Hydrological and nutrient modelling of the Wilson Inlet catchment

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Hydrological and nutrient modelling of the Wilson Inlet catchment

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Summary

The Department of Water and Environmental Regulation has developed a catchment model that estimates river flow volume and nutrient loads to Wilson Inlet, an estuary on Western Australia's South Coast. We have used this calibrated model to test scenarios on catchment land-use change (urban expansion and plantation reversion to pasture), climate change and management actions to reduce nutrient loading to Wilson Inlet. The catchment model supports the water quality improvement plan (WQIP).

In estuaries like Wilson Inlet, nutrient runoff (nitrogen and phosphorus) can lead to excessive aquatic plant and macroalgal growth, microalgal growth (including toxic species), deoxygenation and fish death events. Actions to address nutrient inflows to Wilson Inlet began in the 1980s and are continuing. We have estimated nutrient targets – these represent the maximum acceptable nutrient load that the inlet can assimilate without unacceptable impacts for a given period and hydrological regime. We found that nitrogen and phosphorus inflows exceeded targets by 27% and 45% respectively. Collectively, Cuppup, Sleeman and Sunny Glen catchments contribute 47% and 88% of the excess nitrogen and phosphorus loads respectively.
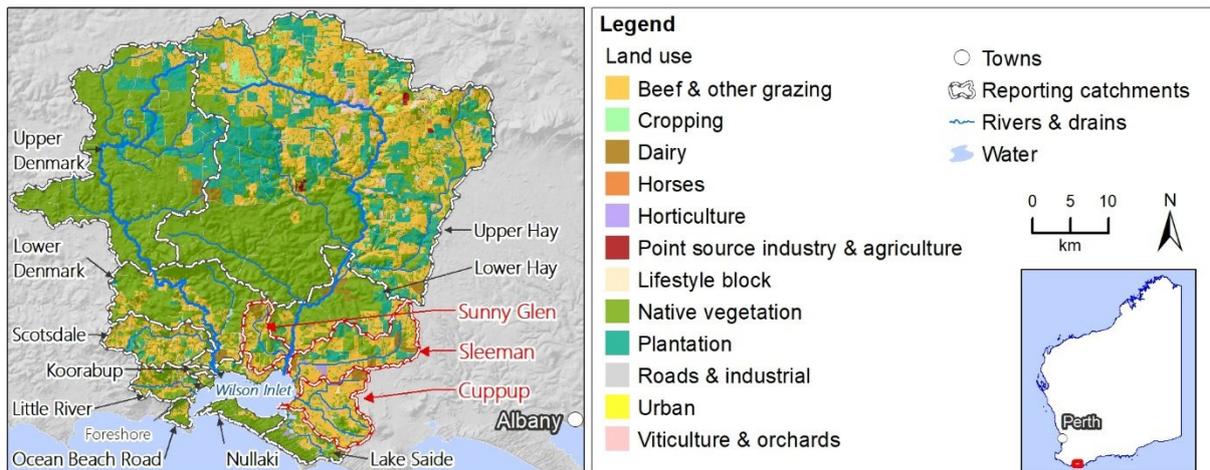
Flow and nutrient model

Using a calibrated hydrological model called LASCAM and the Source power function model for nutrient generation, we present comprehensive results for river flow and nutrient loss for 14 reporting catchments and the combined contribution to Wilson Inlet.

For the period 2010–19, average annual flow and nutrient loads to Wilson Inlet were:

	Flow (GL)	Nitrogen load (t)	Phosphorus load (t)
Wilson Inlet	85	108	8.7

We have used nutrient concentration targets[1] to calculate the maximum acceptable nutrient load for catchments that flow to the inlet for the reporting period. These targets are based on

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[1] Catchments with elevations <150 m AHD (lowland) used 1.2 mg/L total nitrogen and 0.1 mg/L total phosphorus. Other catchments (upland) used 0.45 mg/L total nitrogen and 0.02 mg/L total phosphorus.

the approach we have used for other water quality improvement plans for estuaries in south-west Western Australia.

Target average annual (2010–19) loads of 78 tonnes for nitrogen and 4.8 tonnes of phosphorus mean that the basecase period of 2010–19 had an excess of 30 tonnes of nitrogen (27% reduction required to meet water quality targets) and 3.9 tonnes of phosphorus (45% reduction required).

Nutrient sources

Beef farming and other grazing contributes about 67% of the nitrogen and 65% of the phosphorus to Wilson Inlet. Dairy farming contributes 8% of the nitrogen and 9% of the phosphorus load. Horticulture produces 9% of the phosphorus load and native vegetation produces 9% of the nitrogen load. Native vegetation occupies about 54% of Wilson Inlet's catchment area and has the lowest rates of nutrient loss of all land uses modelled. Horticulture occupies just 0.2% of the catchment and has the highest rates of nutrient loss relative to the area it covers.
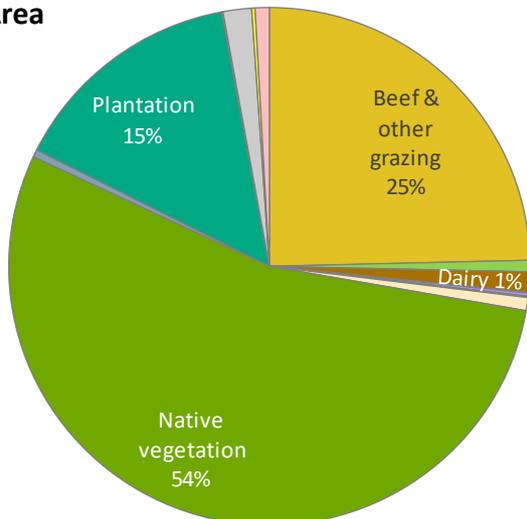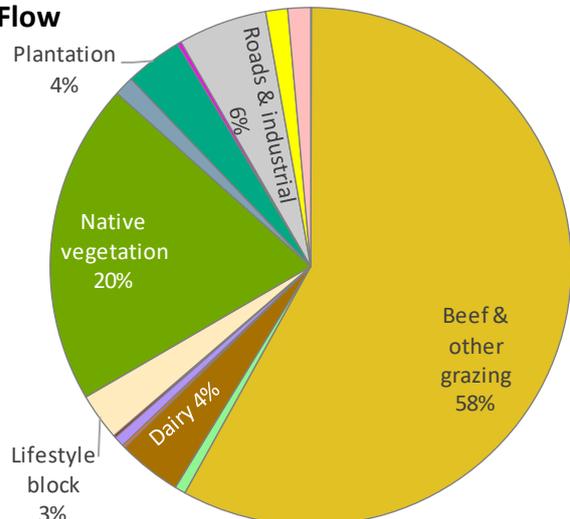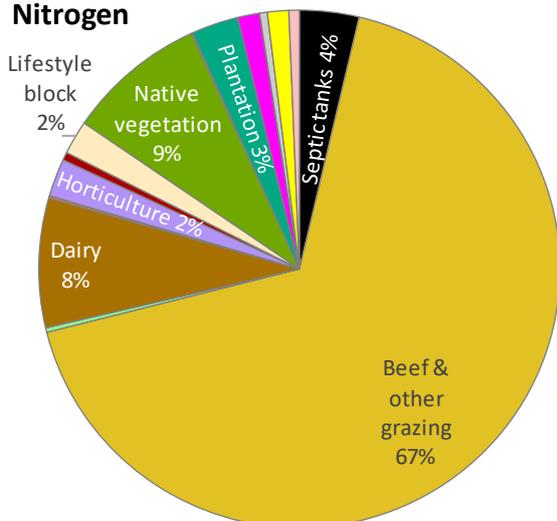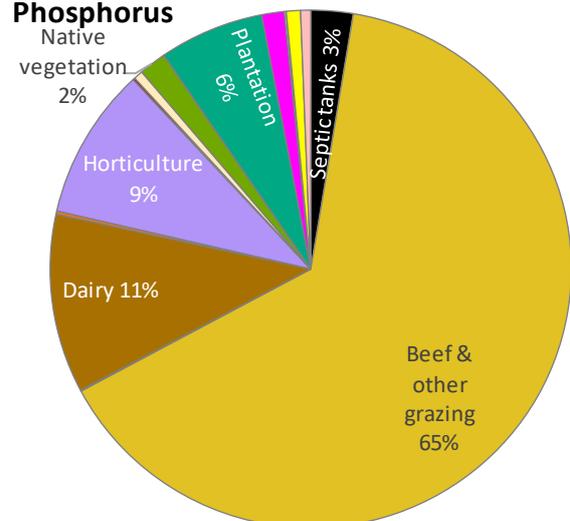
Scenarios

We investigated the effects of changes in land use, climate and land management on catchment flow and nutrient loss by modifying model drivers (land use, rainfall and evapotranspiration). Planners, catchment managers and other agencies can use this scenario modelling to guide future planning and management decisions.

We modelled two land-use change scenarios: urban expansion and plantation reversion. A 2050 **urban expansion** scenario estimated small increases in flow (0.5%) and nutrient loads (<5%) to the inlet. Urban expansion only affected 0.6% of the Wilson Inlet catchment, yet post-development land uses had rates of nutrient loss six to seven times greater than pre-development land uses. A scenario examining the potential effect of **plantation reversion** to grazing agriculture (144 km^2) showed large increases in flow (11%) and loads of nitrogen (15%) and phosphorus (23%). Plantations have rates of nutrient loss that are, on average, five to 13 times lower than beef farming.

We modelled the following management actions:

1. Fertiliser management

2. Low-water-soluble fertilisers

3. Dairy effluent management

4. Soil-amendment application on farms

5. Riparian zone rehabilitation

6. Septic tank removal

No management action alone could achieve nutrient load targets.

A combination of **agricultural management actions** *almost achieved the phosphorus load target for the inlet.* These actions included:

- All beef and dairy farms adopting best-practice fertiliser management, including the use of low-water-soluble phosphorus fertiliser on soils with a low-phosphorus-retention capacity.

- All beef, dairy and horticulture farms with low-phosphorus-retentive soils applying soil amendments or incorporating suitable subsurface clays into topsoils to increase soil phosphorus retention and decrease nutrient losses.

- All dairy sheds using best-practice effluent management.

A scenario that used **non-agricultural management actions only** *did not meet either the nitrogen or phosphorus target for the inlet.* These actions included:

- Fencing and re-vegetating 1,776 km of streams and drains that potentially require management.

- Removing 714 septic tanks in the areas around Ocean Beach, Weedon Hill and along Inlet View Drive.

- Maintaining the improvements in discharge from the Denmark wastewater treatment plant post 2015 upgrade.

Our next step was to model an **all actions (agricultural and non-agricultural**) scenario to take in all the management actions above. This scenario achieved reductions of 18% for nitrogen loads (target of 27%) and 45% for phosphorus loads (thus meeting the catchment's phosphorus load target).

South-west Western Australia is experiencing a drying climate. In the Wilson Inlet catchment, rainfall has become increasingly variable, especially since the year 2000. We estimated the potential impact of climate change for the period centred around 2040 (2025–54) using the department's new guidelines for climate change projections (DWER 2024b). The objective of our climate change modelling was to evaluate whether climate change might alter the basecase model's nutrient management recommendations for the upcoming WQIP. We considered the outputs from 32 climate model projections and applied two that bookended the range of future projected rainfall. We refer to these as the stable rainfall and drier climate scenarios.

Compared with the basecase (2010–19), the 2040 climate scenarios show:

- **Rainfall** was 5% greater in the stable rainfall scenario and 12% lower in the drier climate scenario.

- **Potential evapotranspiration** was 3% greater in both scenarios.

- **Flow** was 9% greater in the stable climate scenario and 56% lower in the drier scenario.

- The **nutrient-reduction requirements** remained similar to the basecase in both scenarios (31% reduction of nitrogen and 47% for phosphorus).

The 2040 climate scenarios did not change the nutrient management recommendations from the basecase model.

1   Introduction

Wilson Inlet is a 48 km² bar-closed estuary on Western Australia's south coast. The closest town is Denmark, located about 50 km west of the city of Albany and 370 km south-east of Perth, the state's capital. Two major rivers flow into the inlet: the Denmark and Hay. Five smaller water courses and many minor tributaries and drains also discharge into the inlet. The inlet's sandbar has been breached most years since the early 1900s to mitigate flooding. Its catchment is the area that collects rainfall into the streams and rivers that flow into the inlet. The catchment covers an area of about 2,200 km² and extends north to the town of Mount Barker.

Aboriginal people have occupied the Australian mainland since at least 65,000 years ago (Clarkson et al. 2017), meaning their ancestors were present during the formation of Wilson Inlet, which is about 6,500 years old (Hodgkin & Hesp 1998). The inlet's catchment is located on Minang and Pibbulmun country, which are groups of the Noongar cultural bloc of south-western Australia. The Minang and Pibbulmun share a common language, Noongar, with differences in dialect. Minang lands are east of the Hay River and the Pibbulmun to the west (Guilfoyle 2011). Both have an inland boundary about 65 km from the coast based on the Horton Map, which does not correctly indicate the Hay River boundary of these groups.

The Aboriginal people call the inlet *Nullaki*, meaning seagrass or *Marjit*, meaning water snake. Nullaki/Marjit is an important site for shelter and food. For instance, the Katelysia Rockshelter (near the mouth of the inlet) was used 1,700 to 2000 years ago (Dortch et al. 2014). Several fish traps remain in the inlet: one on the northern shoreline of Marbelup Farm, one near Crusoe Beach and another near Jacks Island (east of Poison Point).

European settlement in Albany began in 1826 and by 1840 the coastal areas around Denmark (e.g. Nullaki Peninsula) were being used for livestock grazing. In 1895 about 1,000 timber workers and their families settled in Denmark for work at the local lumber mills, until their closure in 1905. By 1910 dairy farming had become the major industry in the area and a butter factory had opened in town. Commercial fishing had also become well established by this time and continues to this day. From 1923, around 15 Group Settlement Schemes were formed between Denmark and Bow Bridge to clear land in the inlet's catchment for agriculture.

Construction of the second Denmark–Albany railway along the inlet's foreshore in the late 1920s required sandbar openings at lower water levels to prevent flood damage. Although later decommissioned in 1958, the sandbar management associated with the second railway enabled farming and development of lower-lying land that was closer to the inlet. Creation of the Albany drainage district in the 1950s was in response to long-running calls to open the remaining uncleared land for agriculture. Extensive artificial drainage enabled further agricultural development of the flat and waterlogged lands of the eastern part of the inlet's catchment (Sleeman, Cuppup and Lake Saide catchments). However, agriculture in this area existed before the 1950s, such as Marbelup Farm (established in the 1840s).

By the 1960s Denmark's population was 1,500 and the area was increasingly being used as a tourist and retirement location. Vineyards started to establish in the area from this time.

Water quality issues became prominent in the 1970s but may have emerged in the 1950s. Commercial fishers and residents noticed an increase in 'aquatic weed' which comprised macroalgae and a native seagrass called *Ruppia*, which is an indicator of nutrient enrichment. However, studies have shown that *Ruppia* plays an important role in the inlet's ecology and provides crucial habitat for fish such as cobbler (Humphries et al. 1992). By the late 1970s, the State Government was receiving reports about excessive *Ruppia* and macroalgal growth in the inlet and their impacts on commercial and recreational fisheries.

A study by Lukatelich et al. (1986), initiated in 1982, aimed to better understand the sources of nutrients in the catchment and inlet. In 1985, Bolland et al. (1995) began trials of slow-release phosphorus fertilisers in Denmark. In the years since, additional studies have been undertaken, while routine catchment and estuary monitoring has been in place since 1995.

Potentially harmful microalgae have been detected in the inlet at concentrations harmful to humans, another sign of estuary eutrophication. Measurements of catchment water quality continue to detect high to very high concentrations of nutrients coming from three catchments (Sunny Glen Creek, Sleeman and Cuppup), which are similar to those measured in other eutrophic estuary catchments (e.g. the Peel-Harvey). Although the inlet has shown signs of eutrophication and its associated impacts, the inlet continues to demonstrate resilience to eutrophication compared with other estuaries (e.g. Torbay Inlet, Vasse-Wonnerup estuary and Peel-Harvey estuary).

The inlet provides important habitat for resident and migratory birds (Taylor & Green Skills 2015). Migratory birds are protected under the following international treaties:

- Japan–Australia Migratory Bird Agreement (JAMBA) 1981

- China–Australia Migratory Bird Agreement (CAMBA) 1988

- Republic of Korea–Australia Migratory Bird Agreement (ROKAMBA) 2007

At present about 10 to 14 commercial fishers operate in the inlet, however since 1975 there have been as many as 23. Most of the state's estuary cobbler is sourced from the inlet. Recreational fishers cherish the estuary for its bountiful fish, particularly the seasonal run of pink snapper after the bar is breached. There is a 12 ha aquaculture lease which cultivated blue mussels and angasi oysters from 2004–08 and resumed operations in 2022. Residents and tourists value the inlet for its amenity and recreational value. Prawn Rock Channel is a popular swimming spot, especially when the sandbar is open and blue ocean water travels through the channel.

There are many reasons to improve the ecological condition and water quality of the Wilson Inlet. It is one of the seven focus estuaries of the State Government's Healthy Estuaries WA program. Priority actions to reduce nutrient inputs to the estuary from agricultural land uses are delivered collaboratively by the department, the Wilson Inlet Catchment Committee, the Department of Primary Industries and Regional Development (DPIRD) and Western Dairy.

Water quality improvement requires interventions at large scales with limited resources. In addition, identifying priority areas for interventions can be difficult given the limited availability of suitable information and data at large scales. Catchment models play an important role in water quality management through simulating the transport of various pollutants (such as nitrogen and phosphorus) from the landscape, through the waterways and to sensitive

receiving waterbodies. These models provide water quality managers with an additional line of evidence to identify and justify intervention decisions and prioritisation.

1.1 Catchment-scale models

Catchment-scale models are used to estimate river flows, as well as the loads and concentrations of nitrogen and phosphorus. We used the eWater Source modelling platform to develop the hydrological and nutrient models. These models require meteorological and land-cover input data, and we calibrate them against data from flow and water quality monitoring sites (Carr & Podger 2012; Welsh et al. 2013).

We used the calibrated Source catchment model to run scenarios for land-use change, catchment management actions and climate change. The model outputs will support the *Nullaki (Wilson Inlet) water quality improvement plan*. We have also coupled a routinely updated version of the catchment model to a hydrodynamic model of the inlet to assist management decisions where opening of the Wilson Inlet sandbar is concerned.

1.2 Model objectives

The study had two main objectives.

1) **Support the development of a water quality improvement plan for Nullaki (Wilson Inlet):**

   a) Estimate average annual flow and loads of nitrogen and phosphorus that are discharged to Wilson Inlet.

   b) Estimate the relative source of flow and nutrient load by reporting catchment and by land use.

   c) Estimate the maximum acceptable average annual nutrient loads for a given period (i.e. the basecase period).

   d) Determine the nutrient load reductions required for reporting catchments individually and combined to meet acceptable annual loads.

   e) Estimate the impact of selected nutrient management actions, land-use changes and future climate.

These model objectives are consistent with the Australian Government's *Framework for marine and estuarine water quality protection* (DEWHA 2002).

2) **Support the development and operation of hydrodynamic models of Wilson Inlet:**

   a) Estimate daily river flow for use as input data in hydrodynamic models of Wilson Inlet. Collectively, these models account for the processes that generate river flow in response to rainfall, as well as ocean exchange influenced by the dynamics of the sandbar. The movement of these water inputs to the inlet and their loss to the ocean are simulated at high resolution, both temporally and spatially. This allows us to examine the fate and retention time of catchment inflows to the inlet and to optimise sandbar management to protect the inlet's ecology and amenity.

To achieve these objectives, we developed a contemporary catchment-scale hydrological and nutrient model in the eWater Source modelling framework.

2 Catchment description

The Wilson Inlet catchment covers about 2,300 km². Around 47% of the catchment is cleared of native vegetation and its predominant land uses are livestock grazing (cattle and sheep), plantations, dairy farming, horticulture and residential. The two major rivers flowing into the inlet are the Denmark and Hay. Other tributaries include Scotsdale Brook, Sunny Glen Creek, Sleeman River, Cuppup Creek and Little River.

2.1 Location

Denmark and Mount Barker are the two largest towns in the Wilson Inlet catchment. These towns are located on the western side of the inlet and the north-eastern catchment boundary respectively (see Figure 2.1). About 7,600 people live in the catchment (ABS 2016; see Table 2.1 and Figure 2.1).

There are three local government authorities in the Wilson Inlet catchment: the Shire of Denmark, City of Albany and Shire of Plantagenet. The Hay River and the mouth of the inlet serve as the boundary of the Shire of Denmark and the City of Albany. The Shire of Plantagenet occupies the upper portions of the inlet's catchment.

Table 2.1: Population by suburb (ABS 2016) and estimated population in the Wilson Inlet catchment

Upper/lower catchment	Suburb	Suburb	Wilson Inlet catchment	
		(# people)	(# people)	%
Lower catchment	Ocean Beach	947	947	12%
	Denmark	2637	2637	35%
	Shadforth	687	687	9%
	Hay	332	332	4%
	Scotsdale	455	455	6%
	Nullaki	31	31	0%
	Youngs Siding	336	336	4%
	Lowlands	154	154	2%
	Redmond West	72	72	1%
	Redmond	205	10	0%
	Torbay	320	2	0%
	Narrikup	492	300	4%
Upper catchment	Mount Barker	2741	1400	18%
	Denbarker	75	75	1%
	Mount Lindesay	0	0	0%
	Mount Romance	0	0	0%
	Perillup	46	46	1%
	Forest Hill	147	147	2%
Subtotal: lower catchment		6668	5963	78%
Subtotal: upper catchment		3009	1668	22%
Total		9677	7631	100%

Figure 2.1: Location of the study area (Wilson Inlet catchment)

2.2 Climate

The Wilson Inlet catchment has a temperate climate with cool to cold wet winters and warm dry summers. Figure 2.2 shows the average annual rainfall for the period 1975 to 2003, which ranges from 1,100 mm in the south-west to 600 mm in the north-east of the catchment.

We have analysed the climate data from Denmark (BoM ref. 9531) and Mount Barker (9581) derived from SILO (Jeffrey et al. 2001). About 60% of rain falls from May to September, with rainfall exceeding potential evapotranspiration in these months (see Figure 2.3).

Since 2000, average annual rainfall in the catchment has reduced, while rainfall variability and evapotranspiration has increased. Between the 30-year periods of 1901–30 and 1991–2020, rainfall decreased by about 17% and potential evapotranspiration (PET) increased by about 8% at Denmark and Mount Barker. This drying trend is more evident in Figure 2.5,

which shows the moving 10-year mean annual rainfall deviation from mean annual rainfall for 1901 to 2020. Both Denmark and Mount Barker have substantially lower rainfall after 1975 than was experienced beforehand, with Mount Barker seeing a greater reduction in rainfall than Denmark. In addition, since about 2000 both Denmark and Mount Barker have seen increasing variability in rainfall, as indicated by the increasing magnitude of the moving 10-year standard deviations shown in Figure 2.6. This increasing variability comes after a period (~1990 to 2001) of the lowest rainfall variability in the 120-year rainfall record at both Mount Barker and Denmark.
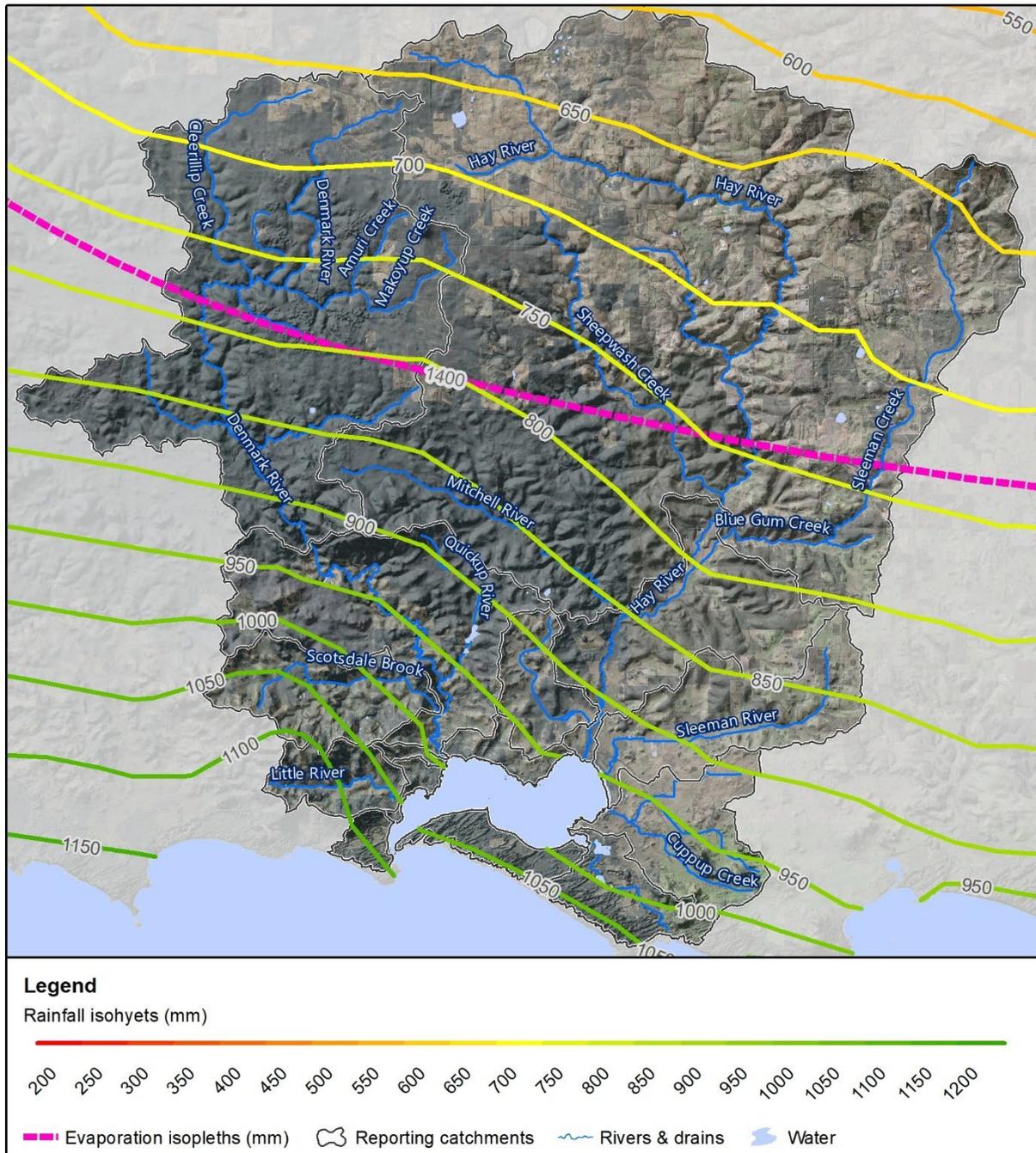
Figure 2.2: Rainfall and evaporation (1973–2003)
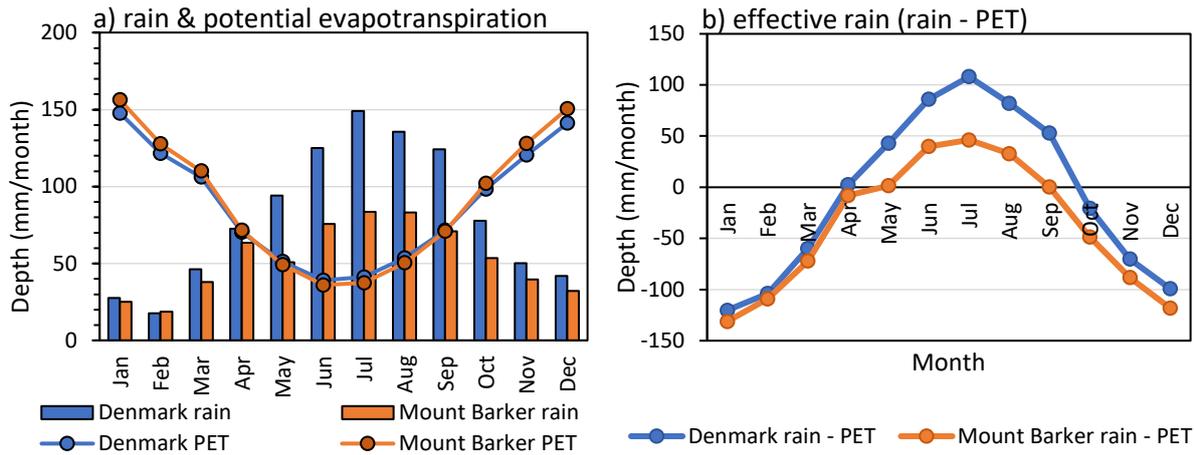
Figure 2.3: Average monthly rainfall, potential evapotranspiration and effective rainfall (2005–19)
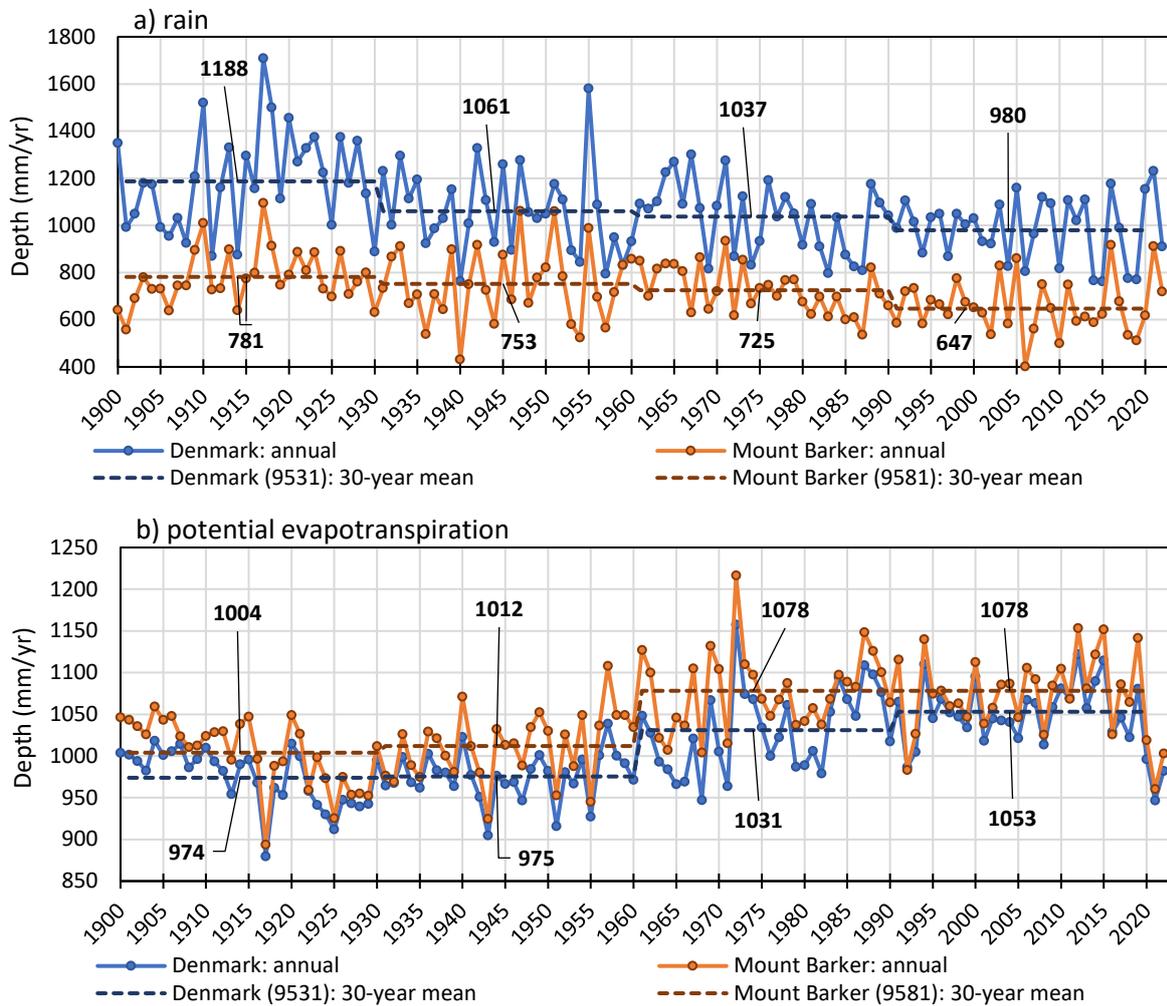
Figure 2.4: Annual (1900–2022) and 30-year mean annual a) rainfall and b) potential evapotranspiration
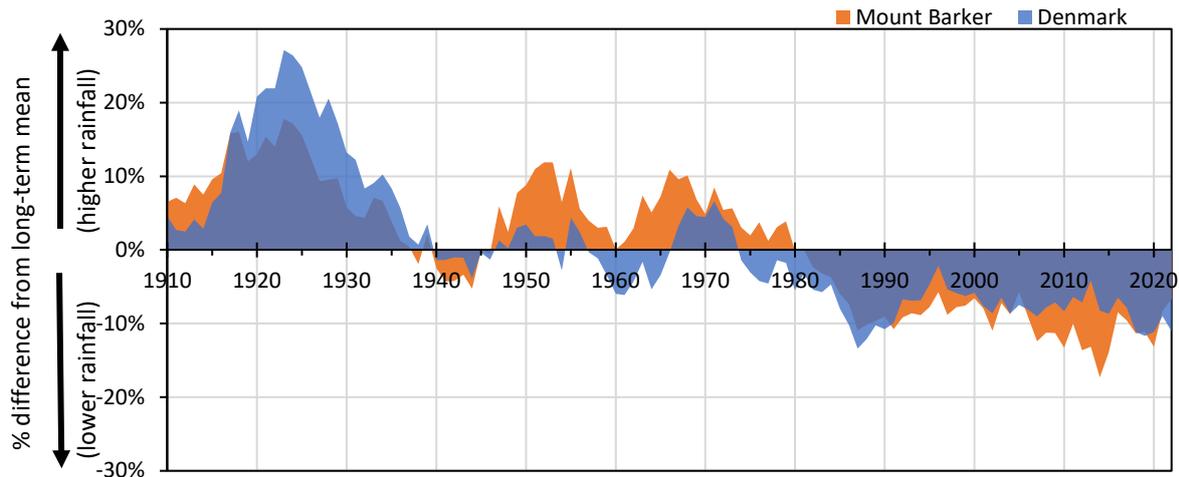
Figure 2.5: Moving 10-year mean deviation from long-term mean annual rainfall (1910–2020)
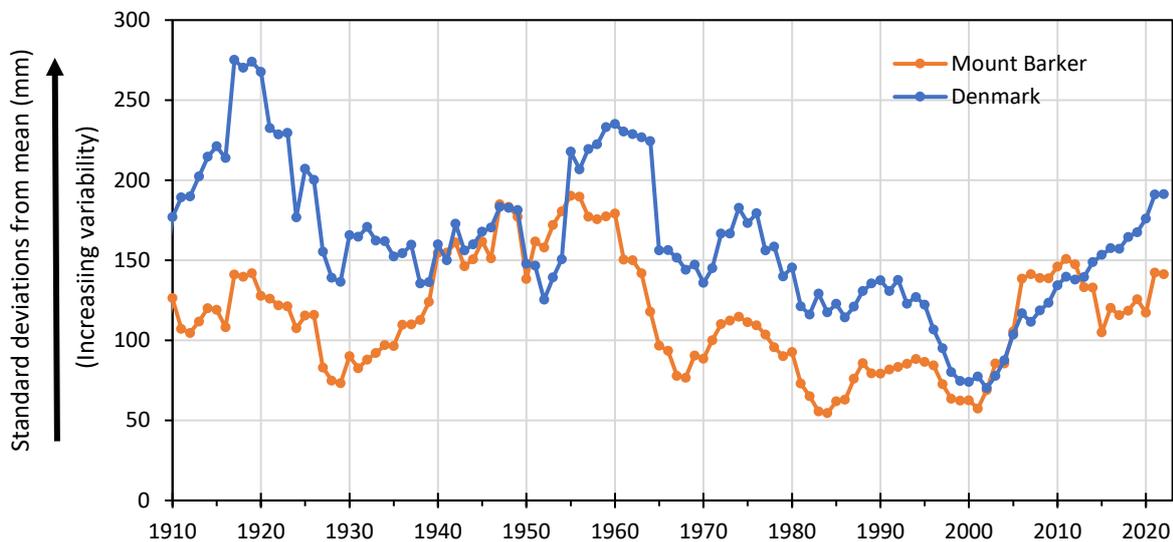
Figure 2.6: Moving 10-year standard deviations from 1910–2020

2.3   Hydrology

Wilson Inlet receives flow from two major rivers (the Denmark and Hay), one significant stream (Little River), four major drains (Sunny Glen Creek, Sleeman River, Cuppup Creek and Lake Saide drain) and at least 16 smaller tributaries and drains (see Figure 2.7).

Early last century the State Government began to construct arterial drainage through low-lying and waterlogged land, beginning with the Lake Saide drainage district in the 1910s and then part of the Cuppup catchment in 1923. In the 1950s the Wilson drainage district was implemented, which involved the rejuvenation of drainage in the Lake Saide drainage district and the creation of new arterial drainage in the remaining parts of the Cuppup catchment, the Sleeman catchment and likely the lower parts of Sunny Glen Creek. Today the Wilson and Lake Saide drainage districts are part of the Albany drainage district, which is managed by the Water Corporation. It is not clear when the area around and including Lake Barnes (near Narrikup) had drainage put in, however it may have been in 1930 for potato farming.

The Wilson Inlet catchment has many wetlands (see Figure 2.1). Nenamup Inlet and Lake Saide are the largest named wetlands in the lower part of the catchment. Wetlands in the low-lying and waterlogged Cuppup, Sleeman and Lake Saide catchments have been drained for use as agricultural land and none appear to be officially named. There are 12 named wetlands in the upper catchment with many more wetlands being unnamed. The wetlands in the upper catchment range from being completely drained and degraded (e.g. Lake Barnes) to being mostly undisturbed (e.g. Lake Mowilyilip and Blue Lake).

There are two town water supply dams and an estimated 4,016 farm dams in the Wilson Inlet catchment (see Figure 2.8). The Denmark dam was constructed in 1960–61 and the Quickup dam in 1989.
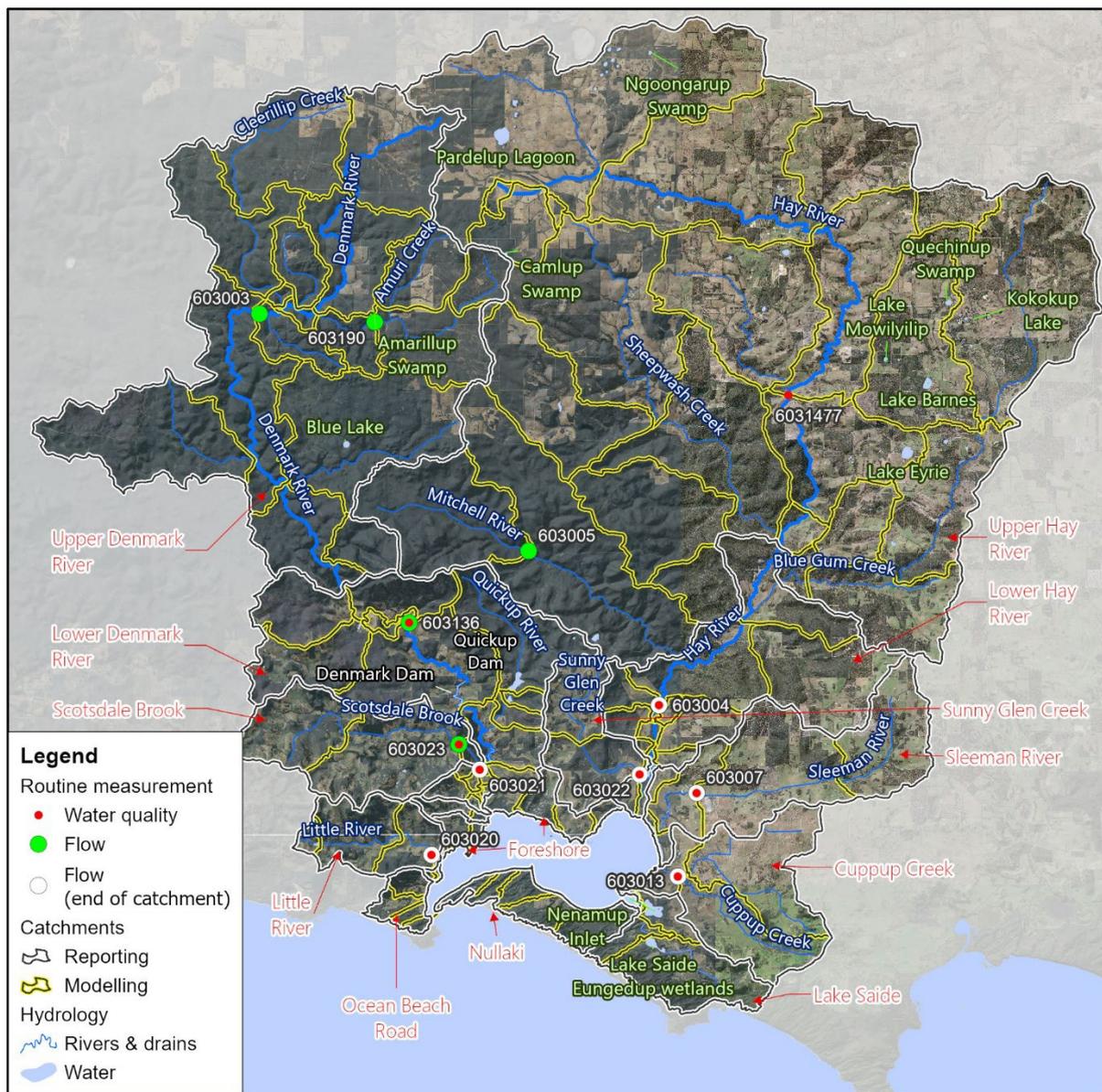
Figure 2.7: Hydrology, measurement sites and catchments (reporting catchment names are in red)
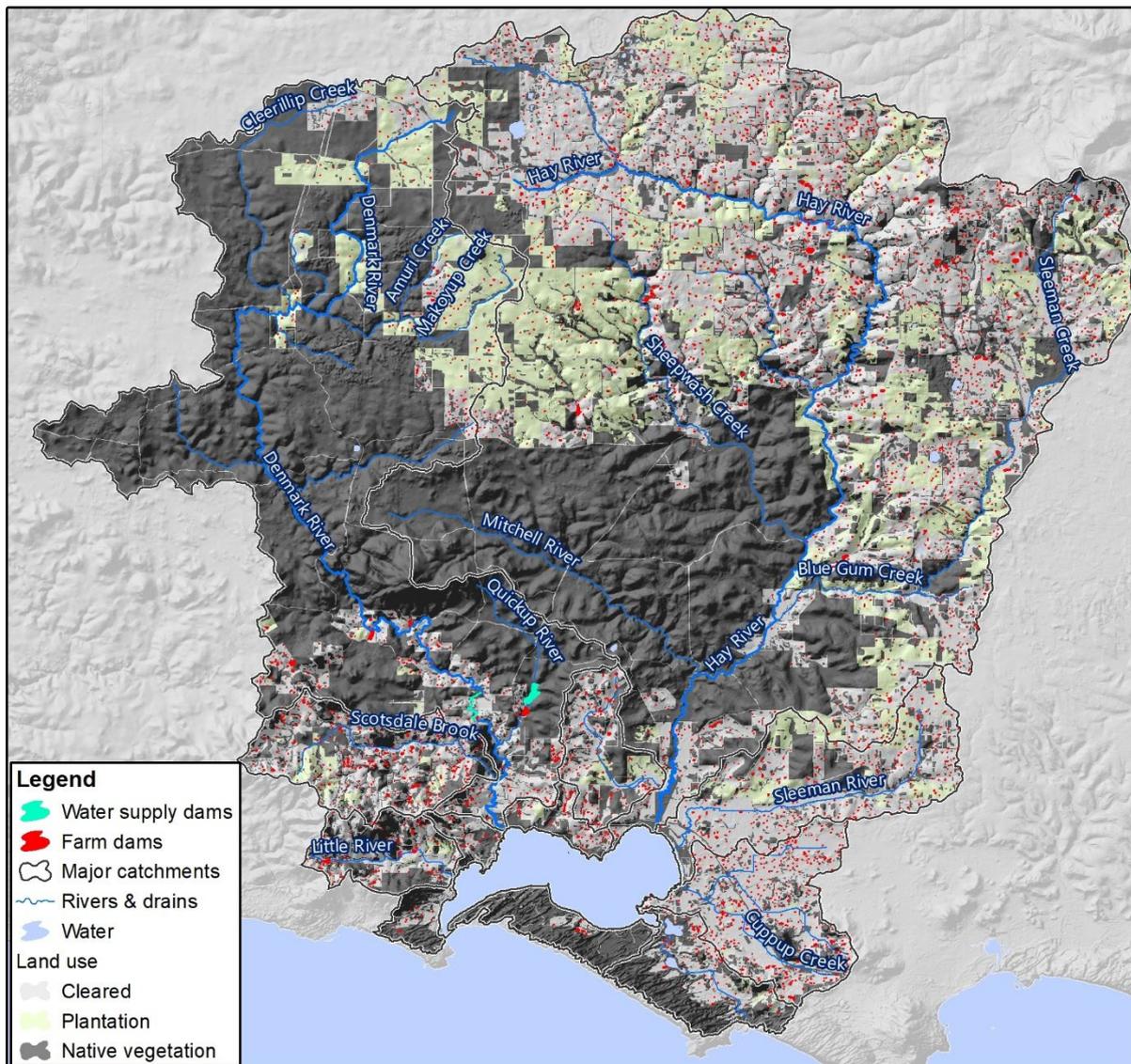
Figure 2.8: Water supply and farm dams

The following is a summary of the hydrological characteristics of measured flows at sites in the Wilson Inlet catchment (see Figure 2.7). Of these sites, five are located close to the inlet and when summed, represent the total measured inflow to the inlet. These end-of-catchment sites are the focus of this summary.

On average from 2010–19, about 85% of the river flow occurred from July to October with peak flow occurring in August (see Figure 2.9). Flow in the months of January to March made up about 1% of the annual flow volume, with Little River contributing most of the measured flows during these months. This was despite Little River contributing only 8% of the average annual flow for 2010–19 (see Figure 2.10). The baseflow signal of rivers is most evident when viewing the log of flow yield[2]. As shown in Figure 2.11, Little River's baseflow is more pronounced than the Denmark and Hay rivers and persists year-round. Both Sunny

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[2] Flow expressed as a depth (mm) of its upstream catchment area. Flow yield is a statistic that allows the direct comparison of the relative magnitude of flow from rivers of different sizes.

Glen Creek and Cuppup Creek will typically stop flowing by November to December, whereas Sleeman River tends have a slightly longer duration of flow in the summer months (see Figure 2.11).

Figure 2.12 shows the intensity of flow from all active flow measurement sites. Little River, Scotsdale Brook and Cuppup Creek have the highest intensity of flow. Both Little River and Scotsdale Brook receive the highest rainfall in the Wilson Inlet catchment (1,050–1,100 mm/yr) and have steep terrain. Cuppup Creek has lower rainfall (900–1,000 mm/yr) but has the highest drainage density in the catchment (see Figure 2.13). The large areas of deep-rooted vegetation and lower rainfall (600–850 mm/yr) in the upper Denmark and Hay catchments results in lower flow yields.
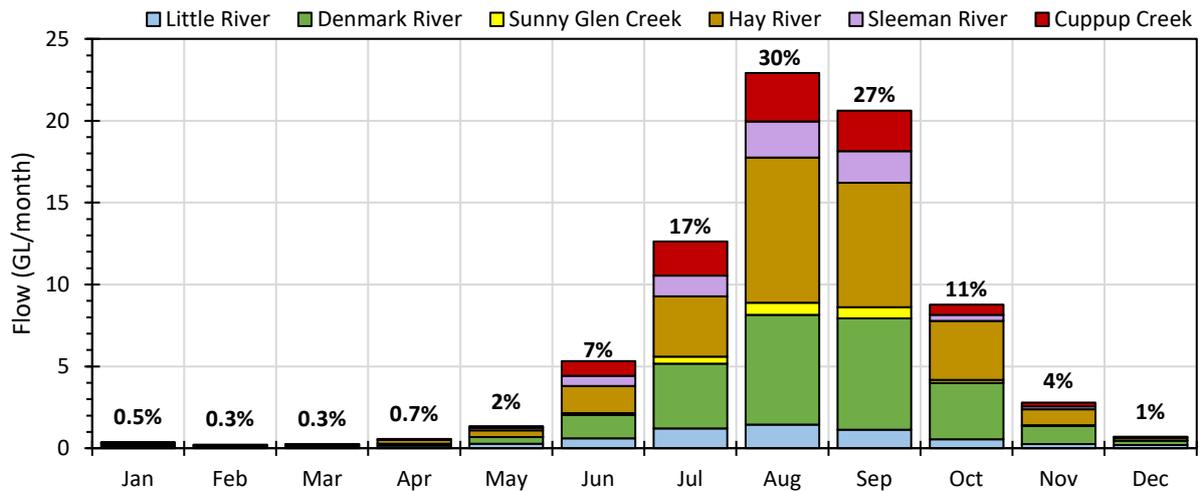
Figure 2.9: Average monthly measured flow contributions to Wilson Inlet (2010–19). Coloured bars show the contributions from end-of-catchment flow sites. Percentages above each month are the proportion of annual flow calculated from the sum of these flow sites.
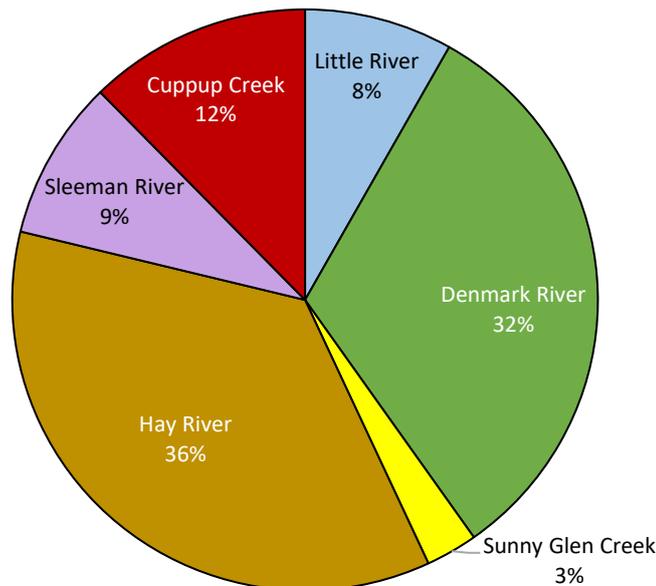
Figure 2.10: Proportion of measured average annual flow (2010–19)
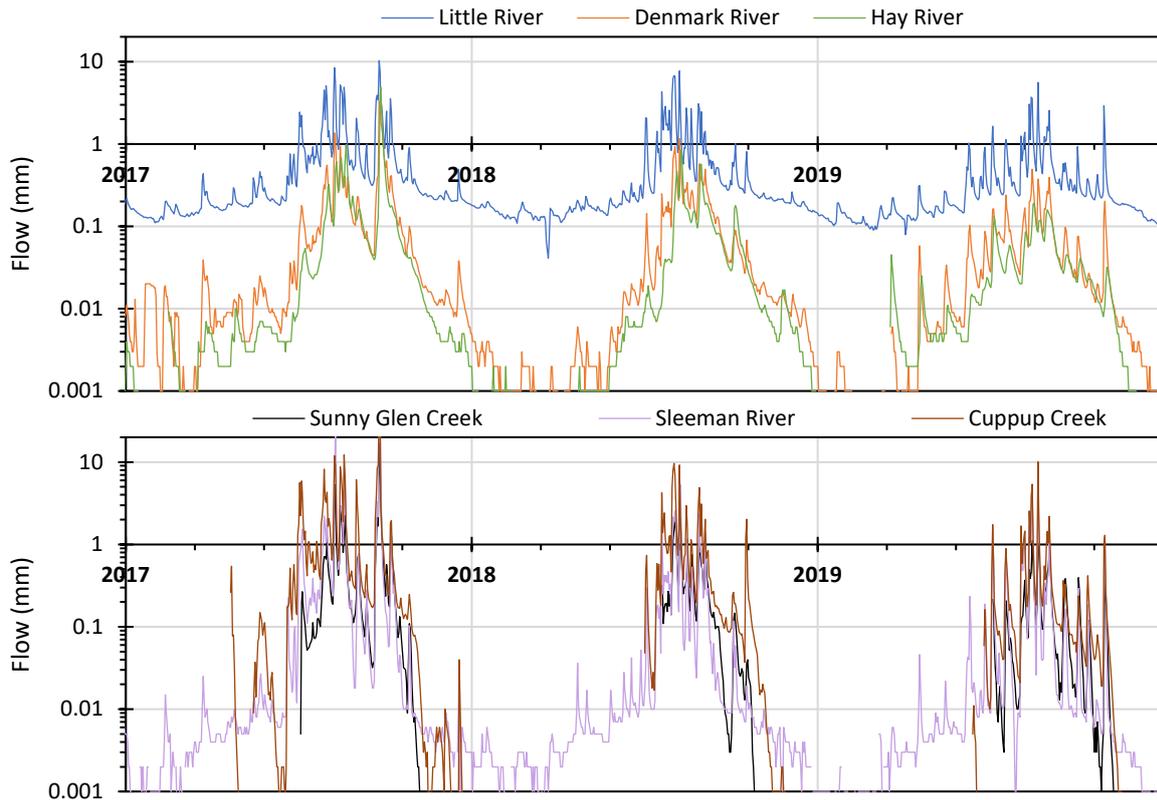
Figure 2.11: Log of daily measured flow yield from 2017–19
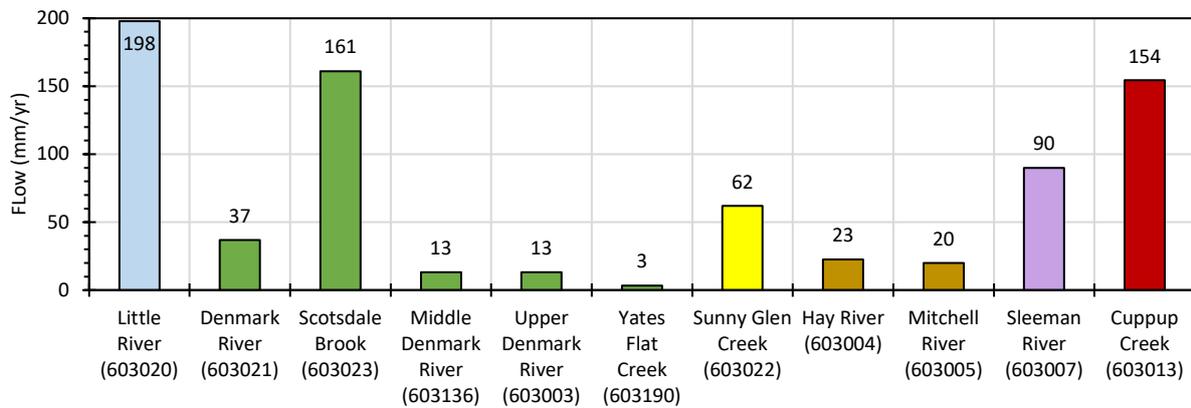
Figure 2.12: Average annual measured flow yield (2010–19)
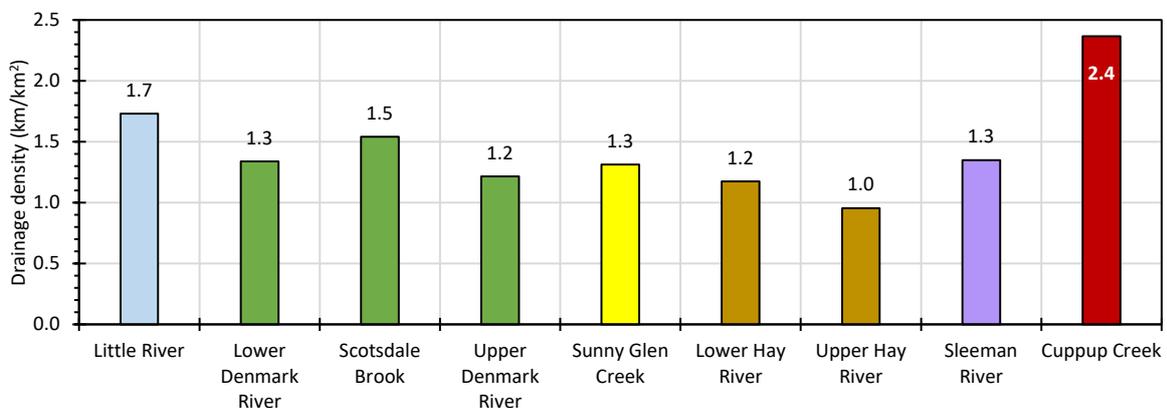
Figure 2.13: Reporting catchment drainage density

2.4 Water quality

Below is a summary of the water quality monitoring data for the Wilson Inlet catchment collected through the department's catchment report cards. Three-year winter medians (2017–19 during the months of June to October inclusive) are used to characterise nutrient concentrations. A three-year median reduces the impact of interannual variability. Because most catchment flow typically occurs between June and October, calculating the three-year median over this 'winter' period results in a statistic that better represents the concentrations when most of the catchment nutrient load is generated. From November to May, most waterways are either dry, not flowing, or flow is low to near-stagnant. Nutrients associated with these flows represent a very small fraction of the nutrient loads, and the concentrations can be misleading due to internal nutrient cycling in warm, near-stagnant waterways. Hence we have not used data from November to May.

We have compared the measured three-year winter median concentrations with the water quality targets that are commonly used in the water quality improvement plans for south-western Australia. These are 1.2 mg/L total nitrogen (TN) and 0.1 mg/L total phosphorus (TP) in lowland catchments (<150 mAHD) and 0.45 mg/L TN and 0.02 mg/L TP in upland catchments (see Section 6 for more information about these targets). Note that only one site (6031477 – Upper Hay) has its entire catchment in upland areas.

