, restore hydrological balances and sequester carbon (Soils for Life 2012). The SWCC report notes that confusion about the definition of regenerative agriculture is a barrier to adoption: this could be overcome by clearer communication and successful whole-farm demonstrations.

The *Western Australian Soil Health Strategy draft* (DPIRD (Department of Primary Industries and Regional Development) 2021) notes that better soil health leads to improved water quality as nutrient and sediment runoff is minimised. The adoption of regenerative farming practices is encouraged by the Minister for Agriculture and Food and supported by RegenWA, a network of committed Western Australian farmers and industry stakeholders who are striving to identify, implement and share innovative land management practices to help other farmers with the transition.

The *Carbon Credits (Carbon Farming Initiative) Act 2011* and the subsequent *Carbon Farming Initiative Amendment Act 2014*, which established the Emissions Reduction Fund (ERF), have created opportunities for farmers to transition to regenerative agricultural practices. The ERF has three elements: crediting emissions reductions, purchasing emissions reductions, and safeguarding emissions reductions.[42] The State Government, through the Carbon Farming and Land Restoration Program, intends to provide seed funding to farmers to transition in advance of receiving ERF funding for soil stored carbon.[43] The program funds the implementation of activities on farms that sequester carbon in the landscape and deliver additional, positive outcomes referred to as ‘co-benefits’ (agricultural productivity, salinity mitigation, soil health, Aboriginal economic and cultural opportunities, biodiversity and conservation).

Irrespective of whether regenerative farming practices are advocated from the perspective of improving soil health, representing best practice in agriculture or

[42] Further information on the ERF is available on the Department of the Environment website: Emissions Reduction Fund.

[43] Western Australian Carbon Farming and Land Restoration Program

carbon farming, it is highly suitable for the catchments of the Peel-Harvey and aligns with the objectives of this WQIP.

Healthy Estuaries WA and Soil Wise are partnering with local experts to provide educational workshops for grazing farmers and local communities in south-western Australia, including the Peel-Harvey estuary coastal catchment. These aim to promote the benefits of regenerative agriculture, and to work with farmers to develop and implement best practice to improve soil health, minimise soil and nutrient loss, and reduce inorganic fertiliser/pesticide dependence. Other important goals are to extend the growing season and improve farm productivity. Some of this work will be conducted within the plan area.

Healthy Estuaries WA is jointly funding the Grazing Matcher Program which aims to improve productivity and profit for farmers while minimising impacts to the environment. Grazing Matcher supports farmers to adopt best-practice pasture and grazing management across their sheep and beef farms. The program advocates rotational grazing to maximise production and considers how pasture responds to grazing and weather conditions. Farmers learn about and implement rotational grazing plans for their properties.

Guidance for implementation

- Address any confusion among farmers and the community around the definition and objectives of regenerative agriculture.
- Work with industry to develop a shared understanding of what regenerative agricultural practices are suitable and profitable for the nutrient-poor soils in the plan area.
- Support farmers in the transition to the agreed regenerative agricultural practices through training, demonstrations and farm conversions. Measure and monitor results over time to allow comparison to conventional agriculture (in terms of fertiliser use, soil condition and potential to improve water quality). In particular, profitability and on-farm benefits should be demonstrated in beef/dairy farms in the plan area.
- Ensure research and development for regenerative agriculture is communicated widely at the local level and accessible to industry.
- Raise awareness of premium-priced products under the clean green label (e.g. Dirty Clean Food, Wide Open Agriculture).

Perennial pastures

(See recommended action 5.)

Annual pastures are shallow-rooted and less drought tolerant than perennial pastures. They also require more fertiliser applied at a higher frequency and are associated with a higher rate of water and nutrient loss.

Perennial pastures (e.g. kikuyu, paspalum, couch, Rhodes and veldt grass) have long been promoted in grazing management. They require fewer nutrients than annual pastures and are associated with lower nutrient export and water loss. The deeper roots of perennial pastures allow for greater access to nutrients and water, which extends over a larger portion of the year. Continuing growth into late spring and summer reduces the presence of bare soils and the risks of erosion, waterlogging and salinity (Neville 2005). There is also evidence that perennial pastures can be more productive than annual pastures (Neville 2005) and they can be used to provide out-of-season feed, increase land carrying capacity and improve farm profitability.

In 2004 about 40 per cent of farmers in the Peel-Harvey catchment were using perennial pastures (most commonly Kikuyu or couch grass) (Lavell et al. 2004), but whether these pastures were managed for improved nutrient removal is unknown.

DPIRD has published a comprehensive guide on *Perennial pastures for Western Australia* (Moore et al. 2006).

Further investigation is needed to determine which perennial pasture species are best suited to the Peel-Harvey estuary coastal plain catchment, both for reducing nutrient losses to receiving waterbodies, and improving farm productivity among other benefits. Surveying farmers to establish the current use of perennial pastures may help to better understand barriers to uptake. Extension work and demonstration sites may encourage more farmers to use perennial pastures across the catchment.

The use of perennial pastures, either to replace or use in combination with annual grasses, remains a strongly recommended management practice consistent with the principles of regenerative agriculture.

Improved irrigation practices

6. Recommended action

Conserve water and reduce nutrient runoff from irrigated agriculture by requiring Nutrient Irrigation Management Plans (NIMPs) as part of planning approvals and water licensing processes and applying best management practice to irrigation design to achieve appropriate pressure, reach and uniform distribution. Irrigation scheduling should carefully consider soil moisture content and local evaporation rates.

Where to implement? All reporting catchments, except Mandurah.

Large areas of agricultural land in the Peel-Harvey estuary coastal plain catchment are irrigated for annual and perennial horticulture, and for growing pasture and fodder. Excess irrigation water returns to waterways and drains via surface flow or infiltration to groundwater, transporting nutrients to the estuary.

Centre pivot, sprinkler and flood irrigation are all used in the catchment. Flood irrigation involves releasing water to flat (typically laser-levelled) irrigation bays to grow pasture in the warmer months. It is less water efficient than centre pivot irrigation because of overwatering and poor water distribution (River 2012) and is associated with higher nutrient loss, as excess flooded water coming off the paddocks can contain high nutrient concentrations (River 2012). Centre pivot is preferable and can reduce water consumption by 15 to 27 per cent (ACIL Tasman

2004) but it needs to be designed and used appropriately – following best practice to minimise water runoff and the export of sediment and nutrients.

Because of small volumes of excess irrigation water (7 GL, about 2 per cent of annual flow), it is estimated that the nutrient loads from this source are small (< 1 per cent of the P and N loads to the estuary). However, as these nutrients are delivered to the estuary when water temperatures are high and water retention times are long, BMPs remain important for reducing the risk of algal blooms. In addition, substantial water saving gains can be made through reduced evaporation.

BMPs vary with crop type, planting density and the layout of the crops and land but the following general principles apply:

- systems should be designed with appropriate pressure, reach and uniform distribution to minimise water loss and nutrient runoff
- irrigation should be carefully scheduled and consider local evaporation rates and soil moisture monitoring
- pasture and fodder crops should use centre pivots in preference to flood irrigation (ACIL Tasman 2004).

Guidance for implementation

- Use appropriately designed, efficient irrigation systems (e.g. appropriate pressure, reach and uniformity) and follow BMPs for rural irrigation on the Swan coastal plain to minimise water runoff and the export of sediment and nutrients.
- To save water we recommend that farmers use certified irrigation professionals to design, install and maintain irrigation systems. A professional irrigation designer will help to design irrigation systems customised to the farm's crops, soils, climate and water supply. Irrigation Australia Limited is the national body for irrigation professionals both for urban and rural irrigation.
- For new or changing land uses that involve irrigation/fertigation of crops, gardens, trees or turf, or where fertiliser is applied to irrigated land, minimise water wastage and fertiliser losses by implementing *Water quality protection note 33: Nutrient and irrigation management plans* (DoW 2010b) and *Water quality protection information sheet 4: Nutrient and irrigation management plan checklist* (DoW 2010a), where appropriate.[44] Activities likely to need a nutrient and irrigation management plan include:
  - land irrigated with animal industry wastewater, such as from farm dairies and feedlots
  - piggeries and stables
  - land receiving treated effluent from municipal wastewater treatment plants

[44] Where appropriate, nutrient and irrigation management plans (NIMPs) in the Peel-Harvey catchment are developed by applicants as part of the local government planning approval process. The NIMP must demonstrate how nutrients will be managed and detail monitoring, contingencies and reporting requirements. If planning approval is granted, the NIMP is then reflected in the water licensing operating strategy.

- intensive animal holding in paddocks (where feed is brought onto the site)
- where fertiliser or stabilised animal manure (including chicken litter) is applied to irrigated land such as golf courses, pasture, recreation areas, sports grounds, turf farms and woodlots
- where food product processors dispose of treated wastewater onto the land such as abattoirs, commercial dairies, canneries, rendering works, vegetable processors and wineries
- intensive agricultural or horticultural industries such as exotic flower growing (e.g. orchards)
- vineyards or market gardens.

Riparian zone management (stock exclusion and revegetating riparian zones)

7. Recommended action

Help farmers and other landholders exclude stock from waterways and drains to reduce erosion and the input of sediment and organic matter to the estuary and its tributaries.

Linked to recommended action 19.

Where to implement? This action reduces the export of organic matter (from animal waste) as well as nutrients, and so it is recommended for all reporting catchments where dairy and/or beef grazing is occurring in, or near, a waterway. Priority should be given to those areas with higher stocking rates. To implement this action, more detailed mapping of waterways, drains and existing fencing may be required on a local scale.

Where to start? Harvey, then Dirk Brook, Lower Murray and Upper Serpentine, followed by Nambeelup and Mayfield.

On much of the land currently used for beef or dairy grazing, stock have direct access to waterways and drains. This destabilises and erodes banks, damages riparian vegetation and allows animal wastes to be directly deposited into the water or wash in from the banks with rainfall. Excluding stock by fencing reduces soil erosion and the amount of animal waste (high in organic matter and nutrients) entering the waterway or drain (Figure 9-2). On farmlands, the fenced area will no longer have fertiliser applied, which also contributes to a reduction in nutrient export to the waterway. In addition to fencing, this action also includes the construction of gates, stock crossings and the provision of off-stream stock watering points, as appropriate.

Figure 9-2 Cattle in waterways and drains leads to erosion of the banks and direct inputs of animal waste

Once stock are excluded from the waterway, revegetating the riparian zone stabilises the banks and slows surface runoff from the land. It also improves the ecological function of the waterway, which contributes to improved water quality (see recommended action 22). Efforts to revegetate riparian zones should focus on natural waterways where ecological function can be significantly improved. Appendix L outlines the environmental benefits of vegetated riparian zones and provides further information relevant to implementing stock-exclusion fencing.

There are 2,361 km of waterways and drains in the plan area. Fifty-nine per cent (1,394 km) of these have cleared riparian zones, and 25 per cent of those (351 km) are fenced (Hennig et al. 2021).[45] The model estimates that fencing the remaining 75 per cent (1,043 km) would reduce nutrient loads to the Peel-Harvey estuary by an average of 2.6 per cent for P and 7 per cent for N. This scenario only considers those fertiliser-derived nutrients that are intercepted by the fenced-off riparian zone and does not include reductions associated with preventing the direct deposition of animal waste to the water.

If the 1,394 km of waterways and drains with cleared riparian zones were fenced and replanted with native species, P loads were predicted to reduce by a further 0.8 per cent (3.4 per cent reduction in total) and N loads by a further 11 per cent (18 per cent reduction in total). Of the scenarios modelled, this was the most effective

[45] Fencing of one or both sides of the waterway or drain.

management action to reduce N loads, although reporting catchment targets were still not met.[46] The largest reductions in N occurred in the Harvey, Upper Serpentine, Lower Murray and Nambeelup reporting catchments (9.3–41.4 t, 9–23 per cent).

While stock exclusion from waterways is important in most of the Peel-Harvey estuary coastal plain catchment, it is impractical on minor agricultural drains. Stock exclusion along main drains managed by Water Corporation is particularly important and along some drains revegetation may also be appropriate. To manage fire risk, a regular and effective weeding program is an important aspect of maintaining fenced-off areas, particularly while native vegetation is establishing.

The provision of off-stream watering points for cattle is often necessary when fencing to exclude stock from waterways

Stock-exclusion fencing and revegetation of the riparian zone has been progressing across the plan area through successful collaborations between landholders, industry and NRM groups such as the PHCC and the Harvey River Restoration Taskforce (HRRT). For example, Connecting Corridors and Communities – Restoring the Serpentine River is a collaboration between Alcoa and the PHCC that is engaging the local community to improve the health of the Serpentine River. The *Serpentine*

[46] Excluding the implementation of bottom-of-catchment treatment wetlands which are not considered feasible (see Use of constructed wetlands, page 172) .

River action plan includes works to fence and protect existing vegetation while rehabilitating other areas along the river, aiming to reduce nutrients and sediment entering the waterways and drains and improve ecological health. Stock exclusion fencing and riparian revegetation was also achieved as part of the REI, helping to reduce the export of nutrients and organic matter via farm waterways to the estuary.

To achieve a substantial reduction in nutrient loads (particularly N) and organic matter) entering the estuary, an accelerated rate of fencing and revegetating the riparian zone is needed.

We support the strategic riparian management performed by NRM groups in the catchment, with the following work helping to inform priorities:

- river action plans (including the *Serpentine River action plan* and *Murray River action plan*)
- river health assessments and ecological health assessments conducted by the department (Section 3.2) and NRM groups
- catchment nutrient reports published by the department.

This action is also currently being implemented through Healthy Estuaries WA and implementation of the *Bindjareb Djilba Protection Plan* (DWER 2020b).

See also the related recommended action 22 which addresses river restoration and riparian revegetation.

Guidance for implementation

- Target reaches most likely to improve water quality and improve the ecological health of waterways and drains. Use existing water quality reports and river health assessments to help with site selection.
- In identified priority areas, document existing river reaches that are fenced and map the location, land tenure, accessibility, and buffer areas of reaches that should be fenced to protect water quality.
- Work with landholders of grazing properties to exclude stock from waterways and drains, with priority given to those areas with higher stocking rates. Stock exclusion fencing should be installed at least 20 m from the top of the bank, with a minimum of 10 m where that is not possible.
- Where appropriate, construct fencing on both sides of the waterway and construct stock/vehicle crossings and gates. Where the farmer has previously relied on the waterway/drain for stock watering, ensure off-stream watering points are also constructed and carefully consider the siting of these to minimise erosion. Where possible, provide incentives for farmers through cost-sharing arrangements for fencing.
- Revegetate fenced-off waterways and drains with endemic native plants to provide bank stability, shade and habitat, and reduce erosion. Aim to mimic the structure and diversity of plants present along local, natural waterways.
- Stock exclusion fencing should be extended to major Water Corporation drains, especially those straightened portions of natural waterways, and revegetated using native plants as appropriate. Liaise with Water Corporation on what approvals and standards may apply.

- Refer farmers to the factsheet developed by the Healthy Estuaries WA program *Why should we fence and revegetate our waterways?* (DWER 2023b) to help communicate the multiple benefits of stock exclusion fencing.
- Along very small or paddock drains on farms where stock exclusion is considered impractical, no fertiliser should be applied to a 10 m buffer zone from the drain. Use best-practice fertiliser management elsewhere (see recommended action 1).

Use of constructed wetlands

8. Recommended action

Industry to consider integrating drainage networks with engineered, constructed wetlands to reduce the export of intensive, diffuse sources of nutrients, such as those from free-range chicken farms, rotational outdoor piggeries (free-range and outdoor bred), and irrigated horticulture.

Where to implement? Consider all reporting catchments with industries that are an intensive source of diffuse nutrients with the potential to impact on water quality in waterways and/or the estuary (e.g. outdoor piggeries (free-range/outdoor bred), free-range chicken farms, and irrigated horticulture).

Constructed wetlands may be considered as an element in the treatment train to improve water quality. These wetlands are artificial, engineered water treatment systems designed specifically to receive diverted flow and improve water quality by maximising physical, chemical and biological nutrient-removal processes.

Constructed wetlands to treat agricultural drainage waters are not common in Australia, and worldwide there is a scarcity of reliable efficacity data. Much of the literature (for example, Kadlec and Wallace 2008) is based either on constructed wetlands in urban environments or constructed wetlands that treat effluent from industry that contains very high nutrient concentrations.

In the absence of data related to constructed wetlands in agriculture, data from constructed wetlands in urban settings was used to model the effect of such wetlands at the outlet of seven reporting catchments (Peel Main Drain, Upper Serpentine, Dirk Brook, Nambeelup, Mayfield, Harvey and Meredith), but these findings must be interpreted with caution. It was estimated that loads to the estuary would reduce TP by 23 t (38 per cent) and TN by 119 t (22 per cent). This scenario is based on about 811 ha of constructed wetlands (using the standard 0.5 per cent of catchment area upstream of the wetland).

While modelling this scenario was a useful ‘thought exercise’ on how diffuse agricultural drainage waters could potentially be treated to reduce nutrient loading to the estuary, such a vast area of land is simply not available. The costs to construct and maintain wetlands at this scale would be prohibitively expensive, and orders of magnitude more expensive than any other possible treatment. In addition, most of the N load in the reporting catchments included in this scenario (except Harvey and

Dirk Brook) is DON (2016–18 data, Section 3.2) which is generally not removed by constructed wetlands.

This WQIP does not recommend the use of constructed wetlands at the bottom of a catchment; however, they should be considered to reduce nutrient concentrations in runoff from intensive, diffuse sources. Examples of these types of land uses include free-range chicken farms, rotational outdoor piggeries (free-range or outdoor bred) and irrigated horticulture that requires high nutrient input. For example, in addition to vegetated buffer strips and/or terminal ponds, as recommended in the *National environmental guidelines for rotational outdoor piggeries* (Tucker and O'Keefe 2012), constructed wetlands may further reduce concentrations of nutrients and organic matter.

Similarly, well-designed and maintained constructed wetlands have the potential to reduce nutrient concentrations and organic matter in drainage water from beef and dairy farm paddocks before discharge to local waterways (B. Oversby 2022, personal communication, 5 May).

Constructed wetland systems can be enhanced using microalgae and macroalgae cultures (Murdoch University Algae Research and Development Centre). See Appendix L for further general information on the use of constructed wetlands to improve water quality.

Diverting nutrient-rich flow into existing natural wetlands as part of a treatment train for nutrient removal is not an acceptable or effective way to improve water quality and we do not recommend it. If effluent from intensive land uses contaminates natural wetlands that have environmental or social values and are protected, this may constitute an offence under the EP Act. Furthermore, we do not recommend the diversion of drainage water or agricultural effluent into degraded natural wetlands for the purpose of nutrient removal, as systems in poor condition have no capacity to treat high nutrient inflows.

As well as considering the objectives and recommendations of this WQIP, all industries should comply with relevant local, state and national guidelines to ensure they are following best practice.

Improved management of point source agricultural nutrients

Improved management of dairy shed effluent

9. Recommended action

Improve effluent management within dairy operations to minimise discharge and maximise reuse of water and nutrients to standards in the code of practice.

Linked to recommended action 28.

Where to implement? All reporting catchments that have an operating dairy shed which, as recorded by Hennig et al. (2021), includes the Upper Serpentine, Dirk

Brook, Nambeelup, Lower Murray, Coolup (Peel), Coolup (Harvey), Mayfield and Harvey.

Where to start? Harvey and Nambeelup, followed by Upper Serpentine, then Dirk Brook.

Dairy farms generate large volumes of nutrient-rich liquid and solid effluent (animal wastes) and wash-down water from sheds, yards and runways. The proportion of P and N exported from a dairy shed as a total of the dairy farm varies considerably between farms and catchments.

While dairy farming is less prevalent in the Peel-Harvey than other parts of the South West, many of the reporting catchments in this WQIP have at least one dairy farm and surveys have indicated that many dairy sheds did not meet the *Code of practice for dairy shed effluent Western Australia* (Western Dairy 2012) (the code of practice, 2012). The code of practice (2012) specified dairy effluent management systems should minimise adverse impacts to the environment, while also achieving productive and cost-efficient operations. See Appendix L for survey details and information on best-practice management of dairy shed effluent to meet the code of practice.

Modelling indicates that if all dairy farms in the estuary coastal plain catchment managed their effluent to meet the code of practice (2012), P exports originating from dairy sheds would be reduced by 60 per cent, which is an overall reduction of 1 t (1.7 per cent) of P and 2.3 t (0.4 per cent) of N reaching the estuary.[47] The Harvey reporting catchment was estimated to have the largest reduction for both N and P.

While load reductions appear small on a catchment scale, they may have a significant impact on local water quality at the reporting catchment scale. Associated reductions in organic matter (which contributes to low oxygen levels in receiving waters) was not modelled but would be an additional benefit to water quality from improved effluent management.

Through the REI Sustainable Agriculture – Dairy Care project, the department and Western Dairy supported farmers to develop and implement effluent management plans, with six farms in the Peel-Harvey implementing upgrades to meet the code of practice, at the time (2012) (see Appendix L for further information). Through this project, a revised *Code of practice for dairy farm effluent management WA* (2021) was developed.

Every dairy in the Peel-Harvey estuary coastal plain catchment should be upgraded to meet the revised code. As part of Healthy Estuaries WA, Western Dairy is continuing this important work. In addition, a dairy processor is offering higher milk prices to dairy sheds that have completed an effluent system review, developed an effluent management plan and implemented an upgrade to meet the code of practice (2012).

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[47] This scenario considered 25 dairy properties with a total of 5,775 dairy cattle.

Guidance for implementation

- Review the operating dairies in the estuary coastal plain catchment to assess which are meeting the *Code of practice for dairy farm effluent management WA* (2021) (the revised code) and which require upgrades.
- Encourage and support dairy farmers to adopt and maintain best-practice management of their dairy effluent system, adhering to the revised code of practice (2021) and published versions of relevant water quality protection notes and information sheets, currently:
  - *Water quality protection note* (WQPN) *4: Sensitive water resources (DoW 2016) (as updated)*
  - *WQPN 6: Vegetation buffers to sensitive water resources* (DoW 2006) (as updated)
  - *WQPN 22: Irrigation with nutrient-rich wastewater* (DoW 2008b) (as updated)
  - *WQPN 26: Liners for containing pollutants using synthetic membranes* (DoW 2013a) (as updated)
  - *WQPN 27: Liners for containing pollutants using engineered soils* (DoW 2013b) (as updated)
  - *WQPN 33: Nutrient and irrigation management plans* (DoW 2010b)
  - *Water quality information sheet 4: Nutrient and irrigation management plan checklist* (DoW 2010a) (as updated)
  - *WQPN 39: Ponds for stabilising organic matter* (DoW 2009) (as updated)
  - *WQPN 80: Stockyards* (DoW 2015b) (as updated).
- Promote the benefits of best-practice dairy effluent management to dairy farmers through awareness programs. Work with farmers (extension programs) to educate and advise on maintenance/upgrades/expansions to effluent management systems, as appropriate for individual dairy farms.
- Support research into alternative ways to recycle and reuse effluent on farms, or for commercial use.
- Work with the dairy industry to implement incentivisation programs for dairies that have better environmental practices, such as those that meet the revised code of practice (2021).
- Promote adherence to the revised code of practice (2021) so that dairy farmers are better equipped for the possibility of future regulation of the industry.

Improved management of nutrient export from intensive animal industries

Intensive animal industries may stockpile nutrient-rich materials and/or dispose of, or reuse, liquid effluent on-site. In the Peel-Harvey estuary coastal plain catchment, there are 48 intensive animal industries which include piggeries, abattoirs, feedlots, stockyards and poultry sheds.

10. Recommended action

Manage effluent, stormwater and other sources of nutrients from intensive animal industries (e.g. piggeries, poultry sheds, feedlots and abattoirs) to national or international best-practice standards.

Linked to recommended actions 25–28.

Where to implement? This is a whole-of-industry focused action – all reporting catchments that have intensive animal industries (piggeries, poultry sheds, feedlots/stockyards and abattoirs).

Operators that are currently responsible for the highest nutrient loads to the estuary should be the focus of this recommended action.

Where to start? Targeting the largest nutrient exporters first will have the greatest impact. These premises are in the Meredith, Lower Serpentine and Dirk Brook reporting catchments. The largest total load reduction across the catchment would come from the Upper Serpentine, where most intensive animal industries are located – although the load removed per premises would be much smaller.

Modelling identified that most of the nutrient emissions from intensive animal industries were from poultry farms and feedlots. However, in the Lower Serpentine and Meredith reporting catchments, piggeries contributed the largest proportion of nutrient load of all intensive animal industries. Modelling suggests that in the Meredith reporting catchment, a single piggery contributes 13 per cent of the N load and 17 per cent of the P load.

There are state and/or national guidelines and codes of practice for the management of effluent from piggeries, abattoirs, feedlots and poultry sheds (see Appendix M). Best-practice guidelines for effluent management for intensive animal industries generally involve careful siting of operations with appropriate buffer distances to water resources; management, storage and reuse of liquid and solid effluent to minimise water and nutrient loss; appropriate disposal of dead animals; and management of stormwater runoff.[48]

Modelling indicates that by following best-practice guidelines at piggeries, abattoirs, feedlots and poultry sheds, nutrient loads to the estuary from these sources would be reduced by about 1 tonne (1.7 per cent) for P and 23 tonnes (4.1 per cent) for N.[49] Improvements to the management of poultry effluent are particularly important for addressing N loads. Like dairy sheds, intensive animal industries are also a source of organic matter, which can lead to low oxygen concentrations downstream of

[48] For potentially polluting land uses, an additional buffer may be required to mitigate potential impacts to water quality in addition to the required wetland buffer or foreshore area.

[49] Following best-practice guidelines is assumed to result in a reduction in nutrient load export of 95 per cent (remaining 5 per cent is attributed to unexpected events or extreme weather) which is consistent with the best-practice guidelines for beef feedlots (Meat & Livestock Australia 2012b).

discharges. Treatment of effluent for reduced nutrient export will also reduce the export of organic matter.

These findings support a need for improved regulation of discharges from intensive agricultural industries, particularly poultry farms, feedlots, piggeries and abattoirs. Additional benefits of managing the effluent from intensive animal uses (other than reducing nutrient export) include minimising *E. coli*, other pathogens and endocrine-disrupting compounds from entering the groundwater and waterways.

Through implementation of the *Environmental Protection Amendment Act 2020* which significantly reforms the EP Act, the department is reviewing how discharges from point sources of pollution are licensed and will implement an activity-based regime under the new Part V Division 3 of the EP Act (including reviewing and replacing Schedule 1 licensing categories). This will replace the current approach of licensing prescribed premises. The EP Act amendments provide a stronger mechanism for reducing discharges to sensitive aquatic environments like the Peel-Harvey estuary system.[50]

Intensive animal industries should be sited well away from waterways, drains and protected wetlands, which is challenging on the heavily drained coastal catchments. When considering future land use development applications, these industries should not be located on the Swan coastal plain. For existing premises, improvements to site and effluent management should be a priority, supported by appropriate regulation. Relocation of these industries away from the estuary drainage system should also be considered.

The reporting catchments that would have the greatest N load reduction from point source management of intensive animal industries (i.e. their load reductions were greater than 6 per cent) were the Upper Serpentine (8.7 t reduction), Lower Murray (6.6 t), Dirk Brook (4.1 t), and Lower Serpentine, Meredith and Peel Main Drain (0.9 t each).

See Appendix L for a summary of how the department regulates industrial discharges to the environment through the works approval and licensing process under Part V of the EP Act.

Guidance for implementation

- Promote adoption of the Western Australian guidelines for new and existing intensive animal industries as appropriate for the Peel-Harvey estuary coastal plain catchment (see Appendix M).
- Management of effluent at piggeries and other intensive animal industries should aim to contain the effluent, prevent any animal wastes reaching groundwater or waterways, and appropriately reuse the nutrients on the farm.
- Ensure industry licence conditions relating to nutrient concentrations in discharge are appropriate to prevent or minimise the export of nutrients and

[50] For information on the amendments to the EP Act, see Amendments to the Environmental Protection Act 1986.

non-nutrients to waterways/drains and groundwater in the estuary coastal plain catchment.

- A formal review of existing industry licence and works approval conditions for prescribed premises/activities, through the provisions of the EP Act and the Environmental Protection Regulations 1987, may be required to ensure the licence and works approval conditions are adequately protecting the Peel-Harvey estuary system from further water quality decline.

Improved management of nutrient export from intensive horticulture

11. Recommended action

Develop and implement intensive horticulture best-management practices suited to high nutrient-leaching environments, including optimising fertiliser use to agronomic requirements, as determined by soil testing and agronomic advice, and investigating the feasibility of implementing closed agricultural systems (annual horticulture).[51]

Linked to recommended action 26.

Where to implement? This is a whole-of-industry action.

Where to start? Upper Serpentine is the reporting catchment to target for changes in horticultural practices based on very large reductions in P loads (and loads/implementation area) modelled.

In the Peel-Harvey estuary coastal plain catchment, intensive horticulture includes in-ground annual horticulture, irrigated orchards and turf farms. The plants and pastures grown in these industries often require high nutrient inputs to optimise production and this can lead to intense, diffuse nutrient export to the environment via leaching to superficial groundwater and runoff to local waterways.

In-ground horticulture contributes 6 per cent of the P load to the estuary, and turf farms contribute an additional 0.3 per cent (Section 7.6) (Hennig et al. 2021). As these land uses cover less than 1 per cent of the plan area, it is evident they are high-risk industries for nutrient export to the estuary. Like intensive animal industries, conventional in-ground horticulture is not suited to the poor nutrient-retaining soils of the Swan coastal plain.

Local and national guidelines have been developed (see Appendix M) to help the industry design and manage their operations to reduce environmental impacts. Yet the national standards may be insufficient in very sensitive environments, including some areas of the Peel-Harvey estuary coastal plain catchment. In these locations, land use planning controls must guide the appropriate location of intensive industries.

[51] See DPIRD Horticulture.

For existing horticulture in nutrient-sensitive areas, conversion to closed agricultural systems may be a solution in the long term. Modelling estimates that the P load to the estuary could be reduced by 5.9 per cent (3.5 t) from this action.

When the expansion of conventional in-ground horticulture was modelled in unsuitable locations (with respect to very low PRI soils, degree of inundation and estuary connectivity) in the Peel-Harvey (such as Nambeelup reporting catchment), massive increases in nutrient export to the estuary were predicted (see Section 8.2). State Government and local planning policies (WAPC 1992, 2006, Shire of Murray 2018a, Shire of Serpentine Jarrahdale 2018b, Shire of Waroona 2021) acknowledge the limitations of soils in these areas. New planning or development proposals must demonstrate that nutrient input rates can be met so as to achieve the maximum acceptable nutrient loads to the estuary (Section 7.5), as well as adhere to other relevant state policy (including consistency with *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) and local government policies.

For much of the Swan coastal plain, closed agricultural systems may be the only suitable option for annual horticulture. The transition of the agricultural industry towards this change is likely to be gradual; however, there has been recent investment into this technology in the catchment. If these operations prove successful, this may facilitate further sustainable development for intensive horticulture in the Peel-Harvey estuary coastal plain catchment in the future.

In the short term, intensive horticulture industries (in-ground horticulture, orchards and turf farms) must be supported to optimise fertiliser use and reduce nutrient export. There is also an opportunity to amend soils with clays or other soil amendments to retain P and reduce P export to waterways.

Guidance for implementation

- Encourage industry development of contemporary best practice for annual horticulture that makes the protection of environmental water quality a key objective.
- Investigate local clays to amend soils at existing horticulture operations on sandy soils with poor P retention for reducing P losses to waterways.
- Support innovative research to investigate horticulture methods that involve closed agricultural systems with zero export of nutrients to the environment.

Improved management of diffuse urban nutrients

Manage nutrient export from urban gardens and public open spaces

12. Recommended action

Help householders improve water use efficiency in existing urban gardens and minimise nutrient export risk through the Waterwise Council Program and other waterwise education programs (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).

13. Recommended action

Public open space managers to reduce nutrient application (fertiliser and others) and export risk, and improve water efficiency in existing public open space (see Waterwise Council Program and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*)

14. Recommended action

Developers of new urban land and public open space should evaluate and use soil amendments to reduce phosphorus losses in areas with sandy soils that have low phosphorus retention.

Where to implement recommended actions 12 to 14? All reporting catchments with urban areas.

In urban areas the increased area of impervious surfaces (e.g. pavement and rooftops) alters the natural hydrology, leading to decreased infiltration, increased runoff, and shortened residence times for water and nutrients in the soil. This change, together with higher rates of nutrient application (i.e. fertilisers on lawn and gardens in residential areas and public open spaces), can lead to increased concentrations of N and P in surface runoff and contribute to water quality decline in the receiving waterbodies.

Action to improve water use efficiency and reduce nutrient export from urban areas is critical (e.g. reduce fertiliser use and/or increase the use of soil amendments to improve nutrient retention in public open spaces). Designing gardens with native plants that require less water and fertiliser also reduces nutrients lost from urban landscapes. Targeted public awareness and education programs promoting environmentally responsible gardening through appropriate use of fertiliser, watering and planting will continue. The Waterwise Council Program, *Waterwise Perth – Two year action plan* (Government of Western Australia 2021a) and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2* (Government of Western Australia 2022a) align with these actions and their implementation will contribute to this work.

Guidance for implementation

- Continue to raise public awareness that excess fertiliser and over-watering contributes to nutrients entering the waterways, affecting water quality and overall health of the estuary.
- Promote best-management practices for design, watering and fertiliser use (Right source, Right rate, Right time, Right place, see page 155) in urban gardens to help householders improve water use efficiency and minimise nutrient export risk (aligned with *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).
- Promote the use of native plants that have low nutrient and water requirements when landscaping public open spaces.

- Landscaping in urban environments should include the use of soil amendments to improve nutrient retention where appropriate, and the planting of native vegetation (preferably endemic).
- Raise public awareness and help local government and greenspace managers to reduce water use and nutrient runoff from irrigated public open space (aligned with *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).
- Encourage the use of soil amendments when new public open space is developed on sandy soils with low P retention.

Retrofitting of urban areas using water sensitive urban design (WSUD)

15. Recommended action

Target upgrades to existing stormwater systems in priority areas according to water sensitive urban design principles (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).

Linked to recommended actions 16, 31 and 32.

Where to implement? All reporting catchments with urban areas.

Where to start? Harvey, Mandurah, Lower Murray and Lower Serpentine.

16. Recommended action

Increase training and development opportunities for local government and the stormwater management industry to adopt water sensitive urban design principles.

Linked to recommended actions 15, 31 and 32.

Urban areas (offices, commercial, educational, recreational and residential) cover 1.6 per cent of the plan area, with runoff (excluding septic tanks) contributing about 1.7 per cent of the N load and 2.6 per cent of the P load to the Peel-Harvey estuary.

As a result of reform in urban water management in Western Australia (see Appendix L for a summary), stormwater in new urban developments is managed to protect the environment, generally employing WSUD principles. WSUD integrates the urban water cycle (potable water, wastewater and stormwater) with built and natural landscapes to provide multiple benefits to the community.

The Urban Nutrient Decision Outcomes (UNDO) tool is a conceptual decision-support tool that evaluates nutrient-reduction decisions for urban developments on the Swan coastal plain. It has been designed to support proponents of urban development and decision-making authorities during the land use planning process: it predicts the nutrient impacts of an urban development and assesses the nutrient export associated with the proposed management practices (see recommended action 31). The UNDO tool also helps decision-making authorities to determine the likely reduction in nutrient export if existing stormwater systems were retrofitted.

New developments should be designed to manage nutrient export from stormwater runoff and subsoil drainage, in accordance with best practice for water quality, water quantity, supply and liveability outcomes. WSUD concepts and infrastructure (e.g. rain gardens, biofilters, infiltration basins, litter and sediment traps, constructed wetlands and living streams) can also be retrofitted to existing urban areas (at the lot, street or suburb scale) when existing structures are upgraded or redeveloped.

If WSUD infrastructure were retrofitted to all existing urban areas in the Peel-Harvey estuary coastal plain catchment, it is estimated that exported N and P loads from the highly urbanised reporting catchment of Mandurah would reduce by 0.8 t (16 per cent) and 0.2 t (31 per cent) respectively. In the Lower Serpentine reporting catchment (which also has a considerable urban area relative to its size), N and P loads were predicted to reduce by 6 to 9 per cent respectively.

Retrofitting WSUD in urban areas has other benefits. Small rainfall events in the summer months are likely to infiltrate in rural areas but create runoff from impervious areas in urban landscapes. This summer runoff transports nutrients to the estuary when the weather is warm and water temperatures are high, so the risk of algal blooms is elevated. The use of WSUD mitigates this risk. Areas that integrate WSUD principles also have better social amenity and community health outcomes, with greener, cooler urban environments – reducing the ‘urban heat island’ effect and thereby minimising heat-related deaths and stress incidents (Rogers et al. 2015). See Appendix L for further information about the benefits of retrofitting traditional drainage infrastructure using WSUD principles.

All redevelopments and infill/brownfield developments should incorporate WSUD principles as recommended by Waterwise Perth (Government of Western Australia 2021a, Government of Western Australia 2022a), and follow state planning and local government policies. Support and training for local government staff is essential.

Opportunities to retrofit existing stormwater systems according to WSUD principles (aligned with *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*) should be identified, particularly when upgrades to infrastructure are required (with due consideration to subsurface water). Stormwater management plans for local government areas are a good way to do this strategically. Retrofitting projects should be prioritised in reporting catchments where the reductions to nutrient loads are likely to be substantial, namely the Harvey, Mandurah, Lower Murray and Lower Serpentine reporting catchments.

Guidance for implementation

- Identify opportunities and priorities to retrofit existing stormwater systems; for example, as part of redevelopment and/or infrastructure upgrades.
- Use the UNDO tool to assess the likely efficacy of any retrofitting activity.

Improved management of point source urban nutrients

Management of discharges from wastewater treatment plants (WWTPs)

17. Recommended action

Increase the reuse of treated wastewater from wastewater treatment plants on green spaces where there is a low risk of leaching into waterways and promote the reuse of wastewater within the industrial (e.g. mining) and agricultural sectors by identifying opportunities and addressing barriers.

Where to implement? Reporting catchments where WWTPs are discharging effluent to the environment.

Where to start? Waroona WWTP in the Harvey and Kwinana WWTP in the Peel Main Drain reporting catchment.

WWTPs provide sewage disposal services for the community by receiving and treating wastewater, mostly from urban and industrial areas. In Western Australia, WWTPs are regulated by the department under Part V of the EP Act. Disposal methods for treated wastewater in the plan area include discharge to drains, irrigation of public open spaces, infiltration or industrial reuse. Discharging treated wastewater to the ground can result in export of nutrients to the Peel-Harvey estuary via infiltration to groundwater.

There are six WWTPs (Pinjarra, Harvey, Gordon Road, Mandurah no. 3, Waroona and Kwinana) operating within or just outside of the boundary of the plan area. The Pinjarra WWTP sends all treated wastewater to the Alcoa Refinery for industrial reuse and the Harvey WWTP discharges to the ocean via the Harvey Diversion Drain. Gordon Road and Mandurah no. 3 both discharge their treated wastewater to the ground where it enters groundwater via infiltration, and it is uncertain if this impacts the estuary. The Gordon Road WWTP is in a coastal subcatchment that drains to the ocean (beyond the plan area); however, it is possible that infiltrated treated effluent in groundwater could move east and express in Goegrup Lake (connected to the Serpentine River) although the load has not been quantified (Hennig et al. 2021). Similarly, the Mandurah no. 3 WWTP infiltrates treated wastewater adjacent to the ocean but is 1.3 km west of the estuary. We did not find any published reports that quantify the flow paths of infiltrated treated wastewater. While there are no related management actions in this plan, studies to determine the fate of infiltrated treated wastewater from these WWTPs may be warranted.

The Waroona WWTP in the Harvey reporting catchment discharges treated effluent to Drakesbrook Main Drain, with an estimated contribution of 2.8 t of N and 0.14 t of P to the estuary per year. In 2014, the PHCC, the Department of Water and Water Corporation constructed a nutrient-stripping swale on the Drakesbrook Main Drain. After one year, observations suggested the swale was reducing N and P concentrations by 30 and 50 per cent respectively. However, the long-term effectiveness of this treatment system needs to be confirmed. It is estimated that if the swale were carefully maintained and managed, the loads from the Waroona WWTP to the estuary could be reduced by 0.8 t for N and 0.07 t for P (both 0.4 per cent) each year.

The Kwinana WWTP discharges treated effluent via infiltration. It contributes nutrients to the Spectacles wetlands via groundwater infiltration (Shams 2000). The Peel Main Drain passes through the Spectacles wetlands and connects them to the estuary, with an estimated contribution of 1.4 t of N and 0.03 t of P per year.

See the modelling report that supports this WQIP (Hennig et al. 2021) for further details of all WWTPs in the Peel-Harvey estuary coastal plain catchment.

It is extremely important that operating licences and works approvals for WWTPs in the catchment include conditions that avoid or, where appropriate, minimise the export of nutrients and non-nutrient contaminants to the Peel-Harvey estuary.

Where wastewater is to be disposed of using irrigation, *Disposal of effluent using irrigation – technical guideline* (Tennakoon and Ramsay 2020) should be followed. This guideline helps operators and regulators understand what to evaluate when designing and managing effluent irrigation systems and has a particular focus on environmental and sustainability aspects.

Population growth in the Peel-Harvey region will increase wastewater effluent volumes, and hence future upgrades to WWTP infrastructure are likely. More efficient treatment technology and suitable reuse of fit-for-purpose treated wastewater (e.g. for golf courses or public open spaces where there is no risk of leaching to the estuary or its tributaries) will see larger volumes of wastewater being treated, while still reducing nutrient loads to the estuary. The demand for seasonal water for irrigation and for industrial mineral processing is an opportunity for further reuse of treated wastewater and reducing direct discharge to the environment, especially from the Kwinana and Gordon Road WWTPs.

Guidance for implementation

- Seek fit-for-purpose reuse of treated wastewater to increase the proportion of treated wastewater being recycled, with the aim of recycling all WWTP wastewater in the future.
- When WWTPs are expanded or upgraded to process increased volumes of wastewater, ensure no net increase in nutrient load (i.e. upgrade the technology and/or amount of waste being reused).
- Ensure licence conditions relating to nutrient concentrations in discharge are appropriate to prevent or minimise any further pollution of the catchment waterways, drains and the estuary.
- A formal review of industry licence and works approval conditions for prescribed premises/activities, through the provisions of the EP Act and the Environmental Protection Regulations 1987, may be required to ensure those conditions are adequately protecting the Peel-Harvey estuary system from further water quality decline.

Septic tank removal and connection to reticulated sewerage

18. Recommended action

Encourage the replacement of existing septic systems by way of connection to a reticulated sewerage network, where available. If reticulated sewerage is not available, a secondary treatment system with nutrient removal capability should be fitted.

Linked to recommended action 30.

Where to implement? Mandurah, Lower Serpentine, Upper Serpentine, Peel Main Drain, Lower Murray and Harvey (most remaining septic tanks are clustered in these catchments).

Where to start? Mandurah, Harvey and Lower Serpentine – see Table 9-1.

Disposing of sewage by reticulated sewerage poses the lowest health, environmental, social and economic risks to the community (Government of Western Australia 2019a). All new residential land subdivisions and developments are required to comply with the *Government Sewerage Policy* (Government of Western Australia 2019a), *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b).[52] These require that in sewerage sensitive areas such as the Peel-Harvey catchment, reticulated sewerage must be provided for all new lots less than 1 ha.[53]

Yet many existing residential properties in the plan area use septic tanks. Between 1994 and 2018 Water Corporation undertook an infill sewerage program to connect properties that were using septic tanks to reticulated sewerage services. This program enabled more than 100,000 septic tanks to be decommissioned, including in the suburb of Falcon. Of those, 1,900 properties in the plan area were connected to reticulated sewerage from 2000–15 (Appendix N).

In 2023, the State Government launched the Strategic Water Infrastructure Program, investing $55 million in water and wastewater infrastructure to support the creation of more diverse, affordable housing in areas marked for new or higher density development.

It is estimated that decommissioning septic tanks and connecting properties to reticulated sewerage as part of the infill program reduced the nutrient loading to the Peel-Harvey estuary by 6.6 t of N (1.2 per cent) and 0.33 t of P (0.6 per cent), with

[52] The *Government Sewerage Policy* (State of Western Australia 2019) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are published.

[53] The Peel-Harvey catchment is regarded as a sewerage sensitive area in the *Government Sewerage Policy* (Government of Western Australia 2019a) and a sensitive water resource area in *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) as it is an estuary catchment on the Swan coastal plain.

most of this load reduction (76 per cent) from the highly urbanised Mandurah reporting catchment.

About 12,000 septic tanks remain in the plan area (Appendix N). Most are clustered in the reporting catchments of Mandurah, Lower Serpentine, Upper Serpentine, Peel Main Drain, Lower Murray and Harvey. It is estimated that these septic tanks are contributing 4.2 per cent of the N and 2.6 per cent of the P loads to the estuary (Section 7.6). Although the nutrient loads attributed to septic tank leachate are relatively small compared with other land uses in the plan area, they are disproportionately large given the small area of the catchment they occupy.

The contribution of existing septic tanks to nutrient loads in more urbanised catchments can be significant. For example, septic tanks are estimated to contribute 32 per cent of the P load in the Lower Serpentine and 11 per cent of the N load in the Upper Serpentine. Note there are many other human health and ecological benefits in reducing sewage losses to waterways and drains.

Targeted infill sewerage results in an immediate and permanent removal of a source of nutrients and non-nutrient contaminants to the estuary, improving water quality and reducing odours and risks to human health. For existing residential properties with septic tanks in the plan area where sewerage connection is not feasible, we recommend upgrades to systems with secondary treatment for nutrient removal.

Septic tanks have advanced considerably in recent decades, but significant risks associated with their use remain. Regular inspection and maintenance of secondary treatment units is essential; health regulations require that these are serviced regularly by licensed personnel to achieve an acceptable level of treatment. See Section 6.2 of the *Government Sewerage Policy* (Government of Western Australia 2019a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) for full details of the maintenance requirements for secondary treatment systems.

Decommissioning septic tanks on lots adjacent to the Peel-Harvey estuary and the estuarine reaches of the Serpentine River (1,074 septic tanks) and connecting to reticulated sewerage, or even all septic tanks on smaller lots (< 1 ha) near waterways (1,926 septic tanks) (see Appendix N for septic tank locations), is estimated to reduce N and P loads to the estuary by less than 1 per cent. However, the localised impact of this action would be more significant. Within the Mandurah reporting catchment, the N load is estimated to reduce by 60 per cent (meeting the N load target for that catchment) and the P load by 29 per cent. Modest N reductions were also predicted in the Lower Serpentine (9 per cent) and the Peel Main Drain (5 per cent) reporting catchments.

Infill sewerage programs should prioritise the 1,074 properties with septic tanks on lots adjacent to the estuary in the Harvey, Mandurah, Lower Serpentine and Peel Main Drain reporting catchments – see Table 9-1 and Figure 9-3. The priority lots were selected based on the estimated nutrient contribution to the estuary, density of unsewered lots, and proximity to existing sewerage infrastructure and to the estuary.

See Appendix L for further background and benefits of this action are described in Appendix L, along with relevant objectives of in the *Government Sewerage Policy* (Government of Western Australia 2019a) that align with this recommended action. *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are also relevant.[54]

Table 9-1 Priority areas for inclusion in future infill sewerage program

Unsewered area	**Reporting catchment**	**No. properties**	**Average lot size** (m^2)
Park Ridge-Bouvard	Harvey	229	1,200
Falcon	Mandurah	525	850
Coodanup	Lower Serpentine	123	1,050
Pleasant Grove	Mandurah	197	4,000

[54] The *Government Sewerage Policy* (State of Western Australia 2019) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are published.

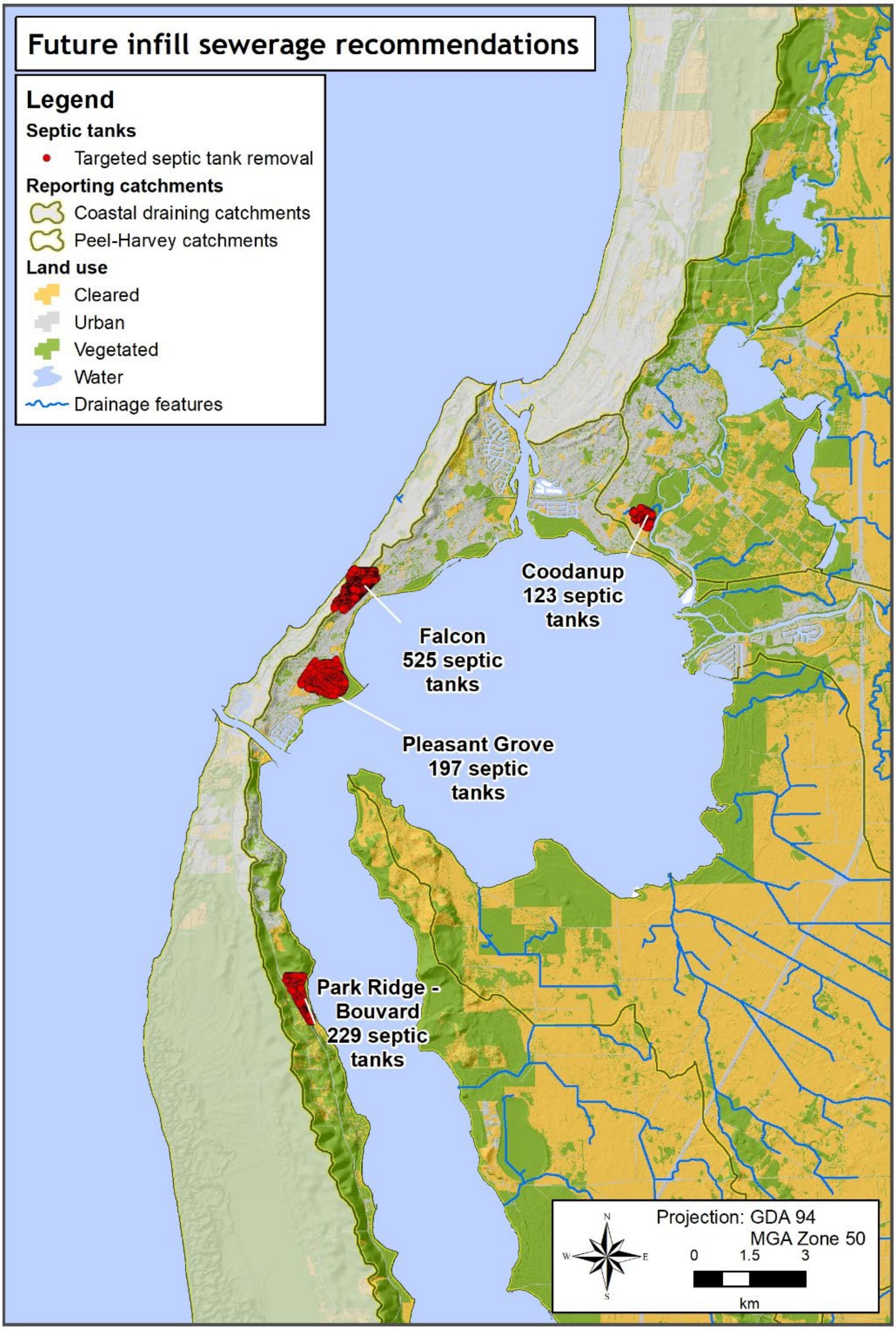

Figure 9-3 Location of unsewered areas recommended for inclusion in future infill sewerage programs

Guidance for implementation

- Infill sewerage programs should prioritise the 1,074 properties with septic tanks on lots adjacent to the estuary in the Harvey, Mandurah, Lower Serpentine and Peel Main Drain reporting catchments (Table 9-1 and Figure 9-3).
- For existing properties with septic tanks where sewerage connection is not available, we recommend a targeted approach to upgrade existing on-site systems with secondary treatment systems that have low-nutrient-emission secondary treatment units (nutrient-retention capabilities).
- Where septic tanks are fitted with secondary treatment units for nutrient removal, regular inspection and maintenance is essential. Health regulations require that secondary treatment units are serviced regularly by licensed personnel to achieve an acceptable level of treatment.

Drainage works and in-stream management to improve water quality

Drainage works

19. Recommended action

Implement the 2017 Drainage Partnering Agreement between Water Corporation, the Department of Water and Environmental Regulation and the Peel-Harvey Catchment Council.

Where to implement? All reporting catchments with Water Corporation drains that flow to the estuary. To implement this action, more detailed mapping of drains and existing fencing may be required on a local scale.

This action includes excluding stock from Water Corporation drains to reduce the export of organic matter (from animal waste) and nutrients. We recommend stock exclusion for all reporting catchments where dairy and/or beef grazing is occurring in or near a drain. Areas with higher stocking rates should be prioritised.

Where to start? Drains high in nutrient concentrations, depending on the selected management intervention. For stock exclusion: Harvey, then Dirk Brook, Lower Murray and Upper Serpentine, followed by Nambeelup and Mayfield.

Linked to recommended action 7.

20. Recommended action

For all drains across the catchment, evaluate approaches (e.g. in-drain vegetation and sediment traps) to improve water quality in drains that discharge to the Peel-Harvey estuary and its tributaries. Implement approved approaches in prioritised drains.

Where to implement? All reporting catchments with drains that flow to the estuary.

Where to start? Drains high in nutrient concentrations, depending on the selected management intervention.

The engineered drainage (main drains) on the Peel-Harvey coastal plain has facilitated agricultural and urban development over what was once an enormous complex of wetlands (Bradby 1997). The 1,320 km drain network is the main conduit of nutrients and non-nutrient contaminants to the estuary. Sediments and organic matter may settle out in these channels but are nevertheless a source of nutrient and organic loading to the estuary that can mobilise during floods or large flow events.

Water Corporation is responsible for the design, construction, operation and maintenance of most of the urban and rural drains in the catchment, including all the main drains, which carry the bulk of the agricultural contaminants to the estuary. In this role, Water Corporation must meet the requirements of its operating licence under the Economic Regulation Authority, with a focus on conveying drainage water for flood protection. However, Water Corporation acknowledges the importance of considering water quality in the management of drainage water and has committed to improved environmental and liveability outcomes for the drainage systems in the Peel-Harvey catchment (Peel-Harvey Catchment Council, Water Corporation and Department of Water 2017).

There has been significant interest in drainage interventions to reduce nutrient loadings to estuaries. Several approaches have been tested Swan coastal plain, but very few have been applied at scale. Integrated drainage design seeks to reduce peak instantaneous flows from cleared and developed lands, thereby slowing the flow of nutrients and organic matter and reducing in-channel sediment movement. The PHCC has tested this approach in the Mayfield reporting catchment with funding from the REI, and while long-term reductions in nutrient loading are yet to be documented, there have been notable benefits to the farmer and on-farm biodiversity.

Preventing stock access (through stock-exclusion fencing) and avoiding the use of fertilisers adjacent to drains offers significant water quality benefits, particularly for local waterways as discussed for recommended action 7 (page 168).

Some drains in the catchment are already highly bioactive (Wells et al. 2019), attenuating N and reducing the amount of N that reaches the estuary. Increasing vegetation in drains may improve nutrient attenuation but it can also impede flow and result in upstream flooding during large flow events. Flood risks could be managed through a hydrological assessment, with consideration given to species selection and long-term maintenance. We recommend more work to investigate the relationship between drain features (e.g. morphology, groundwater input, flow rate and vegetation) and N attenuation (Wells et al. 2019) to identify elements of the drainage system that can be maintained or enhanced as part of a management strategy.