Figure 2.14 shows the three-year median concentrations that are calculated at measurement sites, with catchments coloured red if they exceed targets, or green if they are at or below target concentrations. Catchments downstream of measurement sites are coloured grey (unmeasured catchments). Figure 2.15 shows the components of total nitrogen and phosphorus measurements.
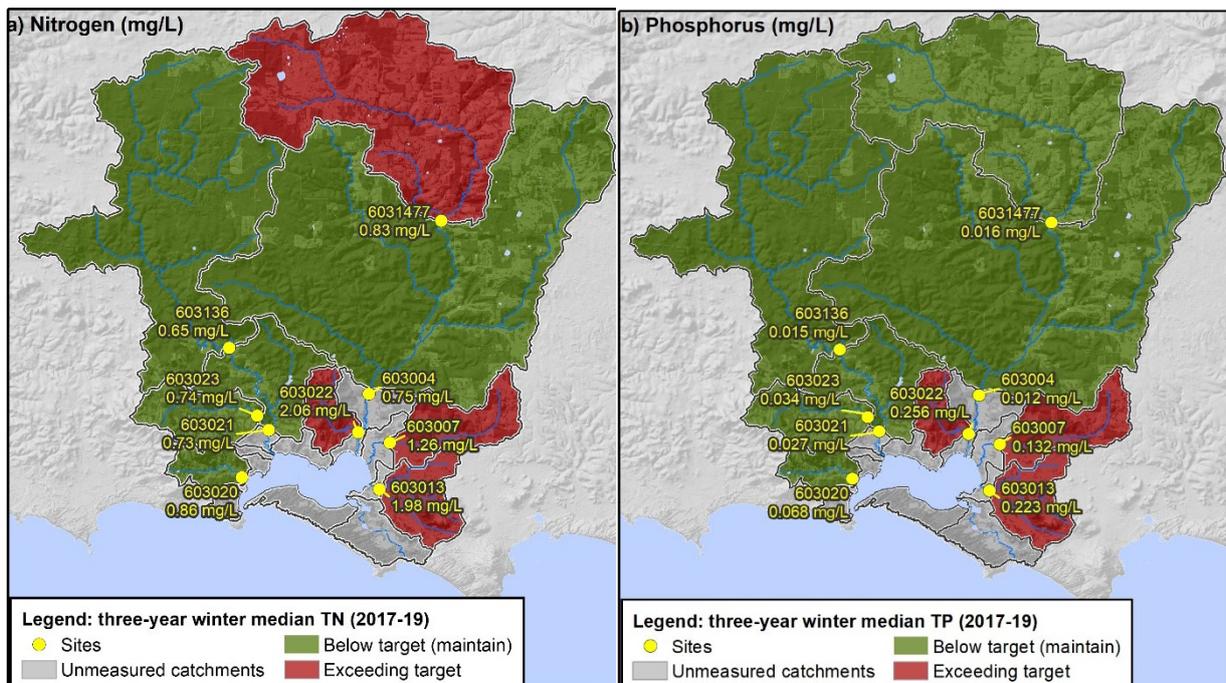
Figure 2.14: Three-year winter median concentrations calculated from measurements and upstream catchments that exceed concentration targets
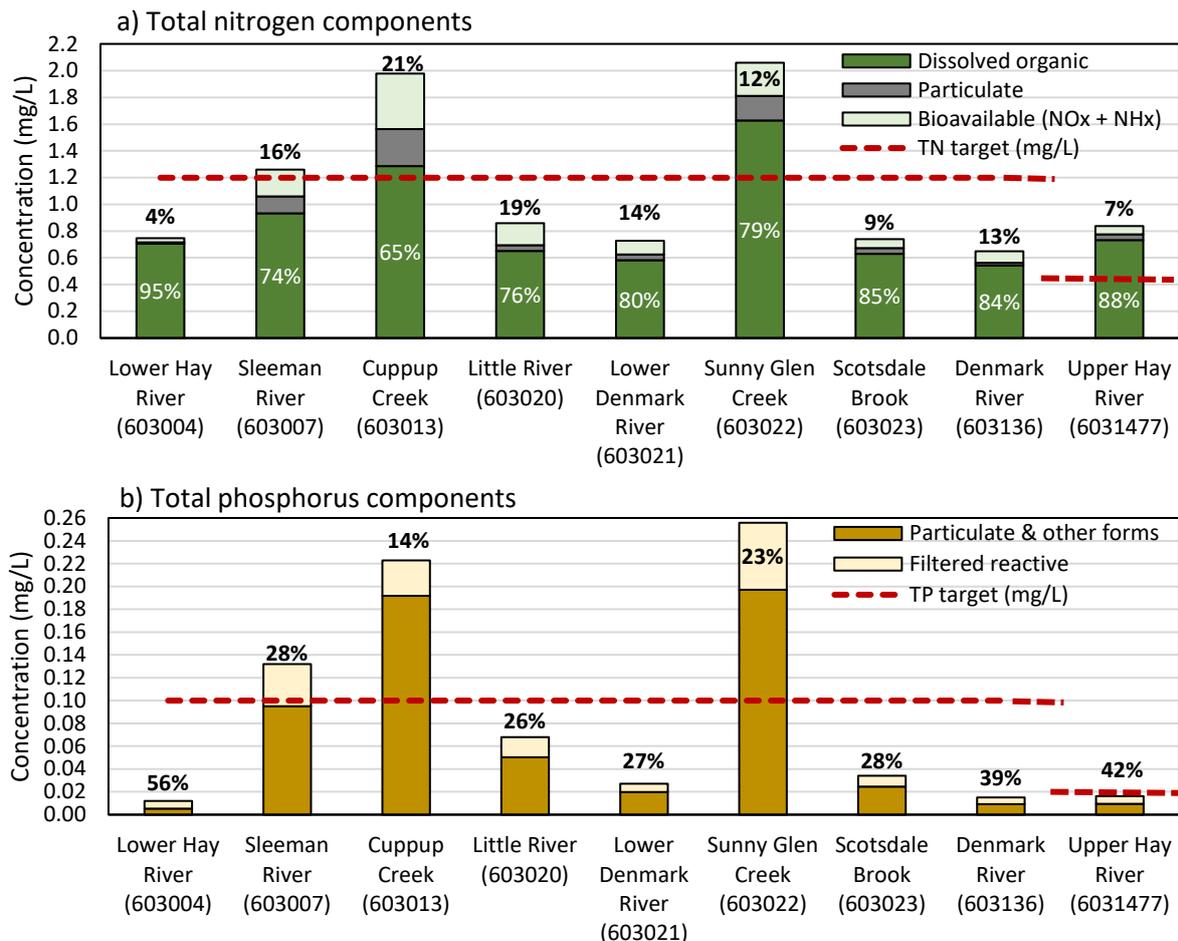
Figure 2.15: Components of total nitrogen and total phosphorus measurements

Bioavailability of nutrient species

Bioavailable nutrients are those that are immediately available for uptake by bacteria, plants and algae through biological processes. Oxidised nitrogen (nitrate + nitrite) and total ammoniacal nitrogen (ammonia + ammonium) are highly bioavailable. Dissolved organic nitrogen (DON) forms most of the TN pool in the waterways that flow into Wilson Inlet (typically 80%, see Figure 2.15). The bioavailability of DON is more complex, and less easily understood.

DON contains a mixture of diverse molecules, of which a great part is of unknown chemical structure. DON is mostly derived from decaying organic matter, comprising molecules with both high bioavailability and low bioavailability. The DON pool also includes urea. Urea can originate from mammal urine and is also a major agricultural fertiliser. Urea breaks down rapidly in the soil to form ammonium and carbon dioxide, and whilst it is not used by biota directly, it is considered a highly bioavailable component of DON.

Recent studies in the Peel-Harvey catchment found that 4 to 14% of DON was converted to bioavailable forms within 10 days under freshwater laboratory conditions with a simulated diurnal day/night cycle (Martin & Middleton 2023). Investigations by Petrone et al. (2007) in the Swan-Canning catchment (Perth, Western Australia) found the bioavailable portion of DON to be 28% on average (4 to 44%) after 14 days incubated at 25°C. The bioavailable

portion of DON was 4% for a forested catchment, 20% for the Avon River catchment at Walyunga (AWRC ref. 616011) and 21% to 46% for eight mixed urban and agricultural catchments. The proportion of DON in TN measurements in these same catchments was 63%, 86% and 46 to 86% respectively. In the Wilson Inlet catchment, DON makes up 65 to 95% of TN concentration measurements.

We used a conservative tracer model to investigate how long nutrient-rich water from the catchment takes to reach the ocean once it enters Wilson Inlet from the main rivers and creeks.[3] This modelling found that after 31 days, only half the tracers had exited to the ocean, indicating a long residence time for catchment inflows even when the sandbar is open. This, combined with the findings on DON conversion to bioavailable forms (in the studies mentioned above), suggests DON contributes enough bioavailable N to warrant management. For instance, of the 108 tonnes/yr of nitrogen estimated to be delivered to Wilson Inlet, if 78% of nitrogen was DON, 14% was dissolved inorganic nitrogen (DIN) and 8% was particulate (assume the latter is completely recalcitrant in this example):

- If DON had a bioavailability of 5% (i.e. a small value) then it would contribute about 22% of the total load of DIN from catchment sources.

- If DON had a bioavailability of 15%, then about 46% of the total load of DIN from catchment sources would be produced by DON.

This suggests that even if a small proportion of DON is bioavailable then it would produce enough bioavailable nitrogen to warrant management.

However, most management actions do not impact the non-bioavailable proportion of the DON pool. This can be problematic when attempting to meet N targets in catchments with a high proportion of DON (e.g. the Sunny Glen Creek catchment). From a value-for-money point of view, it may be desirable for managers to target catchments with a high bioavailable N load, rather than those comprised mostly of DON.

Filterable reactive phosphorus is the pool of phosphorus (P) that is bioavailable or can be bound chemically or electrostatically to particles that contain iron, aluminium or calcium. Whilst particulate phosphorus is not immediately bioavailable, it can be released through biological processes that encourage desorption, or it can be released chemically/ biochemically from sediments into the water column. Biochemical release of P from sediment into a soluble form can be a rapid process in low-oxygen environments. Thus, both the particulate and the soluble component of P are important to manage, as both have the potential to readily supply P for biological processing.

2.5   Topography, geology, hydrogeology and soils

The catchment's elevation, geology, hydrogeology and soils are important and interrelated topics that influence catchment hydrology and the processes of nutrient retention and loss.

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[3] Modelling completed by the department and presented to members of the Denmark community on 22/9/2021 at a community estuary forum event.

We have distilled the relevant aspects of these topics to help build an understanding of the relevant characteristics of the catchment.

Topography

Figure 2.16 shows the surface elevation of the Wilson Inlet catchment. From south to north, the catchment starts with limestone cliffs reaching up to 180 m in height, and then transitions to sea level at the foreshore of Wilson Inlet. There is a gradual upward slope in the terrain from the inlet to the northern headwaters of the Denmark and Hay rivers. The region has pronounced land undulation, which has greater undulation and slope to the west of the Hay River and less so to the east.

The headwaters of the Denmark and Hay rivers are surrounded by moderate to gently sloping hills that lead to flat plains in the Biranup zone (Figure 2.18). These plains can be poorly draining due to their shallow duplex soils and small slope. The upper catchments of the Denmark and Hay rivers feature steep incisions through these plains.

The tallest feature in the Wilson Inlet catchment is Mount Lindesay, with an elevation of about 460 m AHD. The Denmark River flows through Lindesay Gorge just west of Mount Lindesay, which is about 60 m AHD. The landscape east of the Hay River is generally less undulating, with exceptions being the area around Mount Barker and the region between the Sleeman River and Blue Gum Creek.

Wetlands are associated with flat and waterlogged land in the Hay River and Blue Gum Creek catchments. There are considerable areas of flat terrain surrounding Lake Eyrie, Lake Barnes, Lake Mowilyilip, Kokokup Lake, and Quechinup Swamp near Blue Gum Creek (see Figure 2.1), each of which have been extensively drained by farmers. Similar flat terrain surrounds Pardelup Lagoon at the headwaters of the Hay River catchment. Wetlands and associated flat terrain are not prevalent in the Denmark River catchment.

Flat, swampy land dominates most of the lower east portion of the Wilson Inlet catchment, which gradually increases in grade from the inlet to the eastern boundary. The Sleeman, Cuppup and Lake Saide catchments in this area have extensive artificial drainage due to their flat landscape and heavy soils. Outcrops of granite and gneiss are the only significant elevation in these catchments, forming part of the eastern boundary. However, lower-lying sections of this boundary can be as low as 20 m AHD. It is believed that during the 2 million years when sea levels were higher, the Wilson Inlet covered most low-lying areas in these catchments and may have been part of a larger coastal lagoon extending to Princess Royal Harbour (Hodgkin & Clark 1988).

Little River lies to the west of Wilson Inlet, with Mount Hallowell (290 mAHD) to the south and Mount Shadforth (310 mAHD) to the north.
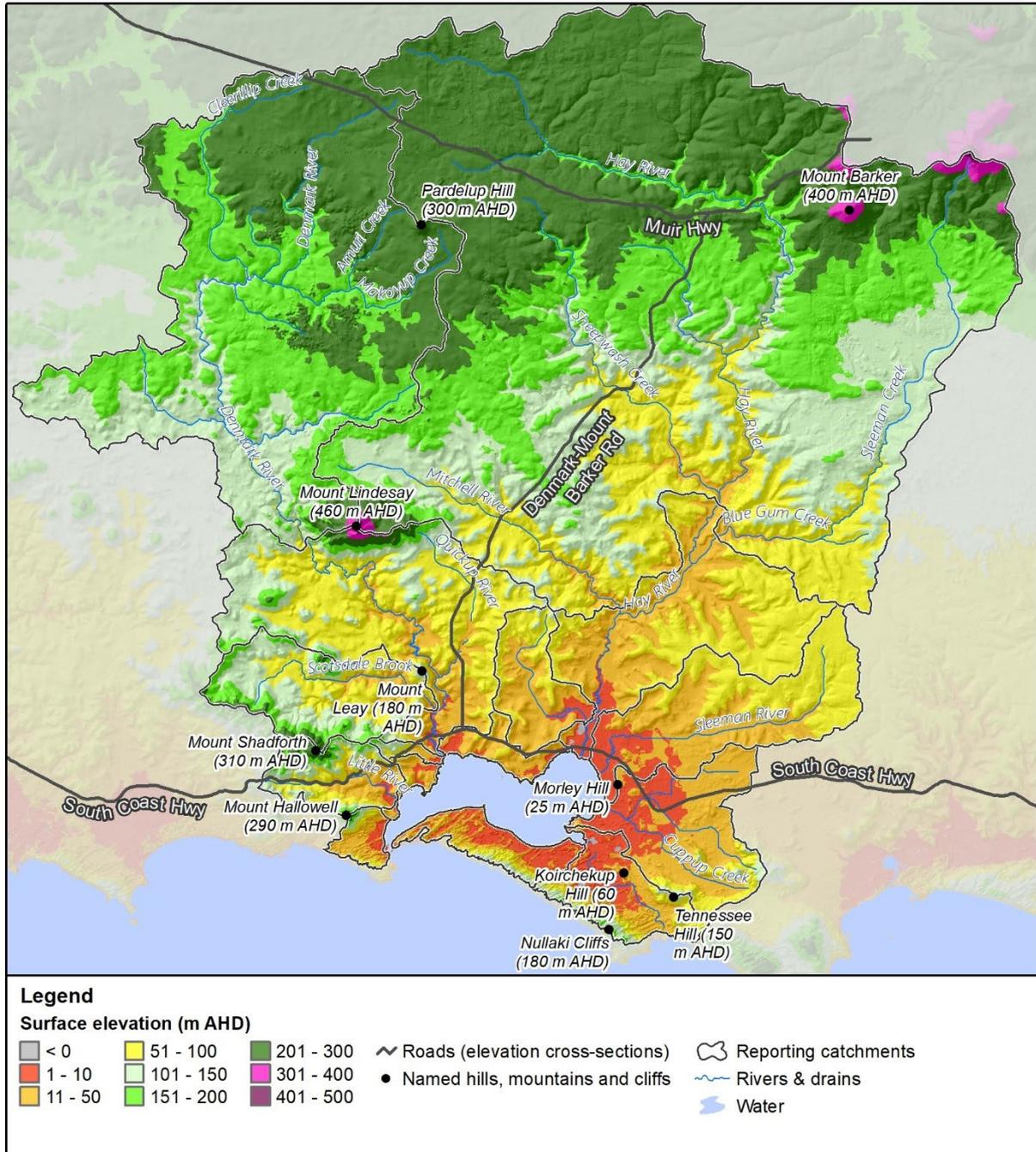
Figure 2.16: Surface elevation and named hills, mountains and cliffs
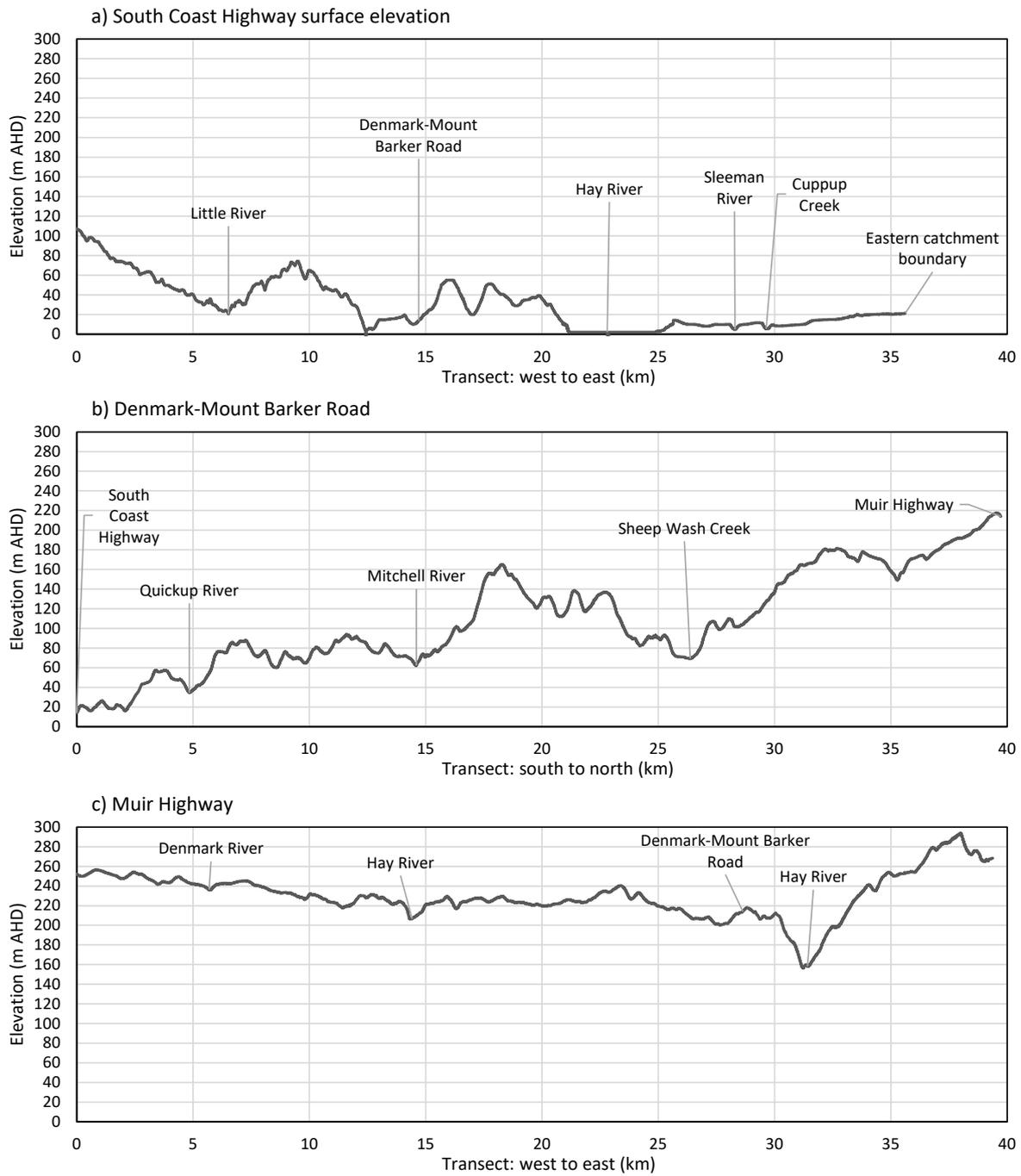
Figure 2.17: Surface elevation of the a) South Coast highway, b) Denmark–Mount Barker Road, and c) Muir Highway. See Figure 2.16 for the location of these roads.

Geology

The Wilson Inlet catchment is part of the Nornalup and Biranup zones of the Albany–Fraser orogen, a region formed by a series of mountain-building geological events (see Figure 2.18). The basement rock consists of metamorphic orthogneiss with intrusions of igneous metagabbro and remnant Archean granite (Spaggiari et al. 2014). The formation of these basement rocks occurred 1,140 to 1,810 million years ago through a series of geological events. The Stirling Ranges to the north-east of the catchment also formed during this period, while the Porongurup Ranges formed in its latter stages (1,140 to 1,330 million years ago).

The break-up of Gondwana resulted in the separation of India from Australia on the west coast (119 to 280 million years ago) and the separation of Australia and Antarctica on the south coast (42 to 150 million years ago) (Commander et al. 2000). This resulted in mountain building across most of south-west Western Australia, as well as the reversal of some southerly flowing rivers between Bremer Bay and Esperance (Beard 1999). The breakup of Gondwana does not appear to have altered the drainage of the Wilson Inlet catchment to the extent that occurred to the catchments between Bremer Bay and Esperance (Beard 1999).

The Nullaki cliffs mark the southern catchment boundary of the inlet. These limestone cliffs are up to 180 m tall in some locations. The formation of these cliffs is suggested to have occurred 120,000 to 130,000 years ago during the last interglacial period (Hesp 1993).

It is important to note the impact of sea-level rise since the last ice age – about 19,000 to 21,000 years ago – when sea levels were about 125 m lower than the present (Lewis et al. 2013). The ocean shoreline was beyond the continental shelf, which is about 40 to 90 km south of its current location. Wilson Inlet may have been a river valley that went beyond its current sandbar, flowing many kilometres before perhaps draining to estuaries located at or beyond the continental shelf. Between 2,000 and 8,000 years ago sea levels may have been 1 to 2 m higher than the present, before lowering to current levels (Lewis et al. 2013). The inlet is estimated to have formed about 6,500 years ago (Hodgkin & Hesp 1998).
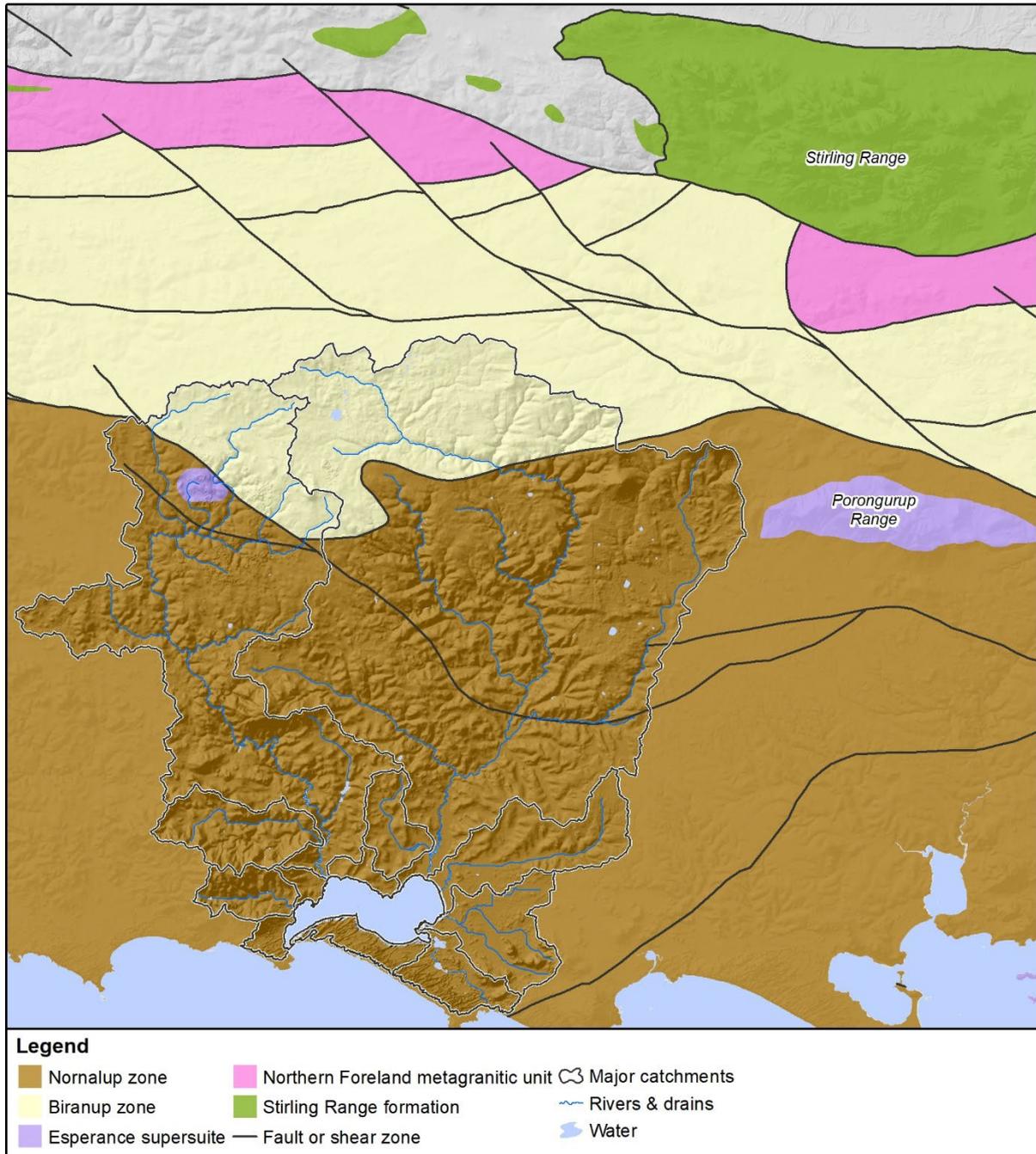
Figure 2.18: Basement geology, faults and shear zones

Hydrogeology

The Wilson Inlet catchment has relatively limited groundwater resources and thus has not been studied to the same extent as the Albany groundwater area to the east. The entirety of the inlet's catchment is classified as an unproclaimed groundwater zone, meaning that the department does not regulate groundwater abstraction.

We show the department's 1:250 000 hydrogeology and groundwater salinity maps of the Wilson Inlet catchment in Figure 2.19. We also incorporated stratigraphy age data into Figure 2.19, which is from the Australian Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission 2017).

Most of the Wilson Inlet catchment (90%) has localised fractured rock aquifers with limited to no groundwater resources. We summarise the remaining areas where groundwater resources are greater, based on information from Smith (1997) and Ryan et al. (2017).

Aquifers of surficial Quaternary and Cainozoic sediments (5% of catchment area):

These aquifers formed during periods of higher sea levels and consist of limestone, sand, silt, clay, gravel and gypsum. Surficial sediments can be up to 70 m thick along the coast but are generally about 10 m thick inland from the coast (e.g. adjacent to the Hay River – see Smith 1997). The salinity of groundwater at the watertable is generally less than 1,000 mg/L except for areas adjacent to the Hay River where salinities range from 1,000 to 3,000 mg/L (Smith 1997).

Plantagenet group (5% of catchment area):

The Plantagenet group includes the Pallinup siltstone formation which can overlay the Werrillup formation:

- The Pallinup formation is an unconfined aquifer that consists of unconsolidated silts with interbedding of fine silts, sands and clays. The surface of the Pallinup may have lateritic sediments. In the King River area (in the Torbay/Oyster Harbour catchments), the Pallinup formation has an average thickness of 15 m (7–40 m). Groundwater supply is likely to be small due to the low permeability of the aquifer. Salinity of the aquifer ranges from under 1,000 mg/L to about 3,000 mg/L.

- The Werrillup formation consists of an upper clay aquitard followed by a lower sandy aquifer and is only found in paleochannels or on the coastal plain. The Werrillup aquifer is <24 m thick in the Torbay/Oyster Harbour catchments and can be more than 50 m below ground (Ryan et al. 2017). The top of the Werrillup aquifer generally has salinities of less than 1,000 mg/L but can become increasingly saline with depth.

The largest areas of the Plantagenet group aquifers are in the eastern half of the Sleeman catchment and adjacent to Lake Eyrie in the Upper Hay. Surface outcrops of the Werrillup formation are found to the south-west of Lake Eyrie. Small fragments of the Plantagenet group are found just north of Wilson Inlet.

Legend

Aquifers

Surficial aquifer: local aquifer, possible sedimentary aquifer beneath, minor groundwater resources

- Quaternary (Qa): 0 to 2.6 Ma
- Cainozoic (Cza): 0 to 66 Ma

Sedimentary aquifer with intergranular porosity: extensive aquifers, major groundwater resources

- Plantagenet group (TP): 36.5 to 51.5 Ma
- Werillup formation (TPw): 39.5 to 51.5 Ma
- Werillup formation outcrop (TPwo): 39.5 to 51.5 Ma

Fractured rock and saline aquifers: Proterozoic

- Fractured and weathered rocks: local aquifer, minor groundwater resources
- Fractured and weathered rocks: local aquifer, very minor or no groundwater resources
- Very minor local aquifers; saline

Groundwater salinity at the watertable   ⌂ Reporting catchments

- < 1000 mg/L   ∿ Rivers & drains
- > 1000 mg/L   �£ Water

Figure 2.19: Groundwater resources

Soils

Figure 2.20 shows the three soil supergroups in the Wilson Inlet catchment (Schoknecht & Pathan 2013). Soil supergroups are a high-level classification of the broad soil types which include ironstone or gravelly soils (i.e. lateritic soils), deep sandy soils and waterlogged soils.

Legend

- Deep sands
- Ironstone gravelly soils
- Wet or waterlogged soils
- Blackwater gleyed duplex phase
- Low phosphorus retention index (<7)

- Reporting catchments
- Rivers & drains
- Water
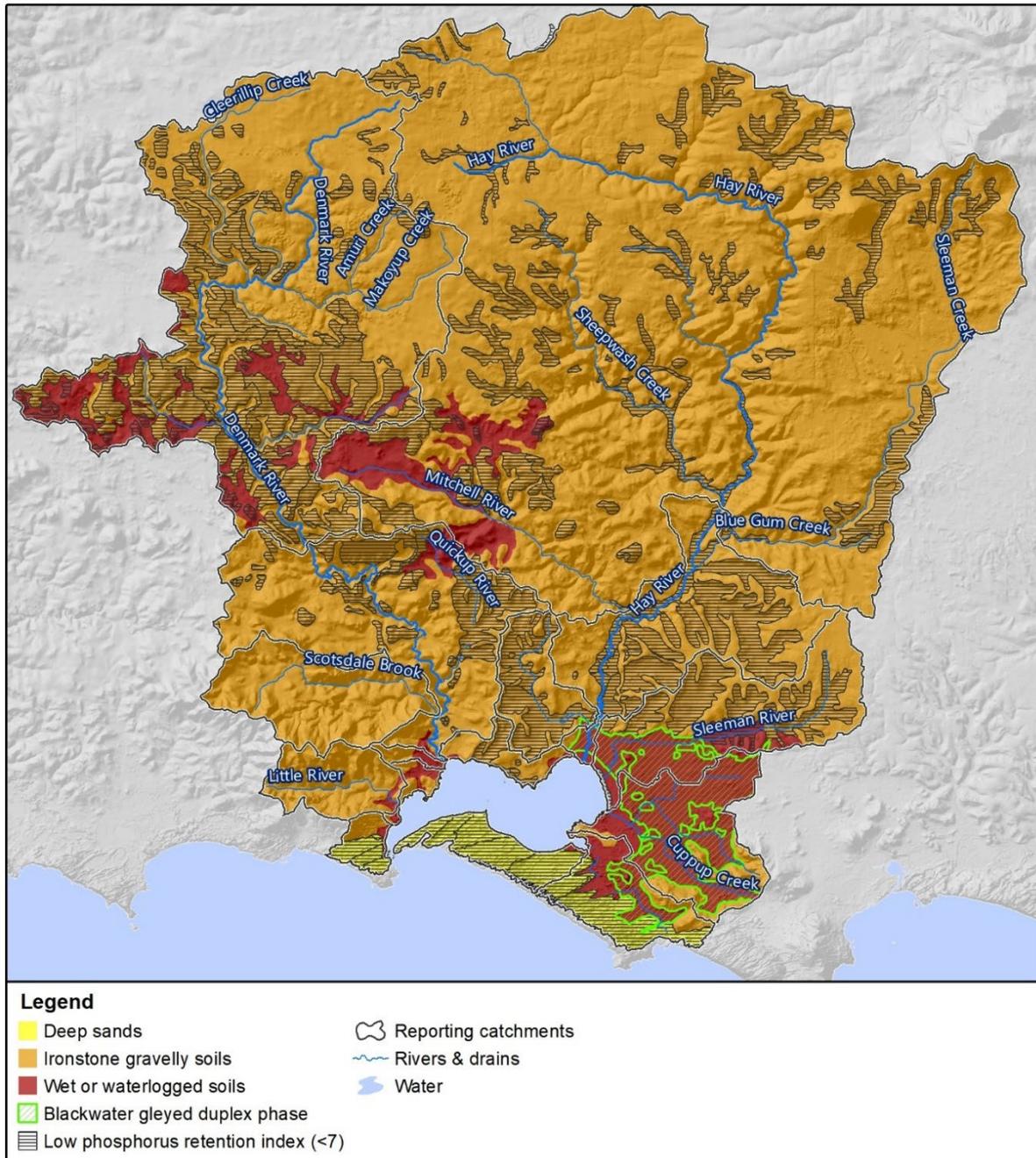
Figure 2.20: Soil supergroups, the Blackwater gleyed duplex phase and low phosphorus retention index soils (<7)

Most of the Wilson Inlet catchment has **ironstone soils**. We have briefly described the soils found on a hill crest, slopes and valley floor:

- At the crests of hills, the soils are generally gravelly lateritic soils, stony soils or can have coarse sandy soils as well as areas of exposed rock.

- The slopes of hills typically have duplex soils[4], deep sands or gravelly earths. Lateritic soils are common and consist of red earthy soils with deep sands that can exist in place of duplex soils in some locations. Stoneman (1990) refers to these soils as Kojaneerup sands, deep sands or sandy duplex soils which are seen on the Denmark–Mount Barker Road near Quickup River and at the junction of Hunwick and Hennings roads in the Sleeman River catchment (see Figure 2.21).

- The valley floor can contain swampy soils that are heavier in clays or can contain similar soils as described for the slopes. Generally, swampy soils are found in lower-order streams or in areas with wetlands, such as in the mid to upper catchment.
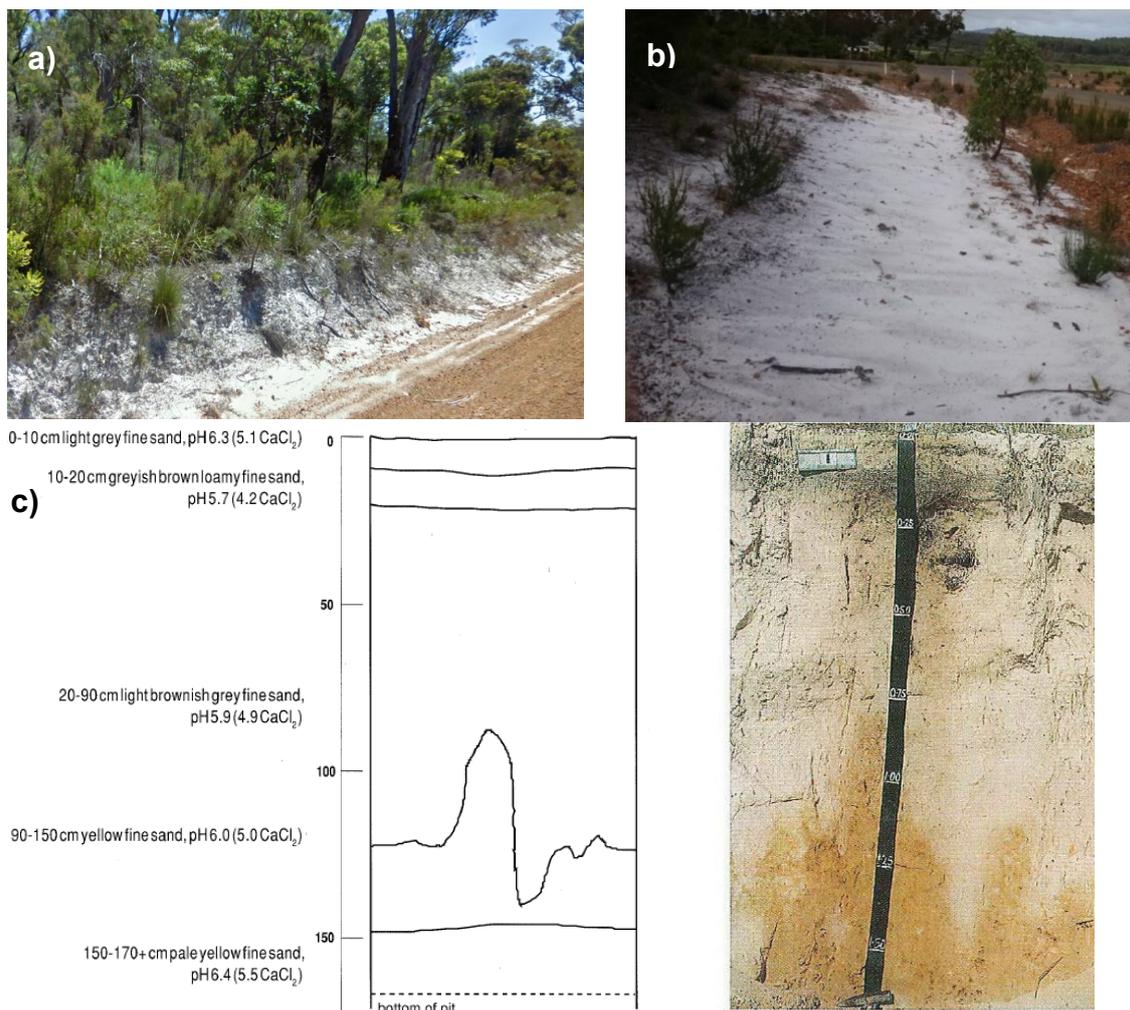
Figure 2.21: Deep sands a) near Quickup River on Denmark–Mount Barker road, b) the intersection of Hunwick and Hennings roads (Sleeman River catchment), and c) a soil profile description and photo of Kojaneerup deep sands (Stoneman 1990)

Waterlogged soils are present throughout most of the Sleeman and Cuppup catchments, as well as areas of the vegetated portions of the Denmark and Hay river catchments. We show

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[4] Duplex soils have contrasting textures of their topsoils and subsurface soil layers.

the waterlogging risk based on the land characteristic dataset from DPIRD in Figure 2.25 – this is mapped at a higher resolution (i.e. soil phase) than the soil supergroups shown in Figure 2.20. The main **waterlogged soils** in the Wilson Inlet catchment are:

- **Blackwater soils (Lower Hay, Sleeman, Cuppup and Lake Saide catchments):** The waterlogged soils of the Sleeman and Cuppup catchments are part of the Broke system. The soils here are typically shallow gleyed[5] duplex phase, which have sandy or loamy topsoils that are underlain by heavy clays. Podzols (leached grey sands) occur under dunes. The flat terrain, combined with the heavy subsoils, makes this area very susceptible to waterlogging. The depth of subsurface clay varies, as seen by the shallow heavy clays in a Cuppup drain (Figure 2.22b) compared with the lighter soils (fine sands to loams) in the drained portion of the Sleeman River (Figure 2.23b). Mapping of the soil phosphorus retention index (PRI) shows that the entire soil phase has good phosphorus retention (PRI ≥7). However, grey sands are visible across large areas (Figure 2.23a, b) and soil test data indicates that about 26% of the area should be classified as low PRI (<7). This area was one of the last in the catchment to be drained for agriculture in the 1950s and 60s. This soil type is not detailed by Stoneman (1990).

- **Caldyanup soils (upper Hay and Denmark catchments)**: Caldyanup subsystem soils have large flat plains with shallow yellow sandy duplex soils and deep humic sands (peaty sands). These soils retain their native vegetation (i.e. clearing for agriculture has not occurred).

The **deep sands** supergroup represents the coastal soils of the Nullaki Peninsula and the area of land that is approximately east of Ocean Beach Road and south of Lights Beach Road. This area has leached sandy soils with low phosphorus retention and overlies calcareous sand dunes.

Figure 2.22: Blackwater gleyed duplex soils (September 2020) a) waterlogged soils in a paddock just east of the Cuppup Creek catchment and b) the heavy subsurface clays exposed in Cuppup drain

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[5] Gleyed soils are formed in waterlogged conditions with low oxygen and are typically grey in colour.

Figure 2.23: Blackwater gleyed duplex soils along Sleeman Road (March 2024) a) a shallow drain of a beef farm showing the grey sandy topsoils, and b) the drained section of the Sleeman River showing sandy to loamy soils with no noticeable heavy subsurface clays.

Soil phosphorus retention and waterlogging

Soils with a phosphorus retention index (PRI) less than 7 have a greater risk of leaching phosphorus to groundwater and surface water. These soils have a low capacity to hold phosphorus, leading to higher rates of phosphorus loss to groundwater and surface water when phosphorus is applied as fertiliser. See detailed mapping of the PRI of the catchment's soils in Figure 2.24 and further discussion of PRI in sections 3.1.2 and 3.2.

All of the deep sands supergroup have low-PRI soils (see Figure 2.20). Significant areas of low-PRI soils are found in the Lower Hay, Sleeman, Sunny Glen and Quickup catchments and parts of the Upper Denmark River catchment. We noticed that low-PRI soils are associated with the slopes and crests of hills in the Denmark River catchments. In contrast, low-PRI soils tended to be associated with the slopes and valley floor of hills (elevations of about 50 mAHD and below) in the Lower Hay, Sleeman, Sunny Glen and Quickup catchments (see Figure 2.16).

The lower sections of the Sleeman catchment and the entire Cuppup catchment have high (>7) PRI soils. However, the heavy soils and flat terrain mean that these areas are highly prone to waterlogging and as such have extensive artificial drainage (see Figure 2.25). The high drainage density and waterlogging mean that these areas have an increased risk of nutrient loss. As a result, these catchments contribute most of the nitrogen and phosphorus to the inlet despite having large areas of high-PRI soils.

Waterlogging risk is also problematic in areas adjacent to the inlet and in areas associated with wetlands, such as the Blue Gum Creek catchment (Upper Hay) and the northern parts of the Upper Hay. There is also extensive artificial drainage next to Lake Barnes (see Figure 2.25). Swampy soils or soils associated with flat plains also have extensive waterlogging, as can be seen throughout the Upper Denmark catchment, however these areas are mostly uncleared.
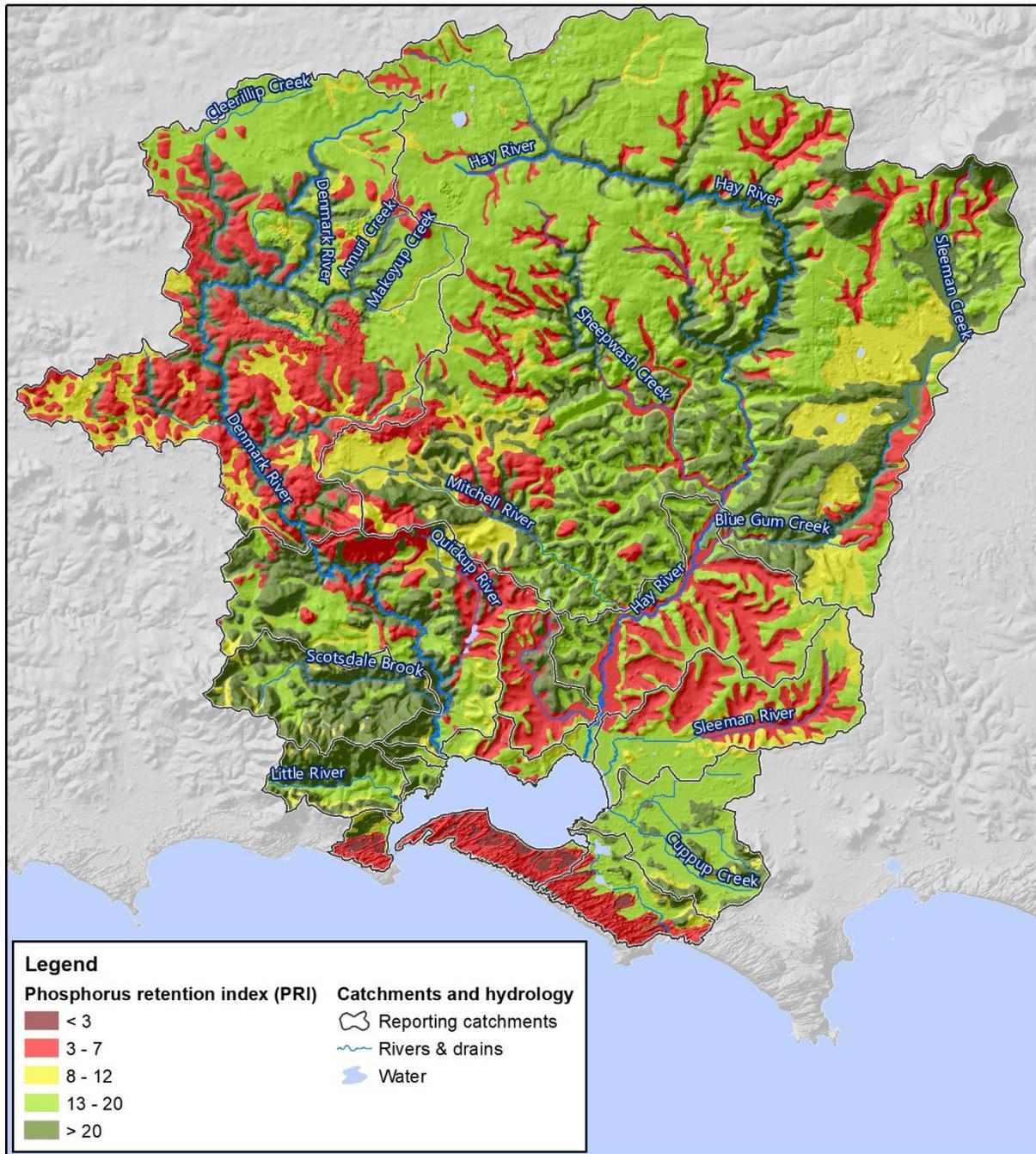
Figure 2.24: Soil phosphorus retention index (DPIRD). Soils with a PRI less than 7 are poor at retaining phosphorus.
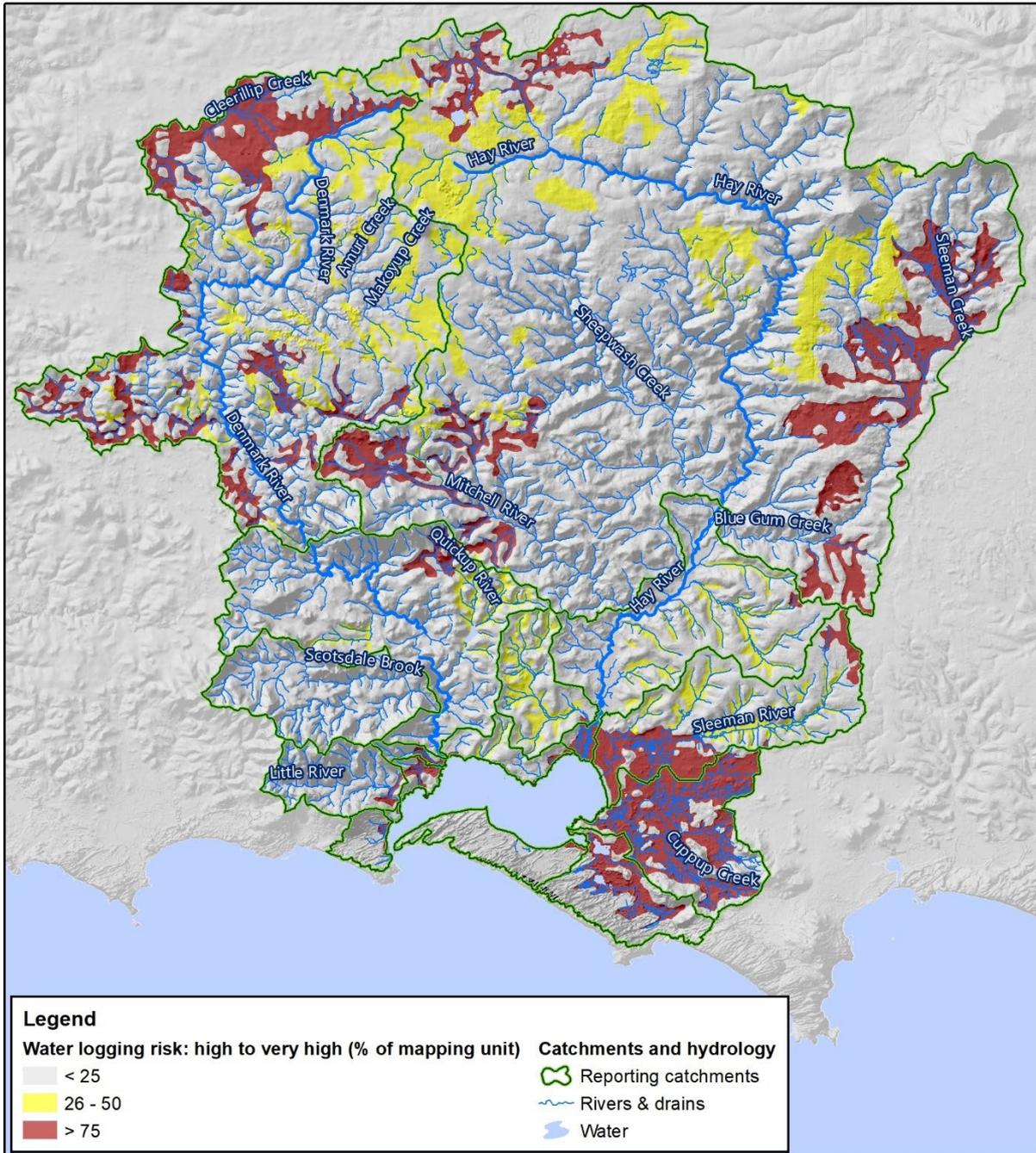
Figure 2.25: Waterlogging risk and drainage

3 Model description and data

3.1 Modelling framework and model description

We used the eWater Source model framework (version 4.11) for the catchment modelling. Source is highly flexible and can create an integrated model tailored to a specific problem. Constructing a model for a particular catchment management situation involves selecting appropriate component models and linking them in the software (including rainfall-runoff models, nutrient export and filtering models, and streamflow routing models). Source is based on the following building blocks:

- **Catchments**: The subcatchment is the basic spatial unit, which is then divided into hydrological response units (or functional units) based on a common response or behaviour such as land use. Within each functional unit, users can assign three models: a rainfall-runoff model, a constituent (nutrient) generation model and a filter model.

- **Nodes**: Nodes represent subcatchment outlets, stream confluences or other places of interest such as stream gauges or dam walls. Nodes are connected by links, forming a representation of the stream network. We have used inflow nodes in this model to include sources of flow and nutrients that are external to the hydrological and nutrient models (e.g. dam releases, dam water transfers, point sources and septic tanks).

- **Links**: Links represent the river reaches. Within each link, users can apply a selection of models to delay the movement of water along the link or apply constituent decay models.

Source has a wide range of data pre-processing and analysis functions that allow users to create and compare multiple scenarios, assess the results, and report on the findings. It features auto-calibration tools to optimise model parameters based on a specified objective function. Source is becoming a national standard for catchment modelling and is at the core of the National Hydrological Modelling Platform program (Welsh et al. 2013).

3.1.1 Hydrological model

The hydrological model consists of the following components:

- Flow generation from functional units using the Large-Scale Catchment Model (LASCAM) hydrological model.

- Stream routing in large catchments using storage routing or straight through (i.e. no routing) in smaller catchments.

- Water storage and transfer nodes to represent wetlands, flood management structures, dams, town water abstraction, dam transfers and releases.

We describe each component of the hydrological model below. See Appendix A for further information about the hydrological models tested in this project, model parameterisation and calibration metrics.

Large-Scale Catchment Model (LASCAM)

LASCAM was originally developed for the large temperate-to-arid catchments of the Western Australian Wheatbelt and has been applied to the Avon Basin in other studies (Viney et al. 2000; Ali et al. 2010; Hennig et al. 2015). As such, physical processes specific to this region (e.g. subsurface runoff from duplex soils) are included in the model. However, LASCAM has been demonstrated to be effective in modelling other catchments in south-western Australia. We also compared the model calibration metrics produced by LASCAM and the more widely used GR4J model (Perrin et al. 2003) in the Wilson Inlet catchment (see Appendix A). LASCAM performed better and allowed us to explicitly model the hydrological impact of plantation establishment and reversion from 1984 to the present.

Because LASCAM is partially based on conceptual parameters, it requires calibration to flow measurements. The hydrological component of LASCAM has five fixed parameters and 23 parameters that require calibration (see Appendix A, tables A.2 and A.3)

LASCAM has six core computational components, as illustrated in Figure 3.1 and Figure 3.2.

- **Canopy interception**: a proportion of rainfall is intercepted by vegetation (based on leaf density) and lost through evaporation.

- **Infiltration and runoff**: this component distributes water into the F and A stores (which represent the soil zone and riparian vegetation zone respectively) or to the stream. When the F and A stores become saturated, or when rain falls at an intensity that exceeds the infiltration rate of the soil, runoff to the stream is generated.

- **The A store**: this store represents the riparian zone of a stream or perched aquifer. Inputs to this store are infiltration, subsurface runoff (i.e. groundwater flow) and discharge from the deeper B groundwater store. Outputs occur through evaporation, discharge to stream or infiltration to the B store. Streamflow cannot enter the A store.

- **The F store**: this store represents the unsaturated soil zone. Water enters this store from upslope perching infiltration and surface infiltration. Outputs from this store include infiltration to the B store and evaporation.

- **The B store**: this store represents the deep groundwater. Water enters this zone from the F and A stores. Water is lost from the B store by discharge to the A store and through evaporation.

- **Upslope perching (subsurface saturation)**: this element accounts for saturated land that is largely disconnected from stream networks.

The following daily input data is required: rainfall, potential evapotranspiration, leaf area index (LAI) and the proportion of directly connected impervious areas. We did not use the latter for this project because of the catchment's small impervious area (especially upstream of calibration sites) and the model's sensitivity to this input data.

The LASCAM model generates flows for each modelling catchment and is traditionally used so that LAI values are 'lumped' at the modelling catchment scale. A lumped model would produce flow from functional units based on their proportion of the modelling catchment area. This is despite cleared, vegetated or urban land uses having quite different flow yields for a

given climate. This issue can be mitigated by creating modelling catchments that aggregate land uses with similar flow yields together. However, this is not always possible or practical.
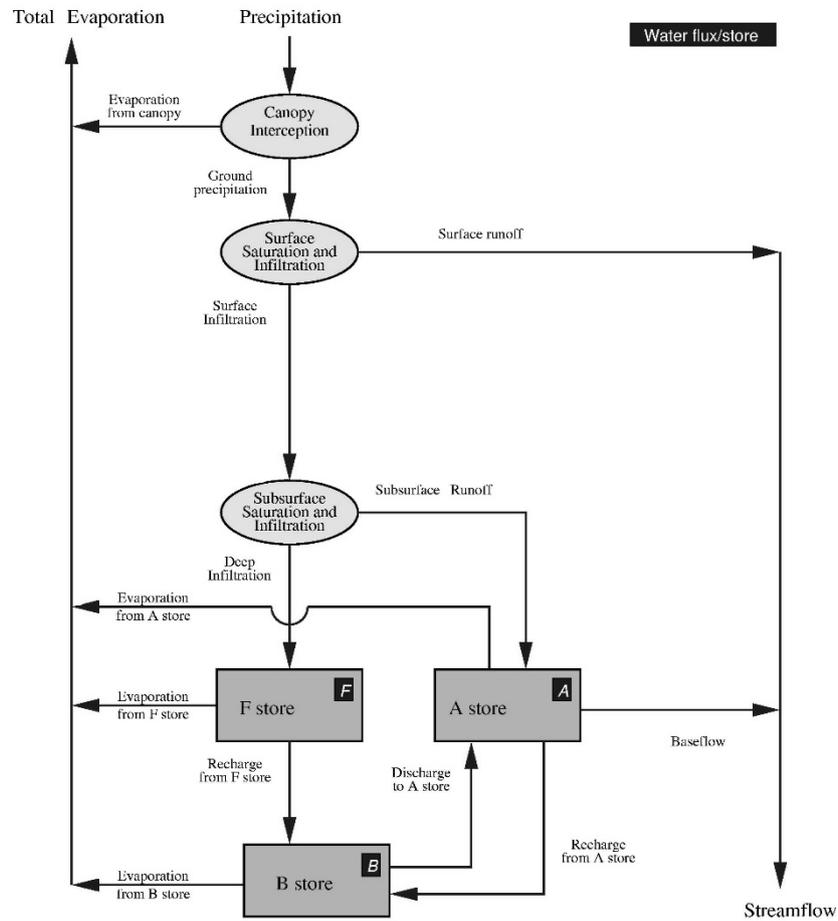
Figure 3.1: Storages and processes in LASCAM (Viney et al. 2000)

Symbol	Definition		
e_A	Evaporation from A store	q_{sse}	Saturation excess subsurface runoff
e_B	Evaporation from B store	p_g	Throughfall
e_F	Evaporation from F store	p_c	Surface infiltration
q_A	A store discharge to stream	f_a	Subsurface infiltration
q_B	B store discharge to A store	r_A	Recharge from A store to B store
q_{se}	Saturation excess surface runoff	r_F	Recharge from F store to B store
q_{ie}	Infiltration excess surface runoff	μ	Upslope perching factore

Figure 3.2: Hill-slope hydrological processes in LASCAM (Viney et al. 2000)

For this project we used LASCAM in a semi-lumped form where LAI is lumped at the modelling catchment scale for three groups of land uses, which we call 'hydrological functional units': cleared, native vegetation and plantations (see Table 3.4). This gave more appropriate flow yields from land uses within modelling catchments at the expense of increased calibration time and model complexity. The area-weighted LAI of modelling catchments is shown in Figure 3.3 to give perspective on the variation of this model input across the Wilson Inlet catchment.
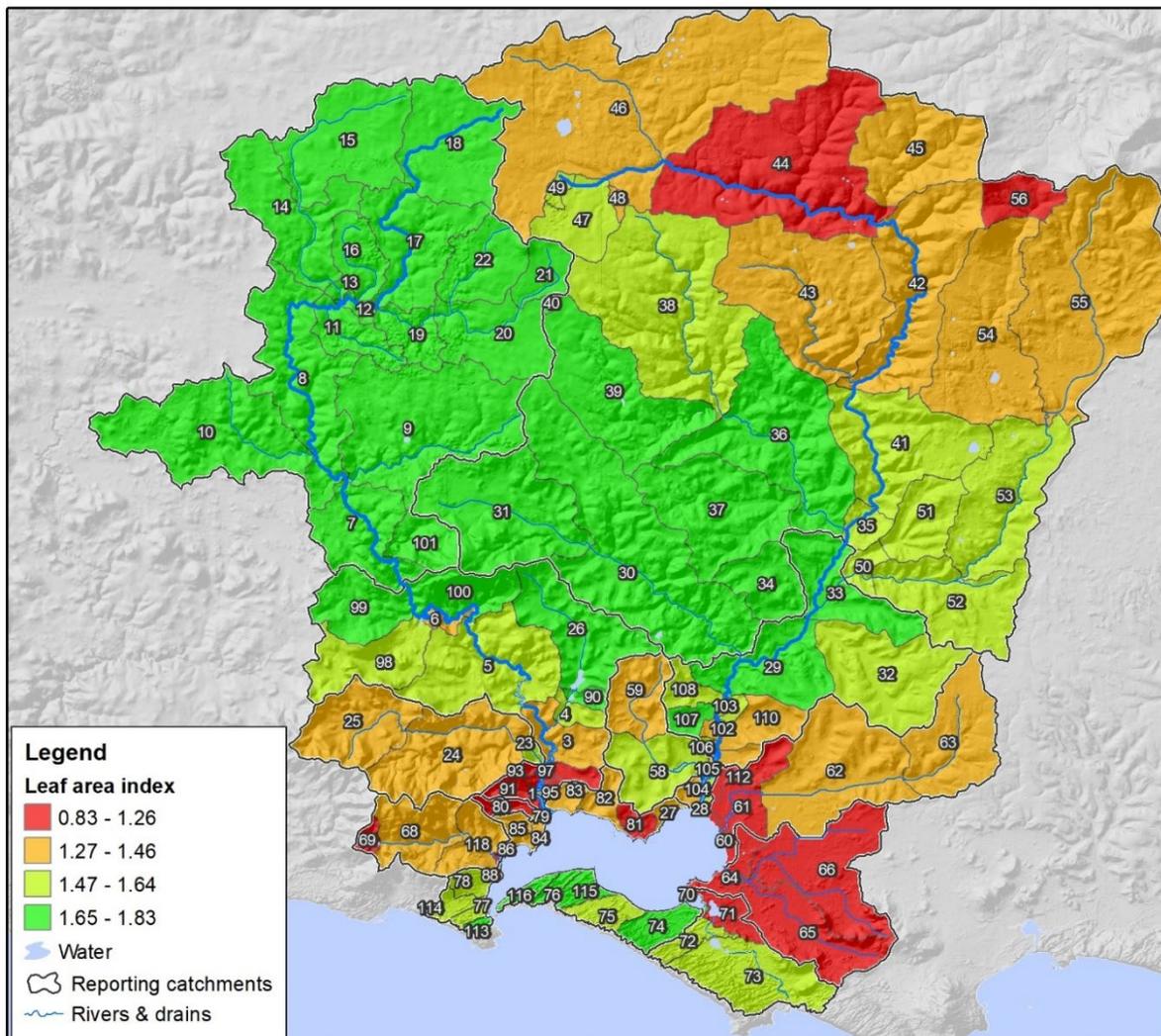
Figure 3.3: Area-weighted modelling catchment leaf area index (LAI)

We included a mechanism in the flow model to represent the flow response to plantation establishment and clearing. This was achieved by modifying the daily LAI input datasets to account for the large-scale land-use changes from pasture to plantations from 1984 to 2010 and partial reversion back to pasture from 2011 to 2020. Testing in the upper Denmark catchment found that a two-year growth response[6] had more desirable model results (see Appendix A). For the first year after planting, areas will have a LAI of 1 (from 1.9), which is

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[6] The number of years it takes for plantations to reach their maximum LAI value when planted. When plantations are at their maximum LAI they have the greatest hydrological impact in the model (i.e. greater evapotranspiration causing reduced groundwater levels and streamflow).

equivalent to a beef paddock. In the second year the LAI increases to 1.45; and in the third year it returns to 1.9. Because plantation LAI is lumped at the modelling catchment scale, there can be multiple plantation areas that are being planted or maturing at the same time. Mature plantations will have reduced rainfall throughfall, increased groundwater evapotranspiration, reduced groundwater levels and reduced surface water flow compared with pasture (Bari & Boyd 1992; Silberstein et al. 2004; Reiter 2012) and plantations in their first year of growth. Note that we tested various plantation LAI responses – see Appendix A.

Figure 3.4 shows the LAI of the hydrological functional units of modelling catchment 18, as well as the net area of plantations in the catchment. The timeline of plantation establishment, harvesting and reversion in modelling catchment 18 is as follows:

- about 400 ha of plantations were progressively established from 1992 to 1999

- in 2008, just over 1,000 ha of plantations were established and have not been harvested since

- in 2011 about 140 ha of plantations were harvested and replanted (see decrease in LAI in Figure 3.4a with no change in Figure 3.4b

- from 2013 to 2016 nearly 220 ha of plantations were reverted to pasture.
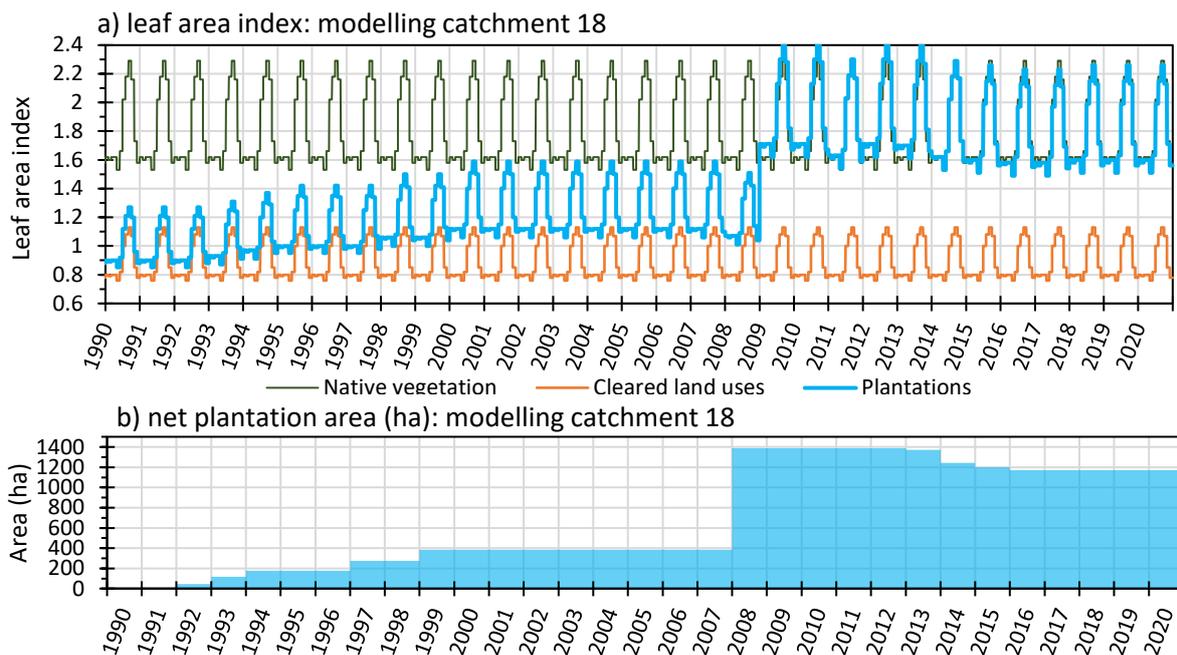
Figure 3.4: Example of a) leaf area index of plantations, native vegetation and cleared land uses, and b) the net area of plantations (area established minus the area reverted)

Stream routing

Stream routing methods are used to delay the timing and magnitude of flow between modelling catchments, to help the model mimic realistic flow patterns. We used two types of stream routing methods for this project:

- **Straight-through routing** (default link model in Source): This method conveys water through a catchment without changes to the timing and magnitude of flow. Straight-

through routing is appropriate for catchments with a time of concentration[7] less than one day. We used this routing method for all modelling catchments that did not receive flows from upstream catchments, as well as when connecting the following node models: storages, inflow nodes, gauges, supply points, water users and minimum flow requirements.

- Storage routing: This routing model can delay the timing and magnitude of flow between modelling catchments and is used for all other link types. We configured storage routing links to use [Muskingum routing](#), which has a storage exponent of 1. The storage exponent determines the shape of the storage-outflow relationship with a value of 1 being linear. All model parameters were set at default values except for:

  - **Reach length**: the distance in metres between modelling catchments using the connected reach from the 'streams' dataset (described in Section 3.2 and given in Appendix B).

  - **Inflow bias (x):** this value was fixed at 0.33 for all links that used storage routing and determined through manual calibration. The inflow bias represents the fraction of storage occupied by inflow.

  - **Storage constant (k):** this was taken as the reach length multiplied by a factor of 1.5 for catchments in the Hay River and a value of 3 for all other catchments. These factors were determined through manual calibration. The storage constant is proportional to the travel time of water in the stream.

Modelling of dams, water abstraction and water releases

Community members have expressed concerns about the impact of dams on river flows and water levels in the Wilson Inlet. It was not possible to comprehensively model the impact of farm dams on river flows in this project, as this would require a specific model design and significantly increase the complexity and run times of the current hydrological and nutrient model. However, we included some of the catchment's largest dams in the model to account for their impact on the flow and nutrients delivered to the inlet. We included the two water supply dams and three large private dams (one downstream of the Quickup dam and two in the Little River catchment) in the model.

Given the model's objectives are to quantify the magnitude and sources of flow and nutrients that are delivered to the Wilson Inlet, by including the dams we can estimate the impact that these structures have on nutrient inputs to the inlet. These impacts are likely to be most apparent in the Lower Denmark and Quickup catchments, given the complexity of water abstraction, transfer and dam discharge. By incorporating the water supply dams into the model, future increases in town water demand could be incorporated into the urban expansion modelling (see Section 7.1).

We included the following five dams in the model (see Figure 3.5):

- Denmark Dam (town water supply, Lower Denmark catchment)

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[7] Time of concentration refers to the time it takes for a flow event to travel from the most distant point of a catchment to the outlet.

- Quickup Dam (town water supply, Lower Denmark catchment)

- Lower Denmark private dam 1: private dam immediately downstream of Quickup Dam, Lower Denmark catchment

- Little River private dam 2: private dam in the upper Little River catchment

- Little River private dam 3: private dam in the middle of the Little River catchment.

The Denmark and Quickup dams are managed by the Water Corporation for town water supply. A privately owned dam is located immediately downstream of Quickup dam. All three dams are in the Lower Denmark catchment and are upstream of the flow calibration site 603021.

We used 'storage nodes' to model these dams. Storage nodes add significantly to model run times so we did not include other private dams (about 4,000).

We modelled the two private dams in the Little River catchment and the private dam in the Lower Denmark catchment as simple fill-and-spill type dams. Catchment inflow, rainfall and evaporation are drivers to these models and we assumed dam volume properties based on farm dam relationships developed by the department. Discharge from the dams used a linear relationship based on manual calibration.

We parameterised the storage properties of the Denmark and Quickup dams based on data provided by the Water Corporation. We used the eWater Source 'minimum flow requirement nodes', 'supply point nodes' and 'water user nodes' to trigger water abstraction, dam transfers or water releases. No data was available to parameterise dam overflow and so this was also manually calibrated.
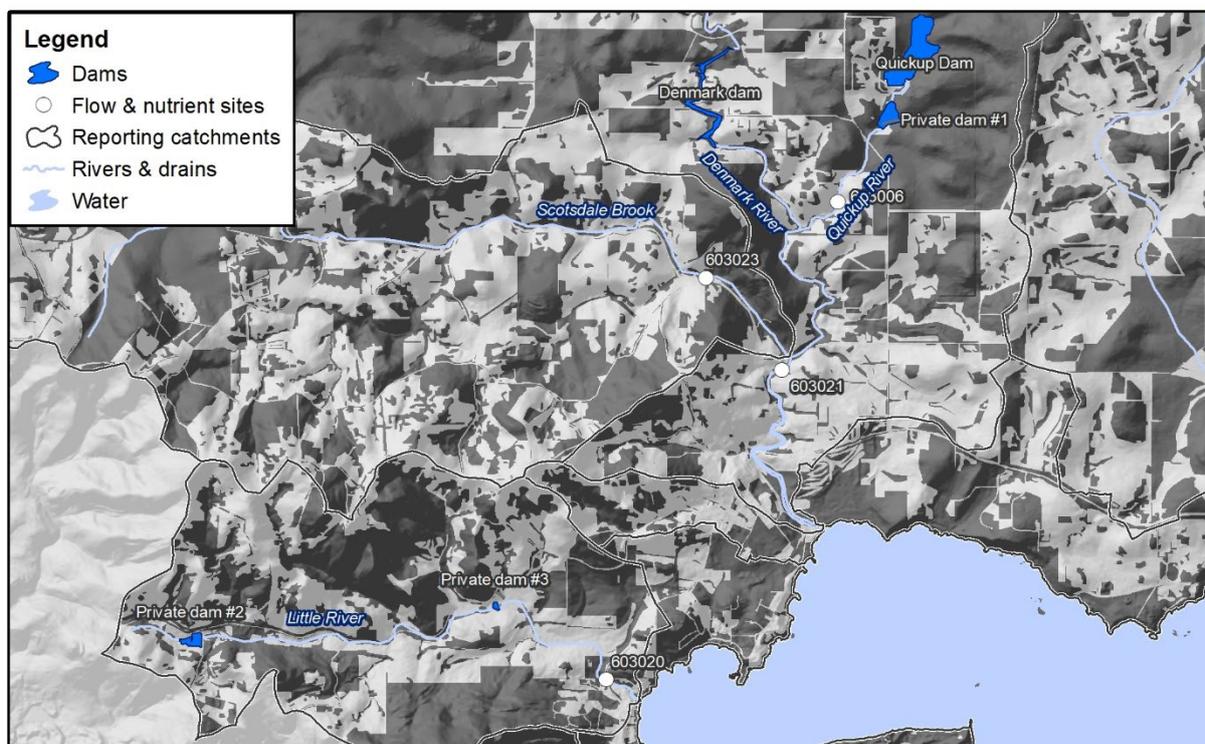
Figure 3.5: Dams included in the hydrological model

The following summarises how we modelled each aspect of the Quickup and Denmark dams – see Appendix A for all storage model parameters.

Town water supply from Quickup dam:

- We assumed Quickup dam was constructed and used for town water supply on 1/1/1989. For the periods 1/1/1989 to 5/1/2010 and 10/6/2020 to 31/12/2020, we assumed water supply was 500 ML/yr, based on water abstraction data from the Water Corporation. Water was abstracted according to the daily rate in Table 3.1.

- The daily town water supply was pumped according to Water Corporation data from 6/1/2010 to 9/6/2020.

Town water supply from Denmark dam:

- We assumed Denmark dam was constructed and used for town water supply from 1/1/1960 to 31/12/1988. Data on water abstraction for this period was unavailable and was outside the period of interest for this project (2005–19). Hence we assumed abstraction from the dam at current rates (see Table 3.1).

- From 6/1/2010 to 9/6/2020 water from Denmark dam was abstracted for town water supply based on the Water Corporation's daily pumping data. During this period, significant water abstraction only occurred in 2010, 2014, 2015 and 2016.

- We assumed no water was pumped from Denmark dam for direct water supply for the following periods:

  o From 1/1/1989 to 5/1/2010 the dam was not used for water supply.

  o From 9/6/2020 to the present no abstraction data from the Water Corporation was available. Direct town supply from the dam is understood to have ceased since the construction of Quickup dam in 1989.

Photo: Denmark dam overflowing in 2020 (Emma Christie)

Pumpback from Denmark dam to Quickup dam:

- We determined water abstraction from Denmark dam to Quickup dam using the Water Corporation's daily pumping data from 27/7/2015 to 11/6/2020.

  After 11/6/2020 and in select scenarios (urban expansion, plantation reversion to pasture and climate change), water is taken from the Denmark River based on criteria that the Water Corporation used at the time (2020). These criteria can be provided on

request. In addition, these criteria may have changed due to construction of the Albany-Denmark pipeline and changes to upstream flow measurement.

Denmark dam overflow and releases

- Denmark dam overflows at a 8.2 m reference level, according to the Water Corporation's capacity table for the dam (Public Works Department 1974, plan 35528). At the time of model construction, we could not source a rating table from the Water Corporation which specifies the discharge and storage relationship of Denmark dam. Hence, we adopted a rating curve that resulted in limited retention of water above the dam's overflow height at a daily timestep (350 ML/day for every 1 cm above the overflow height). We calibrated this relationship according to the reported dam volume on the Water Corporation's website (see Figure 4.4).

- The Water Corporation periodically releases water as part of its ongoing management of Denmark dam. We included a release event of 300 ML in late 2016 and early 2017 through manual calibration to the reported volume of Denmark dam (see Figure 4.4). We did this to improve the flow replication in 2017, which at the time was the main period used to calibrate a hydrodynamical model of the inlet.

Albany–Denmark pipeline:

- We implemented the proposed Albany–Denmark water supply pipeline in scenarios that modelled urban expansion and/or a future climate. We assumed the pipeline replaced all town water supply for days when Quickup dam's storage volume was 400 ML.

Table 3.1: Assumed abstraction for town water supply where no measured data exists. Calculated from the Water Corporation's water abstraction data for 2010 to 2020.

Month	Abstraction rate		
	(ML/day)	(ML/month)	% of total
Jan	2.10	65	13%
Feb	1.75	49	10%
Mar	1.65	51	10%
Apr	1.32	40	8%
May	1.27	39	8%
Jun	1.20	36	7%
Jul	1.04	32	6%
Aug	1.09	34	7%
Sep	1.10	33	7%
Oct	1.13	35	7%
Nov	1.19	36	7%
Dec	1.59	49	10%
Annual	**1.37**	**500**	**100%**

Wetland: Nenamup Inlet, Lake Saide and the Eden Road floodgates

The Eden Road floodgates are a one-way flow structure, installed to block the flow of estuarine water into the Lake Saide catchment. These floodgates allow water flow from Nenamup Inlet to Wilson Inlet when water levels in the former surpass those in the latter. A

second one-way flood management structure exists at Wolfes Pump Road, situated between Nenamup Inlet and Lake Saide (see Figure 3.6).

The Water Corporation manages these flood structures and most of the artificial drainage in the Lake Saide catchment. Water levels are also measured both upstream and downstream of the Eden Road floodgates.

To meet the model's objectives (see Section 1.1), we included the flood structures, as well as Nenamup Inlet and Lake Saide, in the model for the following reasons:

- previous models identified this catchment as a significant source of nutrient loss (Ecotones & Associates 2008)

- the Eden Road floodgates prevent catchment outflow in years when the Wilson Inlet bar is not breached, affecting average annual loads.

To model these features, we employed storage nodes, minimum water requirement nodes and functions. We assumed all flows from Lake Saide to Nenamup Inlet and Wilson Inlet to be one-way. Discharge to the Wilson Inlet occurs only when water levels in Nenamup Inlet exceed those in Wilson Inlet. We used measured water levels in Wilson Inlet (AWRC ref. 603032), available from 24/9/2004, as a data input. In the absence of such data or when modelling a future scenario, we assumed discharge to Wilson Inlet would occur when water levels in Nenamup Inlet exceeded 1 m, which historically has been a typical water level for opening of the Wilson Inlet sandbar to prevent flooding. We assumed that water flowed from Lake Saide to Nenamup Inlet when levels were higher in Lake Saide.

The 2016 Wilson Inlet bathymetry dataset partially covered Nenamup Inlet. We supplemented the missing bathymetry using aerial imagery from 2007 to 2017. This enabled us to create a depth-volume relationship for Nenamup Inlet, which we then applied to Lake Saide as it had no bathymetry data. We did not include the Eungedup wetlands or other low-lying regions in the storage calculations or wetland interactions for Nenamup Inlet or Lake Saide. Furthermore, we did not include the recent restoration of the Eungedup wetlands, previously used for potato farming[8].

See appendices A and B for further details on the model parameters and functions.

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[8] In 2023 the Wilson Inlet Catchment Committee purchased about 103 ha of former potato farming land for wetland restoration and bird conservation. An additional 19 ha of adjacent land that the department owns (most of which was also previously used for potato farming) is being managed for the same environmental objectives.
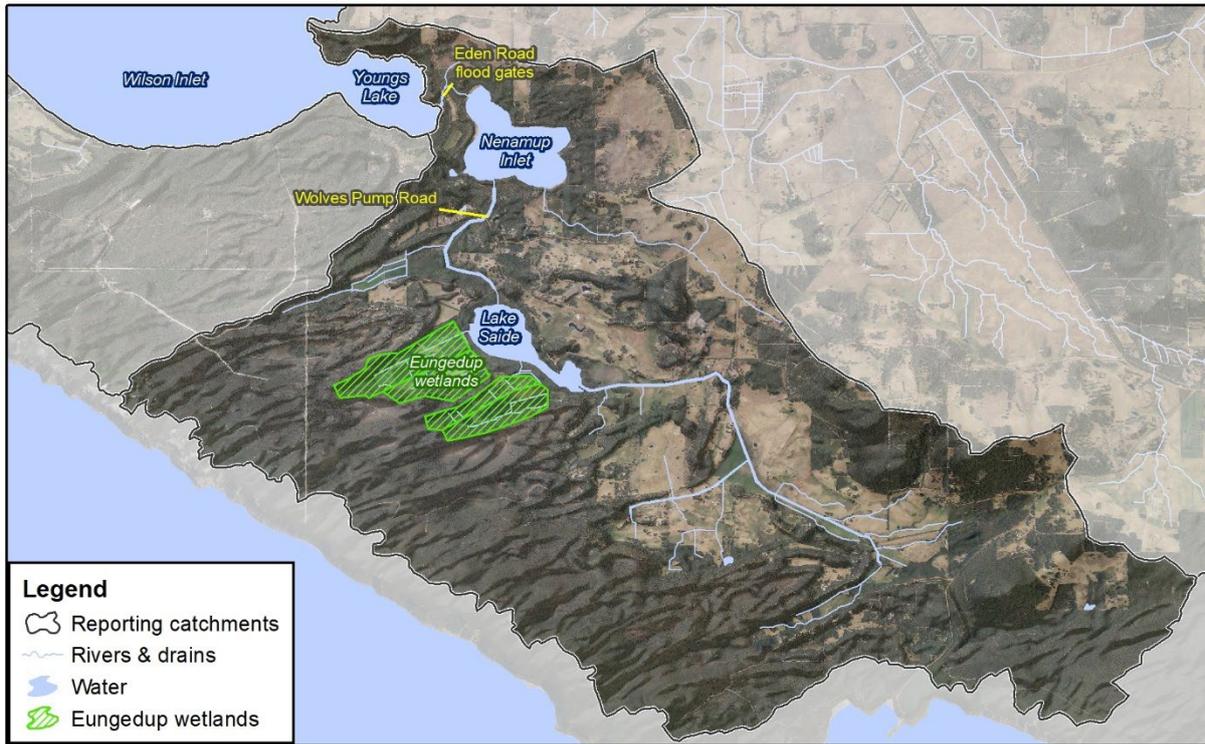
Figure 3.6: Nenamup Inlet, Lake Saide and catchment drainage

Photos: The Eden Road floodgates in 2019 showing: a) the downstream side (Wilson Inlet) of the floodgates, b) the downstream channel looking from the floodgates to the Wilson Inlet, c) the upstream culverts (Nenamup Inlet), d & e) the Water Corporation's upstream (Nenamup Inlet) and downstream (Wilson Inlet) water-level staff gauges respectively.

3.1.2 Nutrient model

The Source framework allows constituents – we used total nitrogen (TN) and total phosphorus (TP) – to be generated, routed and removed/assimilated using the following model components:

- **Constituent generation models:** these determine how constituents are generated by functional units.

- **Filtering models**: these represent the removal/assimilation of constituents at the functional unit scale and take effect just after nutrient generation. We used filtering models to represent nutrient processes in vegetated riparian zones.

- **Inflow nodes:** we used inflow nodes to include point sources of nutrients, septic tanks, and external sources of potable water. The nutrients from these sources are external to the constituent generation and filtering models.

- **In-stream routing and processing models:** constituents are routed in the same way as flow when link storage routing models are used. Constituent decay models can be used in links or storage nodes to represent instream constituent removal/assimilation processes. We used decay models to account for the nutrient removal/assimilation of Nenamup Inlet and Lake Saide.

The diffuse nutrient model

The diffuse nutrient model uses the *power function (flow in mm)* constituent generation model to generate TN and TP concentrations. We selected this model because of:

- the scarcity of locally derived land-use Event Mean Concentration/Dry Weather Concentration (EMC/DWC) concentration data

- its ability to replicate catchment-scale flow-concentration relationships.

The Cooperative Research Centre for Catchment Hydrology developed the power function model. It has been widely used in modelling and discussed in the scientific literature (e.g. Phillips 1999; Asselman 2000; Horowitz 2003).

The power function model generates nutrients at the functional unit scale by a flow-concentration relationship of the form (Equation 1):

Equation 1: $$Concentration = a * flow^b + c$$

where *flow* is the functional unit flow yield, *a* is the slope of the curve on a semi-log axis, *b* is the curvature and *c* is the y-intercept.

We parameterised the power functions for the 46 modelling functional units, which includes 23 land-use categories and two soil-PRI categories. This process produced calibrated land-use nutrient concentrations that are a function of the flow yield, the magnitude of land-use nutrient surplus and soil properties.

The first step in the parameterisation required the calibration of a single catchment-scale power function to observed data (termed the *catchment power curve*). In the second step we separated the calibrated catchment power curves into individual power curves for each modelling functional unit by modifying the "*a*" parameter by (Equation 2):

Equation 2:
$$a_{lu} = a_{cat} \times \frac{C_{lu}}{C_{cat}}$$

Where:

a_{lu} = the "a" value of the power function for each modelling land use

a_{cat} = the "a" value of the power function calibrated to nutrient monitoring data

C_{cat} = *the calibrated flow-weighted nutrient concentration from the catchment power curve*

$C_{lu} = \frac{S \times E}{Q_{lu}}$

S = the surplus nutrient mass of the land use

E = *nutrient export factor. This is the average annual winter catchment nutrient load (determined by the catchment power function) divided by the total nutrient surplus of the catchment.*

Q_{lu} = *the modelled land-use flow-yield volume (ML/year)*

The "b" parameter for modelling land-use power functions was the same as the calibrated catchment power function.

We repeated this process for all catchments upstream of water quality monitoring sites. Parameterisation of the phosphorus model included the effect of soil PRI on phosphorus leaching. We decreased the phosphorus export (*E*) from land uses on high-PRI soils by a factor of eight based on the relationship between average annual locally estimated scatterplot smoothing[9] (LOESS) flow-weighted TP concentrations (2011–15) and the proportion of the catchment with low-PRI soils (see Figure 2.24).

For all native vegetation land uses we used the nutrient parameters from Mitchell River, which is an uncleared catchment with monitoring data from 2007 to 2009. When parameterising the ungauged catchments, we generally used the parameters of the nearest upstream gauge. Exceptions to this were:

- Foreshore reporting catchments, which used the parameters from the Lower Denmark River as they had similar coverage of low-PRI soils.

- Ungauged areas of the Lower Hay and the entire Nullaki and Ocean Beach Road catchments, which used the parameters from Sunny Glen Creek. (These catchments all have large areas of low-PRI-soils – see Figure 3.17.)

See Appendix B for more information about the parameterisation of the nutrient model.

Storage nodes and nutrient decay models

We have used constituent decay models in the Nenamup Inlet and Lake Saide storage nodes to account for nutrient removal/assimilation by these wetlands. We calibrated both catchment nutrient generation and wetland nutrient decay using water quality measurements (sites 6031283 and 6031104) and available literature (DoW 2016). The average annual

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[9] See a description of locally estimated scatterplot smoothing in Hennig and Kelsey (2015).

nutrient load removal of the wetlands is 18 to 20% for nitrogen and 20 to 57% for phosphorus (see Table 3.2)

Table 3.2: Modelled nutrient load removal of the Lake Saide and Nenamup wetlands

	Nitrogen						Phosphorus					
	Lake Saide			Nenamup Inlet			Lake Saide			Nenamup Inlet		
	In	Out	Diff	In	Out	Diff	In	Out	Diff	In	Out	Diff
Year	(t)	(t)	(%)	(t)	(t)	(%)	(t)	(t)	(%)	(t)	(t)	(%)
2010*	1.8	0.8	-53	1.6	-	-	0.10	0.02	-80	0.05	-	-
2011	5.2	4.2	-20	6.2	5.4	-14	0.30	0.13	-58	0.21	0.17	-20
2012	5.1	4.1	-21	6.1	5.0	-19	0.30	0.12	-60	0.20	0.15	-25
2013	6.2	5.2	-17	7.7	6.5	-15	0.36	0.17	-53	0.26	0.22	-15
2014*	1.0	0.4	-61	0.7	-	-	0.05	0.01	-90	0.02	-	-
2015	0.2	0.1	-49	0.1	0.1	-53	0.01	0.00	-95	0.00	0.00	-77
2016	3.2	2.4	-23	3.7	2.6	-28	0.18	0.07	-61	0.12	0.09	-28
2017	5.5	4.7	-16	6.9	5.9	-15	0.32	0.17	-48	0.25	0.22	-14
2018	3.2	2.4	-24	3.7	2.8	-25	0.18	0.06	-66	0.11	0.08	-30
2019*	1.4	0.7	-51	1.2	-	-	0.08	0.01	-84	0.04	-	-
Mean*	4.1	3.3	-20	4.9	4.0	-18	0.24	0.10	-57	0.17	0.13	-20

* Wilson Inlet bar was not opened and therefore there was no outflow from Nenamup Inlet. Average inflow, outflow and difference excludes non-opening years.

Riparian nutrient filtering model

We used a filtering model (% reduction) to represent nutrient removal/attenuation of riparian zones. This filtering model was parameterised to reduce the daily nutrient load generated by a modelling catchment based on the proportion of riparian vegetation or fencing within a modelling catchment.

We determined the maximum nutrient removal of riparian zones using a literature review by Hall (2019). Hall (2019) concluded that the riparian zones on the Swan coastal plain had a lower potential for phosphorus removal due to the large areas of sandy low-PRI soils and high drainage density. Catchments with similar properties exist in the Wilson Inlet catchment and were assumed to have lower maximum phosphorus removal (termed low efficacy catchments) than other catchments (high efficacy catchments). Catchments where no fencing was needed to exclude livestock (native vegetation or urban) were assumed to have the nutrient removal benefits of 100% vegetated or fenced riparian zones respectively. Three mostly vegetated modelling catchments (ID 74, 115, 116) had no mapped streams or drains and therefore did not have riparian filtering models. Figure 3.7 shows the riparian efficacy and fencing requirement of modelling catchments.

We calculated the nutrient removal of riparian zones linearly; that is: 0% removal for modelling catchments with 0% riparian zone vegetation or fencing, and the maximum nutrient removal for catchments with 100% riparian zone vegetation or fencing (Table 3.3, adapted from Hall 2019).

Section 3.2 details the input data for riparian zones and Section 7.3.1 examines the effect of extensive riparian management.

Table 3.3: Riparian management nutrient removal efficacy (adapted from Hall 2019)

Category	Description	N load reduction	P load reduction	
		All catchments	High efficacy	Low efficacy
		(%)	(%)	(%)
Fencing	100% of the riparian zones are fenced on both banks.	15	15	5
Native vegetation (vegetated)	100% of the riparian zone has native vegetation.	30	30	5

Figure 3.7: Riparian filtering efficacy by modelling catchment

3.2 Input data

Meteorological data

We derived rainfall, potential evapotranspiration (FAO56 – see Allen et al. 1998; Ladson 2008) and pan evaporation data from SILO for the period 1960 to 2020. Data was extracted from the 89 points across the catchment and applied to modelling catchments according to their climate ID (see Figure 3.8).
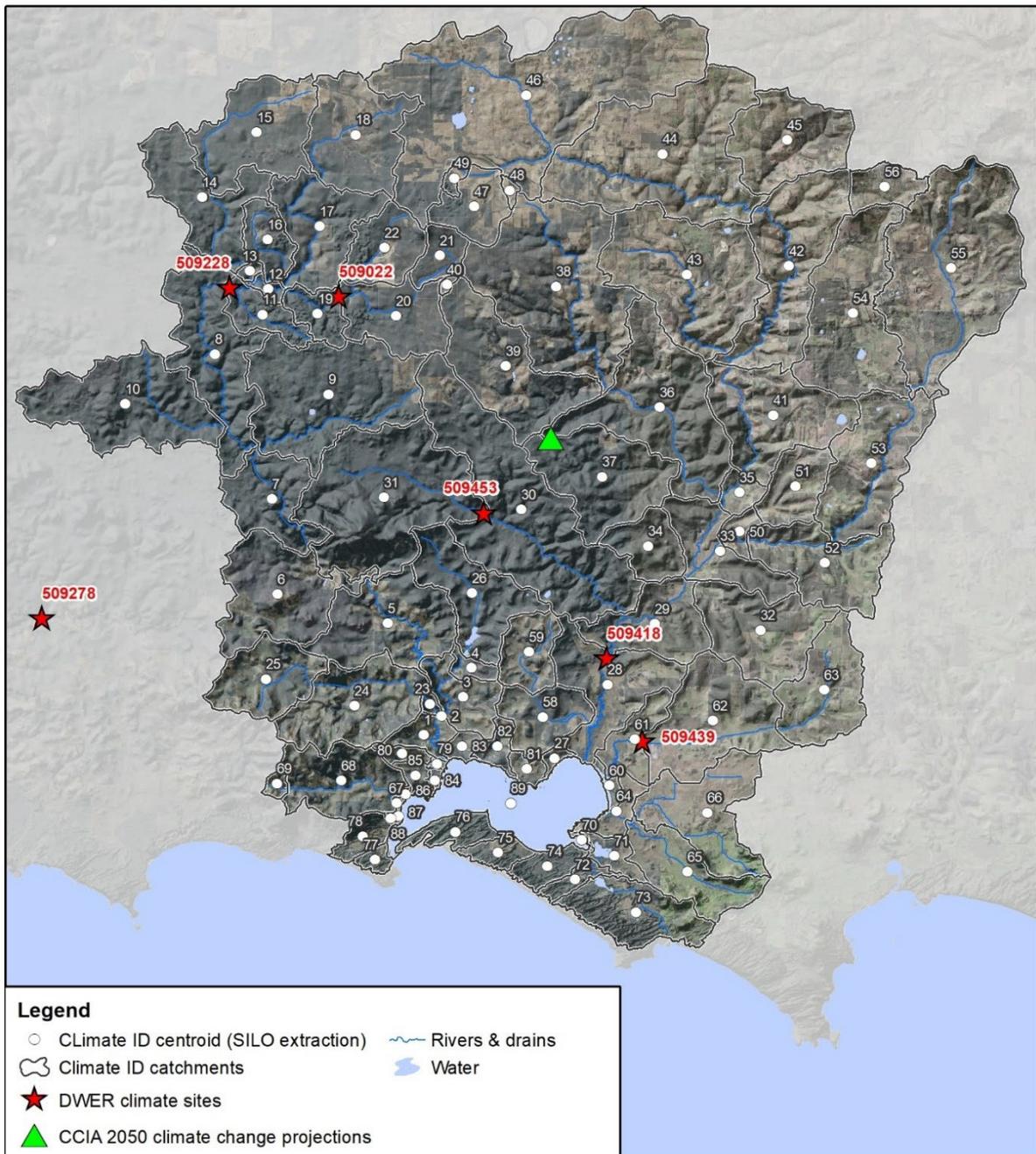
Figure 3.8: Points used to extract SILO data, climate ID catchments and the department's climate sites

Edits to SILO rainfall was necessary, particularly in 2017. This was possible because of the department's climate measurement sites shown in Figure 3.8, which SILO does not use. SILO data tended to overestimate rainfall and had large errors in 2017. Figure 3.9 shows the annual difference between SILO and measured rainfall in the Upper Denmark catchment.
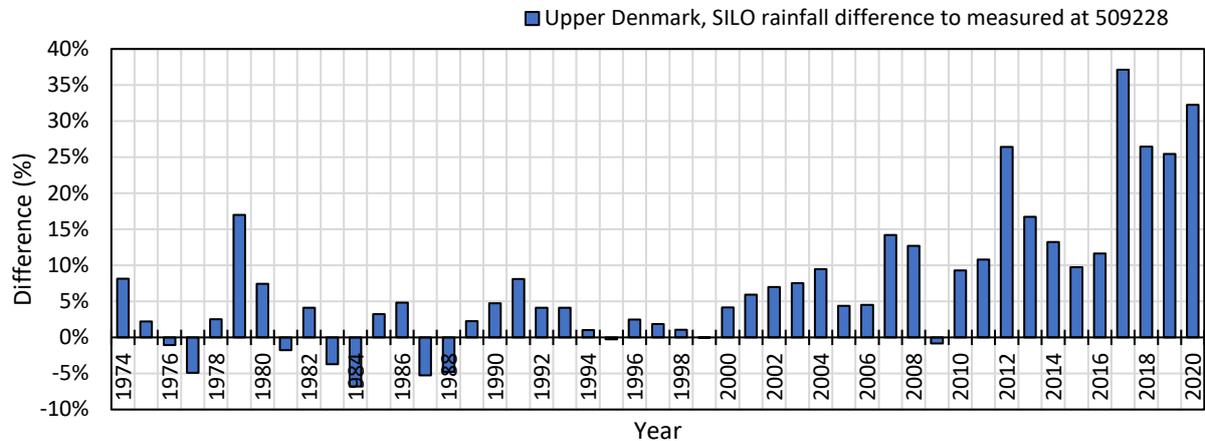
Figure 3.9: Difference in annual rainfall between SILO and measured rainfall at the department's climate site 509228 in the Upper Denmark catchment. A positive difference means that SILO overestimates measured rainfall.

Land-use mapping and nutrient surveys

We created a land-use spatial dataset as part of this project, which represents the period of 2007–20 (Figure 3.11). We used the following to manually map, verify or populate our land-use map:

- the state cadastre dataset (Landgate)

- aerial and satellite photography from 2007–20

- native vegetation data (DPIRD)

- Catchment Scale Land Use for Australia (CLUM) 2018 dataset

- the department's licences and works approval database

- Google Earth Pro desktop aerial photos (2010–20)

- Google Earth Engine Timelapse (1984–2020)

We mapped 37 different land-use types based on the mapping nomenclature from Kelsey et al. (2011). These were simplified into modelling and reporting land-use categories (Table 3.5). The aggregation of land-use categories was based on their expected hydrological response and nutrient surplus.

We manually mapped the establishment, harvesting, replanting and reversions of plantations using the department's aerial photography, images available in Google Earth Pro desktop and Google Earth Engine Timelapse. See Figure 3.13 for when plantations were established.

Our land-use mapping was internally reviewed before external review by farmers in the Sleeman River and Lower Denmark River catchments, as well as officers from the Wilson Inlet Catchment Committee. We also discussed the management of plantations with DPIRD and private industry to ensure that our understanding of past management was correct.

Land-use nutrient surveys

Table 3.5 gives the assigned nutrient input and surplus rates for all modelling land uses. This data was sourced from relevant literature and assumptions, as indicated in the table's notes. The following describes the farm-gate nutrient budget framework (Ovens et al. 2008; Weaver et al. 2008; Figure 3.10):

- **Nutrient inputs:** mass of nutrients brought into a farm or land parcel. Nutrient inputs include fertiliser, animals, feed, atmospheric inputs, nitrogen fixation, disinfectants, detergents, wastes and other chemicals.

- **Nutrient outputs:** mass of nutrients leaving a farm or land parcel, such as the removal of animals, produce and wastes disposed of offsite (e.g. manure sold as fertiliser, urban lawn and garden wastes).

- **Nutrient surplus:** is equal to nutrient input minus nutrient output. Nutrient surpluses can be stored (e.g. in livestock, soil or plant matter) or lost though leaching to groundwater, surface runoff, or atmospheric losses (wind erosion, fire, denitrification, volatilisation).

- **Nutrient use efficiency (NUE):** this is nutrient out divided by nutrient in, expressed as a percentage. In theory, land uses with 100% NUE convert all nutrient inputs to nutrient outputs and therefore have a nutrient surplus of zero. However, in practice, 100% NUE is likely not possible.

In the model, the amount of nutrient loss to surface water is a function of the surplus mass of nutrients in the landscape.
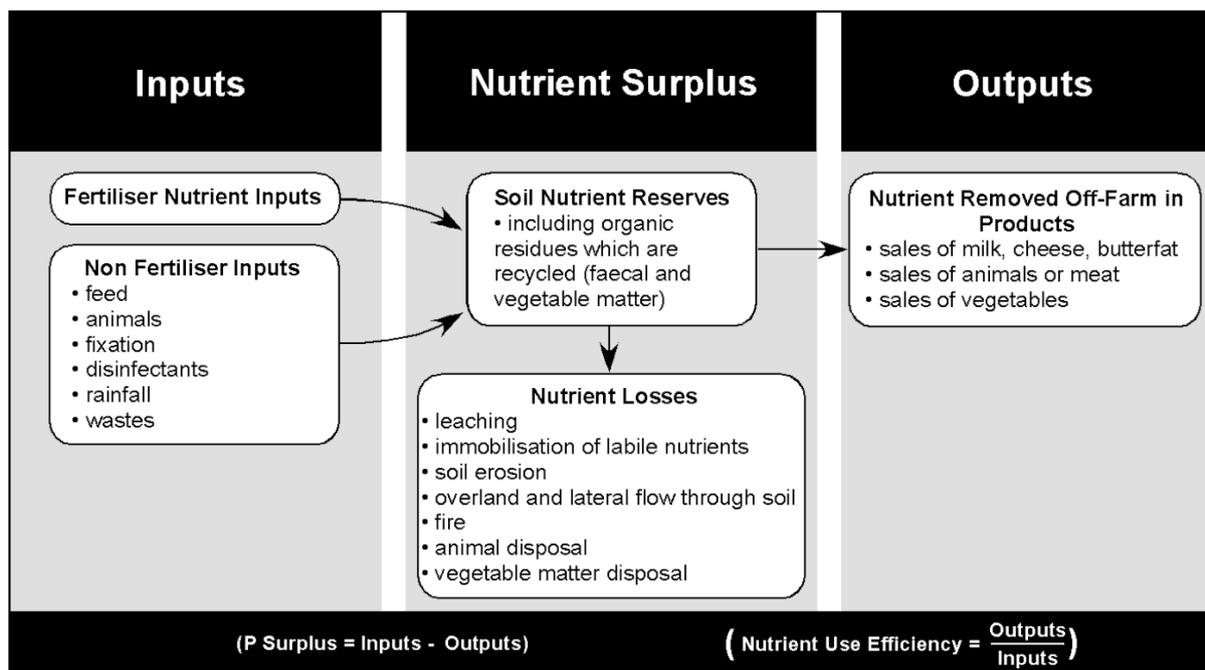
Figure 3.10: The farm-gate nutrient budget framework (Ovens et al. 2008)
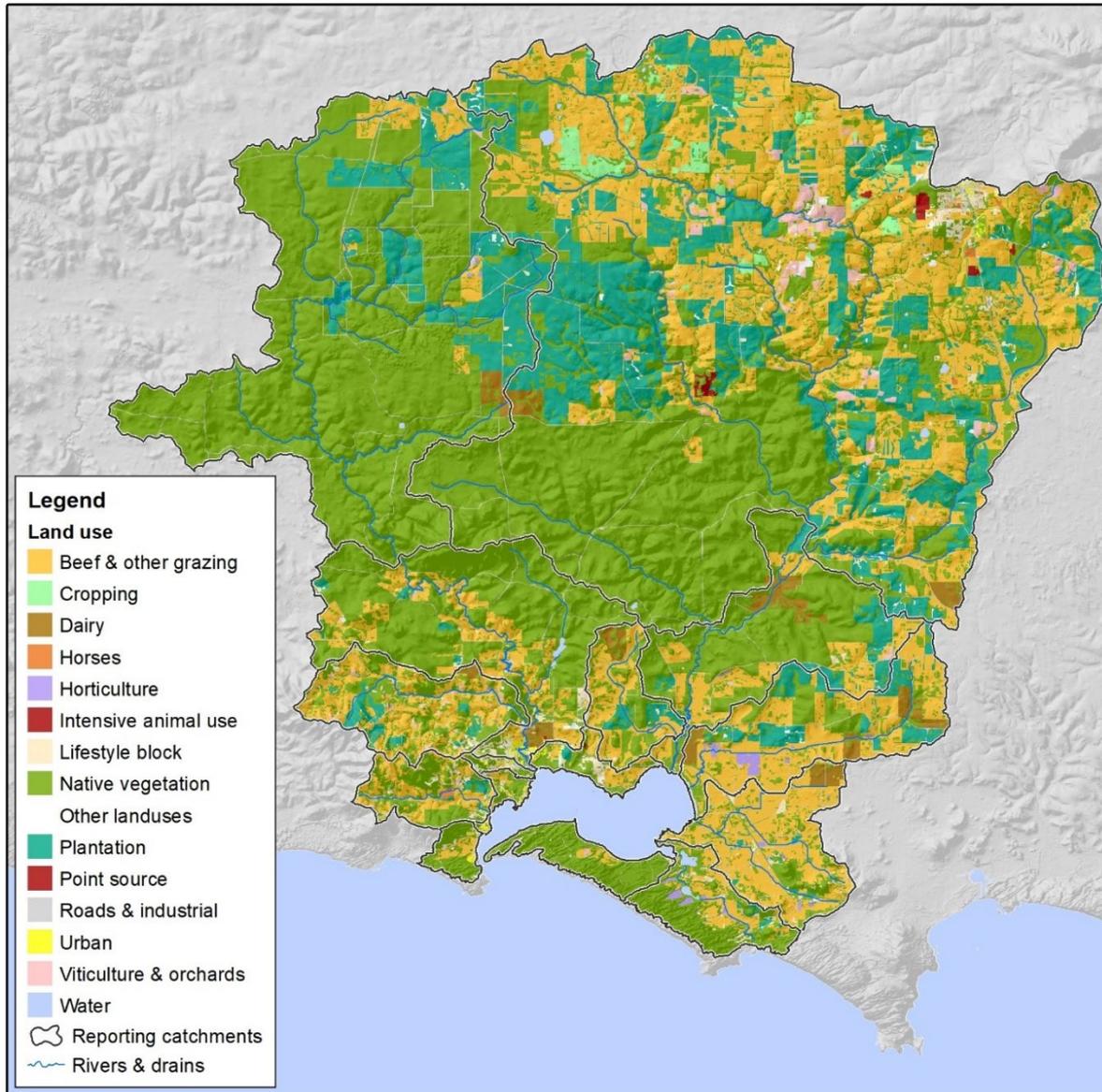
Figure 3.11: Land use mapping in the Wilson Inlet catchment
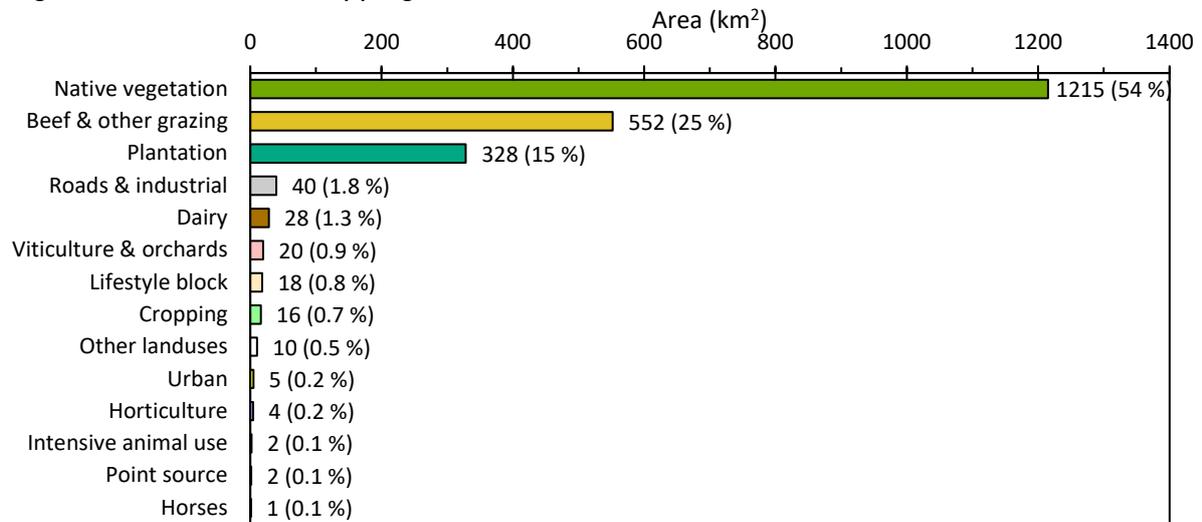
Figure 3.12: Land use by area in the Wilson Inlet catchment
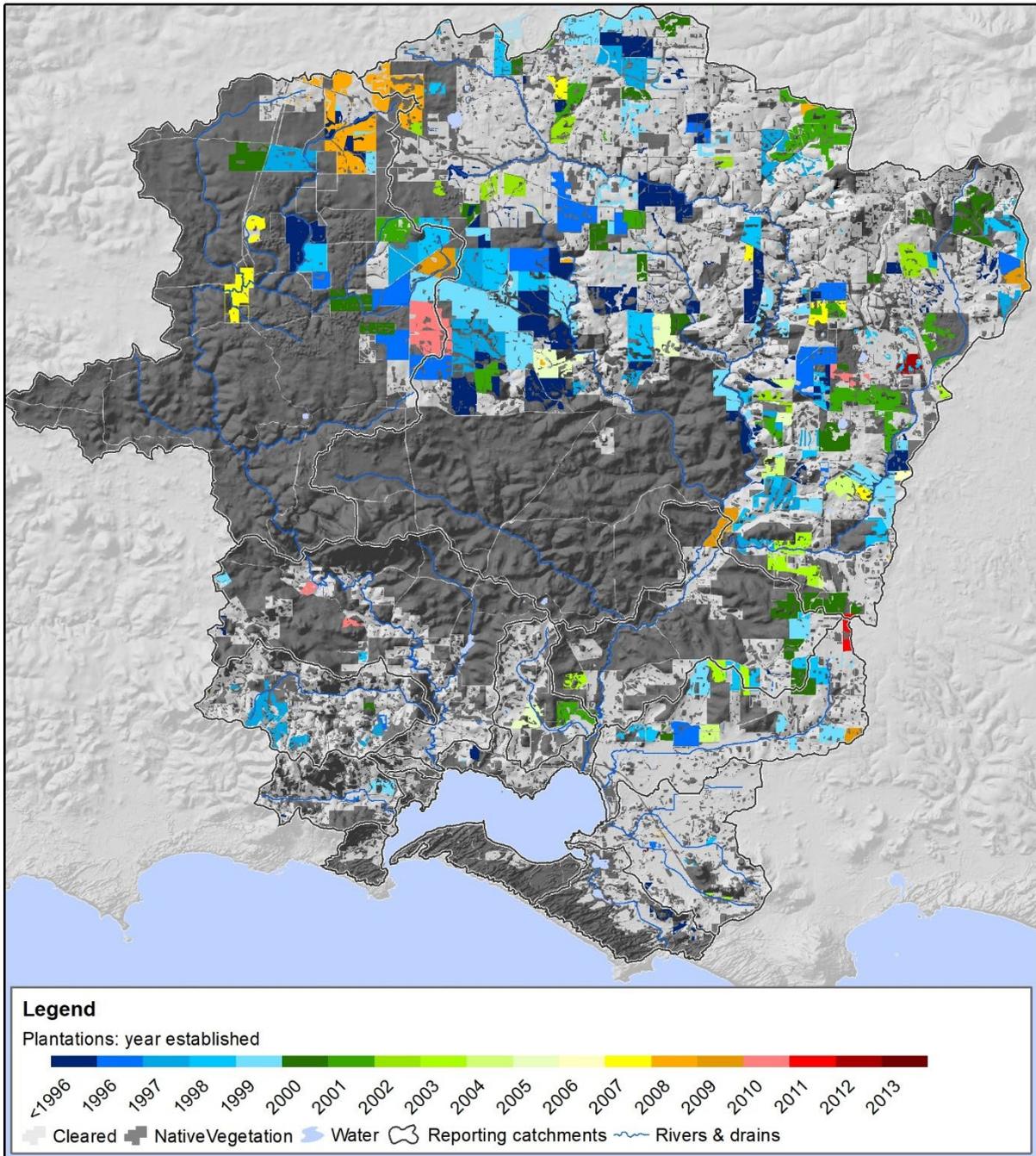
Figure 3.13: Plantation establishment

Table 3.4: Mapping, modelling and reporting land uses and assumed leaf area index (LAI)

Mapping ID	Mapping land use	Modelling land use	Reporting land use	Hydrology FU	LAI
1	Bare soil & other	Bare soil & other	Other landuses	Cleared	1.0
2	Beef	Beef	Beef & other grazing	Cleared	1.0
3	Commercial	Urban	Urban	Cleared	0.2
4	Cropping	Cropping	Cropping	Cleared	0.5
5	Dairy	Dairy	Dairy	Cleared	1.0
6	Feedlots & stockyards	Feedlots & stockyards	Intensive animal use	Cleared	0.5
7	Horses	Horses	Horses	Cleared	1.3
8	Horticulture	Horticulture	Horticulture	Cleared	0.7
9	Industry	Roads & industrial	Roads & industrial	Cleared	0.0
10	Lifestyle block	Lifestyle block	Lifestyle block	Cleared	1.2
11	Mining	Bare soil & other	Other landuses	Cleared	0.0
12	Mixed grazing	Beef	Beef & other grazing	Cleared	0.9
13	Native vegetation	Native vegetation	Native vegetation	NativeVegetation	1.8
14	Offices	Urban	Urban	Cleared	0.0
15	Orchard	Orchard	Viticulture & orchards	Cleared	0.7
16	Piggeries & abattoirs	Piggeries & abattoirs	Intensive animal use	Cleared	0.1
17	Plantation	Plantation	Plantation	Plantation	1.9
18	Point source	Point source	Point source	Cleared	0.5
19	Poultry	Feedlots & stockyards	Intensive animal use	Cleared	0.1
20	Recreation	Recreation	Urban	Cleared	1.0
21	Roads (sealed)	Roads & industrial	Roads & industrial	Cleared	0.6
22	Roads (unsealed)	Roads & industrial	Roads & industrial	Cleared	0.6
23	Rural living (bush block)	Rural living (bush block)	Native vegetation	NativeVegetation	1.8
24	Schools	Urban	Urban	Cleared	0.8
25	Turf farm	Horticulture	Horticulture	Cleared	1.2
26	Urban residential	Urban	Urban	Cleared	0.5
27	Urban residential (very small)	Urban	Urban	Cleared	0.5
28	Viticulture	Viticulture	Viticulture & orchards	Cleared	1.2
29	Water	Water	Native vegetation	Water	0.0
30	Community centre	Urban	Urban	Cleared	0.5
31	Caravan park	Urban	Urban	Cleared	1.0
32	Accommodation	Urban	Urban	Cleared	0.1
33	Multi dwelling/retirement	Urban	Urban	Cleared	0.5
34	Golf course	Recreation	Urban	Cleared	1.2
35	Irrigated beef	Beef	Beef & other grazing	Cleared	1.0
36	Potatoes	Potatoes	Horticulture	Cleared	0.7
37	Wastewater irrigation	Wastewater irrigation	Point source	Plantation	1.9

Table 3.5: Nutrient input and surplus rates for modelling land uses

Modelling land use	Hydrology	Input nitrogen	Input phosphorus	Surplus nitrogen	Surplus phosphorus	Surplus nitrogen¥	Surplus phosphorus¥	Notes
		(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(%)	(%)	
Bare soil & other	Cleared	5.2	0.2	4.7	0.2	1	1	1, 2
Beef	Cleared	86.4	12.7	78.8	11.3	91	89	3
Cropping	Cleared	61.0	7.7	36.0	4.0	59	52	4
Dairy	Cleared	145.1	25.5	121.6	20.1	84	79	3
Feedlots & stockyards	Cleared	3714.6	825.9	590.6	45.4	16	6	3
Horses	Cleared	70.1	13.2	62.9	13.2	90	100	3
Horticulture	Cleared	696.0	170.0	575.0	141.0	83	83	10
Lifestyle block	Cleared	49.2	3.4	49.2	2.4	100	70	3
Native vegetation	Native vegetation	9.2	0.2	0.5	0.0	5	5	1, 2, 5
Orchard	Cleared	27.2	12.3	8.4	6.2	31	50	3
Piggeries & abattoirs	Cleared	629.3	144.7	282.9	67.4	45	47	3
Plantation	Plantation	12.6	8.2	9.5	6.2	75	75	1, 6
Potatoes	Cleared	142.6	126.9	45.8	116.2	32	92	3
Recreation	Cleared	71.2	2.2	64.1	2.0	90	90	1, 2, 7
Roads & industrial	Cleared	5.2	0.2	4.7	0.2	90	90	1, 2
Rural living (bush block)	Native vegetation	9.2	0.2	8.3	0.2	90	90	1, 2, 5
Urban	Cleared	89.7	17.8	80.7	16.0	90	90	1, 8
Viticulture	Cleared	54.5	15.9	47.1	13.5	86	85	3
Water	Water	5.2	0.2	4.7	0.2	90	90	2
Wastewater Irrigation	Plantation	22.0	5.0	16.5	3.8	75	75	9

Note:

¥ Surplus as a percentage of nutrient inputs

Atmospheric deposition was applied to all non-agricultural land uses and turf farms. The farm-gate nutrient survey included nutrient inputs from rainfall (Ovens et al. 2008).

1. Nutrient surplus is assumed to be capped at 90% of nutrient inputs based on data from Ovens et al. (2008)

2. Data taken from the UNDO tool nutrient input fact sheets for atmospheric deposition

3. DPIRD farm-gate nutrient budget (Ovens et al. 2008)

4. Hennig & Kelsey 2015

5. Nutrient input rates taken from the UNDO tool nutrient input fact sheets for native vegetation (natural).

6. Kelsey et al. 2011

7. Krupa 2014

8. Median of all lots > 400 m² from the Urban Nutrient Survey primary data (Kelsey et al. 2010b).

9. Based on the environmental licence requirements for discharge (Appendix C)

10. The median of the values in Table 3.6 of this report.

Table 3.6: Nutrient input rates for various horticulture crops

| Crop | Type | Ref | Fertiliser inputs | | Surplus nutrient | | | |
| | | | N input | P input | N surplus | | P surplus | |
			(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(%)	(kg/ha/yr)	(%)
Celery	A	1, 2	2 230	470	1 717	77%	371	79%
English spinach	A	3	1 612	182	1 572	98%	174	96%
Sweet potatoes: Sand	A	4	368	70	248	67%	53	76%
Sweet potatoes: Loam	A	4	552	175	432	78%	158	90%
Pumpkin: Sand	A	5	1 006	177	897	89%	148	84%
Pumpkin: Loam	A	5	840	165	731	87%	135	82%
Asparagus	P	6	150	50	-	-	-	-
Sweet corn	A	7	190	34	-	-	-	-
Avocados*	PL	8	212	31	-	-	-	-
			(69–528)	(0–100)	-	-	-	-
Horticulture modelling land use (median)	A & P		**696**	**170**	**575**	**83%**	**141**	**83%**

Note:

A = Annual crop, **P** = Perennial crop and **PL** = Plantation

*The nutrient input rates for avocados were not used to calculate medians. This publication was identified during the report writing phase and is included here for context.

1. https://www.agric.wa.gov.au/celery/3phase-program-growing-celery-sandy-soils?page=0%2C2

2. https://www.agric.wa.gov.au/celery/growing-celery-western-australia?page=0%2C5#smartpaging_toc_p5_s0_h2

3. https://www.agric.wa.gov.au/spinach/growing-english-spinach-western-australia?page=0%2C3#smartpaging_toc_p3_s0_h2

4. https://www.agric.wa.gov.au/sweet-potato/growing-sweet-potatoes-western-australia?page=0%2C1

5. https://www.agric.wa.gov.au/pumpkin/growing-pumpkins-western-australia?page=0%2C3#smartpaging_toc_p3_s0_h2

6. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0017/113417/organic-asparagus-production.pdf

7. https://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/commodity-growing-guides/sweet-corn

8. https://avocado.org.au/wp-content/uploads/2018/08/AVOCADO-PLANT-NUTRITION-REVIEW-2018_cover.pdf

Reporting and modelling catchments

We derived modelling catchments using the department's 2016 two-metre-resolution LIDAR mapping of the Wilson Inlet catchment, the Land Monitor 10-metre-resolution Digital Elevation Model, and the 3-arc-second Digital Surface Model for inland areas (Geoscience Australia 2011).

We then compared the derived catchments with the department's Hydrographic Subcatchments dataset, and found they were largely in agreement. Thus, we edited the subcatchments dataset to resolve catchment boundary errors. We then aggregated these catchments to minimise the number of subcatchments, ensuring that:

1. Rainfall changes across the subcatchment were small.

2. Flow and water quality measurement sites aligned with catchment outflow points.

3. Catchments where information may be requested were preserved.

4. Where possible the subcatchment contained similar land uses.

5. All drainage points into Wilson Inlet and the estuarine portions of the Denmark and Hay rivers were preserved (related to providing data for estuary models).

We call the resulting 116 subcatchments the modelling catchments – see Figure 3.14. We then further aggregated the modelling catchments into 14 reporting catchments.

Figure 3.14: Reporting and modelling catchments

Mapping of streams, drains, fencing and riparian vegetation

The mapping of streams, drains, fencing and vegetation within the riparian zones was an important part of this project. The mapping of streams and drains helped us to modify or

validate the catchment boundaries used by the catchment model, as well as to define riparian zones and parameterise the riparian nutrient filtering model (Section 3.1.2). The derivation of these datasets is described below.

Stream and drain mapping was based on the department's 'Linear hydrography' dataset (DWER 2019). We manually edited this dataset as follows:

- Removed errors in stream mapping based on the best-available aerial photos.

- Based on aerial photography, manually mapped all streams and drains in cleared areas that could benefit from fencing and revegetation. We focused our effort on catchments closer to Wilson Inlet due to their higher intensity of nutrient loss per unit area.

- Mapped all artificial drainage in the Water Corporation-managed Albany drainage district (see Figure 7.19) and annotated Water Corporation-managed drains in the dataset. This was for the Sleeman, Cuppup and Lake Saide catchments, the only catchments that contained Water Corporation-managed drains.

We then used the resulting dataset to define the riparian zone, which was taken to be 10 m either side of a stream or drain and intersected with the land-use map created by this project. We calculated the proportion of vegetated (native vegetation and water) and cleared land uses (all other land-use types) in the riparian zone of each modelling catchment and used the result as a parameter in the nutrient filtering model. Figure 3.15 shows the cleared and vegetated reaches of the riparian zone of all mapped streams and drains.