Gull Road Drain (AWRC ref. 614120) has the highest TP and TN concentration of any monitored site within the plan area (Section 3.2) and thus should be considered for drainage work to improve its water quality and reduce impacts on the estuary system downstream.

Drainage work to improve water quality is sometimes at odds with drain management practices intended to get water off the land quickly. The Drainage Partnering

Agreement (2017) between the PHCC, Water Corporation and the department aims to achieve integrated drainage management considering multiple outcomes, including flood management, water quality and community amenity. During the past four years, the partners have worked together on a project to divert waters from the Peel Main Drain through a series of swales designed to test various treatment approaches. The project has identified several procedural, technical and logistical challenges that will need to be addressed in future projects as we move away from conventional practices.

Guidance for implementation

- Evaluate management actions to improve water quality in priority drains, including Water Corporation-managed drains, such as Gull Road Drain (AWRC ref. 614120) and those draining to the Harvey Estuary.

The use of phosphorus-binding clay in waterways and drains

21. Recommended action

Investigate, develop and evaluate the use of innovative materials for phosphorus removal in drains, including phosphorus-binding clays.

Where to implement? Drains with high filterable reactive phosphorus (FRP) concentrations and moderate flows in a suitable location to undertake a trial.

Once nutrients end up in waterways and drains, cost-effective ways to remove them are limited. Applying a P-binding clay may be effective. Phoslock®, developed by the CSIRO and Water and Rivers Commission in the 1990s, is the only commercially available product of its type, with proven results in fresh water worldwide. However, the product cannot be applied to saline or brackish water, which excludes its use in estuaries.

The department has been investigating an alternative P-binding clay, which is made by coating bentonite clay with mineral hydrotalcite (see Appendix A). Hydrotalcite clay (HT-clay) is effective at higher salinities and may be a viable option for treating estuarine waters. In addition, HT-clay has shown promise in the flocculation of algal blooms, although this property needs further investigation.

HT-clay is applied in a similar manner to Phoslock®: it is added as a slurry directly to drains or waterways (Figure 9-4) where it binds with P in the water column – immediately reducing P concentrations and making it unavailable for algal growth. The clay eventually settles to the sediment surface, forming a thin protective layer that reduces the release of P to the overlying water over time. P-binding clays may be a useful interim measure while other long-term actions to reduce nutrient inputs take effect.

Our investigations were supported by the REI and we will continue to refine the production of HT-clay and test its application as part of Healthy Estuaries WA. We will also continue to evaluate its suitability for widespread application, either on its own or in conjunction with Phoslock®.

Figure 9-4 Clay application to stationary water (left) and to a flowing drain (right)

Guidance for implementation

- Continue to refine the production of HT-clay to improve the manufacturing process.
- Strategically select rural waterways and/or agricultural drains (and other water environments, as appropriate) that have ideal conditions for treatment (moderate to high nutrient concentrations, low to moderate flows) to test the application of HT-clay.
- Continue to test HT-clay in rural waterways and agricultural drains to evaluate its suitability and effectiveness for widespread application, either on its own or in conjunction with Phoslock®. Aim to:
  - better understand the optimal application rates, environment and conditions for application
  - conduct a detailed environmental risk assessment
  - provide information to support further research and development.

Other management actions to improve water quality and biodiversity

River restoration to improve ecological function of waterways

22. Recommended action

Reinstate the ecological function of key waterways through restoration works and revegetation of the margins.

Where to implement? All reporting catchments that have key waterways that flow to the estuary. More detailed mapping may be required in priority areas.

Where to start? Nambeelup, Harvey, Mayfield and Upper Serpentine.

Restoring the ecological function of waterways and drains – through restoration works and revegetation – also supports water quality improvement, with nutrients converted to living material or remineralised in the sediments. Appendix L outlines the many environmental benefits of vegetated riparian zones and provides further information relevant to implementing this action.

Excluding stock from the waterways (see recommended action 7) is often the first step to river restoration. It prevents the trampling of vegetation, the destabilisation and erosion of banks, and the direct input of animal waste into the water. This in turn improves macroinvertebrate and plant biodiversity on the banks and in the waterway. Where waterways are heavily degraded and/or artificially straightened, modification of channel morphology may be needed to slow the flow, support the restoration of in-stream habitat, and achieve long-term stability (Water and Rivers Commission 1999–2003). Other river restoration techniques described in the *River restoration manual* (Water and Rivers Commission 1999–2003), such as artificially stabilising banks to reduce erosion or providing in-stream habitat (e.g. riffles, snags and logs), can also help to restore stream function and improve biodiversity.

The Harvey River demonstration project is an example of successful river restoration along the lower Harvey River (Harvey Main Drain at Bristol Road). Managed by the HRRT under the 'Marron, more than a meal – revive our rivers' program, this project aimed to enhance habitat diversity and water quality to improve the long-term resilience of native fish and crayfish communities. Actions included fencing, riparian revegetation with native species, and placement of large logs and rocks to provide in-stream habitat diversity and longitudinal connectivity for aquatic fauna. This project is a good example of how NRM groups can work with Water Corporation and State Government to transform a drain into an ecological asset. In this project, Water Corporation carefully balanced the social, ecological and economic values of waterways with its responsibilities to ensure acceptable flow and water levels.[55]

This action is also being implemented through the Healthy Estuaries WA program and the *Bindjareb Djilba Protection Plan* (DWER 2020b), as well as various other projects managed by NRM groups such as the PHCC and HRRT (see 'Riparian zone management (stock exclusion and revegetating riparian zones), p.168). The PHCC and HRRT also raise awareness about the importance of appropriate riparian management and restoration and build capacity within the community to implement river restoration projects.

Another program that may help to further implement this action is the State Government's Carbon Farming and Land Restoration program (led by DPIRD). This program funds activities such as revegetation on South West farms that sequester carbon in the landscape and deliver additional, positive outcomes referred to as 'co-benefits' (e.g. biodiversity and conservation).[56]

[55] As part of this project, Water Corporation undertook hydraulic analyses to investigate the potential impact of structures (i.e. large logs) on water levels under several flow scenarios.

[56] Western Australian Carbon Farming and Land Restoration Program

As discussed in recommended action 7, we support the strategic riparian management performed by NRM groups in the catchment, with the following work helping to inform priorities:

- river action plans including the *Waangaamaap Bilya Serpentine River action plan* (Urbaqua 2020) and Murray River action plans (Peel-Harvey Catchment Council 2014, Peel-Harvey Catchment Council 2015)
- river health assessments and ecological health assessments conducted by the department (Section 3.2) and NRM groups
- catchment nutrient reports published by the department.

Guidance for implementation

- Raise public awareness of the environmental benefits of revegetating riparian zones and other river restoration actions, such as better water quality and ecological health (both locally and in the receiving estuary), as well as benefits to farmers and landowners (such as reduced local erosion, improved animal health, enhanced amenity and increased land value).
- Identify and prioritise areas in the Peel-Harvey estuary coastal plain catchment for riparian revegetation and/or river restoration to reduce erosion, improve water quality and enhance ecological function. Consider co-benefits such as improved habitat and biodiversity, protection of threatened species, carbon sequestration, and protection of traditional sites and food places. Hydraulic analysis or flow modelling may be necessary to investigate potential impacts to upstream flood risks.
- Develop and implement river action plans, as appropriate, to guide restoration actions (e.g. revegetation, introducing riffles or woody debris, and riverbank stabilisation).
- Request expressions of interest from farmers/landowners in identified priority areas. Then strategically select farmers/landowners to revegetate and restore waterways/drains using best practice. Grazing stock must first be excluded from the waterway/drain (see ‘Riparian zone management (stock exclusion and revegetating riparian zones)’, page 168).

Catchment revegetation

23. Recommended action

Undertake strategic revegetation of the catchment to improve biodiversity, mitigate climate change effects, and contribute to water quality improvement.

Where to implement? All reporting catchments with less than 50 per cent deep-rooted vegetation cover (i.e. all except Meredith Drain).

Where to start? Harvey, followed by Nambeelup, Mayfield and Upper Serpentine.

Deep-rooted native vegetation on the Peel-Harvey coastal plain has been extensively cleared to make way for shallow-rooted annual crops and pasture for animal grazing.

Native vegetation coverage is very low in many of the reporting catchments of the Peel-Harvey (Figure 9-5).

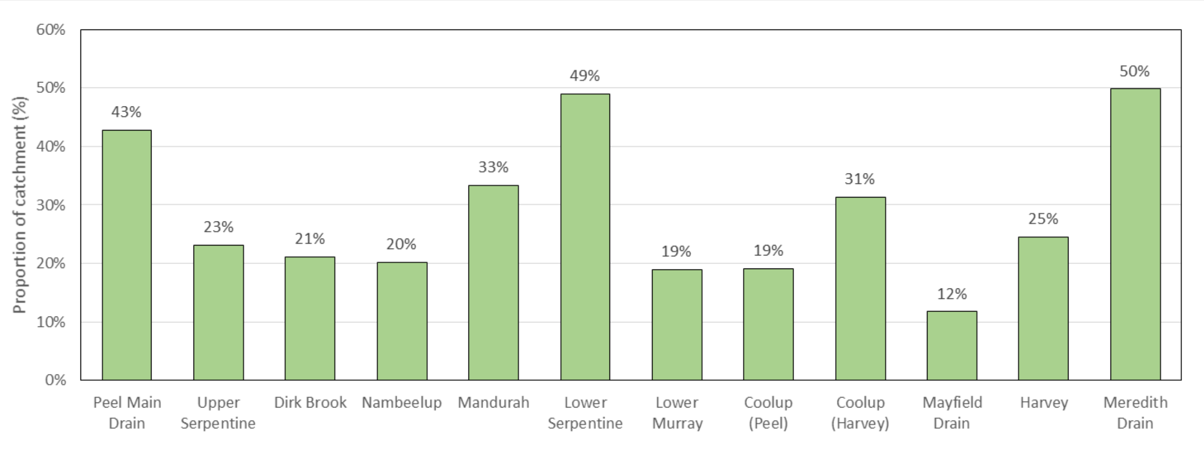

Figure 9-5 Vegetation coverage (native and plantation as per cent) in the reporting catchments of the Peel-Harvey estuary (excluding vegetated areas of the Darling Scarp)

In addition to increased nutrient inputs to the estuary, this land use change has led to rising groundwater tables (see Appendix L for a summary of other impacts). Re-planting with vegetation capable of growing deep roots, such as native trees, can reverse these trends.[57] Substantial areas of deep-rooted vegetation in a catchment have many environmental benefits, including improving the water quality of receiving waterbodies.

In *State Planning Policy 2.1: The Peel-Harvey coastal plain catchment* (WAPC 1992), a target was set for 50 per cent coverage with deep-rooted vegetation across the coastal catchment. But this was difficult to apply to local government and lot-scale development applications (where a target of 25–30 per cent vegetation cover is considered more feasible and has more typically been achieved).

A scenario was modelled where 248 km^2 of beef and cropping land (preferentially low PRI soils) was revegetated with deep-rooted native species to achieve 50 per cent coverage across the reporting catchments. In this scenario, flow reduced by 11 per cent, while N loads to the estuary were predicted to reduce by 15 per cent (84 t) and P loads by 33 per cent (20 t).[58]

[57] Native plants capable of growing deep root systems can access deeper groundwater. But where groundwater levels are high, these plants may not need to develop deep root systems.

[58] The modelled scenario included some vegetated areas of the Darling Scarp which are outside of the Peel-Harvey coastal plain catchment. Achieving 50 per cent coverage would require slightly more revegetation of cleared land.

Replacing shallow-rooted species with plantations will also likely improve water quality in receiving waterways and drains and may lower the groundwater table.[59] Plantations are often promoted as an alternative land use offering a form of income; however, plantations can have large offsite impacts, such as sending large sediment loads to streams from increased erosion during regular operation and maintenance work (road access), or during harvesting and replanting (Parkyn 2004). In addition, plantations can increase loads of nutrients and non-nutrient contaminants (e.g. pesticides) going to waterways and shallow groundwater if they are not well managed.

Current information and guidelines in place for plantations in Western Australia include:

- *Review of fertiliser use in Australian forestry* (May et al. 2009)
- *Code of practice for timber plantations in Western Australia* (Forest Industries Federation WA Inc. 2014).

The Western Australian plantation industry is encouraged to develop and implement BMPs for minimising the loss of nutrients, organic matter and sediment from plantation sites to ground and surface water that influences the Peel-Harvey estuary.

Revegetating with deep-rooted native species avoids the risks associated with plantation farms, while potentially offering substantial biodiversity gains and long-term carbon sequestration. Revegetating with these species can be incorporated into regional parks and conservation reserves to improve terrestrial biodiversity, preserve waterway foreshore areas (river corridors) and provide waterway buffers.

The PHCC has made some progress with revegetation on farms by supporting farmers to plant native shelterbelts. Shelterbelts are strips of deep-rooted vegetation within crops or pastures (Figure 9-6) which provide shelter for pasture, crops and livestock; act as windbreaks and help to control soil erosion; protect remnant vegetation; improve biodiversity; offer aesthetic benefits; and improve farm productivity and sustainability (Bird et al. 1992). The widespread adoption of shelterbelts on farms could increase the area of deep-rooted vegetation by as much as 56 km^2 on the Peel-Harvey estuary coastal plain (Kelsey et al. 2011).

Wherever possible, remnant vegetation in the coastal plain should be retained and rehabilitated, particularly riparian vegetation along waterways, and new developments should be located on previously cleared areas. The *Native vegetation policy for Western Australia* (DWER 2022c) developed by the department will help protect and conserve remnant vegetation in the Peel-Harvey estuary coastal plain catchment.

Strategically revegetating areas of the Peel-Harvey estuary coastal plain catchment with deep-rooted native species is recommended for water quality improvement, as

[59] Revegetating using tree plantations is estimated to reduce P by 31 per cent, while revegetating with deep-rooted native species is estimated to reduce P by 33 per cent, see Hennig et al. (2021).

well as to support significant biodiversity, ecological and climate change-related outcomes. Appendix L further summarises the benefits of this action.

This WQIP supports a target of 50 per cent deep-rooted vegetation coverage across the Peel-Harvey estuary coastal plain catchment. Note that we do not consider it feasible to achieve this through lot-scale development applications, rather it is likely to require State Government-led initiatives that either buy-back private land or utilise government-owned, cleared or highly degraded land. Priority areas of agricultural land should be identified (e.g. beef farms with low PRI soils) and incentives provided to landowners to increase the area of their property allocated to deep-rooted native vegetation.

The Green Jobs Plan was a $60 million State Government initiative to help Western Australia's economy recover from the impacts of the Covid-19 pandemic. The Green Jobs Plan aimed to support projects that protect the environment and create jobs in the conservation industry. Two of the programs that the department delivered under the plan were the $8 million Offsets Funds for Recovery program and the $15 million Native Vegetation Rehabilitation Scheme. These programs were delivered through the Environmental Revegetation and Rehabilitation Fund (ERRF).

The ERRF targets the restoration of biodiversity values damaged by past clearing. On-ground works such as fencing, weeding, seeding and planting will create employment opportunities, while achieving revegetation, rehabilitation, habitat restoration and protection of existing vegetation.

Another program that may help to further implement this action is the State Government's Carbon Farming and Land Restoration program (led by DPIRD) – see recommended action 22.[60]

[60] Western Australian Carbon Farming and Land Restoration Program

Figure 9-6 Shelterbelts on farms in the wheatbelt. Photo credit: © State of Western Australia (DPIRD, WA).

Guidance for implementation

- Develop and implement a strategic plan to increase deep-rooted native vegetation across the coastal estuary catchment using suitable native species (preferably endemic). Carefully consider effective fire management strategies.
- Encourage increased coverage of deep-rooted vegetation throughout the coastal estuary catchment wherever feasible. Ways to do this could include government buy-back of land for revegetation or by supporting landholders to plant shelterbelts on farms.

Summary of results from modelled catchment management actions

Modelling suggests that no single action will achieve the P and N load targets (calculated using the nutrient concentration objectives of WQOs 1 and 2) (Table 9-2 and Table 9-3).

Table 9-2 The individual scenario N reductions of reporting catchments in the plan area

Reporting catchment	**Basecase**	**Load reduction target**		**Catchment revegetation**		**Dairy effluent management**		**Intensive sources**				**WWTP management**		**Septic tank removal**		**WSUD in existing urban areas**		**Constructed wetlands**		**Riparian zone management**			
				Native vegetation				**Intensive animal industries**		**Intensive horticulture**				**Scenario 1: Targeted septic tank removal**						**Stock exclusion (fencing only)**		**Fencing and revegetation**	
	Load to estuary (kg)	Load reduction (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)	Load removed (kg)	(%)
Peel Main Drain	11,586	3,306	29	1,283	11	0	-	863	7.4	242	2.1	0	-	0	-	549	4.7	3,476	30	1,017	8.8	1,913	17
Upper Serpentine	71,844	31,125	43	5,325	7.4	429	0.6	8,719	12	1,037	1.4	0	-	0	-	933	1.3	21,553	30	5,020	7.0	14,203	20
Dirk Brook	28,748	13,667	48	0	-	51	0.2	4,111	14	541	1.9	0	-	0	-	1	<0.1	8,624	30	1,935	6.7	5,021	17
Nambeelup	40,302	27,616	69	14,638	36	270	0.7	192	0.5	7	<0.1	0	-	0	-	5	<0.1	12,091	30	3,488	8.7	9,265	23
Mandurah	5,007	1,129	23	0	-	0	-	0	-	0	-	0	-	3,011	60	817	16	0	-	0	-	0	-
Lower Serpentine	11,724	5,396	46	182	1.6	0	-	884	7.5	21	0.2	0	-	380	3.2	504	4.3	0	-	641	5.5	1,127	10
Upper Murray	80,210	24,069	30	6,674	8.3	0	-	197	0.2	61	<0.1	143	0.2	0	-	120	0.1	0	-	7,046	8.8	13,150	16
Lower Murray	103,388	42,137	41	0	-	42	<0.1	6,572	6.4	84	<0.1	0	-	0	-	674	0.7	0	-	4,130	4.0	9,812	9.5
Coolup (Peel)	20,999	9,567	46	8,125	39	146	0.7	134	0.6	0	-	0	-	0	-	8	<0.1	0	-	1,704	8.1	4,940	24
Coolup (Harvey)	13,349	5,763	43	3,532	26	116	0.9	54	0.4	71	0.5	0	-	0	-	27	0.2	0	-	1,040	7.8	3,034	23
Mayfield Drain	33,299	15,294	46	13,840	42	117	0.4	77	0.2	18	<0.1	0	-	0	-	1	<0.1	9,990	30	1,070	3.2	7,570	23
Harvey	205,464	100,840	49	37,530	18	1,116	0.5	176	<0.1	420	0.2	830	0.4	201	<0.1	818	0.4	61,639	30	18,097	8.8	41,390	20
Meredith Drain	6,739	4,030	60	0	-	0	-	863	13	13	0.2	0	-	0	-	0	-	2,022	30	584	8.7	1,558	23
Coastal estuary catchment (plan area)	**552,447**	**259,869**	**47**	**84,455**	**15**	**2,288**	**0.4**	**22,646**	**4.1**	**2,454**	**0.4**	**830**	**0.2**	**3,593**	**0.7**	**4,337**	**0.8**	**119,394**	**22**	**38,726**	**7.0**	**99,834**	**18**

Table 9-3 The individual scenario P reductions of reporting catchments in the plan area

Reporting catchment	Basecase	Load reduction target		Catchment revegetation		Fertiliser management		Fertiliser management with LWSP fertilisers		Dairy effluent management		Soil amendment		Intensive sources				WWTP management		Septic tank removal		WSUD in existing urban areas		Constructed wetlands		Riparian zone management	
				Native vegetation										Intensive animal industries		Intensive horticulture				Scenario 1: Targeted septic tank removal						Stock-exclusion fencing and revegetation	
	Load to estuary	Load reduction		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed		Load removed	
	(kg)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)
Peel Main Drain	1,418	728	51	83	5.8	47	3.3	54	3.8	0	-	34	2.4	24	1.7	649	46	0	-	0	-	79	5.6	709	50	37	2.6
Upper Serpentine	9,975	6,581	66	1,444	14	1,945	20	2,364	24	136	1.4	2,215	22	258	2.6	1,911	19	0	-	0	-	107	1.1	4,987	50	353	3.5
Dirk Brook	2,777	1,520	55	0	<0.1	746	27	923	33	19	0.7	883	32	205	7.4	286	10	0	-	0	-	0	0.0	1,388	50	85	3.1
Nambeelup	6,664	5,607	84	2,714	41	2,621	39	3,272	49	53	0.8	3,614	54	23	0.3	22	0.3	0	-	0	-	1	0.0	3,332	50	253	3.8
Mandurah	514	190	37	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	148	29	161	31	0	-	0	-
Lower Serpentine	2,139	1,611	75	49	2.3	496	23	629	29	0	-	662	31	186	8.7	66	3.1	0	-	11	0.5	189	8.9	0	-	37	1.7
Upper Murray	960	0	0	73	7.6	1	0.1	1	0.1	0	-	0	-	3	0.3	18	1.8	41	4.3	0	-	2	0.2	0	-	153	16
Lower Murray	6,212	1,108	18	0	-	2,445	39	2,955	48	14	0.2	2,555	41	54	0.9	190	3.1	0	-	0	-	83	1.3	0	-	111	1.8
Coolup (Peel)	2,747	1,795	65	1,934	70	1,108	40	1,359	49	47	1.7	1,288	47	26	0.9	0	-	0	-	0	-	1	0.0	0	-	107	3.9
Coolup (Harvey)	2,053	1,421	69	843	41	803	39	994	48	39	1.9	1,007	49	22	1.1	82	4.0	0	-	0	-	7	0.3	0	-	77	3.7
Mayfield Drain	3,619	2,119	59	2,607	72	1,466	41	1,773	49	48	1.3	1,597	44	1	0.0	79	2.2	0	-	0	-	0	0.0	1,810	50	136	3.8
Harvey	20,109	11,391	57	9,942	49	7,387	37	8,724	43	669	3.3	6,728	33	25	0.1	204	1.0	71	0.4	60	0.3	66	0.3	10,055	50	773	3.8
Meredith Drain	1,045	819	78	0	-	268	26	340	33	0	-	362	35	167	16	31	3.0	0	-	0	-	0	-	522	50	40	3.9
Coastal estuary catchment (plan area)	**59,272**	**34,890**	**59**	**19,615**	**33**	**19,332**	**33**	**23,387**	**39**	**1,027**	**1.7**	**20,945**	**35**	**990**	**1.7**	**3,521**	**5.9**	**71**	**0.1**	**219**	**0.4**	**694**	**1.2**	**22,803**	**38**	**2,009**	**3.4**

Combined catchment management scenarios

Strategic implementation of a combination of management actions, applied across the plan area, is required to progress towards achieving this WQIP's WQOs. The modelling found:

If a combination of management actions relating to best-practice agriculture were put in place on beef and dairy farms across the estuary coastal plain catchment, including:

- optimising fertiliser use, including slow-release P fertiliser on low PRI soils
- applying soil amendments to low PRI soils
- implementing best-practice effluent management in all dairy operations (i.e. meeting the 2021 *Code of practice for dairy farm effluent management WA*)

then the average annual P load to the estuary would reduce to 25 t (58 per cent reduction) – very close to the target load of 24 t (59 per cent reduction).

If we **add to this** a suite of non-agricultural management actions that reduce N loads to the estuary including:

- revegetating land currently used for grazing and replanting with deep-rooted native species (24,770 ha, preferentially replacing beef/dairy farms on low PRI soils)
- fencing to exclude stock plus riparian revegetation of 1,394 km of waterways and drains
- minimising discharge of point sources including piggeries, feedlots and stockyards to waterways and drains
- decommissioning septic tanks that are in environmentally sensitive areas and connecting those properties to reticulated sewerage (1,074 units)
- retrofitting all urban areas using WSUD principles

then the average annual P and N loads to the estuary would reduce to 20 t (67 per cent reduction) and 358 t (35 per cent reduction) respectively. These modelled loads meet the P load target and come close to meeting the N load target. As the N load target is based on TN, and much of that is known to be DON, further work is needed to ascertain the bioavailability of DON and potentially identify alternative approaches to addressing N export to the estuary (see recommended action 39). This work may determine that targets for the most bioavailable fractions are more appropriate (e.g. nitrate and total ammonia).

As well as reducing nutrient loads to the estuary, revegetating with deep-rooted native species and stock-exclusion fencing with revegetation of the riparian zone, have significant ecological benefits including improving biodiversity and mitigating climate change.

As discussed previously under individual actions, there are assumptions associated within the above scenarios. For example, mining by-products for broadscale soil amendment application have limited commercial availability. Supporting farmers to modify the way they use and apply fertiliser will also take time.

Figure 9-7 compares the effectiveness of selected management actions to reduce nutrient export from the plan area and shows the level of implementation assumed in the Peel-Harvey Catchment Model – see Hennig et al. (2021). It also shows the predicted impact of the combined management scenario (as described above).

Figure 9-7 The impact of land use change and management scenarios in reducing N and P loads exported to the Peel-Harvey estuary

The combined scenario modelling (Figure 9-7) estimates N and P load reductions over time – with full implementation. The modelling highlights the importance of applying management actions in series and matching these to the landscape, the primary land uses and the localised water quality issues to meet WQOs 1 and 2.

When planning for implementation, more precise modelling can estimate the load reductions of management actions at varied adoption rates and in specific reporting catchments. Modelled predictions are based on full implementation of management actions and are thus considered a best-case outcome.

Cost-benefit analysis of modelled management actions

For the management actions that were modelled, we undertook a high-level cost-benefit analysis which compared the indicative capital with the expected benefit, as measured by the reduction in nutrient loading to the estuary (in $/kg nutrient removed/year) (Table 9-4).[61] The numbers indicate which actions deliver the greatest water quality outcomes for investment at a broad scale. Note that when actions are targeted to specific catchments and specific land uses, their cost per unit P or N removed can reduce dramatically. A cost-benefit analysis could not be performed for all management actions because of a lack of data (either on their effectiveness in reducing nutrient exports or costs associated with their implementation).

The figures in Table 9-4 are general only and do not include staff wages or project related on-costs or any economic benefits to the farmer (e.g. savings associated with less fertiliser use or improved soil productivity). Benefits are measured solely by the reduction of nutrient inputs, with the assumption that implemented actions are effective in reducing P loss, as modelled. Many actions to reduce nutrient runoff will result in other tangible outcomes, such as those from stock-exclusion fencing with riparian revegetation, which also improves habitat, biodiversity and bank stability.

The most effective modelled management actions for reducing P loads to the estuary are soil amendments, fertiliser management and catchment revegetation with native plants capable of growing deep roots (Table 9-3). Fertiliser management and soil amendments are also the two least expensive catchment management actions to implement at ~$16/ha (1.8 million total capital) and $1,080/ha ($54.2 million total capital) respectively. They also have the lowest costs per kg of P removed of all actions costed in Table 9-4 ($77–93 per kg P removed for fertiliser management and $5–$2,590 per kg of P removed for soil amendments).[62]

The most effective modelled management actions for reducing N loads are riparian zone management (stock-exclusion fencing with riparian revegetation), catchment revegetation with deep-rooted native vegetation, and improved management of point source pollution (no cost-benefit available for the latter two) (Table 9-2).[63] Riparian zone management options were also the most cost-effective management actions considered in Table 9-4 ($404 per kg N removed for stock-exclusion only; $573 per kg N removed for stock exclusion and riparian revegetation).

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[61] Modelled actions that were not costed include those relating to intensive animal industries, WWTPs, WSUD and catchment revegetation.

[62] For fertiliser management, the upper cost relates to fertiliser management alone while the lower cost relates to fertiliser management using slow-release P fertiliser. For soil amendment, the upper cost relates to soil amendment being applied to all low PRI soils in the plan area, whereas the lower cost of $5 per kg relates to soil amendment being strategically applied to soils with known high P losses (Degens et al. 2023) (as identified from soil testing of farms such as that which occurs as part of the Sustainable Agriculture Strategy of Healthy Estuaries WA).

[63] This excludes the implementation of bottom-of-catchment treatment wetlands which are not considered feasible (see Use of constructed wetlands, page 172).

The use of large, constructed wetlands at the bottom of catchments to remove diffuse-source nutrients was found to be prohibitively expensive, with an estimated capital cost of $1.29 million/ha and high ongoing maintenance costs. Nevertheless, in an agricultural setting they remain a promising option to treat runoff with high nutrient concentrations from intensive, diffuse nutrient sources (see recommended action 8).

Costs included in Table 9-4 are indicative only and should be considered carefully. Appendix O provides information on the data sources used to estimate the costs in Table 9-4. Although managing point sources such as dairy effluent or decommissioning septic tanks and connecting to reticulated sewerage are relatively expensive per unit ($100,000/dairy shed and $45,000/septic tank), these are one-off costs for nutrient removal, compared with other management actions that are ongoing. For example, fertiliser management has an ongoing annual cost ($16/ha) and constructed wetlands have very high maintenance costs.

The three management actions on beef and dairy farms that will have the greatest impact on nutrient loads

This WQIP recommends the State Government supports beef and dairy farmers in the Peel-Harvey estuary coastal plain catchment to undertake the following three fundamental farm management actions for the greatest impact on nutrient loads to the estuary:

- reduce P fertiliser losses by optimising fertiliser use for agronomic requirements, as determined by soil testing, agronomic advice (or DPIRD's nutrient calculator) and demonstration trials (recommended action 1)
- improve P retention in sandy soils used for intensive and broadscale agriculture by using soil amendments (recommended action 4)
- improve effluent management within dairy operations to minimise discharge and maximise reuse of water and nutrients to standards in the code of practice (recommended action 9).

Implementation can be achieved through existing and future programs that support farmers (with co-funding and through extension work). Where high levels of nutrient export exist in a reporting catchment, or there are land uses that constitute point sources of nutrient pollution (other than dairy sheds), we recommend additional management actions, as appropriate.

Table 9-4 Estimated capital cost of implementing each management action relative to the reduction in N and P loads entering the estuary (from reporting catchments that drain to the estuary)

Management practice	**Capital cost per unit** $/unit		**Capital cost** $ (mil)	**N load removed** kg/yr	**P load removed** kg/yr	**Cost per unit N removed** $/kg	**Cost per unit P removed** $/kg
Best-practice fertiliser management (111,830 ha of beef and dairy farms)	$16.0	per ha	$1.8		19,332		$93
Best-practice fertiliser management and slow-release P fertilisers (slow-release P fertilisers on 50,220 ha low-PRI soils and traditional P fertilisers on 61,610 ha high-PRI soils)	$16.1	per ha	$1.8		23,387		$77
Soil amendment (50,220 ha of low-PRI beef and dairy farms)	$1,080	per ha	$54.2		20,945		$5–$2,590 *
Dairy effluent management (25 dairy farms)	$100,000	per shed	$2.5	2,288	1,027	$1,093	$2,435
Infill sewerage (1,074 septic tanks)	$45,000	per septic	$48.3	3,593	219	$13,453	$220,469
Riparian zone management:							
(stock exclusion from 1,043 km of streams and drains)	$15,000	per km	$15.6	38,726	1,536	$404	$10,186
(stock exclusion and revegetation of 1,394 km of streams and drains)	$41,000	per km	$57.2	99,834	2,009	$573	$28,457
Constructed wetlands (811 ha across seven catchments)	$1,291,000	per ha	$1,047.0	119,394	22,803	$8,769	$45,914

* The upper cost estimate relates to soil amendments being applied to all low PRI soils in the plan area, whereas the lower cost estimate relates to soil amendments being strategically applied to soils with known high P losses (Degens et al. 2023) (i.e. as identified from soil testing of farms such as that which occurs as part of the Sustainable Agriculture Strategy of Healthy Estuaries WA).

9.2 Planning and policy actions

As we work to improve water quality through the actions described in Section 9.1, we must also ensure that future land use planning decisions do not lead to a net increase in nutrient loads.

Implementation of the following actions will help coordinate estuary management and improve collective decision-making to ensure future developments are consistent with State Government and local government policies. The link between land use planning decisions and water quality outcomes cannot be overstated. Urban, industrial and agricultural growth can occur in the catchment, but it must be carefully managed.

24. Recommended action

Implement a contemporary statutory framework to achieve water quality improvements in the Peel-Harvey estuary by revising the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* or replacing it with an appropriate alternative.

The *Environmental Protection (Peel-Harvey) Policy 1992* (the EPP) was developed in the early 1990s. Now a more contemporary policy is needed to ensure land planning processes and decisions support water quality improvement in the Peel-Harvey estuary. A comprehensive review of the existing EPP is needed to assess its practicality and suitability as a statutory framework for water quality protection. At its core, the new or updated policy should ensure future changes in land use do not jeopardise this WQIP’s WQOs (underpinned by the community values of the Peel-Harvey estuary). To do this, it will need strong and clear environmental protection measures. The policy should be drafted in a manner that will ensure that it can be effectively implemented by all relevant State and local government decision-makers.

Why it is important to have controls on new developments?

New developments have the potential to significantly increase nutrient exports to waterways, drains, superficial groundwater and the estuary. Land use intensification in the Peel-Harvey estuary coastal plain catchment is a constant pressure: the urban landscape is expanding, and demand is increasing for new horticulture precincts to service the greater Perth region. Some intensive land uses including in-ground annual horticulture, piggeries and poultry farms, have the potential to significantly increase nutrient loads to the estuary, given they have nutrient inputs that are orders of magnitude higher than most existing land uses in the catchment.

All new developments should be appropriately sited and designed so that discharges of nutrients and other contaminants to drains and waterways are prevented or minimised (through effective implementation of the EP Act, state planning policies and local government policies). The department will continue to set licence conditions and monitor regulated activities for compliance (e.g.

beverage and food processing, chemical manufacturing, paper/pulp manufacturing, liquid waste facilities and biomedical industries), so that the discharge of nutrients and other pollutants to drains and waterways is prevented or minimised.

The precautionary principle should be applied when implementing state planning policies and local government policies to ensure developments are appropriately sited and activities managed to minimise the export of nutrient and non-nutrient contaminants to the estuary.

New developments must be compatible with the site characteristics and capability of the soil to retain nutrients. Some intensive land uses such as conventional in-ground horticulture, poultry farms, piggeries and feedlots should not be sited in sensitive areas where high nutrient export is a risk. For much of the Peel-Harvey estuary coastal plain catchment, developments of this type are only suitable if they are completely closed agricultural systems (i.e. zero discharge of nutrient-rich liquid or solids to the immediate environment).

25. Recommended action

Ensure land planning decisions are consistent with relevant State Government and local government policies for the health of the Peel-Harvey estuary.[64] New planning or development proposals – in particular, intensive land uses such as in-ground horticulture, poultry farms, piggeries and feedlots – should not be in areas prone to nutrient export unless they can demonstrate that nutrient input rates can be met to achieve the maximum acceptable nutrient loads to the estuary: 45 kg N/cleared ha/year and 6.5 kg P/cleared ha/year (Section 7.5), or updated nutrient input rates that the State Government may publish in the future.[65]

Existing industry should comply with all relevant local, state and national policies and guidelines that relate to their industry.

Linked to recommended action 10.

26. Recommended action

In areas prone to nutrient export, investigate and support the transition of intensive land uses to closed agricultural systems, with zero discharge of nutrient-rich liquid or solids to the immediate environment.

[64] Including state planning policies, *Horticulture development local planning policy* (Shire of Murray 2018a), *Local Planning Policy 4.12: Horticulture* (Shire of Serpentine Jarrahdale 2018b), *P004 – Local Planning Policy 4 – Intensive agriculture* (Shire of Waroona 2021), the Peel Region Scheme, and the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*, *Model Local Planning Policy – Horticultural development in the Peel-Harvey Coastal Plain Catchment* (PHCC 2023).

[65] 'Intensive land uses' are defined here as intensive animal industries, intensive horticulture, and premises with livestock numbers in excess of recommended stocking rates.

Linked to recommended actions 10 and 11.

27. Recommended action

Develop guidance material for agricultural and intensive animal industries to align and integrate with relevant state planning policies, the *Peel Regional Scheme – Priority agriculture and rural land use policy* (WAPC & DPLH 2017) and *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*.

Linked to recommended action 10.

28. Recommended action

Review regulation of point source discharges from agricultural activities (e.g. dairy sheds, piggeries, feedlots) to ensure treatment to national best practice before discharge to the environment.

Linked to recommended action 10.

29. Recommended action

Reduce or eliminate discharges to waterways through a review and update of licensing and works approval requirements for prescribed premises/activities.

30. Recommended action

Implement the sewerage and on-site wastewater management provisions in the *Government Sewerage Policy* (Government of Western Australia 2019a), *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b). [66]

Linked to recommended action 18.

New developments should be planned and designed to manage nutrient export from stormwater runoff and subsoil drainage, in accordance with best practice for water quality, water quantity, supply and liveability outcomes. WSUD concepts and infrastructure (e.g. rain gardens, biofilters, infiltration basins, litter and sediment traps, constructed wetlands and living streams) can also be retrofitted to existing urban areas (at the lot, street or suburb scale) when existing structures are upgraded or redeveloped (see recommended actions 15 and 16).

31. Recommended action

Apply WSUD principles in new urban and industrial developments to ensure all changes in land use will reduce nutrients entering the estuary (aligned with Waterwise Perth).

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[66] The *Government Sewerage Policy* (Government of Western Australia 2019a) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are published.

Implement:

- relevant state planning policies
- *Better urban water management* (WAPC 2008)
- *Stormwater management manual for Western Australia* (DoW 2004–07)
- *Decision process for stormwater management in Western Australia* (DWER 2017a).

Use the UNDO (Urban Nutrient Decision Outcomes) tool when assessing new developments.

Linked to recommended actions 15, 16 and 32.

32. Recommended action

Update *Local planning policy for WSUD in the Peel-Harvey catchment* (Peel Development Commission 2006b) and *Peel-Harvey coastal catchment water sensitive urban design technical guidelines* (Peel Development Commission 2006a) to reflect current best practice.

Linked to recommended actions 15, 16 and 31.

The next suite of recommended actions focuses on protecting and conserving the ecological values of the estuary, wetlands, waterway vegetation, and remnant vegetation throughout the catchment. See Appendix L for further information on the protection of natural wetlands in the plan area.

33. Recommended action

Protect waterway vegetation:

- identify and map remnant waterway vegetation
- identify and protect waterway foreshore areas consistent with *Operational policy: Identifying and establishing waterway foreshore areas* (DoW 2012b) and *Determining foreshore reserves* (Water and Rivers Commission 2001)
- protect water quality by providing an additional separation distance between potentially polluting intensive land uses and waterways, where required.

The role that natural wetlands play in reducing catchment-derived nutrients reaching the Peel-Harvey estuary is unknown. However, natural wetlands in the estuary catchment should be rehabilitated or protected from further degradation to ensure the wetland’s values (e.g. supporting biodiversity and ecological integrity) are maintained and enhanced for future generations. The State Government’s Healthy Wetland Habitats program (2006–22) financially and technically supported landholders to care for wetlands and develop a wetland management plan (fencing to protect existing vegetation, weed management and revegetation to restore cleared or degraded areas are usually key activities). The State Government’s future Carbon Farming and Land Restoration program (led by DPIRD) will fund activities such as revegetation on

South West farms that sequester carbon in the landscape and deliver additional, positive outcomes referred to as 'co-benefits' (e.g. biodiversity and conservation).[67]

34. Recommended action

Protect wetlands, including their hydrology, water quality and habitats:

- identify and map wetlands
- develop new wetland buffer guidelines to improve protection of wetlands identified as having ecological values
- apply wetland buffer guidelines that protect wetland values
- in addition to wetland buffers, provide further separation distance between potentially polluting land uses and wetlands to protect water quality.

35. Recommended action

Protect and conserve remnant vegetation in the catchment:

- develop and apply policy specific to the Peel-Harvey estuary to protect priority areas of native vegetation and encourage revegetation with deep-rooted perennial species that improve water quality.[68]
- consider incorporating areas of remnant vegetation into regional parks and conservation reserves.

9.3 Actions to partner with Bindjareb Noongar people to look after the estuary and rivers

In Section 1.10 we described the development of the *Bindjareb Djilba Protection Plan* (DWER 2020b) and the strong partnership forged between the Bindjareb Noongar people and the department. This WQIP recognises this partnership and strives to authentically represent Bindjareb values and integrate actions that support their people.

Bindjareb Elders have shared their vision, management goals and priority actions for looking after the Djilba (estuary) and Bilya (rivers) in *Bindjareb Gabi Wonga (Bindjareb Water Story) (Nannup et al. 2019)* – a water plan from the Bindjareb perspective. The water-quality-related actions of *Bindjareb Gabi Wonga* are embedded in this WQIP. This approach respects Bindjareb ownership of these actions while encouraging partnerships across all stakeholder groups to thread knowledge systems (see text box below) and arrive at a shared understanding for improved catchment and estuary management.

[67] Western Australian Carbon Farming and Land Restoration Program

[68] The EPA has a mapping layer called 'Swan Bioplan – Peel Regionally Significant Natural Areas' (digital mapping, spatial dataset with explanatory notes) which identifies regionally significant areas of natural vegetation in the Peel, helping to guide strategic land use and conservation planning.

Threaded knowledge systems

Bindjareb Noongar people have looked after the Djilba and Bilya for more than 50,000 years based on governance and lore. To thread knowledge systems means to recognise that there is more than one way to manage waterways. Respectfully we can work together to thread cultural knowledge and western science for improved governance of the waterways.

The *Bring Together Walk Together Aboriginal partnership engagement framework* (Walley and Grant 2021) communicates the way Bindjareb Noongar Elders and the department have partnered and do business together. The framework makes a pathway to forge, build and maintain strong partnerships for Aboriginal land and water – in policy and planning, participatory research and major and minor projects. Bindjareb people encourage key water stakeholders to Bring Together Walk Together for implementation of this WQIP (Section 9.7).

36. Recommended action

Partner with Bindjareb Noongar people to arrive at a shared understanding and knowledge systems for improved catchment and estuary management.

From *Bindjareb Gabi Wonga* (Nannup et al. 2019):

- work with Elders to develop an agreement for Aboriginal participation and partnering in waterways planning and management of Bindjareb boodja (Bindjareb country) (*Bindjareb Gabi Wonga* action 1.1).
- develop a detailed implementation plan for the *Bindjareb Gabi Wonga* in partnership with key water stakeholders (*Bindjareb Gabi Wonga* action 1.2)
- embed Aboriginal values and Traditional Lore into water planning and management (*Bindjareb Gabi Wonga* action 1.3)
- review the legislative and policy framework, including State Government and local government policies, to implement measures to improve water quality and flows to preserve the cultural values of waterways (*Bindjareb Gabi Wonga* action 1.3.1)
- support the development of joint management responsibility opportunities for Traditional Owners to partner in the management of waterways (*Bindjareb Gabi Wonga* action 1.3.4)
- identify and consider water-dependent values of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.1)
- support initiatives that build capacity for Bindjareb Noongar partnerships in water planning and management including Aboriginal Ranger programs, Bindjareb Waterways Assessment Program, waterways protection and restoration projects (*Bindjareb Gabi Wonga* action 2.2)
- continue to undertake waterway health and scientific investigation programs to monitor the health of traditional sites and food places: the programs to

include opportunities for Aboriginal participation, knowledge sharing, culture-embedded training and employment (*Bindjareb Gabi Wonga* action 2.4)

- continue to implement catchment management initiatives for water quality improvement of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.5)
- implement statutory and non-statutory mechanisms to protect traditional sites and food places (*Bindjareb Gabi Wonga* action 2.6).

9.4 Actions to assess water quality condition and measure progress

An essential part of estuary management is long-term monitoring to report changes in condition and improvements in response to management actions.

The department's monitoring program is continuing through Healthy Estuaries WA. The data will help us determine whether the WQOs (Section 4.2) are being met and broadly indicate if conditions are getting better or worse because of management actions and environmental variability (e.g. because of climate change). In alignment with the *Charter: National water quality management strategy* (Australian Government 2018), the monitoring program supports adaptive management by helping us identify whether new or modified WQOs need to be put into the management strategy. We will also use the monitoring data to improve system understanding and plan future monitoring and research programs.

37. Recommended action

Continue to regularly (fortnightly to monthly) monitor the waterways and drains that flow into the Peel-Harvey estuary for assessment against the catchment Water Quality Objectives in this WQIP, and for the calculation of nutrient status, trends and total loads.

Consider expanding the monitoring program to monitor flow and nutrient concentrations in waterways/drains in the WQIP's reporting catchments that are currently unmonitored, ensuring alignment with the recommendations in this WQIP.

38. Recommended action

Continue to regularly (fortnightly to monthly) monitor water quality in the Peel-Harvey estuary including phytoplankton and nutrients and report on algal blooms. Use data to regularly track against the Water Quality Objectives in this WQIP. Use fixed instrument moorings in the Murray River to track oxygen levels and consider continuous monitoring at additional sites in the estuary.

39. Recommended action

Investigate the bioavailability, composition and sources of DON and DOP across the catchment, to inform management actions.

40. Recommended action

Undertake seagrass and macroalgal surveys every three to five years, as a key component of ecological monitoring.

41. Recommended action

Undertake fish community surveys and report on changes using comparative tools such as the Fish Community Index (developed by Murdoch University).

42. Recommended action

Undertake periodic surveys of sediment condition and benthic invertebrate communities as indicators of changing environmental conditions.

43. Recommended action

Investigate the level of pesticide contamination in surface water, sediments and superficial groundwater across agricultural areas of the Peel-Harvey estuary coastal plain catchment, by monitoring pesticide chemicals across each season, over a year.

44. Recommended action

Periodically evaluate estuary condition (about every five years) and report to the community on observed changes, considering water and sediment quality and biotic indicators such as seagrass, macroalgae, fish community and benthic macroinvertebrate health. Annually report against the Water Quality Index (currently in draft) as a tool for communicating over-arching patterns through time and across the estuary.

45. Recommended action

Review recreational swimming sites within the Peel-Harvey estuary and estuarine reaches of the rivers. Consider more regular and widespread monitoring to determine if the water quality meets the standard required to protect community values associated with recreation and aesthetics.

Explore the possible efficiency gains if the departments of Health and Water and Environmental Regulation partnered to conduct microbiological water quality monitoring.

46. Recommended action

Use the Peel-Harvey coupled estuary-catchment model to integrate monitoring data, predict climate change implications, and guide management decisions.

47. Recommended action

Undertake studies to predict the impact of reduced river flows (under different climate change scenarios) on estuary water levels and estuary processes. Utilise the coupled estuary-catchment model to support such studies.

48. Recommended action

Update the hydrological and nutrient catchment model (Peel-Harvey Catchment Model) every five to 10 years to include changes in land use, land use practices and hydrology to help evaluate the effectiveness of nutrient reduction actions. Improve water quality model capabilities in eWater Source, so that dissolved nutrients and soil and groundwater stores of nutrients are incorporated.

49. Recommended action

Develop paddock-scale nutrient and water balance models to inform an understanding of nutrient losses at the local scale and to support the development of targets and guidelines.

A pre-cursor to this work is increased sampling at the outlets of paddocks to build our understanding of the relationships between water quality, land use, soil and drainage combinations.

50. Recommended action

Measure the effectiveness of management practices at an appropriate scale to improve hydrological and nutrient catchment model predictions and understand the response time between management actions and measurable improvements in water quality (i.e. lag time).

51. Recommended action

Support reporting against Ramsar Limits of Acceptable Change.

52. Recommended action

Report progress on implementing this WQIP to the community every five years.

53. Recommended action

Review and update this WQIP within 10 years.

9.5 Coordinating action

To strengthen cross-agency collaboration and guide the implementation of the *Bindjareb Djilba Protection Plan* (DWER 2020b) the department established the Bindjareb Djilba Policy and Planning Coordinating Committee in 2022. The committee operate under an agreed terms of reference to coordinate plan actions that are not delivered by other programs such as Healthy Estuaries WA. They focus on the more complex statutory, policy and planning reform actions that are required to safeguard the future health of the estuary. The committee is co-chaired by local government members and includes senior representatives from various local governments, the State Government, the Bindjareb Noongar community, and the PHCC. This committee provides an ideal forum to promote implementation of this WQIP.

54. Recommended action

Establish a committee led by the Department of Water and Environmental Regulation to coordinate the policy and planning actions of the *Bindjareb Djilba Protection Plan* (DWER 2020b) and the aligned actions in this WQIP. This committee, supported by working groups, will share information on land development and planning proposals and collaborate with key stakeholders to support implementation of both plans.

9.6 Summary of recommended actions

A summary of all the recommended actions stated in Section 9 of this WQIP is provided in the tables below. For the catchment management actions (Table 9-5), we have included guidance on where implementation should occur in the plan area and where to start, as well as a list of existing programs that are already implementing the actions.

Table 9-5 Recommended catchment management actions for water quality improvement of the Peel-Harvey estuary system

No.	Recommended action	Targeting N, P or both?	Aligned action[69]	Where to implement?	Where to start?	Program/s currently implementing action
Catchment management actions						
Improved management of diffuse agricultural nutrients						
1	Reduce phosphorus fertiliser losses by optimising fertiliser use to agronomic requirements, as determined by soil testing, agronomic advice (or DPIRD's nutrient calculator), and demonstration trials.[70]	P	C1	All, except Mandurah	All areas with low PRI soil adjacent to drains, waterways and the estuary with a strong focus on Harvey and Nambeelup.	Healthy Estuaries WA (Sustainable Agriculture Strategy) Soil Wise[71] Smart Farming Partnership (uPtake)[72] Implementation of the *Bindjareb Djilba Protection Plan*
2	Continue to develop and use fertiliser products that meet the needs of farmers on sandy coastal soils, as indicated by soil and plant tissue testing, including slow-release phosphorus fertilisers.	P	C3	All, except Mandurah and Peel Main Drain	Harvey and Nambeelup	Working with fertiliser industry partners through Healthy Estuaries WA (Sustainable Agriculture Strategy) Smart Farming Partnership (uPtake)[72]
3	Reduce losses of nitrogen by working with farmers to encourage best-practice application of nitrogen fertilisers.[73]	N		All, except Mandurah and Peel Main Drain	Harvey and Dirk Brook	Smart Farms: soil extension activities
4	Improve phosphorus retention in sandy soils used for intensive and broadscale agriculture by using soil amendments.	P	C2	All, except Mandurah and Peel Main Drain	Harvey, followed by Nambeelup, Upper Serpentine and Mayfield	Healthy Estuaries WA (Innovative Remediation Strategy)
5	Develop new best-management practices for broadscale agriculture to encourage holistic management and regenerative agriculture principles that improve soil health, use water efficiently, maintain soil cover and support the *State Soil Health Strategy, Western Australia* (DPIRD 2021). In conventional broadscale agriculture, reduce fertiliser losses and reduce erosion through improved whole-of-farm management practices,	Both	C4	All, except Mandurah	n/a	Healthy Estuaries WA (Sustainable Agriculture Strategy) Implementation of the *Bindjareb Djilba Protection Plan* Soil Wise[71] Western Australia Carbon Farming and Land Restoration Program (ACCU Plus)[74]

[69] Aligned action in *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020b).

[70] See DPIRD Phosphorus for high rainfall clover pastures in Western Australia; and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

[71] Soil Wise is funded by the National Landcare Program Smart Farms Small Grants – an Australian Government initiative. It is supported by Healthy Estuaries WA – a State Government program. See Appendix A and the Healthy Estuaries WA Soil Wise webpage for more information.

[72] See Appendix A and the Healthy Estuaries WA uPtake webpage for summary information on uPtake.

[73] See DPIRD Nitrogen for high rainfall pastures in Western Australia; and Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia (Government of Western Australia 2022b).

[74] Western Australian Carbon Farming and Land Restoration Program

No.	Recommended action	Targeting N, P or both?	Aligned action[69]	Where to implement?	Where to start?	Program/s currently implementing action
	including the use of perennial pastures to avoid bare soils.					Emission Reduction Fund (Clean Energy Regulator) Carbon Farming Initiative[75]
6	Conserve water and reduce nutrient runoff from irrigated agriculture by requiring Nutrient Irrigation Management Plans (NIMPs) as part of planning approvals and water licensing processes and applying best management practice to irrigation design to achieve appropriate pressure, reach and uniform distribution. Irrigation scheduling should carefully consider soil moisture content and local evaporation rates.	Both	C6	All, except Mandurah		Implementation of nutrient and irrigation management plans administered by local government through the *Peel Regional Scheme – Priority agriculture and rural land use policy*[76]
7	Help farmers and other landholders to exclude stock from waterways and drains to reduce erosion and the input of sediment and organic matter to the estuary and its tributaries. Linked to recommended action 19.	Primarily N	C7	All reporting catchments where dairy and/or beef grazing is occurring in or near a waterway. Priority should be given to those areas with higher stocking rates.	Harvey, then Dirk Brook, Lower Murray and Upper Serpentine, followed by Nambeelup and Mayfield	Healthy Estuaries WA (Water in the Landscape Strategy) Implementation of the *Bindjareb Djilba Protection Plan*
Improved management of point source agricultural nutrients						
8	Industry to consider integrating drainage networks with engineered, constructed wetlands to reduce export of intensive, diffuse sources of nutrients, such as those from free-range chicken farms, rotational outdoor piggeries (free-range and outdoor bred), and irrigated horticulture.	Both		All reporting catchments with industries that are an intensive source of diffuse nutrients with the potential to impact on water quality (e.g. outdoor piggeries, free-range chicken farms, and irrigated horticulture)	n/a	
9	Improve effluent management within dairy operations to minimise discharge and maximise reuse of water and nutrients to standards in the code of practice. Linked to recommended action 28.	Primarily P	C8	All reporting catchments that have an operating dairy shed which, as recorded by Hennig et al. (2021) includes the Upper Serpentine, Dirk Brook, Nambeelup, Lower Murray, Coolup (Peel), Coolup (Harvey), Mayfield and Harvey	Harvey and Nambeelup, followed by Upper Serpentine, then Dirk Brook	Healthy Estuaries WA (Sustainable Agriculture Strategy) *Code of practice for dairy farm effluent management WA* (2021)
10	Manage effluent, stormwater and other sources of nutrients from intensive animal industries (e.g. piggeries, poultry sheds, feedlots and abattoirs) to national or international best-practice standards. Linked to recommended actions 25–28.	Both	C8	This is a whole-of-industry focused action – all reporting catchments that have intensive animal industries (piggeries, poultry sheds, feedlots/stockyards and abattoirs)	Meredith, Lower Serpentine and Dirk Brook reporting catchments. The largest total load reduction across the catchment would come from the Upper Serpentine, where most intensive animal industries are located – although the load removed per premises would be much smaller	*Environmental Protection Amendment Act 2020* – includes the implementation of a prescribed activity regime under the new Part V Division 3, including reviewing and replacing Schedule 1 licensing categories (proclamation of Stage 3 amendments)
11	Develop and implement intensive horticulture best-management practices suited to high nutrient-leaching environments, including optimising fertiliser use to agronomic requirements, as determined by soil testing and agronomic advice, and investigating the feasibility of implementing closed agricultural systems (annual horticulture).[77]	P	C5	All reporting catchments that have intensive in-ground horticulture, orchards or turf farms	Upper Serpentine	

[75] Further information on the ERF is available on the Department of the Environment website: Emissions Reduction Fund.

[76] See *Water quality protection note 33: Nutrient and irrigation management plans* (DoW 2010b) (as updated) and *Water quality protection information sheet 4: Nutrient and irrigation management plan checklist* (DoW 2010a) (as updated).