We took the length of fencing from the spatial data of foreshore assessments undertaken from 1995–98 and small additions to this database in 2002 (Waterways Commission 1995; Water and Rivers Commission 1998; Green Skills & Pen 1999). This spatial data provided the fencing status of the left and right banks of some of the riparian zones that we mapped and used in this catchment modelling. We were not able to source the spatial data from later desktop foreshore assessments in the unmapped portions of the Hay and Sleeman catchments (WICC & Green Skills 2007) when preparing the riparian zone datasets for the catchment model. We assumed that areas without a known fencing status were unfenced, excluding the riparian zones in fully vegetated catchments. In addition, the fencing status may have changed since the foreshore assessments were undertaken (1995–2002).

We used this dataset to parameterise the riparian filtering model (see Section 3.1.1). This model requires, as an input, the proportion of riparian zones with adequate fencing for each modelling catchment. For a modelling catchment to have 100% fencing, both sides of all streams and drains either need to be fenced or fencing is not required (native vegetation or no livestock). There are considerable areas without fencing data (e.g. the entire Sunny Glen catchment). We made the following assumptions when there was no fencing data:

- In the Lake Saide catchment, Water Corporation drains that were in vegetated reaches were mapped as not requiring fencing.

- For modelling catchments that were entirely vegetated or urbanised (no livestock), all streams and drains were assumed to <u>not</u> require fencing.

- For modelling catchments with a mix of native vegetation and livestock farming, only the cleared portion of riparian zones was assumed to require fencing.

- All remaining modelling catchments were assumed to require fencing where there was no fencing data.

Figure 3.16 shows the fencing status of riparian zones. Table 3.7 summaries the vegetation and fencing status of all streams and drains that we mapped as part of this project.

Note that in all tables in this report, the length of required fencing represents the length of streams or drains that require fencing on both banks unless stated otherwise. Multiplying this number by two will give the length of fences that are potentially needed.

Table 3.7: Summary of the vegetation and fencing status of all mapped streams and drains by reporting catchment

Reporting catchment	Total riparian zone length	Cleared riparian zone		Total requiring fencing		Fencing data and assumptions							
						Foreshore condition assessment (1995–2002)				No data (assumptions)			
						Fenced or not required		Fencing required		Fenced or not required		Fencing required	
	(km)	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(%)
Ocean Beach	7	3	45%	5	70%	0	0%	0	0%	2	30%	5	70%
Little River	55	15	26%	55	99%	0	0%	0	0%	1	1%	55	99%
Koorabup	7	2	36%	6	84%	0	0%	0	0%	1	16%	6	84%
Lower Denmark	214	33	15%	179	84%	23	11%	8	4%	15	7%	171	80%
Upper Denmark	539	58	11%	222	41%	42	8%	8	2%	312	58%	213	40%
Scotsdale	102	30	29%	38	37%	64	63%	35	35%	0	0%	2	2%
Foreshore	18	7	37%	17	94%	0	0%	0	0%	1	6%	17	94%
Sunny Glen	47	26	56%	47	100%	0	0%	0	0%	0	0%	47	100%
Lower Hay	143	39	28%	105	74%	22	15%	4	3%	24	17%	101	71%
Upper Hay	1072	288	27%	822	77%	26	2%	27	3%	119	11%	795	74%
Sleeman	127	74	58%	104	81%	24	19%	18	14%	0	0%	85	67%
Cuppup	163	142	87%	140	86%	23	14%	13	8%	0	0%	127	78%
Lake Saide	36	20	54%	33	91%	3	9%	0	0%	0	0%	33	91%
Nullaki	2	1	78%	1	74%	0	26%	0	0%	0	0%	1	74%
Wilson Inlet	**2534**	**739**	**29%**	**1773**	**70%**	**227**	**9%**	**114**	**5%**	**476**	**19%**	**1659**	**65%**

Note:

Fencing is given as the length requred to fence both banks of a riparian reach

| Denmark River sub-total |
| Hay River sub-total |
| Sleeman & Cuppup sub-total |
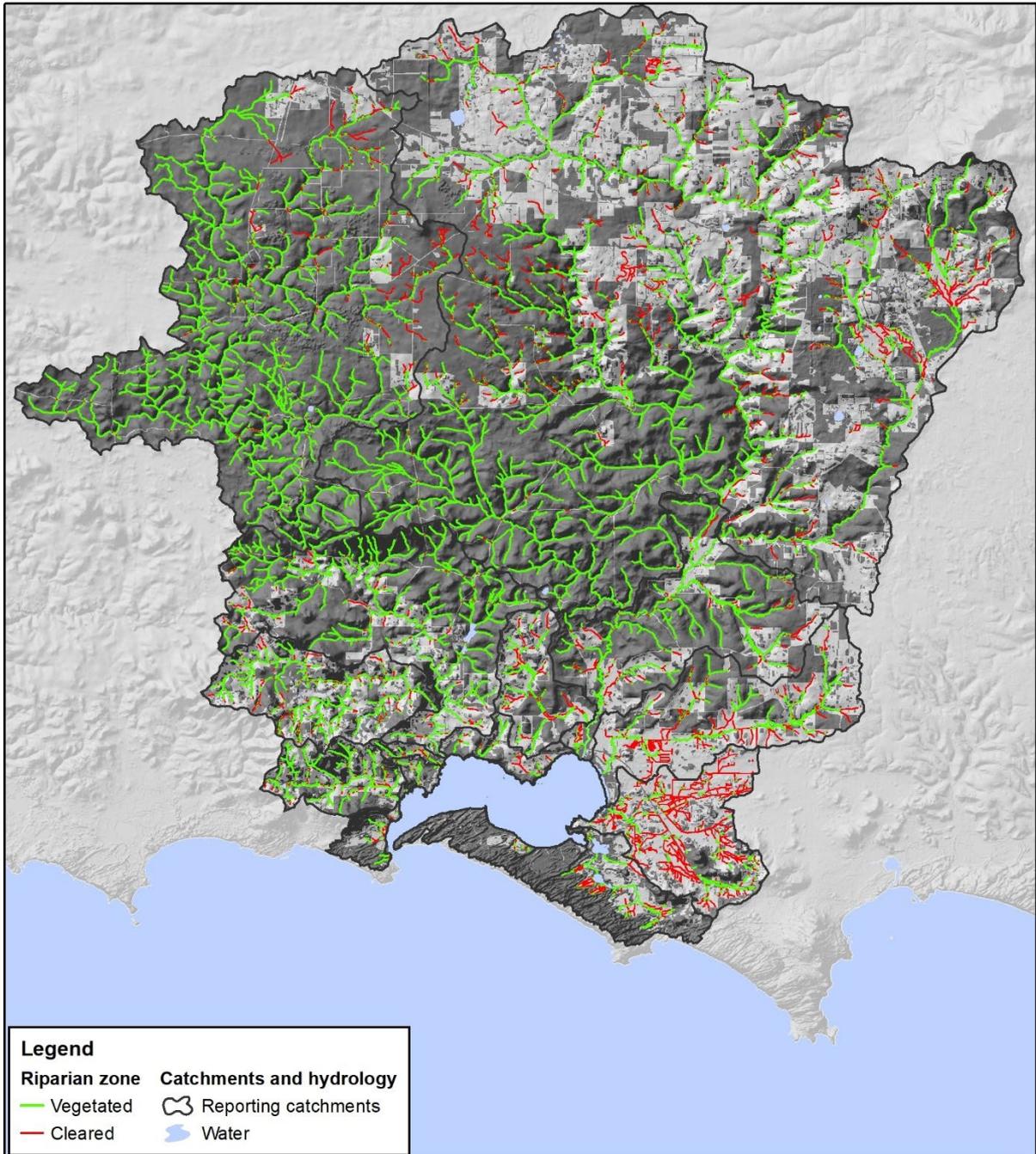
Figure 3.15: Cleared and vegetated riparian zones
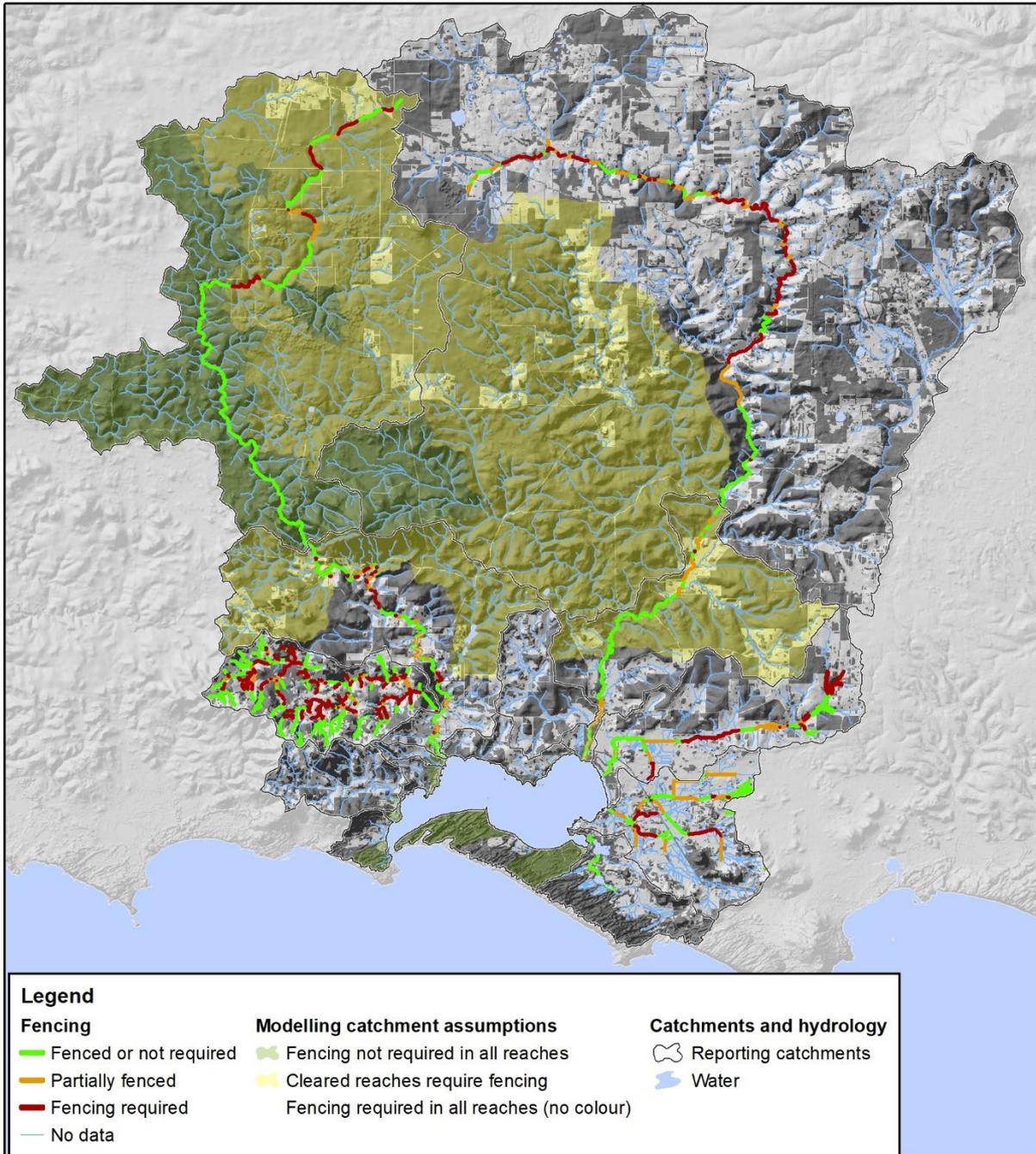
Figure 3.16: Fencing status of riparian zones

Soil phosphorus retention index (PRI)

Soil phosphorus retention index (PRI) is a measure of a soil's capacity to retain phosphorus (Allen & Jeffery 1990). Soils with a PRI of zero would have no capacity to retain phosphorus.

We used DPIRD soil mapping to define soil PRI, from which we made functional units that included both land use and soil type. We created two soil PRI classifications: soils with a PRI of less than 7 being 'low PRI' and soils with a PRI of 7 or greater being 'high PRI' (Figure 3.17).
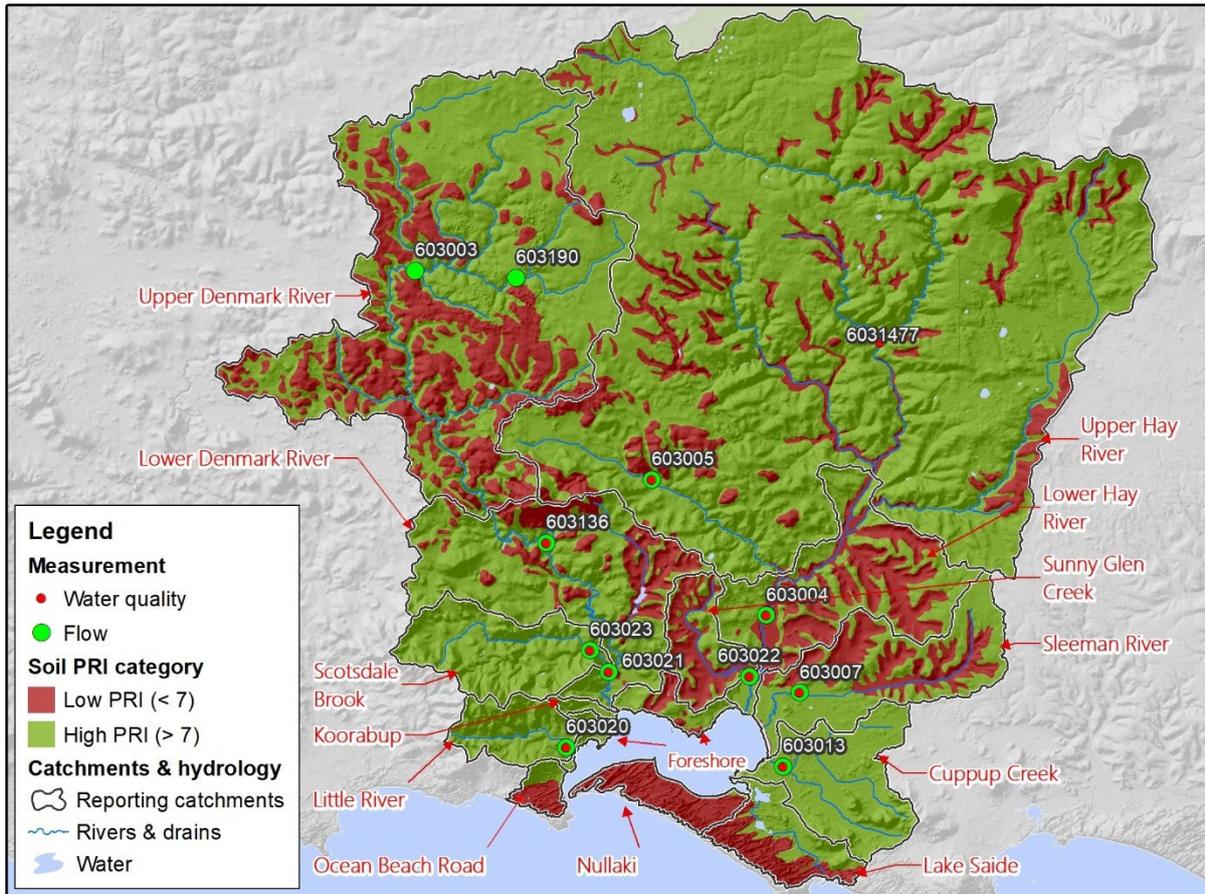
Figure 3.17: High (≥7) and low (<7) soil phosphorus retention index (PRI) categories

Table 3.8: Reporting catchment PRI class area by total and cleared area

Reporting catchment	Total area				Cleared area			
	High PRI	Low PRI			High PRI	Low PRI		
	(km^2)	(km^2)	(% cat)	(% WI)	(km^2)	(km^2)	(% cat)	(% WI)
Ocean Beach	4.0	6.0	60%	1%	1.0	1.5	59%	1%
Little River	32	-	-	-	16	-	-	-
Koorabup	3.7	0.01	<1%	<1%	2.0	<0.01	<1%	<1%
Lower Denmark	121	39	25%	8%	38	3.9	9%	3%
Upper Denmark	288	156	35%	31%	82	6.2	7%	4%
Scotsdale	66	0.04	<1%	<1%	40	0.01	<1%	<1%
Foreshore	15	4.8	24%	1%	7.6	2.1	21%	1%
Sunny Glen	15	20	57%	4%	7	14	66%	9%
Lower Hay	65	56	46%	11%	22	19	46%	13%
Upper Hay	973	149	13%	29%	559	72	11%	49%
Sleeman	59	35	38%	7%	46	24	35%	17%
Cuppup	69	0.3	<1%	<1%	52	0.1	<1%	<1%
Lake Saide	20	19	48%	4%	12	1.8	13%	1%
Nullaki	0.5	23	98%	4%	0.1	1.8	95%	1%
Wilson Inlet	**1732**	**510**	**23%**	**100%**	**886**	**146**	**14%**	**100%**

% cat = % of reporting catchment

% WI = % of Wilson Inlet catchment

Water supply dams, water abstraction and water release data

We used the following data from the Water Corporation to define dam properties, water abstraction and transfers at Quickup and Denmark dams (see Figure 3.18):

- dam volume and surface area relationships based on water depth

- water abstraction data for town water supply (2010–20)

- water transfers from Denmark dam to Quickup dam (2010–20).

Before 2010 we assumed a monthly demand for town water supply (see Table 3.1), which we calculated using the Water Corporation's water abstraction data from 2010–20. We also included a single release in 2016–17 from Denmark dam as part of its regular maintenance, which occurs every few years. We calibrated the volume and timing of this release by comparing our modelled storage volume of Denmark dam with those reported via the Water Corporation's website (see Figure 4.4).
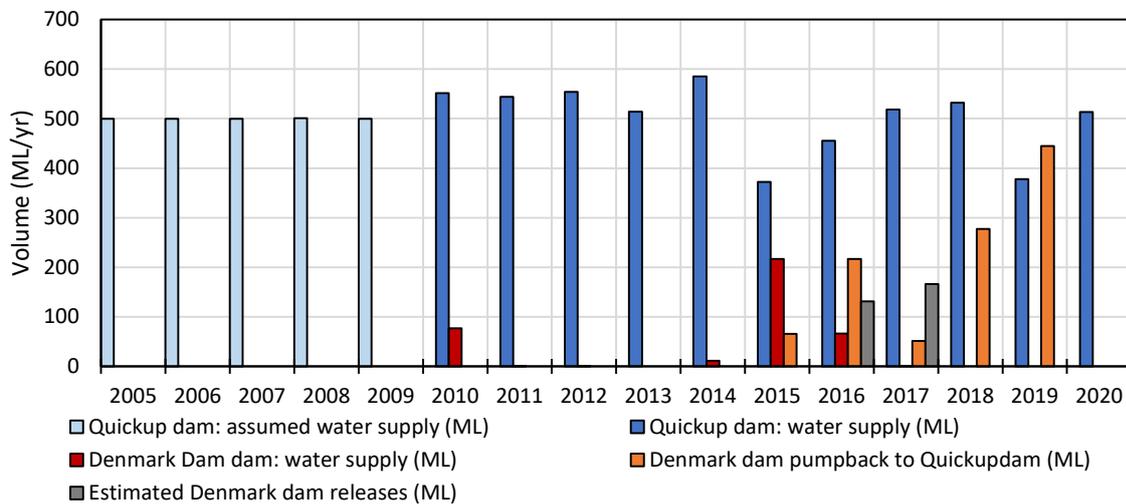
Figure 3.18: Dam water supply (abstraction), transfers and release data that was provided by the Water Corporation or assumed

Onsite wastewater systems (septic tanks)

Onsite wastewater disposal systems such as septic tanks or alternative/aerobic treatment units are used to treat and dispose of domestic wastewater in areas where reticulated sewerage is not available. Onsite wastewater systems, particularly septic tanks, pose a significant risk to the nutrient pollution of surface water ecosystems (Whelan et al. 1981). Raw sewage contains a range of harmful chemicals and has been demonstrated to be ecologically toxic (Reitsema et al. 2010). The contribution of septic tank effluent to surface water environments requires considerable effort to measure. To date, no study has specifically quantified the nutrient or other contaminant emissions from septic onsite wastewater systems to Wilson Inlet or the surface waters of its catchment.

In this report, all onsite wastewater systems are assumed to be septic tanks as there is no known mapping of alternative/aerobic treatment units. Of the 2,289 septic tanks identified, 1,578 (about 59%) were included in the model. Septic tanks were not included in the model if they were on large lots (>1 ha) or were in remote locations (e.g. farms, bush blocks).

We estimated the surface water nutrient contributions from septic tanks using the best-available information. These estimates should be viewed as high-level and validated through measurement if required to inform decision-making. We determined the magnitude of nutrient loss from each septic tank using the septic tank nutrient export categories shown in Figure 3.19. For unsewered caravan parks we assumed one septic tank for each camping spot or building. We used this modelling approach where information about the onsite wastewater systems was unavailable.

See Table 3.9 for the number of septic tanks and their nutrient inputs to land and Figure 3.20 for a map. See Appendix C for our rationale for estimating the surface water nutrient emissions from septic tanks.

Table 3.9: The septic tanks identified and included in the model and their nutrient inputs to land (i.e. discharge via leach drains).

Reporting catchment	Total identified		Included in the model									
	Septic tanks	People	Septic tanks			People			Nitrogen input		Phosphorus input	
	(#)	(#)	(#)	(%)	(% inc)	(#)	(%)	(% inc)	(t/yr)	(%)	(t/yr)	(%)
Ocean Beach	266	585	243	15%	91%	535	15%	91%	2.9	15%	0.6	15%
Little River	251	552	162	10%	65%	356	10%	65%	2.0	10%	0.4	10%
Koorabup	136	299	123	8%	90%	271	8%	90%	1.5	8%	0.3	8%
Lower Denmark	293	645	157	10%	54%	345	10%	54%	1.9	10%	0.4	10%
Upper Denmark	6	13	-	-	0%	-	-	0%	-	-	-	-
Scotsdale	100	220	-	-	0%	-	-	0%	-	-	-	-
Foreshore	688	1514	657	42%	95%	1445	42%	95%	7.9	42%	1.6	42%
Sunny Glen	8	18	-	-	0%	-	-	0%	-	-	-	-
Lower Hay	5	11	-	-	0%	-	-	0%	-	-	-	-
Upper Hay	327	719	233	15%	71%	513	15%	71%	2.8	15%	0.6	15%
Sleeman	5	11	-	-	0%	-	-	0%	-	-	-	-
Cuppup	109	240	-	-	0%	-	-	0%	-	-	-	-
Lake Saide	71	156	-	-	0%	-	-	0%	-	-	-	-
Nullaki	24	53	3	0%	13%	7	0%	13%	0.04	0.2%	0.01	0.2%
Wilson Inlet	**2289**	**5036**	**1578**	**100%**	**69%**	**3472**	**100%**	**69%**	**19.1**	**100%**	**3.8**	**100%**

Note:'%inc' gives the proportion of a reporting catchment's total identified septic tanks that were included in the model. All other percentages give the proportion of the total for the Wilson Inlet catchment.
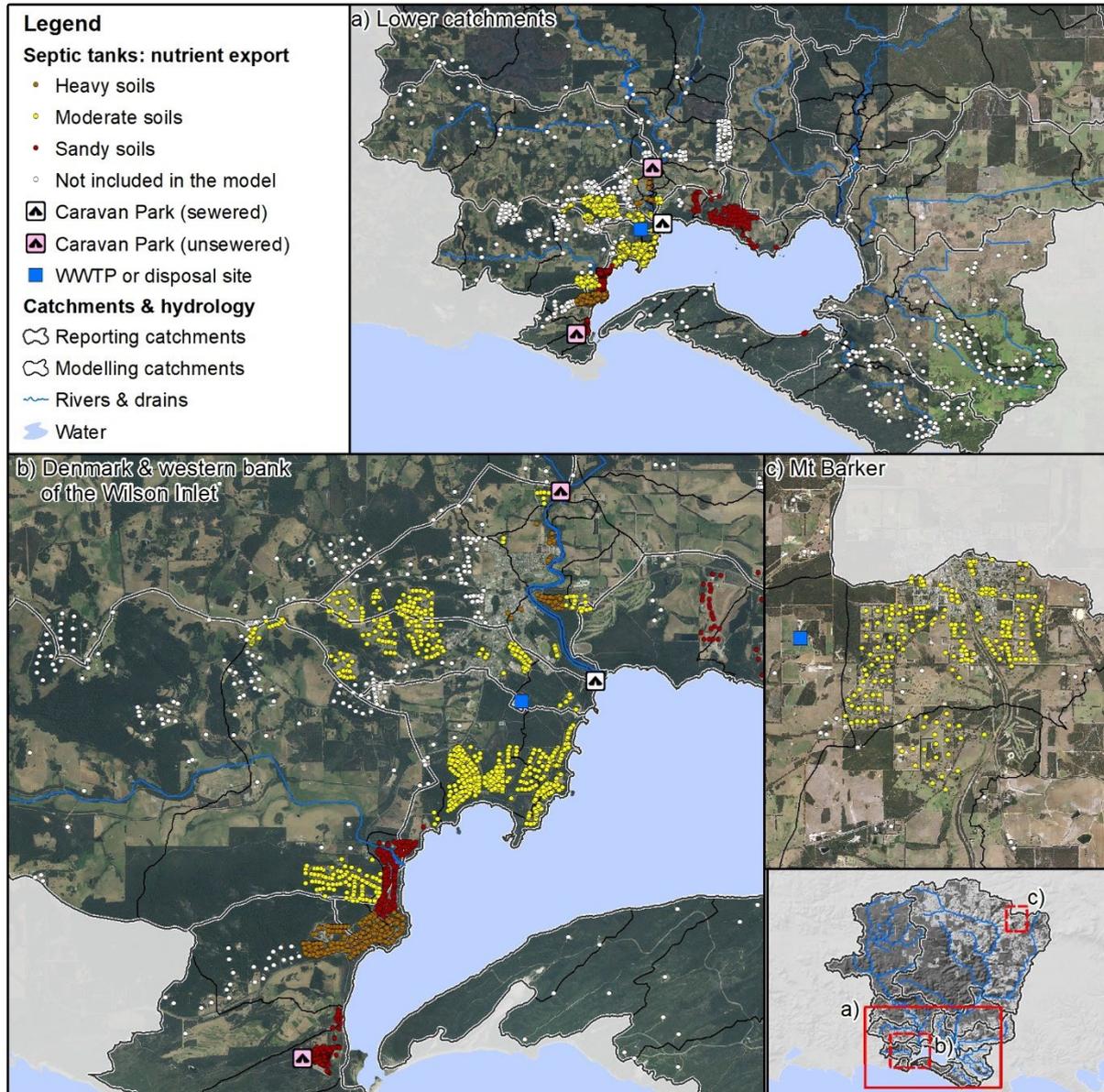
Figure 3.19: Septic tanks

Point sources

This model includes estimated nutrient loads from point sources of nutrients such as beverage making (wastewater irrigation), dairy sheds, intensive animal industries (feedlots, stockyards, piggeries, abattoirs[10]) and wastewater treatment plants. We identified 24 point sources through the land-use mapping process. Figure 3.20 gives the location of the 20 point sources included in the model and Appendix C details how we modelled them. We identified four point sources, but did not include them in the model because there was insufficient information available to do so accurately (see Appendix C for more information).

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[10] It is important to note that there are no abattoirs in the Wilson Inlet catchment. We adopted the 'piggeries & abattoirs' modelling category name and nutrient budget from Hennig et al. (2021) and retained the same land-use name.

Table 3.10 summarises the assumed nutrient inputs from point sources included in the model, categorised by point source type and reporting catchment. In Figure 3.21 we visualise this same information but also include septic tanks. In the Wilson Inlet catchment, point sources make up 3.7% and 4.9% of all nitrogen and phosphorus inputs respectively. Septic tanks contribute 0.3% of the nitrogen and phosphorus inputs, while diffuse sources contribute 95% and 96% respectively. This shows that point sources and septic tanks make up a relatively small proportion of total nutrient inputs.
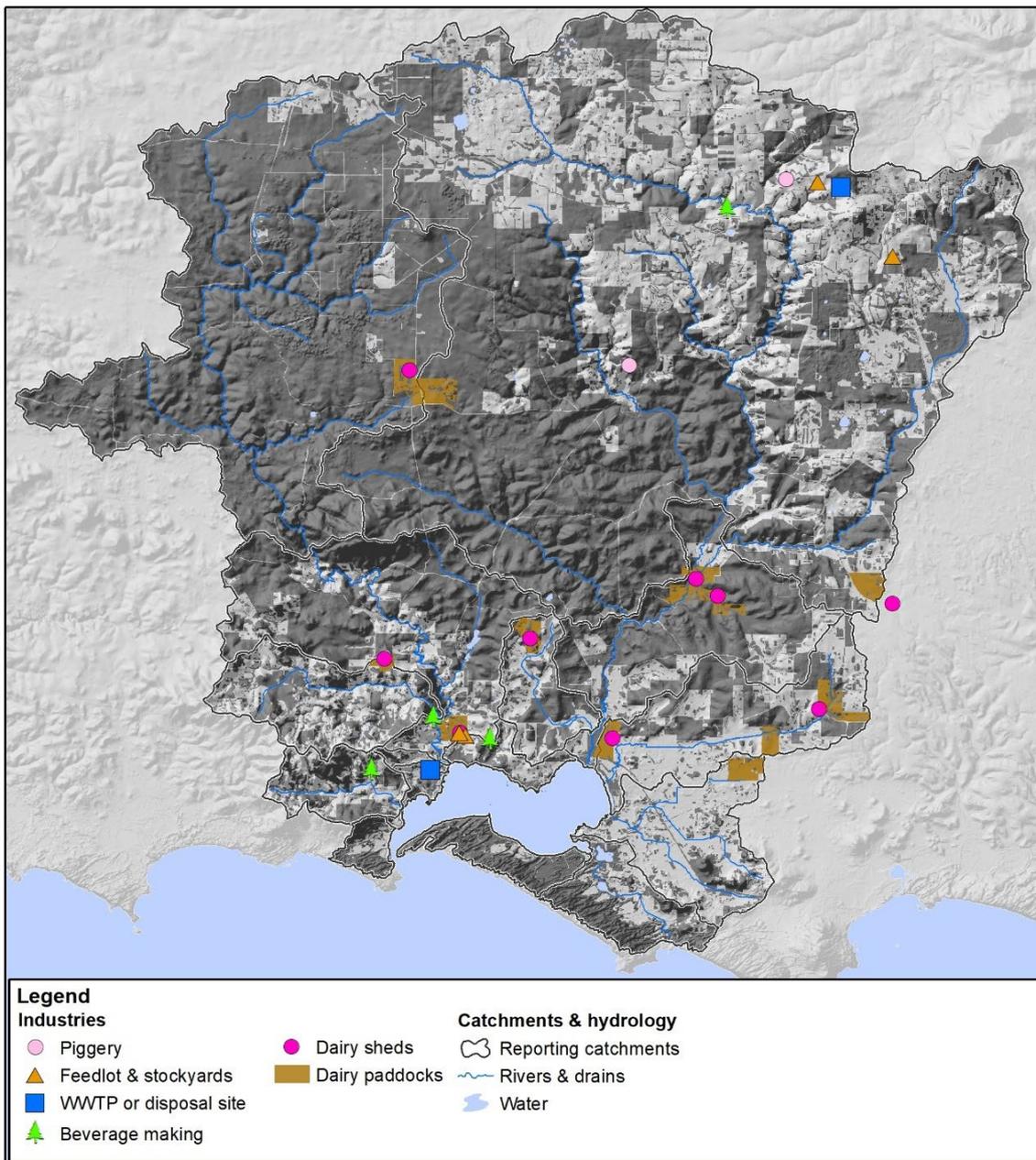
Figure 3.20: Point sources of nutrients

Table 3.10: Point sources and their estimated average annual nutrient inputs

Reporting catchment	Beverage making (wastewater			Dairy sheds			Feedlots & stockyards			Piggeries (free range)			WWTP & disposal area			Total				
	#	N input (t/yr)	P input (t/yr)	#	N input (t/yr)	P input (t/yr)	#	N input (t/yr)	P input (t/yr)	#	N input (t/yr)	P input (t/yr)	#	N input (t/yr)	P input (t/yr)	#	N input (t/yr)	N input (%)	P input (t/yr)	P input (%)
Little River	1	0.03	0.01													1	<0.1	<0.1%	<0.1	<0.1%
Koorabup													1	1.3	0.11	1	1.3	0.5%	0.1	0.2%
Lower Denmark	1	0.03	0.01	1	0.5	0.11	1	18	3.9							3	18.1	7%	4.0	7%
Upper Denmark				1	1.5	0.31										1	1.5	0.6%	0.3	0.5%
Scotsdale	1	0.02	0.01	1	0.8	0.15										2	0.8	0.3%	0.2	0.3%
Foreshore							1	1	0.2							1	0.8	0.3%	0.2	0.3%
Sunny Glen				1	2.2	0.44										1	2.2	0.8%	0.4	0.7%
Lower Hay				2	1.4	0.28										2	1.4	0.5%	0.3	0.5%
Upper Hay	1	0.17	0.04				2	155	34.5	2	87	20.1	1	2.7	0.62	6	246	90%	55.3	90%
Sleeman				2	2.4	0.47										2	2.4	0.9%	0.5	0.8%
Wilson Inlet	**4**	**0.25**	**0.06**	**8**	**8.8**	**1.76**	**4**	**174**	**38.6**	**2**	**87**	**20.1**	**2**	**4.0**	**0.73**	**20**	**274**	**100%**	**61.3**	**100%**
% of point source total		0.1%	0.1%		3%	3%		63%	63%		32%	33%		1%	1%					

Inputs from all other sources	7213	1188
Total inputs	7488	1250
Point source inputs % of total inputs	3.7%	4.9%

a) Nitrogen input (t/yr)

b) Phosphorus input (t/yr)
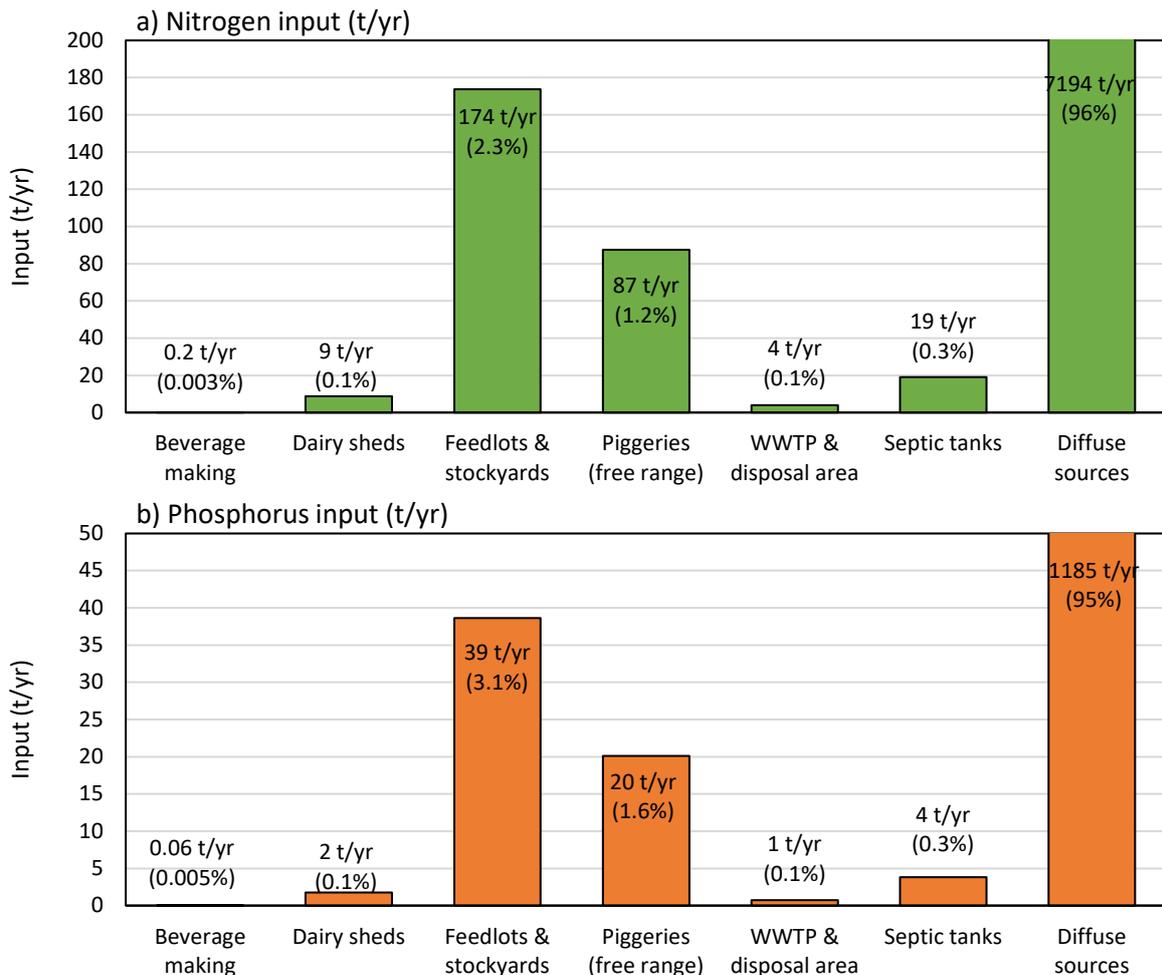
Figure 3.21: Nutrient inputs from point sources, septic tanks and all other diffuse sources

4 Model calibration, model use and limitations

4.1 Calibration process and performance

Calibration is the process of adjusting the independent variables (parameters and fluxes), within realistic limits, to produce the best match between simulated and measured data (surface flow monitoring and nutrient concentration sampling). Calibration aims to increase the model's accuracy by adjusting the unknowns (model parameters) until the solution matches the knowns (flows and concentrations).

We used the auto-calibration tool within Source for hydrological calibration of all catchments, except for the Quickup dam catchment which we calibrated manually. We also calibrated the nutrient model manually. Parameters are adjusted using an optimisation algorithm, which operates for a specified number of iterations or until other closure criteria are reached. The solution of the optimisation algorithm is based on an objective function. The Source auto-calibration tool has a selection of objective functions. We used the daily Nash-Sutcliffe Efficiency (NSE) and log daily NSE[11] and optimised them using the shuffle complex evolution algorithm.

See below for a summary of the calibration, parameterisation and model performance statistics and Appendix A and B for more details.

Hydrological model

We calibrated the hydrological model to flow measurements at 11 sites from 1/1/2005 to 31/12/2018, which we call the calibration period. We validated the hydrological model against flow measurements from 16 flow sites from 1/1/1975 to 31/12/2004, which we call the validation period (Figure 4.1).

The sites used for validation tended to have limited or no data in the calibration period, but have data available for other time periods. However, the Mount Lindesay site (603136) had issues with data quality and therefore was used exclusively for model validation. The downstream site (603021) was used for both model calibration and validation as it had better data quality and HEC-RAS modelling to support high-flow estimates.

All calibration and validation sites were in the Wilson Inlet catchment except for Robinson Drain (602009, Princess Royal Harbour – see Figure 4.2), which was used to parameterise the following ungauged catchments: Ocean Beach Road, Nullaki and Lake Saide. Robinson Drain and these three ungauged catchments have sandy coastal soils with areas of tall dunes and flat, waterlogged land. Thus, we assumed the hydrology of the three ungauged catchments would be more similar to the Robinson Drain catchment than the catchments of other flow sites in the Wilson Inlet catchment.

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[11] https://wiki.ewater.org.au/display/SD54/Calibration+Wizard+for+catchments
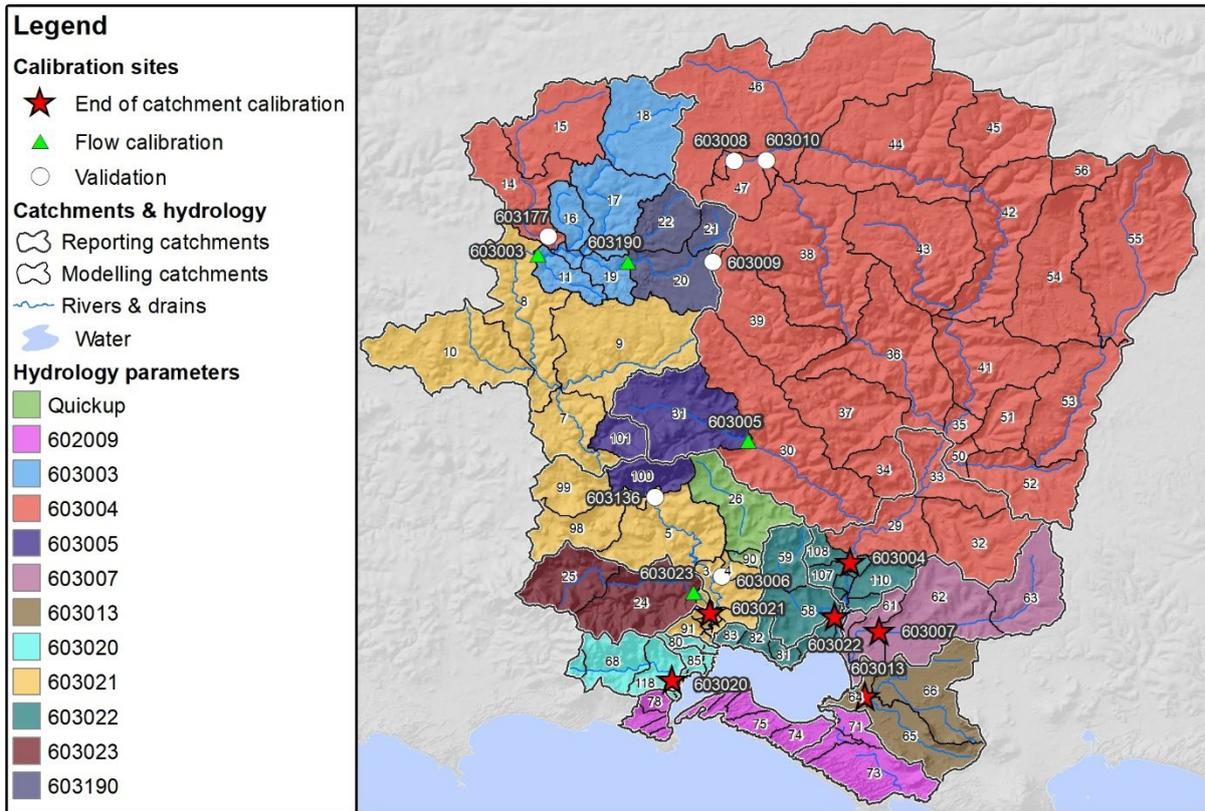
Figure 4.1: Flow calibration and validation sites and flow model parameterisation
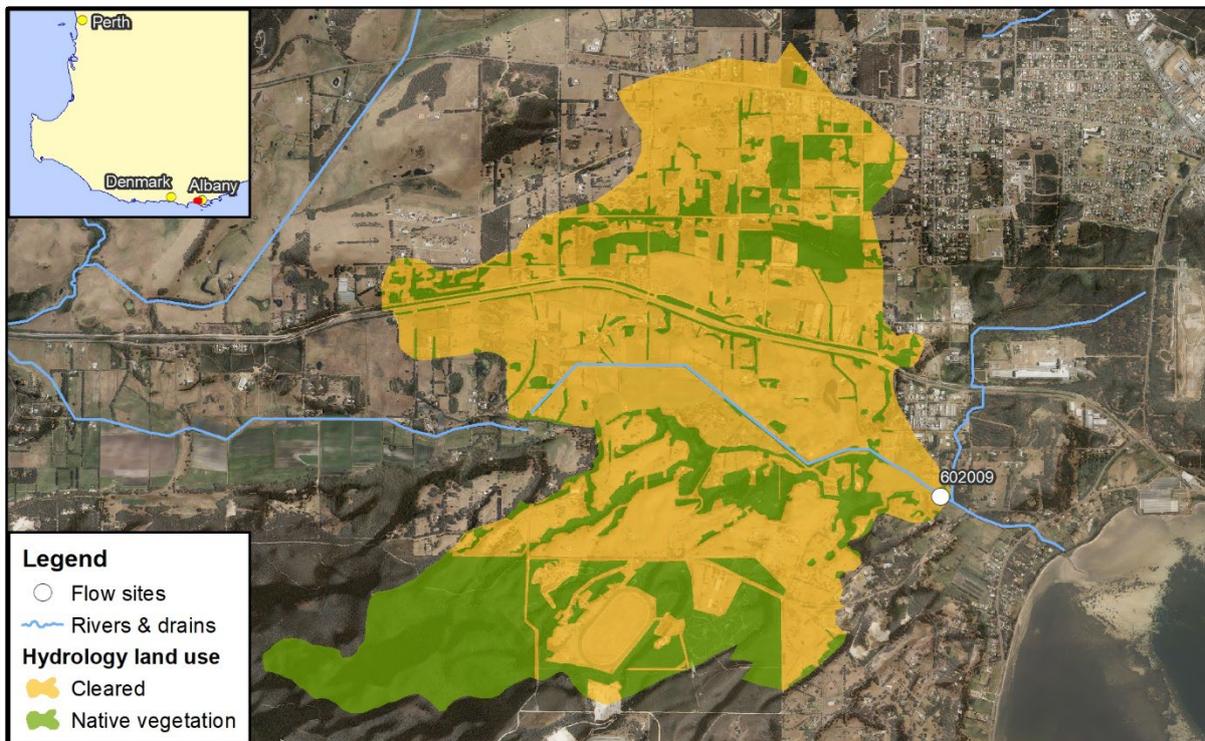
Figure 4.2: Robinson Drain catchment (Princess Royal Harbour, 602009)

We generally assigned model parameters to all upstream catchments and functional units. The exceptions were:

- Modelling catchments 101 and 100 (Lower Denmark River catchment) – we used the native vegetation hydrology functional units from the 603005 (Mitchell River) calibration. These catchments were all vegetated and surrounded Mount Lindesay, the tallest feature in the Wilson Inlet catchment.

- Perillup Brook (catchments 13 to 15) – we assigned the parameters from the Upper Hay catchment, which resulted in better calibration results at 603003 and better validation results at 603177.

- The Lower Hay River catchment and some foreshore modelling catchments – we assigned the hydrology parameters from the calibration at 603022 (Sunny Glen Creek).

We used both of the following objective functions to optimise the hydrological model at a daily timestep:

- **Nash-Sutcliffe Efficiency (NSE) daily and bias penalty.** This objective function is typically best suited to minimising the bias in total streamflow volume (termed volume bias). High-flow events are better replicated at the expense of low flows in some instances. This statistic is commonly used to optimise hydrological models that estimate nutrient loads because higher flow events are associated with larger nutrient loads. This objective function is used in the first instance and the parameters retained if a satisfactory calibration is achieved.

- **NSE log daily and bias penalty.** This objective function is similar to the NSE daily and bias penalty but is typically better at replicating lower flows, baseflow and cease to flow. The bias constraint ensures that volume bias is minimised. In vegetated catchments, this objective function tends to produce better calibration results than the NSE daily and bias penalty. However high-flow events tend to be underestimated. This objective function is used when the NSE daily and bias penalty produces an unsatisfactory calibration. The better calibration of the two optimised parameter sets is retained.

The numerical and qualitative **criteria** that we used to assess the suitability of the flow model in the calibration period were:

- **Volume bias** in total streamflow over the calibration period < ±15% at each calibration site. Volume bias is the percent difference of total measured and modelled streamflow in the calibration or validation period.

- **Objective function used for calibration (NSE daily bias or NSE log daily bias)**: Daily value of ≥ 0.65. Note that a score of >0.8 was desired and a score of >0.9 was very good.

- **Monthly NSE** at calibrated sites of >0.8.

- **Replicating the volume of Wilson Inlet and water levels in Nenamup Inlet** (see Figure 4.3). We developed a water balance model that simulates the volume of the Wilson Inlet when the bar is closed. We also compared the modelled Nenamup Inlet water levels from the catchment model to measured water levels of the wetland. We aimed to visually match the modelled and measured plots with a focus on achieving a close match in 2017. The estuary hydrodynamical model that we are developing uses

outputs from the catchment model. The estuary model is calibrated to measurements that were mostly recorded in 2017 (Mantovanelli et al. in prep).

- **Replicating the reported dam volume in Quickup dam**. We manually calibrated the hydrological parameters of catchments upstream of Quickup dam to match the dam volumes obtained from the Water Corporation's website (see Figure 4.4). The objective was to allow the dam to overflow at the same frequency as the Water Corporation data indicated. Our calibrated model tended to overpredict water levels and overflowed in six out of eight years, whereas the dam was reported to have overflowed in four out of eight years from 2013–20.

- **Other criteria** we used to assess the model were: replication of baseflow, high flow, no-flow conditions, cumulative frequency plots and visual comparison of modelled and observed hydrographs.
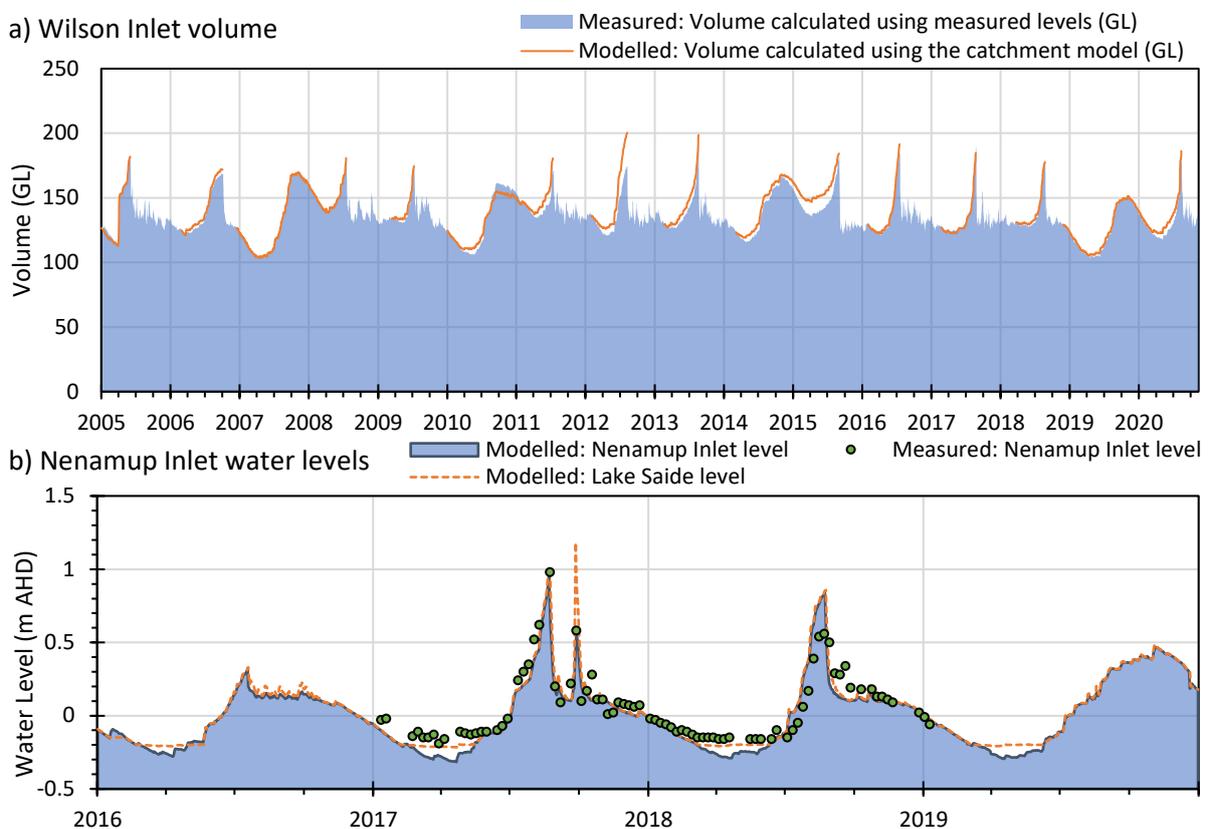
Figure 4.3: a) The volume of Wilson Inlet calculated from measured levels and flows from the catchment model, and b) measured and modelled water levels in Nenamup Inlet
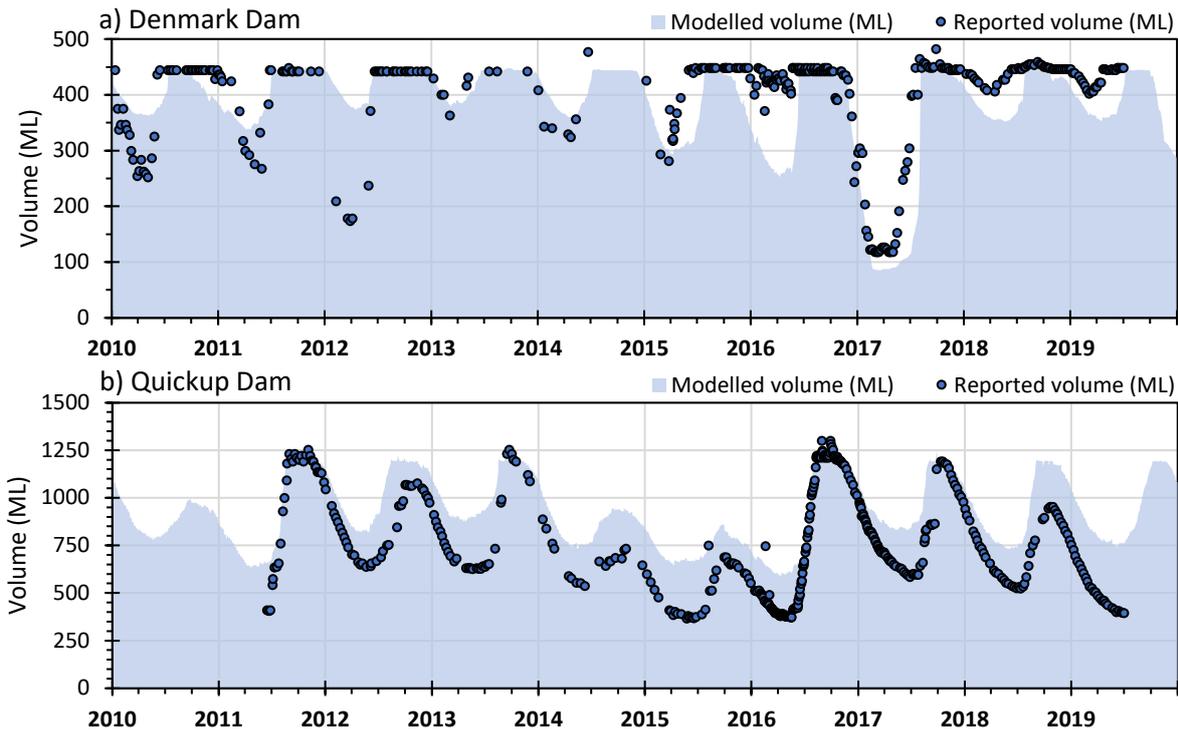
Figure 4.4: Reported and modelled water volume of the Denmark (a) and Quickup (b) dams

Table 4.1 gives the calibration and validation statistics of the hydrological model. We achieved acceptable statistics for sites used for model calibration in the calibration period. The overall model performance, as indicated by end-of-catchment sites, was very good for the calibration period. Figure 4.5 shows the annual measured and modelled flow for end-of-catchment sites, which closely match in all years. The Sleeman River (603007) met the minimum calibration criteria but had a poorer calibration compared with other sites. The Sleeman River calibration had difficulty replicating the baseflow in some years and underpredicted flood flows in 2017 by about half. We believe the issues with the calibration of this site are because of issues with flow data quality (which have recently been improved).

Our catchment model underestimated flows in the validation period by about 35%. We expected this given issues with the non-stationarity of climate and surface water flows (Alilou et al. 2022; Hughes 2021). Because we calibrated to recent climate (from 2005), which is drier with greater interannual variability, our model poorly replicates flows before 2005, particularly for wetter years.
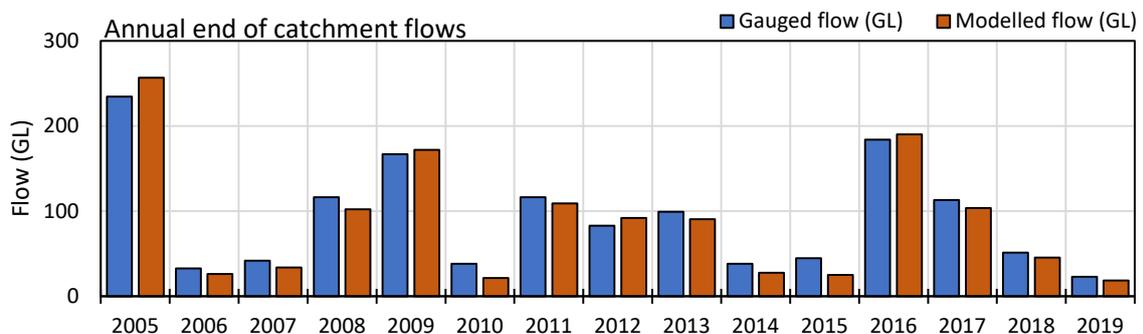
Figure 4.5: Annual modelled and measured flows from the sum of all end-of-catchment sites

Table 4.1: Hydrological model calibration and validation statistics

Site	Calibration period (2005-18)						Validation period (1975-2004)					
	NSE daily	NSE daily & bias penalty	NSE log daily & bias penalty	NSE monthly	NSE annual	Volume bias (%)	NSE daily	NSE daily & bias penalty	NSE log daily & bias penalty	NSE monthly	NSE annual	Volume bias (%)
End of catchment	*0.94*	*0.94*	*0.83*	*0.97*	*0.96*	*-5*	*0.84*	*0.60*	*0.55*	*0.88*	*0.73*	*-35*
603020 ¥	0.80	**0.80**	0.65	0.94	0.87	-4	0.75	**0.67**	0.78	0.84	-0.16	-22
603021 ¥	0.86	**0.86**	0.81	0.89	0.92	2	0.75	**0.48**	0.49	0.78	-0.08	-36
603023 ¥	0.83	**0.83**	0.67	0.95	0.90	4	0.72	**0.70**	0.68	0.91	0.48	-12
603003 €	0.72	0.72	**0.75**	0.80	0.90	-1	0.64	0.15	**0.36**	0.75	0.56	-48
603190 €	0.52	0.52	**0.92**	0.88	0.92	-3	0.20	-0.25	**-0.11**	0.69	0.38	-46
603022 ¥	0.81	**0.81**	0.81	0.89	0.91	-1	0.60	**0.44**	0.68	0.72	-0.04	-29
603004 ¥	0.91	**0.90**	0.70	0.97	0.97	-8	0.77	**0.37**	0.00	0.80	0.41	-44
603005 €	0.84	0.83	**0.69**	0.92	0.91	-9	0.41	-0.45	**-0.10**	0.36	-1.07	-64
603007 ¥	0.71	**0.68**	-0.10	0.82	0.65	-15	0.57	**0.57**	-0.14	0.81	0.58	-5
603013 ¥	0.86	**0.86**	0.39	0.96	0.95	-3	0.81	**0.80**	0.52	0.92	0.67	-9
602009 ¥, Ⅎ	0.72	**0.72**	0.67	0.89	0.71	1	0.74	0.74	0.67	0.91	0.10	-2
603136 *	0.66	0.61	0.66	0.69	0.74	-18	0.57	-0.08	-0.30	0.65	0.16	-56
603177 *	0.44	0.37	0.04	0.44	0.74	-21	-	-	-	-	-	-
603006 *	-	-	-	-	-	-	0.46	-0.45	-0.87	0.36	-0.91	-66
603008 *	-1.78	-2.69	-0.24	0.58	0.51	66	0.37	0.36	0.61	0.73	0.63	9
603009 *	-	-	-	-	-	-	0.22	-0.72	-0.71	0.28	-3.25	-67
603010 *	-	-	-	-	-	-	0.30	-0.03	-0.30	0.67	-0.62	-40

Note:

End of catchment: The sum of flow from 603020, 603021, 603022, 603004, 603007 and 603013

¥ Calibrated using the NSE daily & bias penalty objective function. This statistic is **bold**

€ Calibrated using the NSE log daily & bias penalty objective function. This statistic is **bold**

Ⅎ Located in the Princess Royal Harbour catchment

* Not used for model calibration.

Nutrient model

We calibrated the nitrogen and phosphorus models to measured three-year winter (May–October) median nutrient concentrations[12] at 14 sites (see Figure 4.1). We calibrated to data for 2017–19 for all sites except three – for these we used different periods because of limited data availability (periods given in Table 4.2). We set a difference of ±5% between modelled and observed data as the calibration objective, but we deemed a calibration difference of ±15% as acceptable.

Table 4.2 and Figure 4.7 show the calibration statistics of the nutrient models. All sites had nutrient concentrations within 15% of measurements. The following sites had nutrient concentrations that were outside of the preferred calibration objective of ±5%:

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[12] Daily measurements were excluded when modelled flow was zero.

- 603004 had modelled TN and TP concentrations that were 8% and 9% greater than measured respectively. For nitrogen, we had difficulty achieving an acceptable calibration simultaneously at this site, as well as the upstream calibration site 6031477, which had modelled concentrations within 2% of measured. The calibration presented here was the best compromise without including instream nitrogen decay models, which we felt lacked the justification to include. For phosphorus, modelled concentrations only differed by 0.001 mg/L. For context, the detection limit of TP measurements is 0.005 mg/L.

- 6031283 and 6031104 had limited data and calibrating the storage node nutrient decay model to measured data was not feasible.

See Appendix B for the calibrated land-use nutrient parameters and Section 5.2.2 for the nutrient export rates of land uses. Table B.10 in Appendix B gives the range in modelled land-use nutrient export rates.

Figure 4.6: Nutrient model calibration sites and model parameterisation

Table 4.2: Nutrient model calibration statistics

AWRC ref	Site context & name	TN			TP		
		Observed winter median (mg/L)	Modelled winter median (mg/L)	Diff (%)	Observed winter median (mg/L)	Modelled winter median (mg/L)	Diff (%)
603020	Little River - Ocean Beach Rd	0.83	0.87	5%	0.064	0.065	2%
603021	Denmark River - Denmark Ag College	0.74	0.74	0%	0.027	0.028	3%
603023	Scotsdale Brook - Pipehead	0.72	0.71	-1%	0.033	0.032	-2%
603136	Denmark River - Mt Lindesay	0.68	0.71	5%	0.015	0.016	5%
603022	Sunny Glen Creek - Girrawheen	2.06	2.15	4%	0.246	0.252	2%
603004	Hay River - Sunny Glen	0.84	0.91	8%	0.016	0.017	9%
603005*	Mitchell River - Beigpiegup	0.41	0.40	-2%	0.008	0.008	0%
6031477	Hay River - Evhay01	0.93	0.91	-2%	0.013	0.013	0%
603007	Sleeman River - Sleeman Rd Bridge	1.64	1.70	4%	0.172	0.178	4%
603013	Cuppup River - Eden Rd	1.96	2.04	4%	0.242	0.249	3%
6031283¥	Nenamup Inlet Drain	2.05	1.76	-14%	0.066	0.058	-12%
6031104¥	Lake Saide Drain - Bridge 127-Wolves	2.00	2.17	9%	0.071	0.078	10%

Statistics calculated for: * 2007–2009, ¥ 2008, and all other sites 2017–19
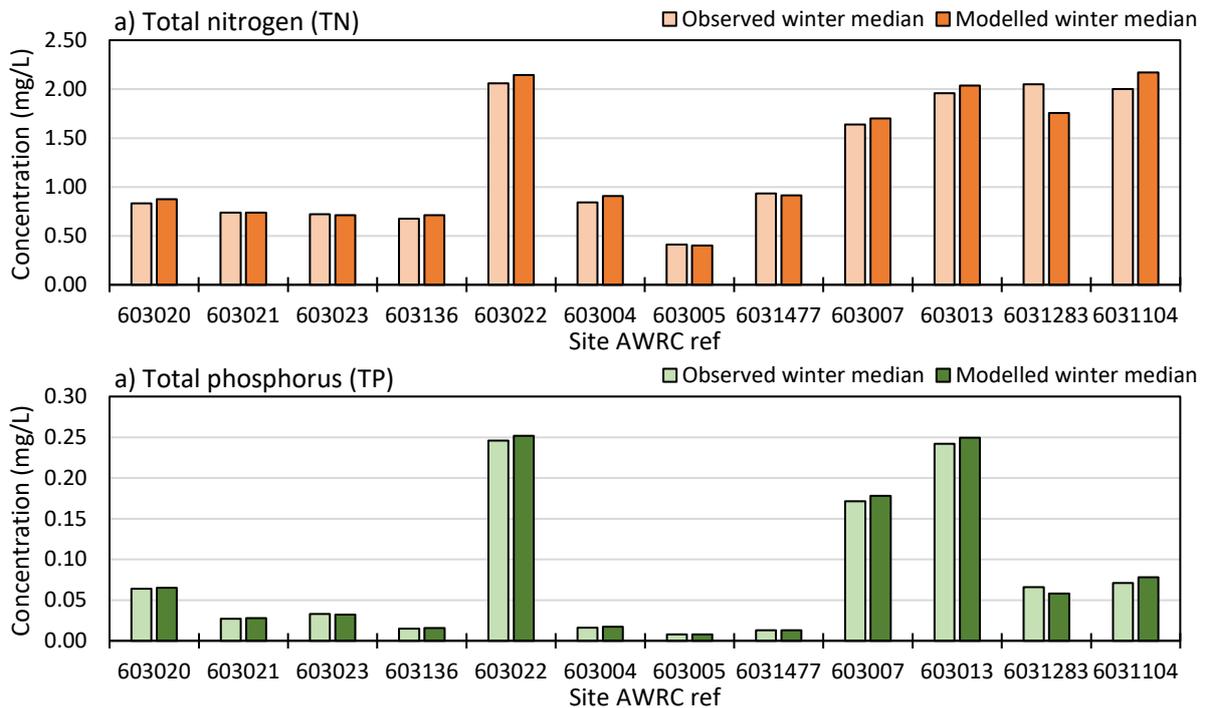
Figure 4.7: Measured and modelled three-year winter median concentrations (2017–19)

4.2   Comparison to previous modelling

Ecotones & Associates (2008) developed nutrient hazard mapping for the Wilson Inlet catchment. The Support System for Phosphorus Reduction Decisions (SSPRED) model estimates the annual source of nutrient load by land use and catchment. Input data to the model include land-use mapping and nutrient surveys, stream mapping, catchment boundary mapping and soil-subsystem mapping. The SSPRED model was calibrated to estimated nutrient loads at measurement sites in 1999, which was an average rainfall year and the reporting period for results.

While the models used by Ecotones & Associates (2008) and our study are different, they are both capable of estimating catchment-scale nutrient loss and informing priorities for future management. Differences and similarities between these models are given below.

Input data

- **Nutrient surveys:** both models derived nutrient-use data from the same survey datasets.

- **Catchments**: total catchment area and catchment boundaries were similar. Our model included an additional 470 ha catchment area (0.2% of the entire catchment) due to the realignment of some catchment boundaries based on more recent spatial data.

- **Land use:** Ecotones & Associates (2008) used land-use mapping based on aerial photography and other datasets that were representative of 2001 to 2007. Our land-use mapping represents the period of 2007 to 2020.

  o Beef and mixed grazing was 8,500 ha larger in Ecotones & Associates (2008). Most of this land was likely converted to plantations and mapped as such in our land-use map (see Figure 7.12 for a timeseries of net plantation area in Section 7.2).

  o The area of dairy in Ecotones & Associates (2008) was 1,090 ha greater. This likely reflects the closure of some dairies since 2007.

  o We mapped an additional 3,000 ha of sealed and unsealed roads, mostly among areas of native vegetation. Ecotones & Associates (2008) had mostly classified these areas as native vegetation.

Differences in modelling

- In our model, nutrient loss is driven in part by modelled flow. Ecotones & Associates (2008) did not estimate flow.

- We calibrated flow at 11 sites and nutrient concentrations at 12 sites. Ecotones & Associates (2008) calibrated to five catchments (without specifying the number of sites used for calibration).

- We accounted for the impact of the Eden Road floodgates and nutrient removal/attenuation of the wetlands in the Lake Saide catchment. The Ecotones & Associates (2008) model did not account for this.

- Our model accounted for surface water abstraction for town water supply and explicitly included the Denmark and Quickup dams (as well as three large private dams). The

impacts of these were implicit in the calibration of the Ecotones & Associates (2008) model.

- Ecotones & Associates (2008) explicitly accounted for in-stream nutrient attenuation whereas these processes were implicit in the calibration of our model.

- We accounted for the nutrient attenuation (paddock to stream) from riparian zone fencing and vegetation.

Comparison of model results

- Ecotones & Associates (2008) estimated lower loads of phosphorus compared with our model.

- Our model tended to estimate lower loads of nitrogen compared with the Ecotones & Associates (2008) model.

- Both models identified the Cuppup catchment as being a major contributor of nutrients to the Wilson Inlet. Our modelling also showed that the Sleeman catchment was a major contributor of nutrients, while Lake Sadie catchment was a small contributor. In the Ecotones & Associates (2008) model, the Sleeman and Lake Saide catchments were both moderate contributors of nutrients. Furthermore, we identified that the cleared portions of the Ocean Beach catchment had high nutrient loss intensity, something not reflected in the results of Ecotones & Associates (2008).

- Both models estimated that beef, dairy and horticulture contributed the largest loads of phosphorus. For nitrogen, both models estimated that beef and dairy produced the greatest nutrient load. However, we estimated that native vegetation contributed about 9% of the nitrogen load to the inlet, whereas this contribution was about 0.2% of the nitrogen load in the Ecotones & Associates (2008) model. We estimated that plantations contributed 7% of the phosphorus load in our catchment model. Plantations contributed less than 0.05% of the phosphorus load in the Ecotones & Associates (2008) model.

4.3   Recommended model uses and limitations

The Source model is a large-scale catchment model designed to support catchment management decisions. Results and output data from the model are produced at a daily timestep at many locations within the model (i.e. results are potentially available for each functional unit within each modelling catchment), and as such can be interpreted and used to inform a variety of projects for which the model was not specifically developed. To support the model's potential use, we have detailed its recommended uses and limitations below.

The Wilson Inlet water quality model is suitable to be used for:

- **Monthly, seasonal and annual flows and nutrient loads and concentrations for major waterways and receiving waterbodies.** The model reports both absolute and relative loads at this scale for the period over which it was calibrated. However, there is most certainty for waterways with flow gauging and nutrient sampling data, and less certainty for waterways with limited or no flow and/or nutrient data.

- **Land-use and long-term climate change impacts.** The model can help explore changes in relative and absolute flows, nutrient loads and concentrations that would result from climate change, reported as average annual flows, loads and concentrations. Reporting changes in flow or nutrient load that result from climate change impacts at smaller temporal and/or spatial scales are subject to the constraints and cautionary notes provided below.

- **Estimate the source of nutrient loads from land uses with a reasonable level of confidence.** Results are likely to be reasonably accurate for land uses that occupy a large proportion of a catchment's area or in catchments that have been calibrated against flow and/or nutrient measurements.

- **Data for receiving estuary models.** Modelled daily flows will be suitable for use in estuary models. In some cases, individual years may have flow bias errors that differ from the bias calculated over the entire calibration period (2005–19). It is important to conduct checks for the period where data is required and, if necessary, recalibrate the catchment model.

In the following cases, it may be appropriate to use the model outputs, but we advise caution and an understanding of the associated constraints. It may be possible to estimate:

- **Low flows for environmental water requirement studies.** At many of the flow calibration sites, the rainfall-runoff model and calibration may be appropriate for use in environmental water requirement studies. However, we advise researchers to check the low-flow calibration metrics and the flow-duration curve to ensure that model outputs are appropriate for their intended use. If low flows are not adequately represented, then the rainfall-runoff model should be re-calibrated with an objective function that specifically targets low flows.

- **Seasonal nutrient loads and the 'first flush' mechanism.** The nutrient generation model is empirical, and not developed to capture first flush or multiple seasonal trends such as elevated summer concentrations. Flows during the summer are generally small and thus nutrient load is also generally small. The focus of this modelling is to replicate nutrient concentrations that have the largest effect on nutrient load (i.e. moderate to high flows).

- **Nutrient loads from catchment outlets that are not gauged or sampled.** As mentioned above, these are likely to have significant uncertainty, and caution should be exercised when using this data. This applies to all modelling catchments that do not have water quality or flow measurements for calibration. Thus, using modelled data at a small spatial scale will have greater uncertainty in modelled flows and nutrient loads. Depending on the accuracy required for the given application, these outputs may or may not be appropriate for use.

- **Nutrient exports from roads**: Modelled nutrient concentrations of road runoff were substantially underestimated based on a comparison to local (Davies et al. 2000) and national literature (Duncan 1999). The underestimation both of road reserve nutrient input rates and their assumed nutrient export factor caused this issue.

- **In-stream assimilation:** In-stream nutrient assimilation processes are implicit in model calibration.

- **Riparian zone re-vegetation:** Several studies have considered the effect of riparian zone re-vegetation on nutrient assimilation and removal. However, the effectiveness of this management action, and how long it lasts, remains uncertain. Thus, we have taken a conservative approach to modelling this action.

- **Mapping of fences:** The fencing status of riparian zones was based on surveys from 1995–2002 and therefore it is possible the fencing status may have changed. In addition, we were unable to source the spatial data from desktop mapping of fencing status in the Hay and Sleeman catchments. Hence, we believe the fencing requirement is substantially overstated in these catchments as well as catchments without any fence status mapping (Sunny Glen Creek, Lake Saide, Little River and Foreshore catchments).

   In catchments where riparian management is being considered, the fencing status of riparian zones should ideally be mapped early in the planning process.

The model did not simulate the following processes and applications:

- **Paddock-scale processes:** The empirical nutrient generation and filtering models are not suitable to model paddock-scale processes (i.e. the nutrient transformations between the application of fertiliser and its loss to groundwater and surface water).

- **Run-down of nutrients:** The Source nutrient model is empirical and does not model nutrient run-down in the soil profile, the stream or groundwater. Note that the stream response to a management intervention is buffered by these nutrient stores and lag times can be large (Meals et al. 2010).

- **Sub-daily outputs (estuary or flood models):** The Source model is simulated at a daily timestep, and results can be aggregated but not disaggregated. This limitation should be well understood before model outputs are used by estuary or flood models.

- **Detailed ecological processes (or estuary processes):** Our models do not include nutrient species other than TN and TP. Potential ecological effects may be inferred but we did not model them explicitly.

- **Groundwater dynamics:** Groundwater is a conceptual store in the rainfall-runoff model and was not calibrated or validated. We do not advise using this model output without validation.

- **Channel hydraulics or estuary hydrodynamics:** This model is a coupled hydrological and nutrient model and does not simulate flow dynamics in the inlet.

4.4 Uncertainty

Uncertainty is an inherent part of catchment-scale modelling due to the complex processes at play and the simplifications and assumptions made during the modelling process. Overall, we believe that our catchment model is robust, well calibrated and capable of being used for its intended purpose (see Section 1.1). Despite this, aspects of the model have varying degrees of uncertainty, which are summarised below.

Uncertainty from model selection and parameterisation

Hydrological model selection

The LASCAM model was developed specifically for south-west Western Australia's conditions and is a well-tested and proven hydrological model. In all testing undertaken in this study, LASCAM results in better calibration metric scores than other models at the expense of increased model complexity and computation time. Despite this, the LASCAM model has some level of associated uncertainty which may increase depending on its application. For instance, LASCAM has difficulty replicating both the wetter pre-2000 and drier post-2000 periods simultaneously. This appears to be a common issue to all hydrological models in Source.

Nutrient generation model

We used the empirical generation model in Source to construct and calibrate the nutrient model but this had some significant limitations. A more complex model was not available within the Source framework, a matter being considered by the National Water Quality Working Group (Fu et al. 2019). Without the understanding or simulation of nutrient generation processes, there was considerable uncertainty in daily nutrient concentrations at times during the year. Furthermore, the assumption of a linear relationship between nutrient surplus and export may not be true for all land uses, and this could potentially affect the separation of load by land-use categories and hence the outputs of the land-use change and management scenarios.

Riparian filtering model

The riparian filtering model used assumed rates of nutrient removal and attenuation based on a review of relevant literature in a narrow field of research. A better understanding of riparian processes and assimilation due to riparian vegetation management would help reduce this uncertainty in future models.

Parameter calibration and assignment

We optimised the parameters of the LASCAM model using Shuffle Complex Evolution (SCE) algorithms, which searches for parameter sets that simulate flow that best fits measured flow. Despite the robustness of the SCE approach, uncertainties remain due to the complexity of the optimisation process. We calibrated the nutrient model manually owing to the simplicity of the model. Although SCE might provide better calibration scores, we do not expect these would meaningfully deviate from our manual calibration results.

Catchments without suitable measurements for calibration use parameters from similar catchments, introducing higher uncertainty.

Dairy shed implementation

To integrate nutrient loss from dairy shed effluent into the catchment model we used assumptions that are not well tested. Although the effluent volume and nutrient load that enters the effluent management system are generally well-understood, the assimilation of this nutrient in processes such as reuse, denitrification and off-farm export have not been

measured. This will affect the amount of load attributed to dairy sheds. Calibration of the dairy shed export parameter accounts for these aggregated effects and worked well when calibrating the nutrient model.

Since dairy sheds are not the major contributor of nutrient load, this uncertainty is unlikely to affect the overall separation of nutrient loss by land use. However, there is a high level of uncertainty about the load attributed to dairy sheds on a subcatchment basis.

Septic tank implementation

Onsite wastewater disposal system locations are well understood, however there is no known mapping of alternative treatment unit systems which treat wastewater to a higher standard than septic tanks. Most of the unsewered lots around Wilson Inlet were developed before 1990 and likely use septic tanks to dispose of wastewater, for which the rates of nutrient leaching are well understood and have a relatively low level of uncertainty. However, the assimilation of nutrient load between the septic tank and receiving waterbody has much greater uncertainty. Hence the absolute load of nutrient loss to the inlet has greater uncertainty.

Data uncertainty

We used the following data in the model: streamflow and water-level data, water quality measurements, interpolated climate data, nutrient surveys, land use mapping, soil mapping, catchment mapping and dam properties.

Interpolated climate data

Interpolated climate data is subject to errors due to the spatial variability of rainfall, the number and proximity of interpolation sites, and changes to interpolation methodologies over time. While we corrected some rainfall events based on the department's rainfall sites, which were not included in the SILO rainfall interpolation at the time, errors in interpolated climate data remain (see Figure 3.9).

Land-use and soil mapping

Land-use mapping is subject to human error and changes over time. While the latter is accounted for in plantation reversion and expected to have a small effect at a catchment scale, changes in land management and land use can be significant in some areas (e.g. potato farming moving from Lake Saide to the lower Sleeman River).

The soil PRI mapping used in this project is a reliable dataset and has been used elsewhere in south-western Australia. However, this dataset may not accurately detail the heterogeneity of soil PRI in all areas. Discrepancies between this soil mapping and the DPIRD whole-farm nutrient mapping data were found, indicating the Cuppup catchment may have a larger area of low-PRI soils (PRI <7) than indicated in the soil PRI mapping.

Land-use nutrient budget data

We used land-use nutrient budget data derived from local studies and relevant literature. This nutrient budget data represents the average, which is reliable when applied at the catchment scale. Nutrient use varies spatially and temporally, both of which increase

uncertainty. Using recent, locally derived nutrient-use data, either by farm or aggregated by catchment, would help reduce this uncertainty.

Streamflow data

The following streamflow measurement sites have issues with flow measurement and, because they were used for model calibration, this introduces greater uncertainty to the calibrated model parameters: Sleeman (603007), Sunny Glen Creek (603022), Little River (603020) and Mount Lindesay (603136). The flow measurement sites at Sleeman and Sunny Glen Creek are not situated in ideal locations for flow measurement, as the landscape is flat and close to the inlet, hence backwater effects are common. Local landholder pumping and waterway alterations can also affect the flow measurement in these areas. Calibration was particularly difficult at the Sleeman site – it had the worst calibration metrics of all the flow calibration sites (see Section 4.1). Thus, modelled flow at Sleeman River has greater uncertainty than the other calibrated catchments. Measured flow at the Little River site appears to be overpredicting baseflow based on discharge measurements below a stage of 10.4 m. Our model also could not replicate this baseflow and underpredicted it. Hence there is greater uncertainty in measured and modelled flows at lower flow ranges at the Little River site. The Mount Lindesay site generally had poor flow data quality (based on quality codes and comparison with other measurement sites and modelled flows) and was only used to validate the hydrological model.

Water supply dam data

The storage-volume data for Denmark and Quickup dams can be affected by sedimentation that varies over time and hence has an associated uncertainty. The measurement of water abstraction, transfers between dams and scheme water supply has inaccuracies depending on pump type and measurement devices. Given this data was used to trigger water abstraction and transfers from Denmark and Quickup dams, some uncertainty is inherent in the measurements. However, because the outflow/abstraction from both dams is small, this uncertainty likely has a small to negligible impact on average annual flow and nutrient loads to Wilson Inlet. In dry years this uncertainty may be greater for Denmark dam, where abstraction may have a larger impact on the volume of dam overflow.

Water-level data

We used water-level data in Wilson Inlet to determine outflow from the Eden Road floodgates in the Lake Saide catchment. This site is at the mouth of the Denmark River and may be affected by river discharge, but more so the wind displacement of water in the inlet. Both may result in small, temporary errors in mean daily water-level data. This likely has a negligible impact on average annual flow and nutrient loads to Wilson Inlet.

Water-level readings upstream and downstream of the Eden Road floodgates are taken manually by the Water Corporation. These readings may be subject to human error and hence have some associated uncertainty. The data was used to calibrate water exchange between Lake Saide, Nenamup Inlet and discharge to Wilson Inlet. The uncertainty in measurement likely has a small impact on flows and nutrient loads to Wilson Inlet.

Propagation of uncertainty

Because of the interconnected nature of hydrological processes, uncertainties in model inputs, parameters and structure can propagate through the model, potentially affecting the accuracy of its outputs. For instance, uncertainty in rainfall data can propagate to affect the simulated flow generation, which could further influence nutrient concentration and load predictions.

Overall, while our catchment model has proven to be robust, as indicated by the calibration metrics in Section 4.1, it is important to interpret these results with an understanding of the inherent uncertainties. Our model is not an absolute representation of reality, but a tool to help us better understand the functioning of the catchment and inform management decisions.

5 Modelling results

5.1 Catchment condition 2010–19

5.1.1 Average annual flows and loads

Table 5.1 gives the average annual flows and nutrient loads for reporting catchments and major catchments[13] for the period 2010–19. The volume of water reaching Wilson Inlet averaged 85 GL/yr. The nutrient load from all catchments is about 108 tonnes/yr of nitrogen and 8.7 tonnes/yr of phosphorus.

Table 5.1: Average annual (2010–19) reporting catchment nutrient loads and flows

Reporting catchment	Total area		Flow		Nitrogen		Phosphorus	
	(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Ocean Beach Road	10	0%	1.2	1%	2.6	2%	0.23	3%
Little River	32	1%	6.1	7%	6.2	6%	0.53	6%
Koorabup Creek	4	0%	1.0	1%	2.1	2%	0.13	2%
Lower Denmark River	160	7%	8.4	10%	7.5	7%	0.20	2%
Upper Denmark River	444	20%	5.3	6%	4.6	4%	0.14	2%
Scotsdale Brook	66	3%	11	13%	12	11%	0.49	6%
Foreshore	20	1%	2.3	3%	3.9	4%	0.20	2%
Sunny Glen Creek	36	2%	2.1	2%	4.4	4%	0.69	8%
Lower Hay River	122	5%	4.3	5%	5.4	5%	0.56	6%
Upper Hay River	1122	50%	21	25%	21	19%	0.47	5%
Sleeman River	94	4%	9.2	11%	16	15%	2.1	24%
Cuppup Creek	69	3%	10	12%	19	18%	2.8	32%
Lake Saide	39	2%	1.6	2%	2.9	3%	0.09	1%
Nullaki	23	1%	0.5	1%	0.6	1%	0.09	1%
Major catchments (sub-total)								
Denmark River	670	30%	25	29%	24	22%	0.8	10%
Hay River	1279	57%	28	33%	30	28%	1.7	20%
Cuppup & Sleeman	163	7%	19	23%	35	33%	4.9	56%
All other catchments	129	6%	13	15%	18	17%	1.3	15%
Wilson Inlet	**2241**	**100%**	**85**	**100%**	**108**	**100%**	**8.7**	**100%**

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[13] The Denmark River includes the upper and lower catchments as well as Scotsdale Brook. The Hay River includes the upper and lower catchments as well as Sunny Glen Creek. The Cuppup and Sleeman catchments were aggregated, and all remaining catchments were aggregated as 'all other catchments'.

5.1.2 Annual flows and loads

Figure 5.1 gives the annual flow and nutrient loads delivered to Wilson Inlet by major catchments[13] for 2005–19. The three wettest years in this period were 2005, 2009 and 2016. There were seven dry years (2006, 2007, 2010, 2014, 2015, 2018 and 2019), with the driest year being 2019 (25 GL). All remaining years had flows between about 110 and 130 GL/yr. Nitrogen and phosphorus loads followed the same pattern as described for flow.

In all years except 2015 the Sleeman and Cuppup catchments contributed the largest loads of phosphorus. These two catchments also contributed similar or greater nitrogen loads than the other major catchments, except for the three wettest years (2005, 2009, 2016) and 2015. The Hay River had the greatest variation in river flow and nutrient loading (particularly nitrogen): in 2005 it contributed 47% of the nitrogen load to the inlet whereas in 2006 it contributed 17%.
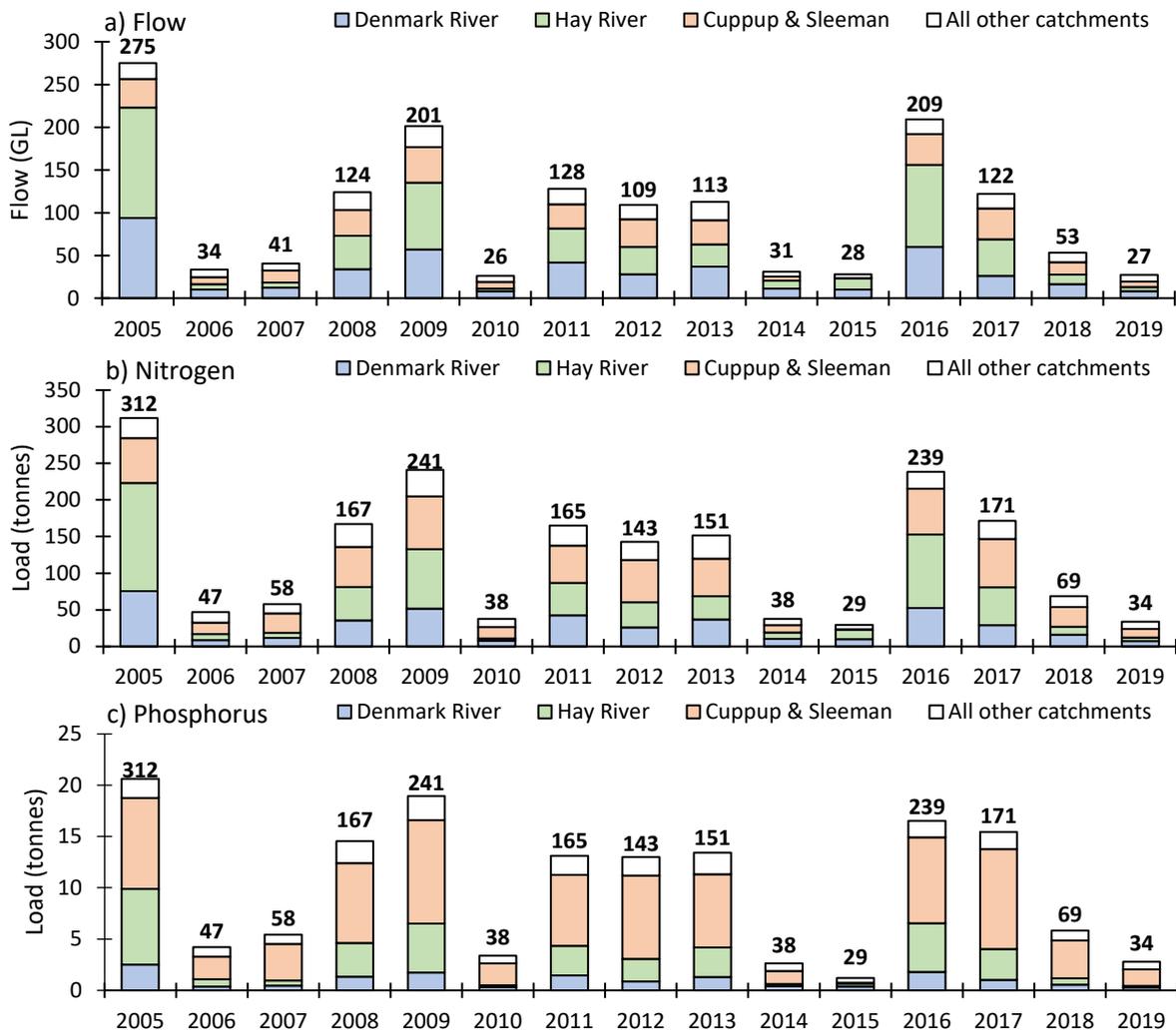
Figure 5.1: Annual flow and loads of nitrogen and phosphorus by major catchment (2005–19)

5.1.3 Seasonal delivery of nutrients

Figure 5.2 shows the average monthly flow and nutrient loads from the major catchments that drain to Wilson Inlet (2010–19). Most of the flow and nutrients were generated in the months of June to October. In the Denmark, Hay, Cuppup and Sleeman catchments, more than 94% of the flow and nutrient loads were delivered from June to October, with August having the highest flows and nutrient loads. For the 'all other catchments' group, about 15% of the flow and nutrient loads were delivered from November to May (see Figure 5.3), due to the greater dry season baseflow from Little River.
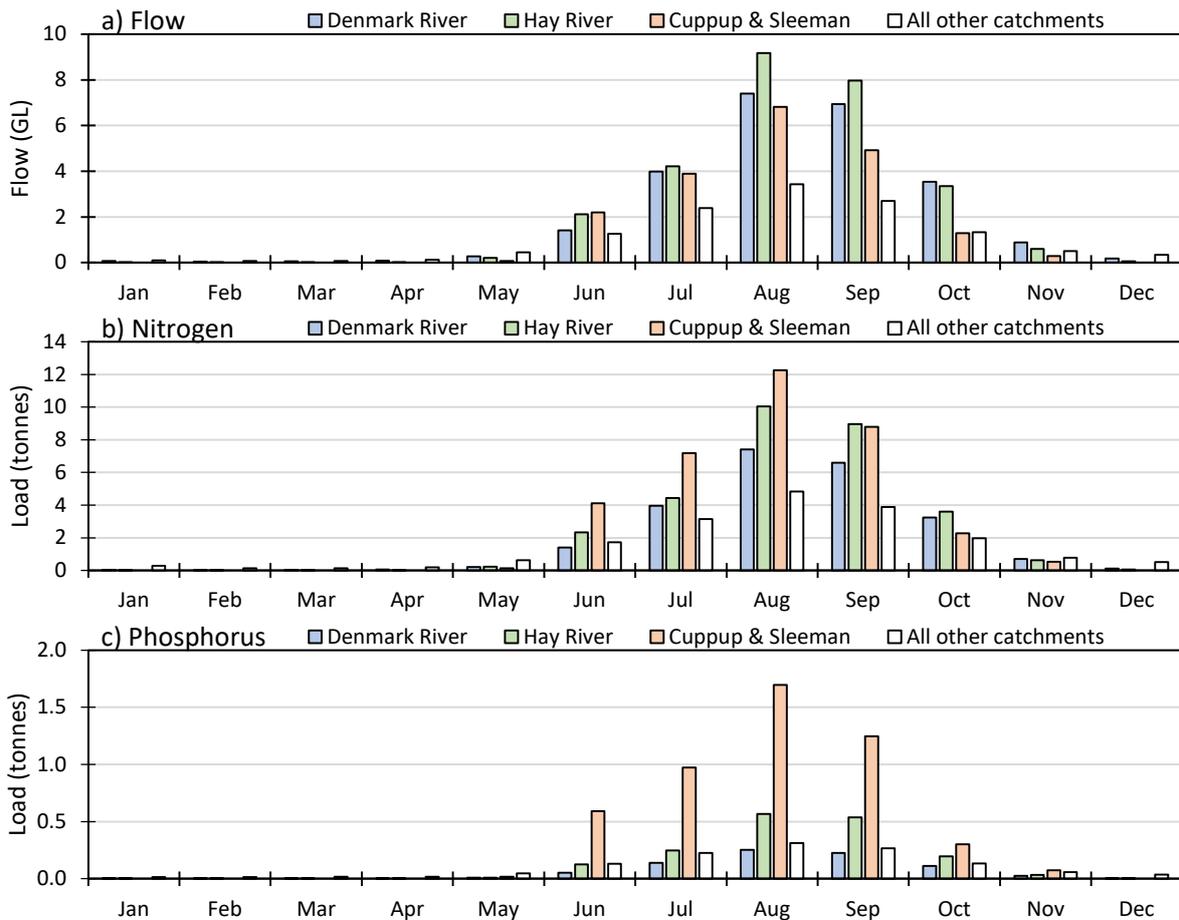
Figure 5.2: Mean monthly flow and nutrient loads by major catchments (2010–19)
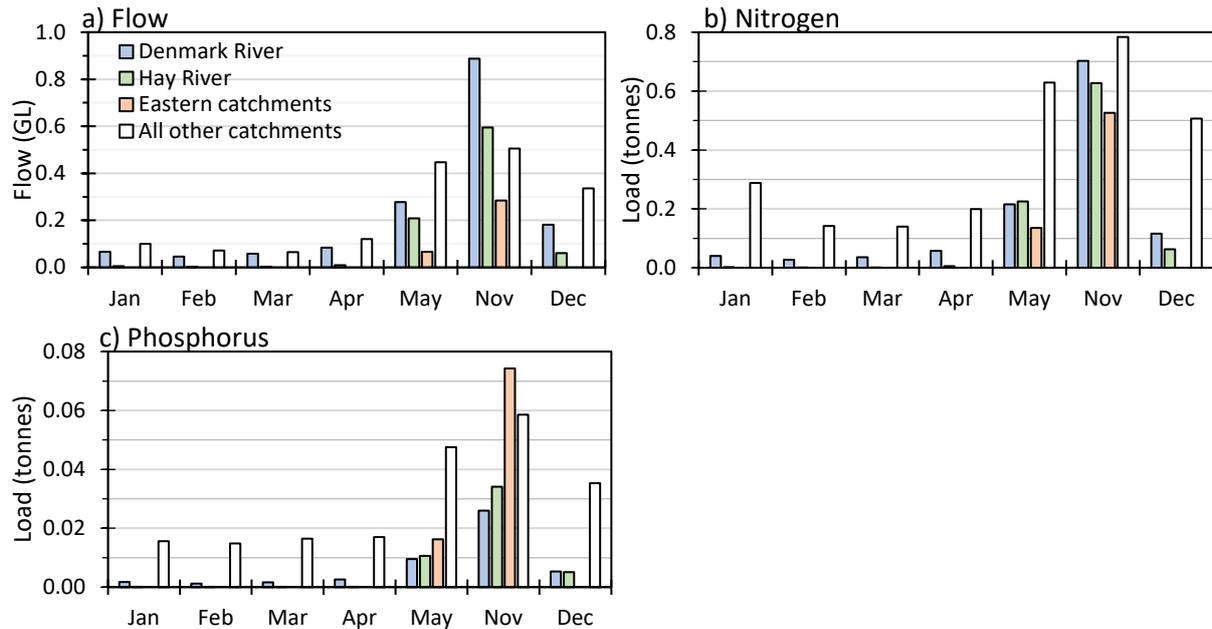
Figure 5.3: Mean monthly (2010–19) flow and nutrient loads by major catchments in the months of November to May

5.2   Sources of nutrients

5.2.1   Reporting catchments

See Figure 5.4 and Table 5.2 for absolute nutrient loads and nutrient load per cleared area.

Absolute nutrient loads

The catchments that delivered the greatest average annual (2010–19) loads of nutrients to Wilson Inlet were:

Nitrogen:

1. Upper Hay River (21 tonnes, 19%)
2. Cuppup Creek (18 tonnes, 18%)
3. Sleeman River (16 tonnes, 15%)

Phosphorus:

1. Cuppup Creek (2.7 tonnes, 32%)
2. Sleeman River (2.1 tonnes, 24%)
3. Sunny Glen Creek (0.7 tonnes, 8%)

Loads per cleared area

The loads per cleared area show the intensity of nutrient loss irrespective of the catchment's size or the amount of native vegetation it contains. Cleared area includes all land uses except for native vegetation, rural living (bush block) and water. The catchments with the greatest average annual nutrient loads per cleared area are:

Nitrogen:

1. Koorabup Creek (10.3 kg/cleared ha/yr)
2. Ocean Beach (10.3 kg/cleared ha/yr)
3. Foreshore (4.0 kg/cleared ha/year)

Phosphorus:

1. Ocean Beach (0.91 kg/cleared ha/yr)
2. Koorabup Creek (0.66 kg/cleared ha/yr)
3. Cuppup Creek (0.53 kg/cleared ha/yr)
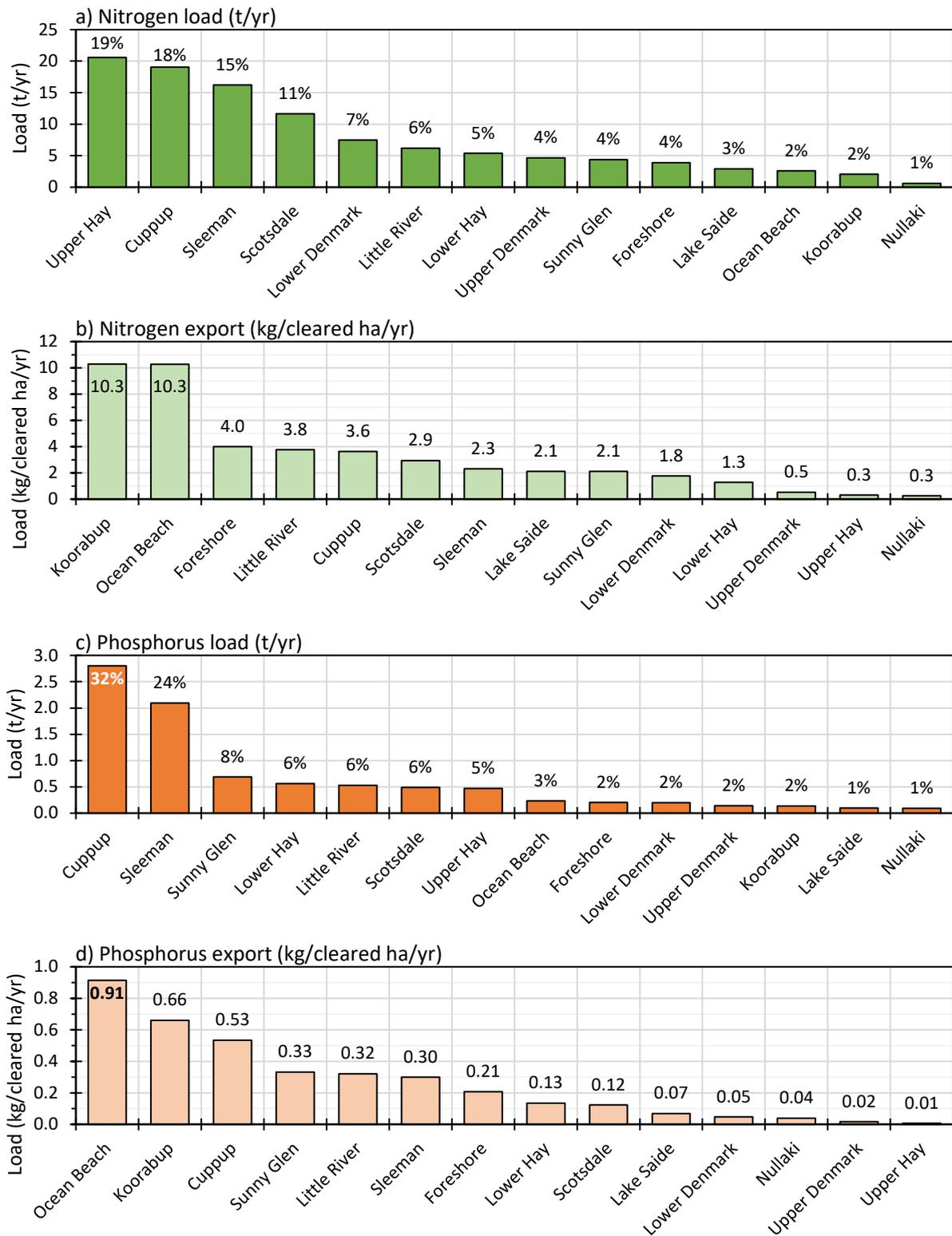
Figure 5.4: Reporting catchment nutrient loss ranked by absolute load and load per cleared area. Data labels show the proportion of load to the Wilson Inlet or nutrient export rate.

Table 5.2: Average annual (2010–19) reporting catchment flow, nutrient load, flow yield and nutrient loads per unit area

Reporting catchment	Area			Flow		Nitrogen		Phosphorus	
	Total	Cleared		Volume	Yield	Load	Load per cleared area	Load	Load per cleared area
	(km²)	(km²)	(% cleared)	(GL)	(mm)¥	(tonnes)	(kg/ha)	(tonnes)	(kg/ha)
Ocean Beach Road	10	3	25%	1.2	120	2.6	10.28	0.2	0.91
Little River	32	16	51%	6.1	191	6.2	3.8	0.5	0.32
Koorabup Creek	4	2	54%	1.0	278	2.1	10.3	0.1	0.66
Lower Denmark River	160	42	26%	8.4	52	7.5	1.8	0.2	0.05
Upper Denmark River	444	88	20%	5.3	12	4.6	0.5	0.1	0.02
Scotsdale Brook	66	40	60%	11	168	12	2.9	0.5	0.12
Foreshore	20	10	49%	2.3	117	3.9	4.0	0.2	0.21
Sunny Glen Creek	36	21	58%	2.1	59	4.4	2.1	0.7	0.33
Lower Hay River	122	42	34%	4.3	35	5.4	1.3	0.6	0.13
Upper Hay River	1122	631	56%	21	19	21	0.3	0.5	0.01
Sleeman River	94	70	74%	9.2	98	16	2.3	2.1	0.30
Cuppup Creek	69	53	76%	10	148	19	3.6	2.8	0.53
Lake Saide	39	14	35%	1.6	39	2.9	2.1	0.1	0.07
Nullaki*	23	2	8%	0.5	22	0.6	0.3	0.1	0.04
Major catchments (sub-total)									
Denmark River	670	170	25%	25	37	24	1.4	0.8	0.05
Hay River	1279	693	54%	28	22	30	0.4	1.7	0.02
Cuppup & Sleeman	163	123	75%	19	119	35	2.9	4.9	0.40
All other catchments	129	46	36%	13	99	18	4.0	1.3	0.28
Wilson Inlet	**2241**	**1032**	**46%**	**85**	**38**	**108**	**1.0**	**8.7**	**0.08**

¥ Flow yield (mm) is calculated using the total catchment area

* Nutrient load per catchment area.

5.2.2   Nutrient loads by land use

Absolute nutrient loads

See Figure 5.6 and Table 5.3 for the average annual (2010–19) nutrient loads from the land uses that drain to Wilson Inlet. The major contributors of nutrient load were:

Nitrogen:

1. Beef & other grazing (67% of total load)
2. Native vegetation (9%)
3. Dairy (8%)

Phosphorus:

1. Beef & other grazing (65%)
2. Dairy (11%)
3. Horticulture (9%)

Load per area

Figure 5.5 ranks the land-use nutrient export per cleared area (excluding septic tanks and point sources). The highest intensity of nutrient load losses are:

Nitrogen:

1. Horticulture (6.0 kg/ha/yr)
2. Dairy (3.1 kg/ha/yr)
3. Urban (3.0 kg/ha/yr)
4. Intensive animal use (2.9 kg/ha/yr)

Phosphorus:

1. Horticulture (1.95 kg/ha/yr)
2. Dairy (0.35 kg/ha/yr)
3. Urban (0.16 kg/ha/yr)
4. Horses (0.15 kg/ha/yr)

Urban land use has the third-highest nutrient loss rate. About 78% of the urban land-use area is in catchments around Denmark town, which have the highest effective rainfall (rain minus potential evapotranspiration) in the catchment. Urban land uses can have a disproportionately greater impact on surface waters in the summer months (see page 112 for more detail). About 97% of the intensive animal land use is in the Upper Hay catchment, which has lower effective rainfall and flow yield and generally better soils for nutrient retention.
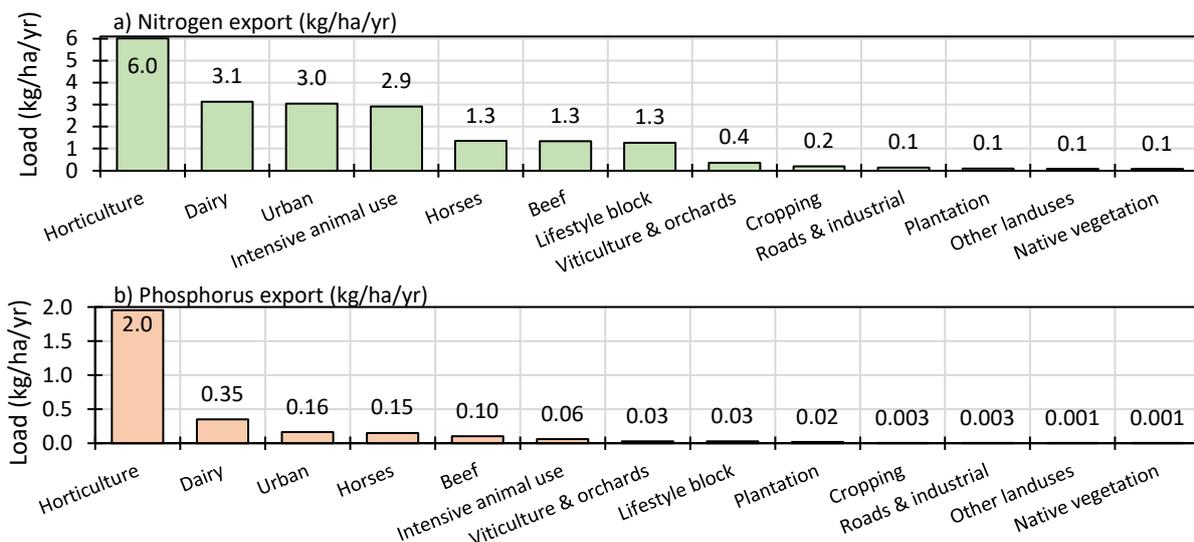
Figure 5.5: Nutrient loss per cleared area for land uses in the Wilson Inlet catchment

Table 5.3: Land-use source separation for catchments draining to the Wilson Inlet

Landuse name	Colour	Area (ha)	(%)	Flow (ML/yr)	(%)	Nitrogen (kg/yr)	(%)	Phosphorus (kg/yr)	(%)
Septic tanks		2 289	-	42	0%	4 039	4%	233	3%
Beef & other grazing		55 194	25%	49 540	58%	73 850	67%	5 745	65%
Cropping		1 601	1%	578	1%	310	0%	4	0%
Dairy		2 827	1%	3 364	4%	8 853	8%	994	11%
Horses		120	0%	171	0%	162	0%	18	0%
Horticulture		431	0%	567	1%	2 588	2%	842	9%
Intensive animal use		186	0%	121	0%	542	0%	11	0%
Lifestyle block		1 822	1%	2 507	3%	2 317	2%	51	1%
Native vegetation		121 533	54%	17 161	20%	9 503	9%	150	2%
Other landuses		1 029	0%	1 052	1%	83	0%	1	0%
Plantation		32 828	15%	3 055	4%	3 193	3%	580	7%
Point source		157	0%	205	0%	1 490	1%	124	1%
Roads & industrial		3 963	2%	4 720	6%	520	0%	11	0%
Urban		477	0%	1 164	1%	1 454	1%	78	1%
Viticulture & orchards		1 962	1%	1 205	1%	707	1%	55	1%
Total: Generated by catchment		224 133	100%	85 451	100%	109 613	100%	8 898	100%
Removal (-) or gain (+)		-		- 670	-1%	-1 986	-2%	- 169	-2%
Total: Leaving catchment		224 133	100%	84 781	99%	107 627	98%	8 729	98%
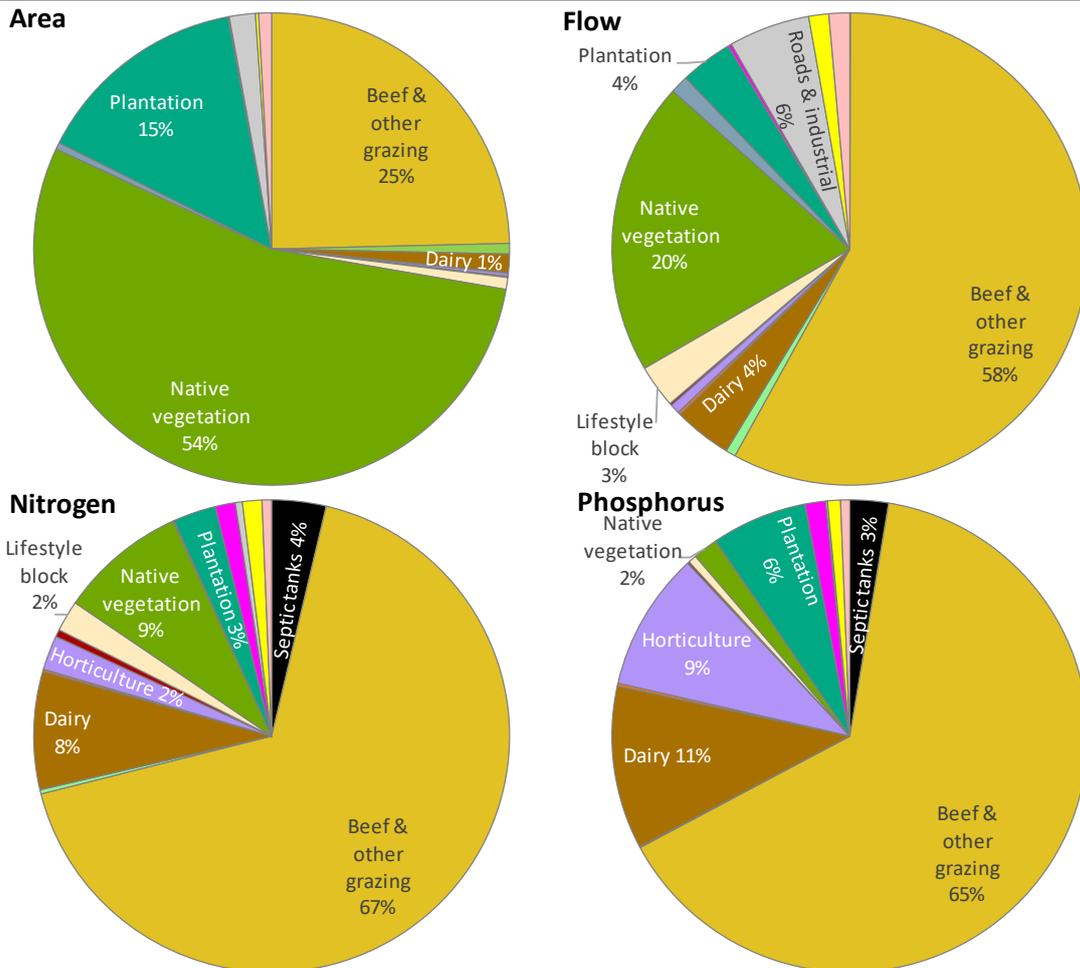
Figure 5.6: Average annual (2010–19) catchment flow and nutrient loads from land uses in the Wilson Inlet catchment

Reporting catchment land-use nutrient contributions

See Figure 5.7 for a summary of the land-use nutrient load contributions and Appendix D for more details. Beef grazing is the major source of nitrogen and phosphorus loads in all catchments except for Koorabup (Denmark WWTP contributed 63% of the nitrogen and 85% of the phosphorus load), Lake Saide (horticulture contributed 51% of the phosphorus load) and Foreshore (septic tanks contributed 45% of the nitrogen and 52% of the phosphorus load). Note: about 85% of horticulture area in the Lake Saide catchment is now used for wetland restoration so we can expect this contribution to decrease in future.
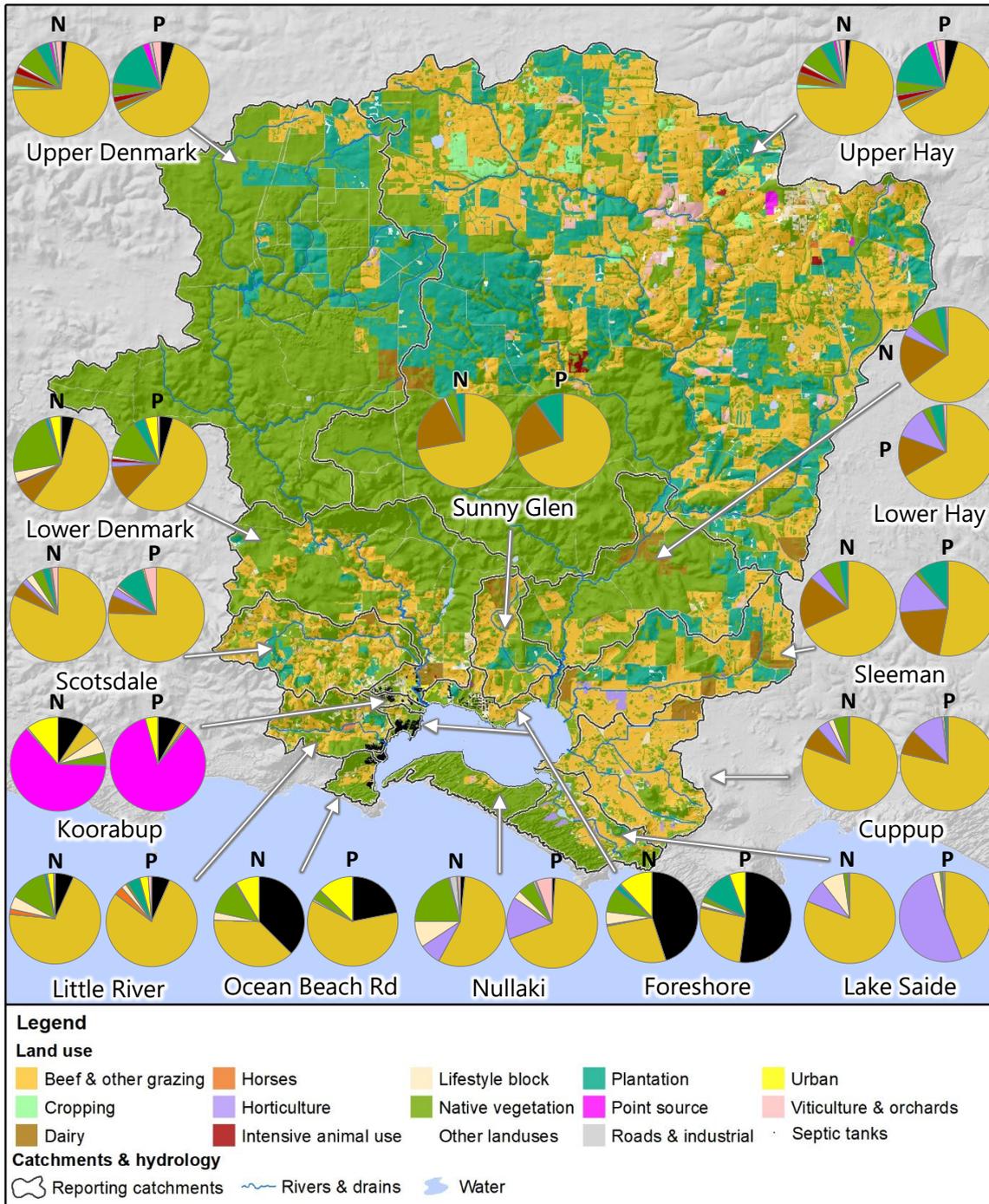
Figure 5.7: Summary of land-use nutrient contributions by reporting catchment

Horticulture

The horticulture reporting land use contributed the third-largest phosphorus loads to Wilson Inlet and had the highest nutrient loss per unit area. Therefore, disaggregating the nutrient contributions of the horticulture reporting land use into its constituent modelling land-use categories is warranted:

- **potato farming**, an annual crop that accounts for 75% of the reporting land-use area

- **'horticulture'**, which encapsulates all other nutrient intensive forms of horticulture, which are predominantly annual crops, except for asparagus and avocado plantations, which are perennial (see Table 3.6).

As seen in Table 5.4, potato farming makes up about 75% of the total reporting catchment area and contributes about half of the phosphorus load from horticultural activities to Wilson Inlet. Potato farming is exclusively found in the Sleeman, Cuppup and Lake Saide catchments. Only about 16.5 ha of the potato farming area in the Lake Saide catchment is understood to be used for potato cultivation at present. The remaining area has either been left fallow or was acquired for ecological conservation purposes. Two potato farmers moved from the Lake Saide catchment to the Sleeman catchment in about 2010, yet potato farming in the Lake Saide catchment appears to have persisted until about 2014.

About 75% of the nitrogen load is from the horticulture modelling land use, predominantly from the Sleeman and Cuppup catchments. These catchments encompass about 45% of the total area of the horticulture modelling land use.