[77] See DPIRD Horticulture.

No.	Recommended action	Targeting N, P or both?	Aligned action[69]	Where to implement?	Where to start?	Program/s currently implementing action
	Linked to recommended action 26.					
Improved management of diffuse urban nutrients						
12	Help householders improve water use efficiency in existing urban gardens and minimise nutrient export risk through the Waterwise Council Program and other waterwise education programs (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).	Both	C9	All reporting catchments with urban areas		Waterwise Council Program
13	Public open space managers to reduce the application of nutrients (fertiliser and others) and export risk, and improve water efficiency in existing public open space (see Waterwise Council Program and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*).	Predominantly P	C10	All reporting catchments with urban areas		Waterwise Council Program
14	Developers of new urban land and public open space should evaluate and use soil amendments to reduce phosphorus losses in areas with sandy soils that have low phosphorus retention.	P	C11	All reporting catchments with urban areas		
15	Target upgrades to existing stormwater systems in priority areas according to water sensitive urban design principles (see *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth action plan 2*). Linked to recommended actions 16, 31 and 32.	Both	C12	All reporting catchments with urban areas	Harvey, Mandurah, Lower Murray and Lower Serpentine	
16	Increase training and development opportunities for local government and the stormwater management industry to adopt water sensitive urban design principles. Linked to recommended actions 15, 31 and 32	Both	C13			
Improved management of point source urban nutrients						
17	Increase the reuse of treated wastewater from wastewater treatment plants (WWTPs) on green spaces where there is a low risk of leaching into waterways and promote the reuse of wastewater within the industrial (e.g. mining) and agricultural sectors by identifying opportunities and addressing barriers.	Both	C14	Reporting catchments where WWTPs are discharging effluent to the environment	Waroona WWTP in the Harvey and Kwinana WWTP in the Peel Main Drain reporting catchment	
18	Encourage the replacement of existing septic systems with connection to a reticulated sewerage network, where available. If reticulated sewerage is not available, a secondary treatment system with nutrient removal capability should be fitted. Linked to recommended action 30.	Both	C15	Mandurah, Lower Serpentine, Upper Serpentine, Peel Main Drain, Lower Murray and Harvey (most remaining septic tanks are clustered in these catchments)	Mandurah, Harvey and Lower Serpentine as identified in Table 9-1	
Drainage works and in-stream management to improve water quality						
19	Implement the 2017 Drainage Partnering Agreement between Water Corporation, the Department of Water and Environmental Regulation and the Peel-Harvey Catchment Council. Linked to recommended action 7.	Both	C16a C16c C16d	All reporting catchments with Water Corporation drains that flow to the estuary For stock exclusion: where beef and/or dairy grazing is occurring in or near a Water Corporation drain, with priority	Drains high in nutrient concentrations, depending on selected management intervention. For stock exclusion: Harvey, then Dirk Brook, Lower Murray and Upper	Regional Estuaries Initiative (ongoing – Peel Main Drain flow diversion through swales). The department has developed an overall guidance document for the partnership to develop projects which can subsequently be funded and costed.

No.	Recommended action	Targeting N, P or both?	Aligned action[69]	Where to implement?	Where to start?	Program/s currently implementing action
				given to those areas with higher stocking rates.	Serpentine, followed by Nambeelup and Mayfield.	
20	For all drains across the catchment, evaluate approaches (such as in-drain vegetation and sediment traps) to improve water quality in drains that discharge to the Peel-Harvey estuary and its tributaries. Implement approved approaches in prioritised drains.	Both	C16c	All reporting catchments with drains that flow to the estuary	Drains high in nutrient concentrations, depending on selected management intervention	Regional Estuaries Initiative (ongoing – Peel Main Drain flow diversion)
21	Investigate, develop and evaluate the use of innovative materials for phosphorus removal in drains, including phosphorus-binding clays.	P	C16b	Drains with high FRP concentrations and moderate flows with a suitable location to undertake a trial		Healthy Estuaries WA (Innovative Remediation Strategy)
Other management actions to improve water quality and biodiversity						
22	Reinstate the ecological function of key waterways through restoration works and revegetation of the riparian zone.	Both	C17	All reporting catchments that have key waterways that flow to the estuary		Healthy Estuaries WA (Water in the Landscape Strategy) Implementation of the *Bindjareb Djilba Protection Plan* Collaborations between landholders, industry and NRM groups e.g. Connecting Corridors and Communities – Restoring the Serpentine River Western Australia Carbon Farming and Land Restoration Program (ACCU Plus)
23	Undertake strategic revegetation of the catchment to improve biodiversity, mitigate climate change effects, and contribute to water quality improvement.	Both	C18	All reporting catchments with under 50 per cent deep-rooted vegetation cover (i.e. all except Meredith Drain)	Harvey, followed by Nambeelup, Mayfield and Upper Serpentine.	Offsets Funds for Recovery program and the Native Vegetation Rehabilitation Scheme under the Green Jobs Plan. Western Australia Carbon Farming and Land Restoration Program (ACCU Plus).

Table 9-6 Recommended actions for: planning and policy change, partnering with Bindjareb Noongar people, assessing water quality and measuring change, and coordinating implementation for water quality improvement of the Peel-Harvey estuary system

No.	Recommended action	Aligned action[78]
Planning and policy actions		
24	Implement a contemporary statutory framework to achieve water quality improvements in the Peel-Harvey estuary by revising the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* or replacing with an appropriate alternative.	P2
25	Ensure land planning decisions are consistent with relevant State Government and local government policies for the health of the Peel-Harvey estuary.[79] New planning or development proposals – in particular, intensive land uses such as in-ground horticulture, poultry farms, piggeries and feedlots – should not be in areas prone to nutrient export unless they can demonstrate that nutrient input rates can be met to achieve the maximum acceptable nutrient loads to the estuary: 45 kg N/cleared ha/year and 6.5 kg P/cleared ha/year (Section 7.5), or updated nutrient input rates that the State Government may publish in the future.[80] Existing industry should comply with all relevant local, state and national policies and guidelines that relate to their industry. Linked to recommended action 10.	P3a
26	In areas prone to nutrient export, investigate and support the transition of intensive land uses to closed agricultural systems, with zero discharge of nutrient-rich liquid or solids to the immediate environment. Linked to recommended actions 10 and 11.	P3b
27	Develop guidance material for agricultural and intensive animal industries to align and integrate with relevant state planning policies, the *Peel Regional Scheme – Priority agriculture and rural land use policy* (WAPC & DPLH 2017) and *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*. Linked to recommended action 10.	P4
28	Review regulation of point source discharges from agricultural activities (e.g. dairy sheds, piggeries, feedlots) to ensure treatment to national best-practice before discharge to the environment. Linked to recommended actions 9 and 10.	P7
29	Reduce or eliminate discharges to waterways through a review and update of licensing and works approval requirements for prescribed premises/activities.	

[78] Aligned action in *Bindjareb Djilba – A plan for the protection of the Peel-Harvey estuary* (DWER 2020b).

[79] Including state planning policies, *Horticulture development local planning policy* (Shire of Murray 2018a), *Local Planning Policy 4.12: Horticulture* (Shire of Serpentine Jarrahdale 2018b), *P004 – Local Planning Policy 4 – Intensive agriculture* (Shire of Waroona 2021), the Peel Region Scheme, and the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*, *Model Local Planning Policy – Horticultural development in the Peel-Harvey Coastal Plain Catchment* (PHCC 2023).

[80] 'Intensive land uses' are defined here as intensive animal industries, intensive horticulture, and premises with livestock numbers in excess of recommended stocking rates.

No.	Recommended action	Aligned action[78]
30	Implement the sewerage and on-site wastewater management provisions in the *Government Sewerage Policy* (Government of Western Australia 2019a), *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b).[81] Linked to recommended action 18.	P5
31	Apply water sensitive urban design principles in new urban and industrial developments to ensure all changes in land use will reduce nutrients entering the estuary (aligned with Waterwise Perth). Implement: • relevant state planning policies • *Better urban water management* (WAPC 2008) • *Stormwater management manual for Western Australia* (DoW 2004–07) • *Decision process for stormwater management in Western Australia* (DWER 2017a). Use the UNDO (Urban Nutrient Decision Outcomes) tool when assessing new developments. Linked to recommended actions 15, 16 and 32.	P6
32	Update *Local planning policy for WSUD in the Peel-Harvey catchment* (Peel Development Commission 2006b) and *Peel-Harvey coastal catchment water sensitive urban design technical guidelines* (Peel Development Commission 2006a) to reflect current best practice. Linked to recommended actions 15, 16 and 31.	
33	Protect waterway vegetation: • identify and map remnant waterway vegetation • identify and protect waterway foreshore areas consistent with *Operational policy: Identifying and establishing waterway foreshore areas* (DoW 2012b) and *Determining foreshore reserves* (Water and Rivers Commission 2001a) • protect water quality by providing an additional separation distance between potentially polluting intensive land uses and waterways, where required.	P9
34	Protect wetlands, including their hydrology, water quality and habitats: • identify and map wetlands • develop and apply new wetland buffer guidelines to improve protection of wetlands identified as having ecological values • apply wetland buffer guidelines that protect wetland values • in addition to wetland buffers, provide further separation distance between potentially polluting land uses and wetlands to protect water quality.	P10
35	Protect and conserve remnant vegetation in the catchment:	P11

[81] The *Government Sewerage Policy* (Government of Western Australia 2019a) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) are published.

No.	Recommended action	Aligned action[78]
	• develop and apply policy specific to the Peel-Harvey estuary to protect priority areas of native vegetation and encourage revegetation with deep-rooted perennial species that improve water quality [82] • consider incorporating areas of remnant vegetation into regional parks and conservation reserves.	
Actions to partner with Bindjareb Noongar people to look after the estuary and rivers (from *Bindjareb Gabi Wonga*: Nannup et al. 2019)		
36	Partner with Bindjareb Noongar people to arrive at a shared understanding and knowledge systems for improved catchment and estuary management: • work with Elders to develop an agreement for Aboriginal participation and partnering in waterways planning and management of Bindjareb boodja (Bindjareb country) (*Bindjareb Gabi Wonga* action 1.1) • develop a detailed implementation plan for the *Bindjareb Gabi Wonga* in partnership with key water stakeholders (*Bindjareb Gabi Wonga* action 1.2) • embed Aboriginal values and Traditional Lore into water planning and management (*Bindjareb Gabi Wonga* action 1.3) • review the legislative and policy framework, including State Government and local government policies, to implement measures to improve water quality and flows to preserve the cultural values of waterways (*Bindjareb Gabi Wonga* action 1.3.1) • support the development of joint management responsibility opportunities for Traditional Owners to partner in the management of waterways (*Bindjareb Gabi Wonga* action 1.3.4) • identify and consider water-dependent values of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.1) • support initiatives that build capacity for Bindjareb Noongar partnerships in water planning and management including Aboriginal Ranger programs, Bindjareb Waterways Assessment Program, waterways protection and restoration projects (*Bindjareb Gabi Wonga* action 2.2) • continue to undertake waterway health and scientific investigation programs to monitor the health of traditional sites and food places: the programs to include opportunity for Aboriginal participation, knowledge sharing, culture-embedded training and employment (*Bindjareb Gabi Wonga* action 2.4) • continue to implement catchment management initiatives for water quality improvement of traditional sites and food places (*Bindjareb Gabi Wonga* action 2.5) • implement statutory and non-statutory mechanisms to protect traditional sites and food places (*Bindjareb Gabi Wonga* action 2.6).	P12, P13, P14
Actions to assess water quality condition and measure progress		

[82] The EPA has a mapping layer called 'Swan Bioplan – Peel Regionally Significant Natural Areas' (digital mapping, spatial dataset with explanatory notes) which identifies regionally significant areas of natural vegetation in the Peel, which helps to guide strategic land use and conservation planning.

No.	Recommended action	Aligned action[78]
37	Continue to regularly (fortnightly to monthly) monitor the waterways and drains that flow into the Peel-Harvey estuary for assessment against catchment Water Quality Objectives in this WQIP, and for the calculation of nutrient status, trends and total loads. Consider expanding the monitoring program to monitor flow and nutrient concentrations in waterways/drains in this WQIP's reporting catchments that are currently unmonitored, ensuring alignment with the recommendations in this WQIP.	M4
38	Continue to regularly (fortnightly to monthly) monitor water quality in the Peel-Harvey estuary including phytoplankton and nutrients and report on algal blooms. Use data to regularly track against the Water Quality Objectives in this WQIP. Use fixed instrument moorings in the Murray River to track oxygen levels and consider continuous monitoring at additional sites in the estuary.	M3
39	Investigate the bioavailability, composition and sources of DON and DOP across the catchment, to inform appropriate management actions.	
40	Undertake seagrass and macroalgal surveys every three to five years, as a key component of ecological monitoring.	M5
41	Undertake fish community surveys and report on changes using comparative tools such as the Fish Community Index (developed by Murdoch University).	M6
42	Undertake periodic surveys of sediment condition and benthic invertebrate communities as indicators of changing environmental conditions.	M7
43	Investigate the level of pesticide contamination in surface water, sediments and superficial groundwater across agricultural areas of the Peel-Harvey estuary coastal plain catchment, by monitoring pesticide chemicals across each season, over a year.	
44	Periodically evaluate estuary condition (about every five years) and report to the community on observed changes, considering water and sediment quality and biotic indicators such as seagrass, macroalgae, fish community and benthic macroinvertebrate health. Annually report against the Water Quality Index (currently in draft) as a tool for communicating over-arching patterns through time and across the estuary.	M2, M3
45	Review recreational swimming sites within the Peel-Harvey estuary and estuarine reaches of the rivers. Consider more regular and widespread monitoring to determine if the water quality meets the standard required to protect community values associated with recreation and aesthetics. Explore the possible efficiency gains if the departments of Health and Water and Environmental Regulation partnered to conduct microbiological water quality monitoring.	
46	Use the Peel-Harvey coupled estuary-catchment model to integrate monitoring data, predict climate change implications, and guide management decisions.	E9
47	Undertake studies to predict the impact of reduced river flows (under different climate change scenarios) on estuary water levels and estuary processes. Utilise the coupled estuary-catchment model to support such studies.	E7
48	Update the hydrological and nutrient catchment model (Peel-Harvey Catchment Model) every five to 10 years to include changes in land use, land use practices and hydrology to help evaluate the effectiveness of	

No.	Recommended action	Aligned action[78]
	nutrient reduction actions. Improve water quality model capabilities in eWater Source, so that dissolved nutrients and soil and groundwater stores of nutrients are incorporated.	
49	Develop paddock-scale nutrient and water balance models to inform an understanding of nutrient losses at the local scale and to support the development of targets and guidelines. A pre-cursor to this work is increased sampling at the outlets of paddocks to build our understanding of the relationships between water quality, land use, soil and drainage combinations.	
50	Measure the effectiveness of management practices at an appropriate scale to improve hydrological and nutrient catchment model predictions and understand the response time between management actions and measurable improvements in water quality (i.e. lag time).	M9
51	Support reporting against Ramsar Limits of Acceptable Change.	M8
52	Report progress on implementing this WQIP to the community every five years.	
53	Review and update this WQIP within 10 years.	
Coordinating action		
54	Establish a coordinating committee led by the Department of Environmental Regulation to coordinate the policy and planning actions of the *Bindjareb Djilba Protection Plan* (DWER 2020b) and the aligned actions in this WQIP. This committee, supported by working groups, will share information on land development and planning proposals and collaborate with key stakeholders to support implementation of both plans.	P1

9.7 Implementing this plan

This WQIP outlines a series of actions which – if taken together and over time – will lead to improvements in water quality. Many actions are like those in the 2008 WQIP, which are still relevant because they are yet to be implemented at a sufficient scale or length of time.

It is envisaged that this WQIP will provide guidance over a 10-year period during which there will be several implementation stages. For this reason, we have not quantified the required funding or lead agencies as many of the actions can be undertaken at different scales and by different organisations using different funding sources. Some of the actions are less dependent on funding and more reliant on changing the way we link water quality outcomes to planning and development decisions.

The value of investing in water quality improvement through a coordinated multiple-partner approach has been demonstrated through the Regional Estuaries Initiative and Healthy Estuaries WA. We will continue to need long-term programs of this nature, built on partnerships and collaborative effort across government, with landholders, NRM groups and the wider community.

Protecting the health of the Peel-Harvey estuary is a responsibility shared across State Government agencies, local governments, and the community. The department has taken the lead in coordinating the implementation of the WQIP. The Department of Planning, Lands and Heritage and local governments are responsible for land use planning and development controls. Water Corporation manages the rural drainage system and DPIRD provides advice on best-management practices for agricultural activities, agricultural expansion in the catchment, fisheries management and regional economic development. The PHCC provides a community and non-government focus on a range of catchment, estuary and wetland values. The Department of Biodiversity, Conservation and Attractions (DCBA) is the lead agency for conservation estate and other DBCA-managed lands. It coordinates the management of wetlands listed under the Ramsar Convention (Ramsar wetlands), the Swan Canning Development Control Area and Riverpark and other non-flowing (or non-waterway) wetlands that are not waterways or estuaries. The *Bindjareb Djilba Protection Plan* (DWER 2020b) has been developed by the State Government to deliver against the objectives and recommended actions in this WQIP. The *Bindjareb Djilba Protection Plan* is a strategic policy document that highlights the importance of reducing nutrient inputs across the catchment.

A planning and policy committee guides the implementation of the *Bindjareb Djilba Protection Plan* (DWER 2020b) and aligned WQIP actions. The State Government has provided funding to implement the most important actions from this WQIP, supported by Healthy Estuaries WA. Not all actions in either plan will be implemented in this first implementation period as many will require further development and definition. It is hoped that additional actions identified in the WQIP will be undertaken by a range of organisations including the private sector.

Cost-effectiveness and practicality need to be considered when prioritising actions for implementation. If helpful, further modelling can refine the predicted P and N reductions associated with selected management actions, looking at specific adoption rates in selected reporting catchment/s, to refine plans for implementation.

Lag time

When investing in management practices to reduce nutrient concentrations in waterways, 'lag time' is an important consideration. Lag time is the period between a management change and a related water quality improvement in a downstream waterbody. Lag time is site and system dependent but is likely to range from years to decades for excessive P in the agricultural soils in the Peel-Harvey catchment.

This is particularly relevant for diffuse sources of nutrients, as large amounts may be stored in soils from previous land use practices that will continue to leach out even if no additional nutrients are applied.

In contrast, management actions that address point sources of nutrients may result in immediate improvements to water quality, by removing or substantially reducing the source (e.g. removal of septic tanks or implementing best-management practices for animal effluent in dairies and piggeries).

Lag time should be considered in the design of monitoring programs to detect water quality responses to management actions. This will help to ensure they have a suitable temporal and spatial scale, and the most appropriate indicators.

Statutory context

Environmental protection policies (EPPs) are created under Part III of the EP Act and have the force of law. It is mandatory for all stakeholders to comply with EPPs and their associated regulations.

The *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992* defines the beneficial uses of the estuary (which align with the community values presented in this WQIP) and sets environmental quality objectives in the form of maximum P loads to the estuary system – aiming to prevent the excessive growth of algae. It outlines principles to achieve the objectives and requires all government and private activities in the catchment to contribute to reaching the environmental quality objectives.

It has been recognised that the current EPP has limitations, and hence this WQIP recommends that the policy be reviewed to provide a contemporary statutory framework and address these limitations or be replaced with an appropriate alternative instrument (Section 9.2). In the interim, it is recommended that the Water Quality Objectives (WQOs) in this WQIP be used to benchmark overall health of the Peel-Harvey estuary, given they are informed by contemporary science and current hydrological characteristics of the estuary. The EPP environmental quality objectives use loads measured at the flow gauging stations where the Serpentine, Murray, and Harvey rivers enter the estuary. These loads are expressed as the total mass delivered to the estuary over a year. Nutrient loads may be small under low-flow conditions, even when nutrient concentrations are high (see text box in Section 7.2 for information on nutrient concentration versus load). Since river flows have substantially declined with the drying climate (see Section 8.1), the calculated loads have decreased on average but the phosphorus concentration (mass in a standard volume of water) has remained high (see Section 3.2). Nutrient concentration in the water is the primary driver of algal growth and reduction in nutrient concentration is the primary objective of the EPP, even though the environmental quality objectives are expressed as loads. We now see loads below the EPP environmental quality objectives in some years because of the low flows. However, the primary objective of reducing concentrations has not been achieved and water quality is still poor. Water quality can only be improved by reducing nutrient concentration in the tributaries that flow to the estuary.

This WQIP's WQOs for nutrients (WQO 1 and 2) are expressed as nutrient concentrations including nitrogen which is a critical driver of algal growth and can be applied for all subcatchments that flow to the estuary. WQO 1 (TN concentrations in waterways and drains entering the estuary to be </= 1.2 mg/L) and WQO 2 (TP concentrations in waterways and drains entering the estuary to be </= 0.1 mg/L) in this WQIP should be used as the current environmental quality objectives for overall system health, which is reflective of the intent of the EPP.

A key strategy to reduce inputs of nutrients and other non-nutrient contaminants to the estuary system is to ensure that new developments or land use changes are compatible with the site characteristics and capability of the soil to retain nutrients. Any future developments or land use changes in the Peel-Harvey catchment must be managed very carefully through effective implementation of the EP Act and State Government and local government planning policies to ensure minimal or zero net increases in the nutrient loading to the Peel-Harvey estuary. The EPP retains its role within statutory decision-making, requiring new planning or development proposals to demonstrate that nutrient input rates can be achieved (Section 7.5).

The *Draft State Planning Policy 2.9 Planning for water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for water guidelines* (WAPC 2021b) will replace several existing state planning policies (see Appendix B) and will apply to proposals prepared and assessed under the *Planning and Development Act 2005*. The policy and guidelines will outline how water resource management should be integrated into land planning processes. This includes guidance on the siting of appropriate land uses in the Peel-Harvey catchment, as well as on suitable methods to prevent or adequately manage nutrient and non-nutrient pollution in the catchment.[83]

Partnering with Bindjareb Noongar people

This WQIP will be implemented in partnership with Bindjareb Noongar people. The *Bring Together Walk Together Aboriginal partnership engagement framework*

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[83] The entire draft policy and guidelines are relevant to the Peel-Harvey estuary coastal plain catchment. Section 7.6 of the draft policy and Section 10 of the draft guidelines provide advice that apply only to the Peel-Harvey estuary coastal plain catchment (referred to as the Peel-Harvey estuary coastal plain catchment).

(Walley and Grant 2021) makes a pathway to forge, build and maintain strong partnerships for land and water (Figure 9-8). It is important to walk this pathway with an open heart, open mind and embrace the practice of reflective thinking to arrive at a shared understanding, making conditions right for new innovative ways of doing, to thread knowledge for managing waterways. *Our knowledge our way in caring for Country: Indigenous-led approaches to strengthening and sharing our knowledge for land and sea management, Best practice guidelines from Australian experiences* (Woodward et al. 2020) supports the interpretation of this framework.

Figure 9-8 Bring Together Walk Together Aboriginal partnership engagement framework (Walley and Grant 2020)

Alongside actively partnering with Bindjareb Noongar people to deliver this WQIP, water stakeholders must uphold their statutory obligations under the federal *Native Title Act 1993* and Western Australia's *Aboriginal Heritage Act 1972* (AHA Act).

The South West Native Title Settlement (the settlement) is a landmark native title agreement negotiated between the Noongar people and the State Government. The Gnaala Karla Booja (GKB) Indigenous Land Use Agreement (ILUA) of the settlement represents the native title rights and interests of the Bindjareb Noongar (Mandurah, Pinjarra and Harvey area) (within the area relevant to this WQIP), Wilman Noongar people (Narrogin area) and the Geneang Noongar people (Donnybrook area). The Gnaala Karla Booja Aboriginal Corporation (GKBAC) is the newly appointed Noongar Regional Corporation under the settlement. The role of the GKBAC is to work with the GKB ILUA group to benefit, advance and promote their rights and interests. This includes the administration of the Noongar Land Estate, co-operative and joint management of lands, and the Noongar Land Fund.

The ACH Act (amended in 2023) provides a framework for the recognition, protection, conservation and preservation of Aboriginal heritage while recognising the fundamental importance of Aboriginal heritage to Aboriginal people. The State Government has developed regulations and statutory guidelines to support implementation of the Act to ensure it will have its intended effects. It is important to walk in partnership with Bindjareb people and make certain that GKBAC engage with local Traditional Owners about implementing this WQIP.

10 Research needs

Priorities for science and monitoring of estuaries in south-western Australian were identified in a study led by the West Australian Marine Science Institution (Thomson et al. 2017) and should be considered in addition to the following identified research needs.

10.1 Estuary response to climate change and reduced flows

Climate change will significantly alter hydrological dynamics in the Peel-Harvey estuary. Average inflows of fresh water will decrease, air temperatures and evaporation will increase, and rising sea levels will elevate salinities and nutrient residence times. Extreme rainfall events are predicted to occur more often, with high river flows transferring large loads of organic matter and nutrients from the catchment to the estuary. These events are associated with harmful algal blooms, deoxygenation of the water column and fish kill events, particularly when they occur in the warmer months.

Modelling how the estuary is likely to respond to climate change enables us to plan for the management of ecological impacts, as well as understand how infrastructure and coastal communities may be affected (Thomson et al. 2017). This information is helpful when making planning decisions around our estuaries and assessing future health risks; for example, those associated with mosquito-borne viruses (Thomson et al. 2017).

The coupled catchment-estuary model developed by the ARC Linkage project *Balancing estuarine and societal health in a changing environment* (Valesini et al. 2019b) considers freshwater inflow; groundwater interaction; and sea level, tide and meteorological data (see Appendix A for a short summary and Hipsey et al. (2019) for detailed information). It can be used to estimate the residence time and fate of inflows and nutrients entering the estuary and predict the influence of climate change on estuary processes and water levels.

The department will maintain and continually improve the coupled catchment-estuary model. It is recommended that studies and modelling are undertaken to predict how the estuary water levels and processes will respond to climate change and reduced flows. This will help to evaluate management scenarios, and to inform management decisions and climate change adaptation strategies, to protect the health of the estuary and community values.

10.2 Investigate dissolved organic nitrogen

When addressing N loads to the estuary, we want to prioritise catchment management actions that reduce bioavailable N, which is strongly linked to eutrophication. Most of the N in the tributaries of the Peel-Harvey estuary is in dissolved organic form (DON, see Section 3.2) yet knowledge about the bioavailability of this fraction is limited. As such, management actions to address N in this report have focused on dissolved inorganic nitrogen (DIN) species, which are known to be highly bioavailable despite being a much smaller fraction of the TN present. Further investigations are needed to determine composition of the DON, the likely source in each catchment and, most importantly, the bioavailability of this fraction.

Depending on the bioavailability and sources of DON in the catchment, it may be appropriate to develop locally specific WQOs for different fractions of N.

10.3 Innovative ways to reduce nitrogen export to the estuary

Further work is needed to identify practical, efficient approaches for reducing DIN (ammonia and nitrate) concentrations in the tributaries of the estuary. We do not recommend expensive interventions to intercept N (other than those that bind P as well) until we have a better understanding of the bioavailability of DON (Section 10.2).

There is evidence that substantial N attenuation is occurring in several drains in the catchment, suggesting that rural drains may play an important role in controlling how much N reaches the estuary (Wells et al. 2019). Future studies are encouraged to investigate the relationship between drain features (e.g. morphology, groundwater input, flow rate, vegetation) and N attenuation (Wells et al. 2019).

As discussed in Section 9.1, we know that to reduce N export from the catchment to the estuary there are various management tools currently available:

- stock-exclusion fencing and riparian revegetation of waterways/drains
- catchment revegetation
- improved effluent management at dairies and intensive animal industries (such as piggeries, feedlots and abattoirs)
- retrofitting urban drainage infrastructure using WSUD principles
- decommissioning septic tanks to connect to reticulated sewerage.

However, modelling indicates that even when these measures are fully implemented across the plan area, N loads to the estuary are not sufficiently reduced to meet the N target (see 'Combined catchment management scenarios', page 201). An important area for trials and future research is to further explore innovative, effective and feasible solutions to retain N close-to-source and reduce N concentrations in drains and tributaries in the plan area.

10.4 Nutrient-contaminated groundwater

Many of the land uses in the Peel-Harvey estuary coastal plain catchment leach nutrients and non-nutrient contaminants into the superficial groundwater that intercepts with waterways, drains and the estuary. Potential sources include:

- infiltration of fertiliser (urban and rural)
- infiltration from nutrient-rich stockpiles or discharges from intensive land uses (e.g. piggeries, poultry sheds)
- leaching from septic tanks
- infiltration from discharged treated wastewater from WWTPs
- industrial estates
- contaminated sites including historic landfill sites.

The department's snapshot monitoring of catchment water quality has identified high levels of N and P over the summer months when there is little or no surface water flow, indicating the inflow of nutrient-rich groundwater (see Section 3.2) that is likely contaminated by leachates from catchment land uses.

Wells et al. (2019) identified some areas in the coastal estuary catchment where superficial groundwater had very high concentrations of N, although across the catchment concentrations were highly variable. Some groundwater sites had high concentrations of all three N forms (total ammonia, nitrate and DON), particularly in the Murray River catchment. The estuarine reaches of the Murray River receive a larger contribution of groundwater than the estuarine reaches of the Serpentine River or lower reaches of the Harvey River. Thus groundwater likely contributes a higher proportion of nutrients in the Murray River compared to the other rivers (Wells et al. 2019) and may be a significant source of N enrichment to the estuary.

We recommend further research to characterise nutrient concentrations in shallow groundwater across the coastal estuary catchment and the interaction of this with waterways, drains and the estuary. In addition, forensic techniques to identify the entry location and sources of groundwater pollutants would assist in targeting management interventions.

10.5 Investigation of non-nutrient contaminants in the estuary

We have a limited understanding of the presence and impact of non-nutrient contaminants in the water and sediments of the Peel-Harvey estuary. Those that are likely to be present include detergents, petroleum hydrocarbons, endocrine-disrupting chemicals, metals (e.g. lead, aluminium, chromium, copper, zinc, arsenic, cadmium, manganese, nickel), hydrocarbons, pathogens, pesticides, herbicides and chemicals.

Studies in the Swan and Canning rivers and stormwater drains (Evans 2009, Foulsham 2009, Nice 2009) have established the presence of non-nutrient contaminants including organic chemicals, pesticides including DDT (dichlorodiphenyltrichloroethane: an organochlorine insecticide) and dieldrin, hydrocarbons and heavy metals from human activities relating to urban, agricultural, industrial and mining land uses. A similar list of contaminants is expected in the Peel-Harvey estuary system because of the similar historic and present land uses. Studies to investigate concentrations of non-nutrient contaminants in the sediments of the estuary are warranted, in addition to ecotoxicity testing of key contaminants. We also need to better understand the impacts of urban stormwater on estuarine ecology, including the effect that herbicides and pesticides have on seagrasses, saltmarsh, macroinvertebrates, fish and other biota.

10.6 Synthesise knowledge on sediment health in the Peel-Harvey

A synthesis of all previously collected sediment data is needed to inform the development of dredging management plans in the Peel-Harvey estuary in the future.

Shortened forms

ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ARC	Australian Research Council
ASS	acid sulfate soil
ATU	aerobic treatment unit
AWRC	Australian Water Resources Council
BMP	best-management practice
CAMBA	China–Australia Migratory Bird Agreement
CCI	Coastal Catchments Initiative
DAFWA	Department of Agriculture and Food
DBCA	Department of Biodiversity, Conservation and Attractions
DDT	dichlorodiphenyltrichloroethane: an organochlorine insecticide
DEC	Department of Environment and Conservation
DIN	dissolved inorganic nitrogen
DO	dissolved oxygen
DOC	dissolved organic carbon
DON	dissolved organic nitrogen
DoH	Department of Health
DOP	dissolved organic phosphorus
DoW	Department of Water (now Department of Water and Environmental Regulation)
DPIRD	Department of Primary Industries and Regional Development
DPLH	Department of Planning, Lands and Heritage
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DWER/the department	Department of Water and Environmental Regulation
EPA	Environmental Protection Authority
EP Act	*Environmental Protection Act 1986*
EPBC Act	*Environmental Protection and Biodiversity Conservation Act 1999*
EPP	*Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*

ERMP	Environmental Review and Management Plan
ERRF	Environmental Revegetation and Rehabilitation Fund
EWR	ecological water requirements
FRP	filterable reactive phosphorus
GKB	Gnaala Karla Booja
GKBAC	Gnaala Karla Booja Aboriginal Corporation
GL	gigalitres
HRRT	Harvey River Restoration Taskforce
HT-clay	hydrotalcite clay
ILUA	Indigenous Land Use Agreement
IWSS	Integrated Water Supply Scheme
JAMBA	Japan–Australia Migratory Bird Agreement
LGAs	local government authorities
LOESS	Locally estimated scatterplot smoothing
LWSP	low-water-soluble phosphorus
N	nitrogen
NHMRC	National Health and Medical Research Council
NIMP	nutrient and irrigation management plan
NRM	natural resource management
NSHA	Noongar Standard Heritage Agreement
P	phosphorus
PDC	Peel Development Commission
PHCC	Peel-Harvey Catchment Council
PRI	Phosphorus Retention Index
REI	Regional Estuaries Initiative
RGW	Revitalising Geographe Waterways
ROKAMBA	Republic of Korea–Australia Migratory Bird Agreement
spp.	several species
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids

USEPA	United States Environmental Protection Agency
WAPC	Western Australian Planning Commission
WQI	Water Quality Index
WQIP	water quality improvement plan
WQO	water quality objective
WQPN	water quality protection note
WSUD	water sensitive urban design
WWTP	wastewater treatment plant

Glossary

Algal bloom	A rapid increase or accumulation of macro or microalgae (phytoplankton) in freshwater or marine water systems, usually in response to high nutrient concentrations and favourable conditions for growth.
Anoxic/anoxia	A total decline in dissolved oxygen in the water column (0 mg/L)
Annual nutrient load/total annual load	A measure of the total weight of a particular nutrient delivered to or by a waterway over a year (usually an annual average over several years). Calculated by multiplying daily flow with daily nutrient concentration and aggregating over the year.
ANZECC guideline value	The ANZECC guideline values are intended to provide government, industry, consultants and community groups with a framework to maintain ambient water quality in rivers, lakes, estuaries and marine waters. The core concept is to manage water quality to protect environmental values. These values may include protection of aquatic ecosystems, drinking water, primary and secondary recreation, visual amenity, and agricultural water for irrigation, livestock and growing aquatic foods. Formerly known as ‘trigger values’.
ANZECC & ARMCANZ Guidelines	Guidelines published by the Australian and New Zealand Environment Conservation Council for ecological and recreational water quality in marine and freshwater environments. It is a framework for conserving ambient water quality in rivers, estuaries, lakes and marine waters.
Basecase	The land use, climate and other model inputs for the period 2006–15 for which all modelled scenarios were compared against in the modelling that supports this plan (Hennig et al. 2021).
Benthic	Relating to or occurring at the sea, estuary or lake bottom.
Best practice management	Best practice management refers to management practices that use the most current and recommended information, science and technology
Bioavailable	Nutrients or compounds readily accessible for uptake or absorption by algae and plants, such as inorganic forms of N and P. Compounds that are easily broken down tend to be more bioavailable than those that do not.
Biota	Life forms
Closed agricultural system	A system of intensive agricultural production or animal husbandry where there is zero discharge of nutrient rich liquid or solids or non-nutrient contaminants to the immediate environment. Nutrient enriched liquid and solids waste and non-nutrient contaminants are removed from the property and disposed in an environmentally safe manner.

Catchment	The area of land that collects precipitation and drains via waterways (creeks, streams, rivers) and drains into estuaries and/or the ocean.
Catchment management action	On-ground actions in the estuary catchment that aim to improve the water quality draining to the estuary (e.g., by reducing nutrient export from the land to the waterways/drains).
Catchment model	Shortened name for the department's hydrological and nutrient model of the Peel-Harvey catchment. The model uses the eWater Source framework (Version 4.3), is calibrated to observed water quality data and determines how nutrients are generated by various land uses (diffuse and point sources), and how they are processed as they move through the catchment.
Chlorophyll a	A green pigment found in plants and algae that is essential for photosynthesis.
Chlorophytes	A group of algae characterised by green chloroplasts. They include unicellular phytoplankton and large leaf macroalgae.
Community values	Specific characteristics or uses of the environment that are important for a healthy ecosystem or public benefit, welfare, safety or health.
Constructed wetland	An engineered water treatment system with constructed basins designed to specifically maximise physical, chemical and biological nutrient removal processes.
Contaminant	A substance that has the potential to present a risk of harm to human or environmental health.
Cyanobacteria	Also known as blue-green algae, these are a photosynthetic bacteria that occur as single cells or as colonies (which can form filaments).
Dairy shed	Any structure where the milking of animals is undertaken, including any associated yards or areas in which animals are confined prior to or following milking.
Diatoms	Microscopic one-celled or colonic algae of the class Bacillaophycae, having cell walls of silica consisting of two interlocking symmetrical valves.
Diffuse source	Nutrients derived from large areas in the catchment, mainly from broad scale, rural land uses rural including cattle grazing, lifestyle blocks and horticulture but also from urban land uses such as industry, residential, recreational and offices. Diffuse sources of nutrients provide most of the nutrients to the waterways/drains in the Peel-Harvey estuary catchment.
Dinoflagellate	Chiefly protozoans, characteristically having two flagella and sculptured shell or pellicle that is formed from plates of cellulose deposited in membrane vesicles.
Dissolved oxygen	The amount of oxygen that is present in water

Drain	An artificially constructed passage for water flow in an urban or rural setting that was never a waterway.
Estuary	Partially enclosed coastal body of water, having an open connection with the ocean, where freshwater from inland is mixed with saltwater from the sea.
Estuarine reaches	The lower reaches or portions of a river that are marine influenced (that is, influenced by tides and salt water).
Eutrophication	A deterioration of water quality caused by the excessive input of nutrients. It leads to overgrowth of aquatic plants, macroalgae and/or phytoplankton, and the decomposition of this growth may lead to hypoxia/anoxia (low or no oxygen in the water).
First flush	The first rainfall after an extended dry period (usually beginning of the wet season), resulting in rainfall runoff dislodging and entraining relatively high loads of sediments, particulates and pollutants that have built up in the period between rainfall events.
Fish kill	Mass fish deaths, sometimes attributed to low-oxygen events
Floodplain	The area adjacent to a waterway that is inundated in a flood event.
Foreshore area	The land that adjoins or directly influences a waterway. It is the area of transition between the edge of the waterway channel and the furthest extent of riparian vegetation, the floodplain and riverine landforms.
Groundwater	Water that occupies the pores and crevices of rock or soil beneath the land surface.
Hypersaline	Water that is saltier than seawater (>35 parts per thousand).
Hypoxic/ hypoxia	Conditions of low dissolved oxygen in the water column (<2 mg/L).
Indicator	A measured variable that can be used to provide a measure of a pressure, stressor and/or response. Indicators are most frequently used to monitor resource condition against a standards/target framework, which is how they are applied in this WQIP. Indicators are selected based on an understanding of the ecosystem such that changes in the indicator value represent a change in the condition of the resource.
Infiltration	The downward movement of water or effluent through the ground into groundwater reserves.
Intensive animal industry	Includes piggeries, abattoirs, poultry farms, stockyards, feedlots.
Intensive horticulture	Includes annual and perennial horticulture, production of flowers, exotic and native plants, nuts, irrigated fodder production, turf farms and plant and fruit nurseries.

Intensive land uses	Defined here as intensive animal industries, intensive horticulture, and premises with livestock numbers in excess of recommended stocking rates.
Invertebrates	An animal without a backbone, includes zooplankton and macroinvertebrates (for example, shellfish, worms, bivalves).
Lag time	The period between a management change and a related water quality improvement in a downstream water body
Load reduction target	The amount of nutrient load that would need to be reduced from the current load, to meet the maximum acceptable load. It is simply the difference between the average annual load and the maximum acceptable load.
Macroalgae	Photosynthetic plant-like organisms that can be seen with the naked eye. Macroalgae may be divided into the groupings: reds (rhodophytes), greens (chlorophytes), browns (phaeophytes) and blue-greens (cyanophytes). These divisions are primarily based on pigments in their tissues, which are also usually evident in their appearance.
Macrophyte (aquatic)	Rooted aquatic plants that can be seen with the naked eye, and grow submerged, emergent or floating within marine, estuarine and riverine environments, e.g., seagrasses.
Management action	Documentation of actions and approaches to achieve the Water Quality Objectives and management goals to protect the community values.
Management goal	Measures or statements used to assess whether the community values are being protected. They should be unambiguous, measurable, and achievable and reflect the desired level of protection of the community values.
Maximum acceptable load	The total estimated amount of nutrient load delivered from a reporting catchment/s for which a reasonable water quality outcome would be expected (i.e., the water quality objective (nutrient concentration) will be met).
Modelled flow-weighted annual mean concentration	The annual nutrient load divided by the annual flow.
Nitrate	The term refers to the combined concentrations of both forms of oxidised inorganic nitrogen generally found in aquatic environment: nitrate (NO_3) and nitrite (NO^{2-}). The term nitrate is used for simplicity in this document, as the vast majority (>99%) of oxidised inorganic nitrogen will generally be in the form of nitrate, as nitrite is highly reactive and tends to transition quickly to either nitrate (NO_3) or

	ammonium (NH^{4+}). When water samples are analysed by standard laboratory methods, nitrate is converted to nitrite, and the total concentration of nitrite is reported and represents the concentration of oxidised inorganic nitrogen.
Nitrogen (N)	The chemical element with the symbol N. An element or nutrient that is essential to the effective functioning of ecosystem biota. Living things need nitrogen to produce amino acids that allow the organism to live and grow. It is a major limiting nutrient for primary production in estuaries.
Nitrogen mineralisation	The conversion of organically bound nitrogen in soil organic matter, crop residues, manure and other organic amendments into inorganic forms of ammonium and nitrate.
Nutrient concentration	The amount of a nutrient in a specified volume of water determined by laboratory analysis, which can be measured over time through a routine sampling program.
Nutrients	Chemicals that are important for plants to survive and grow; however, water quality is reduced by excess nutrients entering waterways for example, nitrogen and phosphorus.
Nutrient load	A measure of the total weight of a particular nutrient delivered to or by a waterway over a given period (usually an annual average over several years) and is a function of concentration and flow.
Nutrient surplus	Equal to nutrient input minus nutrient output. Nutrient surpluses can be stored (for example, in livestock, soil or plant matter) or lost from the land. Nutrient losses can occur though leaching to groundwater, in surface water, or to the atmosphere. A surplus means that there is loss of N and P into soil and in the case of nitrogen, also into the air.
Nutrient use efficiency (NUE)	Nutrient out divided by nutrient in, expressed as a percentage. Land uses with 100% NUE convert all nutrient inputs to nutrient outputs and therefore have a nutrient surplus of zero.
Oligotrophic	Relatively low nutrient conditions in a waterway, normally associated with low primary productivity.
Organic matter	The collection of carbon-based compounds aquatic and terrestrial environments
Pathogen	An infectious organism which can cause disease.
Peel-Harvey estuary coastal plain catchment	The land area on the Swan coastal plain that collects precipitation and flows via waterways (rivers, creeks, streams or brooks) and drains into the Peel-Harvey estuary.
Phosphorus (P)	The chemical element with the symbol P. An element or nutrient that is essential to the effective functioning of ecosystem biota. It plays a

	critical role in the nutrition of all plants as it is an essential element that contributes to a wide array of physiological and biochemical processes.
Phosphorus retention index (PRI)	A measure of a soil's capacity to retain phosphorus (Allen & Jeffery 1990). Soil with a PRI of zero would have no capacity to retain phosphorus. Two soil PRI classifications were assumed: soils with a PRI of < 7 being 'low PRI' and soils with a PRI of ≥ 7 being 'high PRI'.
Phytoplankton	Microscopic, photosynthetic organisms, usually single-celled. Includes microalgae and cyanobacteria.
Plan area	The area bounded by the reporting catchments on the Swan coastal plain, as modelled by Hennig et al. (2021).
Point source	An identifiable source of nutrient pollution or other contaminants, such as discharge of effluent from an intensive animal like a piggery.
Pressure	Any human activity or biophysical pattern of change that has the potential to impact on the natural environment.
Reporting catchments	A spatial boundary used to report results from the modelling of land use and catchment contributions of flow and nutrient loads to the estuary. The reporting catchments used by Hennig et al. (2021) are based on the major drainage catchments in the Peel-Harvey.
Response	As in the Pressure-Stressor-Response model. The ecological response of a natural system such as a waterway is the result of pressures and stressors impacting that system.
Residence time	The length of time water or nutrients spend in part of the hydrological cycle; for example, an estuary basin.
Reticulated sewerage	A network of sewers and associated wastewater treatment plant managed by a sewerage service provider.
Riparian zone management	Usually refers to riparian revegetation, stock exclusion and/or river restoration techniques
Riparian zone	The zone along or surrounding a water body where the vegetation and natural ecosystems benefit from and are influenced by the passage and storage of water.
Release reach	A release reach is the area of river (longitudinal and lateral extent) known to be influenced by dam river releases.
River release	River releases are agreed release volumes from dams to meet downstream water-dependent objectives (for example, maintaining social, cultural and ecological values and/or providing water for licensed or riparian users) for river reaches below the dams.
Runoff	The draining away of water (or substances carried in it) from the land surface.

Salinity	The concentration of salt in water.
Sediment	Loose particles of sand, clay, silt and other substances that settle at the bottom of a body of water. Sediment can be derived from the erosion of soil or from the decomposition of plants and animals.
Sensitive water resource	Areas in which development has the potential to affect water dependent ecosystems, natural waterways and estuaries, wetlands and selected coastal inlets and embayment that have been recognised at either the State or National level as having high ecological, social, cultural and/or economic values and are sensitive to contamination associated with land use and development.
Sewage	Any kind of sewage, faecal matter or urine, and any waste composed wholly or in part of liquid.
Slow-release phosphorus fertiliser	Sometimes referred to as low-water-soluble fertiliser. A type of fertilisers that are designed to slowly release the P to the soil. The P is less likely to leach from the soil when used on sandy, acidic low-PRI soils, compared to more traditional, highly water-soluble fertilisers.
Stormwater	Water that flows over ground surfaces and in natural streams and drains, as a direct result of rainfall over a catchment. Stormwater consists of rainfall runoff and any material (soluble and insoluble) mobilised in its path of flow.
Stratification	The forming of water layers based on differences in salinity, oxygen or temperature.
Stressor	Any physical, chemical or biological substance or process arising from a pressure that has the potential to induce an adverse environmental response to a community value.
Surface water allocation plan	A plan that outlines how much water can be taken from surface water resources, while safeguarding the sustainability of the resource and protecting the water-dependent environment.
Target nutrient concentration	A concentration of TN or TP set out in the Water Quality Objectives (WQO 1 and 2) of this plan below which the risk of nuisance algal blooms is considered low. Nutrient concentrations above these levels may lead to declining water quality and ecological health in the estuary system.
Total ammonia	This term refers to combined measures of both ammonia (NH_3) and ammonium (NH^{4+}) which are present in aquatic systems at equilibrium in proportions dependent on the pH, temperature and salinity. Both species are bioavailable to phytoplankton and aquatic plants, while toxicity to fauna is primarily attributed to ammonia. Under typical conditions the most common form is ammonium (NH^{4+}). When water samples are analysed by standard laboratory methods the pH is increased to > 10, which converts any ammonium (NH^{4+}) to ammonia

	(NH_3) before measurement. While the lab reports on the concentration of nitrogen in ammonia (NH_3), this value represents the combined concentration of both ammonia (NH_3) and ammonium (NH^{4+}). As there is the same amount of N in both ammonia and ammonium, the concentration will be the same irrespective of the relative proportions of species.
Total nitrogen	The sum of all forms of nitrogen found in the water column. This includes particulate and dissolved forms of an inorganic and organic nature.
Total phosphorus	The sum of all forms of phosphorus found in the water column. This includes particulate and dissolved forms of an inorganic and organic nature.
Toxicity	The degree to which a substance or combination of substances can damage an exposed organism.
Treatment train	An approach of applying catchment management actions either in parallel or sequentially to minimise nutrient pollution at source, in transit and at the end of the pipe before they reach the receiving waterbody.
Tributary	A river, stream or creek which flows into another larger river.
Turbidity	Opaqueness of water because of suspended particles in the water causing a reduction in the transmission of light.
Water quality	The physical, chemical and biological characteristics of water and the measure of its condition relative to the requirements for one or more biotic species and or to any human need or purpose.
Water Quality Objective	Guideline values (a measurable quantity, such as a concentration) for relevant indicators, or are narrative statements, which if met, support the management goals and the protection (or recovery) of community values.
Water regime	A description of the variation of flow rate or water level over time; it may also include a description of water quality.
Waterway	Any river, creek, stream or brook, including its floodplain and estuary or inlet. This includes systems that flow permanently, for part of the year or occasionally; and parts of the waterway that have been artificially modified (e.g., excavated or straightened as part of historical management practices). Waterways do not include drains.
Wetland	An area of seasonally, intermittently or permanently waterlogged or inundated land, whether natural or otherwise, and includes a lake, swamp, marsh, spring, dampland, sumpland, palusplain.

References

ACIL Tasman 2004, *Options to improve efficiency of irrigation water use in WA – An assessment of options for improving water use efficiencyin the South West Irrigation Scheme*, Final report, November 2004.

Allinson, G, Bui, A, Zhang, P, Rose, G, Wightwick, AM, Allinson, M & Pettigrove, V 2014, 'Investigation of 10 herbicides in surface waters of a horticultural production catchment in southeastern Australia'. *Archives of environmental contamination and toxicology,* vol. 67**,** 358-373.

ANZECC (Australian and New Zealand Environment and Conservation Council) & ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) 2000a, *Australian and New Zealand Guidelines for Water Quality Monitoring and Reporting, Volume 2: Aquatic Ecosystems — Rationale and Background Information*, Canberra, ACT.

ANZECC (Australian and New Zealand Environment and Conservation Council) and ARMCANZ (Agriculture and Resource Management Council of Australia and New Zealand) 2000b, *Australian and New Zealand Guidelines for Water Quality Monitoring and Reporting, Volume 1: The Guidelines*, Canberra, ACT.

Australian Government 2018, *National Water Quality Management Strategy Charter*, Canberra, March CC BY 3.0.

Bainbridge, M, Barron, O & Hodgson, G 2018, *Assessment of ecological water requirements for the Peel Integrated Water Initiative*, CSIRO, Australia.

Bird, P, Bicknell, D, Bulman, P, Burke, S, Leys, J, Parker, J, Van Der Sommen, F & Voller, P 1992, The role of shelter in Australia for protecting soils, plants and livestock. IN PRINSLEY, R. T. (Ed.) *The role of trees in sustainable agriculture. Forestry Sciences 43.* Springer, Dordrecht.

BoM (Bureau of Meteorology) 2022, National Hydrological Projections - Design and Methodology, Bureau Research Report No. 061. Melbourne Victoria.

Bradby, K 1997, *Peel-Harvey, the decline and rescue of an ecosystem,* Greening the Catchment Taskforce (inc.), Mandurah, Western Australia.

Brearley, A 2005, *Ernest Hodgkin's Swanland: Estuaries and Coastal Lagoons of South-Western Australia,* UWA Publishing, Western Australia.

Bussemaker, P, Kelsey, P & Zammit, C 2004, *Nutrient status and trend in the waterways of the Peel-Harvey catchment*, [unpublished internal document], Department of Environment, Western Australia.

Charles, S, Fu, G, Barron, O & G, H 2019, *Historical and Projected Climate of the Peel Region: The Peel Integrated Water Initiative*, CSIRO, Australia.

Chem Centre 2018, *Ellen Brook soil amendment trial: Ellen Brook Western Australia. A report for the Department of Parks and Wildlife*, Chem Centre Project T233.

City of Mandurah 2009, *Town Planning Scheme No. 3, Local Planning Policy 15 – Water Sensitive Urban Design*, Mandurah, Western Australia.

City of Mandurah, 2019, *Water sensitive urban design policy POL-RDS 07,* Mandurah, Western Australia.

Cloern, JE 2001, 'Our evolving conceptual model of the coastal eutrophication problem'. *Marine ecology progress series,* vol. 210**,** 223-253.

Conley, DJ, Carstensen, J, Ærtebjerg, G, Christensen, PB, Dalsgaard, T, Hansen, JL & Josefson, AB 2007, 'Long-term changes and impacts of hypoxia in Danish coastal waters'. *Ecological Applications,* vol. 17**,** S165-S184.

Cronin-O'Reilly, S, Valesini, F & Hallett, C 2019, *Assessing the health of the Peel-Harvey Estuary through its benthic invertebrate fauna. Balancing estuarine and societal health in a changing environment*, [unpublished report], Murdoch University, Perth, Western Australia.

Davidson, WA 1995, *Hydrogeology and groundwater resources of the Perth region, Western Australia*, Vol. 142, Geological Survey of Western Australia.

Deeney, AC 1989, 'Geology and groundwater resources of the superficial formations between Pinjarra and Bunbury, Perth Basin.'. *Western Australia Geological Survey, Perth, WA,* vol. Report 26**,** 31-57.

Degens, B & Lam, A 2019, *Fact sheet: keeping phosphorus on your farm using Iron Man Gypsum*, Internal report, Department of Water and Environmental Regulation.

Degens, B, Shackleton, M, Grant, B, Tulipani, S & Giura, R 2023, *Treatment of agricultural soils with Iron Man Gypsum to reduce leaching and runoff loss of P to waterways: Mucca Dairy experiments*, Water Science Technical Series Report, Department of Water and Environmental Regulation, Western Australia.

Del Marco, A, Taylor, R, Clarke, K, Savage, K, Cullity, J & Milles, C 2004, *Local Government biodiversity planning guidelines for the Perth metropolitan region, Perth Biodiversity Project*, Western Australian Local Government Association, Perth, Western Australia.

Department of Environment Water Heritage and the Arts 2002, *Framework for marine and estuarine water quality protection*, Department of Agriculture and Water Resources, Canberra, March. CC BY 3.0.

Department of Fisheries 2015a, *Blue Swimmer Crab Resource of The Peel-Harvey Estuary Harvest Strategy 2015 - 2020, Version 1.0. West Coast Estuarine Managed Fishery (Area 2) and the Peel-Harvey Estuary Blue swimmer Crab Recreational Fishery*, Department of Fisheries, Western Australia.

— 2015b, *Finfish Resources of the Peel-Harvey Estuary Harvest Strategy 2015 – 2020, West Coast Estuarine Managed Fishery (Area 2)*, Department of Fisheries, Western Australia.

Department of Planning Lands and Heritage (DPLH) 2023, *Aboriginal Heritage Act 1972 Guidelines*, November 2023, Perth, Western Australia.

Douglas, G, Adeney, J, Johnston, K, Wendling, L & Coleman, S 2012, 'Major element, trace element, nutrient, and radionuclide mobility in a mining by-product-amended soil'. *Journal of Environmental Quality,* vol. 41, 1818–1834.

Douglas, G, Wendling, L, Adeney, J, Johnston, K & Coleman, S 2010, *Investigation of mineral-based by-product use as a soil amendment: Results from the Bullsbrook Turf Farm, WA*, Water for a Healthy Country Flagship, CSIRO.

DoW (Department of Water) 2004–07, *Stormwater management manual for Western Australia*, Department of Water, Perth.

— 2006, *Water Quality Protection Note 6 Vegetation buffers to sensitive water resources* Department of Water, Perth, Western Australia.

— 2008a, *Rockingham-Stakehill Groundwater Management Plan*, Perth, Western Australia.

— 2008b, *Water Quality Protection Note 22 Irrigation with nutrient-rich wastewater*, Department of Water, Perth, Western Australia.

— 2009, *Water Quality Protection Note 39 Ponds for stabilising organic matter* Department of Water, Perth, Western Australia.

— 2010a, *Water Quality Information Sheet 4 Nutrient and irrigation management plan checklist*, Department of Water, Perth, Western Australia.
— 2010b, *Water Quality Protection Note 33 Nutrient and irrigation management plans*, Department of Water, Perth, Western Australia.
— 2012a, *Murray Groundwater Allocation Plan*, Perth, Western Australia.
— 2012b, *Operational policy 4.3: Identifying and establishing waterway foreshore areas*, Perth, Western Australia.
— 2013a, *Water Quality Protection Note 26 Liners for containing pollutants using synthetic membranes* Department of Water, Perth, Western Australia.
— 2013b, *Water Quality Protection Note 27 Liners for containing pollutants using engineered soils* Department of Water, Perth, Western Australia.
— 2015a, *Peel Coastal Groundwater Allocation Plan*, Perth, Western Australia.
— 2015b, *Water Quality Protection Note 80 Stockyards* Department of Water, Perth, Western Australia.
— 2016, *Water Quality Protection Note 4 Sensitive Water Resources* Department of Water, Perth, Western Australia.
DPIRD (Department of Primary Industries and Regional Development) 2021, *State Soil Health Strategy, Western Australia*, Department of Primary Industries and Regional Development, Perth.
DPIRD (Department of Primary Industry and Regional Development) 2018, *Freshwater fish database (accessed on 29 June 2018)*, Department of Primary Industry and Regional Development, Western Australia.
DWER (Department of Water and Environmental Regulation) 2017a, *Decision process for stormwater management in Western Australia*, Department of Water and Environmental Regulation, Perth.
— 2017b, *Managing releases for the Serpentine River, Serpentine River allocation statement. Integrated Water Supply Scheme release review*, Perth, Western Australia.
— 2017c, *Managing releases from the North Dandalup Dam, North Dandalup allocation statement. Integrated Water Supply Scheme release review*, Perth, Western Australia.
— 2020a, *Aquatic biota data from field sampling 2007 to 2020*, [unpublished data], River Science, Perth, Western Australia.
— 2020b, *Bindjareb Djilba – A plan for the protection of the Peel-Harvey Estuary*, Perth, Western Australia.
— 2021a, *Peel-Harvey estuary catchment nutrient reports 2018*, Perth, Western Australia.
— 2021b, *Transform Peel - Peel Integrated Water Initiative*, Department of Water and Environmental Regulation, Perth, Western Australia.
— 2022, *Murray groundwater area allocation statement*, Perth, Western Australia.
— 2023a, *Bindjareb Djilba (Peel-Harvey estuary): Condition of the estuary 2016-2019*, Perth, Western Australia.
— 2023b, *Why should we fence and revegetate our waterways?*, Healthy Estuaries Western Australia, Department of Water and Environmental Regulation, Perth.
—2024, *Waangaamaap - Serpentine groundwater allocation statement*, Perth, Western Australia.
Economic Consulting Services 2019, *Peel Waterways - An Economic Valuation*, Perth, Western Australia.

Environment Australia 2001, *A directory of important wetlands in Australia*, 3rd edition, Environment Australia, Canberra.
EPA (Environmental Protection Authority) 1985, *Peel Inlet and Harvey Estuary Management Strategy, Assessment of Stage 1 Environmental Review and Management Programme, Report and Recommendations by the Environmental Protection Authority*, Department of Conservation and Environment Bulletin No. 243. December 1985.
— 2003, *Peel Inlet and Harvey Estuary System Management Strategy: Progress and Compliance by the Proponents with Environmental Conditions set by the Minister for the Environment in 1989, 1991 and 1993. Advice of the Environmental Protection Authority*, Perth, Western Australia.
— 2008a, *Guidance statement 33 – Environmental guidance for planning and development*, Western Australia.
— 2008b, *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management*, Environment Protection Authority, Perth, Western Australia.
— 2015, *Perth and Peel @ 3.5 million - Environmental impacts, risks and remedies. Interim strategic advice of the Environmental Protection Authority to the Minister for Environment under section 16(e) of the Environmental Protection Act 1986*, Office of the Environmental Protection Authority, Perth, Western Australia.
— 2018, *Environmental Factor Guideline – Inland Waters* Perth, Western Australia.
Evans, S 2009, *A baseline study of contaminants in groundwater at disused waste disposal sites in the Swan Canning catchment, Water Science Technical Series Report No. 4*, Department of Water, Western Australia.
Forest Industries Federation WA Inc. 2014, *Code of practice for timber plantations in Western Australia, Second edition*, Western Australia.
Foulsham, G 2009, *A snapshot of contaminants in drains of Perth's industrial areas*, Water Science technical series report No.12, Department of Water, Western Australia.
Gerritse, R & Schofield, N 1989, ' The movement of phosphate in a catchment with a shallow ephemeral water table'. *Journal of contaminant hydrology,* vol. 4**,** 313-331.
GHD 2017, *Report for Department of Agriculture and Food – Planning for the Peel Food Zone*, Perth, Western Australia.
Gibbs, M 2011, 'An Aboriginal fish trap on the Swan Coastal Plain: the Barragup mungah'. *Records of the Western Australian Museum,* vol. 4**,** 15.
Government of Western Australia 2010, *Vasse Wonnerup Wetlands and Geographe Bay water quality improvement plan*, Department of Water, Perth, Western Australia.
— 2019a, *Government Sewerage Policy*, Department of Planning, Lands and Heritage, Perth, Western Australia.
— 2019b, *Waste Avoidance and Resource Recovery Strategy – Western Australia's waste strategy*, Waste Authority, Department of Water and Environmental Regulation, Perth, Western Australia.
— 2021a, *Waterwise Perth – Two Year Action Plan*, Western Australia.
— 2021b, *Western Australian climate projections – Summary*, Perth, Western Australia.

— 2022a, *Kep Katitjin – Gabi Kaadadjan (Waterwise Perth Action Plan 2)*, Western Australia.
— 2022b, *Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia*, Western Australia.
— 2022c, *State Native Vegetation Policy for Western Australia*, Government of Western Australia.
— 2023, *uPtake trial summary 2019–2023*, Western Australia.
Grell, T, Marchuk, S, Williams, I, McCabe, BK & Tait, S 2023, 'Resource recovery for environmental management of dilute livestock manure using a solid-liquid separation approach'. *Journal of Environmental Management,* vol. 325**,** 116-254.
Haine, B, Coade, G & McSorley, A 2011, *Nutrient export monitoring: agricultural nutrient exports and mitigation in the Hawkesbury-Nepean*, Report prepared by the New South Wales Office of Environment and Heritage for the Australian Government, New South Wales, Australia.
Hale, J & Butcher, R 2007, *Ecological Character Description of the Peel-Yalgorup Ramsar Site*, Report to the Department of Environment and Conservation and the Peel-Harvey Catchment Council, Perth, Western Australia.
Hale, J & Kobryn, H 2017, *Peel Yalgorup Littoral and Fringing Vegetation: Extent and condition*, Peel-Harvey Catchment Council, Mandurah, Australia.
Hall, J 2019, *Managing rural drains to facilitate the removal of nutrients on the Swan Coastal Plain – Literature review*, [unpublished report], Department of Water and Environmental Regulation, Western Australia.
Hallett, C, Trayler, K & Valesini, F 2019a, 'The Fish Community Index: A Practical Management Tool for Monitoring and Reporting Estuarine Ecological Condition'. *Integrated environmental assessment and management,* vol. 15 (5)**,** 726-738.
Hallett, CS, Valesini, FJ, Kilminster, K, Wells, NS & Eyre, BD 2019b, 'A rapid protocol for assessing sediment condition in eutrophic estuaries'. *Environmental Science: Processes & Impacts,* vol. 21**,** 1021-1037.
Hammer, K, Rogers, B & Chesterfield, C 2018, *Vision and Transition Strategy for a Water Sensitive Greater Perth. Melbourne*, Australia: Cooperative Research Centre for Water Sensitive Cities.
Hennig, K, Kelsey, P & Hall, J 2018, *Peel Integrated Water Initiative (PIWI) hydrological and nutrient modelling*, [unpublished internal report], Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.
Hennig, K, Kelsey, P, Marillier, B, Hall, J, Gunaratne, GG & Robb, M 2021, *Hydrological and nutrient modelling of the Peel-Harvey Estuary catchment*, Water Science Technical Series no. 84, Department of Water and Environmental Regulation, Perth, Western Australia.
Hipsey, M, Huang, P, Busch, B & Hennig, K 2019, *Integrated modelling assessment of nutrient cycling and water quality in the Peel-Harvey Estuary. Balancing estuarine and societal health in a changing environment*, [unpublished report], Murdoch University, Perth, Western Australia.
Hodgkin, EP & Lenanton, R 1981, Estuaries and coastal lagoons of south western Australia. IN BJ, N. & CRONIN, L. (Eds.) *Estuaries and nutrients.* Contemporary Issues in Science and Society. Humana Press.

Horticulture Australia Ltd. 2014, *Guidelines for environmental assurance in Australian horticulture – second edition*, Developed by Horticulture for Tomorrow.

Howarth, R, Chan, F, Conley, DJ, Garnier, J, Doney, SC, Marino, R & Billen, G 2011, 'Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems'. *Frontiers in Ecology and the Environment,* vol. 9**,** 18-26.

Hugues-dit-Ciles, J, Kelsey, P, Marillier, B, Robb, M, Forbes, V & McKenna, M 2012, *Leschenault estuary water quality improvement plan* Department of Water, Western Australia.

Kadlec, RH & Wallace, S 2008, *Treatment wetlands*, CRC press, Florida.

Kelsey, P, Hall, J, Kretschmer, P, Quinton, B & Shakya, D 2011, *Hydrological and nutrient modelling of the Peel-Harvey catchment*, Department of Water, Perth, Western Australia.

Kinhill Engineers Pty. Ltd. 1988, *Peel Inlet and Harvey Estuary Management Strategy Environmental Review and Management Programme - Stage 2*, Department of Agriculture and Department of Marine and Harbours, Western Australia.

Kookana, RS, Baskaran, S & Naidu, R 1998, 'Pesticide fate and behaviour in Australian soils in relation to contamination and management of soil and water: a review'. *Soil Research,* vol. 36**,** 715-764.

Kraal, P, Burton, ED & Bush, RT 2013, 'Iron monosulfide accumulation and pyrite formation in eutrophic estuarine sediments'. *Geochimica et Cosmochimica Acta,* vol. 122**,** 75-88.

Lamb, A, Wilson, G & Leng, M 2006, 'A review of coastal palaeoclimate and relative sea-level reconstructions using d13C and C/N ratios in organic material'. *Earth-Science Reviews,* vol. 75**,** 29– 57.

Latto, A, Noonan, J & Taylor, R 2000, *Environmental guidelines for new and existing piggeries*, Department of Agriculture and Food, Bulletin 4416, Perth, Western Australia.

Lavell, K, Summers, R, Weaver, D & Clarke, M 2004, *The Peel Harvey coastal catchments initiative: Preliminary findings on the adoption of water quality best management practices*, Nutrient Management Forum April 2004, Albany, Western Australia.

Lovett, S, Price, P & Edgar, Be 2007, *(eds) Salt, Nutrient, Sediment and Interactions: Findings from the National River Contaminants Program*, Land & Water Australia.

Lukatelich, R & McComb, A 1989, *Seasonal changes in macrophyte abundance and composition in the Peel-Harvey Estuarine system*, Report to the Waterways Commission, Perth, Western Australia.

Mac Loughlin, TM, Peluso, ML & Marino, DJ 2022, 'Multiple pesticides occurrence, fate, and environmental risk assessment in a small horticultural stream of Argentina'. *Science of The Total Environment,* vol. 802**,** 149893.

Maddern, R 2012, Low water-soluble superphosphate fertiliser for pasture production in south-western Australia. PhD thesis. Perth, Curtin University.

Marine and Freshwater Research Laboratory 2019, Data provided by Oliver Krumholz, 2019, monitoring undertaken by MAFRL, . Murdoch University, Perth.

May, B, Smethurst, P, Carlyle, C, D. Mendham, Bruce, J & Baillie, C 2009, *Review of fertiliser use in Australian forestry, Prepared for Forest & Wood Products Australia Ltd.*, Victoria, Australia.

McComb, A & Lukatelich, R 1995, The Peel-Harvey Estuarine System, Western Australia IN MCCOMB, A. (Ed.) *Eutrophic Shallow Estuaries and Lagoons.* Boca Rata, CRC Press Inc.

McFarlane, D 2005, *Context report on south west water resources for expert panel examining Kimberley water supply options. Client report to WA Government.* , CSIRO: CSIRO Water for a Healthy Country Flagship Canberra.

McGahan, E, Wiedemann, S & Gould, N 2018, *Egg industry environmental guidelines*, Australian Eggs Limited publication no. 1PS701AA, Sydney, New South Wales.

Meat & Livestock Australia 2011, *National procedures and guidelines for intensive sheep and lamb feeding systems*, Prepared by Productive Nutrition Pty Ltd June 2011, Sydney, New South Wales.

— 2012a, *National beef cattle feedlot environmental code of practice – second edition*, Sydney, New South Wales.

— 2012b, *National guidelines for beef cattle feedlots in Australia – third edition*, Sydney, New South Wales.

Moore, G, Sanford, P & Wiley, T 2006, *Perennial pastures for Western Australia, Bulletin 4690*, Department of Agriculture and Food, Perth, Western Australia.

Myers, N, Mittermeier, RA, Mittermeier, CG, Da Fonseca, GA & Kent, J 2000, 'Biodiversity hotspots for conservation priorities'. *Nature,* vol. 403**,** p. 853.

Nannup, H, Kearing, G, Nannup, F, Nannup, J, Ugle, R & Walley, G 2019, *Bindjareb Gabi Wonga (Bindjareb Water Story)*, Mandurah, Western Australia.

Neville, SD 2005, *SSPRED: The Support System for Phosphorus Reduction Decisions - Model Framework Development Report*, Denmark, Western Australia.

NHMRC (National Health and Medical Research Council 2006, *Guidelines for Managing Risks in Recreational Waters*, Australian Government Publishing Service, Canberra.

Nice, H, Grassi, M, Foulsham, G, Morgan, B, Evans, S & Robb, M 2009, *A baseline study of contaminants in the Swan and Canning catchment drainage system*, Water Science Technical Series WST3, Department of Water, Western Australia.

Nice, HE 2009, *A baseline study of contaminants in the sediments of the Swan and Canning estuaries*, Water Science technical series report no. 6, Department of Water, Western Australia.

North Carolina State University 2000, *National management measures to control nonpoint source pollution from agriculture, draft*, Raleigh, NC.

Ovens, R, Weaver, D, Keipert, N, Neville, S, Summers, R & Clarke, M 2008, *Farm gate nutrient balances in south west Western Australia – An overview,* Western Australia.

Oversby, B 2022, (personal communication). Oversby Consulting, Western Australia.

Parkyn, S 2004, *Review of riparian buffer zone effectiveness*, MAF Technical Paper no. 2004/2005, Wellington, New Zealand.

Pearce, A, Helleren, S & Marinelli, M 2000, *Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes*, Fisheries Western Australia, Perth, Western Australia.

Peel-Harvey Catchment Council 2014, *Lower Murray River Action Plan*, Western Australia.
— 2015, *Middle Murray River Action Plan*, Western Australia.
Peel-Harvey Study Group 1985, *Peel Inlet and Harvey Estuary Management Strategy: Environmental review and management programme, Stage 1*, Department of Conservation and Land Management, Perth, Western Australia.
Peel Development Commission 2006a, *Peel-Harvey Coastal Catchment Water Sensitive Urban Design Technical Guidelines*, Prepared for the Peel Development Commission, October 2006, Western Australia.
— 2006b, *Peel-Harvey Water Sensitive Urban Design Local Planning Policy – a model local planning policy to aid the achievement of integrated urban water management within the EPP Policy Area of the Peel*, March 2006, Western Australia.
PHCC (Peel-Harvey Catchment Council) 2012, *Draft subcatchment implementation plan for water quality improvement in selected subcatchments: Nambeelup, Dirk Brook-Punrak and Mayfield*, Mandurah, Western Australia.
— 2013, *Peel-Harvey Catchment Water Quality Improvement Plan Implementation Review 2008-2011*, Report prepared by the Peel-Harvey Catchment Council, Mandurah, Western Australia.
— 2015, *Binjareb Boodja Landscapes 2025, A Strategy for Natural Resource Management in the Peel-Harvey Region*, A Report to the Peel-Harvey Catchment Council, Jane O'Malley & Andrew Del Marco (eds.) Mandurah, Western Australia.
— 2017, *Wetlands and People Plan for the Peel Yalgorup System - A CEPA Action Plan for Ramsar Site 482*, A report prepared by Andrew Del Marco and Amanda Willmott to the Peel-Harvey Catchment Council; Mandurah, Western Australia.
— 2019, *Draft Ecological Character Description for the Peel-Yalgorup Ramsar site: Addendum*, A report by Jennifer Hale for the Peel-Harvey Catchment Council, Mandurah Western Australia.
— 2021, *Bindjareb Boodja Landscapes – A strategy for natural resource management in the Peel-Harvey region, Western Australia*. Mandurah, Western Australia.
— 2023, *Model Local Planning Policy – Horticultural Development in the Peel-Harvey Coastal Plain Catchment*. Prepared by the Bindjareb Djilba (Peel-Harvey estuary) Protection Plan Policy and Planning Coordinating Committee. Mandurah, Western Australia.
— 2024, *Horticulture in the Peel-Harvey – A guide for investors and growers.* Revised guidelines prepared by the Bindjareb Djilba (Peel-Harvey estuary) Protection Plan Policy and Planning Coordinating Committee. Mandurah, Western Australia.
PHCC (Peel-Harvey Catchment Council), Water Corporation & Department of Water 2017, *Drainage partnering agreement: Integrating drainage and catchment management in the Peel-Harvey catchment*, [unpublished agreement], Western Australia.
Potter, I, Veale, L, Tweedley, J & Clarke, K 2016, 'Decadal changes in the ichthyofauna of a eutrophic estuary following a remedial engineering modification and subsequent environmental shifts'. *Estuarine, Coastal and Shelf Science,* vol. 181**,** 345-363.

Radke, L, Prosser, I, Robb, M, Brooke, B, Fredericks, D, Douglas, G & Skemstad, J 2004, 'The relationship between sediment and water quality, and riverine sediment loads in the wave-dominated estuaries of south-west Western Australia'. *Marine and Freshwater Research,* vol. 55**,** 581-596.

Ramsar Convention 1971, *The Convention on Wetlands of International Importance, especially as Waterfowl Habitat*, Ramsar, Iran.

Reitsma , T, Nice, H, Leusch, F, Quayle, P, Chapman, H, Khan, S, Trinh, T, Coleman, H, Rawson, C, Gagnon, M & Blair, P 2010, *Development of an 'ecotoxicity toolbox' to characterise water quality for recycling*, Department of Water, Western Australia.

River, M 2012, *Spatial and temporal variations and patterns in water and nutrient dynamics within agriculturally-dominated watersheds in south west Australia*, [unpublished Doctor of Philosophy thesis], University of Western Australia.

Rogers, BC, Hammer, K, Werbeloff, L & Chesterfield, C 2015, *Shaping Perth as a Water Sensitive City: Outcomes of a participatory process to develop a vision and strategic transition framework*, Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Ruprecht, J & George, P 1993, 'Hydrology of the Peel-Harvey estuary catchment'. *Fertilizer research,* vol. 36**,** 127-133.

Ruprecht, J & Schofield, N 1991, *The effect of partial clearing on the hydrology and salinity of the Lemon catchment, Report No WS 74*, Surface Water Branch of the Water Authority, Perth, Western Australia.

Schofield, N & Bari, M 1991, 'Valley reforestation to lower saline groundwater tables: Results from Stene's Farm, Western Australia '. *Australian Journal of Soil Research,* vol. 29**,** 635-650.

Shams, R 2000, *Hydrogeological and nutrient balance of Spectacles wetlands*, Hydrogeology report no. HR 168, Perth, Western Australia.

Shire of Murray 2018a, *Horticulture Development Local Planning Policy*, Pinjarra, Western Australia.

— 2018b, *Local Planning Policy – Water Sensitive Urban Design*, Pinjarra, Western Australia.

Shire of Serpentine Jarrahdale 2018a, *Local Planning Policy 2.4: Water Sensitive Urban Design Guidelines*, Western Australia.

— 2018b, *Local Planning Policy 4.12: Horticulture*, Western Australia.

Shire of Waroona 2021, *PP004 – Local Planning Policy 4 – Intensive Agriculture*, Waroona, Western Australia.

Soils for Life 2012, *Innovations for Regenerative Landscape Management. Case studies of regenerative land management in practice. A Soils for Life Report.*, ©Outcomes Australia, Soils for Life Program 2012.

State of NSW 2015, *NSW Coastal Management Manual, Part C: Coastal Management Toolkit. A guide to managing estuary ecosystems*, Office of Environment and Heritage, Sydney, NSW.

Summers, R 2004, 'A Review of Best Management Practices for Achieving Reductions in Nutrient and Sediment Loads to Receiving Waterways'. *Department of Agriculture and Food Western Australia,* vol.

Summers, R, Richards, P, Weaver, D & Rowe, D 2020, *Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative*, Resource management technical report 416, Department of Primary Industries and Regional Development, Perth.

Swan River Trust 2009, *Swan Canning water quality improvement plan*, Swan River Trust, East Perth, Western Australia.

SWCC (South West Catchments Council) 2020, *Final Report — Supporting farmers to make the transition to regenerative agriculture, State NRM grant - CSGL18102*, South West Catchments Council, Western Australia.

Tennakoon, S & Ramsay, I 2020, *Disposal of effluent using irrigation technical guideline*, Department of Environment and Science, Queensland Government, Brisbane.

Thomson, C 2021, *Water Quality Index for the Peel-Harvey Estuary, Western Australia*, [unpublished report], Department of Water and Environmental Regulation, Perth.

Thomson, C, Kilminster, K, Hallett, C, Valesini, F, Hipsey, M, Trayler, K, Gaughan, D, Summers, R, Syme, G & Seares, P 2017, *Research and information priorities for estuary management in southwest Western Australia*, Report prepared for the Western Australian Marine Science Institution, Perth, Western Australia.

Tourism Research Australia 2021, National Visitor Statistics – December 2021. [unpublished data], Australian government.

Tucker, R 2018, 'National environmental guidelines for indoor piggeries'. *Australian Pork Limited: Canberra, ACT, Australia,* vol.

Tucker, R & O'Keefe, M 2012, 'National Environmental Guidelines for Rotational Outdoor Piggeries'. *FSA Consulting Report,* vol. 7634**,** 10.

Tulipani, S, Degens, B, Shackleton, M & Grant, B 2019, *Sediment sampling for 2020 clay trial*, [unpublished report], Aquatic Science Branch, Department of Water and Environmental Regulation, Western Australia.

Tulipani, S, Degens, B, Shackleton, M & Grant, B 2020, *Reducing algal blooms in the lower Serpentine River, Phosphorus-binding clay trial 2020*, [unpublished report], Department of Water and Environmental Regulation, Western Australia.

Tweedley, JR, Hallett, CS, Warwick, RM, Clarke, KR & Potter, IC 2016, 'The hypoxia that developed in a microtidal estuary following an extreme storm produced dramatic changes in the benthos'. *Marine and Freshwater Research,* vol. 67**,** 327-341.

Urbaqua 2020, *Waangaamaap Bilya Serpentine River Action Plan*, Prepared for the Peel-Harvey Catchment Council by Urbaqua Land and Watr Solutions.

USEPA (United States Environmental Protection Agency) 2000, 'Ambient aquatic life water quality criteria for dissolved oxygen (saltwater): Cape Cod to Cape Hatteras'. *Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington DC, US,* vol. Report No.: EPA-822-R-00-012.

Valesini, F, Hallett, C, Hipsey, M, Kilminster, K, Huang, P & Hennig, K 2019a, Peel-Harvey Estuary, Western Australia. IN WOLANSKI, E., DAY, J., ELLIOTT, M. & RAMACHANDRAN, R. (Eds.) *Coasts and estuaries: The future.* Elsevier.

Valesini, F, Hipsey, M, Eyre, B, Kilminster, K, Plummer, P, Elliott, M, Hallett, C, Huang, P, Busch, B, Wells, N, Hennig, K, Cronin-O'Reilly, S, Reshid, M, Krumholz, O, Horsley, J & Trinh, J 2019b, *Balancing estuarine and societal health in a changing environment*, [unpublished report], Murdoch University, Perth, Western Australia.

Walley, G 2018, *Peel-Harvey Estuary*, Prepared for the Regional Estuaries Initiative website, Department of Water and Environmental Regulation, Western Australia.

Walley, G & Grant, B 2021, *Bring Together Walk Together Aboriginal Partnership Engagement Framework*, Western Australia, Accessed 7 March 2023. https://www.wa.gov.au/government/publications/bring-together-walk-together-aboriginal-partnership-framework

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*, Western Australia.

WAPC (Western Australian Planning Commission) 1992, *Statement of Planning Policy no. 2.1 Peel-Harvey coastal plain catchment*, Western Australian Planning Commission, Perth.

— 2003a, *Statement of Planning Policy no. 2.0 Environment and Natural Resources Policy*, Western Australian Planning Commission, Perth.

— 2003b, *Statement of Planning Policy no. 2.3 Public Drinking Water Source Policy*, Western Australian Planning Commission, Perth.

— 2006, *State Planning Policy No. 2.9 Water Resources*, Western Australian Planning Commission, Perth.

— 2008, *Better Urban Water Management*, Western Australian Planning Commission, Perth.

— 2018a, *Perth and Peel @ 3.5 million*, Perth, Western Australia.

— 2018b, *Perth and Peel @ 3.5 million - Sub-regional Planning Framework*, Perth, Western Australia.

— 2021a, *Draft State Planning Policy 2.9 Planning for Water*, Western Australian Planning Commission, Perth.

— 2021b, *Draft State Planning Policy 2.9 Planning for Water Guidelines*, Western Australian Planning Commission, Perth.

WAPC (Western Australian Planning Commission) & DPLH (Department of Planning Lands and Heritage) 2017, *Peel Regional Scheme – Priority Agriculture and Rural Land Use Policy* Perth, Western Australia.

Water and Rivers Commission 1998, *Dawesville Channel Monitoring Programme, Technical Review: Summary*, Water and Rivers Commission, East Perth.

— 1999–2003, *River Restoration Manual (RR 1–16)*, Water and Rivers Commission, Perth, Western Australia.

— 2000a, *Statewide Policy No. 5 Environmental Water Provisions Policy for Western Australia, Water and Rivers Commission*, Perth, Western Australia.

— 2000b, *Water note 10: Protecting riparian vegetation*, Perth, Western Australia.

— 2001a, *Determining foreshore reserves, Report No. RR 16*, Perth, Western Australia.

— 2001b, *Water note 23: Determining foreshore reserves* Perth, Western Australia.

Water and Rivers Commission, Western Australian Horse Council (Inc), Department of Environmental Protection & Department of Health 2002, *Environmental management guidelines for horse facilities and activities*, WQP Guideline 13, Perth, Western Australia.

Water Sensitive Transition Network 2019, *Vision and Transition Strategy for a Water Sensitive Greater Perth – Implementation Plan 2019–2021*, Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Waterways Commission, Department of Transport & Department of Agriculture 1994, *Securing the Future: Achievements of the Peel Inlet and Harvey Estuary Management Strategy 1989-1994*, Waterways Commission, Perth, Western Australia.

Weaver, D, Neville, S, Ovens, R, Keipert, N, Summers, R & Clarke, M 2008, *Farm gate nutrient balances in south west Western Australia – understanding nutrient loss risk within agricultural land-uses*, 12th International Conference on Integrated Diffuse Pollution Management, Thailand, August 2008.

Wells, NS, Reshid, MY, Hennig, K, Gooddy, D & Eyre, B 2019, *The what, where, when and why of nutrient transport to the Peel-Harvey Estuary. Balancing estuarine and societal health in a changing environment*, ARC Linkage Project LP150100451, November 2019.

Welsh, WD, Vaze, J. Dutta, D. Rassam, D. and Rahman, J.M 2013, 'An integrated modelling framework for regulated river systems'. *Environmental Modelling and Software,* vol.

Wendling, L, Douglas, G & Coleman, S 2009a, *Characterisation of Mining and Industrial By-Products with Potential for Use as Environmental Amendments*, CSIRO, Perth, Western Australia.

Wendling, L, Douglas, G, Coleman, S, Yuan, Z & Klauber, C 2010, *Nutrient and DOC Removal from Ellen Brook Waters: Evaluation of Mining By-Products, CSIRO: Water for a Healthy Country National Research Flagship Report*, February 2010, CSIRO: Perth, Western Australia.

Wendling, L, Douglas, G, Petrone, K & Coleman, S 2009b, *Best Management Practices: Investigation of Mineral-Based By-Products for the Attenuation of Nutrients and DOC in Surface Waters from the Swan Coastal Plain. Report for the Water Foundation, Western Australian Department of Water*, CSIRO: Water for a Healthy Country National Research Flagship.

Western Dairy 2012, *Code of Practice for Dairy Shed Effluent Western Australia*, Western Australia.

— 2021, *Code of Practice for Dairy Farm Effluent Management WA*, Western Australia.

Wilson, C, Hale, J & Paling, E 1999, 'Macrophyte abundance and composition in the Peel-Harvey Estuary: Comparisons before and after the opening of the Dawesville Channel (July 1985 to June 1999)'. *Institute for Environmental Science, Report No. MAFRL,* vol. 99.

Woodward, E, Hill, R., Harkness, P. & Archer, R. (Eds) 2020, *Our Knowledge Our Way in caring for Country: Indigenous-led approaches to strengthening and sharing our knowledge for land and sea management. Best Practice Guidelines from Australian experiences.* , NAILSMA and CSIRO, accessed 7 March 2023. www.csiro.au/en/research/indigenous-science/indigenous-knowledge/our-knowledge-our-way/okow-resources.

Zammit, C, Bussemaker, P & Hall, J 2006, *Establishment of a Decision Support System for Water Quality Improvment and Protection of the Peel Inlet and Harvey Estuary*, Department of Environment, NRM and Salinity Division, Aquatic Sciences Branch, Perth, Western Australia.

Appendices (A–O)

Contents

Appendix A: Supporting projects

A.1 Long-term monitoring

The Department of Water and Environmental Regulation (the department) and its predecessor agencies have been monitoring river flow and water quality of the Peel-Harvey waterways since 1995, with an increase in frequency from 2016 (to a fortnightly–monthly regime, see Appendix A.2.1).

Auto-sampling ‘load measuring units’ were historically used at three main sites on the Serpentine, Murray and Harvey rivers to capture flow event nutrient delivery. These units were used to understand the daily and weekly changes in nutrients through the hydrological cycle, and to compare against regular sampling. The measurements were used to report against the environmental quality objectives targets set in the *Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992*.

In 2024, water quality is monitored at 13 sites in the Peel-Harvey estuary coastal plain catchment. Collecting and reporting catchment water quality data helps us understand the estuarine systems and allows us to direct investment towards the most effective actions in the catchments to protect and restore the health of our waterways and estuaries. Catchment nutrient reports published by the department provide information on observed nutrients (nitrogen and phosphorus) as well as total suspended solids, pH and salinity for the 13 monitoring sites in the Peel-Harvey estuary coastal plain catchment.

The department has also regularly monitored water quality in the estuary itself (since 2000), with an increase in frequency from 2016 (to a fortnightly–monthly regime, see Appendix A.2.1). In 2024, water quality monitoring is conducted at 12 sites across the estuary and estuarine portions of the rivers. As well as water quality, estuary monitoring also includes sampling for phytoplankton and reporting on the potential for algal blooms and the presence of potentially harmful or nuisance species.

Water quality data in the catchment waterways and the estuary include measurements of dissolved oxygen (DO), pH, salinity, turbidity, conductivity, temperature, suspended solids, dissolved carbon, flow (at gauged sites), algae (at estuary sites) and filtered and total nutrients.

A.2 Regional Estuaries Initiative (REI) and Healthy Estuaries WA

The development of this water quality improvement plan (WQIP) was supported by the REI, a four-year program (2016–19) that aimed to better understand and improve the health of the Peel-Harvey estuary and five other estuaries in the south-west of Western Australia. The REI used a collaborative approach working with partners in regional landcare groups, catchment councils and peak agriculture industry bodies. The program developed and implemented on-ground actions for catchment-scale outcomes to improve estuary condition. The REI delivered programs to reduce nutrient pollution in industries not currently subject to regulation (e.g. dairy and beef farming). The program worked closely with industry bodies and provided incentive funding and targeted support for farmers to move towards best practice nutrient management.

Healthy Estuaries WA – a State Government program, began in 2020 and continues much of the work of the REI, with funding until 2024. Healthy Estuaries WA supports the implementation of many of the proposed actions in this WQIP.

A.2.1 Additional estuary and catchment monitoring

The REI funded an expanded monitoring program for the target estuaries and their catchments (including the Peel-Harvey estuary), and this monitoring continues with Healthy Estuaries WA. Water quality is currently monitored at 25 sites in the Peel-Harvey estuary (12) and catchment (13).

A.2.2 Hydrological and nutrient modelling of the Peel-Harvey catchment

The department developed a calibrated, hydrological and nutrient model of the Peel-Harvey catchment to estimate phosphorus (P) loads to the Peel-Harvey estuary (Zammit et al. 2006) and support the development of the *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management* (EPA 2008). This modelling was revised in 2011 (Kelsey et al. 2011) to support the development of subcatchment implementation plans (PHCC 2012). A next-generation model was developed using the eWater SOURCE framework – Peel-Harvey Catchment Model (Hennig et al. 2021). This model synthesises datasets on land use, hydrology and water quality to estimate annual loads of nutrients entering the estuary from the catchment. The modelling identifies land uses as sources of nutrients within the catchment and quantifies the influence that management actions, land use change and climate change will have on nutrients reaching the estuary. The model also identifies combinations of management actions that are predicted to reduce nutrient loads below target nutrient (total nitrogen, total phosphorus) concentrations.

A.2.3 Soil amendment in paddocks and in drains

Paddock trials, catchment monitoring and modelling, and single-paddock modelling provide evidence that adding soil amendments to topsoil in farm paddocks can help hold P and reduce the P lost to waterways and groundwater. In the Peel-Harvey estuary coastal catchment, the REI developed partnerships with farmers to trial soil amendments targeting high P loss areas in paddocks and drains. These trials used Iron Man Gypsum® (IMG) which has a high capacity to hold P and keep this available for plant growth on farms. Trials explored application rates and different incorporation techniques to help understand what works best with the least cost and maximum benefit, and ensure the product is environmentally safe for larger-scale application.

Two 1.5 ha farm trials were conducted in the Peel-Harvey estuary coastal plain catchment and resulted in up to 20 kg of P being retained per hectare on these sites in the first year. Surface application of IMG to paddocks was found to be immediately effective in reducing P loss in runoff by up to 6 kg P/ha/year in addition to reducing loss by leaching to shallow groundwater. If expanded to larger areas of farmland, IMG could reduce P losses by hundreds of kilograms per farm per year.

The REI also explored the use of in-drain treatment designs for incorporating soil amendments to achieve the best P retention. These were conducted in the Gull Road drain, investigating designs ranging from simple to engineered beds that encourage water exchange between drain waters and bed sediments (the hyporheic zone). The latter was most effective, but the treatment rates indicated that extensive lengths of treatment beds would need to be constructed to treat large volumes of drainage waters.

As well as gathering evidence of P loss reductions, monitoring of trial sites also investigated other benefits, limitations and any risks associated with the use of soil amendments. The learnings from these IMG trials are transferable to other high P-retaining materials and will be used to develop guidelines for using soil amendments at a catchment scale on the Swan coastal plain.

Building on from the work of the REI, research and IMG trials are continuing as part of Healthy Estuaries WA.[84]

A.2.4 The use of phosphorus-binding clay in drains and rivers

The REI and Heathy Estuaries WA has led investigations into innovative techniques to treat soluble P in agricultural drains.[85] A key project has been the development and testing of an innovative bentonite clay, modified with a coating of the mineral hydrotalcite, which is able to bind P within its structure. The clay can be added to drains or streams as a slurry, where it binds with P, making it unavailable to algae. Additionally, when the clay settles in pools, it forms a thin layer on top of nutrient-rich sediments, and reduces P released to the overlying water overtime.

As well as investigating the effectiveness of clay treatment at reducing P across different environments, the project aims to:

- understand the optimal application rates and environmental conditions for highest P removal
- undertake a detailed risk assessment for large-scale clay applications
- improve the clay manufacturing process
- provide information to help with further research and development.

A trial in Punrak Drain, in the lower Serpentine River in 2017, demonstrated that the clay was effective in reducing the filterable reactive phosphorus (the bioavailable

[84] See Soil amendment trials.

[85] See New technologies – Phosphorus-binding clay trials.

form of P) in low to medium spring flows. While effective under these lower flow conditions, we found that it was unfeasible to treat this drain in high winter flows (that carry most of the P loads). A detailed environmental risk assessment is recommended for future continuous dosing of the clay to drains, because of the high concentrations of suspended solids that occur during dosing.[86]

A larger dosing trial was completed in early summer 2020 when the department applied 17 t of the P-binding clay to the lower Serpentine River (250 m stretch that contains 4–5 m deep pools). It was the first time that a new optimised clay production process was tested and a concentrated clay-paste was handled and applied in the field.

The Serpentine River clay trial did not show a sustained reduction in P in the water column nor P release from the sediments over the long term because of suboptimal conditions during application, high sedimentation rates, and sediment disturbance from hypersaline water incursions. The trial highlighted the challenges for the clay treatment in a dynamic environment with changing salinities, nutrient concentrations and flow conditions. However, the trial findings improved our understanding of optimal conditions for clay application and proved that the clay-application design and optimised production methods were successful.

When applied under suitable conditions, the clay has the potential to significantly reduce the amount of P that is transported to the estuary. Further large-scale field trialling is planned as part of Healthy Estuaries WA.

A.2.6 Dairy effluent management

Through the REI-funded DairyCare program, the State Government, Western Dairy, catchment groups and farmers worked together to reduce dairy effluent entering our waterways. This was achieved by assisting farmers to upgrade their dairy effluent management systems.

Western Dairy funded through the REI performed reviews of 60 dairies in the South West to assess the state of their dairy effluent management systems and provide a benchmark of whether a dairy was meeting the *Code of Practice for Dairy Shed Effluent WA* (the Code) (Western Dairy 2012). This work informed development of an updated *Code of Practice for Dairy Farm Effluent Management WA* launched in 2021 (Western Dairy 2021).

Six of the twelve dairies reviewed in the Peel-Harvey estuary coastal plain catchment were involved in the program. Dairies were provided with subsidy funding to upgrade their dairy effluent management systems to reduce nutrients from leaving their farms and entering waterways.

The REI also supported the Augusta-Margaret River Clean Community Energy (AMRCCE) group to trial an alternative piece of dairy effluent management technology (Z-filter). The AMRCCE investigated the suitability of using Z-filters in

[86] The increased level of suspended solids settles out a few hours after dosing finishes.

reusing and managing effluent nutrients on dairy farms in the South West. They examined alternative methods of transforming waste into a sustainable, easy-to-distribute fertiliser alternative. The Z-filter effectively separates the solids and liquid components of the effluent, allowing the farmer to reuse the liquid for irrigation. As well as saving on costs for synthetic fertiliser, it provides separated solids to apply to the land, assisting with boosting soil productivity in underperforming areas. For more detailed information refer to Grell et al. (2023) who discuss the results of the trial in a scientific paper, *Resource recovery for environmental management of dilute livestock manure using a solid-liquid separation approach*.

The important work of supporting the transition of dairy farms to best practice is continuing with Healthy Estuaries WA through the Dairy for Healthy Estuaries project. The project is led by Western Dairy in partnership with catchment groups, dairy farmers and State Government agencies. Western Dairy offers technical advice and resources to support Western Australian dairy farmers with best-practice effluent management, optimising pasture growth by reusing effluent, and minimising nutrient losses to waterways and estuaries.

A.2.7 Optimal fertiliser use based on soil testing

Through the REI and continuing with Healthy Estuaries WA, farmers are supported to make evidence-based decisions about fertiliser use to optimise agricultural productivity and minimise nutrients being washed into the waterways/drains.[87] Farmers are provided with access to accredited soil and tissue testing, workshops and one-on-one tailored advice and support from an accredited agronomist.

The best practice fertiliser management programs are delivered in partnership with the Department of Primary Industries and Regional Development (DPIRD), Peel-Harvey Catchment Council, Leschenault Catchment Council, Lower Blackwood LCDC, Wilson Inlet Catchment Committee and Oyster Harbour Catchment Group. The programs have utilised and expanded upon nutrient mapping work that has been done intermittently (when funding has been available) by DPIRD and its predecessor departments since 1982. The programs are also supported by a Project Reference Group that includes membership of project partners along with Fertiliser Australia, Western Dairy, fertiliser industry, agronomists and farmer representatives.

A.2.8 Better collaborative drainage management

The REI partnered with Peel-Harvey Catchment Council (PHCC) and Water Corporation to develop an offline-treatment system along the Peel Main Drain.[88] The Peel Main Drain is a fast-flowing drain in the Peel-Harvey estuary catchment that delivers nutrients into the Serpentine River. Six 225 m long swales were constructed on the Serpentine floodplain to treat a portion of the water flowing past the site, with the actual portion still being determined in trials. Water from the drain is diverted

[87] See Soil testing to support better fertiliser decisions.

[88] See Peel Main Drain Swales Project (2021).

down the series of clay-lined swales with the aim of stripping nutrient loads. The swales became operational in late 2021 and results from the first year of operation are encouraging with retention of total phosphorus in individual swales varying between 27 and 86 per cent.[89] Trials are ongoing in 2023 to assess optimal configuration of the swales.

In addition, several weirs were built on farm drains in the Peel-Harvey estuary coastal plain catchment. These weirs aimed to slow down the movement of water, improve filtration and infiltration and reduce the transport of nutrients to the estuary. By retaining water in the landscape, farmers can benefit from extended pasture growing seasons, providing a mutual benefit to farmers, productivity and the environment. Modelling using MUSIC (Model for Urban Stormwater Improvement Conceptualisation) predicted that all weirs would reduce the nutrient load entering the estuary system, however, water quality monitoring was not conducted to confirm this.

A.3 uPtake

Jointly funded by the REI, Healthy Estuaries WA and the Australian Government's National Landcare Program, uPtake was a partnership project designed to improve nutrient use efficiency on grazing farms in south-west Western Australia. The program implemented from 2019–23 aimed to improve farmer and industry knowledge, as well as confidence and uptake of the science supporting the fertiliser recommendations. uPtake was a highly collaborative project with involvement from fertiliser and livestock production industry bodies, catchment groups and State Government agencies.

The uPtake project:

- established 52 fertiliser trials across south-west Western Australia (including six sites in the Peel-Harvey coastal estuary catchment) over a range of soil types with contemporary pasture species to develop P-response curves
- trialled innovative technology to provide rapid feedback on pasture growth and soil nutrient status including drones, near infrared and X-ray fluorescence
- built partnerships and capacity across industry, catchment groups and farmers to work together to optimise productivity and minimise nutrient loss off-farm.

Key learnings from the trial results (Government of Western Australia 2023) were that:

- the national critical soil test P values are relevant to south-west Western Australian soils and contemporary pasture species
- adding P to soils with adequate P will not grow more pasture but will increase the risk of P leaching to the environment

[89] See Peel MD Swales project (2023).

- addressing limiting nutrients like nitrogen, sulphur, potassium and trace elements will increase productivity if nutrients are deficient
- soil testing is critical to identify nutrients that may be limiting production
- applying P following national critical values will optimise productivity and profitability, and reduce impacts on the environment.

A.4 Soil Wise

Soil Wise is a collaborative project running over three years (2022–24) to help farmers and land managers improve their soil health and nutrient management in south-west Western Australia, including in the Peel-Harvey catchment. Soil Wise is funded by the National Landcare Program Smart Farms Small Grants – an Australian Government initiative – and is supported by Healthy Estuaries WA. The aim is to promote best practice sustainable agriculture so that farmers can increase productivity and profitability, whilst protecting and improving the condition of natural resources. The program runs extension activities, such as educational materials, field days, workshops and webinars, to increase adoption of best practice sustainable agriculture and the capacity of land managers to adopt best practice sustainable agriculture. Soil Wise promotes the benefits of soil testing to:

- inform soil management decisions
- improve soil testing knowledge and skills among land managers and farmers
- increase the capacity of land managers and farmers to interpret soil test results
- support land managers and farmers to undertake land management practices to improve soil health
- encourage land managers and farmers to contribute soil data to relevant national databases
- facilitate collaboration and communication between soil scientists, extension officers, advisers, natural resource management and farming systems groups, land managers and farmers
- establish fertiliser trials across south-west Western Australia over a range of soil types with contemporary pasture species, with a focus on best management practice for phosphorus, nitrogen, potassium and sulfur.

Soil Wise is part of the *National Soil Strategy* – a 20-year plan outlining how Australia will value, manage and improve its soil.

A.5 Australian Research Council Linkage project – *Balancing estuarine and societal health in a changing environment*

As part of the Australian Research Council Linkage project *Balancing estuarine and societal health in a changing environment* (Valesini et al. 2019), a sophisticated coupled model of the Peel-Harvey estuary and catchment was developed (Hipsey et al. 2019). The research team was led by Murdoch University and The University of Western Australia along with scientists from Southern Cross University (NSW), University of Hull (UK) and the department. Partner organisations were PHCC, the Department of the Premier and Cabinet, City of Mandurah and the Shire of Murray.

Significant amounts of ecological data were collated as well as new data collected to support the model. This included datasets on the condition of the benthic invertebrates, macrophytes, fish, sediments and estuarine water quality. The model was developed to consider:

- inflows from the rivers
- freshwater input from rain
- groundwater interaction with the estuary
- sea level and tides
- meteorological data
- climate change.

The model predicts water levels, currents, salinity, water temperature, and nutrient and oxygen status, as well as estimating the resident time and fate of inflows and nutrients entering the estuary. The model can be used by managers and scientists to better understand how the estuary will respond under a range of scenarios including changes in climate, land uses and catchment and estuary management.

A.6 Joint projects with Alcoa, PHCC, Greening Australia and The Nature Conservancy

Alcoa Foundation partnered with Peel-Harvey Catchment Council, Greening Australia and The Nature Conservancy to fund three environmental projects across the Peel-Harvey catchment. Over three years (2018–20), the projects helped to deliver on-ground environmental actions in consultation with the community, to improve the health of the Peel-Harvey catchment and waterways. Further funding was provided by the Alcoa Foundation to continue the partnership for a subsequent three years (2020–23). The projects are summarised below.

A.6.1 PHCC Connecting Corridors and Communities – Restoring the Serpentine River

The PHCC delivered on-ground environmental actions and community engagement to improve the health of the Serpentine River. The funding enabled works on private land, including:

- community engagement events and field days
- fencing to protect and conserve existing areas of riparian and bushland vegetation
- revegetation to reconnect areas of bushland, riparian zones and patches of remnant vegetation
- bank stabilisation to improve water quality, habitat and food availability for invertebrates and finfish
- biosecurity management of feral animals, weeds and diseases
- working with local Noongar community through all aspects of the project
- developing a River Action Plan for the mid and upper reaches of the Serpentine River.

This work continued for a subsequent three-year PHCC project (2020–23) 'Healing Bilya – Restoring the Murray and Serpentine Rivers', with similar actions across both rivers.[90]

A.6.2 Greening Australia – Three Rivers One Estuary Initiative

Greening Australia implemented local, on-ground action across the Peel region, working on identified priority projects with industry, community and local land management groups to improve the condition of 13 sites across the Serpentine, Murray and Harvey rivers. Projects aimed to reverse the loss of habitat for threatened species and integrate priority restoration into the catchment's fragmented landscape.[91]

A.6.3 The Nature Conservancy – Revitalising the Peel-Harvey estuary through nature-based solutions

Addressing the growing threats of urban development, fisheries decline and climate change on the long-term health and resilience of the Peel-Harvey estuary, this project complemented existing work undertaken in the upper catchment. It focused on marine habitat restoration opportunities for improving fisheries, biodiversity and natural solutions to coastal defence in the estuary. The project used The Nature Conservancy's proven approach for catalysing large-scale investments in estuary

[90] Access the project summary via Healthy Rivers, Estuary and Wetlands.

[91] See Three Rivers, One Estuary Initiative.

protection and repair, as being conducted in Oyster Harbour (Western Australia), and in South Australia and Victoria.

One such project is a shellfish reef restoration research project – a collaboration with The Nature Conservancy and the community that aims to restore marine habitat in the estuary while also improving the water quality.[92] By developing pilot reefs seeded with grown blue mussels (which are filter feeders), there is potential for the mussels to help clean the estuary water and for the growing reefs to provide habitat for other marine species. Mussels grown by local shellfish 'gardeners' were used to seed the first trial beds in the Peel-Harvey estuary in 2022. The field research will be complemented by further laboratory studies and risk assessments to assess exactly which native shellfish species have the best chance of long-term survival and reef creation in the estuary.

A.7 Harvey River restoration

The Harvey River Restoration Taskforce (HRRT) is a community-based organisation that works to protect and rehabilitate waterways and wetlands in the Harvey River catchment. For many years it has been successfully conducting river restoration work collaborating with State and local government, universities, schools and the local community to achieve improvements in water quality and ecological health in the Harvey River and its tributaries. Some of the on-ground works have included fencing waterways to achieve stock-exclusion, weed removal and revegetation of the riparian zone, bank stabilisation and aquatic habitat restoration (e.g. for marron and other freshwater native species), all of which help to improve the ecological function of the waterways and drains.

The Harvey River Restoration demonstration project is an example of a successful river restoration project along the lower Harvey River (Harvey Main Drain at Bristol Road). Managed by the HRRT, under the 'Marron, more than a meal – revive our rivers' program, the project aimed to enhance habitat diversity and water quality to improve the long-term resilience of native fish and crayfish communities. Actions included fencing, riparian revegetation with native species, and placement of large logs and rocks to provide in-stream habitat diversity and longitudinal connectivity for aquatic fauna. This project is a good example of how Natural Resource Management (NRM) groups can collaborate with Water Corporation and the State Government to transform a drain into an ecological asset. In this project, Water Corporation carefully balanced social, ecological and economic values of waterways with their responsibilities for ensuring acceptable flow and water levels.[93]

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[92] For more information, refer to Revitalising the Peel-Harvey Estuary.

[93] As part of this project, Water Corporation undertook hydraulic analyses to investigate the potential impact of structures (i.e. large logs) on water levels under several flow scenarios. For more information, refer to Restoring life in the Harvey River and Harvey River Restoration Taskforce (Facebook).

A.8 Healthy Wetland Habitats Program

From 2006 to 2022 the State Government ran the Healthy Wetland Habitats program, administered by the Department of Biodiversity, Conservation and Attractions. The program provided technical and financial support to landholders who volunteered their time to care for wetlands. The program helped landholders to develop a wetland management plan to protect and care for their wetlands. The management plan identified priority actions, such as fencing and weed control, to ensure the wetland's values were maintained and enhanced for future generations.

Appendix B: *Draft State Planning Policy 2.9 Planning for Water*

When *Draft State Planning Policy 2.9 Planning for Water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for Water Guidelines* (WAPC 2021b) are finalised, the following will be replaced and repealed:

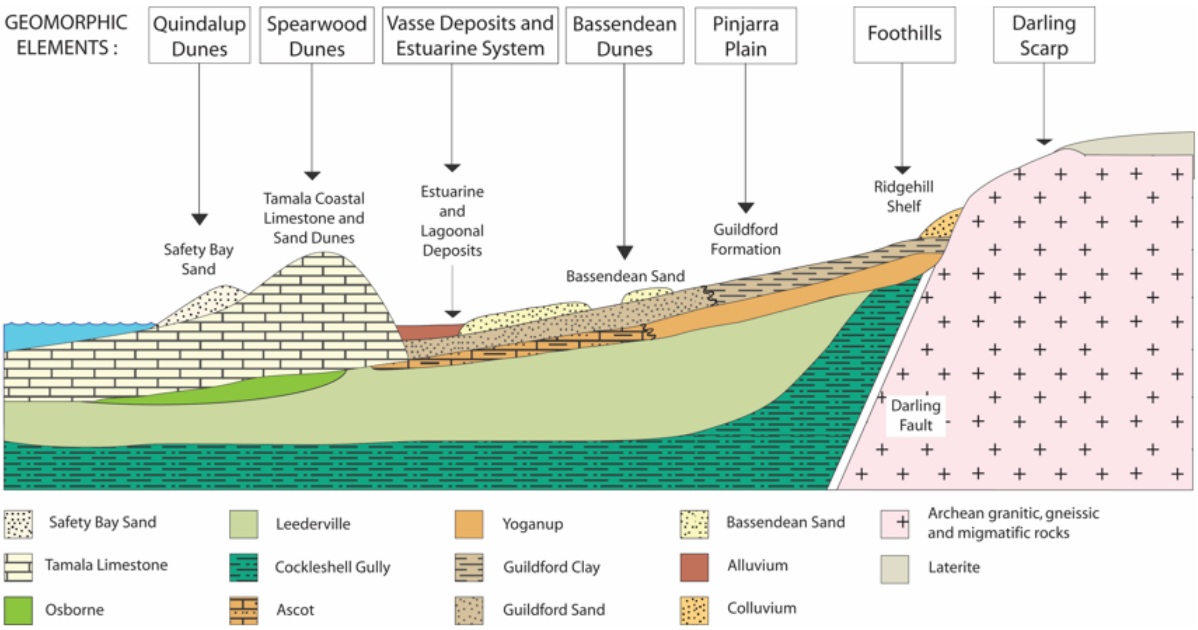
- *Statement of Planning Policy 2.1 Peel Harvey Coastal Plain Catchment* (1992)
- *State Planning Policy 2.2 Gnangara Groundwater Protection* (2005)
- *State Planning Policy 2.3 Jandakot Groundwater Protection* (2017)
- *State Planning Policy 2.7 Public Drinking Water Source* (2003)
- *State Planning Policy 2.9 Water Resources* (2006)
- *State Planning Policy 2.10* Swan Canning River System (2006)
- *Better Urban Water Management* (WAPC 2008)
- *Government Sewerage Policy* (2019).

In addition, the following departmental guidance may either be repealed or modified when *Draft State Planning Policy 2.9 Planning for Water* (WAPC 2021a) and *Draft State Planning Policy Planning for Water Guidelines* (WAPC 2021b) are finalised:

- *Guidelines for district water management strategies* (DoW 2013a)
- *Interim: Developing a local water management strategy* (DoW 2008a)
- *Urban water management plans: Guidelines for preparing plans and complying with subdivision conditions* (DoW 2008b).

Appendix C: Geological formations of the Peel-Harvey coastal estuary catchment

East to west stratigraphic succession around Mandurah and Pinjarra (copied from Kelsey et al. 2011).