Table 5.4: Area and nutrient loads from the components (horticulture and potatoes) of the horticulture reporting land use

Reporting catchment	Area					Nitrogen load					Phosphorus load				
	Horticulture		Potatoes		Total	Horticulture		Potatoes		Total	Horticulture		Potatoes		Total
	(ha)	(%)	(ha)	(%)	(ha)	(ha)	(%)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)
Lower Denmark	2	100%			2	0.02	100%			0.02	0.004	100%			0.004
Upper Denmark	24	100%			24	0.27	100%			0.27	0.005	100%			0.005
Scotsdale	8	100%			8	0.20	100%			0.20	0.014	100%			0.014
Lower Hay	11	100%			11	0.18	100%			0.18	0.063	100%			0.063
Upper Hay	10	100%			10	0.04	100%			0.04	0.001	100%			0.001
Sleeman	19	9%	192	91%	211	0.36	56%	0.29	44%	0.64	0.102	34%	0.201	66%	0.303
Cuppup	29	54%	25	46%	54	0.74	94%	0.05	6%	0.79	0.182	59%	0.127	41%	0.310
Lake Saide	3	3%	107	97%	110	0.10	26%	0.29	74%	0.39	0.019	14%	0.112	86%	0.131
Nullaki	1	100%			1	0.05	100%			0.05	0.014	100%			0.014
Wilson Inlet	**107**	**25%**	**324**	**75%**	**431**	**1.96**	**76%**	**0.63**	**24%**	**2.59**	**0.402**	**48%**	**0.440**	**52%**	**0.842**

*The following catchments did not have this land use: Ocean Beach, Little River, Koorabup, Foreshore and Sunny Glen
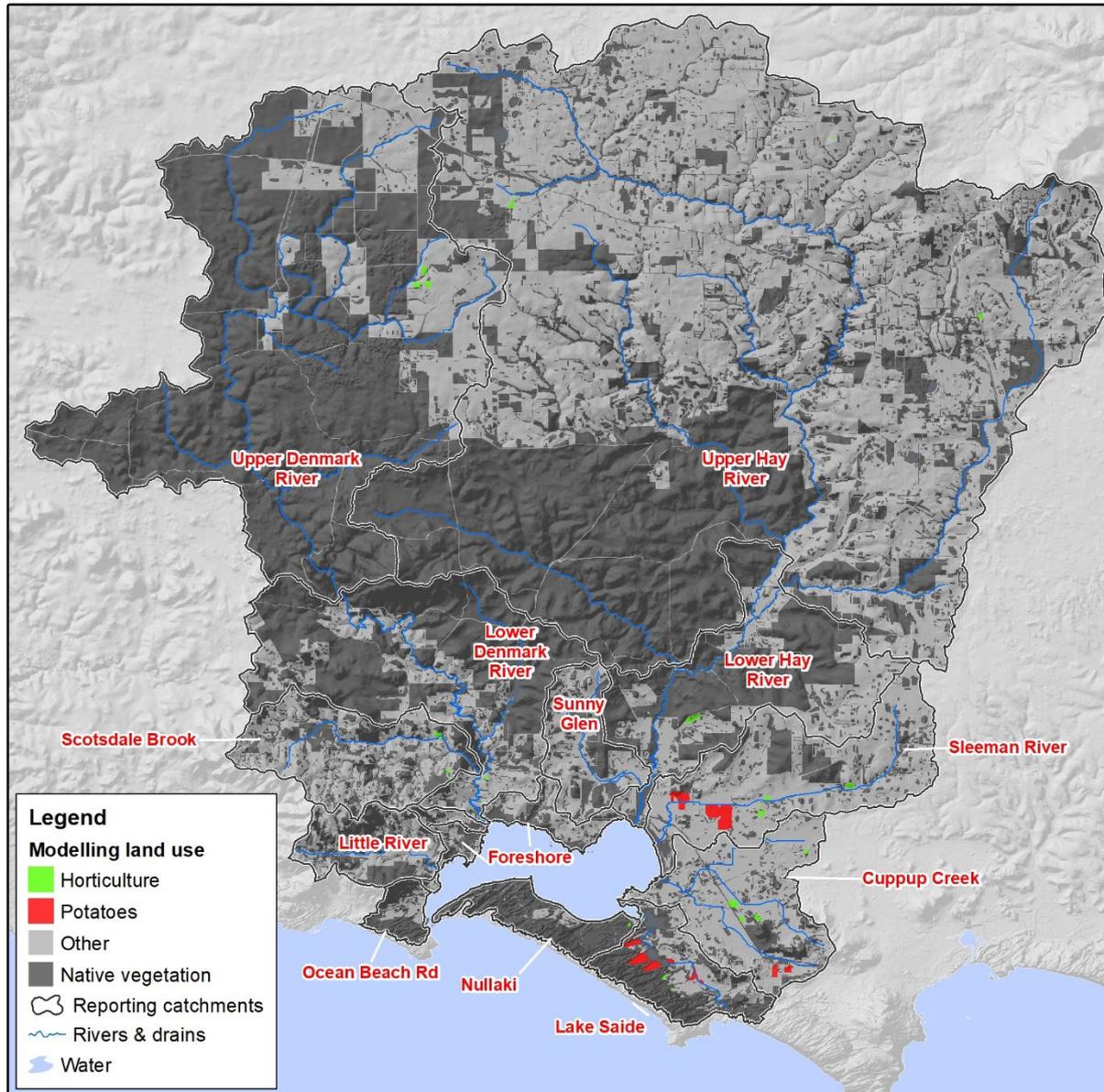
Figure 5.8: The location of horticulture and potato farming modelling land uses which make up the 'horticulture' reporting land use

Septic tanks

The Foreshore catchment has the highest number of modelled septic tanks (657 septic tanks or 42% of the modelled tanks) and the largest nutrient loads to Wilson Inlet: 1.6% and 1.2% of nitrogen and phosphorus load to the inlet respectively (Table 5.5). The Ocean Beach, Little River, Koorabup and Lower Denmark catchments account for an additional 685 (43%) septic tanks and contribute 1.8% and 1.2% of the nitrogen and phosphorus loads to the inlet respectively. The septic tanks in the Upper Hay contributed less than 0.5% of the nutrient load to the inlet due to its drier climate and better soils. Septic tanks are discussed further in Section 7.3.6.

Table 5.5: Average annual septic tank nutrient loss (2010–19)

Reporting catchment	Septic tanks		People	Nitrogen loss			Phosphorus loss		
	(#)	(%)	(#)	(t/yr)	(%)	(% WI)	(t/yr)	(%)	(% WI)
Ocean Beach	243	15%	535	1.0	24%	0.9%	0.05	22%	0.6%
Little River	162	10%	356	0.4	10%	0.4%	0.03	15%	0.4%
Koorabup	123	8%	271	0.2	5%	0.2%	0.01	5%	0.1%
Lower Denmark	157	10%	345	0.3	8%	0.3%	0.01	4%	0.1%
Upper Denmark	-	-	-	-	-	-	-	-	-
Scotsdale	-	-	-	-	-	-	-	-	-
Foreshore	657	42%	1445	1.7	43%	1.6%	0.10	45%	1.2%
Sunny Glen	-	-	-	-	-	-	-	-	-
Lower Hay	-	-	-	-	-	-	-	-	-
Upper Hay	233	15%	513	0.4	9%	0.4%	0.02	9%	0.2%
Sleeman	-	-	-	-	-	-	-	-	-
Cuppup	-	-	-	-	-	-	-	-	-
Lake Saide	-	-	-	-	-	-	-	-	-
Nullaki	3	0.2%	7	0.01	0.2%	0.0%	0.001	0.4%	0.0%
Wilson Inlet	**1578**	**100%**	**3472**	**4.0**	**100%**	**3.8%**	**0.23**	**100%**	**2.7%**

% WI = % of nutrient load to the Wilson Inlet that originated from septic tanks

% = % of total septic tank nutrient load in the Wilson Inlet catchment

Point sources

Given that point sources of nutrients are of interest to catchment management, we have provided a more detailed breakdown of nutrient loss. Table 5.6 gives the estimated nutrient loss from point sources at the modelling land-use scale. The Denmark wastewater treatment plant (WWTP) (located in the Koorabup catchment) produced the largest load of nutrients out of all the point sources. The Mount Barker WWTP disposal site (Upper Hay) contributed the next-largest nutrient load.

Collectively, the eight dairy sheds in the Wilson Inlet contributed about 1% of the nutrient load to the Wilson Inlet. The dairy shed in the Sunny Glen catchment contributed the largest nutrient load per shed.

The nutrient losses from feedlots, stockyards and free-range piggeries were comparatively small because most were located in the Upper Hay catchment, resulting in a smaller nutrient loss due to its drier climate and better soils. In the Lower Denmark, the Denmark Agriculture School had animal pens that appeared to be equivalent to feedlots or stockyards. The Foreshore catchment had a small stockyard at a freight yard.

Beverage-making industries had small nutrient losses. These industries irrigate woodlots (forested areas) with small volumes of effluent that contain high concentrations of nutrients

(resulting in low rates of nutrient application). In the model, woodlots yield less surface runoff and hence mobilise lower loads of nutrients.

Table 5.6: Average annual point source and dairy shed nutrient loss (2010–19)

Reporting catchment	Beverage making (treated wastewater disposal)			Dairy sheds			Feedlots & stockyards			Piggeries (free range)			WWTP or treated wastewater disposal			Total				
	#	N load	P load	#	N load	P load	#	N load	P load	#	N load	P load	#	N load	P load	#	N load		P load	
		(t/yr)	(t/yr)		(t/yr)	(t/yr)		(t/yr)	(t/yr)		(t/yr)	(t/yr)		(t/yr)	(t/yr)		(t/yr)	(%)	(t/yr)	(%)
Little River	1	0.002	<0.001													1	0.002	<0.1%	<0.001	0.1%
Koorabup													1	1.30	0.113	1	1.30	42%	0.113	53%
Lower Denmark	1	0.001	<0.001	1	0.06	0.004	1	0.052	0.002							3	0.11	4%	0.007	3%
Upper Denmark				1	0.22	0.016										1	0.22	7%	0.016	7%
Scotsdale	1	0.002	<0.001	1	0.11	0.008										2	0.11	3%	0.008	4%
Foreshore							1	0.003	<0.001							1	0.003	0.1%	<0.001	<0.1
Sunny Glen				1	0.26	0.018										1	0.26	8%	0.018	9%
Lower Hay				2	0.18	0.013										2	0.18	6%	0.013	6%
Upper Hay	1	<0.001	<0.001				2	0.170	0.001	2	0.32	0.008	1	0.18	0.011	6	0.67	21%	0.020	9%
Sleeman				2	0.28	0.020										2	0.28	9%	0.020	9%
Wilson Inlet	4	0.004	<0.001	8	1.10	0.079	4	0.226	0.004	2	0.32	0.008	2	1.48	0.124	20	3.13	100%	0.214	100%
% of total point sources		0.1%	0.2%		35%	37%		7%	2%		10%	3.7%		47%	58%		100%		100%	
% Wilson Inlet (all sources)		<0.1%	<0.1%		1.0%	0.9%		0.2%	<0.1%		0.3%	<0.1%		1.4%	1.4%		**2.9%**		**2.5%**	
													Nutrient loss to the Wilson Inlet (all sources)				107.6		8.7	

Dams

The Denmark and Quickup dams on average remove 0.6 GL/yr of water, 0.3 tonnes/yr of nitrogen and 0.01 tonnes/yr of phosphorus[14]. If these dams and the Lower Denmark private dam (located immediately downstream of Quickup dam) were removed, then flow-weighted concentration of the combined Denmark River catchment would decrease by about 1.2% for nitrogen and 1.3% for phosphorus. Removal of the two agricultural dams in the Little River catchment had a negligible effect on flows (3 ML/yr) and nutrient loads (<1 kg/yr of nitrogen and <0.001 kg/yr of phosphorus).

5.2.3 Nutrient loads from the Denmark and Mount Barker townsites

Denmark townsite

Pollution from the Denmark townsite is a community concern. Because the town spans several reporting catchments, we have aggregated the nutrient emissions from urban land uses and modelling catchments to quantify the nutrient loads that the town produces (see Figure 5.9). Urban land uses included are septic tanks, roads & industrial, urban, recreation, lifestyle blocks and the Denmark WWTP.

On average (2010–19) the Denmark town contributed **6.1% of the nitrogen** load (6.6 tonnes/year) and **4.3% of the phosphorus** load (0.37 tonnes/year).

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[14] Note that we assume that all water and nutrients are removed from the system. We do not account for any treatment of this water which may discharge a portion of this volume and nutrients to land or water.
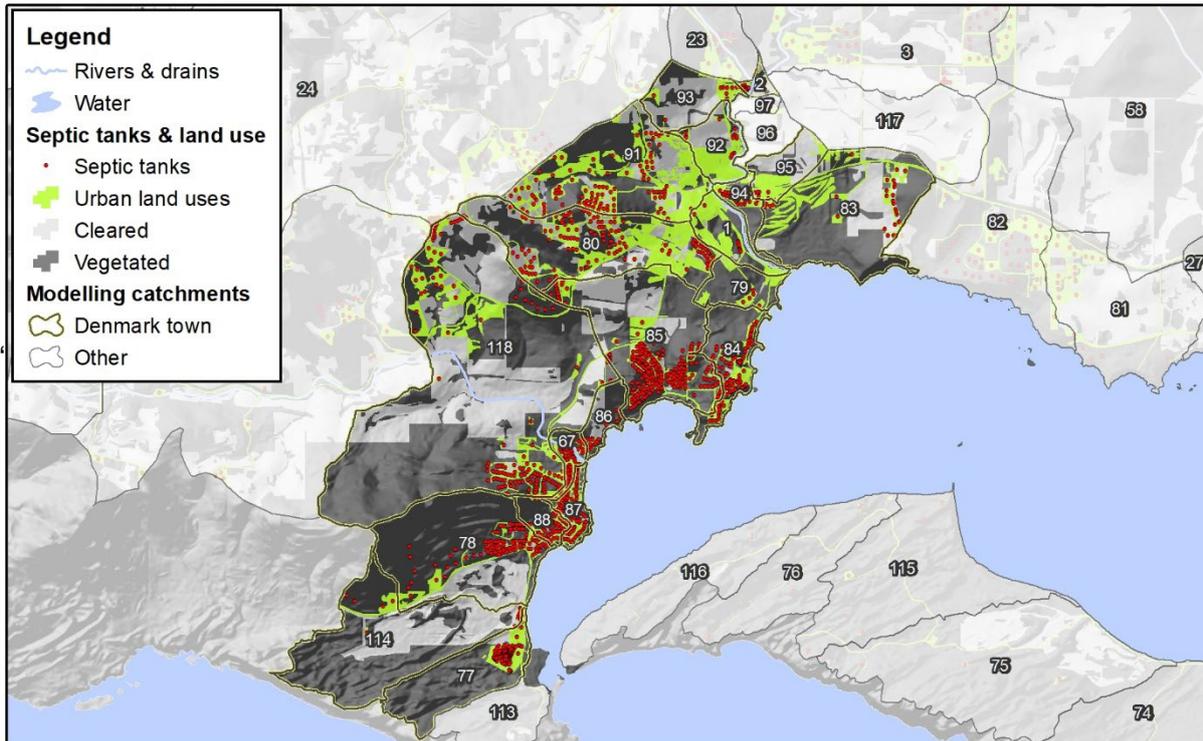
Figure 5.9: Urban land uses and modelling catchments representing the Denmark townsite

Photo: Sediment from drainage from the Denmark townsite into the Denmark River. The photo at left was taken in 1995 (B. Schur); the photo at right was taken in the same location in 2017 (K. Hennig).

Mount Barker townsite

A large area of urban development around the Mount Barker townsite is proposed by 2050 (see Section 7.1). Most of the townsite is to the north of the Wilson Inlet catchment, with runoff draining to the Kalgan River (Oyster Harbour). The following nutrient emissions for the Mount Barker townsite were aggregated from the following land uses in modelling catchments 42 and 54–56: septic tanks, roads & industrial, urban, recreation, lifestyle blocks and the Mount Barker WWTP disposal site.

On average (2010–19) the Mount Barker townsite contributed **0.7% of the nitrogen** load (0.8 tonnes/year) and **0.4 % of the phosphorus** load (0.02 tonnes/year).
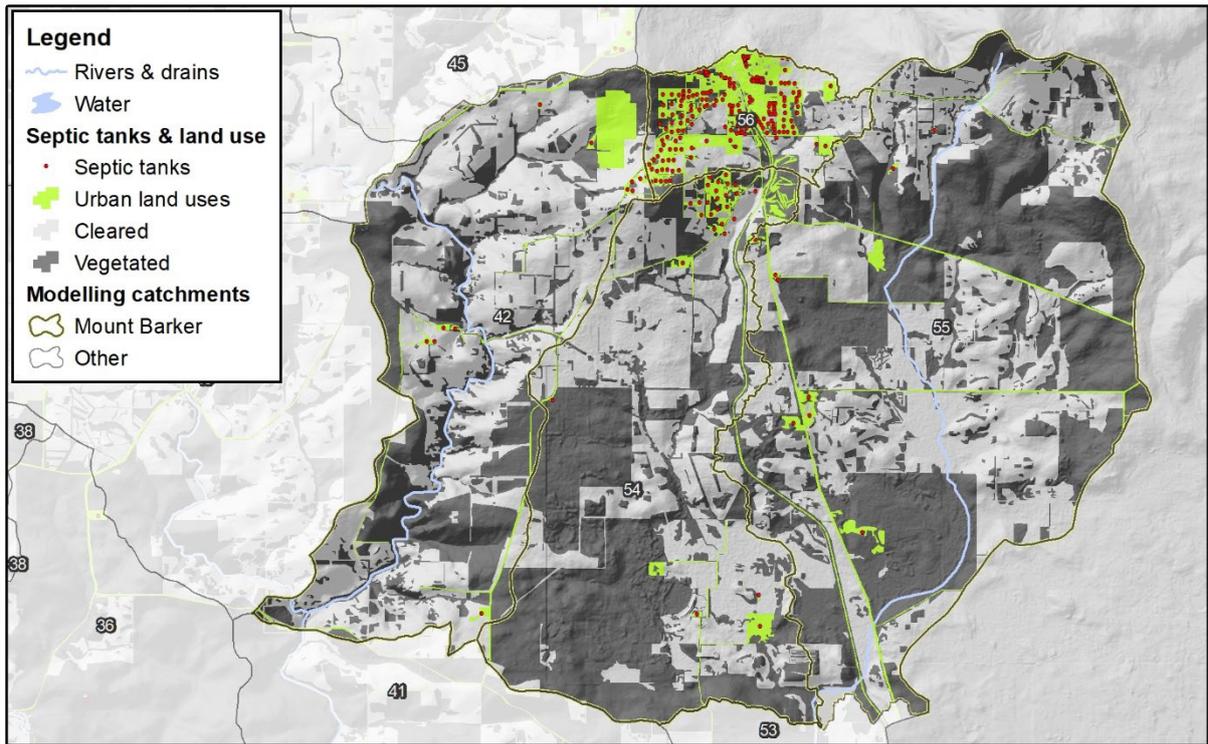
Figure 5.10: Urban land uses and modelling catchments representing the Mount Barker townsite

6 Water quality targets

6.1 Catchment nutrient targets

All waterbodies need water and nutrient inflow to support their ecosystems. The impact of nutrients on Wilson Inlet's ecological condition depends on their concentrations, loads and their fate in the inlet. Ideally, catchment nutrient targets would be derived from suitable studies that account for varying catchment flow regimes and the inlet's capacity to receive nutrients without affecting ecological, social and economic values.

We have used the catchment model to estimate the maximum acceptable nutrient load from the catchment to achieve the water quality objectives expressed as nutrient concentrations. The maximum acceptable load for the inlet calculated for the modelled period is specific for the climate, hydrology and area of native vegetation for 2010–19.

The nutrient concentrations we used to model the maximum acceptable nutrient loads in this study are based on the following:

- **Nitrogen:** 1.2 mg/L for lowland subcatchments and 0.45 mg/L for upland subcatchments[15]. These concentrations are based on the ANZECC guidelines for slightly to moderately disturbed systems for lowland and upland rivers respectively (ANZECC & ARMCANZ 2000).

- **Phosphorus:** 0.1 mg/L for lowland subcatchments and 0.02 mg/L for upland subcatchments. The lowland nutrient concentration is widely used in catchment water quality improvement plans in south-western Australia. The concentration for upland subcatchments is based on the ANZECC guidelines for slightly to moderately disturbed systems (ANZECC & ARMCANZ 2000).

We compared the flow-weighted nutrient concentrations with the water quality objectives to determine the maximum acceptable nutrient load (i.e. the load target) and load reduction target (defined in Table 6.1) for each modelling catchment[16]. We then aggregated the results from the modelling catchments to the reporting catchment scale (see Table 6.2).

The main purpose of the load reduction targets is to identify catchments where interventions are most necessary to reduce nutrient export to the inlet. Different management scenarios can then be modelled to determine optimum combinations of actions for different catchments.

Similar approaches for setting nutrient targets are used for other estuary catchments in Western Australia (see Appendix E in Hennig et al. 2021).

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[15] Upland catchments are defined as areas above 150 m in elevation according to ANZECC & ARMCANZ (2000) – see Figure 6.1.

[16] If the maximum nutrient load is more than the current average annual nutrient load, nutrient reduction from that individual modelling catchment is not required.

Table 6.1: Definition of flow-weighted concentrations, maximum acceptable nutrient loads and load reduction targets

Term	Calculation
Maximum acceptable load or load target	$= Nutrient\ Concentration\ Target$ $* Mean\ Annual\ Flow\ (2010-19)$
Excess nutrient load or *nutrient load reduction target*	$= Mean\ Annual\ load\ (2010-19)$ $- Maximum\ Acceptable\ Load$
Flow-weighted concentration	$= \dfrac{Mean\ Annual\ load\ (2010-19)}{Mean\ Annual\ flow\ (2010-19)}$

Figure 6.1: Upland and lowland catchments

Wilson Inlet requires a 27% (30 tonnes/yr) reduction in nitrogen and a 45% (3.9 tonnes/yr) reduction in phosphorus loads to meet the nutrient targets (Table 6.2).

Nitrogen reductions of 4 to 51% (Table 6.2) are needed in the catchments of Ocean Beach Road, Koorabup Creek, Upper Denmark, Foreshore, the Upper and Lower Hay, Sunny Glen Creek, Sleeman, Cuppup and Lake Saide.

Phosphorus reductions of 22 to 69% (Table 6.2) are needed in the catchments of Ocean Beach Road, Koorabup Creek, Upper Denmark, the Upper and Lower Hay, Sunny Glen Creek, Sleeman, Cuppup and Nullaki.

The proportion of excess nutrient load by reporting catchment in Figure 6.2 show that the Cuppup and Sleeman catchments are priorities for future nutrient management. Sunny Glen Creek is an important catchment given its small size and poor water quality, particularly for phosphorus. It also has the highest measured nutrient concentrations. When aggregated, the **Sleeman, Cuppup and Sunny Glen Creek** catchments encompass **9% of the Wilson Inlet catchment area** yet contribute **47% of the excess nitrogen load** and **88% of the excess phosphorus load**.

The Upper Hay is the largest contributor of excess nitrogen load but is also the largest reporting catchment by area. Compared with the Cuppup catchment, which contributes the second-largest excess nutrient load, the Upper Hay is 16 times larger in area.

We show the magnitude of flow-weighted nutrient concentrations spatially in Figure 6.3 and the exceedance of nutrient concentration targets in Figure 6.4.
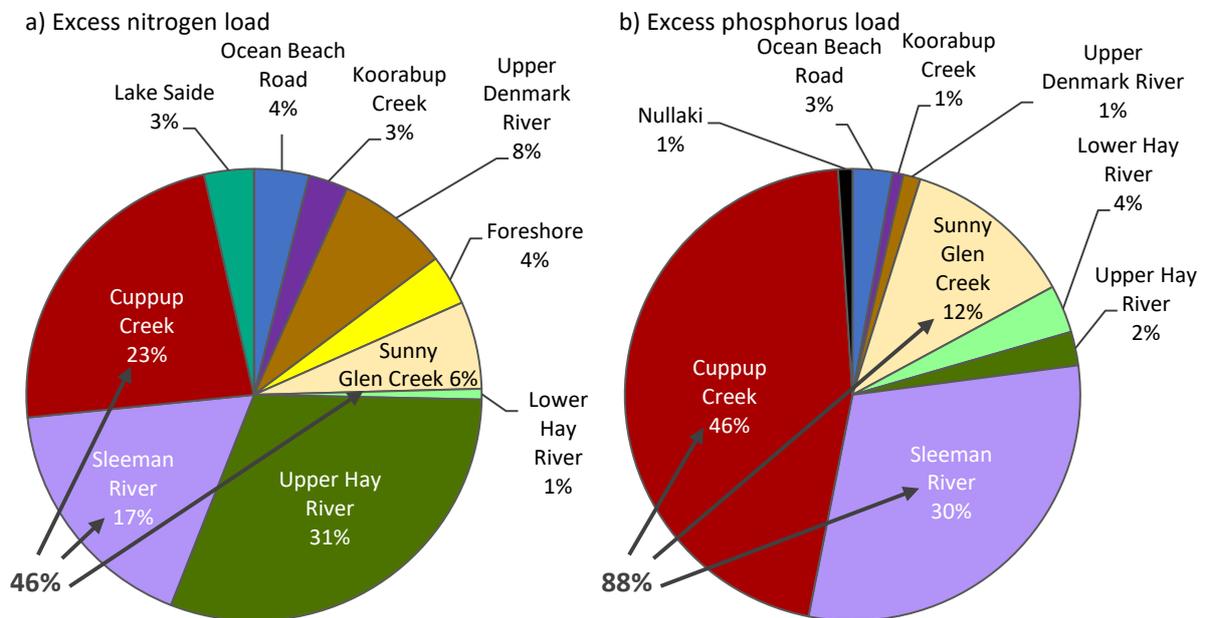
Figure 6.2: Excess nutrient load by reporting catchment
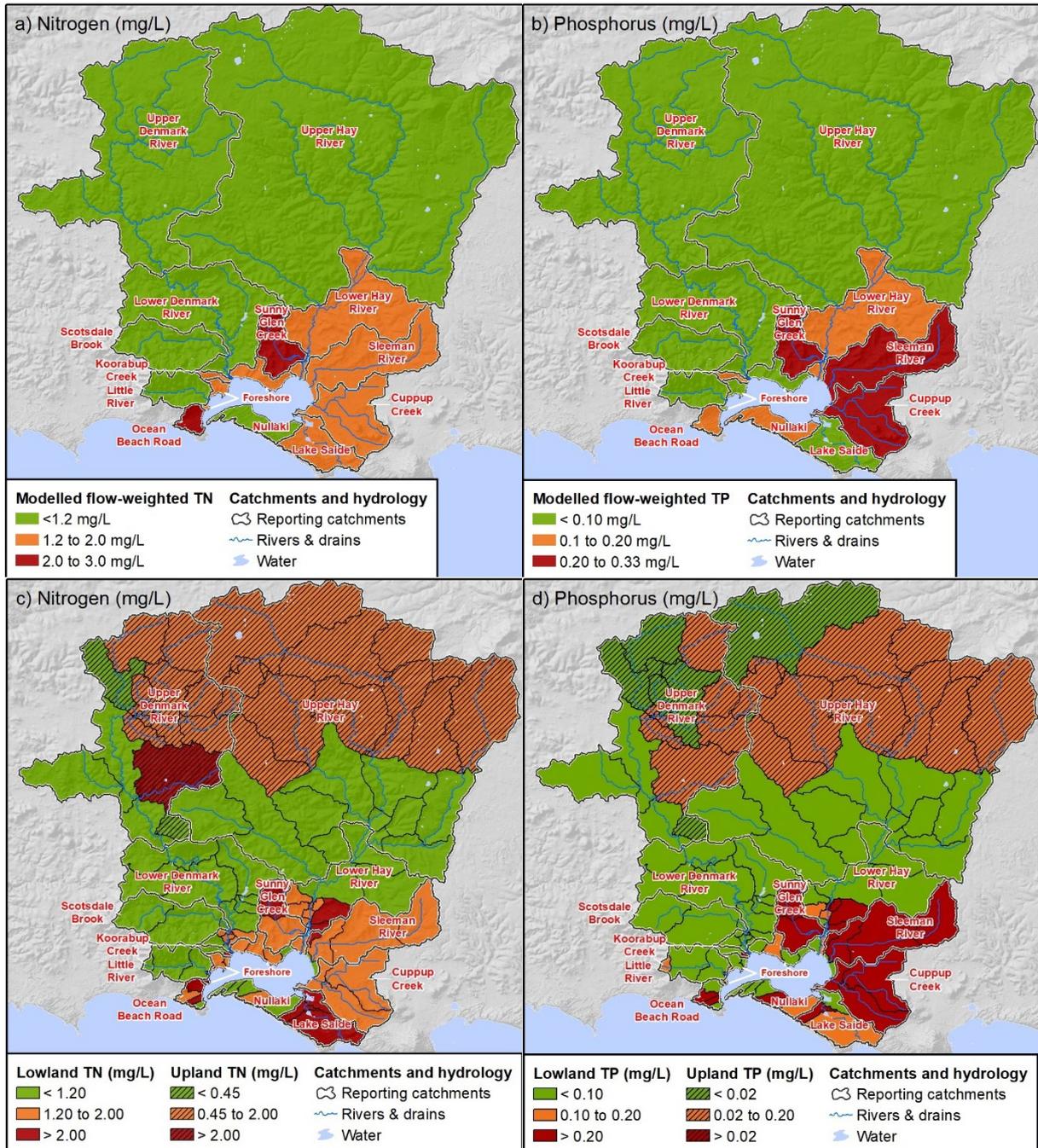
Figure 6.3: Modelled flow-weighted nutrient concentrations for the current period (2010–19) where concentrations are given for reporting (a & b) and modelling (c & d) catchments
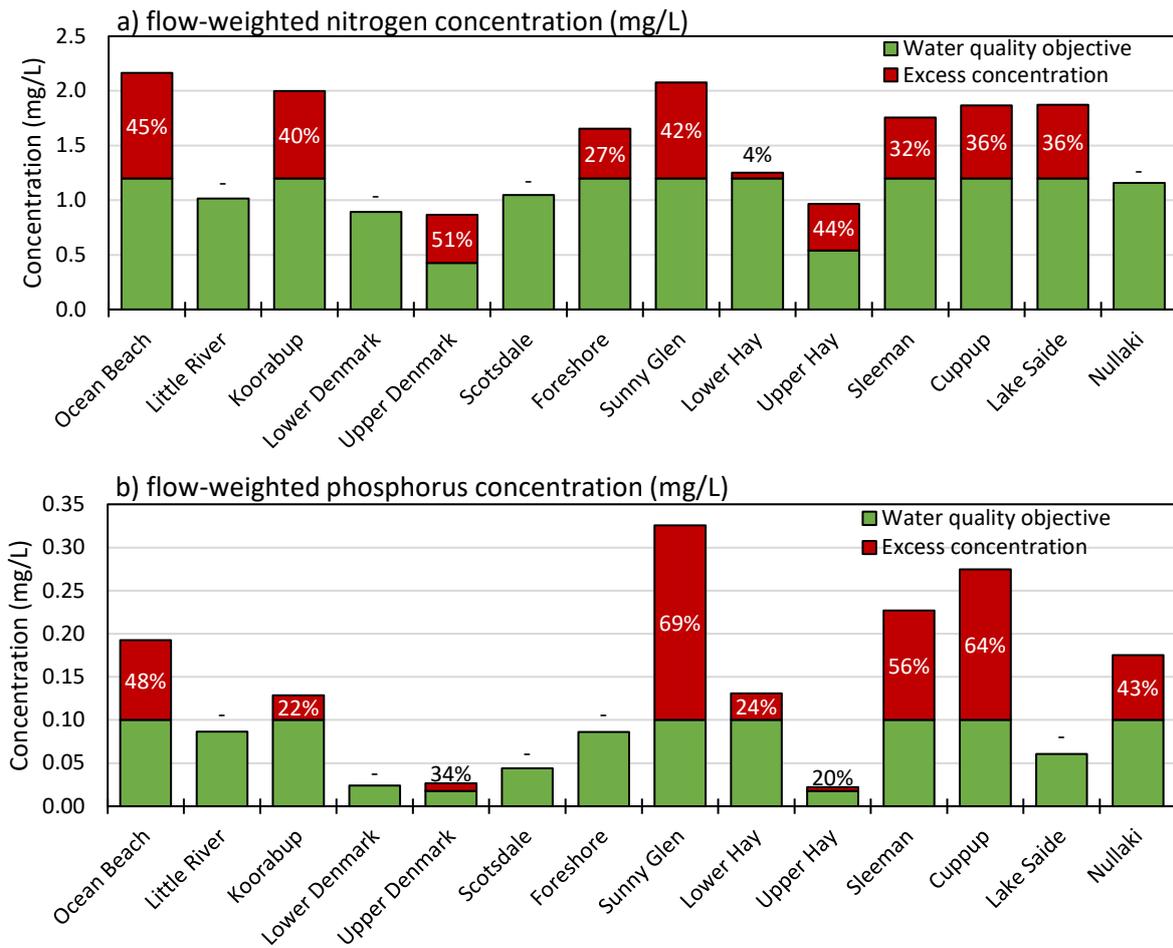
Figure 6.4: Modelled reporting catchment water quality objective and excess flow-weighted TN and TP concentrations

Table 6.2: Reporting catchment nitrogen and phosphorus water quality objective concentrations and load targets

Reporting catchment	Current (2010–19)			Target (2010–19)				
	Flow	Nutrient load	Nutrient conc*	Water quality objective	Maximum acceptable load	Excess nutrient load (2010–19)		Reduction to meet target
	(GL/yr)	(t/yr)	(mg/L)	(mg/L)	(t/yr)	(t/yr)	(% inlet)	(%)
Nitrogen								
Ocean Beach	1.2	2.6	2.16	1.20	1.4	1.1	4%	45%
Little River	6.1	6.2	1.02	1.02	6.2	0.0	-	Maintain
Koorabup	1.0	2.1	2.00	1.20	1.2	0.8	3%	40%
Lower Denmark	8.4	7.5	0.89	0.89	7.5	0.0	-	Maintain
Upper Denmark	5.3	4.6	0.87	0.43	2.3	2.4	8%	51%
Scotsdale	11	12	1.05	1.05	11.7	0.0	-	Maintain
Foreshore	2.3	3.9	1.65	1.20	2.8	1.1	4%	27%
Sunny Glen	2.1	4.4	2.08	1.20	2.5	1.8	6%	42%
Lower Hay	4.3	5.4	1.25	1.20	5.2	0.2	1%	4%
Upper Hay	21	21	0.96	0.54	11.5	9.0	31%	44%
Sleeman	9.2	16	1.76	1.20	11.1	5.1	17%	32%
Cuppup	10	19	1.87	1.20	12.2	6.8	23%	36%
Lake Saide	1.6	2.9	1.87	1.20	1.9	1.0	4%	36%
Nullaki	0.5	0.6	1.16	1.16	0.6	0.0	-	Maintain
Wilson Inlet	**85**	**108**	**1.27**	**0.92**	**78.1**	**30**	**100%**	**27%**
Phosphorus								
Ocean Beach	1.2	0.23	0.192	0.100	0.12	0.11	3%	48%
Little River	6.1	0.53	0.086	0.086	0.53	0.00	-	Maintain
Koorabup	1.0	0.13	0.128	0.100	0.10	0.03	1%	22%
Lower Denmark	8.4	0.20	0.024	0.024	0.20	0.00	-	Maintain
Upper Denmark	5.3	0.14	0.026	0.018	0.09	0.05	1%	34%
Scotsdale	11	0.49	0.044	0.044	0.49	0.00	-	Maintain
Foreshore	2.3	0.20	0.086	0.086	0.20	0.00	-	Maintain
Sunny Glen	2.1	0.69	0.326	0.100	0.21	0.48	12%	69%
Lower Hay	4.3	0.56	0.131	0.100	0.43	0.13	3%	24%
Upper Hay	21	0.47	0.022	0.018	0.38	0.09	2%	20%
Sleeman	9.2	2.1	0.227	0.100	0.92	1.2	30%	56%
Cuppup	10	2.8	0.275	0.100	1.0	1.8	46%	64%
Lake Saide	1.6	0.09	0.060	0.060	0.09	0.00	-	Maintain
Nullaki	0.5	0.09	0.175	0.100	0.05	0.04	1%	43%
Wilson Inlet	**85**	**8.7**	**0.103**	**0.057**	**4.8**	**3.9**	**100%**	**45%**

*Flow-weighted concentration

6.2   Nutrient input targets

This section discusses the maximum amount of nutrient[17] application from cleared land uses that would still achieve the nutrient load targets for Wilson Inlet. By limiting the amount of nutrients applied to land, the loads of nutrients reaching the inlet would decline over time.

The nutrient input targets are derived from the Source model, as

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[17] Includes all nutrients applied to land, such as fertilisers, animal feed, imported livestock and atmospheric deposition. See Ovens et al. (2008) for more information.

Equation 3
$$Input\ target = \frac{Export\ target}{Current\ export} \times Current\ input$$

Where:

Input target: The mass of all forms of nutrient applied to cleared land uses on a per area basis (kg/cleared ha/year)

Export target: The maximum acceptable nutrient load per unit area. This is calculated by dividing the maximum acceptable load by the cleared catchment area.

Current export: The average annual (2010–19) nutrient load per cleared area (kg/cleared ha/year).

This simple approach assumes that current nutrient inputs require the same proportional reduction as catchment nutrient loads to meet targets.

We deduced nitrogen input targets of 53 kg/cleared ha/year and phosphorus input targets of 6.7 kg/cleared ha/year. Input targets of a similar magnitude have been derived for the Peel-Harvey estuary catchment by Kelsey et al. (2011) and Hennig et al. (2021). Kelsey et al. (2011) derived input targets of 45 kg/cleared ha/yr for nitrogen and 6.5 kg/cleared ha/yr for phosphorus. Although Hennig et al. (2021) derived slightly higher nutrient input targets — 55 kg/cleared ha/year for nitrogen and 6.8 kg/cleared ha/year for phosphorus— the targets from Kelsey et al. (2011) were recommended for ongoing use.

Given the similarity in the nutrient input targets of these studies, we have rounded the nutrient input targets to a factor of 5 and 0.5 kg/cleared ha/yr for nitrogen and phosphorus respectively. Therefore, the following nutrient input rates should be used in the Wilson Inlet catchment:

Nitrogen: **55** kg N/cleared ha/ year

Phosphorus: **6.5** kg P/cleared ha/year

We intend that these nutrient input targets be used as a high-level guide to the suitability of future developments where their potential offsite nutrient impacts are concerned. Developments that could feasibly meet these input targets will likely have acceptable offsite nutrient impacts, depending on the development drainage, location and proximity to sensitive environments. Although these input targets have been developed for Wilson Inlet, they would likely apply to similar nearby catchments. Furthermore, these input targets explicitly apply to the total elemental mass of nitrogen and phosphorus applied to land.

7   Scenario modelling

We used scenario modelling to examine the potential impacts of land-use and climate changes. This section discusses:

- potential urban development by 2050

- the impacts of current and large-scale reversion of plantations to pasture grazing

- improved land-use management to reduce nitrogen and phosphorus loads to the inlet.

For the results of each scenario, we identify reporting catchments that:

- have the largest increases/reductions in nutrient loads to Wilson Inlet

- have the largest relative change in nutrient loads compared with basecase reporting catchment loads.

The scenario modelling results will be used to inform the *Nullaki (Wilson Inlet) water quality improvement plan* (WQIP). Figure 7.1 summarises the average annual (2010–19) flows and expected changes to nutrient loads from all land-use change and management scenarios.

Scenario			Input to the Wilson Inlet		
			Flow	Nitrogen load	Phosphorus load
Base-case model	**Current (2010–19)**		85 GL/yr	108 t/yr	8.7 t/yr
	Target (2010–19)		Not quantified	-27%	-45%
Land-use change scenarios	Urban expansion		0.5%	4.3%	3.4%
	Plantation reversion	Maintain 2020 area	0.4%	0.5%	1.1%
		Extensive reversion	11%	15%	23%
Management scenarios	Fertiliser management	Traditional P fertilisers			-22%
		Low water soluble P fertilisers			-24%
	Riparian zone management	Fencing all streams and drains		-11%	-4%
		Fencing & revegetating all streams and drains		-15%	-5%
	Dairy effluent management			-0.3%	-0.2%
	Soil amendments				-21%
	Remove septic tanks			-2%	-1%

Figure 7.1: Summary of all land-use change and management scenarios

7.1   Urban expansion

This scenario models the effect of planned urban expansion by 2050 on average annual flows and nutrient loads using basecase climate drivers for 2010–19. The urban expansion assumed in this scenario is shown in Figure 7.2 and includes:

- **Zoned & undeveloped land:** land that is undeveloped at present, but is zoned urban, industrial and rural residential in local planning schemes.

- **Proposed developments**: land that may be rezoned to account for planned urban, industrial and rural residential expansion by 2050.

We used the following information to map future urban areas:

- the Shire of Denmark Local Planning Scheme no. 3 (DPLH 2019),

- the Shire of Plantagenet Local Planning Scheme no. 3 (DPLH 2018)

- the subdivision guide plan for Springdale beach (Opus 2014).

We did not include all proposed developments in the modelling. There has been a surplus of residential land in the Denmark area in recent years (WAPC 2017). We assumed that about 49 ha of proposed residential (R20) and rural residential developments south of the town would not be developed by 2050 (see Figure 7.2). These developments would likely require a 2050 population that exceeded recent growth rates (< 2.2%/yr), connection to deep sewerage, and are located furthest away from the Denmark WWTP. Hence these areas would likely be the most costly (and therefore least likely to be completed within the modelled timeframe) of all proposed developments.

Photo: Construction of a home in Denmark in 2021

We integrated the urban expansion mapping with our land-use mapping. We then used this integrated map to modify the catchment model's land-use parameters using the following assumptions:

- **Residential** zoned land consists of 80% urban residential blocks, 10% roads and 10% recreation.

- **Rural residential** zoned land consists of 70% lifestyle blocks, 20% horse paddocks and 10% roads.

- **Industrial** zoned land is 100% roads and industrial.

Special industrial comprises 50% free-range piggeries or abattoirs (represented as the 'piggeries & abattoirs' modelling land use) and 50% general industrial (modelled as roads & industrial). These assumptions were based on the following:

- The objectives and permitted land uses of the special industrial zone, as outlined in the Shire of Plantagenet Local Planning Scheme no. 3 (DPLH 2018)[18].

- The assumed nutrient input rates for piggeries & abattoirs in the model (629 kg N/ha/yr and 145 kg P/ha/yr) being generally consistent with the maximum allowed nutrient input rates permitted by environmental licences for intensive animal industries in the past (640 kg N/ha/yr and 120 kg P/ha/yr – see DoW 2008, Water Quality Protection Note no. 22). We also acknowledge different environmental criteria may apply in the future and there is no certainty regarding the specific land uses that will ultimately be developed.

- Half of the area being categorised as general industrial in case more typical industrial land uses are developed (e.g. warehouses, freight and haulage, mechanics etc.).

- An intensive animal industry – an existing saleyard – being located directly north of this zone. While this does not determine the likely future land uses of the special industrial zone, it is relevant information.

Urban development retained the basecase soil PRI category in this scenario.

In total the urban development scenario resulted in 2,795 additional **septic tanks**. Of these, we modelled 2,669 as having nutrient emissions to surface water. Our assumptions around adding these septic tanks to the model were:

- Zoned & undeveloped lots used septic tanks unless they were in an area serviced by existing deep sewerage. In total, we identified 335 unsewered lots. Of these, 309 were modelled as contributing nutrients to surface water.

- All proposed developments in the Denmark area (2,319 properties) would be connected to reticulated sewerage as they are in sewerage-sensitive areas, according to the Government Sewerage Policy (2019). On the other hand, proposed industrial and rural developments near Mount Barker would be serviced by septic tanks at a density of 2.5 septic tanks/ha. This equated to the creation of 410 septic tanks in industrial areas and 2,050 septic tanks in rural residential areas (total of 2,460 septic tanks).

We assumed the Denmark WWTP would be operating at 1.2 ML/day (its maximum capacity). The nutrient concentrations of discharge assume a repeating timeseries from 2019. We based these assumptions on advice from the Water Corporation's wastewater treatment staff, who did not expect a deterioration in treated wastewater quality as the oxidation-ditch system approached and reached its treatment capacity.

We increased water abstraction from the Denmark and Quickup dams to 840 ML/yr to account for increased scheme water demand (draft and unpublished water supply planning by the department). This is a 68% increase (340 ML/yr) from the scheme water demand in

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[18] Page 21 of the local planning scheme (DPLH 2018) states:
'The objective of the Special Industrial Zone is to facilitate the development of special industries such as abattoirs, tanneries, food processing plants etc, and to encourage the development of such uses within Special Industrial estates established for such purposes subject to appropriate conditions of development and, where required, assessment by the Environmental Protection Authority and appropriate regulatory bodies.'

Special approval (SA) and environmental assessment are required for industries such as abattoirs, feedlots and aquaculture while administrative approval (AA) is required for land uses such as horticulture (DPLH 2018).

the basecase model. We assumed future scheme water demand would have the same monthly pattern of demand as the basecase model (see Table 3.1).

We determined water abstraction from Denmark dam for storage in Quickup dam using the abstraction rules described in Section 3.1.1. However, we assumed no direct water supply from Denmark dam to the town water supply scheme. We assumed the Albany–Denmark water supply pipeline would be used to replace all town potable water supply for days when the Quickup dam storage volume was below 400 ML.
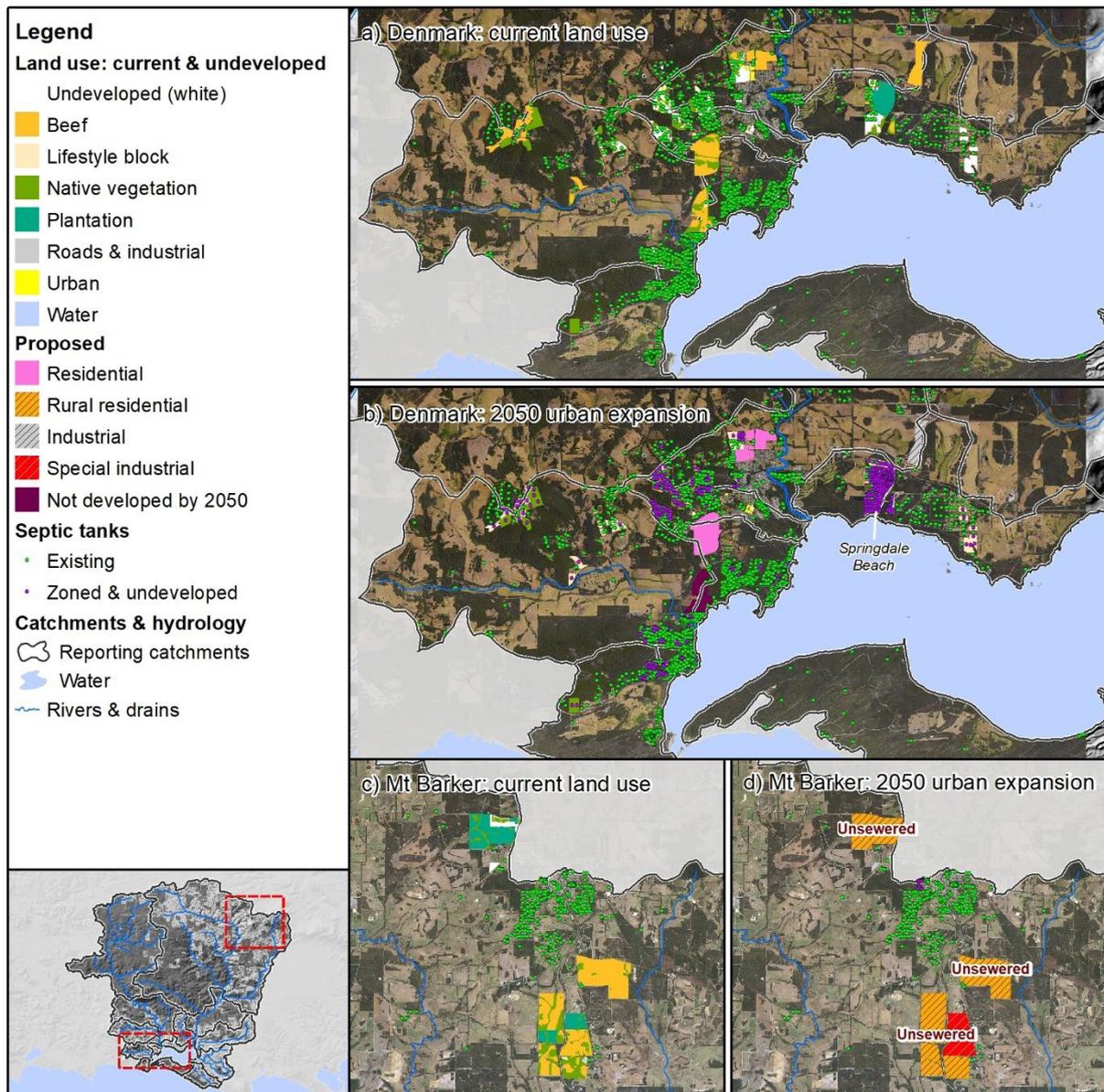
Figure 7.2: Current and assumed 2050 urban expansion in Denmark and Mount Barker

Results

We estimated that Wilson Inlet could receive an additional 0.4 GL (0.5%) flow on average per year (Figure 7.3) due to a reduction in scenario leaf area index. Nitrogen and phosphorus loading to the inlet increased by 4% (5 tonnes/yr) and 3% (0.3 tonnes/yr) respectively in the urban expansion scenario.
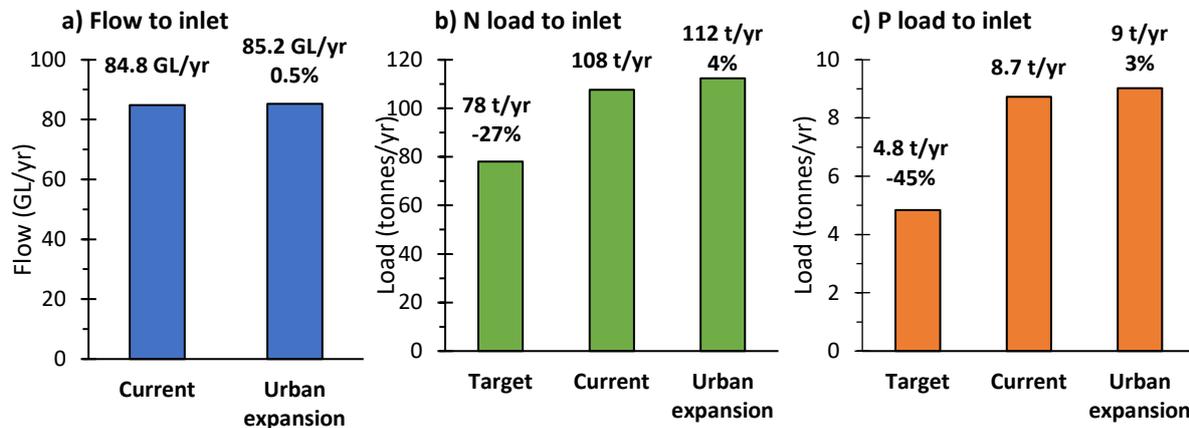
Figure 7.3: Flows, nutrient loads and targets for the Wilson Inlet for current land use and 2050 urban expansion

Although urban expansion had a relatively small effect on nutrient loads, the area of land use change was also small relative to the size of the entire Wilson Inlet catchment (0.6% of the catchment or 1,552 ha). However, urban expansion resulted in land uses that had a greater intensity of nutrient loss. Figure 7.4 compares the intensity of flow and nutrient change using flow and nutrient loss per unit area change of pre- and post-development land uses[19]. Post-development land uses had nutrient exports 5.5 to 6.5 times higher than pre-development land uses for nitrogen and phosphorus respectively. Flow yield also increased in the post-development scenario by about 70%.

The clearing of native vegetation for development contributed to the intensification. About 21% of the pre-development area was native vegetation, which was developed into urban or rural land. Compared with post-development land uses, native vegetation had nutrient exports (per unit area) two orders of magnitude lower and flow yields an order of magnitude lower. As such, even a small reduction in native vegetation area could result in a disproportionately large impact on flow and nutrient loss to Wilson Inlet. Findings for plantations were similar – accounting for 21% of the pre-development area yet had nutrient exports one to two orders of magnitude lower than post-development land uses and 86% lower flow yield.

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[19] **Pre-development land use** includes beef, native vegetation, plantations and undeveloped cleared land.

Post-development land use includes lifestyle blocks, urban residential, horses, roads, intensive animal uses, unsewered properties and the additional treated wastewater discharge from the Denmark WWTP.
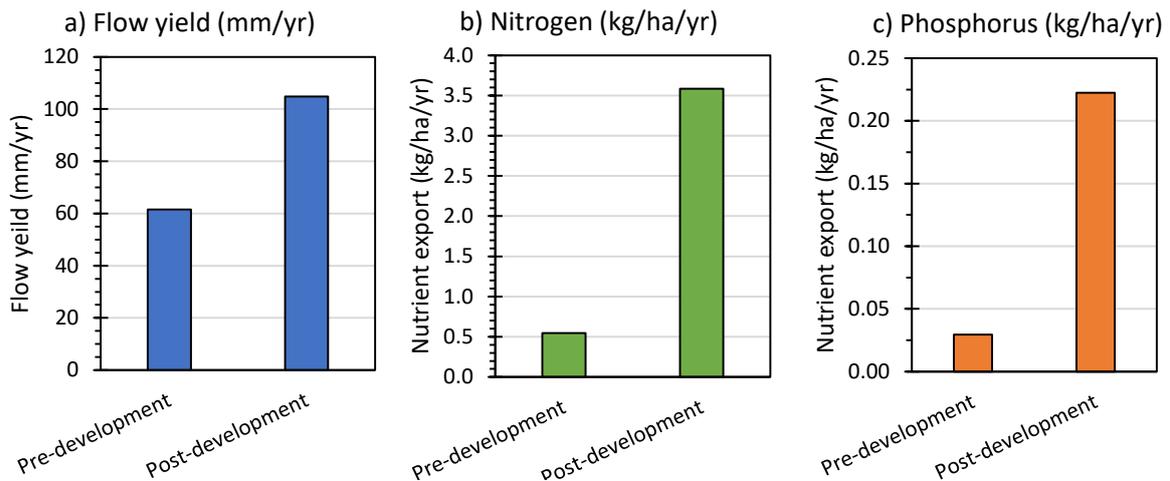
Figure 7.4: Pre- and post-development nutrient loss and flow per unit area of change, in land-use areas altered by the urban expansion scenario

Changes in reporting catchment flow were greatest in the Koorabup Creek catchment – mostly because of the increase in treated wastewater discharge from the Denmark WWTP. In the Lower Denmark catchment, there was a 2.6% reduction in flow (0.2 GL/yr). This was caused by increased water abstraction for town water supply (0.23 GL/yr), which offset slight increases in catchment runoff (0.013 GL/yr). All other reporting catchments had increases in flow of 0.1 to 2.9% (i.e. Ocean Beach, Little River, Foreshore and Upper Hay).

Reporting catchment nutrient loads had greater relative increases for phosphorus than nitrogen (Table 7.1). For phosphorus, the greatest relative increases in load were in the Upper Hay (41%), Koorabup (34%) and foreshore catchments (29%). For nitrogen, load increases were greatest in the Foreshore (21%), Upper Hay (17%) and Ocean Beach (6%) catchments. Nutrient load changes for all other catchments ranged from -0.3 to 5.6%.

By area, about 74% of the land-use change occurred in the Upper Hay catchment. The reporting catchments that contributed the most additional nutrient load to Wilson Inlet were the Upper Hay, Foreshore and Koorabup catchments (see Figure 7.5).
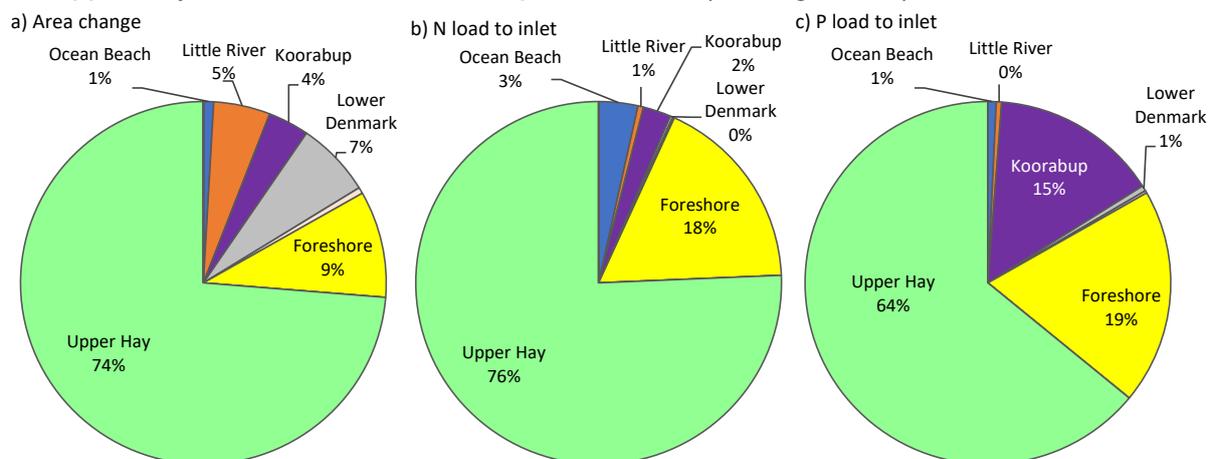
Figure 7.5: Location of land-use area changes and percentage increase in nutrient load to the Wilson Inlet by reporting catchment in the urban expansion scenario

Table 7.1: Average annual (2010–19) flow and nutrient loads for the basecase and urban expansion scenario

Reporting catchment	Flow			Nitrogen			Phosphorus		
	Basecase	Urban expansion	Diff	Basecase	Urban expansion	Diff	Basecase	Urban expansion	Diff
	(GL/yr)	(GL/yr)	(%)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Ocean Beach Road	1.2	1.2	0.9%	2.6	2.7	6.3%	0.23	0.23	1.0%
Little River	6.1	6.1	0.1%	6.2	6.2	0.4%	0.53	0.52	-0.3%
Koorabup Creek	1.0	1.4	32%	2.1	2.2	5.6%	0.13	0.18	34%
Lower Denmark River	8.4	8.2	-2.6%	7.5	7.5	-0.1%	0.20	0.20	0.7%
Upper Denmark River	5.3	5.3	-	4.6	4.6	-	0.14	0.14	-
Scotsdale Brook	11	11	-	12	12	-0.1%	0.49	0.49	-0.1%
Foreshore	2.3	2.4	2.9%	3.9	4.7	21%	0.20	0.26	29%
Sunny Glen Creek	2.1	2.1	-	4.4	4.4	-	0.69	0.69	-
Lower Hay River	4.3	4.3	-	5.4	5.4	-	0.56	0.56	-
Upper Hay River	21	22	1.2%	21	24	17%	0.47	0.67	41%
Sleeman River	9.2	9.2	-	16	16	-	2.1	2.1	-
Cuppup Creek	10	10	-	19	19	-	2.8	2.8	-
Lake Saide	1.6	1.6	-	2.9	2.9	-	0.09	0.09	-
Nullaki	0.5	0.5	-	0.6	0.6	-	0.09	0.09	-
Wilson Inlet	**84.8**	**85.2**	**0.5%**	**108**	**112**	**4.3%**	**8.7**	**9.0**	**3.4%**

Most of the increase in nutrient load in this scenario was from septic tanks (see Figure 7.7). An additional 2,858 septic tanks were created, more than doubling the current number (see Figure 7.6). Rural residential developments near Mount Barker in the Upper Hay catchment resulted in most of the additional septic tanks (2,476), as well as 78% of the development area of the scenario. The Denmark area had an additional 382 septic tanks associated with existing undeveloped lots, such as the remaining stages of the Springdale Beach subdivision (178 septic tanks). Most of these additional septic tanks were in the Foreshore reporting catchment (202) with the rest in the Lower Denmark (48) and Little River (38) reporting catchments.

The average annual nutrient contributions of the Denmark WWTP to Wilson Inlet in this scenario were:

- 1.0% for nitrogen (currently 1.2%)

- 1.6% of the phosphorus (currently 1.3%)

Before the Denmark WWTP was upgraded in 2015, its treatment of nitrogen was poor but its treatment of phosphorus was similar or slightly worse than the new plant (Figure 7.8). As a result, for 2010–15 annual nitrogen loads from the old Denmark WWTP were higher than the new plant operating at full capacity in this scenario. Therefore, this scenario resulted in lower nitrogen loads but higher phosphorus loads than current.

The increase in potable water demand (from about 0.5 GL/yr to 0.8 GL/yr) removed 0.8 GL of water, 0.4 tonnes/yr of nitrogen and 0.01 tonnes/yr of phosphorus. If these dams (including the Lower Denmark private dam) were removed and potable water abstraction ceased, then flow-weighted concentrations in the combined Denmark River catchment would decrease by about 1.6% for nitrogen and 1.8% for phosphorus. These reductions are relative to the

concentrations of the urban expansion scenario with dams and water abstraction, rather than the basecase model.
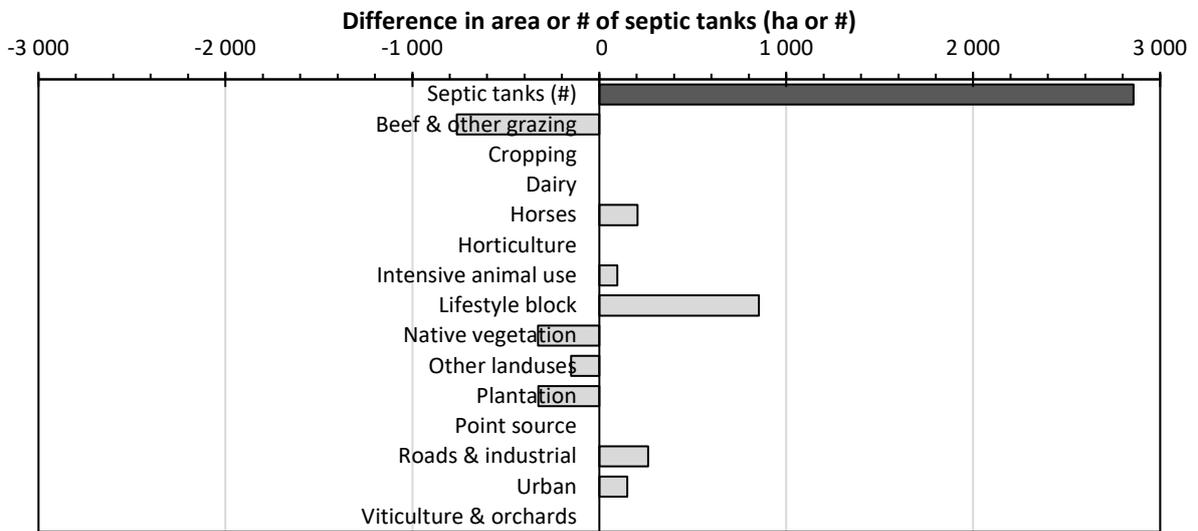
Figure 7.6: Difference in land-use area or the number of septic tanks between the basecase and urban expansion scenario
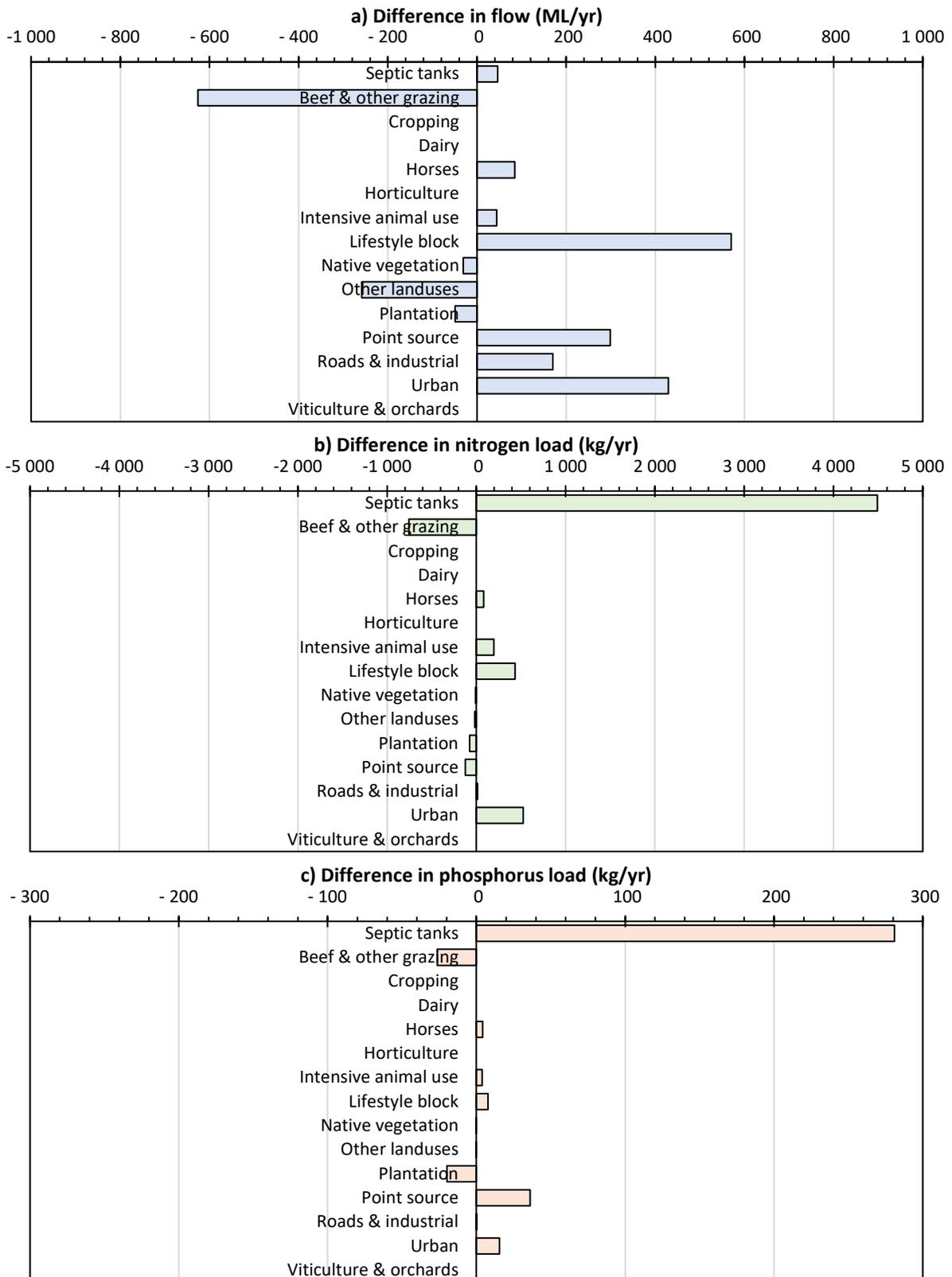
Figure 7.7: Difference in average annual (2010–19) flow and nutrient load between the basecase and urban expansion scenario. Positive values mean that the urban expansion scenario had greater flow/load than the basecase scenario.
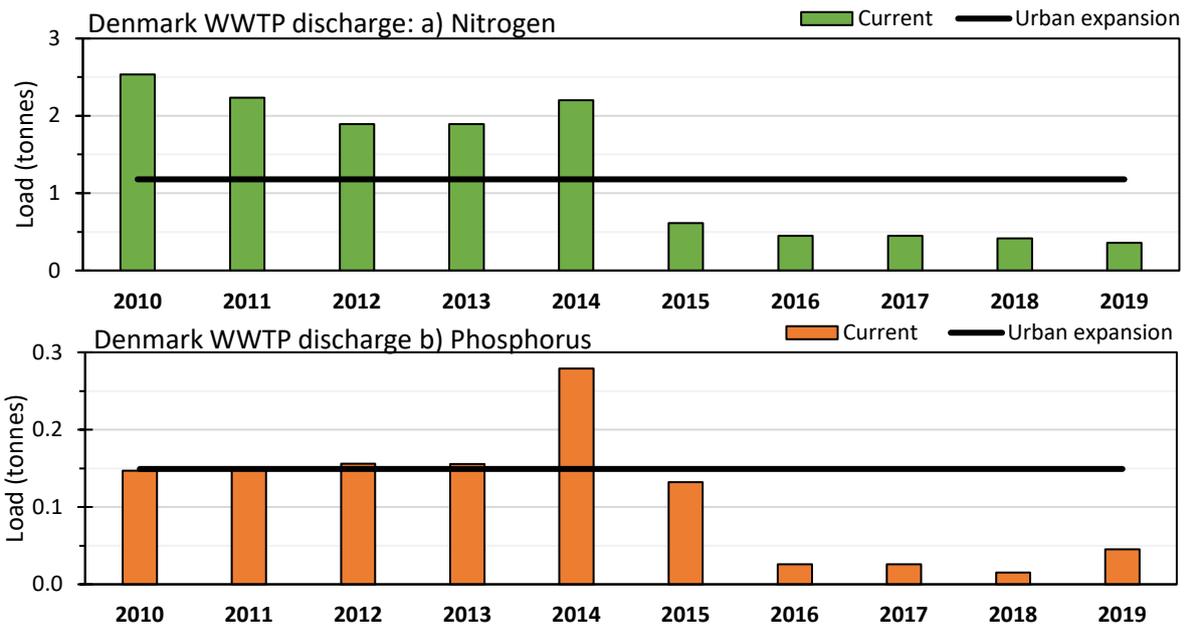
Figure 7.8: Annual nitrogen and phosphorus loads from the Denmark WWTP for the basecase and urban expansion scenario

Impact of townsites

Figure 7.9 gives the urban area, flow and nutrient loads of the Denmark and Mount Barker townsites from the basecase and urban expansion scenario.

The Denmark townsite had a greater relative increase in flow (35%) than nutrient loads, particularly for nitrogen (18%), while phosphorus loads increased by 26%. This corresponds with an urban area increase of about 28%. In the urban expansion scenario, the Denmark townsite contributed about 4%, 6.9% and 5.2% of the flow, nitrogen load and phosphorus load to Wilson Inlet respectively. Contributions to the inlet in the basecase were 3%, 6.1% and 4.3% respectively.

The Mount Barker townsite had a 59% increase in urban area. Flows increased by 69% while nitrogen and phosphorus loads increased by about 358% and 443% respectively. Most of the increase in nutrient load came from the 1,918 additional septic tanks (254 in the basecase). The Mount Barker townsite contributed about 1.0%, 3.2% and 2.1% of the flow, nitrogen load and phosphorus load to the inlet respectively. Contributions in the basecase were 0.6%, 0.7% and 0.4% respectively.
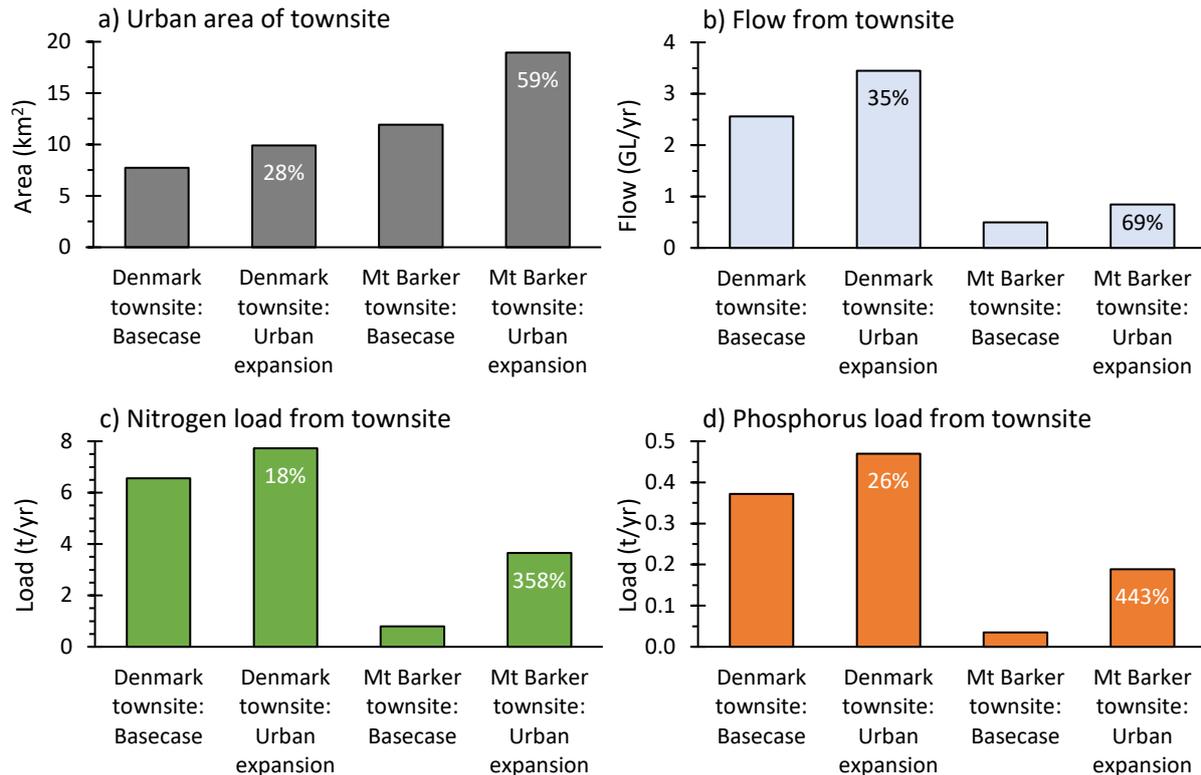
Figure 7.9: Area of urban land uses and average annual flows and nutrient loads for Denmark and Mount Barker in the basecase and urban expansion scenario

Urban impacts in summer

Because of the higher proportion of impervious surfaces in urban areas (such as roads and roofs), rainfall events yield greater flow than for other land-use types. Traditionally, urban impervious areas are directly connected by drainage, allowing the rapid transport of water and contaminants to waterways. During the summer months, urban land uses can contribute a disproportionately large amount of flow and nutrients to surface waters. This coincides with a period when temperatures are higher and the potential for algal growth and biogeochemical activity is the greatest. In this respect, the impact of urban areas may be much greater than would be indicated by merely considering their area and contributions of flow and nutrient loads on an annual basis.

Hence in Figure 7.11 we show the average annual (2010–19) summer[20] flow from urban[21] versus all other land uses in the Wilson Inlet catchment. Flows are presented for the basecase and urban expansion scenario. Although urban land uses make up just 3% of the catchment area, they contribute 33% of the flow to Wilson Inlet in the basecase and 41% in the urban expansion scenario. Furthermore, the flow yield is 16 and 19 times larger than other land uses in the summer months in the basecase and urban expansion scenario respectively.

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[20] December to March inclusive

[21] Urban land uses included: urban, recreation, lifestyle blocks, roads & industrial, septic tanks, the Denmark WWTP and wastewater irrigation. The latter includes the nutrient loss from beverage-making wastewater irrigation (i.e. a commercial enterprise) and the Mount Barker WWTP disposal area.
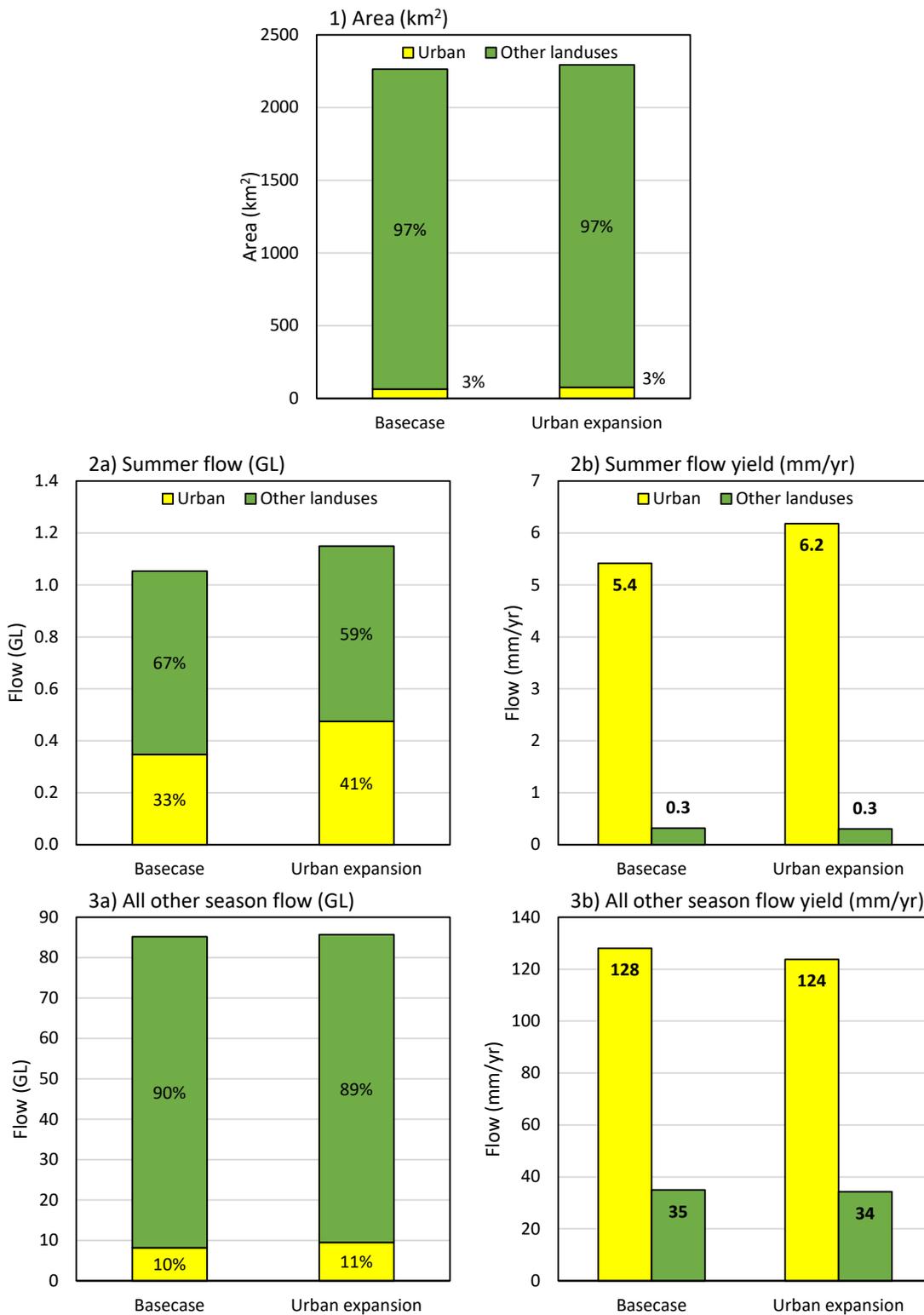
Figure 7.10: Urban and all other land uses in the Wilson Inlet catchment by 1) area (km² and average annual), 2) summer flow (December to March inclusive), and 3) flows from all other months.

Mitigating the impacts of future and existing urban areas

Our scenario modelling evaluated the hydrological and nutrient impacts if urban expansion were designed and managed similarly to equivalent existing land uses. However, new urban developments are required to adopt the principles of water-sensitive urban design (WSUD), with specific guidance provided in the stormwater management manual. Resources such as the department's Urban Nutrient Decision Outcomes (UNDO) tool are available to plan for acceptable nutrient emissions in new urban developments.

To effectively remove or reduce nutrient exports from new urban developments, developers should:

* Adopt WSUD principles and follow the guidance in the stormwater management manual.

* Use the UNDO tool to design and evaluate new urban developments to ensure acceptable nutrient loss. (Note default soil types for the South Coast were not included in the UNDO tool at the time of publishing this report. We recommend contacting undo@dwer.wa.gov.au for advice on soil parameterisation.)

It is also important to acknowledge that existing urban areas can be retrofitted to include WSUD, specifically technologies that mitigate nutrient impacts. Our scenario modelling has not sought to inform such actions. Retrofitting existing urban areas requires solutions that are tailored to the challenges and conditions of each catchment – and our catchment model is not of sufficient scale to undertake this task. The UNDO tool may be a more suitable model for designing and evaluating WSUD retrofits. However, outputs from our modelling can be provided on request[22]. See also the investigations on this topic by the Denmark Environment Centre (1995).

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[22] Note that not all drainage catchments have been captured individually in the catchment model and may have been aggregated with adjacent catchments.

7.2 Plantation reversion to pasture

This scenario estimates the effect of large-scale plantation reversion to beef grazing by 2050. The basecase modelling found that on average, plantations produce 13 times less nitrogen load and 5 times less phosphorus load per unit area than beef grazing. Therefore, on average, large-scale reversion of plantations to beef grazing would likely increase nutrient loading to Wilson Inlet.

Photo: Plantation harvesting in the Lower Hay River catchment in 2016

Plantations are the third-largest land use in the Wilson Inlet catchment by land area. Most plantations cultivate Tasmanian blue gum which are a deep-rooted 'hardwood' tree. Trees are harvested every 10 to 12 years and are typically used for wood pulp.

During the 1990s and 2000s, large areas of cleared farmland were converted to plantations, peaking at about 32,500 ha in 2010. This area has since declined by 14% as of 2020 (see Figure 7.12). The area of plantations in the Wilson Inlet catchment is in decline and being replaced by beef grazing or wheat and sheep farming.

The decline in plantations since 2010 was preceded by the global financial crisis in 2008 and the financial collapse of the Great Southern Group in 2009. At the time, Great Southern Group managed most of the plantations on the South Coast through purchased land or lease agreements. The company's collapse affected the retention of plantations locally, with many landowners opting to revert their land to pasture or cropping. The reversion was also likely influenced by a sustained increase in the value of beef from 2014 to 2020. However, other factors/drivers may have contributed to the decline in net plantation area since 2010.

Numerous studies have shown the effect of deep-rooted vegetation on groundwater levels, salinity and river flow, as shown in Figure 7.11 (Bari & Boyd 1992; Silberstein et al. 2004; Bari & Smettem 2006). The establishment of plantations in the catchments upstream of Denmark dam reduced salinity below 500 mg/L, making the previously salty water fresh and enabling its use for town water supply (Ward et al. 2011).

Plantations have lower nutrient loss per unit area because:

- plantations are deep-rooted plants that lower groundwater levels and result in less surface water flow and therefore nutrient load

- nutrient inputs to plantations are lower than pasture on average (85% lower nitrogen inputs and 35% lower phosphorus inputs).

However, plantations have the potential to cause water quality issues when harvested or fertilised (Baillie & Neary 2015; Binkley et al. 1999).
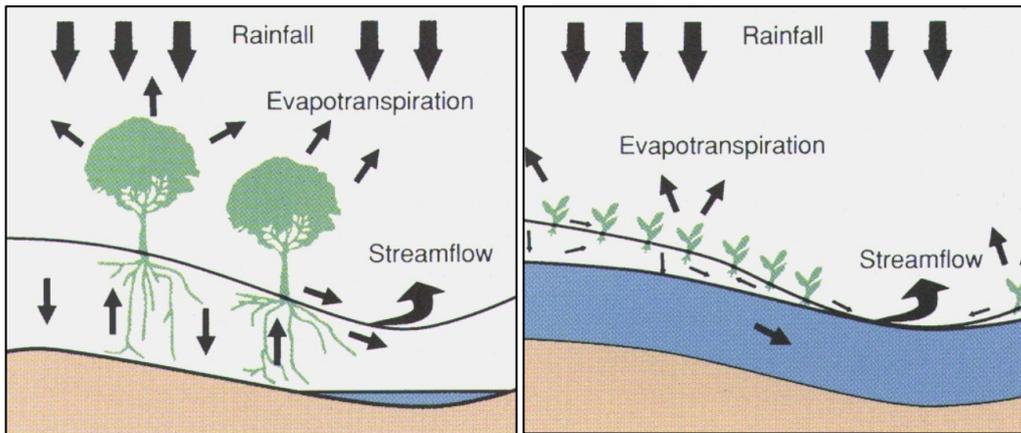
Figure 7.11: The impact of removing deep-rooted vegetation on the ground and surface water (©2021 State Salinity Council)

Forest Industries Federation Western Australia Inc (FIFWA 2016) acknowledges that some plantations were grown in isolated areas and had low financial returns due to the cost of harvesting and haulage. Strategic hubs are recommended to ensure that the location of plantations are profitable (less than 150 km from the Albany port and more than 600 mm/year of annual rainfall). All of the plantations in the Wilson Inlet catchment are within 80 km of the Albany port and have greater than 600 mm/yr rainfall (1975–2003).

The Australian Bureau of Agriculture and Resource Economics and Sciences estimated that climate change would negatively impact all socioeconomic factors for the national plantation industry (log availability, harvesting, mill capacity, mill input, value of production and employment) (ABARES 2011).
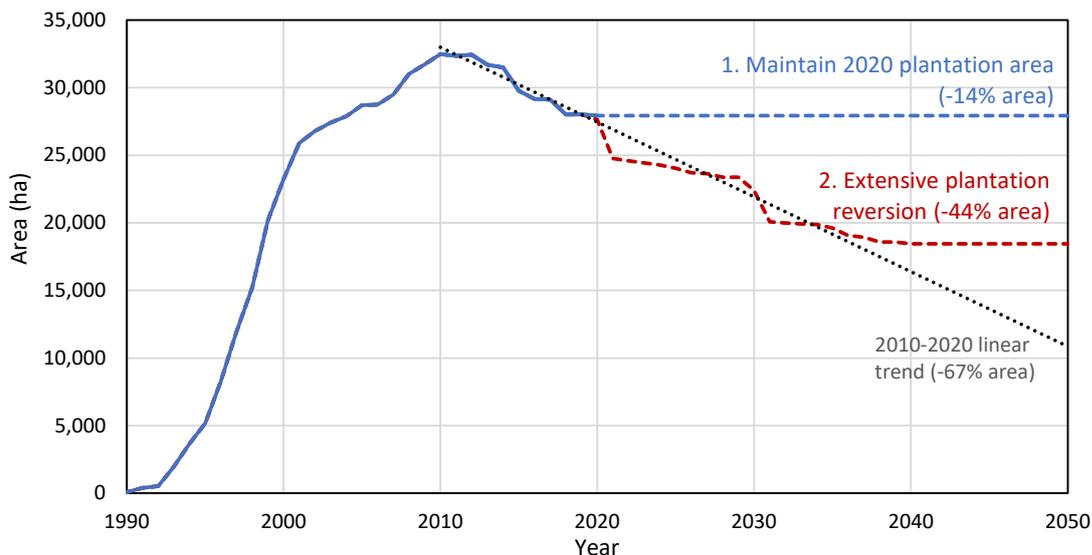
Figure 7.12: Area of plantations mapped from 1990–20, linear trends in area decline (2010–20) and the assumed plantation reversion scenarios

A barrier to the reversion of plantations to grazing or cropping is the cost of stump removal and land preparation. Farmers may need to apply large amounts of fertiliser in the first few years to increase soil fertility for pasture while also dealing with increased groundwater levels and surface water runoff (Ossinger pers. comm. 2017).

While this scenario is primarily concerned with the effect of a decline in plantations, Whittle et al. (2019) estimates the effect of various market drivers on increasing the area of plantations at a national scale. These estimates are given for the major regions where plantations are grown and the type of plantations. For short-rotation hardwoods in south-western Australia, the authors found that an increase in demand of 15 to 30% had no effect on the area of new plantations by 2050. The drivers that increased the area of new plantation establishment by 2050 were either productivity improvements, a reduction in agricultural land price, a drop in the value of the Australian dollar or a reduction to the required rate of return (discount rate).

Implementation

Because the future extent of plantation reversion is not known, we modelled two plantation reversion scenarios (see Figure 7.12):

1. Maintaining the area of mapped plantations in 2020 (14% area decline since 2010[23]).

2. Extensive plantation reversion (44% area decline since 2010). We used this scenario to represent a 'plausible worst case' that falls between the 2020 area of plantations and the extrapolated 2010–20 linear trend to 2050 (70% area decline since 2010). Of the plantations that remained in 2020, we assumed 20% reverted to beef grazing in all modelling catchments after their next harvest[23]. We then assumed all remaining plantations in catchments with less than 600 mm/year of rainfall, based on a climate change scenario, reverted to beef grazing when harvested from 2030. Figure 7.13 highlights these catchments in red[24].

We created a plantation reversion dataset as described above for 2021–2050 (see Figure 7.12). We used the leaf area index (LAI) from this dataset for 2036–2050 to replace the basecase LAI from 2005–2019. Other than LAI, all other model inputs and parameters were the same as the basecase model.

The development of this scenario and its underpinning assumptions were informed by relevant literature as well as discussions with people with local industry experience. The following summarises the relevant literature that informed this scenario:

• FIFWA (2016) estimated that hardwood plantations in the Lower Great Southern region could have long-term reductions of 60–70% from their maximum extent in 2009–10. This is approximately equal to the linear trend shown in Figure 7.12 that suggests a 70% reduction in net plantation area from 2010 to 2050.

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[23] Existing plantations that were more than 10 years old were assumed to be harvested in 2021. All other plantations were harvested 10 years after establishment or replanting.

[24] Hadley Centre Global Environment Model version 2 (HadGEM2-CC) using the relative concentration pathway 4.5 (moderate effort to curb emissions). Out of 12 future climate scenarios, this had the 56th percentile average annual rainfall of a projected 30-year climate centred around 2050. All climate scenarios were derived from Climate Change in Australia.

- Whittle et al. (2019) forecast a 10% decline in hardwood plantations nationally from 2018 to 2050. This decline would be about 15% from 2010 to 2050.

- Although ABARES (2011) did not specify the impact of climate change on the area of plantations, it demonstrated significant impacts. FIFWA (2016) recommends the retention of plantations in areas with more than 600 mm/yr of average rainfall. Therefore, in this scenario, we consider it reasonable to constrain plantations to the projected 600 mm rainfall extent from the 2050 median climate (see Section 7.4).
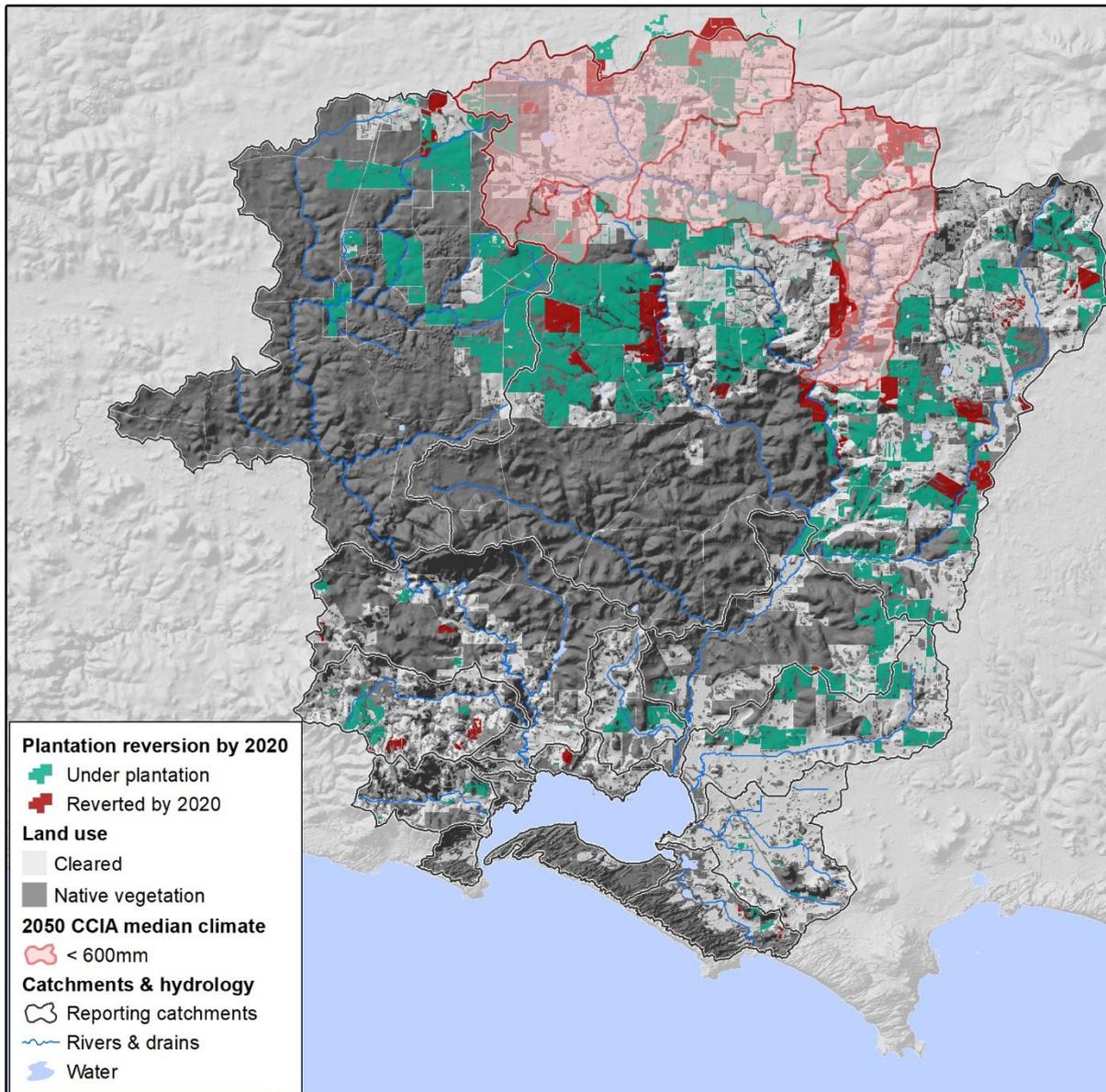
Figure 7.13: Plantation reversion to pasture by 2020 and the modelling catchments which are projected to have less than 600 mm/yr of rainfall (30-year average) from the median climate change scenario

Results

Maintain 2020 plantation area

The 'maintain 2020 plantation area' scenario increased average annual flow and loads of nitrogen and phosphorus to Wilson Inlet by 0.4% (0.3 GL), 0.5% (0.6 tonnes) and 1.1% (0.1 tonnes) respectively (see Figure 7.14). Increases in flow to the inlet were primarily from the Scotsdale Brook (74% of additional flow), Lower Denmark (10%) and Upper Hay catchments (9%) – see Figure 7.15. Most of the plantation area reduction in this scenario was in the Upper Hay (90%). Increases in nitrogen and phosphorus loads were mostly from the catchments of Scotsdale Brook (54% and 59% respectively) and Upper Hay (30% and 28% respectively).

Increases in reporting catchment flows and loads from the basecase were small (< 3%), except for phosphorus loads in the Upper Hay catchment which increased by about 6% (see Figure 7.16 and Table 7.2).
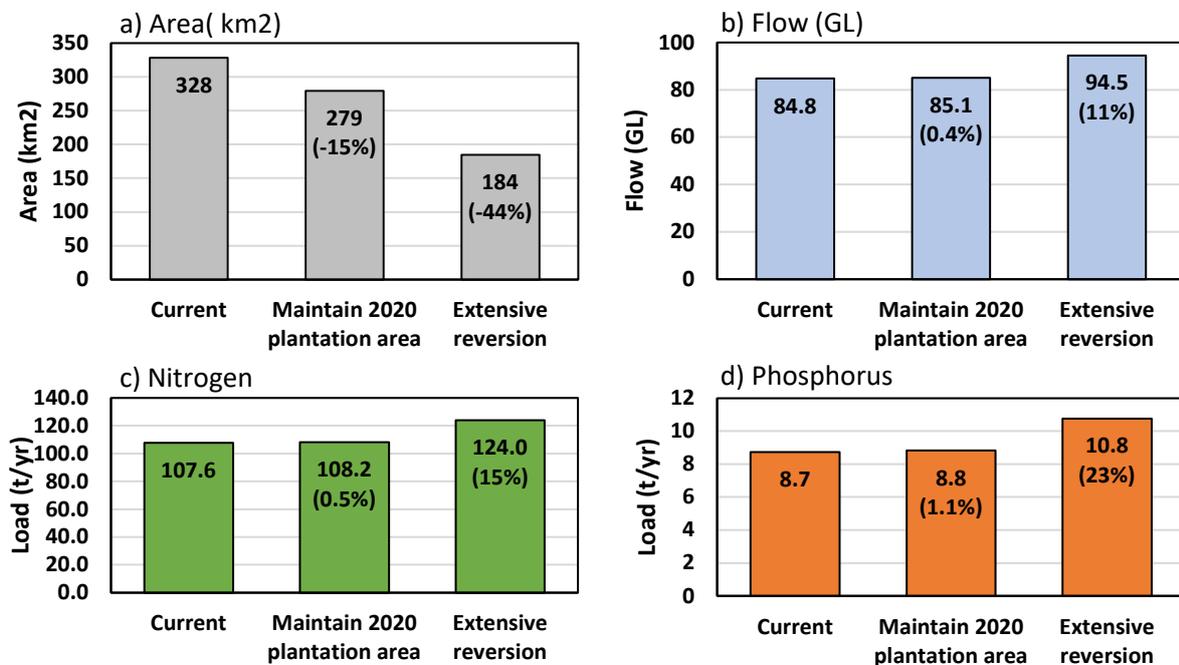
Figure 7.14: Plantation area, and average annual flow and nutrient loads to the Wilson Inlet for the basecase and plantation reversion scenarios

Extensive plantation reversion

The 'extensive plantation reversion' scenario increased average annual flow and loads of nitrogen and phosphorus to Wilson Inlet by 11% (9.7 GL), 15% (16 tonnes) and 23% (2 tonnes) respectively. To meet targets for the Wilson Inlet catchment in this scenario, load reductions of 37% for nitrogen and 55% for phosphorus would be required. Overall a 10% increase in the nutrient load reduction would be required compared with the basecase model (27% for nitrogen and 45% for phosphorus respectively).

Most of the **additional** flow was from the Upper Hay (52%), Upper Denmark (17%) and Scotsdale (12%) catchments. Most of the increase in nitrogen load came from these same catchments (Upper Hay 63%, Upper Denmark 13% and Scotsdale 9%). Increases in

phosphorus load were mainly from the Upper Hay (46%), Sunny Glen Creek (15%) and Scotsdale (14%) catchments.

Changes to reporting catchment flows were the largest in the Upper Denmark catchment, which increased by 30% compared with the basecase (see Figure 7.16 and Table 7.2). This is concerning since the Upper Denmark was responsible for increasing salinity in the Denmark dam before the plantations were established (Ward et al. 2011). The Upper and Lower Hay catchments had flow increases of 24% and 15% respectively, compared with the basecase. Flows from Sunny Glen Creek, Scotsdale and Sleeman increased by 11%, 10% and 6% respectively compared with the basecase. The catchments of Little River, Lower Denmark River, Foreshore, Cuppup and Lake Saide had flow increases of less than 3%.

The largest increase in reporting catchment nitrogen loads from the basecase were in the Upper Hay (50%) and Upper Denmark (47%). Nitrogen load increases of 17%, 14%, 13% and 6% were from the Lower Hay, Sunny Glen Creek, Scotsdale and Lake Saide catchments respectively. All other catchments had nitrogen load increases that were less than 2% (Little River, Lower Denmark River, Foreshore, Sleeman and Cuppup).

For phosphorus, the load in the Upper Hay catchment increased by about 200% compared with the basecase. In the Upper Denmark catchment there was a 100% increase in phosphorus load compared with the basecase. For the Scotsdale, Sunny Glen Creek and the Lower Hay catchments, phosphorus load increased by 56%, 45% and 27% respectively. The Lower Denmark, Lake Saide and Sleeman catchments had phosphorus load increases of 6 to 9% while Cuppup had a 0.9% increase.
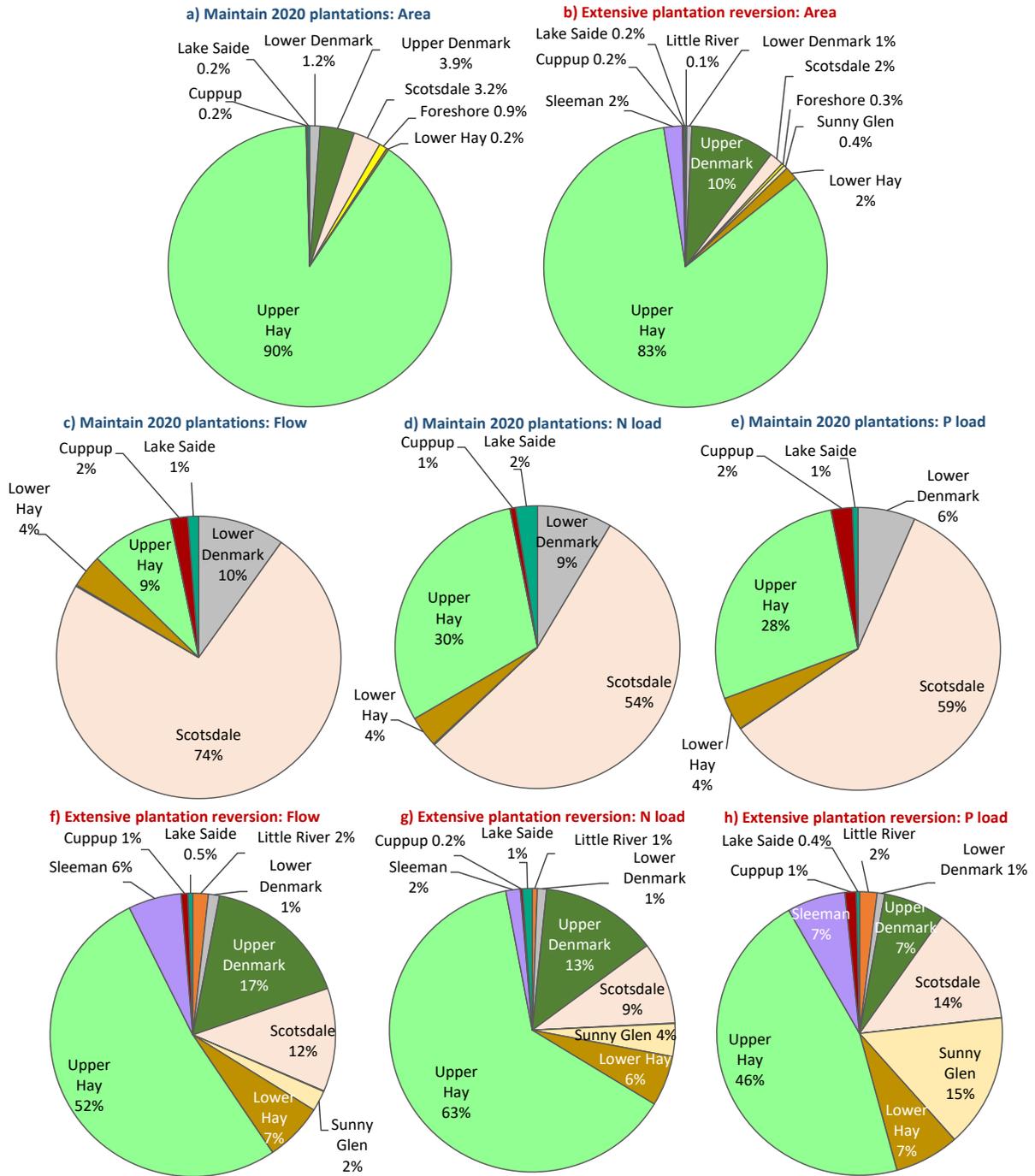
Figure 7.15: Proportion of plantation area reduction and increases in flow and nutrient load for the plantation reversion scenarios
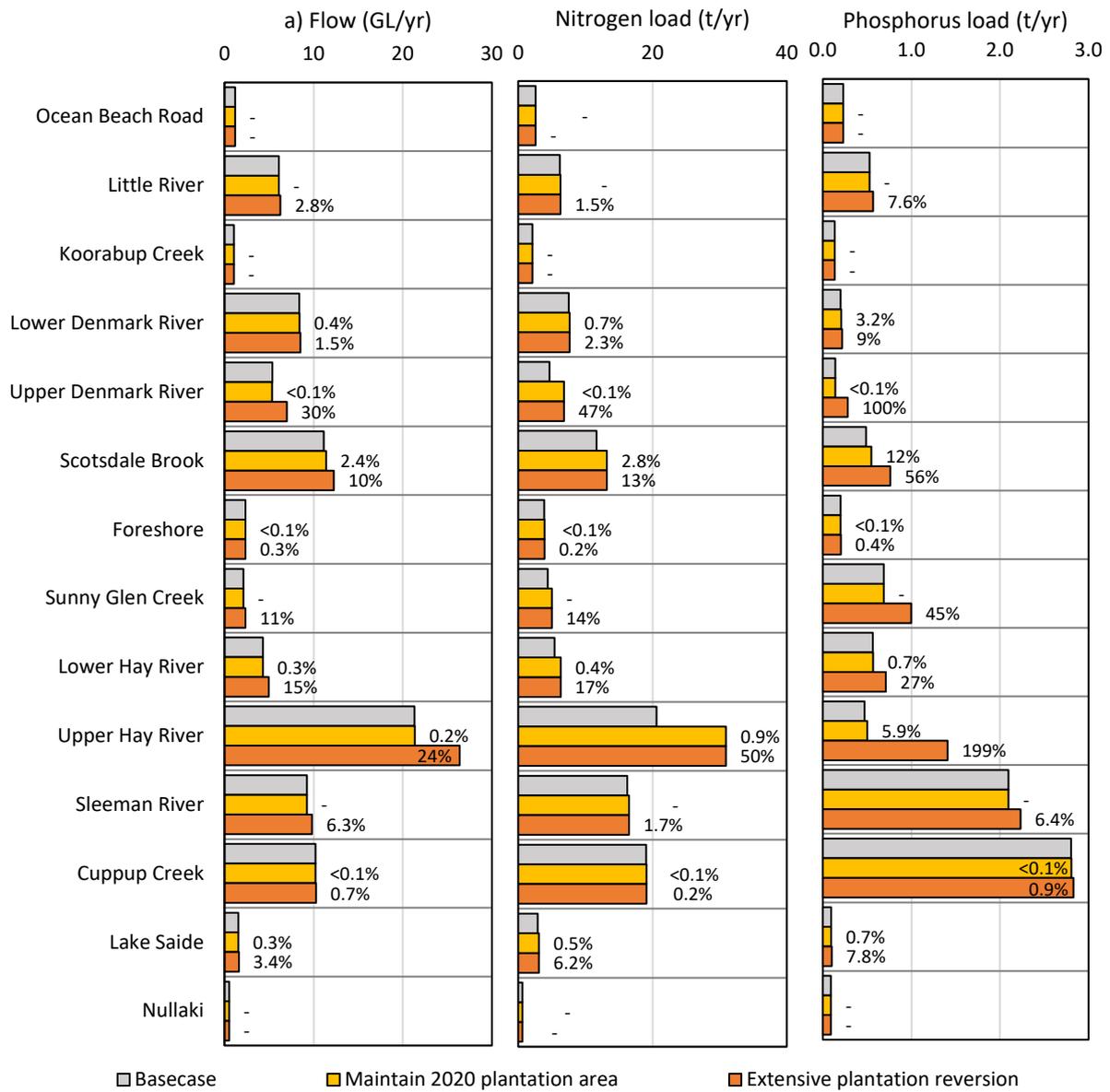
Figure 7.16: Average annual (2010–19) reporting catchment flow and nutrient loads from the basecase and the plantation scenarios, and percentage difference from the basecase

Table 7.2: Changes in the area of plantations and beef & other grazing in the plantation reversion scenarios

Reporting catchment	Catchment area	Plantation area								
		Base case		Maintain 2020 plantation area			Extensive plantation reversion			
	Area	Area	% of catchment	Area	Difference		Area	Difference		
	(ha)	(ha)	(%)	(ha)	(ha)	(%)	(ha)	(ha)	(%)	
Ocean Beach Road	997	0	-	0	-	-	0	-	-	
Little River	3 198	105	3%	105	-	-	84	- 21	-20%	
Koorabup Creek	374	0	-	0	-	-	0	-	-	
Lower Denmark River	16 002	186	1%	127	- 59	-31%	102	- 84	-45%	
Upper Denmark River	44 399	6 131	14%	5 940	- 191	-3%	4 752	- 1 379	-22%	
Scotsdale Brook	6 626	543	8%	388	- 155	-29%	310	- 232	-43%	
Foreshore	1 996	49	2%	4	- 45	-92%	3	- 46	-94%	
Sunny Glen Creek	3 575	318	9%	318	-	-	254	- 64	-20%	
Lower Hay River	12 162	1 048	9%	1 036	- 12	-1%	829	- 219	-21%	
Upper Hay River	112 181	22 763	20%	18 342	- 4 421	-19%	10 776	- 11 987	-53%	
Sleeman River	9 435	1 509	16%	1 509	-	-	1 207	- 302	-20%	
Cuppup Creek	6 899	94	1%	85	- 8	-9%	68	- 25	-27%	
Lake Saide	3 943	84	2%	72	- 12	-14%	58	- 26	-31%	
Nullaki	2 345	0	-	0	-	-	0	-	-	
Wilson Inlet	**224 133**	**32 828**	**15%**	**27 925**	**- 4 903**	**-15%**	**18 443**	**- 14 385**	**-44%**	

Table 7.3: Average annual (2010–19) flow from the plantation scenarios

Reporting catchment	Flow						
	Basecase	Maintain 2020 plantation area			Extensive plantation reversion		
	Flow	Flow	Difference		Load to inlet	Difference	
	(GL/yr)	(GL/yr)	(GL/yr)	(%)	(GL/yr)	(GL/yr)	(%)
Ocean Beach Road	1.2	1.2	-	-	1.2	-	-
Little River	6.1	6.1	-	-	6.3	0.17	2.8%
Koorabup Creek	1.0	1.0	-	-	1.0	-	-
Lower Denmark River	8.4	8.4	0.04	0.4%	8.5	0.12	1.5%
Upper Denmark River	5.3	5.3	<0.01	<0.1%	7.0	1.6	30%
Scotsdale Brook	11.1	11.4	0.3	2.4%	12.3	1.1	10%
Foreshore	2.3	2.3	<0.01	<0.1%	2.4	<0.01	0.3%
Sunny Glen Creek	2.1	2.1	-	-	2.3	0.23	11%
Lower Hay River	4.3	4.3	0.01	0.3%	4.9	0.65	15%
Upper Hay River	21.3	21.4	0.03	0.2%	26.4	5.1	24%
Sleeman River	9.2	9.2	-	-	9.8	0.58	6.3%
Cuppup Creek	10.2	10.2	<0.01	<0.1%	10.3	0.08	0.7%
Lake Saide	1.6	1.6	<0.01	0.3%	1.6	0.05	3.4%
Nullaki	0.5	0.5	-	-	0.5	-	-
Wilson Inlet	**85**	**85**	**0.4**	**0.4%**	**95**	**9.7**	**11%**

Table 7.4: Average annual (2010–19) nitrogen loads from the plantation scenarios

Reporting catchment	Nitrogen load						
	Basecase	Maintain 2020 plantation area			Extensive plantation reversion		
	Load	Load	Difference		Load	Difference	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Ocean Beach Road	2.6	2.6	-	-	2.6	-	-
Little River	6.2	6.2	-	-	6.3	0.09	1.5%
Koorabup Creek	2.1	2.1	-	-	2.1	-	-
Lower Denmark River	7.5	7.5	0.05	0.7%	7.7	0.17	2.3%
Upper Denmark River	4.6	4.6	<0.01	<0.1%	6.8	2.2	47%
Scotsdale Brook	12	12	0.3	2.8%	13	1.5	13%
Foreshore	3.9	3.9	<0.01	<0.1%	3.9	<0.01	0.2%
Sunny Glen Creek	4.4	4.4	-	-	5.0	0.61	14%
Lower Hay River	5.4	5.4	0.02	0.4%	6.3	0.94	17%
Upper Hay River	21	21	0.2	0.9%	31	10	50%
Sleeman River	16	16	-	-	16	0.27	1.7%
Cuppup Creek	19	19	<0.01	<0.1%	19	0.04	0.2%
Lake Saide	2.9	2.9	0.01	0.5%	3.1	0.18	6.2%
Nullaki	0.6	0.6	-	-	0.6	-	-
Wilson Inlet	**108**	**108**	**0.6**	**0.5%**	**124**	**16**	**15%**

Table 7.5: Average annual (2010–19) phosphorus loads from the plantation scenarios

Reporting catchment	Phosphorus load						
	Basecase	Maintain 2020 plantation area			Extensive plantation reversion		
	Load	Load	Difference		Load	Difference	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Ocean Beach Road	0.23	0.23	-	-	0.23	-	-
Little River	0.53	0.53	-	-	0.57	0.04	7.6%
Koorabup Creek	0.13	0.13	-	-	0.13	-	-
Lower Denmark River	0.20	0.21	0.006	3.2%	0.22	0.02	8.8%
Upper Denmark River	0.14	0.14	<0.001	<0.1%	0.28	0.14	100%
Scotsdale Brook	0.49	0.55	0.059	12.0%	0.76	0.27	56%
Foreshore	0.20	0.20	<0.001	<0.1%	0.20	<0.001	0.4%
Sunny Glen Creek	0.69	0.69	-	-	1.00	0.31	45%
Lower Hay River	0.56	0.57	0.004	0.7%	0.71	0.15	27%
Upper Hay River	0.47	0.50	0.028	5.9%	1.41	0.94	199%
Sleeman River	2.1	2.1	-	-	2.2	0.13	6.4%
Cuppup Creek	2.8	2.8	0.002	<0.1%	2.8	0.03	0.9%
Lake Saide	0.09	0.09	<0.001	0.7%	0.10	0.01	7.8%
Nullaki	0.09	0.09	-	-	0.09	-	-
Wilson Inlet	**8.7**	**8.8**	**0.10**	**1.1%**	**10.8**	**2.0**	**23%**

7.3   Management scenarios

We modelled the following management scenarios to estimate their potential contribution to decreasing nutrient loads and achieving targets (Section 6.2):

1. Riparian zone rehabilitation
2. Best-practice fertiliser management on farms
3. Use of low-water-soluble phosphorus fertilisers
4. Dairy effluent management
5. Soil amendments
6. Infill sewerage and septic tank removal

We used a modelling approach similar to the recent catchment modelling of the Peel-Harvey estuary catchment (Hennig et al. 2021) and the Vasse-Wonnerup catchment (Hall in prep.). Where possible, we used the farm-scale model Overseer® to estimate the effectiveness of agricultural management practices. We adapted other scenarios from the best-available information. We did not model improvements to WWTP discharge. Instead, we discuss the long-term effects of upgrades to the Denmark WWTP and potential impacts when the plant reaches capacity. See Section 7.3.8 for a list of potentially relevant management actions that we did not model.

We ran all the scenarios using the land use, climate and other model inputs of the basecase period (2010–19). See Table 7.6 for a summary of the assumed effectiveness of the management practices. Appendix E.2 gives the results of all management scenarios by reporting catchment.

Table 7.6: Summary of management scenario nutrient removal efficacy

Management practice	Scenario, category or land use	Nitrogen load reduction	Phosphorus load reduction	Reference[1]
Riparian zone management[1]	Fencing and revegetation	30%	Coastal plain: 5% Upland: 30%	Hall 2019 (Section 7.3.1)
	Fencing only	15%	Coastal plain: 5% Upland: 15%	
Best-practice fertiliser management[2]	Beef (low PRI)	0%	31% (21 to 58%)	Overseer modelling (Section 7.3.2)
	Dairy (low PRI)	0%	17% (-24 to 30%)	
	Beef (high PRI)	0%	25% (12 to 38%)	
	Dairy (high PRI)	0%	-2% (-17 to 18%)	
Best-practice fertiliser management using low-water-soluble phosphorus fertilisers[2]	Beef (low PRI)	0%	38% (29 to 62%)	Overseer modelling (Section 7.3.3)
	Dairy (low PRI)	0%	27% (-9 to 38%)	
Dairy effluent management[2]	Dairy sheds	60%	60%	Literature review (Section 7.3.4)
Soil amendments[2]	Low PRI beef, dairy, horticulture and potato farming	0%	60%	Hennig et al. 2021 (Section 7.3.5)
Infill sewerage[2]	Septic tank removal	100%	100%	Manipulation of basecase model (Section 7.3.6)
Wastewater treatment plants	Treated wastewater discharge	No scenario modelling: Details recent improvements		Section 7.3.7

[1] Load reduction relative to catchment.

[2] Load reduction relative to the source of nutrient (e.g. land use or septic tank)

7.3.1 Riparian management

Riparian management is an action that encompasses waterway fencing, riparian zone revegetation and in some cases drainage modifications. Healthy riparian zones and stock exclusion (fencing) have helped remove nutrients and sediment and improve stream ecology in many locations in Australia and elsewhere. However, Western Australian literature relating to nutrient removal in riparian zones is often inconsistent with the national and international literature. In response to this, Hall (2019) conducted a detailed literature review of the effectiveness of riparian revegetation to remove, attenuate or prevent the export of nutrients, with a focus on Western Australian south coastal plain catchments.

Fencing and re-vegetating riparian zones have the following main functions:

- Fencing prevents livestock from accessing waterways. Livestock can destabilise the bed and banks of waterways and inhibit plant regrowth. They add nutrients (faeces and urine) directly to waterways and the riparian zone.

- Re-vegetating riparian zones:

    - stabilises waterway banks and reduces erosion

    - traps sediment and particulate nutrients in overland flow

    - uses nutrients in overland and groundwater flows

    - promotes denitrification of groundwater nitrate

    - restores and/or maintains waterway ecosystems

    - provides biodiversity corridors to link fragmented natural landscapes and provide refuge for terrestrial fauna.

Riparian revegetation is likely to be an effective solution for reducing phosphorus loads to waterways in catchments with greater slope, finer textured soils, lower infiltration rates, and hence overland flow as the dominant hydrological pathway. Riparian zones efficiently trap and process particulate nutrients in overland flow.

Photo: Cattle in an unfenced and degraded stream in the Wilson Inlet catchment in 2020

In contrast, flat and sandy riparian areas are likely to achieve smaller phosphorus removal. Much of the phosphorus is lost from these landscapes in a soluble form, which is not efficiently treated by riparian zones. Also, most phosphorus is mobilised during winter when plant uptake is generally lower than other months. The primary mechanisms for phosphorus load reduction via riparian zone rehabilitation in these landscapes results from stock exclusion and reduced fertilised area on farms. Plant nutrient uptake, trapping of particulate phosphorus in the riparian zone and soil adsorption are secondary factors.

In flat, waterlogged catchments with heavy soils and high drainage density, a larger proportion of the land area is drained and can mobilise phosphorus. As a result, a much greater length of riparian zone management would be required for a beneficial effect, thus taking a larger area of land out of traditional farming. We question the extent that riparian-zone restoration would be effective in these catchments, as waterlogged land already has slow rates of lateral water movement and infiltration through the soil (i.e. a major nutrient removal pathway) would not occur for most of the winter. In areas with strong surface soil phosphorus stratification, the top few millimetres of heavy textured soils are over-saturated with phosphorus, allowing for soluble phosphorus losses in overland flow. The lower portions of the Sleeman and the entire Cuppup catchment have flat, waterlogged landscapes with extensive artificial drainage. These catchments also have a similar proportion of soluble phosphorus as catchments in the Peel-Harvey with similar catchment characteristics. These Peel-Harvey catchments were assumed to have a lower efficacy of riparian nutrient removal by Hennig et al. (2021), particularly the Harvey (613036), South Dandalup (6142623) and Upper Serpentine (615030).

Vegetated riparian zones have high soil carbon content, which promotes microbial denitrification of nitrates. Plant uptake of nitrogen (nitrate and ammonia) is also larger than for phosphorus. Dissolved organic nitrogen (DON) removal in riparian zones is much less than inorganic nitrogen (Wegner 1999).

Riparian zone management in south-west Western Australia generally involves:

- Fencing programs that are implemented by landholders, which may be partially or fully funded by external parties (e.g. government, private industry). Fencing can also be implemented by Landcare and catchment groups when undertaking rehabilitation works on behalf of the landholder.

- In some instances, drains are modified to better represent natural streams. This can involve the flattening and widening of drains to replicate a floodplain. However, this is less common due to the space requirement, cost and potential for increased flood risk.

- Riffles can sometimes be introduced to replicate natural obstructions (e.g. fallen trees). Riffles are used to increase the upstream standing water depth for habitat, and to aerate water as it flows over the riffle.

- Riparian areas can be stabilised and re-vegetated with local plant species. The species diversity and density of re-vegetation differs according to location, seedling availability and funding.

Photo: The vegetated lower reach of Bluegum Creek in 2016

The width of riparian management varies and depends on the landholder. Widths of 5 to 15 m from a stream are common.

It is far easier and less costly to prevent the degradation of natural riparian zones than it is to restore them. Therefore, the protection of existing riparian areas is valuable, in addition to the need to restore degraded riparian zones in the Wilson Inlet catchment.

Natural Resource Management (NRM) groups such as the Wilson Inlet Catchment Committee (WICC) have undertaken riparian zone rehabilitation in conjunction with landholders. Rates of riparian zone revegetation have been dependent on funding (state and/or federal government), the priorities of NRM groups and the capacity for NRM groups to implement rehabilitation.

WICC is an important stakeholder of Gondwana Link – a strategic restoration initiative to connect natural remnant land from the great western woodlands to the wetter forests in south-western Australia (see Figure 7.17). WICC developed the conservation action plan for the Lindesay Link, which spans most of the cleared areas of the Hay River and Upper Denmark River catchments (WICC 2013). Past riparian rehabilitation efforts in the Hay River catchment are an example of management actions striving to achieve multiple benefits.

Figure 7.17: The three zones of the Gondwana Link (left, Gondwana Link Ltd 2020) and the Lindesay Link (right, WICC 2013)

Implementation

We modelled the following:

1. The potential effect of fencing funded by the Regional Estuaries Initiative (REI) implemented by WICC from 2016–20.

2. Fencing all unfenced Water Corporation-managed drains (34 km).

3. Fencing all unfenced riparian zones (1,773 km).

4. Fencing and revegetating all unfenced and cleared riparian zones (1,773 km).

We assumed fencing and revegetation of riparian zones had different phosphorus load reduction efficacies in low- and high-efficacy catchments (see Table 3.3). Sandy low-PRI catchments or catchments with a high drainage density were 'low-efficacy catchments' and had a lower riparian phosphorus filtering efficacy. This applied to part or the entirety of the following reporting catchments; Ocean Beach Road, Foreshore, Sunny Glen Creek, Lower Hay, Sleeman, Cuppup, Lake Saide and Nullaki (see Figure 3.7).

This scenario modifies the parameters used in the basecase riparian filtering component of the nutrient model (see Section 3.1.2). Table 7.8 gives the riparian filtering parameters (a percentage reduction in land-use-generated nutrients) when aggregated at the reporting catchment scale.