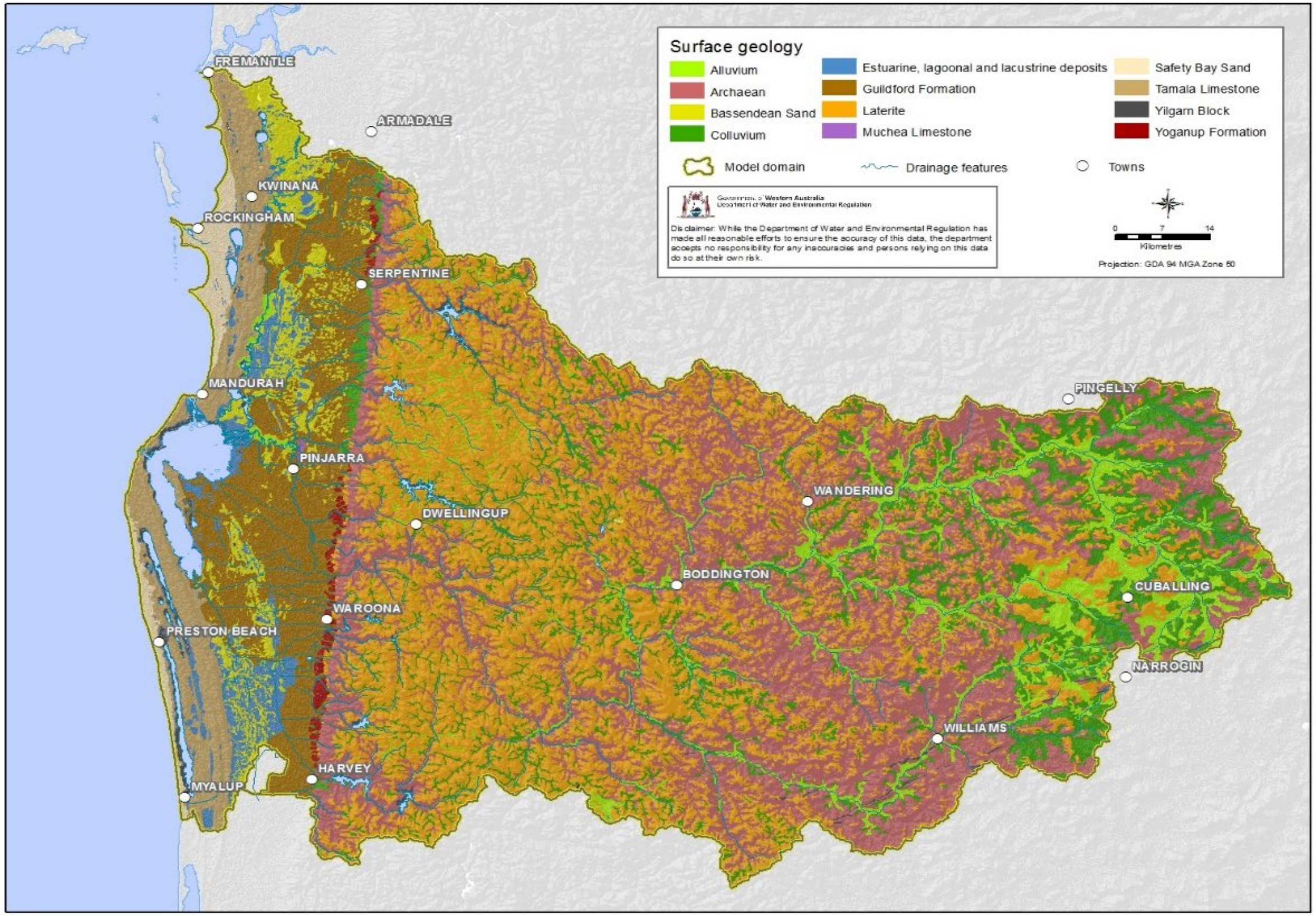
Appendix D: Stratigraphic and lithology of the Swan coastal plain

Age	Stratigraphic unit and lithology		
	West	Central	East
QUATERNARY **Holocene**	Alluvium, estuarine, lagoonal and swamp deposits (15) (sand, silt, clay and peat)		
	Safety Bay Sand (50) (sand, calcareous and unlithified)		Colluvium (5) (lithic sand, silt, clay, laterite, debris)
Pleistocene Middle–late	Tamala Limestone (90) (limestone, sand, calcarenite, minor clay, minor fossils)	Bassendean Sand (15) (sand)	
Early–middle		Guildford Formation sand (30) (sand, minor clay, calcareous sand and fossils)	Guildford Formation clay (27) (clay, sandy clay)
Early	Ascot Formation (25) (sand, silt, minor limestone, fossiliferous)		Yoganup Formation (25) (sand, clayey sand)
CRETACEOUS Early–late	Osborne Formation (siltstone and clay)		
Early	Leederville Formation (sand, siltstone, clay, shale)		
JURASSIC Early–middle	Cattamarra Coal Measures (sand, siltstone, clay, shale)		

Notes:
(a) Colluvium ranges in age from Tertiary to recent
(b) Figures in brackets are estimated maximum thickness in metres
(c) Unconformities are represented by jagged lines

(copied from Kelsey et al. 2011)

Appendix E: Main surface soils and geomorphic elements of the Peel-Harvey coastal estuary catchment



Appendix F: List of aquatic fauna present in the Peel-Harvey coastal estuary catchment

Fifteen native species of freshwater/fresh-estuarine fish and crayfish are represented in the coastal estuary catchment. Species expected to be found based on actual and interpolated data collected by the department, DPIRD, universities and other research groups (DPIRD 2018, DWER 2020a) include:

- *Pseudogobius olorum* (Swan River goby or blue-spot goby)
- A*furcagobius suppositus* (south-western goby)*
- *Acanthopagrus butcheri* (southern black bream)
- *Leptatherina wallacei* (western hardyhead)*
- *Mugil cephalus* (sea mullet)
- *Galaxias maculatus* (common jollytail)
- *Bostockia porosa* (nightfish)*
- *Galaxias occidentalis* (western minnow)*
- *Nannoperca vittata* (western pygmy perch)*
- *Tandanus bostocki* (freshwater cobbler)*
- *Geotria australis* (pouched lamprey)
- *Cherax cainii* (smooth marron)*
- *Cherax quinquecarinatus* (gilgie)*
- *Cherax preissii* (koonac)*
- *Cherax crassimanus* (restricted gilgie)*.[11,12]

Ten of these species (marked *) are endemic to the south-west of Western Australia.

The most common species expected to be found are *Cherax quinquecarinatus, Galaxias occidentalis* and *Nannoperca vittata*, occurring in about half of the subcatchments that have data (note: of the 191 subcatchments in the area only 93 have aquatic biota sampling points). Several species – *A. butcheri, A. suppositus, M. cephalus, A. forsterim, C. crassimanus, C. preissii, G. australis* and *G. maculatus* – have only been found rarely in one or two subcatchments. The highest species richness (up to 8 species) occurred in middle subcatchments of the Serpentine and Murray rivers and on Logue Brook, just upstream of the Harvey Main Drain.

Several species in the catchment have conservational significance (under the *Biodiversity Conservation Act 2016* (WA); *Environment Protection and Biodiversity Conservation Act 1999* (Cth); and the 2014 IUCN Red List of threatened species):

[11] See the department's Healthy Rivers program.

[12] Data can be accessed online: Freshwater Fish Distribution in Western Australia.

- *Geotria australis* (pouched lamprey) is listed as a priority species in the *Biodiversity Conservation Act 2016* (WA) and requires further monitoring (although it has only been found once in the Lower Murray catchment).
- *Westralunio carterii* (Carter's freshwater mussel) listed as is listed as vulnerable in both the *Biodiversity Conservation Act 2016* (WA) and *Environment Protection and Biodiversity Conservation Act 1999* (Cth).
- *Hydromys chrysogaster* (rakali/water rat). Although common and widespread throughout Australia, there has been local declines because of loss and degradation of streamside habitat, salinisation, drying (largely because of climate change), and predation by introduced species such as cats and foxes. This species is currently listed as a priority four species under the *Biodiversity Conservation Act 2016* (WA), meaning that it is rare and adequately known, but does not meet the criteria for near threatened.

For more information on each of the species refer to Fauna biodiversity (Healthy Rivers).

Nine non-native fish, crayfish and shrimp species have also been recorded, presenting threats to native fish and crayfish populations:

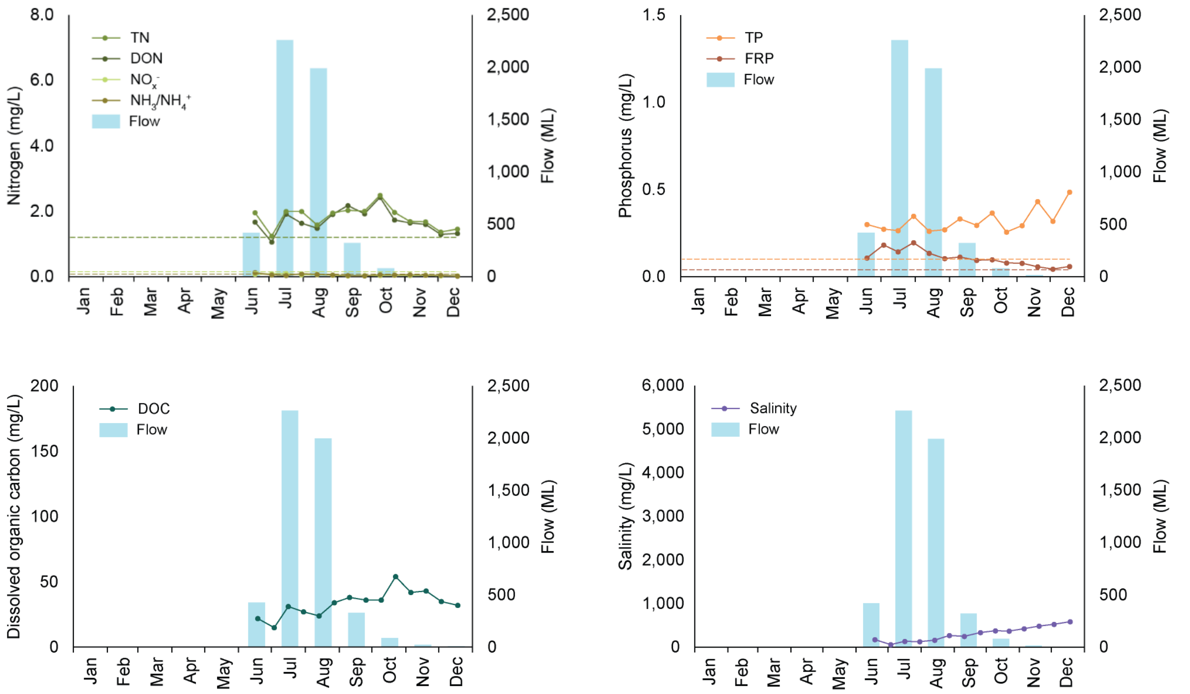
- *Gambusia holbrook* (eastern gambusia)
- *Cyprinus carpio* (common carp)
- *Perca fluviatilis* (redfin perch)
- *Carassius auratus* (goldfish)
- *Cherax destructor* (yabby)
- *Oncorhynchus mykiss* (rainbow trout)
- *Salmo trutta* (brown trout)
- *Phalloceros caudimaculatus* (one spot livebearer)
- *Caridina indistincta* (indistinct river shrimp; a recently discovered exotic invertebrate pest).

Appendix G: Monitored catchment water quality (2018)

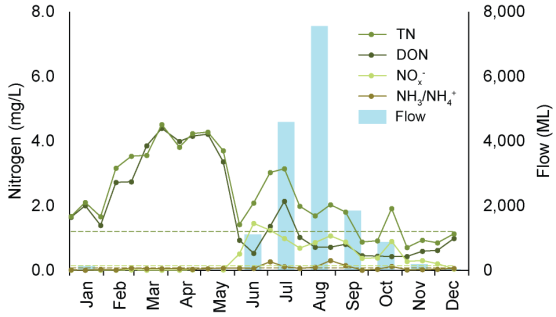
The following graphs show the measured nutrient concentrations, salinity and total monthly flow (where flow data was available) during 2018 for the monitoring sites in the Peel-Harvey estuary coastal plain catchment. The nitrogen graphs also show the WQIP's target total nitrogen (TN) concentration (1.2 mg/L) as well as ANZECC trigger values for lowland rivers for oxidised inorganic nitrogen (NO3- + NO2-, i.e. NO_x^-) and total ammonia (NH_3/NH_4^+). The phosphorus graphs show the WQIP's target total phosphorus (TP) concentration (0.1 mg/L) and the ANZECC trigger value for lowland rivers for filterable reactive phosphorus (FRP). All target and guideline concentrations are shown as dashed lines in colours matching that nutrient. Note: the y-axis has been set at the same value for each graph for N, P, dissolved organic carbon and salinity to allow comparison between sites.

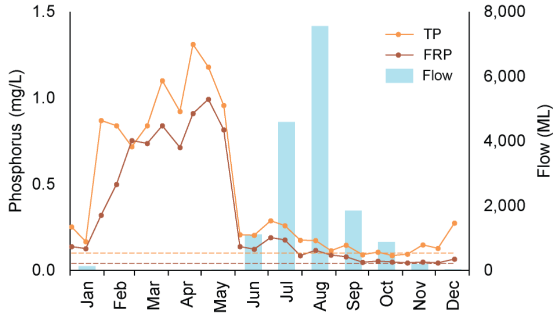
Raw data for these water quality monitoring sites are publicly available at the Department of Water and Environmental Regulation's Water information reporting webpage.

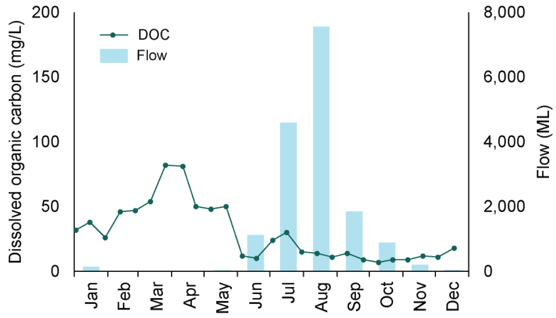
Coolup South Main Drain – 613027

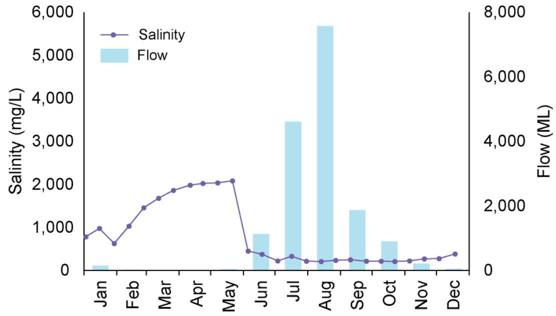


Punrak Drain – 614094

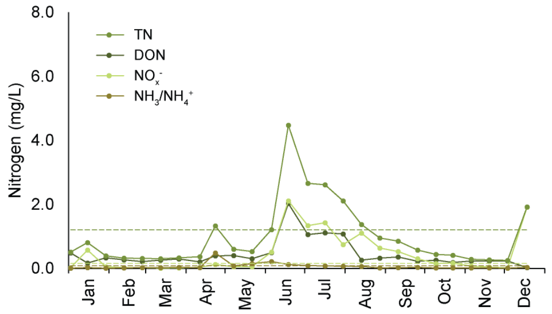


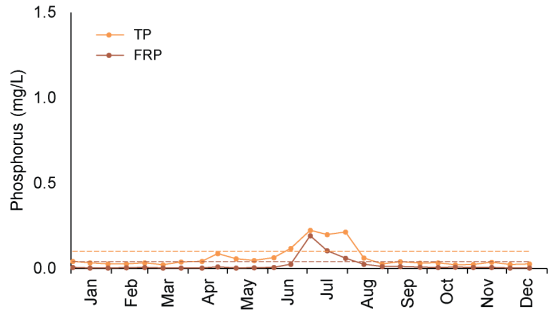


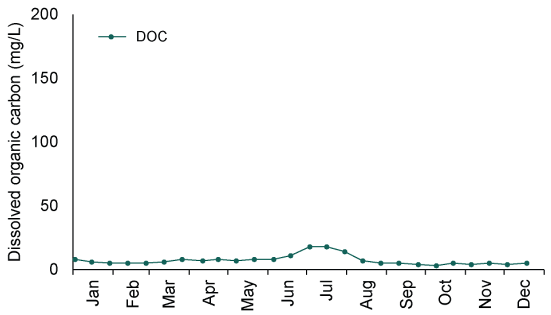


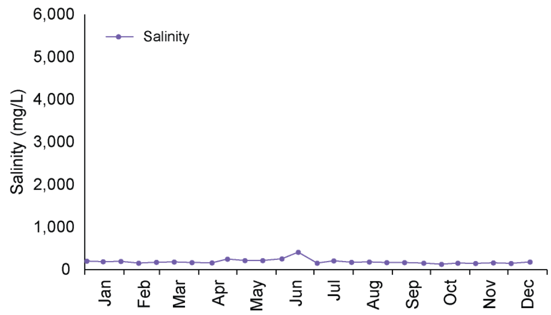


Drakesbrook Drain – 6131335

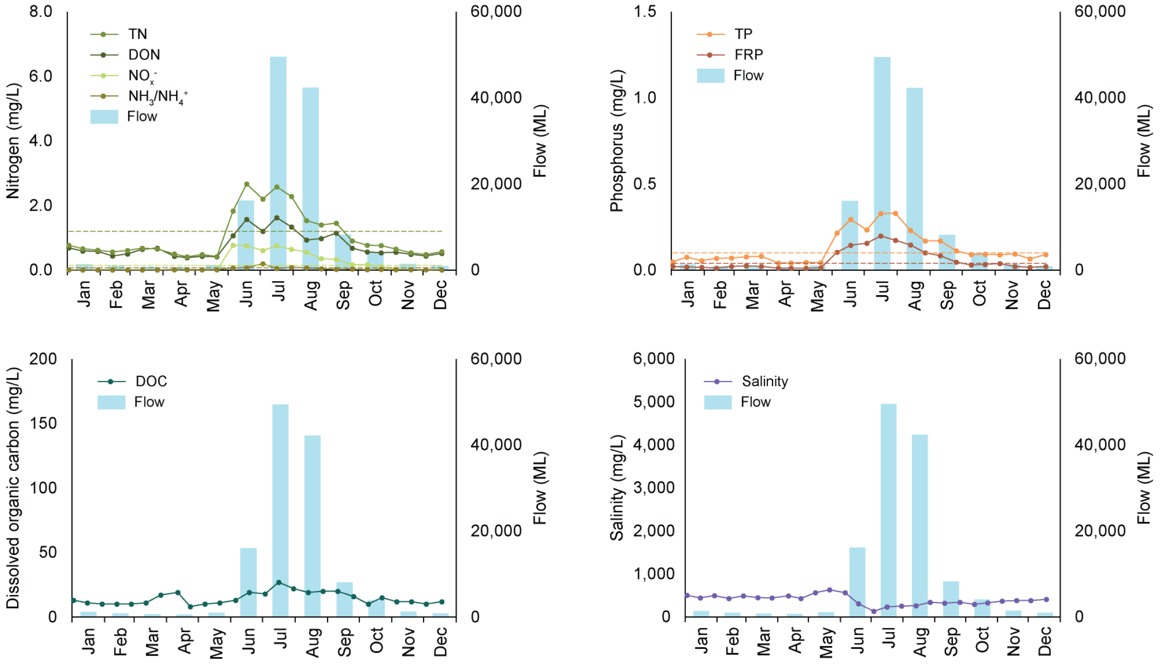




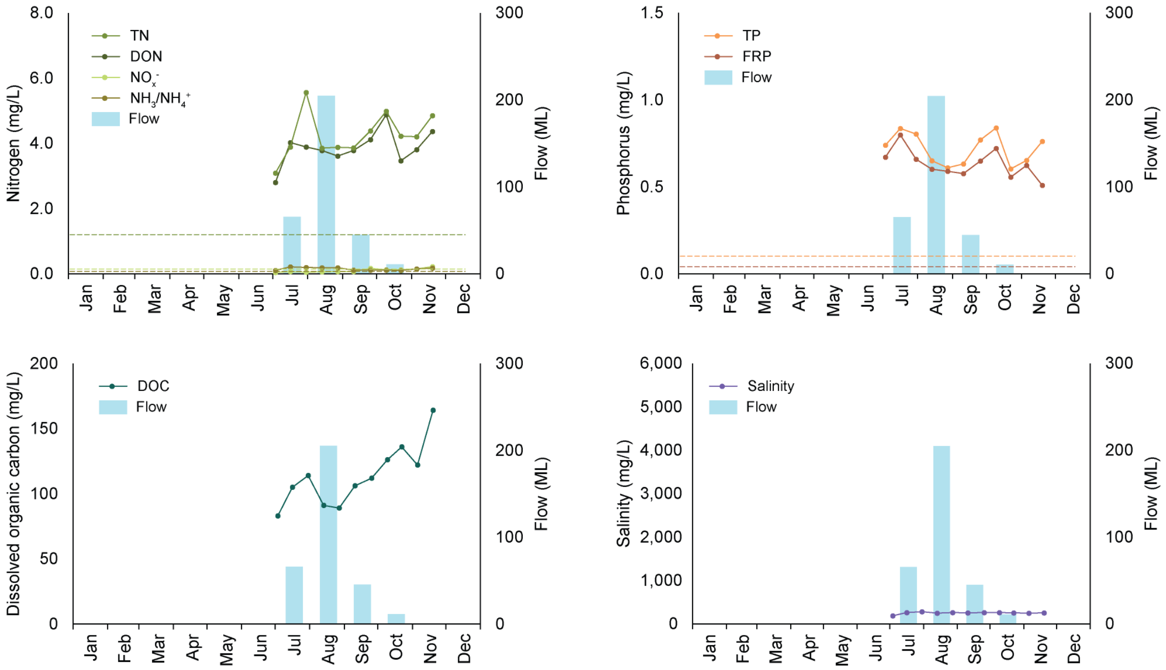




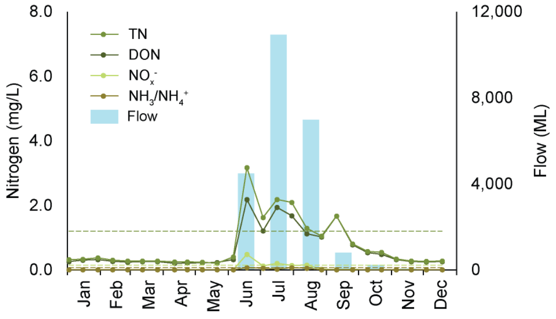
Harvey River – 613036

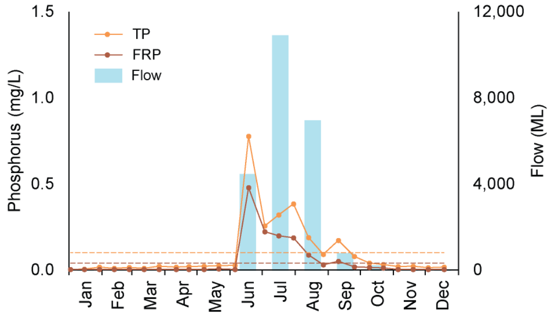


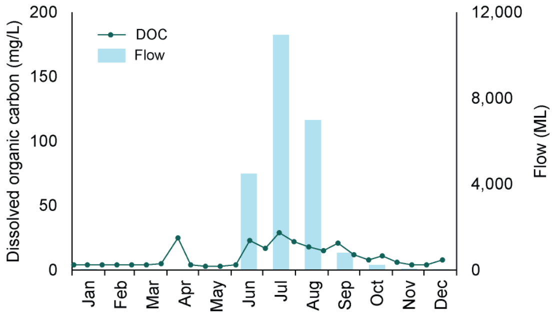
Lower Serpentine River – Gull Road Drain – 614120

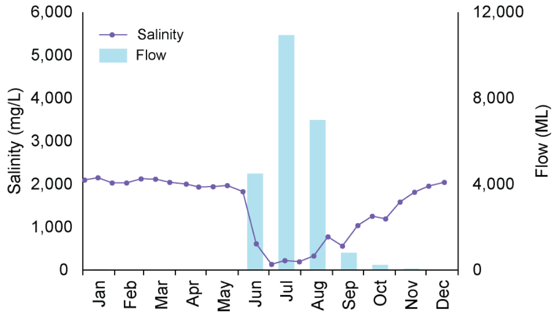


Mayfield Drain – 613031

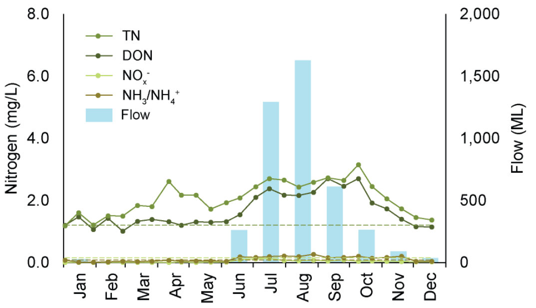


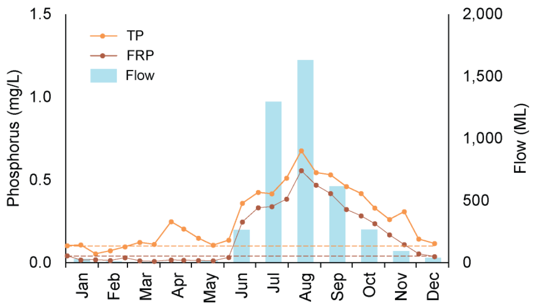


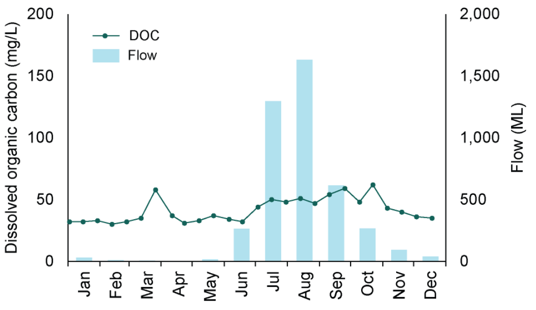


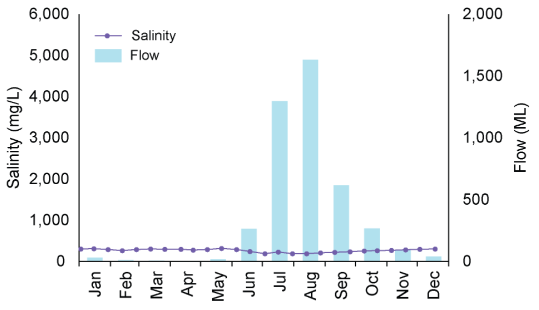


Meredith Drain – 613053

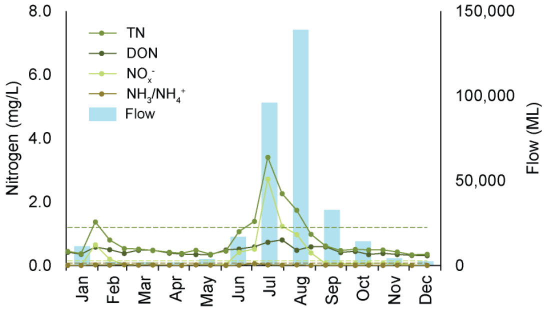


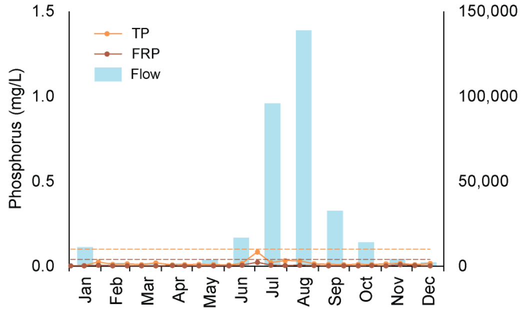


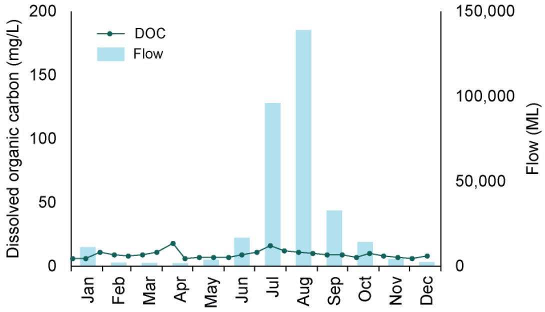


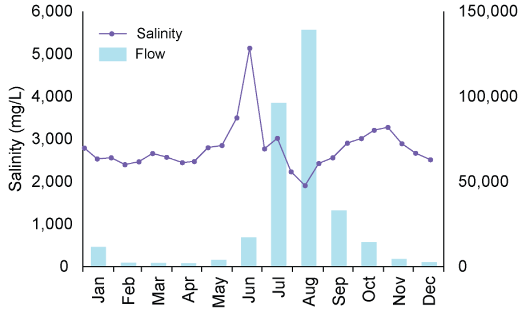


Middle Murray – 614065

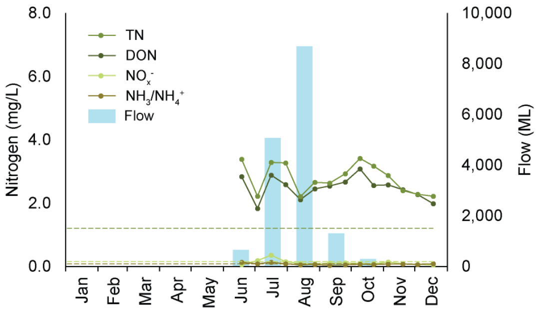


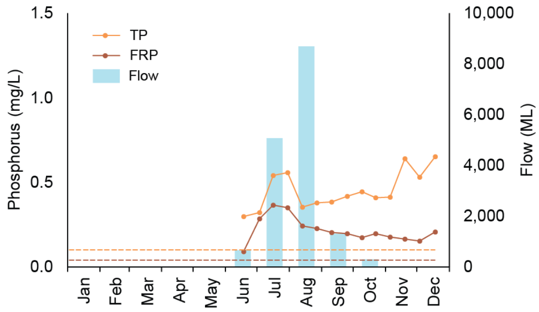


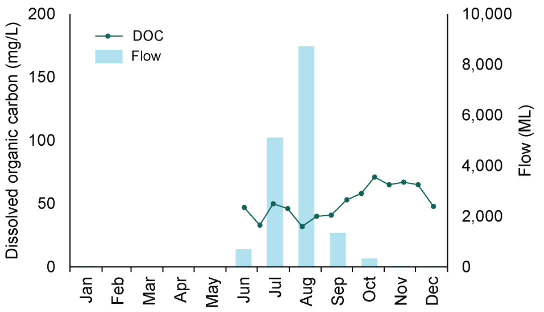


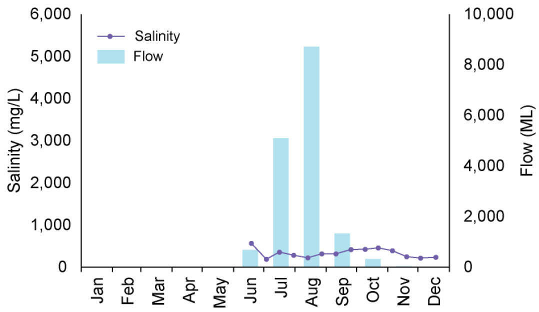


Nambeelup Brook – 614063

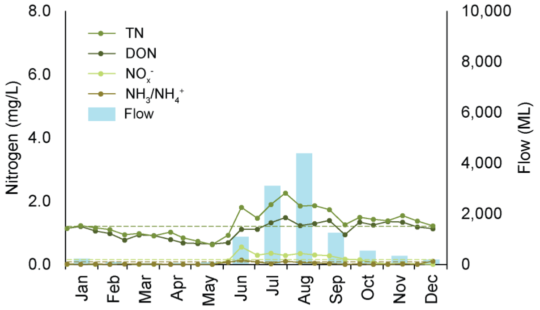


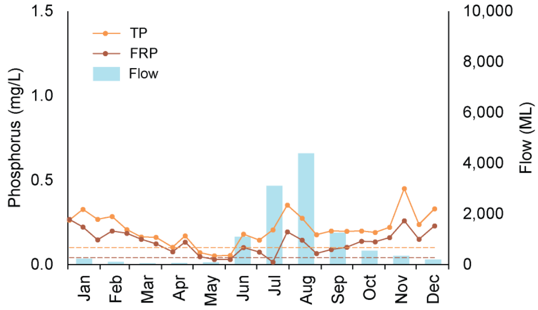


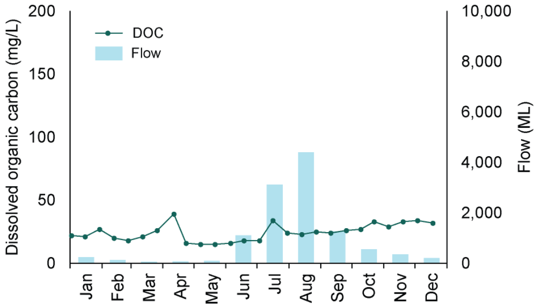


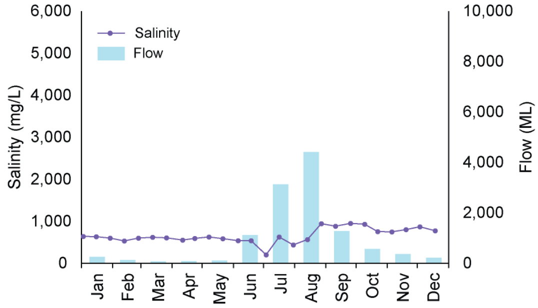


Peel Main Drain – 614121

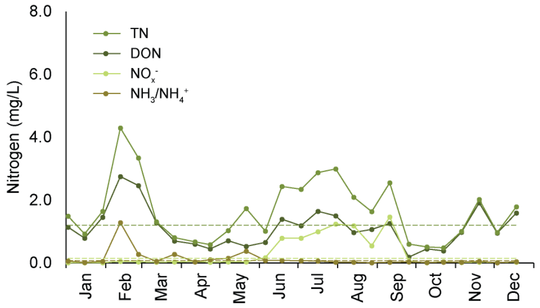


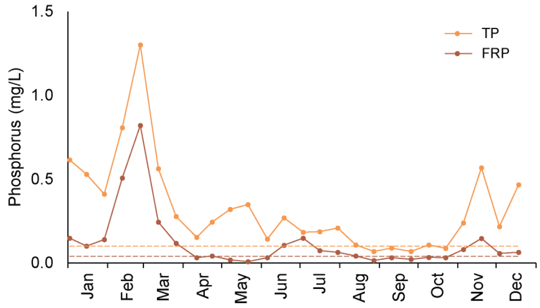


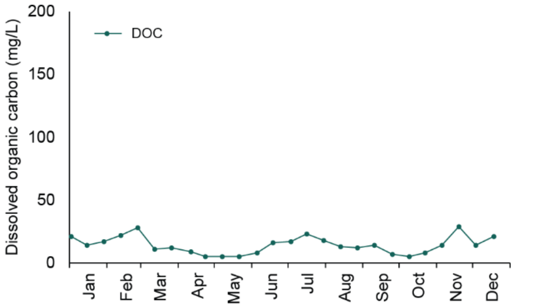


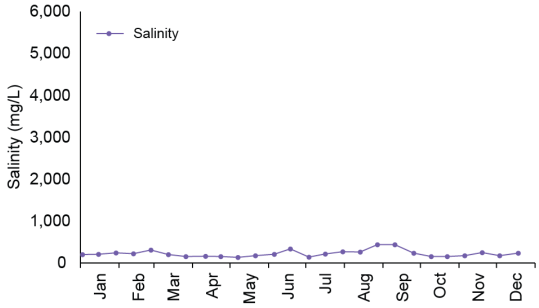


Samson North Drain – 613014

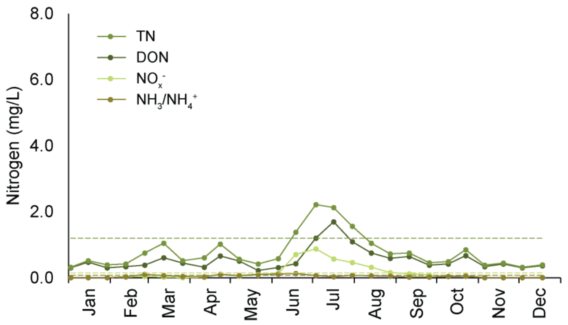


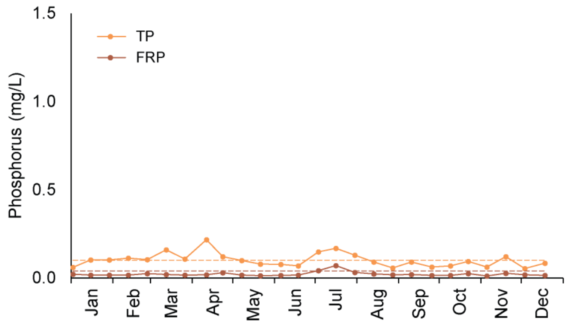


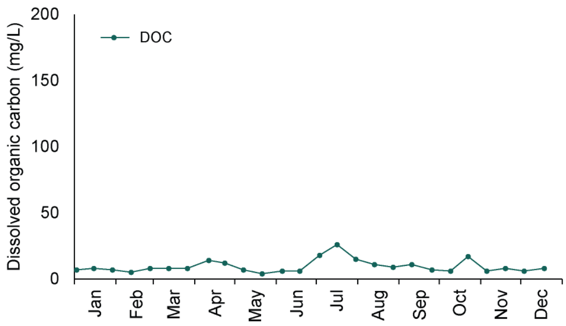


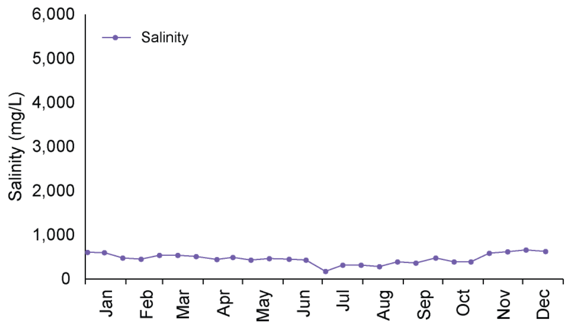


South Dandalup River – 6142623

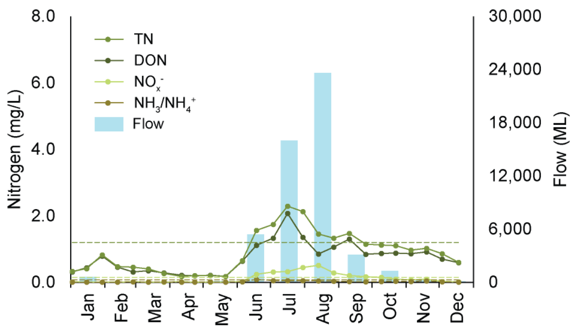


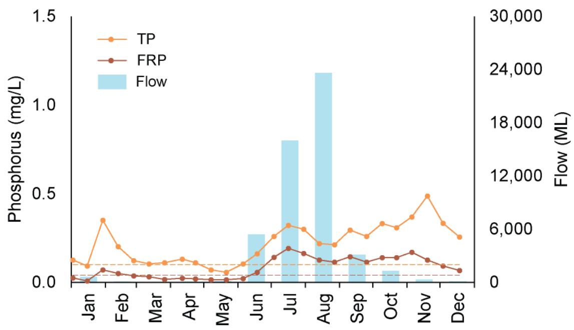


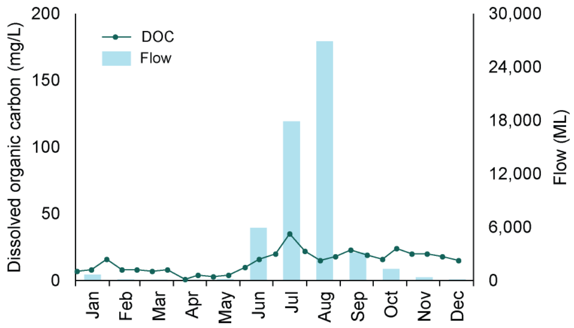


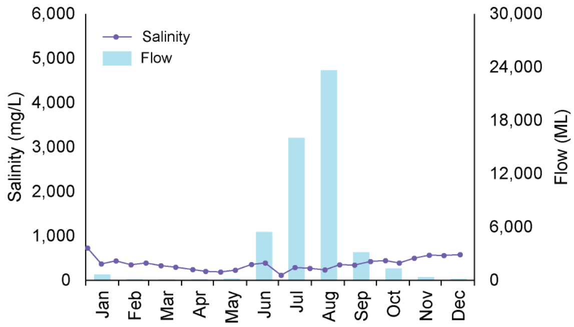


Upper Serpentine River – 614030









Appendix H: Interim Water Quality Index for the Peel-Harvey estuary 2017–18

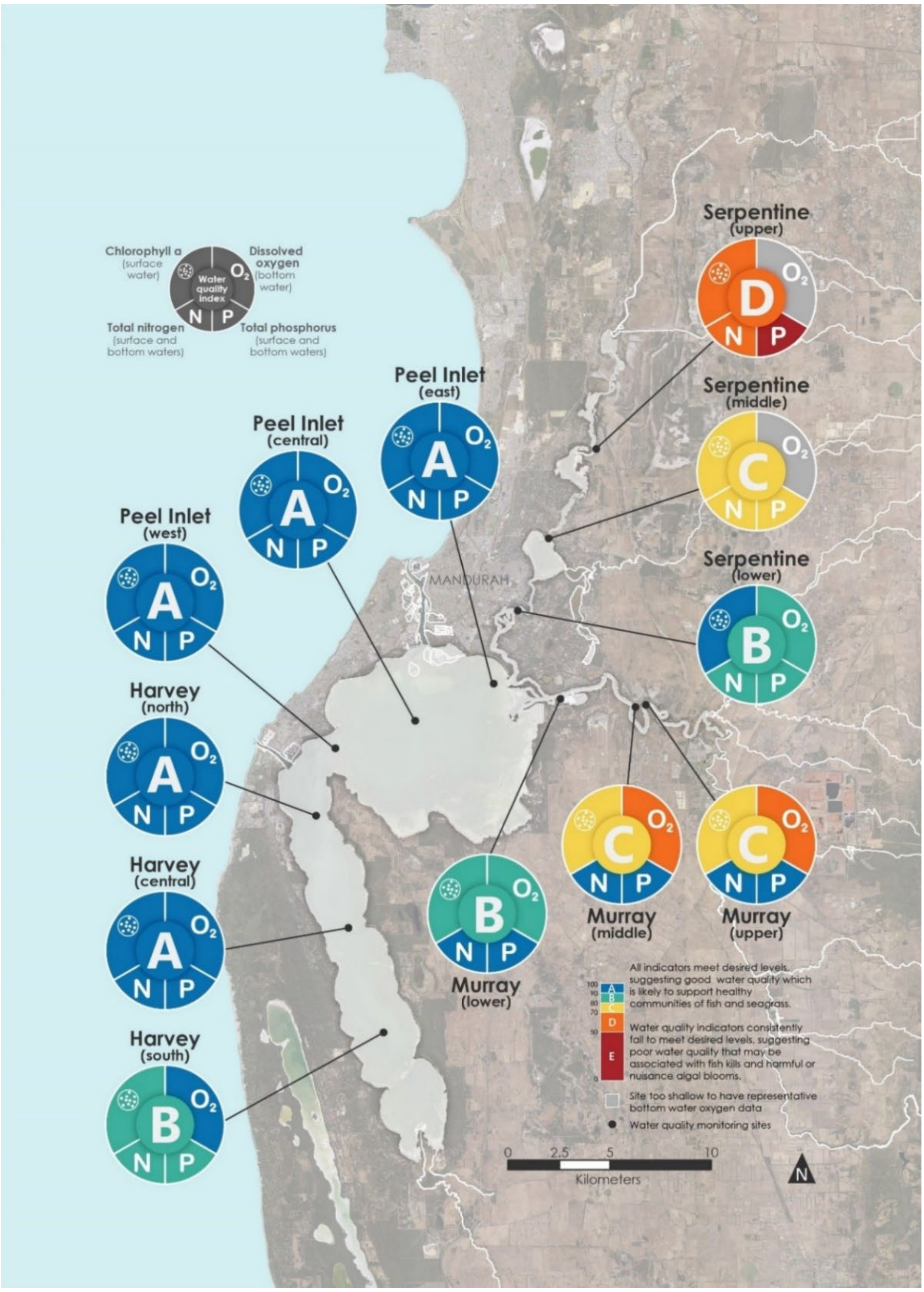


Figure H.1 Interim Water Quality Index for the Peel-Harvey estuary calculated from water quality monitoring data from June 2017 to May 2018

Appendix I: Assessment of water quality objectives (WQOs) by sampling site (2016–19 water quality monitoring data)

This table shows Water Quality Objectives (WQOs) targets and measures, and an assessment of whether they are currently being met (based on 2016–18 catchment water quality data for WQOs 1 and 2, and 2016–19 estuary water quality data for WQOs 3 and 4). The areas that are currently achieving the WQOs are marked with a ✓, areas where concentrations exceed the targets a marked with an X, and **in part** for WQO 4, indicates that the WQOs are partially met (i.e. during summer or autumn but not both). The concentrations from the monitoring data that are assessed are shown underneath in each cell.

WQOs 5 and WQO 6 are measures of comparative change and will be assessed at the first review of the WQIP.

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
Target			0.1 mg/L	1.2 mg/L	5 mg/L	2 mg/L	≤ 3 µg/L: Peel and Harvey Basins ≤ 5 µg/L: Serpentine and Murray Rivers	Reduction in exceedences	Water quality improved or maintained
Measure			Total P concentration – winter medians of 3-year dataset	Total N concentration – winter medians of 3-year dataset	Surface DO (mg/L) – 5th percentile of 3-year dataset	Bottom DO (mg/L) – 5th percentile of 3-year dataset	Summer & autumn chlorophyll *a* concentration (ug/L)	Exceedences of individual algal species concentrations against	Median secchi depth at five 'sentinel' sites

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
							medians of 3-year dataset	established trigger values over a 3-year period (#)	(m)
	Serpentine River catchment	Upper Serpentine River (AWRC Ref. 614030)	X 0.21	X 1.40					
		Peel Main Drain (AWRC Ref. 614121)	X 0.18	X 1.51					
		Punrak Drain (AWRC Ref. 614094)	X 0.18	X 1.75					

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
		Nambeelup Brook (AWRC Ref. 614063)	X 0.43	X 3.27					
		Gull Rd Drain (AWRC Ref. 614120)	X 0.80	X 4.22					
	Murray River catchment	South Dandalup River (AWRC Ref. 6142623)	✓ 0.09	✓ 0.96					
		Middle Murray River	✓ 0.01	✓ 0.70					

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
		(AWRC Ref. 614065)							
	Harvey River catchment	Coolup South Main Drain (AWRC Ref. 613027)	X 0.27	X 1.99					
		Mayfield Drain (AWRC Ref. 613031)	X 0.16	X 1.59					
		Harvey River (AWRC Ref.	X 0.21	X 2.00					

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
		613052/ 613036)							
		Drakesbrook Drain (AWRC Ref. 6131335)	✓ 0.07	X 1.96					
		Samson North Drain (AWRC Ref. 613014)	X 0.14	X 2.46					
		Meredith Drain (AWRC Ref. 613053)	X 0.44	X 2.60					

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
	Harvey Estuary	PHE-31			✓ 5.2	✓ 5.1	✓ (summer – 3, autumn – 2)	n/a	n/a
		PHE-1			✓ 5.5	✓ 5.4	✓ (summer – 2, autumn – 1)	n/a	n/a
	Dawesville Channel	PHE-58			✓ 6.1	✓ 5.4	✓ (summer – 0.5, autumn – 0.5)	n/a	n/a
		PHE-2			✓ 6.5	✓ 6.4	✓ (summer – 0.5, autumn – 0.5)	n/a	n/a
	Peel Inlet	PHE-7			✓ 6.3	✓ 6.1	✓	n/a	n/a

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
							(summer – 1, autumn – 0.5)		
		PHE-4			✓ 5.8	✓ 5.6	✓ (Summer – 1, Autumn – 1)	n/a	n/a
	Estuarine reaches of Serpentine River	PHRS-4			X 2.8	✓ 2.8	in part (summer – 6, autumn – 5)	n/a	n/a
		PHRS-6			X 3.7	✓ 3.2	in part (summer – 5, autumn – 10)	n/a	n/a
		PHRS-7			X 4.0	✓ 3.6	X	n/a	n/a

	Sampling zone	Sampling site (AWRC reference)	WQO 1 TP	WQO 2 TN	WQO 3 (a) Surface DO	WQO 3 (b) Bottom DO	WQO 4 Chlorophyll *a*	WQO 5 * Nuisance/ harmful phyto-plankton	WQO 6 * Water clarity
							(summer – 13, autumn – 23)		
	Estuarine reaches of Murray River	PHRM-2			✓ 5.8	X 1.9	✓ (summer – 5, autumn – 4)	n/a	n/a
		PHRM-4			✓ 5.9	X 0.2	in part (summer – 4, autumn – 6)	n/a	n/a
		PHRM-9			✓ 5.9	X 0.2	in part (summer – 5, autumn – 11)	n/a	n/a

* WQO 5 and WQO 6 are measures of comparative change and will be assessed at the first review of the WQIP.

WQO 1 and WQO 2 were assessed against catchment water quality data (winter medians for TN and TP, 2016–18), provided in Section 3.2 of the main document. WQO 3 and WQO 4 were assessed against estuary water quality data (2016–19), as summarised in the *Bindjareb Djilba (Peel-Harvey estuary): Condition of the estuary 2016–2019* (DWER 2023a), and shown below (see Figure I.1 and I.2).

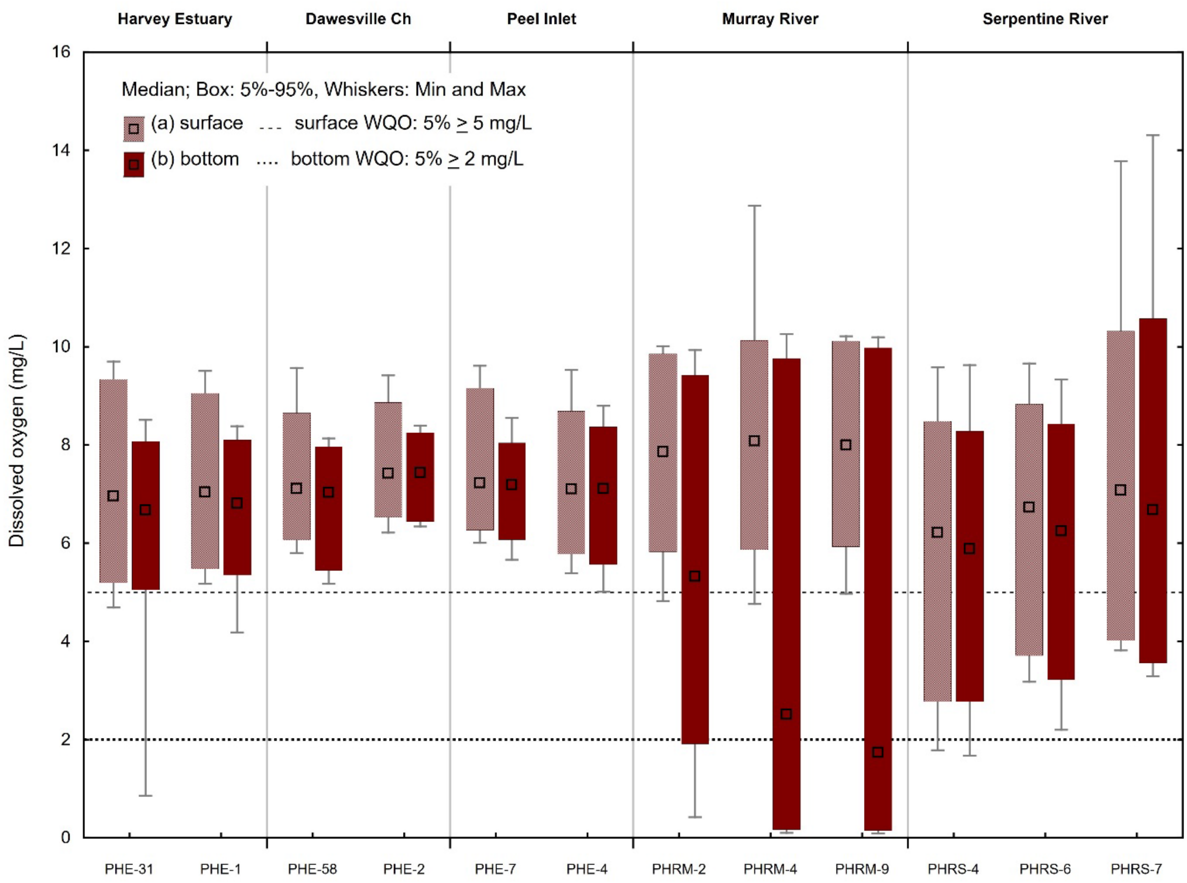


Figure I.1 Box plot of dissolved oxygen concentrations in the surface and bottom waters of regular monitoring sites in the Peel-Harvey estuary from 2016–19

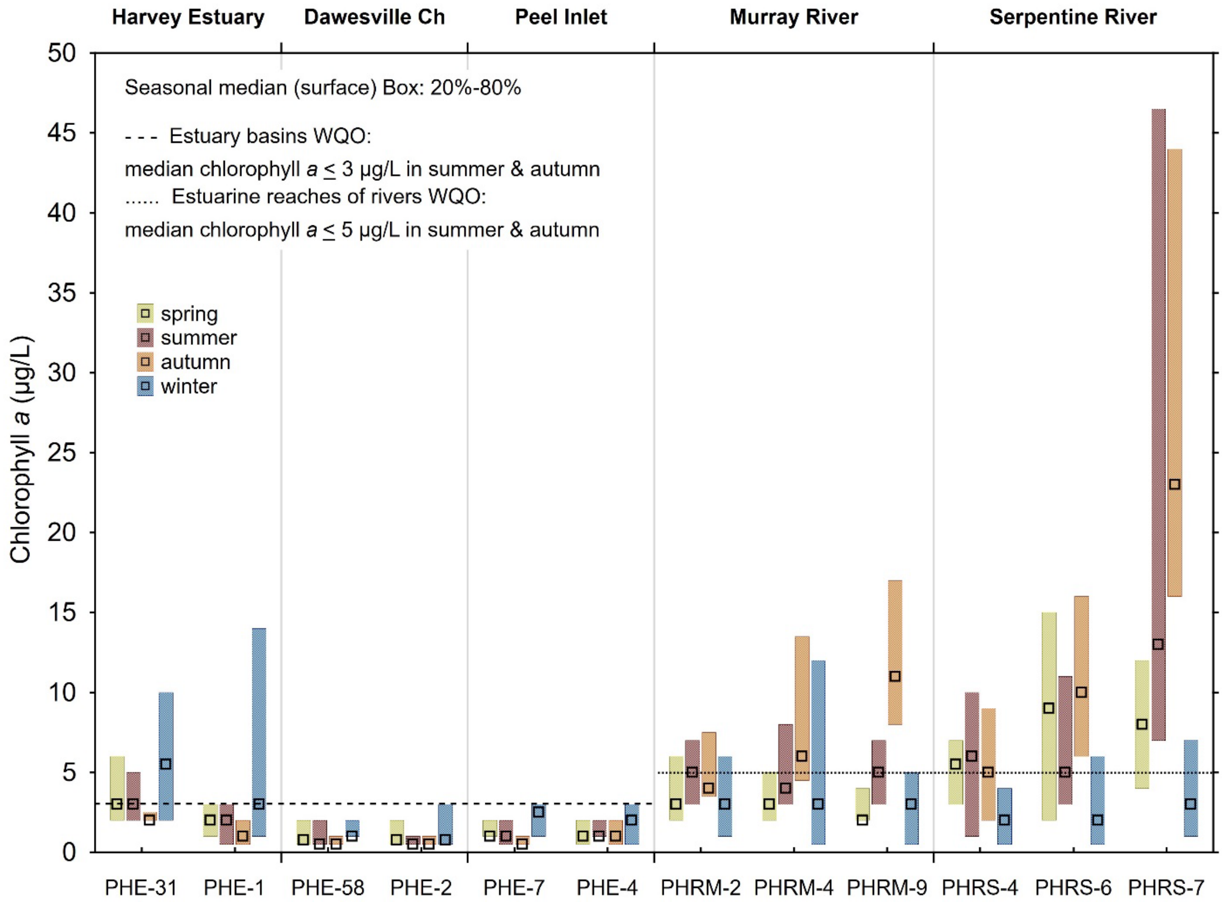


Figure I.2 Box plot of Chlorophyll a concentration at regular monitoring sites in the Peel-Harvey estuary from 2016–19

Appendix J: Land uses by the three major river catchments

For land use data (2010–15), from Hennig et al. (2021).

Serpentine River WQIP catchments (including Mandurah)

Land use	Colour	Area (km2)	(%)	Runoff (GL)	(%)	Nitrogen (tonnes)	(%)	Phosphorus (tonnes)	(%)
Septic (#)		8262.0	-	0.2	0.3	17.8	10.5	0.9	3.8
Point sources		0.7	0.1	0.4	0.6	1.8	1.0	0.1	0.3
Horses		75.2	7.4	6.8	9.4	16.4	9.7	3.0	12.8
Beef		289.0	28.4	26.5	36.6	84.0	49.6	11.9	50.7
Dairy		16.7	1.6	2.0	2.7	11.1	6.6	1.6	7.0
Native vegetation		455.7	44.8	11.3	15.5	1.3	0.8	0.0	0.1
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horticulture		15.1	1.5	1.6	2.2	2.1	1.2	3.1	13.4
Industry, manufacturing & transport		42.0	4.1	10.5	14.5	0.7	0.4	0.0	0.1
Intensive animal use		8.8	0.9	0.6	0.8	15.5	9.2	0.7	3.1
Lifestyle block		62.6	6.1	5.2	7.1	9.7	5.7	0.4	1.8
Mixed grazing		16.3	1.6	1.1	1.5	2.4	1.4	0.3	1.4
Offices, commercial & education		3.6	0.4	0.9	1.2	1.0	0.6	0.2	0.8
Plantation		4.8	0.5	0.0	0.1	0.1	0.0	0.0	0.2
Recreation		5.3	0.5	0.3	0.5	1.0	0.6	0.0	0.1
Residential		21.4	2.1	5.0	7.0	4.3	2.6	1.0	4.2
Viticulture		0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Total		**1017.5**		**72.5**		**169.2**		**23.5**	

Murray River WQIP catchments (including Coolup Peel)

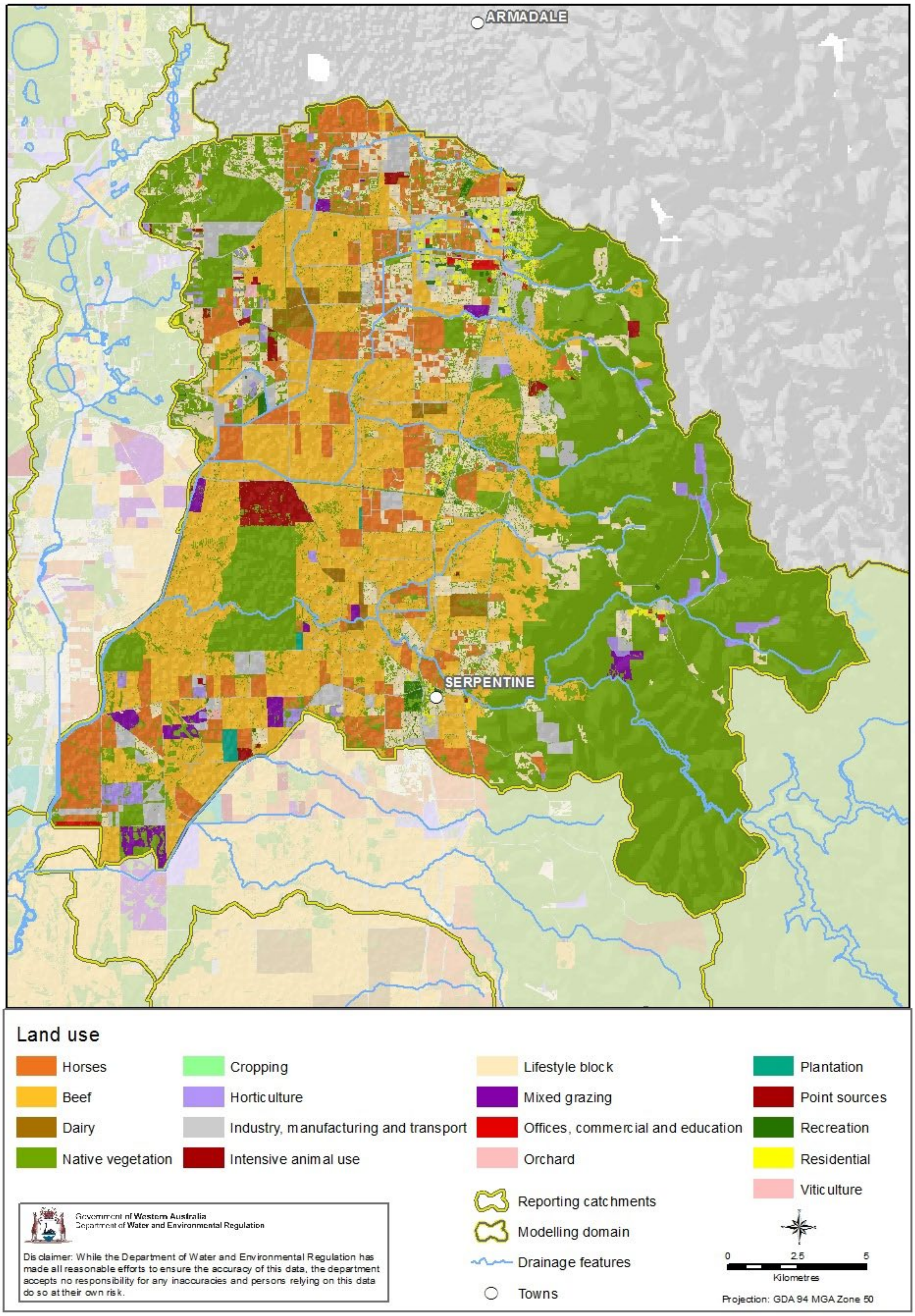
Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		1271.0	-	0.0	0.1	3.4	2.8	0.1	0.6
Point sources		0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horses		7.1	0.9	0.7	1.1	1.2	1.0	0.2	2.4
Beef		354.0	45.0	43.7	72.1	104.3	83.9	7.7	86.4
Dairy		4.2	0.5	0.3	0.5	1.4	1.1	0.2	2.4
Native vegetation		371.5	47.2	6.7	11.0	0.6	0.5	0.0	0.1
Cropping		0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horticulture		3.8	0.5	0.7	1.1	0.3	0.2	0.2	2.4
Industry, manufacturing & transport		15.7	2.0	4.4	7.2	0.3	0.2	0.0	0.1
Intensive animal use		1.0	0.1	0.2	0.3	7.1	5.7	0.1	0.9
Lifestyle block		9.0	1.1	1.1	1.9	1.7	1.3	0.0	0.3
Mixed grazing		10.2	1.3	1.2	2.0	2.4	1.9	0.2	2.1
Offices, commercial & education		0.6	0.1	0.2	0.3	0.2	0.2	0.0	0.3
Plantation		1.5	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Recreation		2.7	0.3	0.2	0.4	0.4	0.3	0.0	0.1
Residential		3.7	0.5	1.0	1.6	0.9	0.8	0.1	1.7
Viticulture		0.9	0.1	0.1	0.2	0.2	0.2	0.0	0.2
Total		**786.2**		**60.6**		**124.4**		**9.0**	

Harvey River WQIP catchments (including Coolup Harvey)

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		2419.0	-	0.0	0.0	2.1	0.8	0.6	2.3
Point sources		0.1	0.0	0.1	0.1	2.8	1.1	0.1	0.5
Horses		1.9	0.2	0.2	0.2	0.5	0.2	0.1	0.3
Beef		429.4	51.6	68.4	61.7	204.4	79.0	20.5	76.4
Dairy		25.0	3.0	12.3	11.1	30.5	11.8	3.0	11.2
Native vegetation		285.7	34.3	17.2	15.5	3.2	1.2	0.1	0.2
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horticulture		7.0	0.8	1.3	1.1	1.4	0.5	1.0	3.7
Industry, manufacturing & transport		17.6	2.1	4.8	4.3	0.6	0.2	0.0	0.1
Intensive animal use		1.3	0.2	0.1	0.1	1.2	0.5	0.2	0.8
Lifestyle block		10.4	1.3	2.0	1.8	3.5	1.3	0.1	0.3
Mixed grazing		19.3	2.3	2.5	2.2	5.5	2.1	0.6	2.1
Offices, commercial & education		0.3	0.0	0.1	0.1	0.3	0.1	0.0	0.1
Plantation		28.3	3.4	0.4	0.4	0.5	0.2	0.3	1.3
Recreation		0.6	0.1	0.1	0.1	0.3	0.1	0.0	0.0
Residential		2.7	0.3	0.8	0.7	1.3	0.5	0.1	0.5
Viticulture		2.1	0.3	0.5	0.4	0.9	0.4	0.1	0.3
Total		**831.7**		**110.8**		**258.9**		**26.8**	

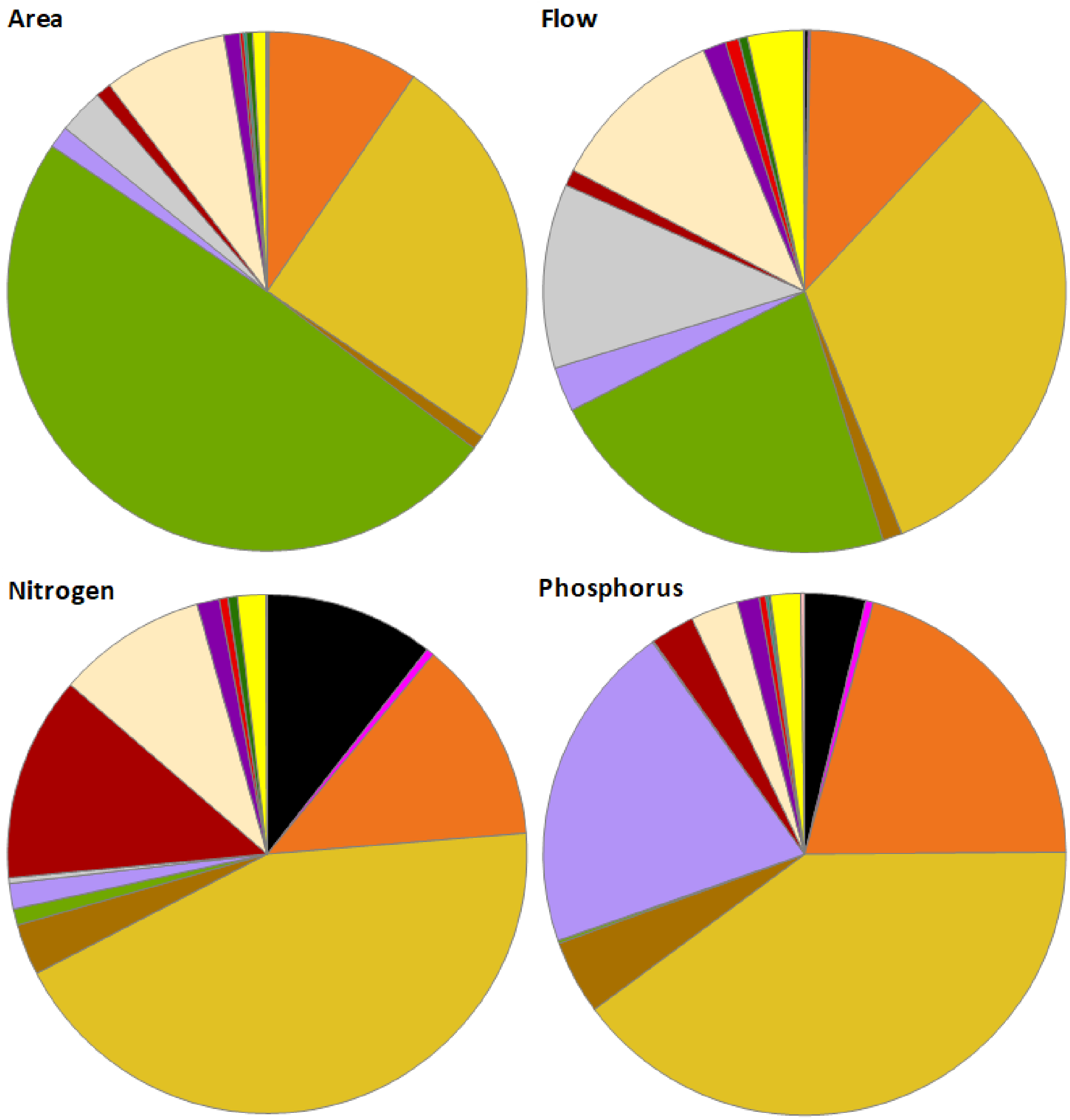
Appendix K: Land uses by reporting subcatchment (2010–15)

K.1 Land uses of the Upper Serpentine reporting subcatchment

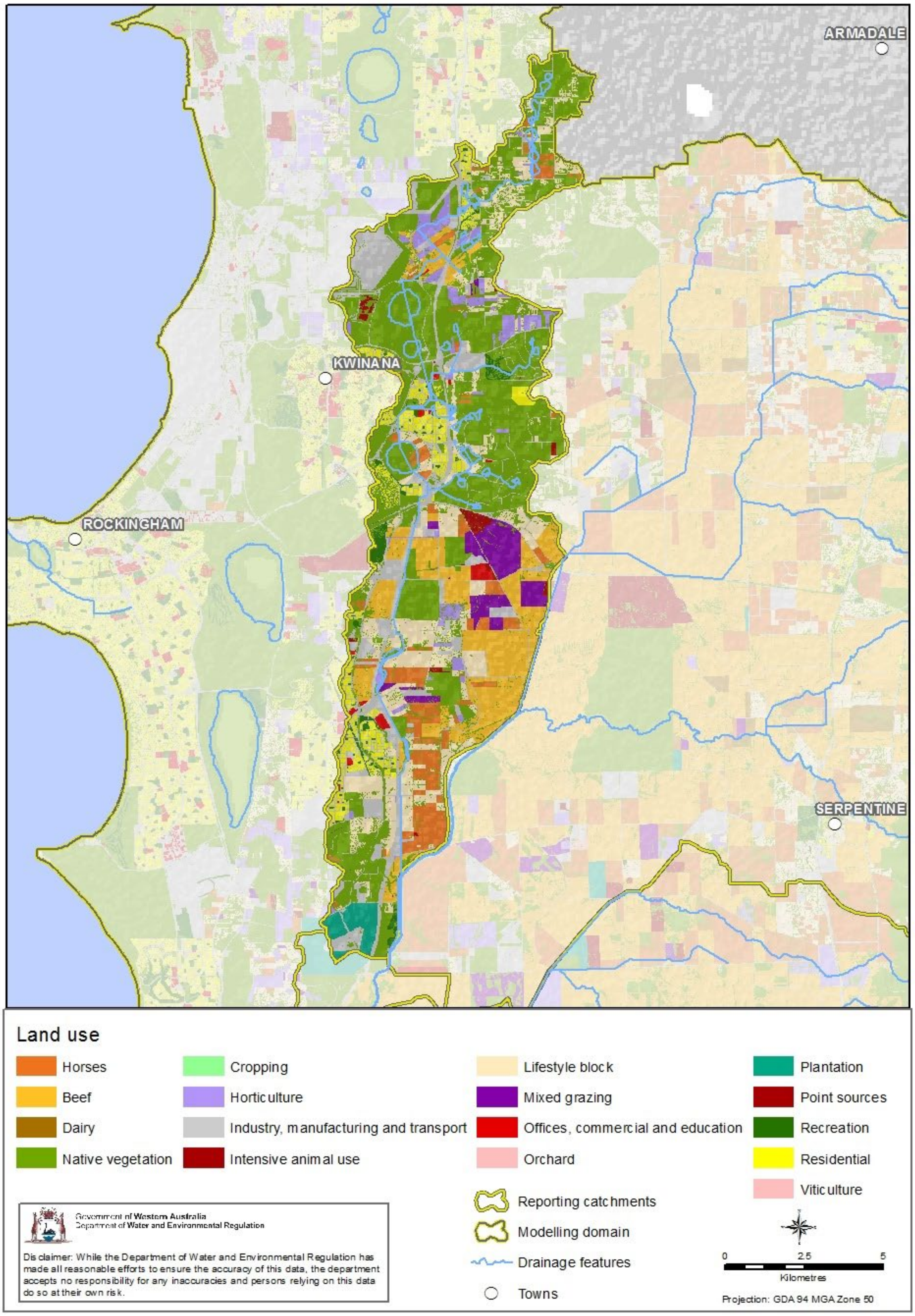


Upper Serpentine nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		4187.0	-	0.1	0.2	7.6	10.6	0.38	3.8
Point sources		0.6	0.1	0.0	0.1	0.3	0.5	0.05	0.5
Horses		46.1	9.4	3.9	11.6	9.1	12.7	2.06	20.6
Beef		122.4	25.0	10.9	32.0	31.4	43.7	3.99	40.0
Dairy		4.2	0.9	0.4	1.2	2.3	3.2	0.46	4.6
Native vegetation		240.8	49.1	7.6	22.3	0.7	1.0	0.02	0.2
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		6.7	1.4	0.9	2.8	1.1	1.6	2.04	20.5
Industry, manufacturing & transport		13.9	2.8	3.9	11.4	0.3	0.4	0.01	0.1
Intensive animal use		4.7	0.9	0.3	1.0	9.2	12.8	0.27	2.7
Lifestyle block		37.9	7.7	3.7	11.0	6.7	9.3	0.29	2.9
Mixed grazing		4.9	1.0	0.5	1.4	1.0	1.4	0.13	1.3
Offices, commercial & education		1.0	0.2	0.3	0.8	0.4	0.5	0.04	0.4
Plantation		0.9	0.2	0.0	0.0	0.0	0.0	0.02	0.2
Recreation		1.8	0.4	0.2	0.5	0.4	0.6	0.01	0.1
Residential		4.1	0.8	1.2	3.5	1.3	1.8	0.18	1.8
Viticulture		0.3	0.1	0.0	0.1	0.0	0.1	0.02	0.2
Total		**490.4**		**33.9**		**71.8**		**9.97**	



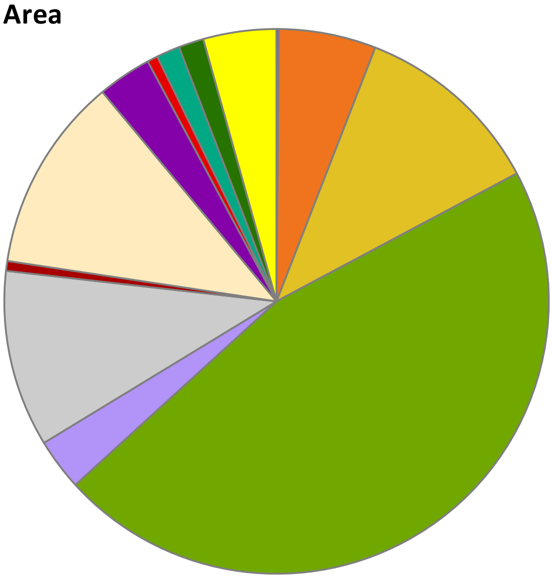
K.2 Land use of the Peel Main Drain reporting subcatchment



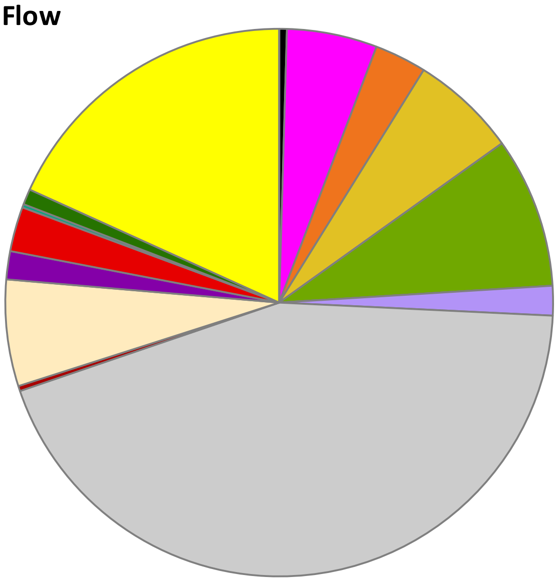
Peel Main Drain nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		1632.0	-	0.0	0.5	3.0	26.1	0.22	15.4
Point sources		0.2	0.1	0.4	5.3	1.4	12.1	0.03	2.3
Horses		7.2	5.8	0.2	3.1	0.8	6.6	0.09	6.4
Beef		14.1	11.3	0.4	6.3	2.0	17.2	0.10	7.1
Dairy		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Native vegetation		57.5	46.0	0.6	8.9	0.2	2.0	0.01	0.4
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		3.8	3.1	0.1	1.7	0.3	2.3	0.69	48.4
Industry, manufacturing & transport		13.1	10.5	3.0	44.0	0.1	1.1	0.00	0.3
Intensive animal use		0.7	0.6	0.0	0.3	0.9	7.8	0.03	1.8
Lifestyle block		14.5	11.6	0.4	6.3	1.2	10.5	0.04	3.1
Mixed grazing		4.0	3.2	0.1	1.7	0.4	3.6	0.02	1.3
Offices, commercial & education		0.8	0.6	0.2	2.6	0.2	1.4	0.02	1.1
Plantation		1.7	1.4	0.0	0.2	0.0	0.2	0.01	1.0
Recreation		1.9	1.5	0.1	0.9	0.2	2.1	0.00	0.3
Residential		5.4	4.3	1.3	18.2	0.8	7.1	0.16	11.0
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**124.9**		**6.9**		**11.6**		**1.42**	

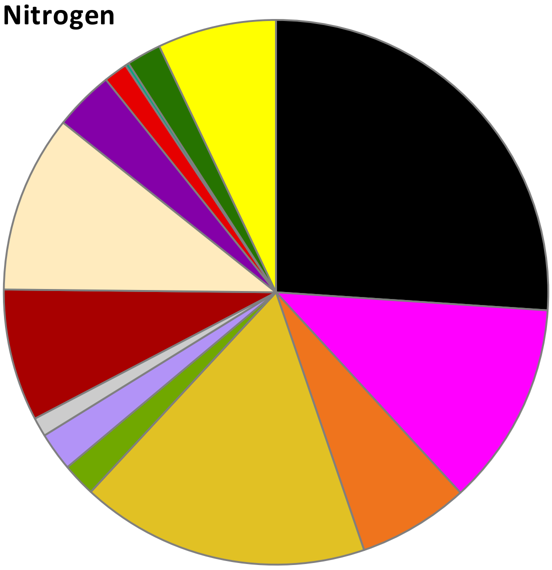
Area



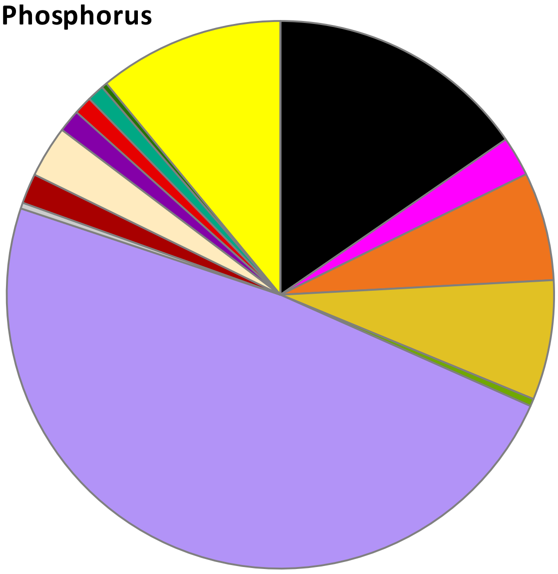
Flow



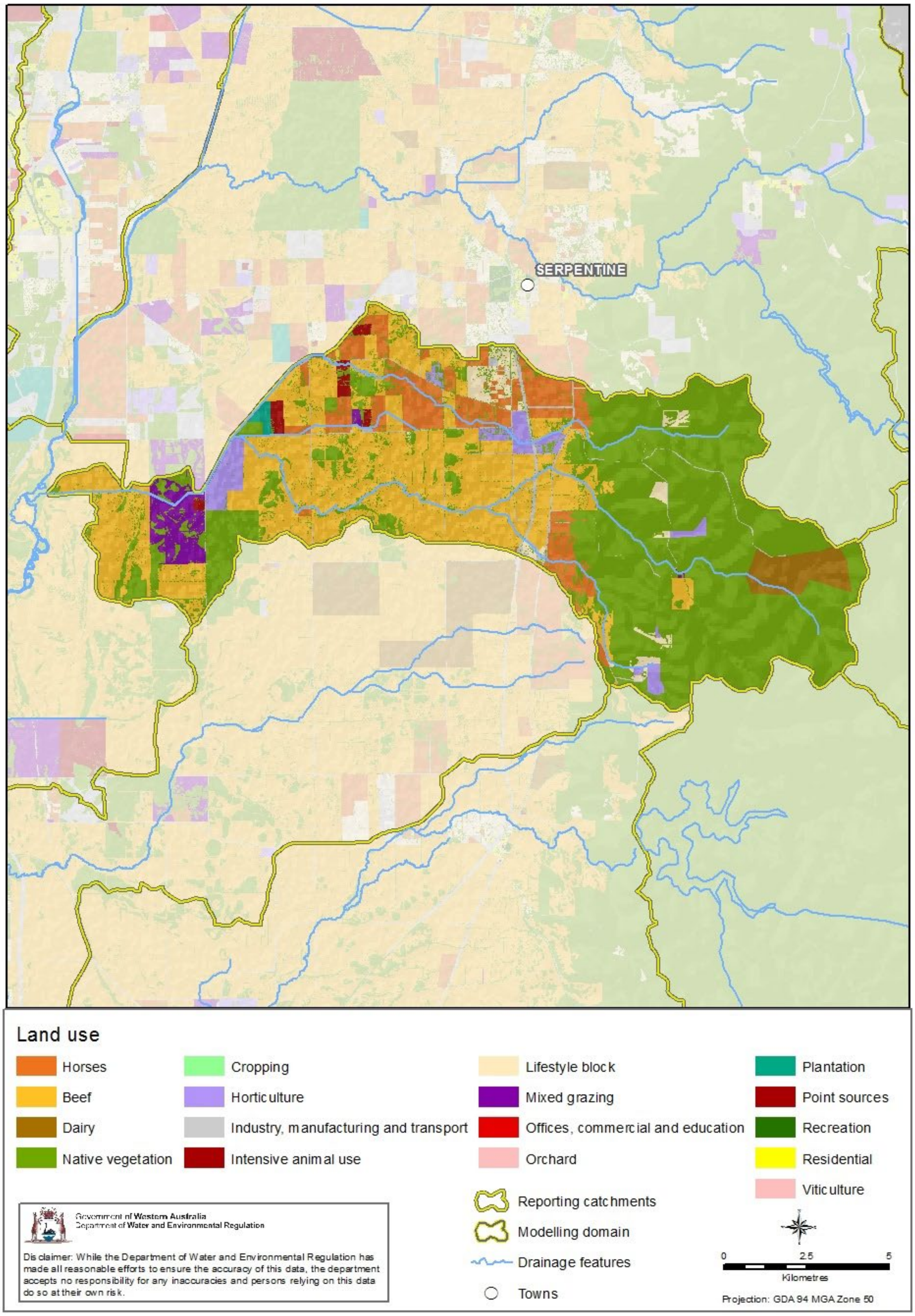
Nitrogen



Phosphorus



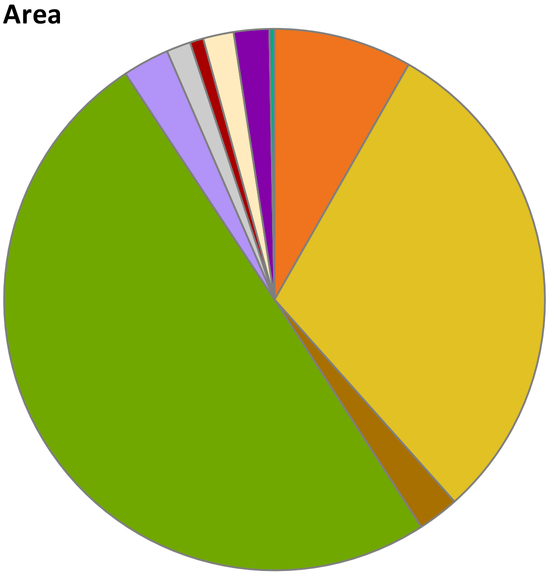
K.3 Land uses of the Dirk Brook reporting subcatchment



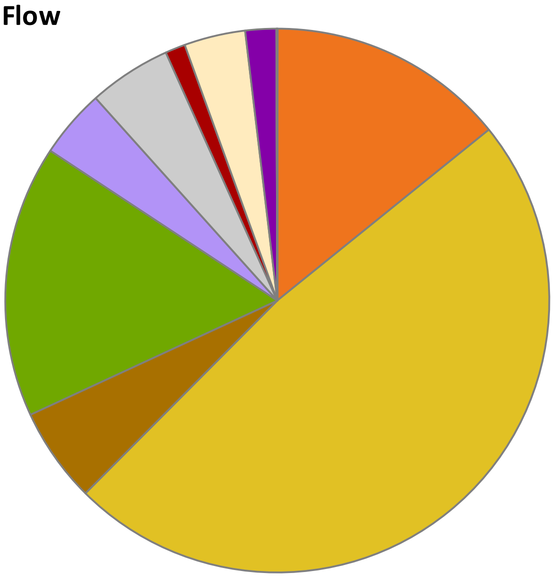
Dirk Brook nutrient sources

Land use	Colour	Area (km^2)	Area (%)	Runoff (GL)	Runoff (%)	Nitrogen (tonnes)	Nitrogen (%)	Phosphorus (tonnes)	Phosphorus (%)
Septic (#)			-	0.0	0.0	0.3	1.0	0.01	0.5
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		11.5	8.3	1.8	14.2	3.6	12.7	0.44	15.7
Beef		42.0	30.1	6.1	48.3	15.5	54.0	1.62	58.4
Dairy		3.4	2.5	0.7	5.6	2.9	10.2	0.10	3.7
Native vegetation		69.5	49.8	2.0	16.2	0.1	0.5	0.00	0.0
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		3.9	2.8	0.5	4.1	0.6	2.2	0.31	11.1
Industry, manufacturing & transport		2.0	1.4	0.6	4.9	0.1	0.2	0.00	0.0
Intensive animal use		1.1	0.8	0.1	1.2	4.3	15.1	0.22	7.8
Lifestyle block		2.5	1.8	0.5	3.6	0.7	2.6	0.01	0.4
Mixed grazing		3.0	2.1	0.2	1.8	0.4	1.5	0.06	2.1
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		0.4	0.3	0.0	0.0	0.0	0.0	0.01	0.2
Recreation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**139.5**		**12.6**		**28.7**		**2.78**	

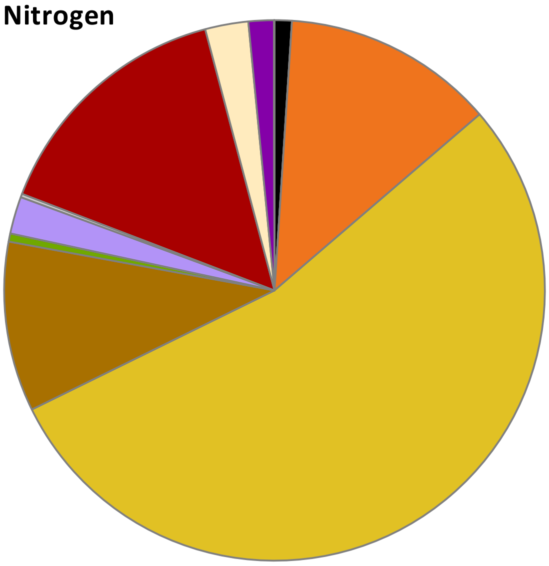
Area



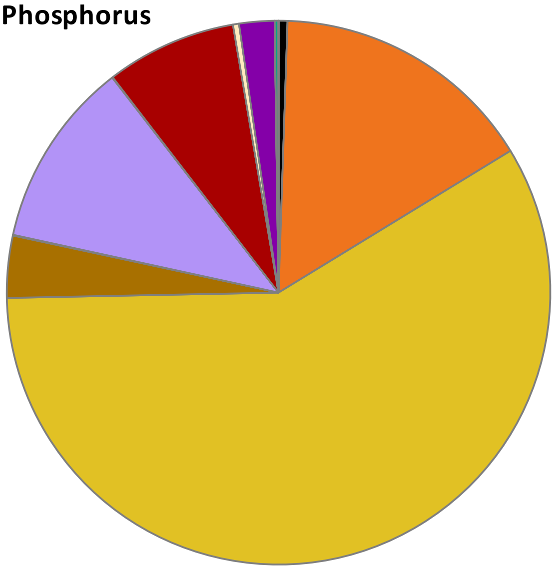
Flow



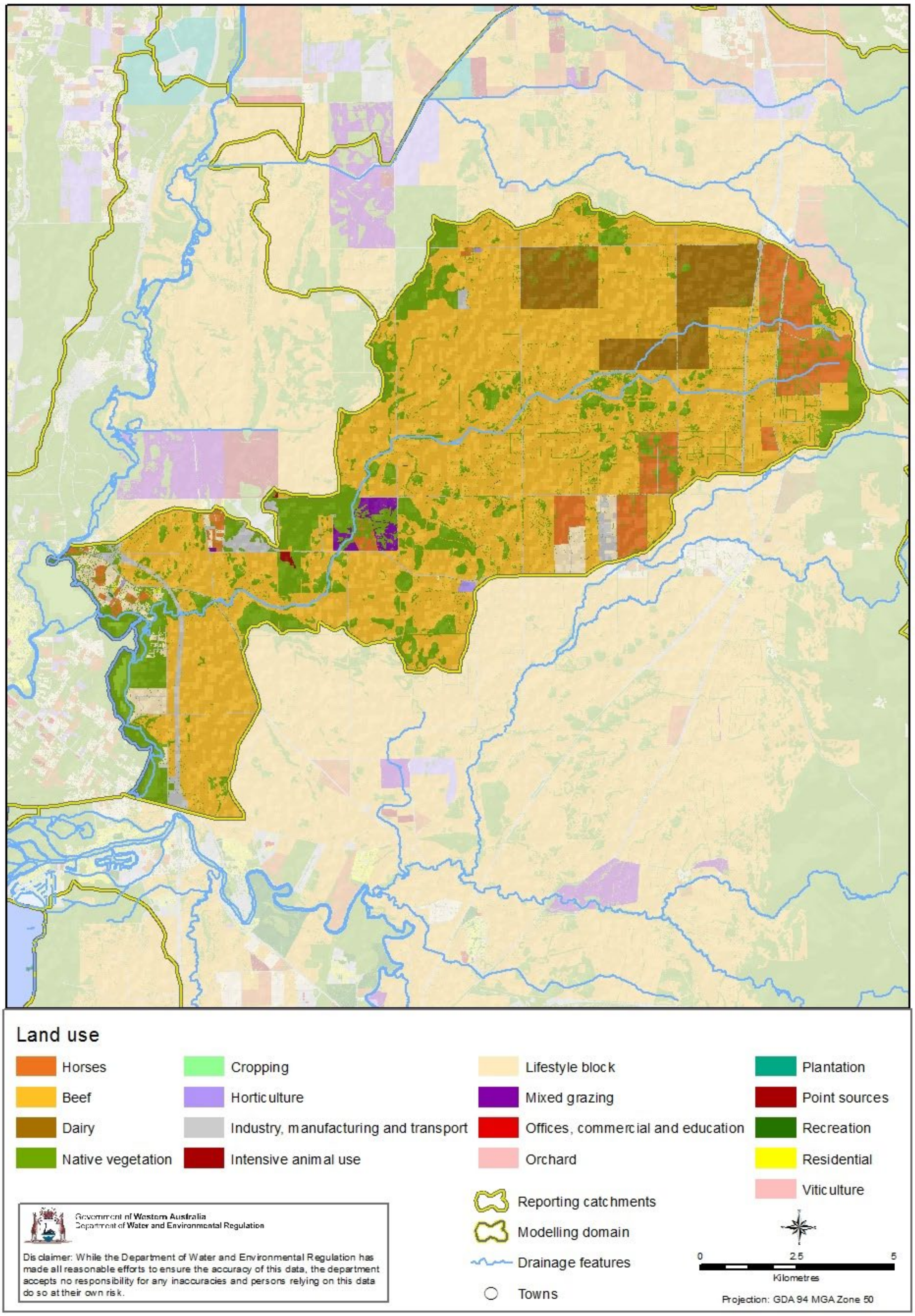
Nitrogen



Phosphorus



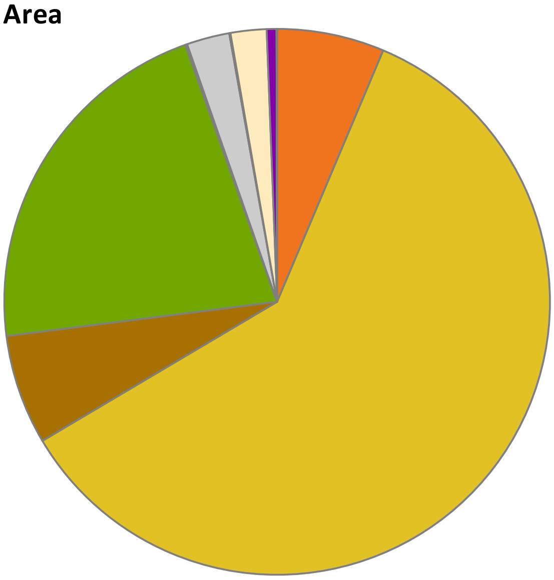
K.4 Land uses of the Nambeelup reporting catchment



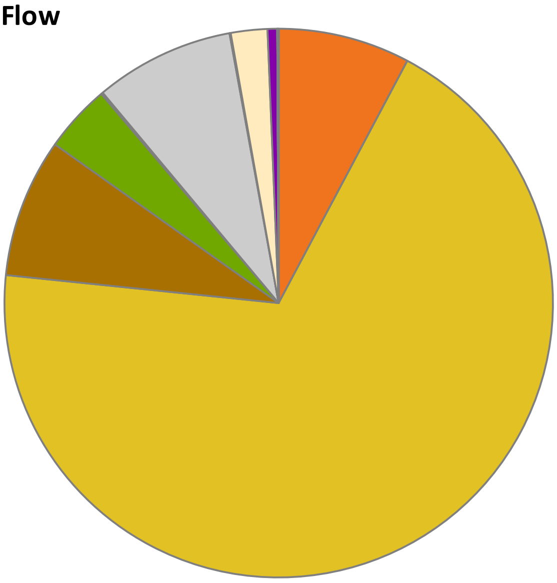
Nambeelup nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km²)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		316.0	-	0.0	0.0	0.1	0.2	0.02	0.3
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		8.8	6.4	0.8	7.8	2.8	6.9	0.36	5.3
Beef		83.4	60.1	7.3	68.9	30.4	75.3	5.08	76.2
Dairy		9.0	6.5	0.9	8.2	5.9	14.7	1.09	16.3
Native vegetation		29.9	21.6	0.4	4.0	0.1	0.2	0.00	0.0
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.1	0.1	0.0	0.1	0.0	0.0	0.03	0.4
Industry, manufacturing & transport		3.5	2.5	0.9	8.2	0.1	0.2	0.00	0.1
Intensive animal use		0.1	0.1	0.0	0.1	0.2	0.5	0.02	0.4
Lifestyle block		3.0	2.1	0.2	2.2	0.6	1.4	0.03	0.5
Mixed grazing		0.8	0.6	0.1	0.6	0.2	0.5	0.03	0.5
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Recreation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.0	0.0	0.0	0.1	0.0	0.0	0.00	0.0
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**138.7**		**10.6**		**40.3**		**6.66**	

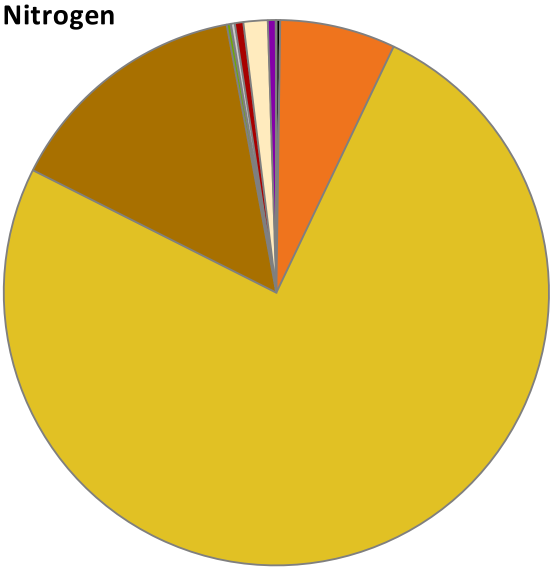
Area



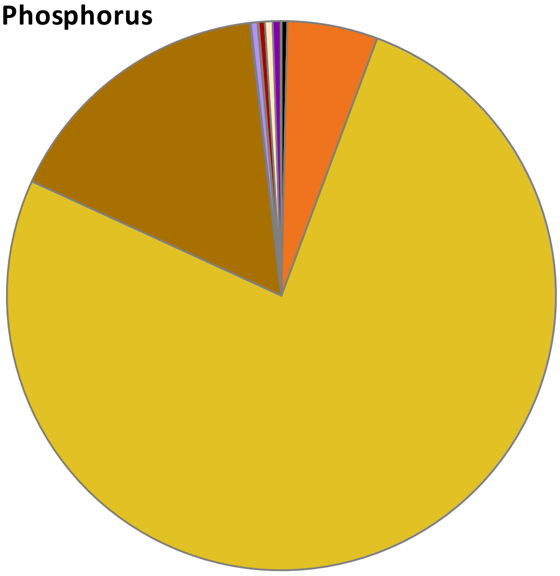
Flow



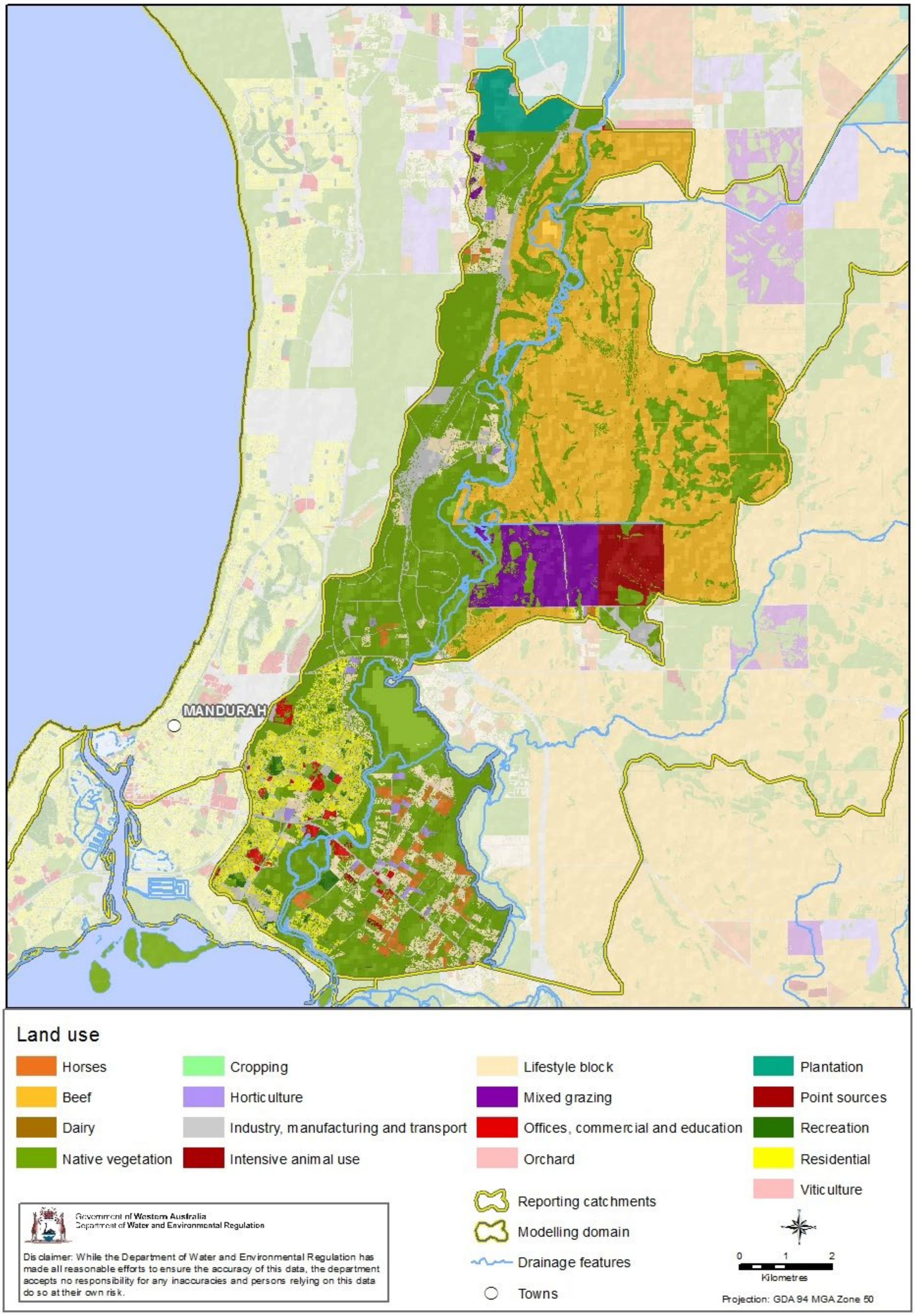
Nitrogen



Phosphorus



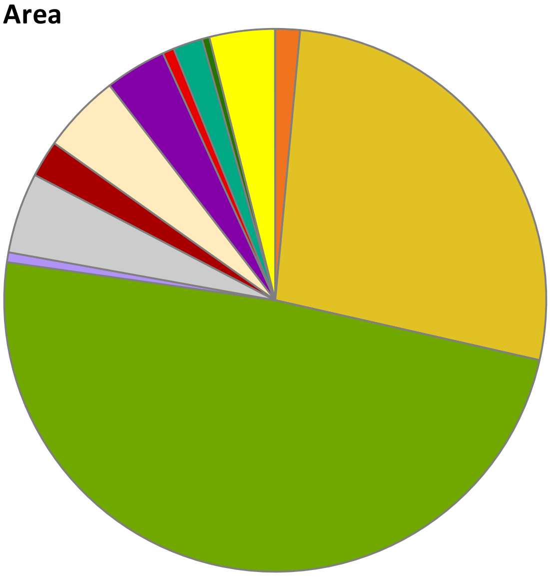
K.5 Land uses of the Lower Serpentine reporting catchment



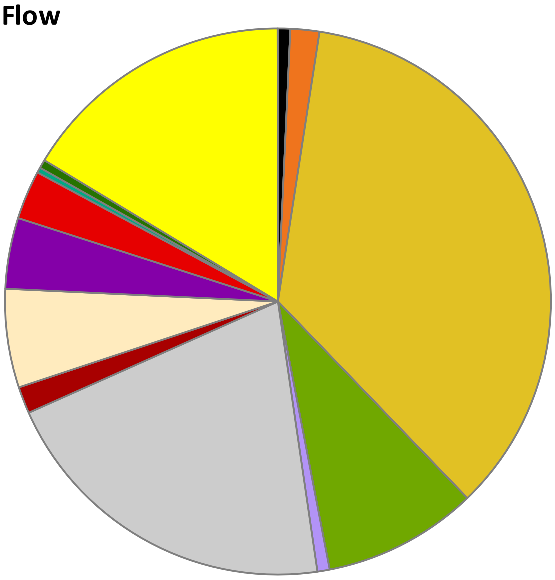
Lower Serpentine nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		1206.0	-	0.0	0.7	3.7	31.8	0.11	5.1
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		1.5	1.5	0.1	1.7	0.2	1.4	0.06	2.9
Beef		27.1	27.1	1.9	35.4	4.7	40.0	1.13	52.6
Dairy		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Native vegetation		48.7	48.7	0.5	9.2	0.1	0.9	0.00	0.2
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.6	0.6	0.0	0.7	0.0	0.2	0.08	3.6
Industry, manufacturing & transport		4.8	4.8	1.1	20.6	0.1	0.6	0.00	0.2
Intensive animal use		2.2	2.2	0.1	1.6	0.9	7.9	0.20	9.1
Lifestyle block		4.7	4.7	0.3	5.8	0.5	3.9	0.04	1.7
Mixed grazing		3.7	3.7	0.2	4.2	0.4	3.6	0.09	4.2
Offices, commercial & education		0.7	0.7	0.2	2.9	0.2	1.6	0.07	3.1
Plantation		1.8	1.8	0.0	0.3	0.0	0.2	0.01	0.5
Recreation		0.4	0.4	0.0	0.5	0.0	0.4	0.00	0.1
Residential		3.9	3.9	0.9	16.3	0.9	7.5	0.35	16.5
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**100.0**		**5.3**		**11.7**		**2.14**	

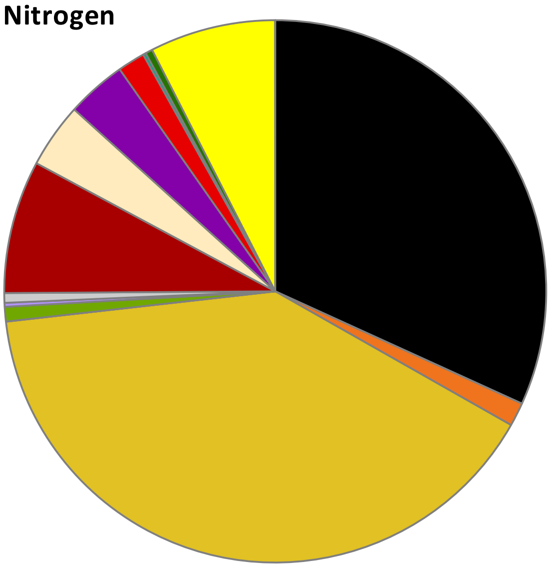
Area



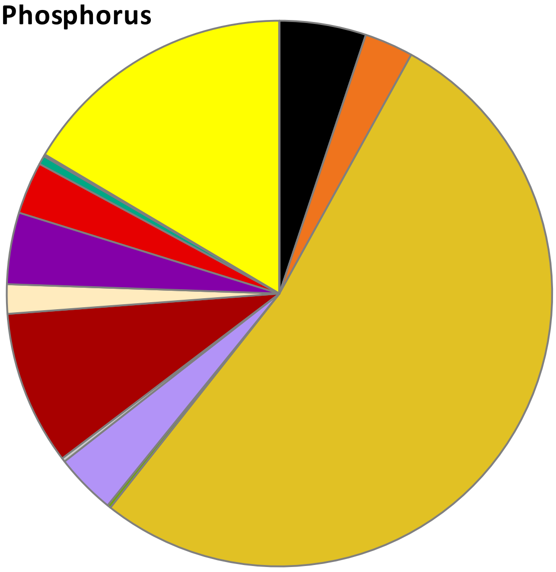
Flow



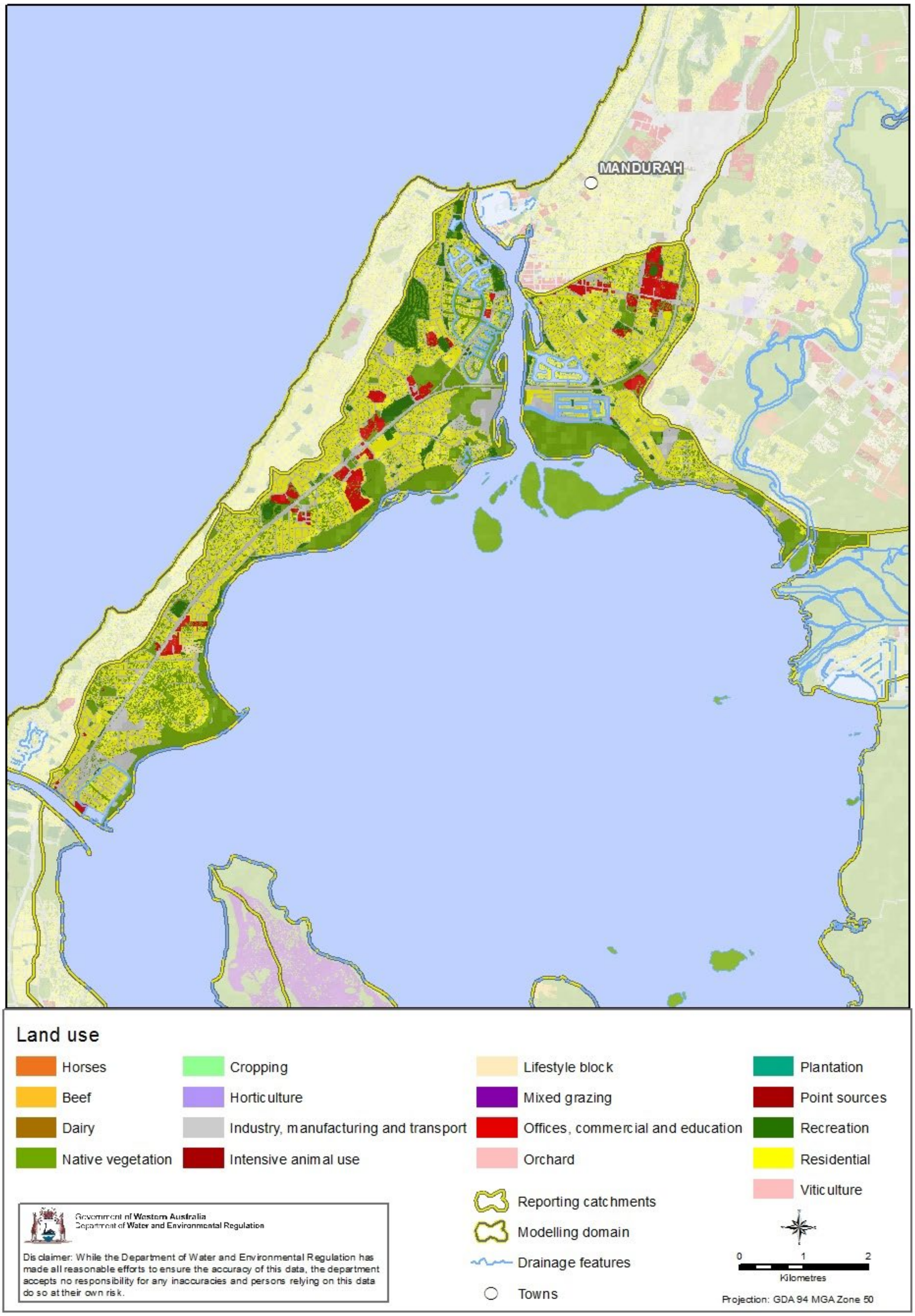
Nitrogen



Phosphorus



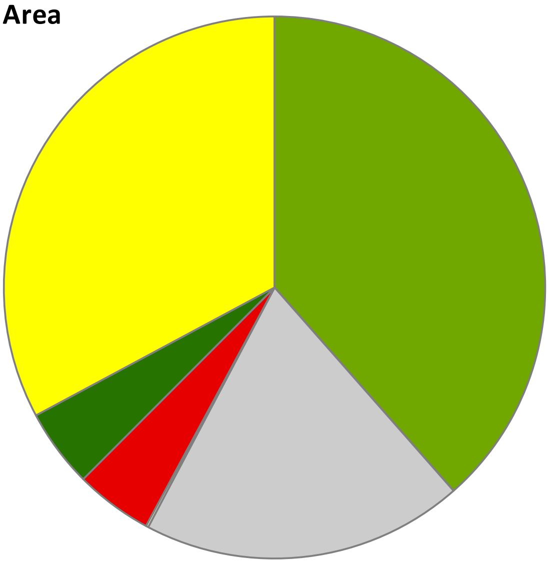
K.6 Land uses of the Mandurah reporting catchment



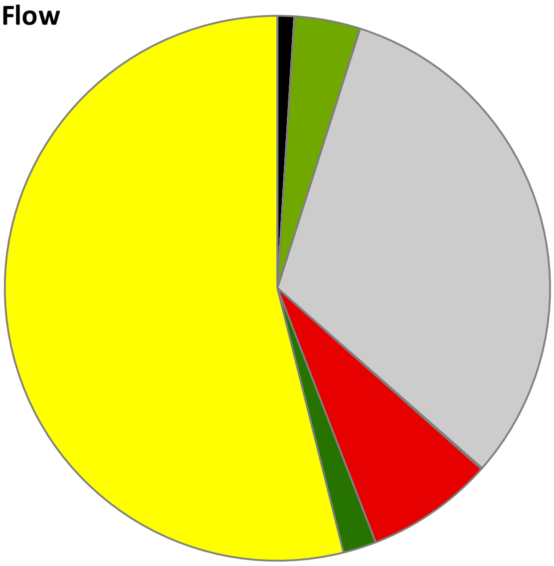
Mandurah nutrient sources

Land use	Colour	Area (km^2)	Area (%)	Runoff (GL)	Runoff (%)	Nitrogen (tonnes)	Nitrogen (%)	Phosphorus (tonnes)	Phosphorus (%)
Septic (#)		746.0	-	0.0	1.0	3.1	62.1	0.15	29.7
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Beef		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Dairy		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Native vegetation		9.3	38.5	0.1	3.9	0.0	0.5	0.00	0.2
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Industry, manufacturing & transport		4.7	19.2	1.0	31.6	0.0	0.9	0.00	0.4
Intensive animal use		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Lifestyle block		0.0	0.1	0.0	0.1	0.0	0.1	0.00	0.1
Mixed grazing		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Offices, commercial & education		1.1	4.6	0.2	7.6	0.2	4.6	0.06	11.5
Plantation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Recreation		1.1	4.7	0.1	2.0	0.3	5.1	0.01	1.5
Residential		7.9	32.8	1.7	53.9	1.3	26.6	0.29	56.6
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**24.2**		**3.2**		**5.0**		**0.51**	

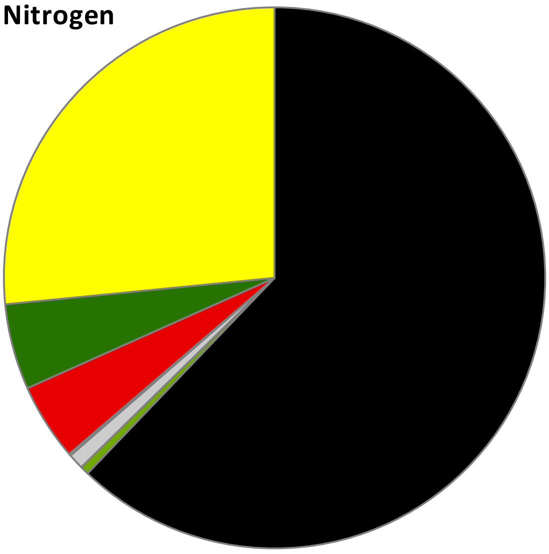
Area



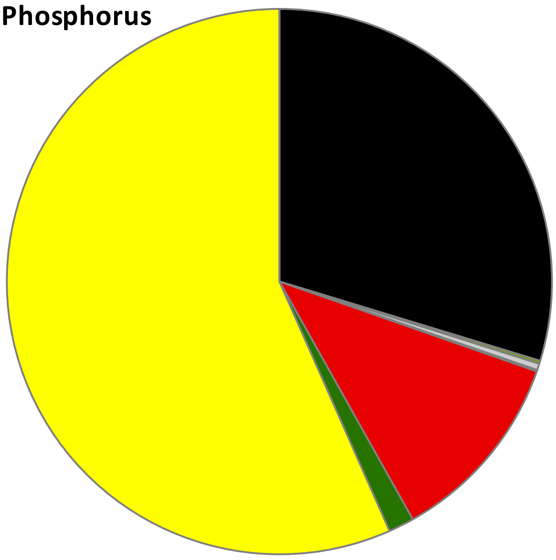
Flow



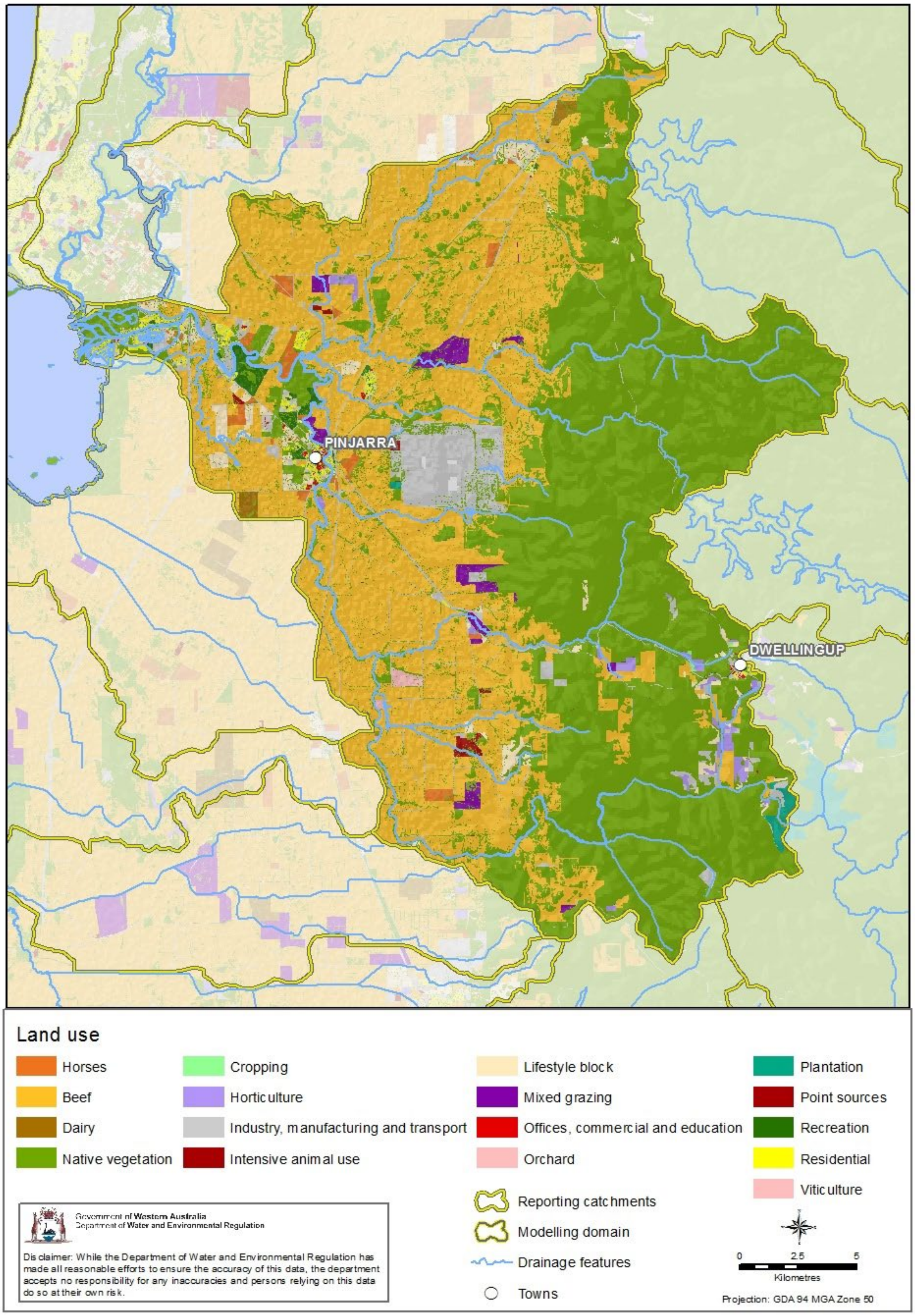
Nitrogen



Phosphorus

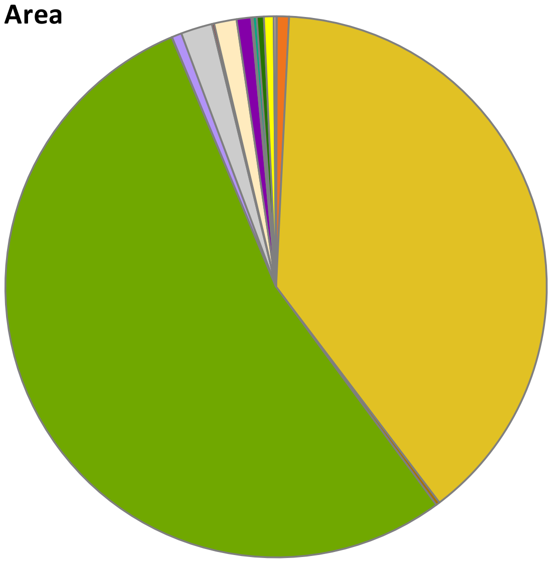


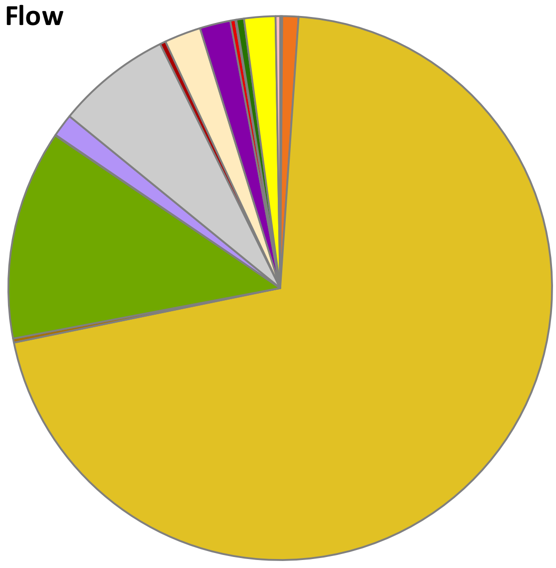
K.7 Land uses of the Lower Murray reporting catchment

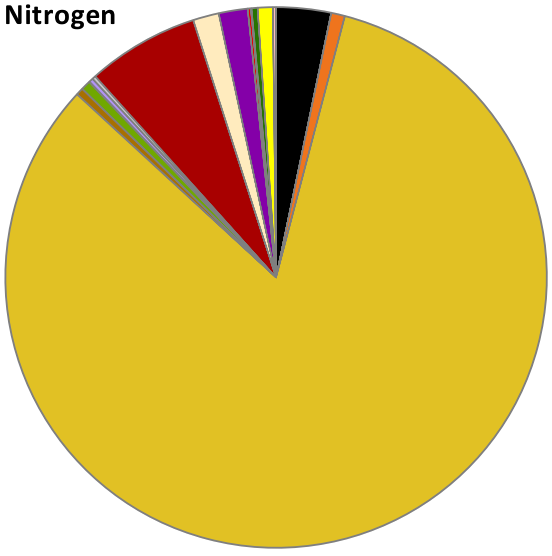


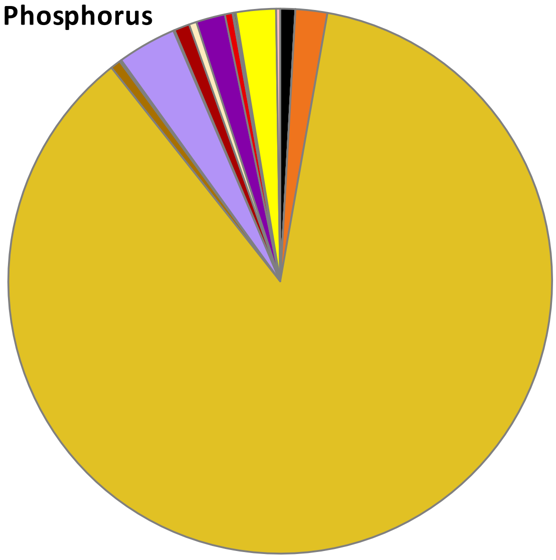
Lower Murray nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		1172.0	-	0.0	0.1	3.4	3.3	0.06	0.9
Point sources		0.3	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		4.6	0.7	0.5	1.0	0.8	0.8	0.12	1.9
Beef		247.6	38.9	36.1	70.7	85.6	82.8	5.38	86.6
Dairy		1.4	0.2	0.1	0.2	0.5	0.4	0.04	0.6
Native vegetation		342.1	53.8	6.4	12.5	0.6	0.6	0.01	0.1
Cropping		0.1	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		3.8	0.6	0.7	1.4	0.3	0.3	0.22	3.5
Industry, manufacturing & transport		12.0	1.9	3.5	6.8	0.2	0.2	0.00	0.1
Intensive animal use		0.8	0.1	0.2	0.3	6.9	6.7	0.06	0.9
Lifestyle block		8.5	1.3	1.1	2.2	1.6	1.6	0.03	0.4
Mixed grazing		5.6	0.9	0.9	1.8	1.8	1.7	0.11	1.7
Offices, commercial & education		0.6	0.1	0.2	0.3	0.2	0.2	0.03	0.5
Plantation		1.5	0.2	0.0	0.1	0.0	0.0	0.00	0.1
Recreation		2.7	0.4	0.2	0.5	0.4	0.4	0.01	0.1
Residential		3.7	0.6	0.9	1.9	0.9	0.9	0.15	2.4
Viticulture		0.9	0.1	0.1	0.3	0.2	0.2	0.02	0.2
Total		**636.1**		**51.0**		**103.4**		**6.21**	

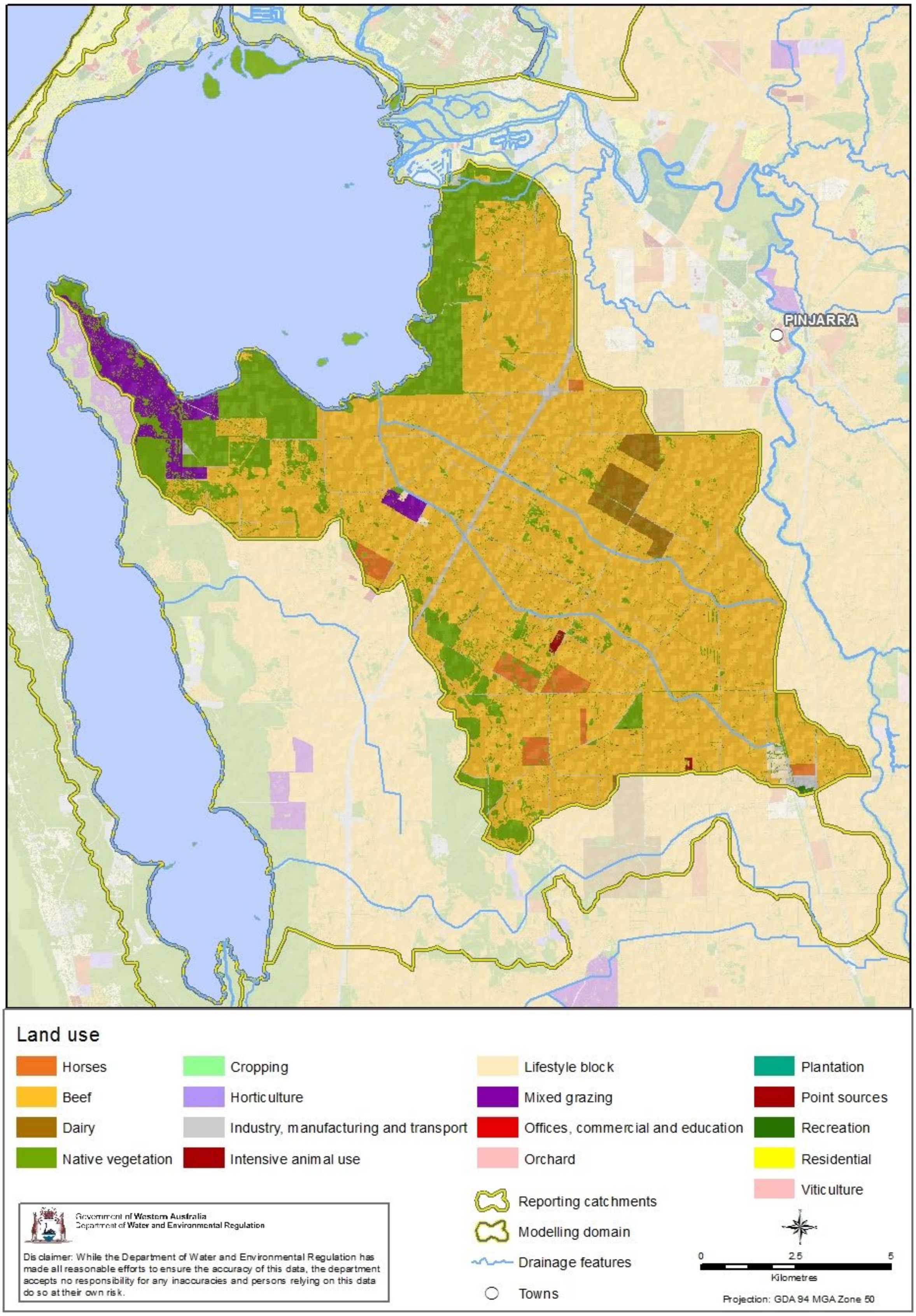






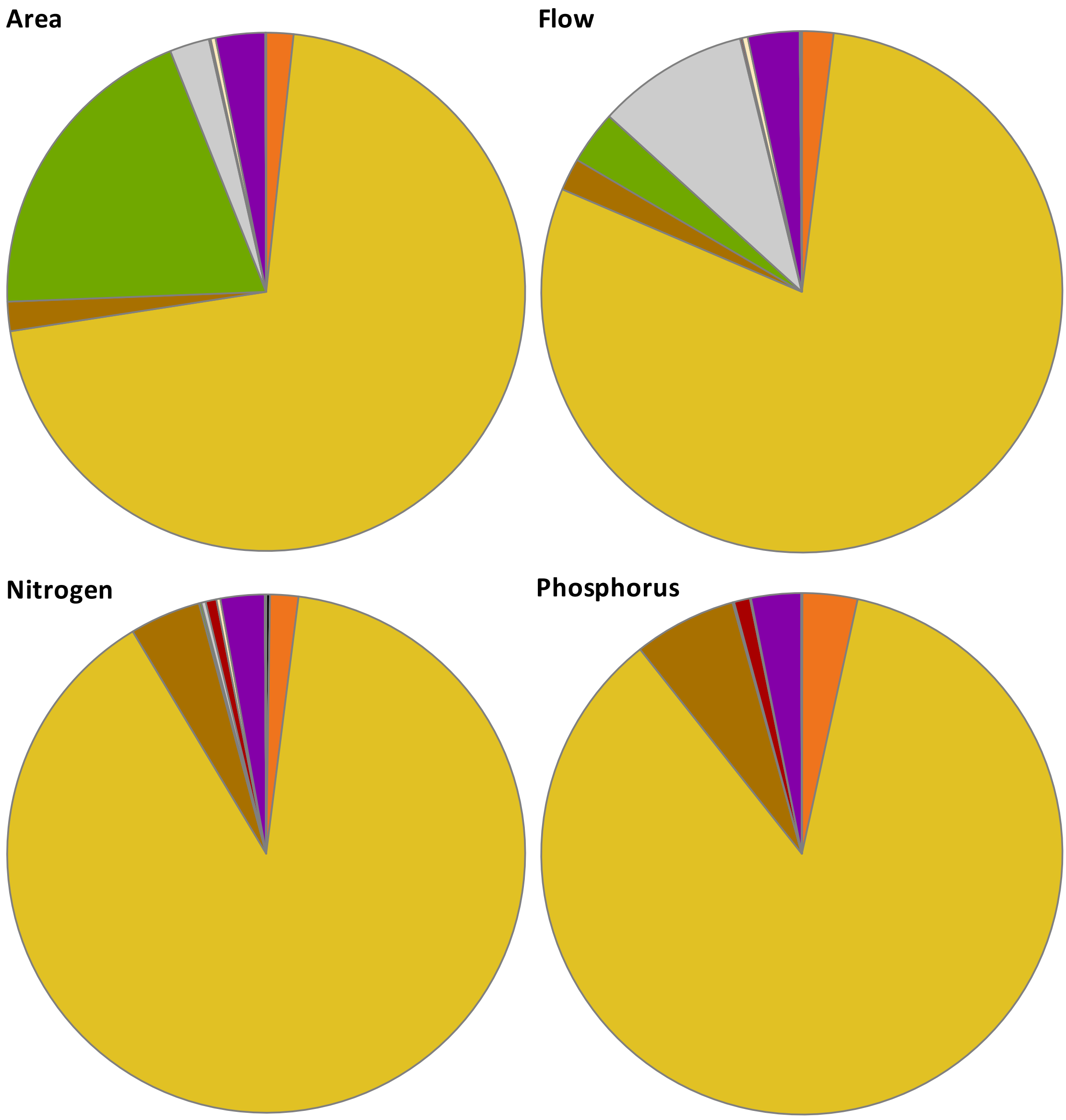


K.8 Land uses of the Coolup (Peel) reporting catchment

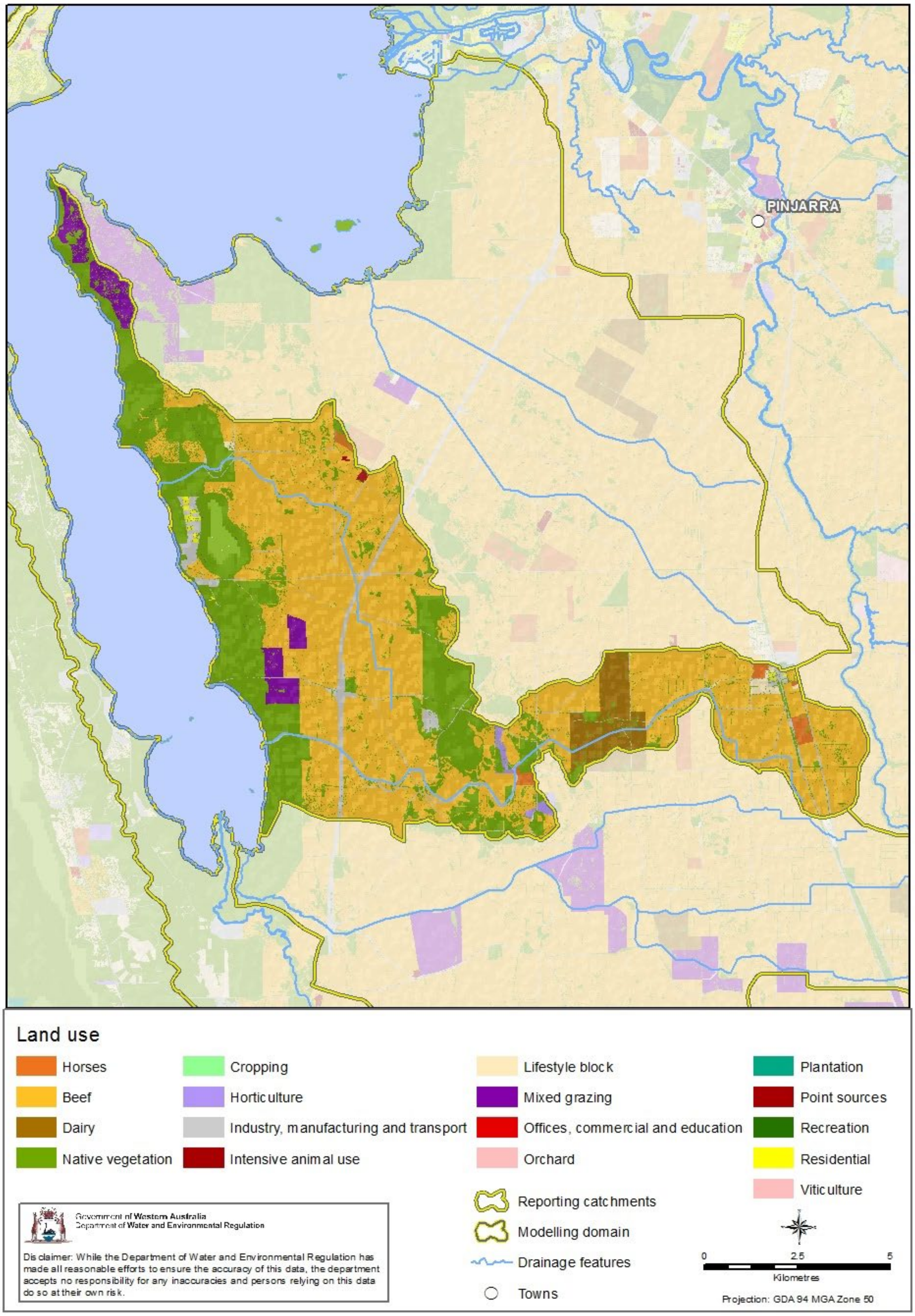


Coolup (Peel) nutrient sources

Land use	Colour	Area (km^2)	Area (%)	Runoff (GL)	Runoff (%)	Nitrogen (tonnes)	Nitrogen (%)	Phosphorus (tonnes)	Phosphorus (%)
Septic (#)		99.0	-	0.0	0.0	0.0	0.2	0.00	0.0
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		2.5	1.7	0.2	2.0	0.4	1.8	0.09	3.4
Beef		106.4	70.9	7.6	79.5	18.8	89.4	2.36	85.9
Dairy		2.7	1.8	0.2	2.0	0.9	4.4	0.17	6.4
Native vegetation		29.4	19.6	0.3	3.3	0.0	0.1	0.00	0.0
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Industry, manufacturing & transport		3.7	2.5	0.9	9.4	0.1	0.3	0.00	0.1
Intensive animal use		0.2	0.1	0.0	0.1	0.1	0.7	0.03	1.0
Lifestyle block		0.5	0.3	0.0	0.3	0.1	0.2	0.00	0.1
Mixed grazing		4.6	3.1	0.3	3.2	0.6	2.8	0.08	3.1
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Recreation		0.1	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.0	0.0	0.0	0.1	0.0	0.0	0.00	0.0
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**150.2**		**9.5**		**21.0**		**2.75**	



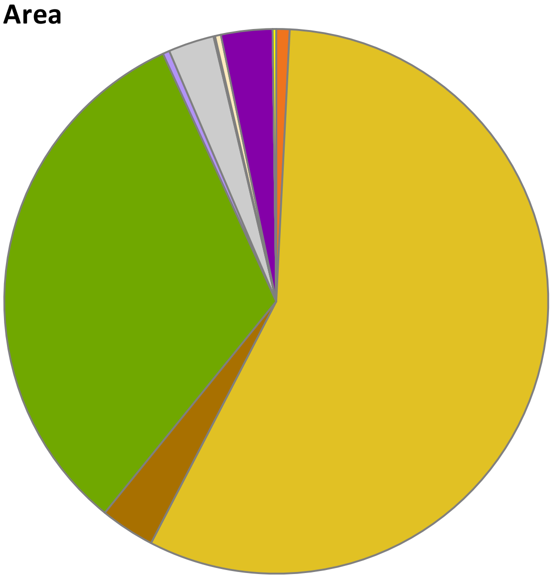
K.9 Land uses of the Coolup (Harvey) reporting catchment



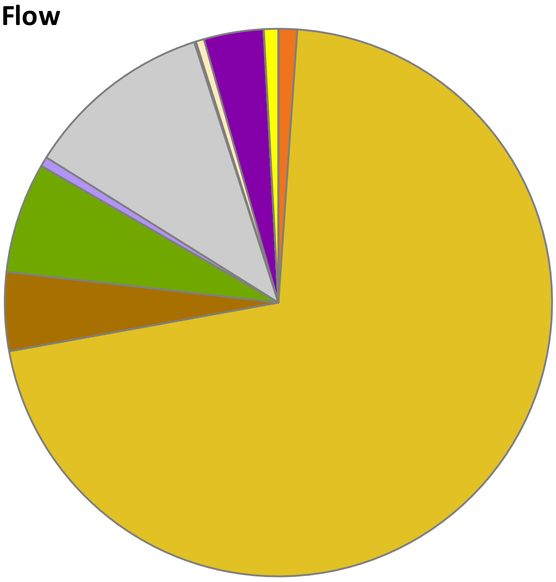
Coolup (Harvey) nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		115.0	-	0.0	0.0	0.1	0.5	0.00	0.1
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		0.8	0.8	0.1	1.1	0.1	1.0	0.02	0.8
Beef		58.8	56.8	4.5	71.0	11.1	83.4	1.68	81.7
Dairy		3.4	3.2	0.3	4.6	1.3	9.4	0.17	8.1
Native vegetation		33.4	32.3	0.4	6.5	0.0	0.3	0.00	0.1
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.4	0.4	0.0	0.6	0.1	0.6	0.09	4.3
Industry, manufacturing & transport		2.8	2.7	0.7	11.1	0.0	0.3	0.00	0.1
Intensive animal use		0.1	0.1	0.0	0.1	0.1	0.4	0.02	1.1
Lifestyle block		0.4	0.3	0.0	0.5	0.0	0.4	0.00	0.1
Mixed grazing		3.2	3.1	0.2	3.5	0.4	3.2	0.06	3.0
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Recreation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.2	0.2	0.1	0.9	0.1	0.4	0.02	0.7
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**103.4**		**6.3**		**13.3**		**2.05**	

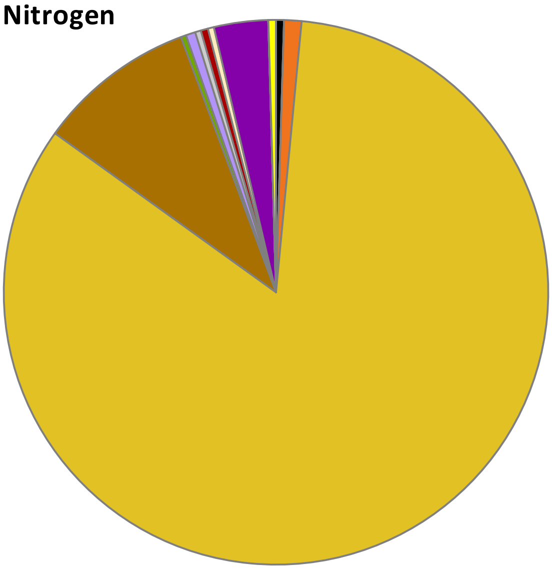
Area



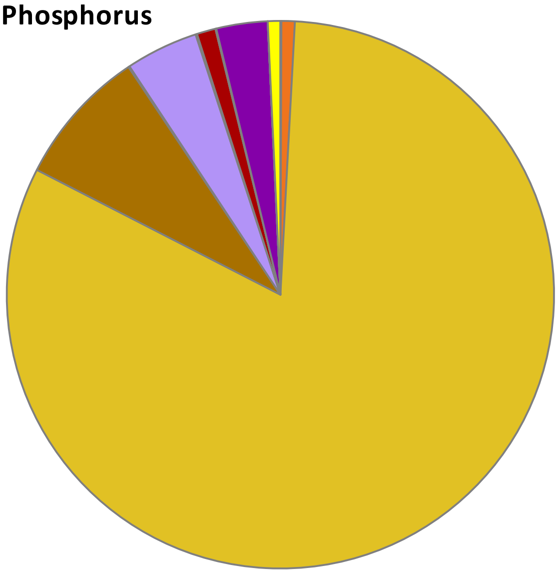
Flow



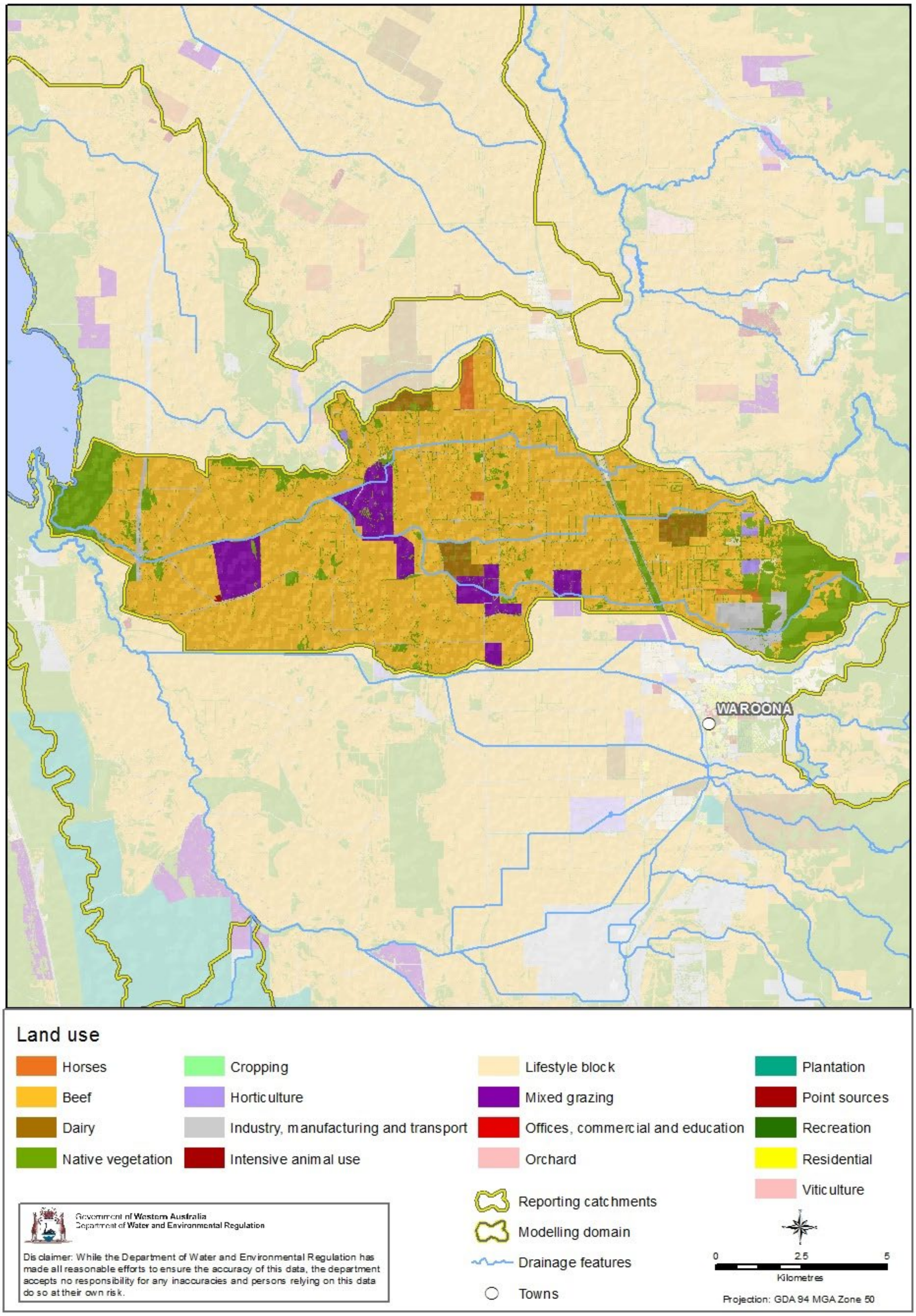
Nitrogen



Phosphorus



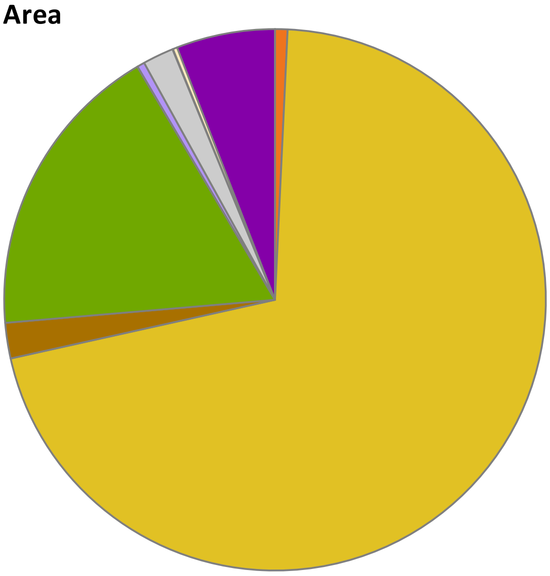
K.10 Land uses of the Mayfield Drain reporting catchment



Mayfield Drain nutrient sources

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km²)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		63.0	-	0.0	0.0	0.0	0.1	0.01	0.4
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		0.9	0.7	0.1	0.9	0.2	0.7	0.06	1.6
Beef		86.4	70.8	12.1	80.9	29.3	88.0	3.09	85.3
Dairy		2.6	2.1	0.4	2.4	1.5	4.4	0.21	5.8
Native vegetation		21.8	17.9	0.6	4.1	0.1	0.2	0.00	0.0
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.5	0.4	0.1	0.5	0.0	0.1	0.09	2.4
Industry, manufacturing & transport		2.3	1.9	0.6	4.1	0.1	0.2	0.00	0.1
Intensive animal use		0.0	0.0	0.0	0.0	0.1	0.2	0.00	0.0
Lifestyle block		0.3	0.3	0.0	0.3	0.1	0.2	0.00	0.0
Mixed grazing		7.2	5.9	1.0	6.8	1.9	5.8	0.16	4.4
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Recreation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Viticulture		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Total		**122.1**		**15.0**		**33.3**		**3.62**	

Area



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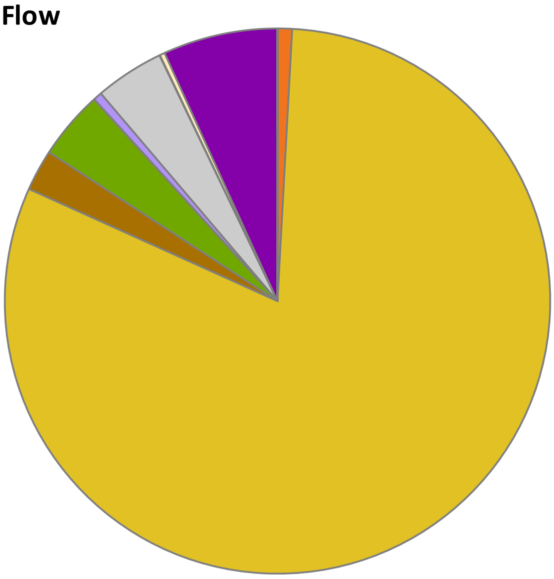
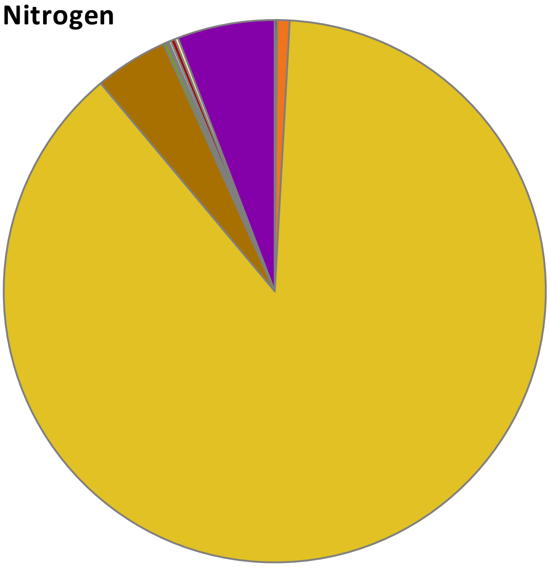
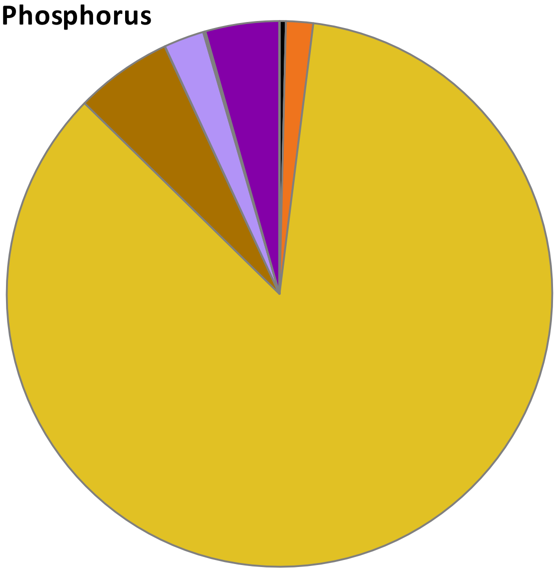


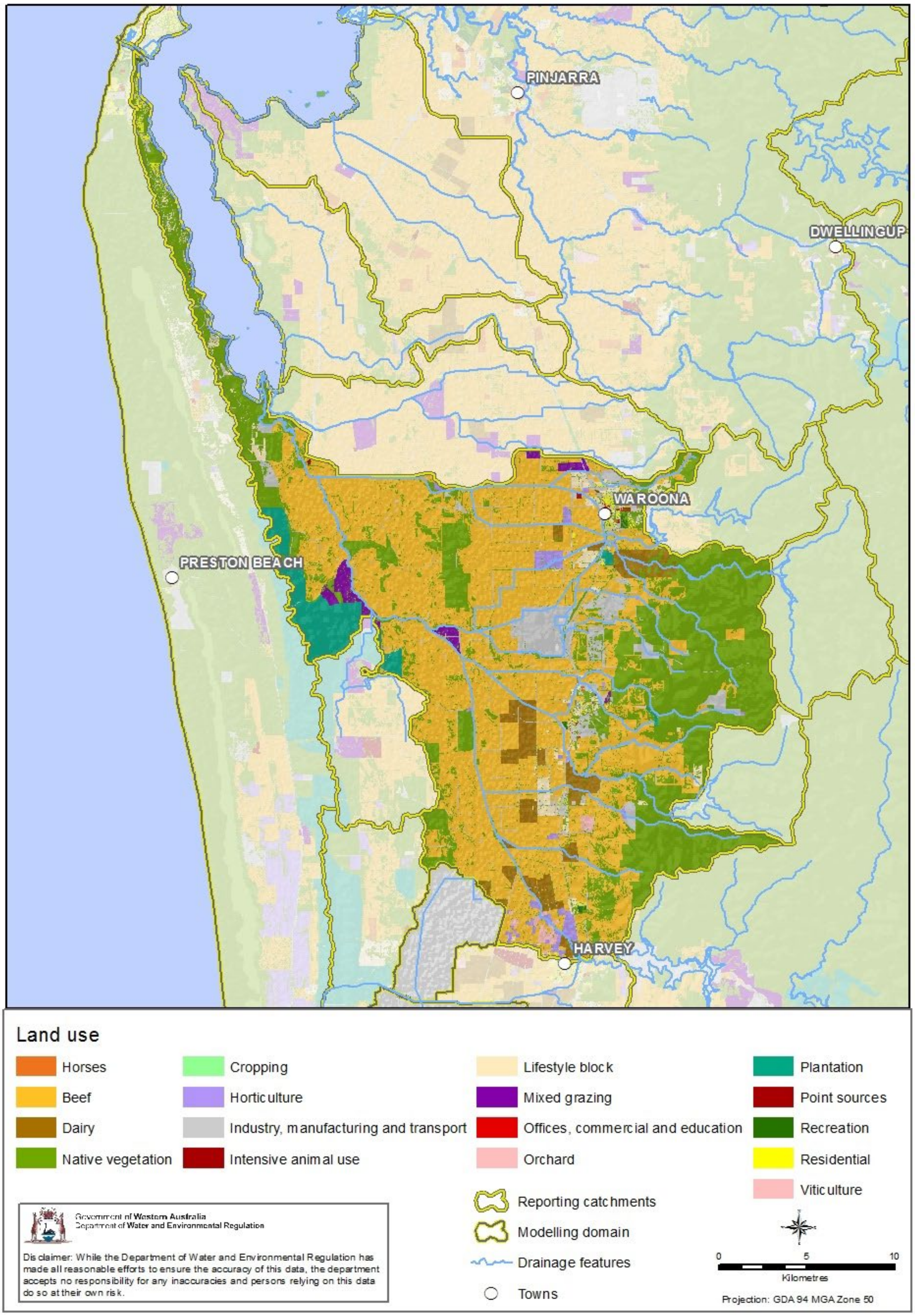
Nitrogen



Phosphorus



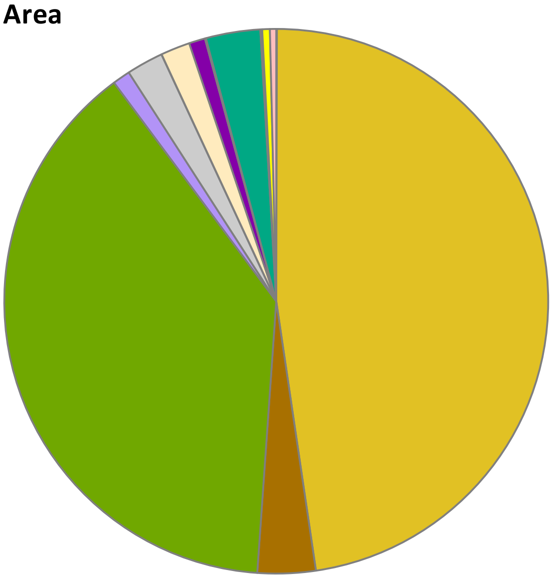
K.11 Land uses of the Harvey reporting catchment



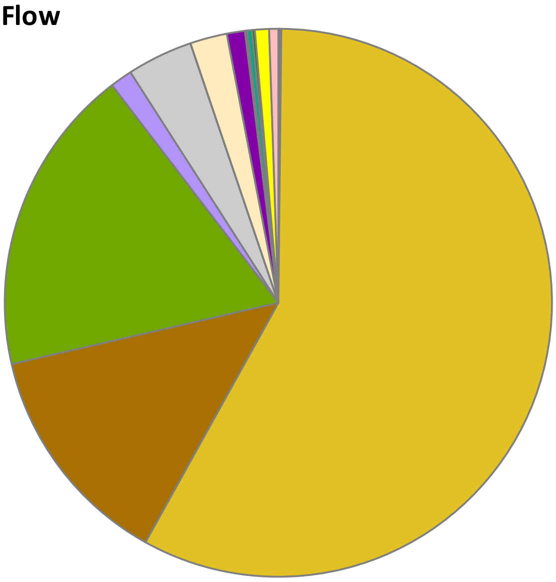
Harvey nutrient sources

Land use	Colour	Area (km^2)	Area (%)	Runoff (GL)	Runoff (%)	Nitrogen (tonnes)	Nitrogen (%)	Phosphorus (tonnes)	Phosphorus (%)
Septic (#)		2229.0	-	0.0	0.0	2.0	1.0	0.59	2.9
Point sources		0.1	0.0	0.1	0.1	2.8	1.3	0.14	0.7
Horses		0.1	0.0	0.0	0.0	0.1	0.0	0.01	0.1
Beef		263.4	47.6	50.5	57.9	159.3	77.6	15.12	75.2
Dairy		19.1	3.4	11.6	13.3	27.8	13.5	2.62	13.1
Native vegetation		214.1	38.7	15.9	18.2	3.0	1.5	0.05	0.3
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		5.8	1.0	1.1	1.3	1.2	0.6	0.78	3.9
Industry, manufacturing & transport		12.1	2.2	3.4	3.9	0.5	0.2	0.01	0.1
Intensive animal use		0.1	0.0	0.0	0.0	0.2	0.1	0.03	0.1
Lifestyle block		9.6	1.7	1.9	2.2	3.3	1.6	0.07	0.4
Mixed grazing		5.3	1.0	0.9	1.1	2.2	1.1	0.22	1.1
Offices, commercial & education		0.3	0.1	0.1	0.1	0.3	0.1	0.02	0.1
Plantation		17.8	3.2	0.3	0.3	0.2	0.1	0.23	1.2
Recreation		0.6	0.1	0.1	0.2	0.3	0.2	0.01	0.0
Residential		2.5	0.5	0.7	0.8	1.2	0.6	0.12	0.6
Viticulture		2.1	0.4	0.5	0.5	0.9	0.5	0.07	0.3
Total		**553.0**		**87.2**		**205.5**		**20.11**	

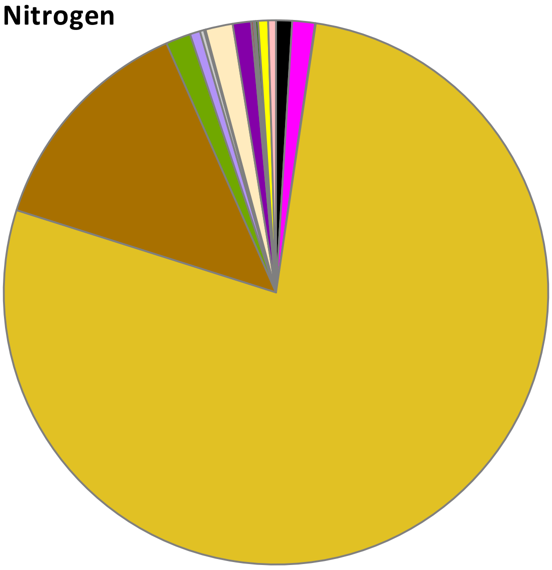
Area



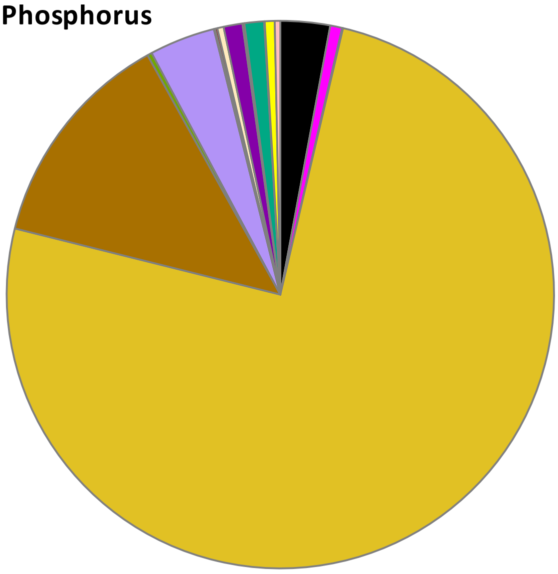
Flow



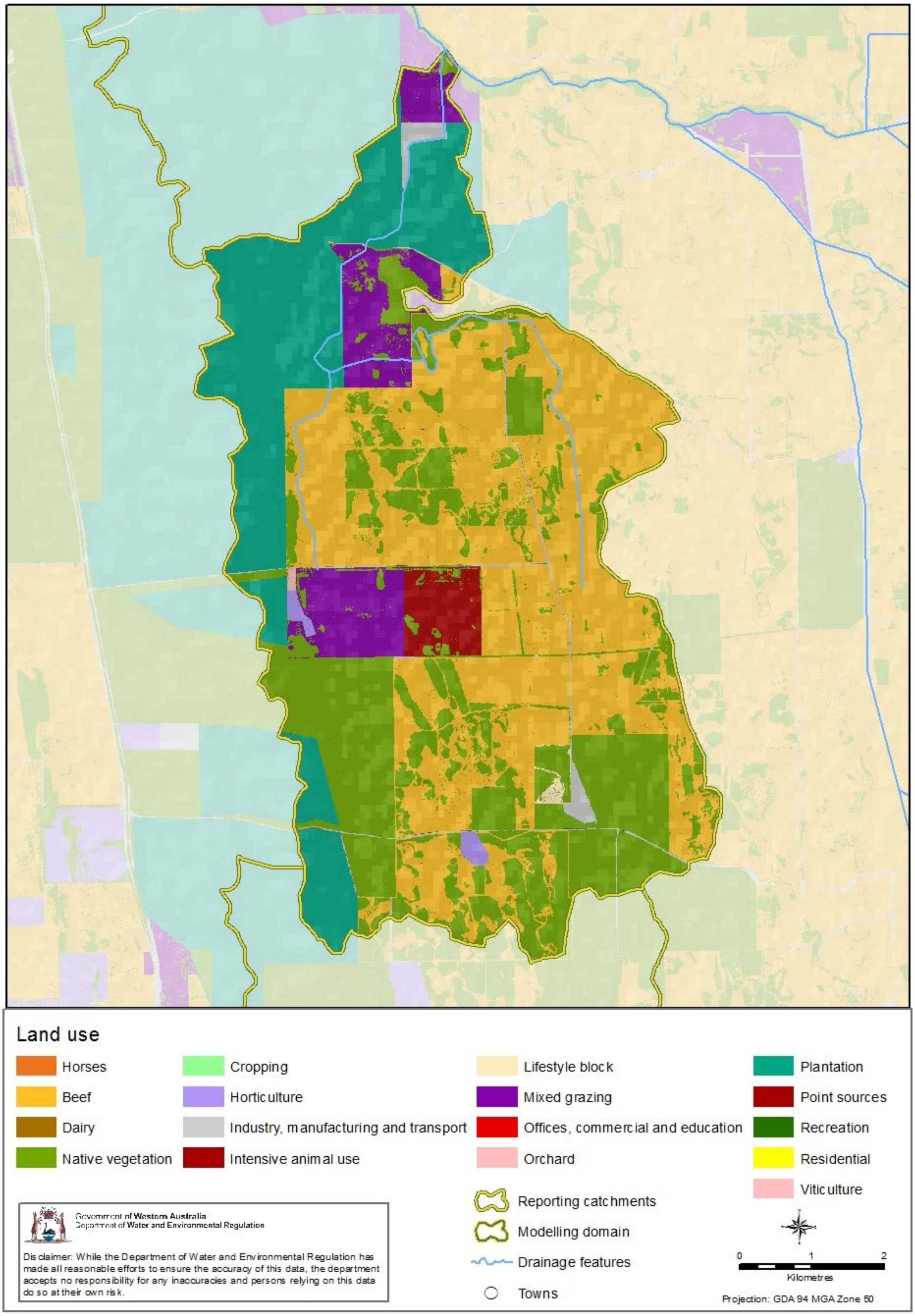
Nitrogen



Phosphorus

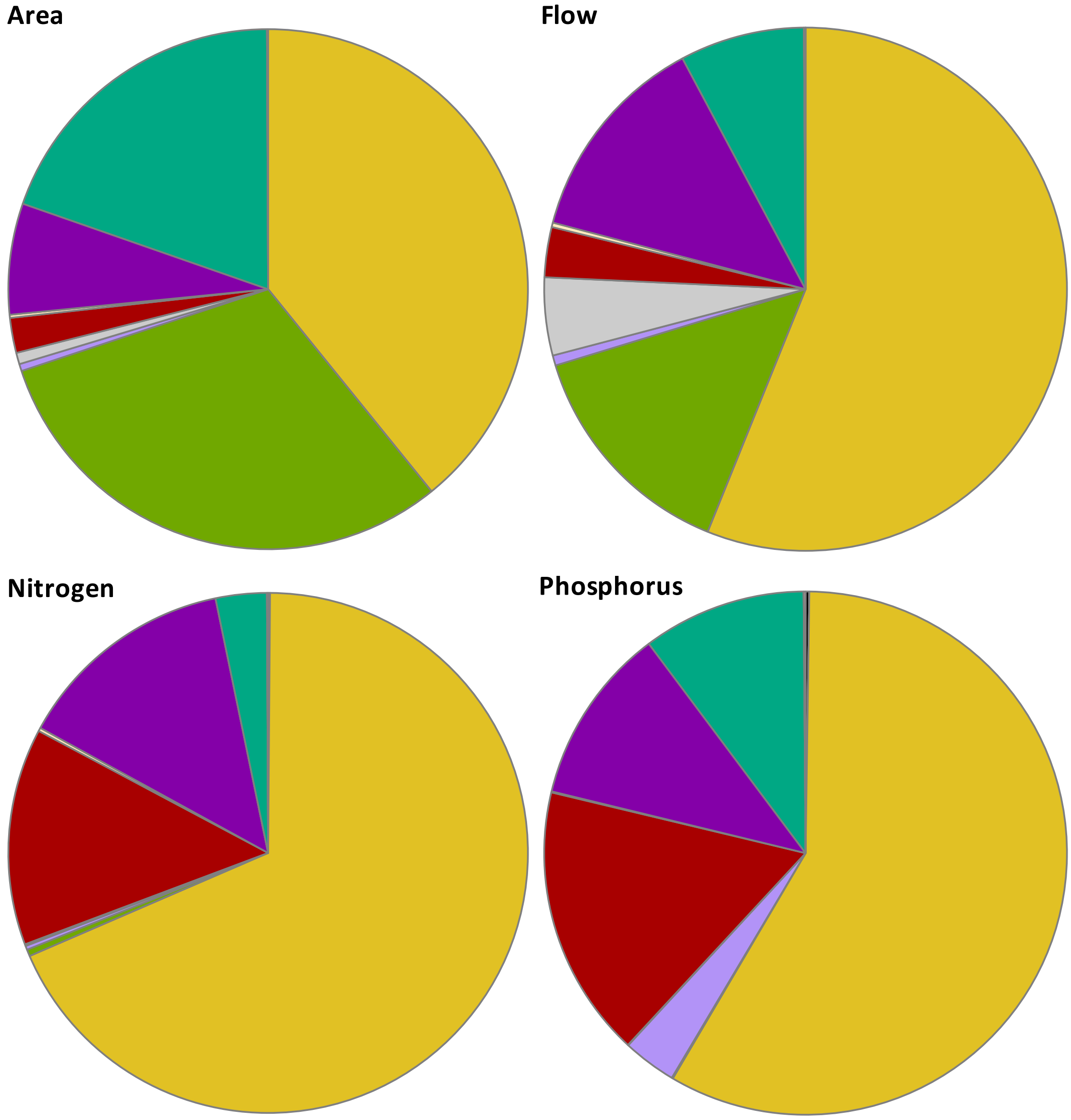


K.12 Land uses of the Meredith Drain reporting catchment



Meredith Drain nutrient sources

Land use	Colour	Area (km²)	Area (%)	Runoff (GL)	Runoff (%)	Nitrogen (tonnes)	Nitrogen (%)	Phosphorus (tonnes)	Phosphorus (%)
Septic (#)		12.0	-	0.0	0.0	0.0	0.1	0.00	0.2
Point sources		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horses		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Beef		20.8	39.2	1.3	56.1	4.6	68.4	0.61	58.3
Dairy		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Native vegetation		16.3	30.7	0.3	14.2	0.0	0.4	0.00	0.1
Cropping		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Horticulture		0.2	0.4	0.0	0.6	0.0	0.2	0.03	3.3
Industry, manufacturing & transport		0.4	0.7	0.1	4.8	0.0	0.1	0.00	0.0
Intensive animal use		1.2	2.2	0.1	3.1	0.9	13.5	0.18	16.8
Lifestyle block		0.1	0.2	0.0	0.3	0.0	0.2	0.00	0.1
Mixed grazing		3.7	6.9	0.3	13.1	0.9	13.8	0.11	11.0
Offices, commercial & education		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Plantation		10.4	19.6	0.2	7.7	0.2	3.2	0.11	10.1
Recreation		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Residential		0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.0
Viticulture		0.0	0.1	0.0	0.1	0.0	0.1	0.00	0.1
Total		**53.1**		**2.3**		**6.7**		**1.04**	



Appendix L: Further information on the catchment management actions

L.1 Optimal fertiliser use in beef and dairy grazing

Effective fertiliser management involves knowing when, where and how to apply appropriate fertilisers at the right rate to supply optimal nutrients to maintain production, reduce fertiliser expenses, and minimise nutrient loss and off-site environmental effects. Best practice fertiliser management should apply the 'four Rs' to reduce fertiliser wastage and nutrient export:

- **R**ight source – matches fertiliser type to crop needs
- **R**ight rate – matches amount of fertiliser type to crop needs
- **R**ight time – makes nutrients available when crops need them
- **R**ight place – keeps nutrients where crops can use them.

Through REI, Healthy Estuaries WA, Revitalising Geographe Waterways programs, the State Government has developed the *Nutrient best management practice guidelines for beef, sheep and dairy enterprises in south-west Western Australia* (Government of Western Australia 2022b). These provide practical and locally relevant guidance for farmers. The guidelines were developed with input from local farmers, fertiliser and grazing industry bodies, scientists, agronomists and catchment groups.

Active monitoring and interpretation of the current nutrient conditions on farmlands is crucial to effectively managing fertiliser applications and minimising nutrient export to our waterways and groundwater.

What is a Phosphorus (P) fertility index?

The P fertility index is used to indicate whether soil plant-available phosphorus (P) content is above or below the agronomic optimum for a given pasture productivity target:

- A farm paddock with a P fertility index = 1 has the optimum amount of plant-available P for a given pasture productivity (e.g. 85 per cent of maximum) and does not require P fertiliser.
- A farm paddock with a P fertility index < 1 means that a paddock is deficient in plant-available soil P and requires fertiliser to maintain the pasture productivity target.
- A farm paddock with a P fertility index = 2 means that a paddock has double the amount of plant-available soil phosphorus required for target pasture productivity. In this case, where P is present in excess, applying additional P will not grow more pasture, but will increase the risk of P leaching to the environment.

Nitrogen (N) and P applications are only effective if there are no other limitations or deficiencies in the soil profile. In some cases, P fertiliser is applied on farms in excess with the aim of boosting pasture production. However, other nutrients such as potassium and sulfur may, in fact, be deficient and limit pasture productivity.

The optimal use of fertiliser based on soil and tissue test results can increase profitability and significantly reduce nutrient loss. Recommended fertiliser rates based on soil and plant tissue results are often much lower than a farmer would normally apply. Most beef and dairy farms in the plan area have P fertility indexes around 2 (Whole Farm Nutrient Mapping by DPIRD 2009–20 data, as summarised in Hennig et al. 2021), which far exceeds what is required for productive pasture growth. As the fertility index increases, the additional pasture yield resulting from fertiliser applications declines (Figure L.1).

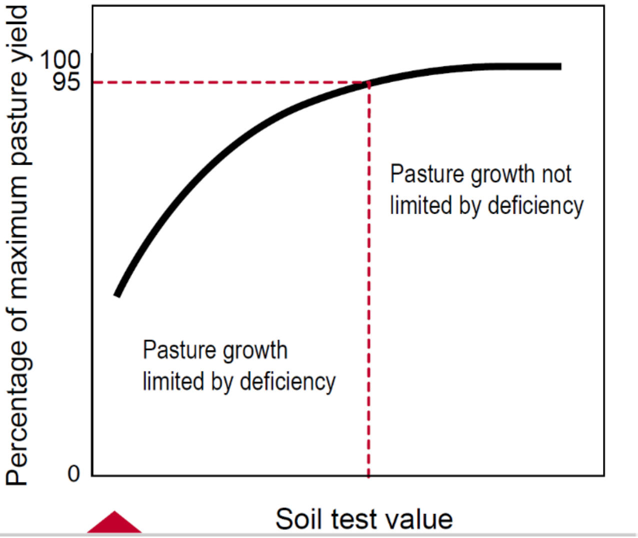


Figure L.1 A generalised calibration relationship between relative pasture production and soil test value

The earlier programs such as DPIRD's whole farm nutrient mapping were very effective in providing soil testing and information about deficiencies and surpluses. However, the percentage of farmers that then transitioned to optimal fertiliser application based on soil and plant tissue testing results was low. Working directly with farmers in workshops to review the farm maps and identify fertiliser needs combined with one-on-one advice through Fertcare® accredited agronomists has substantially accelerated the adoption of improved fertiliser regimes.

Soil testing and agronomic advice related to the best fertiliser regime for the desired productivity has been shown to be more effective and popular when undertaken in a collaborative partnership with State Government agencies, farmers, industry, fertiliser companies and catchment groups. The addition of demonstration trials has further strengthened this whole-of-industry, whole-of-catchment approach.

To move towards this becoming standard practice for beef and dairy farmers in the Peel-Harvey estuary coastal plain catchment, we need to consider why some farmers resist change to optimal fertiliser use based on soil testing. Some landowners:

- apply fertiliser at rates that have always been applied on their properties over multiple generations and may not consider soil-testing a priority
- view P application as 'cheap insurance' – that is, they deliberately over-apply to maximise yields and minimise the potential to buy feed over the summer/autumn months, as the cost of fertiliser is much lower than the cost of feed
- continue to apply the same amount of fertiliser each year believing that most P is leached from the sandy soils and needs to be replaced each year
- do not have confidence in the soil-test recommendations because of a lack of trust in the quality and relevance of the recommendations and/or of government programs
- who are participating in soil-testing programs, choose to apply 'a little extra' above the recommended rates, with the belief they will achieve target yields.

Demonstration trials under the uPtake project co-funded by the Australian Government's National Landcare Program and REI/ Healthy Estuaries WA have been effective in demonstrating pasture growth with the recommended fertiliser mix based on the national nutrient use efficiency guidelines, compared with traditional application rates and other treatments.[13] The fertiliser manufacturers and agronomists have co-delivered the trials and will themselves be modifying their advice to farmers. All parties to the trials have benefited from new learnings and testing of assumptions.

L.2 Slow-release phosphorus fertilisers

Single superphosphate is the main P fertiliser used by grazing farms in Western Australia. Eighty-six per cent of single superphosphate is water-soluble, which is the form most likely to leach in soils with low P retention (Maddern 2012). When these fertilisers are applied to sandy, acidic, low phosphorus retaining index (PRI) soils such as much of the Swan coastal plain, much of the P is lost through the soil profile. The agricultural use of highly water-soluble P fertilisers has long been identified as an environmental issue. Even as far back as 1918, a farmer raised concerns about the use of highly soluble fertilisers and P leaching to rivers in the Peel-Harvey catchment (Bradby 1997).

By altering the constituents of the fertiliser, it is possible to reduce the rate at which P leaches, thereby increasing the likelihood that P will be accessed by the plant (Maddern 2012). A variety of slow-release P fertilisers (also sometimes referred to as low water-soluble P fertilisers) have been trialled locally since the 1980s. The water solubility of these fertilisers is typically 0–40 per cent; however, some newer fertilisers may have a water solubility of about 50 per cent. Pasture yield studies have demonstrated that slow-release P fertilisers generally result in similar pasture yields as those from single superphosphate when used on sandy acidic soils (Hennig et al.

[13] See uPtake trials summary 2019-2023.

2021). However, the application of low water-soluble P fertilisers at rates far more than plant requirements has been demonstrated to cause P leaching equivalent to that from single superphosphate. Thus, low water-soluble P fertilisers will only result in a decrease in P export if paired with optimal fertiliser use, based on accurate soil and tissue testing.

Slow-release P fertilisers are not generally recommended to be used on heavier soils such as loamy and clay soils as these soils generally have a large capacity to store soluble P. Optimal fertiliser management alone is recommended to reduce P export in these heavier soils (Hennig et al. 2021).

See Appendix F in Hennig et al. (2021) for a more comprehensive review of the relevant literature on the use of slow-release P fertilisers (referred to there as low water soluble P fertilisers).

L.3 Soil amendment

Natural clay and loam soils hold P which limits the loss of P from these soils. The coastal plain of the Peel-Harvey estuary catchment is low in natural clay and loams and instead has sandy soils with little to no capacity to hold P. However, combined with good fertiliser management, the addition of soil amendments can significantly reduce P export from these sandy soils to waterways.

Soil amendment involves adding an agent to the soil that increases the capacity of the soil to hold P. This allows more P to be retained in the productive topsoil zone and available for plant growth, instead of being lost to waterways and groundwater. The use of some soil amendments can improve retention of organic N in soils with the benefit of reducing offsite N export (Degens et al. 2022).

Investigations and use of soil amendments for nutrient management in Western Australia have focused on the use of inexpensive, bulk mining by-products, such as Red Sands™, Alkaloam® and IronMan Gypsum (IMG) (a titanium mining by-product made by Iluka Resources Ltd). Other options of using local on-site clays (i.e. mixing subsoil clays with sandy topsoils) and bentonite to improve sandy soil P binding capacity have also been investigated (Summers et al. 2020, Degens et al. 2022).

Early experimental work with areas in the Meredith Drain catchment amended with bauxite residue (Alkaloam) at rates of 20 t/ha showed the potential of soil amendments to reduce P runoff from this catchment by up to 70 per cent (Waterways Commission et al. 1994, Summers 2004). Despite early promising results in laboratory and field trials, the product was withdrawn for use by Alcoa in 2002 because of public concerns about potential environmental toxicity and livestock health.

Trials with other soil amendments have continued, with alternatives also shown to be very effective at reducing the loss of P from runoff and leaching (Chem Centre 2018, Summers et al. 2020). P export from paddocks treated with IMG has been shown to reduce by more than 80 per cent (Wendling et al. 2009a, Douglas et al. 2010, Wendling et al. 2010, Chem Centre 2018), and more than 60 per cent with clays produced by mineral sand mining (Summers et al. 2020). These studies showed reductions in phosphate and total phosphorus concentrations in either leachate or runoff by increasing the PRI of soils.

IMG has also been successfully used in urban drainage applications. Blending IMG with sand fill (at a rate of 10 per cent) can reduce phosphate export from shallow groundwater to subsurface drains by more than 90 per cent (Degens and Shackleton 2016), with ongoing monitoring showing the effect is sustained for more than eight years (pers. communication, B. Degens 2022).

Extensive characterisation, laboratory and field trials suggest IMG is the most promising soil amendment currently available for use on the Swan coastal plain. The material has one of the highest P retention properties of tested soil amendments (Wendling et al. 2009b, Chem Centre 2018). The results of recent trials of IMG on dairy and beef grazing farms have shown reductions in P loss ranging from 87 to 99 per cent when applied at 20 t/ha (Degens et al. 2022, Degens et al. (in press)). Guidance on use, based on these and other trials and accompanying risk assessments, are provided in Degens and Lam (2019). Laboratory testing found that IMG had low environmental toxicity and radioactivity (Wendling et al. 2009a, Douglas et al. 2012). IMG is available for purchase and use on agricultural properties and urban public open space. Since it is a gypsum amendment with some neutralising capacity, it may also reduce soil acidity.

Claying of soils to improve moisture and fertiliser retention in sandy agricultural soils is a practice used elsewhere in Western Australia but is uncommon on the Swan coastal plain. One potential source of suitable clays is from the overburden stripped during mineral sand mining operations but many farms on the Pinjarra Plain (closer to the Darling Scarp) have clayey subsoils beneath sand topsoils. Studies have demonstrated that the naturally occurring clays found at the MZI Resources mineral sands mine at Keysbrook can be reworked into the surface sands during the rehabilitation of mine sites (Summers et al. 2020). This practice greatly improves the nutrient retention capacity and productivity of the soils. Clay from this resource, however, is unlikely to be available for widespread use in agriculture as it is required for site rehabilitation and the area to be mined for mineral sands is less than previously estimated.

Claying of soils elsewhere in Western Australia (particularly the south coast and northern Wheatbelt) involves localised mining of shallow, clay subsoils on farms and spreading this on paddocks (Davenport et al. 2011). The practice generally requires suitably high PRI clays to be present near the surface of the soil profile and would be impractical for deep sands.

Current constraints around the use of soil amendments include:

- feasibility of product use: transport and spreading costs of soil amendments can be high, as large quantities are generally required
- uncertainties around the progression towards environmental regulation of waste-derived materials (see text box ‘Environmental regulation of waste-

derived materials' in Section 9.1 of the main document under 'Soil amendment')

- the need for further assessments to manage risks and provide additional information from large-scale trials to support the regulatory approval process.

For some soil amendments, such as IMG, although they have been shown to be effective at reducing P export, more scientific trials are required to:

- further investigate optimal application rates and methods of application relative to the soil P status including how to target problem areas within farms
- trial strategies for targeting and prescribing application rates for P problem areas on farms, linking this with soil testing programs.
- assess the longevity of benefits to water quality, soils and agricultural productivity
- define materials handling protocols for use on farms including avoiding dust generation.

L.4 Riparian zone management (stock exclusion and revegetating riparian zones)

In Western Australia, riparian zone management generally refers to the fencing of waterways to prevent stock access, along with revegetation of the riparian zone, preferably with native, endemic species. Where appropriate, this includes the construction of stock/vehicle crossings and/or the provision of off-stream stock watering points.

Riparian management can also include river restoration techniques such as introducing woody debris or riffles to improve aquatic habitat and support greater biodiversity. Riffles are used to increase the upstream standing water depth for habitat and to aerate water as it flows over the riffle. In the plan area, these activities have traditionally been done by NRM groups, such as the Peel-Harvey Catchment Council (PHCC) and the Harvey River Restoration Taskforce (HRRT).

Nutrient-rich waste from horses and cattle

Horses and cattle produce large amounts of waste (dung and urine). For example, a standard light horse (450 kg) produces approximately 5.5 t of dung and 5.5 kL of urine each year which contains 62 kg of N and 5.5 kg of P (Water and Rivers Commission et al. 2002), while cattle in feedlots produce 20–30 kg of N per year and more than 6 kg of P per year (DoW 2009a).

If a farmer has 250 cattle, then that is equivalent to 5–7.5 t of N and 1.5 t of P being produced every year. By excluding stock from waterways and drains and thereby minimising the amount of organic matter and nutrients directly entering the estuary system, each grazing farm can make an important difference to the nutrient loads reaching the estuary.

The primary purpose of stock exclusion by fencing is to reduce or eliminate direct deposition of dung and urine (organic matter and nutrients) from entering the waterways/drains. It also minimises bed and bank erosion and pugging of the soil from animal movement. The fenced off area no longer has fertiliser applied which also contributes to a reduction in nutrient export from the land to the waterways/drains.

Revegetating the riparian zone (also referred to as the foreshore area) helps to stabilise the banks and slow the surface runoff, thereby reducing soil erosion. The vegetation also supports greater biodiversity and ecological health by providing aquatic/terrestrial habitat and refuge, food and shelter, and wildlife corridors that help to link our fragmented natural landscapes. The promotion of denitrification of groundwater nitrate is also known to occur in healthy riparian zones. In addition, the shade provided by riparian vegetation helps to reduce light and heat reaching the waterway and this helps to reduce the production of excessive algal growth (Lovett et al. 2007).

Vegetated banks of a waterway have a secondary role in intercepting overland flow of sediment-bound nutrients, contaminants and organic matter, even in the predominantly flat landscapes of the estuary coastal plain catchment. This aids in maintaining water clarity (Hall 2019).

A literature review by Hall (2019) found that healthy riparian zones are an effective tool for nutrient removal in Western Australia coastal catchment waterways and drains. When runoff passes through a healthy riparian zone, nutrients can be reduced through plant uptake, trapping of particulate P and soil adsorption. Riparian zones are most effective at reducing the P entering waterways in escarpment catchments compared with those on the Swan coastal plain. This is because there is limited sediment-bound P entering the drainage system from the sandy catchments of the Swan coastal plain – here much of the P is lost to the waterways/drains in soluble form. There are still likely to be P load reductions when riparian zones are rehabilitated on the Swan coastal plain, but benefits are mostly attributed to stock exclusion and a reduced area being fertilised on farms. However, the conditions on the Swan coastal plain are ideal for N removal. Vegetated riparian zones have high soil carbon content, which promotes microbial denitrification of nitrates. Plant uptake of N (nitrate and ammonia) is also larger than for P (Hall 2019).

Protecting the riparian zone maintains or improves the physical condition and ecological health of waterways, allowing for restoration of degraded waterways. Identifying the width of the area to protect along the waterway should be guided by the *River restoration report 16: Determining foreshore reserves* (Water and Rivers Commission 2001a), *Water note 23: Determining foreshore reserves* (Water and Rivers Commission 2001b) and *Water note 10: Protecting riparian vegetation* (Water and Rivers Commission 2000). On small farm waterways, the minimum riparian width that should be fenced and revegetated is 10 m from bank full but preferably 20 m or greater, as appropriate. Traditionally 1st, 2nd and 3rd order streams are targeted for riparian zone management; however, these streams often criss-cross through paddocks in farms on the Peel-Harvey coastal plain, making fencing unfeasible. Therefore, in the Peel-Harvey estuary coastal plain catchment it is more practical to focus on fencing higher order waterways and drains.

Rates of riparian zone management are largely dependent on the level of funding available, the priorities of NRM groups and the capacity for groups to implement rehabilitation. The fencing is usually implemented by the landholders and partially or fully funded by the government or private industry. Fencing can also be implemented by landcare and catchment groups when undertaking rehabilitation works on behalf of the land holder.

NRM groups funded to support landowners to exclude stock and revegetate rural waterways should work closely with each landowner to understand their personal objectives for their property and any concerns they may have about project implementation. Discussions should be balanced with information about the multiple benefits of restoring waterways on farms. Healthy Estuaries WA has published a factsheet which is ideal to engage with landowners – *Why should we fence and revegetate our waterways?* (DWER 2023b) – which summarises the multiple benefits of restoring waterways on grazing farms, including specific benefits to the farmer and their stock, the community and the environment.

Generally, after about two to three years of effective weed management along a fenced and revegetated waterway, the need to manage weeds diminishes as the native vegetation establishes. The native, lower-storey ground cover and shrubs spread and outcompete the weeds, while larger shrubs and trees will increasingly shade out and prevent weeds from germinating. Well-managed, riparian vegetation can help to slow the spread of fire across farms because of the higher moisture content and the creation of a windbreak by the mid and upper storey (Country Fire Authority 2017).

The mapping of waterways by Hennig et al. (2021) did not include small drains at the paddock scale (i.e. paddock drains, scoop drains). Therefore, in the planning stages of implementation of this action, NRM groups, in consultation with landholders, may need to finely map the waterways/drains where implementation is to be focused. Such investigations should accurately record land tenure and accessibility.

L.5 Use of constructed wetlands

Constructed wetlands are artificial, engineered water treatment systems. They are designed specifically to improve water quality by maximising physical, chemical and biological nutrient removal processes.

Constructed wetlands can be effective at removing N (as ammonia or nitrate) through biological removal and remineralisation, where the wetland is designed and constructed with that purpose. To also remove P, the wetland must incorporate P-sorbing materials that are replenished once saturated with P.

The capacity for constructed wetlands to act as biological nutrient filters is not infinite; maintenance of the wetland is crucial for ongoing nutrient reduction. Constructed wetlands need to be appropriately designed and regularly maintained to ensure that they do not become a nutrient source themselves. Their effectiveness relies partially on the maintenance of the wetland and its buffer vegetation.

In Western Australia, constructed wetlands have mostly been used to capture and treat urban stormwater and wastewater before environmental discharge. However, the Ellen Brook wetland constructed in 2010 was designed to treat agricultural drainage water that had high P concentrations. It was designed in two parts: a soil amendment (IMG) infiltration basin to remove P and a constructed wetland downstream to remove N and to create wetland habitat. There have been ongoing technical problems with clogging of the infiltration medium and breakthrough of P through preferential pathways. To date, there is insufficient evidence from this ongoing trial to support similar approaches in the Peel-Harvey estuary coastal plain catchment.

A fundamental challenge when designing constructed wetlands to treat diffuse runoff is ensuring adequate residence time during high flows in winter, when ground water discharges into drains and P concentrations are often at their highest.

Industry should consider the use of constructed wetlands to reduce nutrient concentrations in runoff from intensive, diffuse sources – for example, individual, agricultural properties such as free-range chicken farms, outdoor piggeries (free-range, outdoor bred) or properties that have irrigated horticulture requiring high nutrient input (e.g. leafy greens). Diverting runoff using drainage networks into well-maintained, engineered, constructed wetlands could potentially reduce nutrient concentrations discharging to local waterways. If a constructed wetland connects with groundwater though there is potential for nutrients to contaminate the groundwater, so this would need to be carefully considered.

Well designed and maintained constructed wetlands may also have the potential to reduce nutrient concentrations and organic matter in drainage water from beef and dairy farm paddocks, before discharge to local waterways (pers. communication, B. Oversby 2022).

L.6 Natural wetlands

Healthy, natural wetlands have the potential to improve water quality by filtering out pollutants such as organic and inorganic matter, and by trapping sediments and attenuating nutrients. However, the use of natural wetlands to treat agricultural effluent or drainage waters is not recommended or supported by this WQIP. Degraded, natural wetlands have no capacity to treat nutrient-rich agricultural effluent. If effluent from intensive land uses contaminates natural wetlands that do have environmental or social values and are protected, this may constitute an offence under the *Environmental Protection Act 1986.*

The Department of Biodiversity, Conservation and Attractions (DBCA) and Department of Water and Environmental Regulation are working together and with the Department of Planning, Lands and Heritage to revise the mapping of wetlands and waterways and their ecological values for the Swan coastal plain. Multiple spatial datasets are being used to identify wetlands and waterways that have high remaining habitat (water or native vegetation) and/or other values, such as threatened plants, animals, or ecological communities, vegetation types with less than 30 per cent of its extent remaining on the coastal plain, or connections to other bushland areas. The new mapping will indicate wetlands that are priorities for protection during land planning and development, based on their ecological values. It will also identify wetlands where more information is required to assess their conservation value. It is important to note that many wetlands and waterways also have social, cultural, aesthetic and economic values that must also be assessed and considered during planning and development stages around wetlands.

Wetlands that are to be conserved require a vegetated buffer around them to protect their values from the potential impacts of adjacent land uses. Wetland buffers provide habitat for native plants and animals, reduce the risk of erosion and weed invasion, and protect water quality by reducing sediments and nutrients in runoff that enters the wetland. Wetland buffers can also protect the community from potential impacts such as flooding and nuisance insects. DBCA is the lead agency for wetland advice, and is currently working to develop clear guidance on determining wetland buffer requirements, with the current advice recommending a minimum wetland buffer width of 50 m.

A large proportion of the remaining natural wetlands in the Peel-Harvey catchment has been drained. These wetlands have been cleared of vegetation and are substantially degraded. The degree to which a natural wetland can be modified or augmented may be constrained by its conservation status. Generally, though, rehabilitating wetlands has the potential to increase aquatic habitat, retain water for summer agricultural use, filter diffuse runoff, and potentially reduce nutrient and organic (and sediment) loading to drains and streams.

Natural wetlands in the estuary catchment should be rehabilitated or protected from further degradation to ensure the wetland's values (i.e. supporting biodiversity and ecological integrity) are maintained and enhanced for future generations. The State Government's Healthy Wetland Habitats program (2006–22) financially and technically supported landholders to care for wetlands and develop a wetland management plan (fencing to protect existing vegetation, weed management and revegetation to restore cleared or degraded areas are usually key activities). The State Government's future Carbon Farming and Land Restoration program (led by DPIRD) currently funds the implementation of activities such as revegetation on farms that sequester carbon in the landscape and deliver additional, positive outcomes referred to as 'co-benefits' (e.g. biodiversity and conservation).[14]

L.7 Improved management of dairy shed effluent

Dairy farming generates large volumes of nutrient-rich liquid and solid effluent through stock wastes and from wash-down and cleaning of the machinery used in the dairy sheds. This nutrient-rich effluent must be managed appropriately to avoid it washing into waterways and drains, and/or infiltrating into groundwater – both of which result in increased nutrient loading of the estuary. Traditionally, dairies discharged their nutrient-rich wastewater to holding ponds, onto land, or even directly into waterways and drains that flow to the Peel-Harvey estuary.

Best practice management of dairy shed effluent involves carefully considering the collection, conveyance, storage, treatment and reuse of the solid and liquid wastes, plus the efficient use of water, so that nutrient export to the environment is minimised.

Effluent should be regarded as a valuable resource and used appropriately as a fertiliser (e.g. through fertigation which is injection of fertilisers into an irrigation system at a rate to suit pasture and crop needs). By including dairy effluent as part of the whole farm fertiliser program, farming costs can be reduced as the need for commercially sourced fertilisers reduces.

A survey of dairy farms in the Peel-Harvey estuary coastal plain catchment by Lavell et al. (2004) found that:

- 80 per cent of enterprises that produced effluent had management systems which included ponds, tanks, land application and spray irrigation
- the efficacy of management systems varied widely
- one-third of respondents directly discharged effluent to waterways
- one-third of respondents indicated that effluent ponds leaked or overflowed.

Of the 14 dairy farms in the Peel-Harvey estuary coastal plain catchment that were surveyed on their effluent management practices as part of the REI (2016–20), most were not meeting the code of practice at the time – the 2012 Code (Western Dairy 2012) – across five management areas: dairy water efficiency, solid separation, pond (storage), application of effluent, and management maintenance. These results indicated that much work was required to bring the dairy sheds up to standard. As

[14] Western Australian Carbon Farming and Land Restoration Program

part of the REI, six of the dairies upgraded their effluent management systems, with five then meeting the 2012 Code.

Improved dairy effluent management typically requires substantial initial investment, ongoing costs and farmer commitment. However, investments in effluent capture, storage and reuse infrastructure can allow the reuse of effluent and reduce fertiliser use and nutrient losses to the environment.

The *Code of practice for dairy farm effluent management WA* (Western Dairy 2021) updates and replaces the previous Code of Practice (Western Dairy 2012) and clearly sets out updated guidelines relating to the management of dairy effluent to the expected, minimum industry standards for the dairy industry in Western Australia.

Every dairy in the estuary coastal plain catchment should be upgraded to meet the revised Code.[15] By working to meet the standards of the new Code, Western Australian dairy farmers can proactively demonstrate to consumers and the community that their industry is sustainable and responsibly managed to minimise adverse environmental impacts. Through Healthy Estuaries WA, Western Dairy provides extension services to support dairies to work towards the Code, and to understand the potential return on investment of infrastructure upgrades.

In addition to the Code of Practice (2021), there are several highly relevant Water Quality Protection Notes (WQPN) published by the department that provide advice and information on aspects relating to effluent management:

- *WQPN 4 Sensitive Water Resources* (DoW 2016)
- *WQPN 6 Vegetation buffers to sensitive water resources* (DoW 2006)
- *WQPN 22 Irrigation with nutrient-rich wastewater* (DoW 2008c)
- *WQPN 26 Liners for containing pollutants using synthetic membranes* (DoW 2013b)
- *WQPN 27 Liners for containing pollutants using engineered soils* (DoW 2013c)
- *WQPN 33 Nutrient and irrigation management plans* (DoW 2010b)
- W*ater Quality Information Sheet 4 Nutrient and irrigation management plan checklist* (DoW 2010a)
- *WQPN 39 Ponds for stabilising organic matter* (DoW 2009b)
- *WQPN 80 Stockyards* (DoW 2015).

L.8 Improved management of nutrient export from intensive animal uses

Intensive animal industries such as poultry farms, piggeries and abattoirs can also be significant exporters of nutrients and organic matter. It is important that site

[15] As the Code of Practice was revised, dairy sheds that were assessed during REI as meeting the Code of Practice (Western Dairy 2012) may not meet the revised Code of Practice (Western Dairy 2021).

stormwater, stockpiles of nutrient-rich material, and liquid effluent are appropriately managed. Effluent from intensive animal uses may also contain high concentrations of pathogens like *E. coli*, as well as endocrine-disrupting compounds which should not be discharged to groundwater, waterways or the estuary.

The department regulates industrial emissions and discharges to the environment through a works approval and licensing process, under Part V of the *Environmental Protection Act 1986* (EP Act). Industrial premises with potential to cause emissions and discharges to air, land or water are identified as 'prescribed premises' and trigger regulation under the EP Act. Prescribed premises categories are outlined in Schedule 1 of the Environmental Protection Regulations 1987. The EP Act requires a works approval to be obtained before constructing a prescribed industrial premise and makes it an offence to cause an emission or discharge without a licence or registration. Regardless of whether a premise is licensed, wastes should be recycled appropriately, and management actions should prevent wastes reaching waterways and groundwater. Effluent, stormwater and other sources of nutrients from intensive animal industries should be managed to national or international best practice standards.

Environmental guidelines and codes of practice have been developed at the state and national level for intensive animal industries to reduce environmental impacts. However, some standards and guidelines may not sufficiently protect sensitive environments such as the Peel-Harvey estuary. Refer to Appendix M for current environmental guidelines for piggeries, abattoirs, feedlots, poultry farms, intensive horticulture (as listed in Hennig et al. (2021) as well as beef, sheep and dairy farming.

Through implementation of the *Environmental Protection Amendment Act 2020* which significantly reforms the EP Act, the department is reviewing how discharges from point sources of pollution are licensed and will implement an activity-based regime under the new Part V Division 3 of the EP Act (including reviewing and replacing Schedule 1 licensing categories). This will replace the current approach of licensing prescribed premises and provide a stronger mechanism for reducing discharges to sensitive aquatic environments like the Peel-Harvey estuary system.[16]

L.9 Retrofitting of urban areas using Water Sensitive Urban Design

Over the past two decades, reform in urban water management has been achieved in Western Australia through the:

- introduction and implementation of Water Sensitive Urban Design (WSUD) principles in 1994
- release of the *Stormwater management manual* (DoW 2004–07)

[16] For information on the amendments to the EP Act, see Amendments to the Environmental Protection Act 1986.

- release of *Better urban water management* (WAPC 2008), which provides guidance on incorporating WSUD into land development through state planning policies.

Since then, the Cooperative Research Centre for Water Sensitive Cities has undertaken significant research and numerous pilot projects to support the transition of Australian cities and towns to more water sensitive practices. The *Vision and Transition Strategy for a Water Sensitive Greater Perth* (Hammer et al. 2018) (which includes the Peel region) and the *Implementation Plan 2019–2021* (Water Sensitive Transition Network 2019) outline various strategic, coordinated actions to progress Perth (and Peel's) transition to a leading water sensitive city.

The *Waterwise Perth – Two year action plan* (Government of Western Australia 2021) and *Kep Katitjin – Gabi Kaadadjan – Waterwise Perth Action Plan 2* (Government of Western Australia 2022a) align with the recommended actions relating to WSUD in this plan.

The *Peel-Harvey WSUD Local Planning Policy* (Peel Development Commission 2006b) provides a framework for local government which aims to integrate catchment management objectives as set out in the *Water quality improvement plan for the rivers and estuary of the Peel-Harvey system – phosphorus management* (EPA 2008) (referred to as the 2008 WQIP) into local government strategic planning and statutory decision making. The framework was developed to assist the integration of land and water resource planning in urban landscapes, through the implementation of WSUD principles and assessment tools. The *Peel-Harvey Coastal Catchment WSUD Technical Guidelines* (Peel Development Commission 2006a) were developed to support implementation of the *Peel-Harvey WSUD Local Planning Policy* (Peel Development Commission 2006b) and the objectives of the 2008 WQIP. Both documents require updating to ensure they reflect current industry best practice.

In addition to integrating best practice stormwater management into new developments, there are also opportunities to retrofit existing urban areas to better manage stormwater, using WSUD principles. Opportunities for retrofitting (at the lot, street or suburb scale) arise when existing structures are upgraded or redevelopment occurs.

In traditionally drained urban environments, surface flows generally high in nutrients are quickly conveyed off the land into receiving waterbodies via pipes and drains. Retrofitting traditional drainage infrastructure using WSUD (with due consideration to subsurface water) aims to restore more natural flow rates (more reflective of pre-development hydrology) and trap and reduce the nutrients closer to their source. Examples of how this may be achieved include directing stormwater to bioretention basins, vegetated swales, constructed wetlands, or rehabilitation of open drains to create 'living streams'. WSUD can also include the capture and reuse of stormwater for other 'fit-for-purpose' water uses such as irrigating public open spaces. As well as reducing nutrient export from urban areas, WSUD structures may help to reduce other non-nutrient contaminants such as heavy metals and hydrocarbons from entering and polluting the waterways and estuary.

L.11 Decommissioning of septic tanks and connection to reticulated sewerage

The use of conventional on-site sewage systems (septic tanks) that can leach their contents to the environment is widespread in Western Australia and can result in public health, environmental and amenity issues. Sewage discharge contains nutrients, metals, salts, hormone disrupting chemicals, bacteria, viruses and other pathogens.

The *Government Sewerage Policy* (Government of Western Australia 2019), *Draft State Planning Policy 2.9 Planning for Water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for Water Guidelines* (WAPC 2021b) require reticulated sewerage to be provided during the subdivision and development of land.[17] New residential developments in sensitive environments such as the plan area must have reticulated sewerage connection for lots less than one hectare (where reticulated sewerage is, or could be made, available). Smaller lot sizes increase both the likelihood and consequences of environmental and public health impacts. Small lots:

- reduce the area available for sewage disposal
- increase the number of residents exposed to health and amenity issues in the event of system malfunction
- increase nutrient and non-nutrient contaminant loads per unit area.

The *Government Sewerage Policy* (Government of Western Australia 2019) states that in sensitive areas (including the plan area) the desired water quality objectives relating to nutrients can only be achieved in unsewered areas if the recommended minimum lot sizes of one hectare are adhered to.

Where reticulated sewerage is not available or required, best practice on-site sewage treatment and disposal should be adopted. Secondary treatment systems with nutrient removal will generally be required in public drinking water source areas and sewage-sensitive areas such as the plan area. Secondary treatment greatly reduces non-nutrient contaminant concentrations, including endocrine disrupting compounds (Reitsma et al. 2010). The Department of Health has approved several secondary treatment systems (commonly known as aerobic treatment units) for use in Western Australia with regulations requiring systems to be regularly serviced by licensed personnel to achieve an acceptable treatment level. Note that modifying existing standard septic tanks to be fitted with low nutrient emission secondary treatment units is expensive, so cost sharing arrangements are likely to be required for widespread implementation.

[17] The *Government Sewerage Policy* (State of Western Australia 2019) will be repealed when the final versions of *Draft State Planning Policy 2.9 Planning for Water* (WAPC 2021a) and *Draft State Planning Policy 2.9 Planning for Water Guidelines* (WAPC 2021b) are published.

L.12 Catchment revegetation

Nitrogen fixation

Nitrogen (N) fixation is a chemical process by which N in the air (N_2) is converted into ammonia (NH_3) or related nitrogenous compounds in the soil.

In areas of deep-rooted, native vegetation, N inputs to the catchment are limited to atmospheric deposition and a small amount of N fixation by some plants. When deep-rooted native vegetation is cleared – as has occurred on a large scale on the coastal plain of the Peel-Harvey catchment – and replaced with shallow-rooted crops and pastures, the nutrient inputs to the catchment are significantly increased. This is because of the application of fertiliser, increased runoff, fodder, animal waste and increased nitrogen fixation. The removal of deep-rooted vegetation leads to the loss of soil through erosion and loss of nutrients via increased surface runoff and leaching to receiving water bodies. The clearing of native, deep-rooted vegetation can also lead to increasing groundwater levels, waterlogging and secondary salinisation and/or increased stream salinity (Ruprecht and Schofield 1991, Schofield and Bari 1991).

In 1989, a Moratorium on Clearing, proposed as a condition of Stage 2 of the *Peel Inlet and Harvey Estuary Management Strategy* (EPA 1988), was set as Ministerial condition to prevent any further clearing in the catchment. However, significant clearing of the catchment had already occurred and some clearing continued, despite the moratorium. The *State Native Vegetation Policy for Western Australia* (Government of Western Australia 2022c) now aids in protecting and conserving remnant vegetation in the Peel-Harvey catchment.

Revegetating cleared lands with deep-rooted, native species can reduce nutrient export, lower the groundwater table, and help mitigate secondary salinisation and stream salinity. Vegetation also diversifies farm assets, offers amenity, provides windbreaks for stock, supports cooler microclimates and increases habitat diversity, connectivity for movement and food sources for local fauna. Because trees use carbon dioxide, replanting areas with deep-rooted vegetation also mitigates climate change by helping to offset emissions of greenhouse gases.

The key strategies for delivering large scale change through revegetation include:

- targeting areas of priority agricultural land (e.g. beef farming with low PRI soils) in the plan area for revegetating with deep-rooted species (e.g. planting of native shelterbelts and large pockets of native vegetation)
- local government requiring minimum areas of vegetation coverage with lot-scale development (typically 25–30 per cent coverage, moving toward 50 per cent coverage as supported by this WQIP)
- State or local government-led initiatives that either buy back private land or utilise government-owned, cleared or highly degraded land.

Appendix M: Current environmental guidelines and codes of practice for intensive land uses, dairy farms and grazing

Environmental guidelines and codes of practice have been developed under local, State and federal government for intensive animal industries and horticulture. Environmental guidelines are used to help design and manage an industry to reduce environmental impacts. However, these standards and guidelines may not be sufficient in sensitive environments such as the Peel-Harvey estuary catchment on the Swan coastal plain. Below are the current environmental guidelines and regulations, adapted from Hennig et al. (2021).

M.1 Piggeries

- *Environmental guidelines for new and existing piggeries* (Latto et al. 2000)
- *National environmental guidelines for indoor piggeries* (Tucker 2018)
- *National Environmental Guidelines for Rotational Outdoor Piggeries* (Tucker and O'Keefe 2012) piggeries

M.2 Abattoirs

- Environmental Protection (Abattoirs) Regulations 2001
- *Rural abattoirs, Water Quality Protection Note no. 98* (DoW 2007)

M.3 Feedlots

- *National procedures and guidelines for intensive sheep and lamb feeding systems* (Meat & Livestock Australia 2011)
- *National guidelines for beef cattle feedlots in Australia – third edition* (Meat & Livestock Australia 2012b)
- *National beef cattle feedlot environmental code of practice – second edition* (Meat & Livestock Australia 2012a)

M.4 Poultry

- *Environmental code of practice for poultry farms in Western Australia* (Department of Environment 2004)
- *Egg industry environmental guidelines* (McGahan et al. 2018)

M.5 Intensive horticulture

- *Horticulture in the Peel-Harvey: a guide for investors and growers* (PHCC 2024)

- *Guidelines for environmental assurance in Australian horticulture – second edition* (Horticulture Australia Ltd. 2014)

Guidance on nutrient best practice management in Western Australia is also available for managing effluent on dairy farms, as well as for beef, sheep and dairy grazing (see M.7 and M.8 below). Links to additional guidance resources on protecting water quality for agricultural projects, developments and activities are available on the Department of Water and Environmental Regulation's Water quality guidance webpage.

M.7 Dairy farms

- *Code of practice for dairy farm effluent management WA* (Western Dairy 2021)

M.8 Beef, sheep and dairy grazing

- *Nutrient best management practices guideline for beef, sheep and dairy grazing enterprises in south-west Western Australia* (Government of Western Australia 2022b)

Appendix N: Septic tank removal

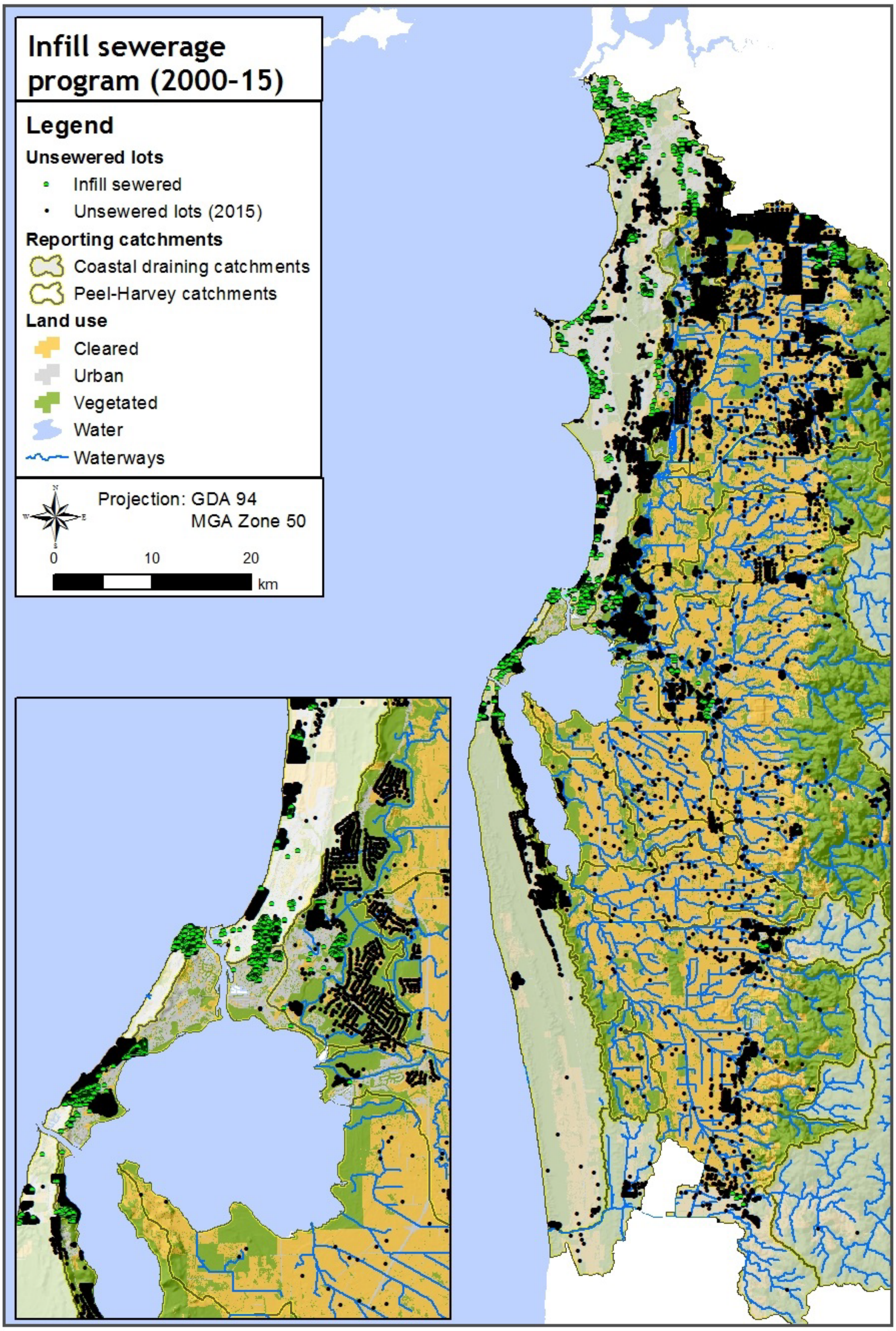


Figure M.1 Septic tanks in the plan area, showing those that were removed by the infill sewerage program between 2000–15

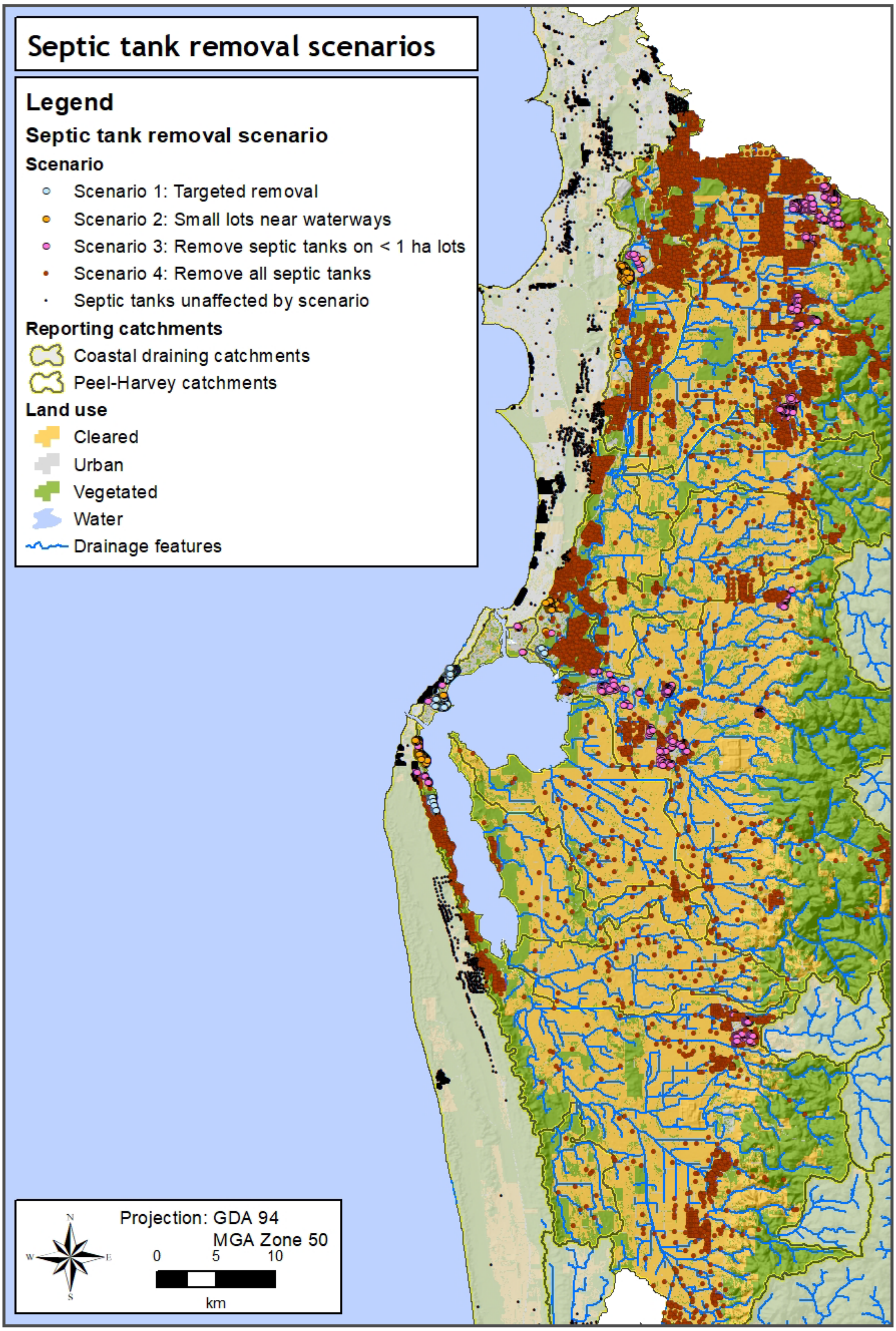


Figure M.2 Septic tanks across the plan area, showing which units were assumed to be removed under various management scenarios as modelled by Hennig et al. (2021)

Appendix O: Cost-benefit table with reference notes

Table O.1 Estimated capital cost of implementing each management action showing the associated reduction in N and P loads entering the estuary. Modelled actions that were not costed include those relating to intensive animal industries, wastewater treatment plants (WWTPs), water sensitive urban design (WSUD) and catchment revegetation. Reference notes are included.

Management practice	Capital cost per unit $/unit		Capital cost $ (million)	N load removed kg/yr	P load removed kg/yr	Cost per unit N removed $/kg	Cost per unit P removed $/kg	Reference notes
Best practice fertiliser management (111,830 ha of beef and all dairy farms)	$16.0	per ha	$1.8		19,332		$93	1
Best practice fertiliser management and slow-release P fertilisers (slow-release P fertilisers on 50,220 ha low-PRI soils and traditional P fertilisers on 61,610 ha high-PRI soils)	$16.1	per ha	$1.8		23,387		$77	2
Soil amendment (50,220 ha of low-PRI beef and dairy farms)	$1,080	per ha	$54.2		20,945		$5–2,590	3
Dairy effluent management (25 dairy farms)	$100,000	per shed	$2.5	2,288	1 027	$1,093	$2,435	4
Infill sewerage (1,074 septic tanks)	$45,000	per septic	$48.3	3,593	219	$13,453	$220,469	5
Riparian zone management:								
(stock exclusion from 1,043 km of streams and drains)	$15,000	per km	$15.6	38,726	1,536	$404	$10,186	6
(stock exclusion and revegetation of 1,394 km of streams and drains)	$41,000	per km	$57.2	99,834	2,009	$573	$28,457	7
Constructed wetlands (811 ha across seven catchments)	$1,291,000	per ha	$1,047.0	119,394	22,803	$8,769	$45,914	8

Reference notes

1. Data from DPIRD in 2020, fertiliser management program for the *Regional Estuaries Initiative*: based on the total area sampled to date and the average cost $3,500/farm with the average farm size is about 200 ha (from the 10-year period) so that would mean between $15.00 and $17.50/ha. That includes all aspects including sampling, chemical analysis, interpretation, mapping, planning, workshops/education and advice.
2. Data from CSBP in 2019, fertiliser management costs and the additional cost of Super SR extra. Note that it is possible that less SR extra maintenance will be required if it is more readily retained in the soil (and not lost to the environment). This has not been considered in the analysis.
3. Data from the department in 2020, soil amendment program for REI: For the Peel-Harvey it would be $25/t freight (for Peel-Harvey), $20/t product (at large scales), $9/t spreading, giving a total of $54/t. Note that there is uncertainty in the product rate. Management rates are based on re-application every 10 years. Rates of 20t/ha may not be required for significant uptake of nutrients, and that there may be other methods to increase the PRI of soils that have different cost profiles (for example, mixing with local clays). If soil amendment was applied strategically to target soils with high P loss as identified during soil testing (rather than to all low PRI soils, as modelled), the cost per unit P loss is estimated to be as low as $5–21/kg P removed (Degens et al. (in press)).
4. Data from the department in 2020, Dairy effluent management program for the *Regional Estuaries Initiative*: Based on the average of 13 dairies that received full management upgrades to bring them up to specification with the Code of Practice. Note that full effluent management means that it complies with the Code of Practice, and it is likely that further improvements could be made at a higher cost.
5. Water Corporation estimated costs in 2021: Based on lot-weighted estimated costs that were provided by Water Corporation in July 2021. Infill recommendations use costs rounded to the nearest $5,000 for Coodanup, Falcon, Halls Head and Pleasant Grove. For the expanded infill scenario, we used the lot-weighted average from all metro and regional infill sewerage costs where lot size was >2,000 m^2. These areas include Bayswater (industrial), Kingsley, Kenwick, Welshpool, Maddington (industrial), Osborne Park (industrial), Pleasant Grove, Bibra Lake (industrial), Denmark (Inlet Drive), Yakamia Creek (Edwards Street).
6. Peel-Harvey Catchment Council, Correspondence to the department in 2018.
7. Based on costs from the Leschenault WQIP (Hugues-dit-Ciles et al. 2012) that were adjusted for inflation between 2010 to 2019.
8. Average capital and maintenance costs from three constructed wetlands (Liege Street, Wharf Street and Eric Singleton). Costs adjusted for inflation (2019) as per ha of wetland, which could be upscaled linearly.

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