Table 7.7: Riparian management nutrient removal efficacy (adapted from Hall 2019)

Category	Description	Nitrogen load reduction	Phosphorus load reduction	
		All catchments (%)	High efficacy (%)	Low efficacy (%)
Fencing	Fencing with stock exclusion, off-stream watering points and stream crossings. Vegetation is limited to the recruitment of pastures, the use of grass buffers or growing and harvesting hay. The fenced area is not fertilised.	15	15	5
Fencing and revegetation	Fencing with stock exclusion, off-stream watering points and stream crossings. Re-vegetated using native canopy and understory vegetation (8,000 plants/ha). The fenced area is not fertilised.	30	30	5

Table 7.8: Length of riparian zones that require management, and a summary of the riparian filtering model parameters used in the basecase model and riparian management scenarios

Reporting catchment	Total riparian zone length (km)	Requiring management (based on spatial data) (km)	Requiring management (based on spatial data) (%)*	Revegetation required (km)	Revegetation required (%)*	Basecase Load reduction parameter N (%)¥	Basecase Load reduction parameter P (%)¥	Max fencing Load reduction parameter N (%)¥	Max fencing Load reduction parameter P (%)¥	Max fencing & revegetation Load reduction parameter N (%)¥	Max fencing & revegetation Load reduction parameter P (%)¥
Ocean Beach Road	7	5	70%	3	45%	16	3	28	5	30	5
Little River	55	55	99%	15	26%	22	22	30	30	30	30
Koorabup Creek	7	6	84%	2	36%	19	19	30	30	30	30
Lower Denmark River	214	179	84%	33	15%	25	25	30	30	30	30
Upper Denmark River	539	222	41%	58	11%	27	27	30	30	30	30
Scotsdale Brook	102	38	37%	30	29%	21	21	27	27	30	30
Foreshore	18	17	94%	7	37%	19	11	28	16	30	16
Sunny Glen Creek	47	47	100%	26	56%	13	2	28	5	30	5
Lower Hay River	143	105	74%	39	28%	22	4	29	5	30	5
Upper Hay River	1072	822	77%	288	27%	22	22	30	30	30	30
Sleeman River	127	104	81%	74	58%	12	2	25	5	30	5
Cuppup Creek	163	140	86%	142	87%	4	1	17	5	30	5
Lake Saide	36	36	100%	20	54%	14	2	28	5	30	5
Nullaki	2	1	74%	1	78%	7	1	18	5	30	5
Wilson Inlet	**2535**	**1776**	**70%**	**739**	**29%**	**-**	**-**	**-**	**-**	**-**	**-**

Note:

Fencing is given as the length of a riparian zone with fencing on both banks. The length of fencing is double the number given

* Percent of total riparian zone by catchment

¥ Percent of nutrient load that is removed by riparian zones.

The effect of REI-funded fencing (2016-19)

From 2016–20 the State Government's Regional Estuaries Initiative (REI) funded about 53 km of fencing, which is the equivalent to 26 km of fencing both banks of a stream or drain. WICC implemented these management actions according to funding criteria and the consent of landowners. The fencing was done in nine reporting catchments (see Figure 7.18).

It is estimated the REI-funded fencing reduced nutrient loads by 0.2% for nitrogen and 0.1% for phosphorus. Note that only 1% of streams were fenced and hence the load reductions were small.

The REI-funded fencing had a much greater relative impact in the Nullaki reporting catchment. The remaining unfenced drains in the Nullaki catchment were completely fenced and nutrient loads were reduced by about 7% for nitrogen and 3% for phosphorus. As discussed later in this section, riparian management in the Nullaki catchment resulted in the greatest benefit per kilometre of management.

About 12 km of streams and drains were fenced in the Upper Hay catchment – a majority of the REI-funded fencing. The Upper Hay catchment is the largest reporting catchment by area and has the greatest length of riparian zones that potentially require management. As a

result, the fencing in this catchment saw only a small reduction in nutrient loads. The fencing was primarily targeted at the Lindesay Link area and the protection of existing riparian areas, hence achieving multiple benefits.
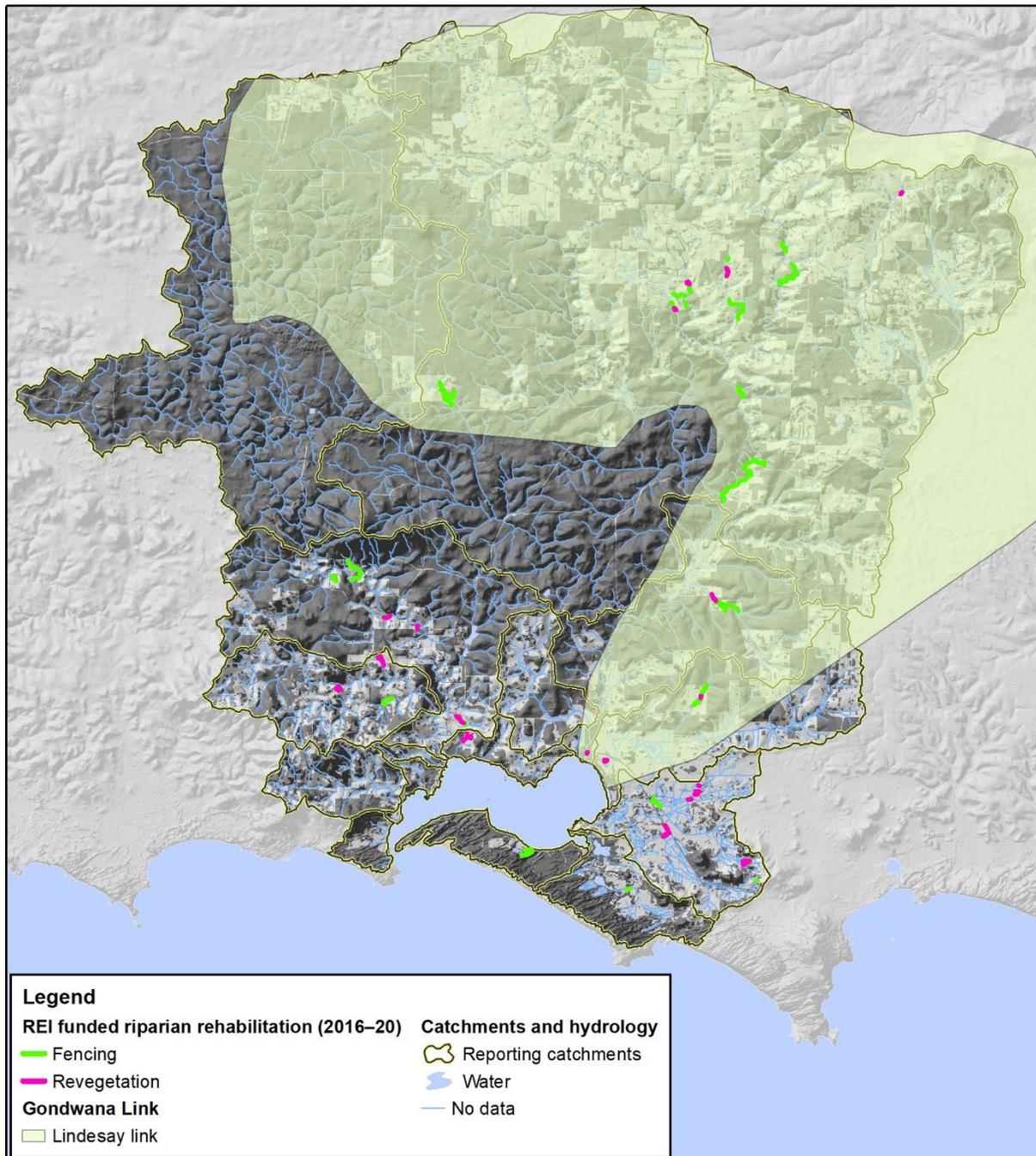
Figure 7.18: REI-funded fencing, riparian revegetation and the Lindesay Link

Table 7.9: Potential load reductions from REI-funded fencing

Reporting catchment	Current		REI funded fencing implemented by WICC (2016–19)								
	N load to inlet	P load to inlet	Fencing required	Length of REI fencing		N load to inlet	Difference		P load to inlet	Difference	
	(t/yr)	(t/yr)	(km)	(km)	(%)*	(t/yr)	(t/yr)	(%)¥	(t/yr)	(t/yr)	(%)¥
Ocean Beach Road	2.6	0.2	5.2	-	-	2.6	-	-	0.2	-	-
Little River	6.2	0.5	55	-	-	6.2	-	-	0.5	-	-
Koorabup Creek	2.1	0.1	5.8	-	-	2.1	-	-	0.1	-	-
Lower Denmark River	7.5	0.2	179	3.0	1.7%	7.5	-0.01	-0.1%	0.2	-0.0003	-0.1%
Upper Denmark River	4.6	0.1	222	-	-	4.6	-	-	0.1	-	-
Scotsdale Brook	12	0.5	38	2.1	5.5%	12	-0.05	-0.4%	0.5	-0.0019	-0.4%
Foreshore	3.9	0.2	17	0.2	1%	3.9	0.00	-0.1%	0.2	0.0000	0.0%
Sunny Glen Creek	4.4	0.7	47	-	-	4.4	-	-	0.7	-	-
Lower Hay River	5.4	0.6	105	2.0	1.9%	5.4	-0.01	-0.2%	0.6	-0.0003	-0.05%
Upper Hay River	21	0.5	822	12	1.5%	21	-0.04	-0.2%	0.5	-0.0008	-0.2%
Sleeman River	16	2.1	104	1.4	1.4%	16	-0.03	-0.2%	2.1	-0.0009	0.0%
Cuppup Creek	19	2.8	140	3.9	2.8%	19	-0.07	-0.4%	2.8	-0.0031	-0.1%
Lake Saide	2.9	0.1	36	0.1	0.4%	2.9	-0.002	-0.1%	0.1	-0.00001	-0.01%
Nullaki	0.6	0.1	1.2	1.2	100%	0.6	-0.05	-7%	0.1	-0.003	-2.8%
Wilson Inlet	**108**	**8.7**	**1776**	**26**	**1.0%**	**107**	**-0.25**	**-0.2%**	**8.7**	**-0.010**	**-0.11%**

Note:

Fencing is given as the length of a riparian zone with fencing on both banks. The length of fencing is double the number given

* Percent of all mapped streams & drains requiring management

¥ Percent load difference to current reporting catchment load

Fencing Water Corporation drains

About 46 km of drains are managed by the Water Corporation in the Albany drainage district. About 59% (28 km) of the riparian zones alongside these drains are cleared, and two-thirds (68%; 34 km) potentially require fencing of at least one bank or have an unknown fencing status.

If the 32 km of Water Corporation drains without fences were fenced, we estimate that loads to Wilson Inlet could reduce by 0.5% for nitrogen and 0.02% for phosphorus (Table 7.11). In the reporting catchments within the drainage district, loads were reduced by 1 to 3% for nitrogen and 0.2 to 0.5% for phosphorus. Note that only a small proportion of drains are managed by the corporation – about 2% of total drainage length in the Wilson Inlet catchment and 14% in drainage district catchments (see Figure 7.19 and Table 7.10), hence the reductions in nutrient load are small.

Table 7.10: Summary of the vegetation and fencing status of Water Corporation-managed drains

Reporting catchment	Total riparian zone	Water Corporation managed							
		Length		Riparian zone			Fence status		
				Cleared		Vegetated	Required/no data		Not required
	(km)	(km)	(%)*	(km)	(%)¥	(%)¥	(km)	(%)¥	(%)¥
Sleeman River	127	11	8%	4	36%	64%	7	61%	39%
Cuppup Creek	163	27	17%	22	80%	20%	19	69%	31%
Lake Saide	36	9	24%	2	21%	79%	7	75%	25%
Drainage district subtotal	**327**	**47**	**14%**	**28**	**59%**	**41%**	**32**	**68%**	**32%**
Wilson Inlet	**2534**	**47**	**2%**						

Note:

Fencing is expressed as the amount required to fence both banks of a stream or drain

* Percent of total riparian zones

¥ Percent of Water Corporation drains

Table 7.11: Potential load reductions from fencing Water Corporation-managed drains

Reporting catchment	Current		Fence Water Corporation drains							
	N load to inlet	P load to inlet	Length managed		N load to inlet	Difference		P load to inlet	Difference	
	(t/yr)	(t/yr)	(km)	(%)*	(t/yr)	(t/yr)	(%)¥	(t/yr)	(t/yr)	(%)¥
Sleeman River	16	2.1	7	6.3%	16	-0.1	-0.8%	2.1	-0.0040	-0.2%
Cuppup Creek	19	2.8	19	13.4%	19	-0.3	-1.8%	2.8	-0.0152	-0.5%
Lake Saide	2.9	0.1	6.5	18.0%	2.8	-0.1	-2.8%	0.1	-0.0004	-0.5%
Wilson Inlet	**108**	**8.7**	**32**	**1.3%**	**107**	**-0.6**	**-0.5%**	**8.7**	**-0.020**	**-0.02%**

Note:

Fencing is given as the length of a riparian zone with fencing on both banks.

* Percent of all mapped streams & drains requiring management

¥ Percent load difference to current reporting catchment load
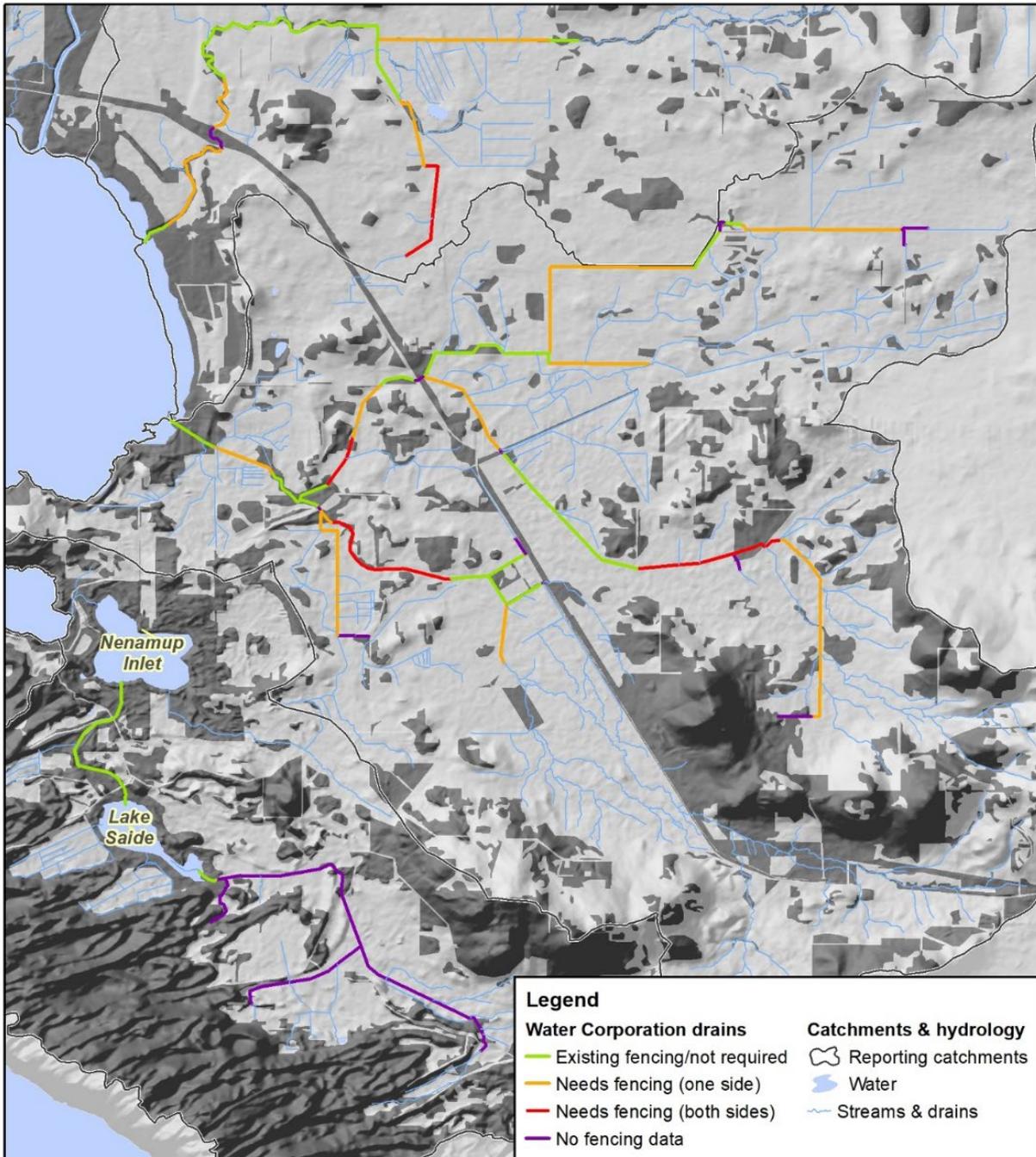
Figure 7.19: Fencing status of Water Corporation-managed drains

Management of all riparian zones

About 1,776 km (70%) of streams and drains in the Wilson Inlet catchment potentially require some form of riparian management, such as fencing and/or revegetation. The management of these streams and drains could result in load reductions of 11 to 15% for nitrogen and 4.5 to 4.7% for phosphorus (Figure 7.20). Fencing all streams (without revegetation) had slightly lower estimated nutrient load reductions than if all streams were adequately fenced and revegetated (11% for N and 4.5% of P). Most of this estimated nitrogen and phosphorus load reduction came from the Sleeman, Cuppup and Upper Hay catchments (13 to 31%, see Figure 7.21). However, about 9 to 13% of the phosphorus load reduction was from the Scotsdale Brook and Little River catchments.
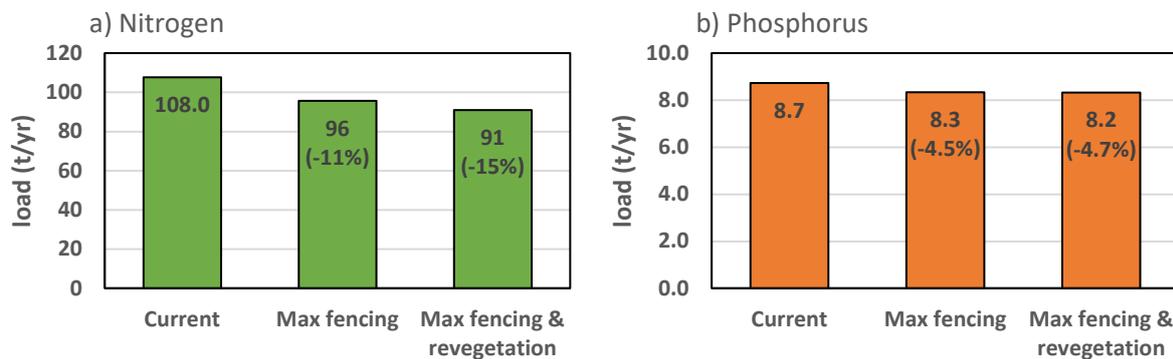
Figure 7.20: Nitrogen and phosphorus loads to Wilson Inlet for the current period (2010–19) and after maximum fencing or fencing & revegetation of the riparian zone

In terms of relative improvement in the reporting catchment nutrient loads, the Cuppup, Sleeman and Upper Hay River catchments had the largest nitrogen load reduction in both scenarios (see Table 7.12 and Table 7.13). However, due to the size of the Upper Hay, it potentially requires four times the length of fencing as the Cuppup and Sleeman catchments combined.

Sunny Glen Creek and Lake Saide had estimated reductions in nitrogen loads of 16 to 17% in the fencing scenario. Both catchments did not have any fencing status mapping. The Nullaki catchment also had large nitrogen reductions (16%) but required just 2 km of fencing because only a small proportion of the catchment is cleared and has surface drainage.

Priorities for future nutrient management

Figure 7.22 ranks the nutrient load removed per kilometre of riparian management. Catchments with a higher nutrient load removed per kilometre would have the greatest benefit from a nutrient management perspective. However, nutrient management is one of many considerations when selecting an appropriate area for riparian management. For example, the willingness and capacity of landowners to fence their waterways is a critical factor.

The Nullaki and Ocean Beach Road catchments had the greatest estimated nutrient load removal per kilometre of riparian management. As previously discussed, the remaining unfenced portions of drains in the Nullaki catchment were fenced as part of REI-funded works.

In general, riparian management would be beneficial in almost all other catchments. The lowest rates of nutrient removal per kilometre were in the Upper Hay and Denmark River catchments, which are expansive. The Lower Denmark and Hay River catchments had a marginally higher rate of nutrient removal per kilometre. The remaining catchments had moderate to low rates of nutrient removal per kilometre of fencing (Scotsdale, Sleeman, Cuppup, Sunny Glen, Koorabup, Lake Saide, Foreshore and Little River).
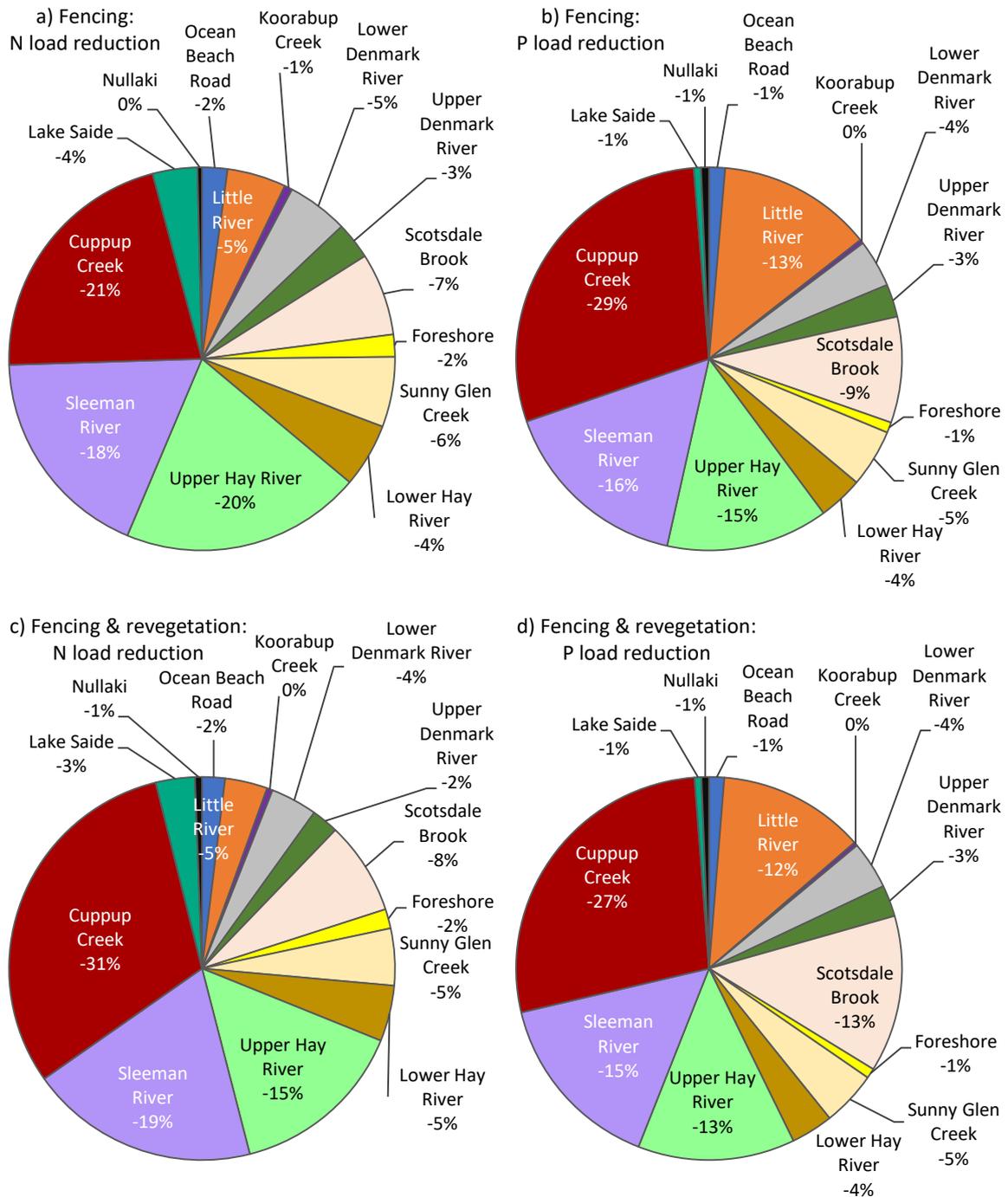
Figure 7.21: Estimated nutrient load reduction to Wilson Inlet from riparian management scenarios
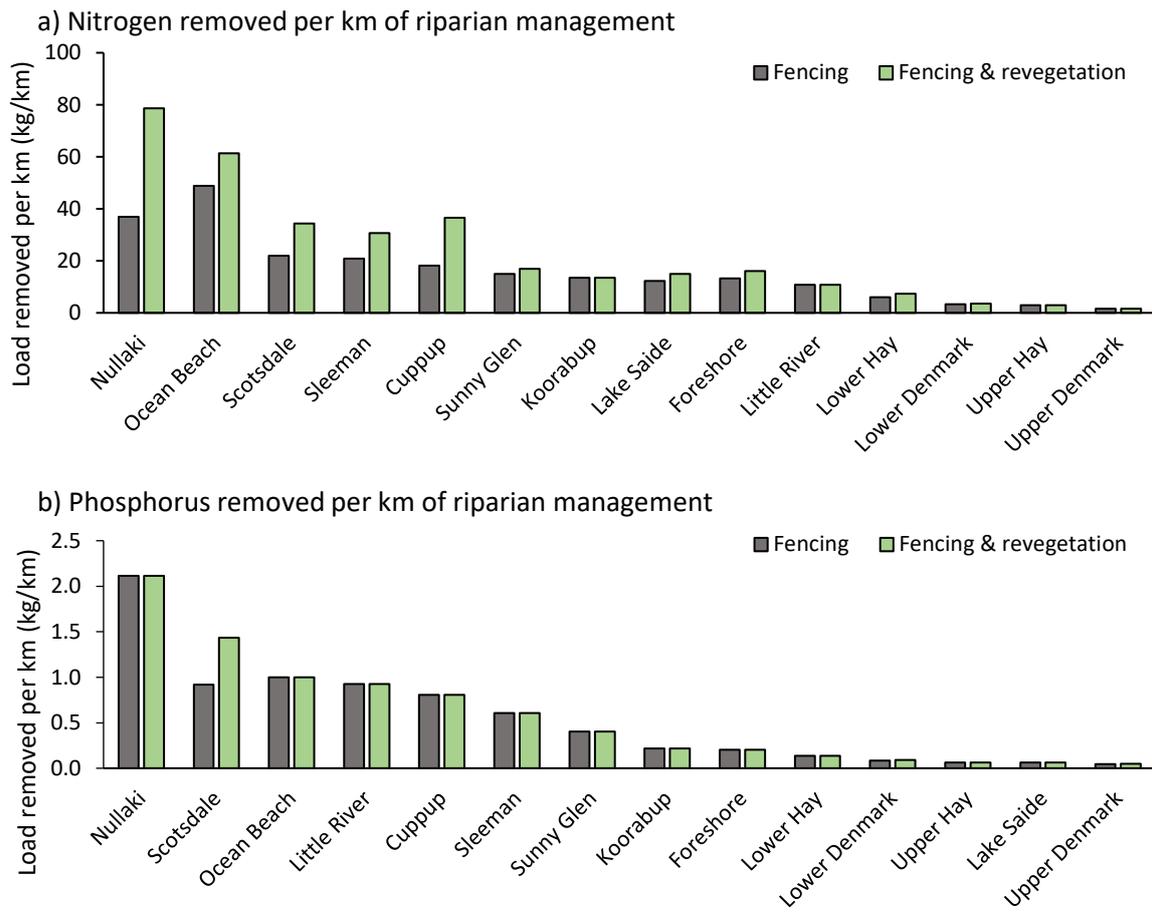
Figure 7.22: Estimated nutrient removed per kilometre of riparian management, by reporting catchment sorted by nutrient removal per kilometre of fencing & revegetation

Table 7.12: Average annual nitrogen loads in riparian management scenarios

Reporting catchment	Basecase N load (t/yr)	Riparian zone requiring management (km)	Riparian zone requiring management (%)*	Scenario: Fence all riparian zones N load (t/yr)	Scenario: Fence all riparian zones Difference (t/yr)	Scenario: Fence all riparian zones Difference (%)¥	Scenario: Fence & revegetate all riparian zones N load (t/yr)	Scenario: Fence & revegetate all riparian zones Difference (t/yr)	Scenario: Fence & revegetate all riparian zones Difference (%)¥
Ocean Beach Road	2.6	5	70%	2.3	-0.25	-10%	2.3	-0.32	-12%
Little River	6.2	55	99%	5.6	-0.59	-10%	5.6	-0.59	-10%
Koorabup Creek	2.1	6	84%	2.0	-0.08	-3.8%	2.0	-0.08	-3.8%
Lower Denmark River	7.5	179	84%	6.9	-0.61	-8.2%	6.8	-0.65	-8.6%
Upper Denmark River	4.6	222	41%	4.3	-0.37	-8.0%	4.3	-0.38	-8%
Scotsdale Brook	12	38	37%	11	-0.83	-7.1%	10	-1.30	-11%
Foreshore	3.9	17	94%	3.7	-0.22	-6%	3.6	-0.27	-7%
Sunny Glen Creek	4.4	47	100%	3.7	-0.71	-16%	3.6	-0.79	-18%
Lower Hay River	5.4	105	74%	4.7	-0.64	-12%	4.6	-0.78	-14%
Upper Hay River	21	822	77%	18	-2.4	-12%	18	-2.5	-12%
Sleeman River	16	104	81%	14	-2.2	-13%	13	-3.2	-20%
Cuppup Creek	19	140	86%	17	-2.5	-13%	14	-5.1	-27%
Lake Saide	2.9	36	100%	2.5	-0.45	-15%	2.4	-0.54	-19%
Nullaki	0.6	1	74%	0.6	-0.05	-7%	0.5	-0.10	-16%
Wilson Inlet	**108**	1776	70%	**96**	**-12**	**-11%**	**91**	**-17**	**-15%**

Note:

Fencing is given as the length of a riparian zone with fencing on both banks

* Percent of all mapped streams & drains requiring management

¥ Percent load difference to current reporting catchment load

Table 7.13: Average annual phosphorus loads in riparian management scenarios

Reporting catchment	Basecase P load (t/yr)	Riparian zone requiring management (km)	Riparian zone requiring management (%)*	Scenario: Fence all riparian zones P load (t/yr)	Scenario: Fence all riparian zones Difference (t/yr)	Scenario: Fence all riparian zones Difference (%)¥	Scenario: Fence & revegetate all riparian zones P load (t/yr)	Scenario: Fence & revegetate all riparian zones Difference (t/yr)	Scenario: Fence & revegetate all riparian zones Difference (%)¥
Ocean Beach Road	0.23	5	70%	0.22	-0.01	-2.3%	0.22	-0.01	-2.3%
Little River	0.53	55	99%	0.48	-0.05	-10%	0.48	-0.05	-10%
Koorabup Creek	0.13	6	84%	0.13	0.00	-1.0%	0.13	-0.001	-1.0%
Lower Denmark River	0.20	179	84%	0.18	-0.02	-7.8%	0.18	-0.02	-8.3%
Upper Denmark River	0.14	222	41%	0.13	-0.01	-8%	0.13	-0.01	-7.7%
Scotsdale Brook	0.49	38	37%	0.45	-0.03	-7%	0.43	-0.05	-11%
Foreshore	0.20	17	94%	0.20	0.00	-1.7%	0.20	-0.003	-1.7%
Sunny Glen Creek	0.69	47	100%	0.67	-0.02	-2.8%	0.67	-0.02	-2.8%
Lower Hay River	0.56	105	74%	0.55	-0.01	-2.6%	0.55	-0.01	-2.6%
Upper Hay River	0.47	822	77%	0.42	-0.05	-11%	0.42	-0.05	-11%
Sleeman River	2.1	104	81%	2.0	-0.06	-3.0%	2.0	-0.06	-3.0%
Cuppup Creek	2.8	140	86%	2.7	-0.11	-4.0%	2.7	-0.11	-4.0%
Lake Saide	0.09	36	100%	0.09	0.00	-2.5%	0.09	-0.002	-2.5%
Nullaki	0.09	1	74%	0.09	0.00	-2.8%	0.09	-0.003	-2.8%
Wilson Inlet	**8.7**	1776	70%	**8.3**	**-0.39**	**-4.5%**	**8.3**	**-0.41**	**-4.7%**

Note:

Fencing is given as the length of a riparian zone with fencing on both banks

* Percent of all mapped streams & drains requiring management

¥ Percent load difference to current reporting catchment load

7.3.2   Best-practice fertiliser management

Beef and dairy farms are the largest sources of nutrients to Wilson Inlet. Most paddocks used for beef and dairy grazing now have soil phosphorus concentrations that exceed the requirements for pasture growth. This is due to ongoing phosphorus fertiliser applications that have led to a build-up of phosphorus in soils. While many farmers apply fertiliser types and rates needed for pasture growth based on soil test results, others routinely apply the same fertiliser types and rates each year. This can lead to nutrients like phosphorus being applied in excess of requirements, or failing to address other productivity constraints such as pH, or deficiencies in other nutrients.

Photo: The process of collecting soil samples, interpreting results, and making fertiliser decisions

Local and international scientific literature details the link between phosphorus fertiliser use and impacts on phosphorus losses:

- Schofield et al. (1985) measured paddock-scale reduction in export resulting from no fertiliser application for two years. The experiment was on Bassendean sands in the Meredith Drain of the Peel-Harvey catchment. They reported ~60% reduction in surface water phosphorus concentrations over the two-year study.

- Silberstein and Schofield (1990) undertook a similar experimental study to Schofield et al. (1985). It went for four years with a smaller study area that had sandy duplex soils. After four years, the phosphorus export from unfertilised plots was 60% lower than plots that were fertilised at 18 kg P/ha/yr of superphosphate. Pasture yield in unfertilised plots was about 90% of fertilised plots. Soil phosphorus content was unchanged in the unfertilised plots and showed no sign of nutrient rundown. Ritchie et al. (1985) estimated that these soil types did not need phosphorus fertiliser for up to seven years given their phosphorus content.

- Robinson et al. (2011) reviewed data from studies by Sharpley et al. (1994) and Vadas et al. (2005) to develop a linear relationship between dissolved reactive phosphorus in runoff, and phosphorus saturation. Colwell P is a measure of phosphorus in the soil that is available to plants. The relationships derived by Robinson et al. (2011) are used in the HowLeaky model (McClymont et al. 2011) for estimating phosphorus runoff.

- McDowell and Condron (2004) estimated phosphorus loss from New Zealand grassland soils and found a linear relationship between phosphorus concentration and Olsen P (a measure of phosphorus in the soil that is available to plants) divided by P retention. They derived functions for dissolved phosphorus concentrations in overland flows and subsurface flows that were a function of Olsen P and phosphorus retention. These were used as a premise for the Overseer phosphorus soil-loss model.

Best-practice fertiliser management asks that farmers follow the '*four Rs*': the **R**ight source/fertiliser, applied at the **R**ight rate, at the **R**ight time in the **R**ight place. This in conjunction with good record keeping, appropriate fertiliser storage and transport, spreader calibration, grazing management and riparian management form the basis of the *Nutrient best management practices for beef, sheep and dairy grazing enterprises in south-west Western Australia* (DWER & DPIRD 2022).

This scenario primarily focuses on the right rate, where farmers determine their farm's fertiliser requirements and apply the right amount of fertiliser. Note that Section 7.3.3 considers the use of low-water-soluble phosphorus fertilisers (the right source) on sandy soils with low-phosphorus-retention capacity (the right place).

RIGHT SOURCE	RIGHT RATE	RIGHT TIME	RIGHT PLACE
Matches fertilizer type to crop needs.	Matches amount of fertilizer type crop needs.	Makes nutrients available when crops needs them.	Keep nutrients where crops can use them.

Figure 7.23: The four R's (https://nutrientstewardship.org/4rs/)

To determine the right rate of fertiliser, farmers need to decide their target pasture productivity. Grazing farms typically aim to achieve maximum pasture production of 85% (beef) and 95% (dairy), as these targets are generally the most profitable. However, the targets will vary from farm to farm and could differ between paddocks of a single farm. We have assumed these productivity targets in our scenario modelling.

Farmers will then need to undertake paddock soil testing to determine the content of soil nutrients, soil properties such as phosphorus retention index (PRI) and buffering index[25], and soil acidity. Using these results, a farmer and/or agronomist can then tailor a fertiliser program to the farm using the following resources:

1)   **DPIRD advice for high-rainfall pastures**, which includes:

- methods of soil and tissue testing

- a nutrient calculator to information phosphorus, sulfur and potassium fertiliser types and rates based on soil and tissue test results

- recommendations for pasture micronutrients (zinc, copper, molybdenum, boron, manganese, iron, cobalt)

- soil acidity management.

2)   **Better fertiliser decisions**. This project produced a comprehensive database of information that has been used to improve fertiliser decisions for grazing industries nationally (DPI 2007). DPIRD, fertiliser companies and agronomists have used the database to develop fertiliser decision-support tools.

3)   ***Nutrient best management practices for beef, sheep and dairy grazing enterprises in south-west Western Australia***. This publication includes additional information and references on the 4Rs, including fertiliser selection, application and storage.

Implementation

For this scenario we modelled two levels of best-practice fertiliser management adoption:

1. **The potential effect of past soil test programs on phosphorus loss**: We assumed that beef and dairy farms adopted fertiliser best-management practices when they were: a) part of the REI soil-testing program (2016–20), and b) part of programs from 2009–20, including REI (i.e. all farms in DPIRD's whole-farm nutrient mapping database). We developed this scenario to estimate the potential long-term water quality benefit of programs aiming to improve farm nutrient-use efficiency.

2. **All farmers in the Wilson Inlet catchment adopt best-practice:** We assumed all beef and dairy farms in the Wilson Inlet catchment adopted best-practice farm fertiliser management (100% adoption).

We used the Overseer lot-scale model to estimate the reduction in phosphorus export from improved fertiliser management on beef and dairy farms using traditional superphosphate fertilisers. We developed models for farms on low- and high-PRI soils (four models in total). Nitrogen is unaffected in this scenario as most farm nitrogen inputs are from nitrogen-fixing pastures rather than fertiliser. See below for a summary of the modelling and Appendix E for a full description.

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[25] Phosphorus Buffering Index (PBI) is a measure of the soil's ability to retain P. The higher the PBI, the more P the soil can hold. The lower a soil's PBI, the less its ability to hold P and therefore the risk of P loss to the environment is greater.

The DPIRD whole-farm nutrient mapping (WFNM) dataset has farm soil measurements taken from 2009–20. It also contains soil testing funded as part of the REI soil-testing program (2016–20) and other government programs (2009–15).

We used a subset of this dataset to parameterise the Overseer models of beef and dairy farms on low- and high-PRI soils (see Appendix E). A total of 180 km^2 was soil tested (133 km^2 from REI-funded programs and 47 km^2 from the earlier programs).

Current beef and dairy farms were parameterised based on the area weighted soil-test results by reporting catchment. Best-practice beef and dairy farm models were parameterised to have soil phosphorus content and fertiliser applications to achieve 85% and 95% of maximum relative pasture yield respectively – the targets sought for the greatest farm profit (Weaver pers. comm. 2019).

Figure 7.24 shows a soil phosphorus statistic called a 'fertility index'. This indicates if a paddock has an excess of soil phosphorus (values greater than 1 – orange to red) or a deficit (values less than 1 – green) to sustain a farm's target productivity for one year. For instance, a farm paddock with a soil fertility index of equal to 1 has the optimum amount of plant-available phosphorus for a given pasture productivity (e.g. 85% of relative maximum) and would not require phosphorus fertiliser. A fertility index of less than 1 means a farm is deficient in plant-available soil phosphorus and would require fertiliser to maintain target pasture productivity. A paddock with a fertility index of 2 means it has double the amount of plant-available soil phosphorus required for the target pasture productivity and phosphorus fertiliser is not necessary.

As shown in Figure 7.25, beef farms in the Wilson Inlet catchment had an area-weighted average fertility index of 1.6 – indicating an excess of soil phosphorus. The fertility index of beef farms by reporting catchment ranged from 1.3 in the Lower Hay catchment to 2.5 in the Scotsdale catchment. The fertility index of catchments with large phosphorus loads to the Wilson Inlet (Cuppup, Sleeman and Sunny Glen) had beef fertility index values of 1.6 to 1.8.

Dairy farms in the Wilson Inlet had an area-weighted fertility index of 1. This indicates that on average, dairy farms in the Wilson Inlet have an appropriate soil phosphorus content. However:

- Dairy farms in the Lower Hay, Upper Hay and Upper Denmark catchments had area-weighted fertility index values of 0.7 to 0.9 (Figure 7.25) and made up nearly 70% of the dairy farm area that was tested. These dairy farms may manage some paddocks to a lower productivity level (~85 to 90%). If these paddocks were managed to achieve a greater target productivity, then they would need to apply additional phosphorus and would ultimately have greater phosphorus loss.

  - The dairy farming area in the Lower Hay catchment had some paddocks with fertility index values of 1.1 to 8.2. While some paddocks appeared to be used to irrigate dairy effluent, most would likely benefit from careful fertiliser management.

- Dairy farms in the Lower Denmark, Scotsdale and Sunny Glen Creek catchments had fertility index values of 1.3 to 1.5. These farms would benefit from improved fertiliser management.
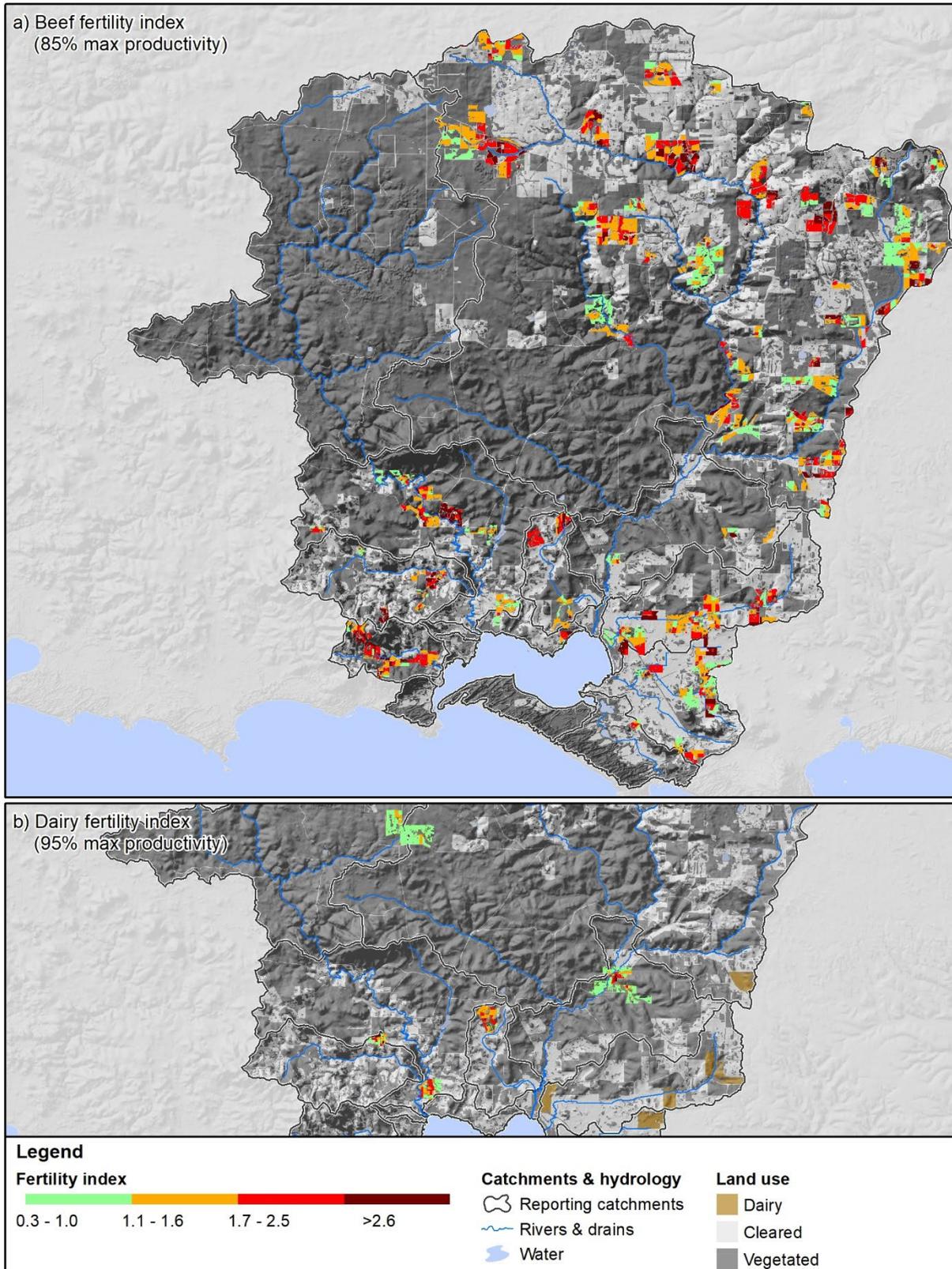
Figure 7.24: Fertility index of beef and dairy farms from soil-testing programs (2009–20)
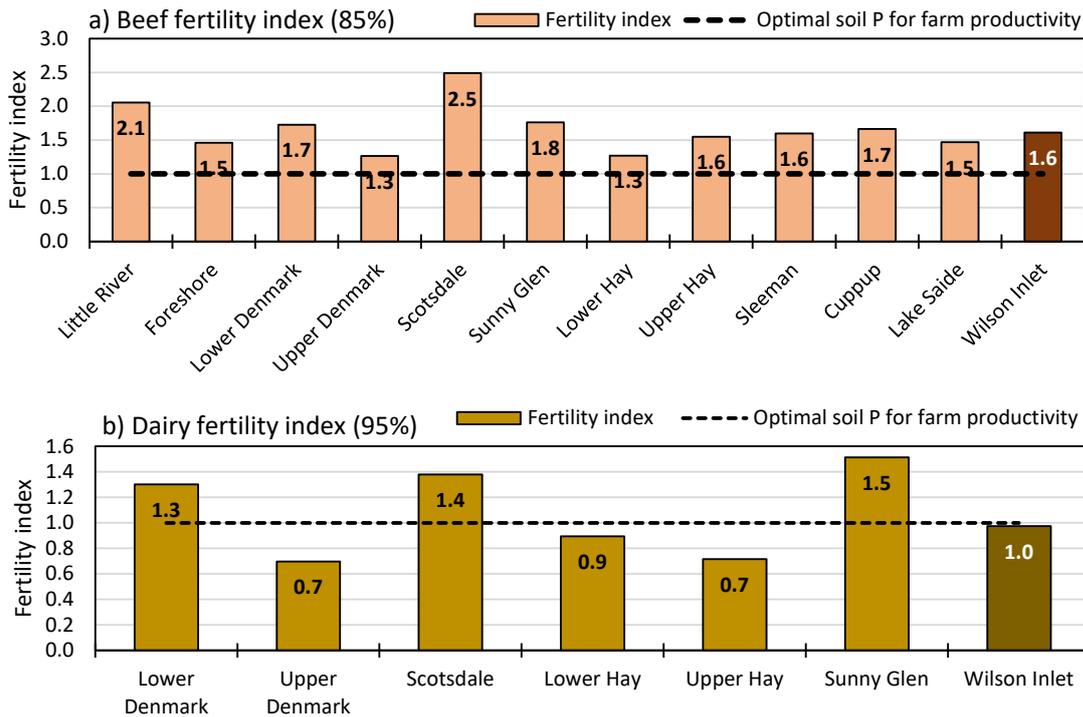
Figure 7.25: Area-weighted fertility index of beef and dairy farms from soil-testing programs (2009–20)

The potential effect of soil-testing programs on phosphorus loss

Table 7.14 gives the estimated phosphorus load reductions from the REI-funded soil-testing program (2016–20) and all soil-testing programs from 2009–20.

The REI-funded soil-testing program tested 23% of all beef and dairy farms in the Wilson Inlet catchment. If these farms continued to use best-practice fertiliser management practices in the long term, then phosphorus loss to the inlet could be reduced by 4.3% (0.4 tonnes/yr). All government-funded programs (2009–20) tested 31% of the beef and dairy farms in the Wilson Inlet catchment and could potentially reduce phosphorus loss to the inlet by 6.2% (0.5 tonnes/yr) if these management practices were adopted in the long term.

Table 7.14: Potential average annual phosphorus load reductions that could result from the REI-funded soil-testing program and all soil-testing programs from 2009–20, if participating farmers adopted best-practice fertiliser management

Reporting catchment	Basecase			REI soil testing (2016–20)				All soil testing programs 2009–20 (including REI)			
	Area		Current P load	Area tested		Load change		Area tested		Load change	
	Beef & dairy	Total									
	(km²)	(km²)	(t/yr)	(km²)	(%)¥	(t/yr)	(%)*	(km²)	(%)¥	(t/yr)	(%)*
Ocean Beach Road	1.6	10	0.23	-	-	-	-	-	-	-	-
Little River	12	32	0.53	5.4	45	-0.06	-11	6.3	52	-0.07	-13
Koorabup Creek	0.3	3.7	0.13	-	-	-	-	-	-	-	-
Lower Denmark River	31	160	0.21	7	22	-0.02	-11	11	37	-0.03	-13
Upper Denmark River	17	444	0.14	3.7	21	0.00	0.6	3.7	21	0.00	0.6
Scotsdale Brook	29	66	0.49	3.1	11	-0.01	-3.0	4.2	14	-0.02	-4.0
Foreshore	4.9	20	0.20	1.2	24	-0.01	-2.8	1.2	24	-0.01	-2.8
Sunny Glen Creek	16	36	0.69	1.2	7	-0.01	-1.6	6.3	38	-0.07	-11
Lower Hay River	28	122	0.56	7.1	26	-0.01	-1.9	7.1	26	-0.01	-1.9
Upper Hay River	333	1122	0.47	85	26	-0.03	-7	114	34	-0.04	-9
Sleeman River	50	94	2.1	13	25	-0.14	-7	13	26	-0.15	-7
Cuppup Creek	47	69	2.8	6	14	-0.08	-2.8	12	25	-0.14	-5.1
Lake Saide	8.4	39	0.09	0.7	7.9	-0.01	-6.0	0.7	7.9	-0.01	-6.0
Nullaki	1.0	23	0.09	-	-	-	-	-	-	-	-
Wilson Inlet	580	2241	8.7	133	23	-0.4	-4.4	180	31	-0.5	-6.3

¥ Percent of beef and dairy area

* Percent of basecase P load from all land uses

All farmers adopting best-practice fertiliser management

Table 7.15 gives the estimated phosphorus load reduction from 100% adoption of best-practice farm fertiliser management.

Phosphorus loads to Wilson Inlet could be reduced by 22% (1.9 tonnes) if all beef and dairy farms adopted best-practice fertiliser management practices in the long term (see Figure 7.26). About 69% of the load reduction to the inlet in this scenario came from the Cuppup (31%), Sleeman (26%) and Sunny Glen Creek (12%) catchments.

The phosphorus load target was not met for the entire Wilson Inlet catchment or any reporting catchments requiring a reduction in phosphorus load. Five catchments that met basecase target phosphorus loads had further load reductions: Little River, Lower Denmark River, Scotsdale Brook, Foreshore and Upper Hay River.
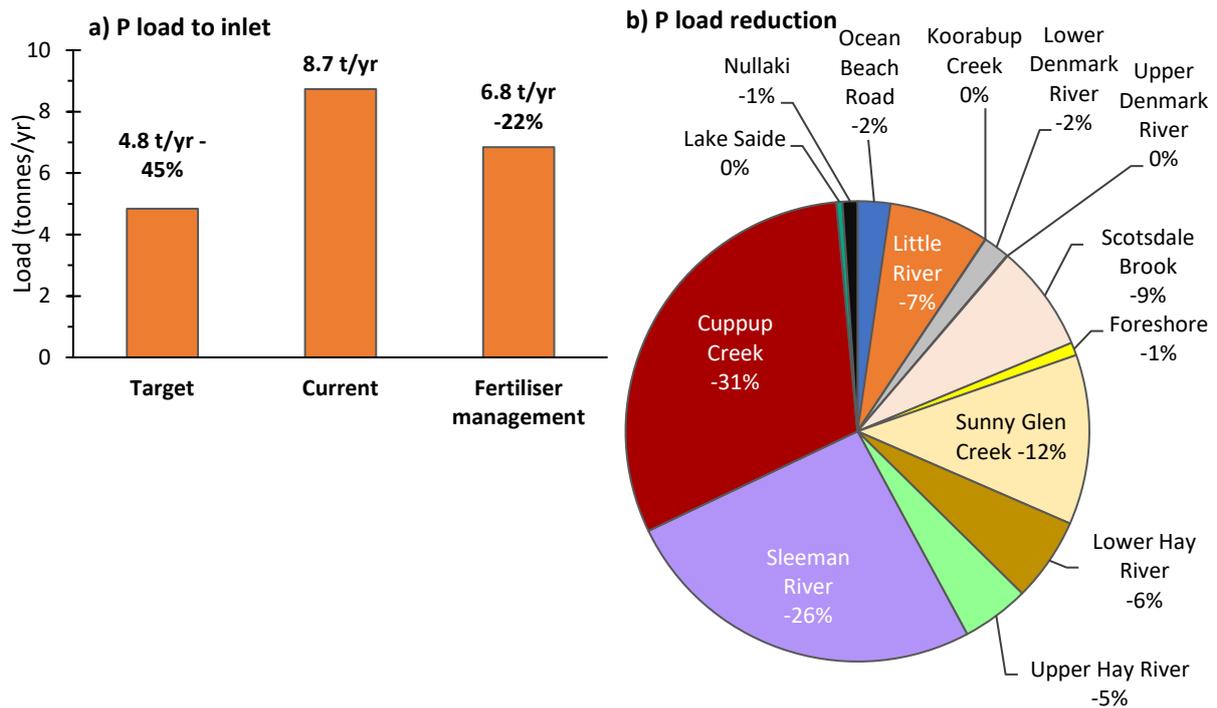
Figure 7.26: Average annual a) phosphorus load to the Wilson Inlet and b) proportion of phosphorus load reduction by reporting catchment for the best-practice fertiliser management scenario

Table 7.15: Average annual phosphorus loads for the basecase and 100% adoption of fertiliser management scenario on beef and dairy farms.

Reporting catchment	Basecase Load to Inlet (t/yr)	Target Load to Inlet (t/yr)	Fertiliser management (traditional fertilisers)			
			Load to Inlet (t/yr)	Difference from basecase (t/yr)	(%)	Reduction to meet load target (%)
Ocean Beach Road	0.23	0.12	0.19	-0.04	-19%	36%
Little River	0.53	0.53	0.39	-0.13	-25%	-34% *
Koorabup Creek	0.13	0.10	0.13	<0.001	0%	22%
Lower Denmark River	0.20	0.20	0.17	-0.03	-17%	-21% *
Upper Denmark River	0.14	0.09	0.14	0.00	1%	34%
Scotsdale Brook	0.49	0.49	0.35	-0.14	-29%	-41% *
Foreshore	0.20	0.20	0.18	-0.02	-9%	-9% *
Sunny Glen Creek	0.69	0.21	0.46	-0.22	-33%	54%
Lower Hay River	0.56	0.43	0.45	-0.11	-20%	5%
Upper Hay River	0.47	0.38	0.38	-0.09	-19%	1%
Sleeman River	2.1	0.9	1.6	-0.49	-23%	43%
Cuppup Creek	2.8	1.0	2.2	-0.58	-21%	54%
Lake Saide	0.09	0.09	0.09	-0.01	-8%	-9% *
Nullaki	0.09	0.05	0.07	-0.02	-21%	27%
Wilson Inlet	**8.7**	**4.8**	**6.8**	**-1.9**	**-22%**	**29%**

* Load target met in basecase

7.3.3 Low-water-soluble phosphorus fertilisers

Single superphosphate is the most common type of phosphorus fertiliser used by grazing agriculture in south-west Western Australia. About 80% of the phosphorus in single superphosphate fertiliser is water soluble and susceptible to leaching when used on sandy soils with low PRI. The use of highly water-soluble phosphorus fertilisers in agriculture has long been identified as an environmental issue. Bradby (1996) noted that a farmer first raised concerns in 1918 about the use of highly soluble fertilisers and phosphorus leaching to waterways and the Peel-Harvey estuary.

Several low-water-soluble phosphorus (LWSP) fertilisers have been trialled in Western Australia since the 1980s, including trials undertaken in Denmark (Bolland et al. 1995). The water solubility of the fertilisers used in the trials before the last decade were typically 0 to 40%, compared with 77% for single superphosphate. However, during the past decade, two local studies (Maddern 2016; Hall 2023) have tested LWSP fertilisers with a solubility of about 50% (Table 7.16). Importantly, the studies by Hall (2023) showed the commercial LWSP fertiliser tested did not have lower phosphorus leaching than traditional phosphorus fertilisers. This indicates the need for further work to develop a slow-release product that substantially reduces phosphorus leaching without compromising pasture yield and other factors (e.g. cost-effectiveness, safety of handling and storage). Furthermore, the leaching of LWSP fertilisers needs to be adequately tested using sound experimental methods. Hence standardised tests and criteria need to be developed for assessing and verifying whether a slow-release phosphorus fertiliser meets these requirements.

Past LWSP fertiliser blends (~27% soluble) were found to have similar pasture yields to single superphosphate (Bolland et al. 1995). However, laboratory tests demonstrated that the overuse of LWSP fertiliser could result in greater phosphorus leaching in the long-term because of the accumulation (and subsequent leaching) of LWSP material in the soil (Ritchie et al. 1985; Ritchie & Weaver 1993). Hence, even if a LWSP fertiliser is found to have substantially lower phosphorus leaching than single superphosphate in the short term, in the long term its overuse poses an environmental risk. As such, the use of LWSP fertiliser will only decrease phosphorus loss if paired with a sound fertiliser management program.

Photo: Slow-release fertiliser, gutless sandy soils and inundated farmland

A review of relevant scientific literature on LWSP fertilisers is given in [Appendix E](#) of Hennig et al. (2021).

Table 7.16: Phosphorus content and water solubility of single superphosphate and LWSP fertilisers

Product	Phosphorus content	Water solubility
	(%)	(%)
Single superphosphate	8.8	77
Lime Reverted Super	7.0	39
CSBP 'coastal super' (Mk I)	7.2	6
CSBP 'coastal super' (Mk II)	9.0	27
Agmin	4.5	17
'Red mud' coated superphosphate	7.1	39
Reactive phosphate rock	10–18	0
Super SR extra*	8.3	51

Note:

*Data taken from Maddern 2016.

All other data was taken from the Fertiliser Action Plan (2007)

Implementation

For this scenario we used the same modelling approach as the best-practice fertiliser management scenario, except that LWSP fertilisers were applied to low-PRI soils. We applied LWSP fertilisers at the same rate as the previous scenario, made up of a blend of reactive phosphate rock (about 60% of P) and single superphosphate (about 40% of P). On high-PRI soils, the modelling and results were identical to the previous scenario. See Appendix E for further information on the modelling approach.

Results

Table 7.19 gives the estimated phosphorus load reduction from 100% adoption of best-practice fertiliser management with LWSP fertilisers applied to low-PRI soils.

Phosphorus loads to Wilson Inlet were reduced by 24% (2.1 tonnes) because of best-practice fertiliser management using LWSP fertilisers on low-PRI soils (see Figure 7.27). This is a further 2% reduction from the previous scenario where traditional fertilisers were used (see Section 7.3.2). About 69% of the load reduction in this scenario came from the Cuppup (28% of load reduction to the inlet), Sleeman (28%) and Sunny Glen Creek (13%) catchments.

The phosphorus load target for Wilson Inlet was not achieved in this scenario. However, phosphorus loads in the Upper and Lower Hay catchments were reduced below their targets. As with the previous scenario, the same five reporting catchments that met target phosphorus load targets in the basecase had phosphorus loads reduced below their targets (Little River, Lower Denmark River, Scotsdale Brook, Foreshore and the Upper Hay River).
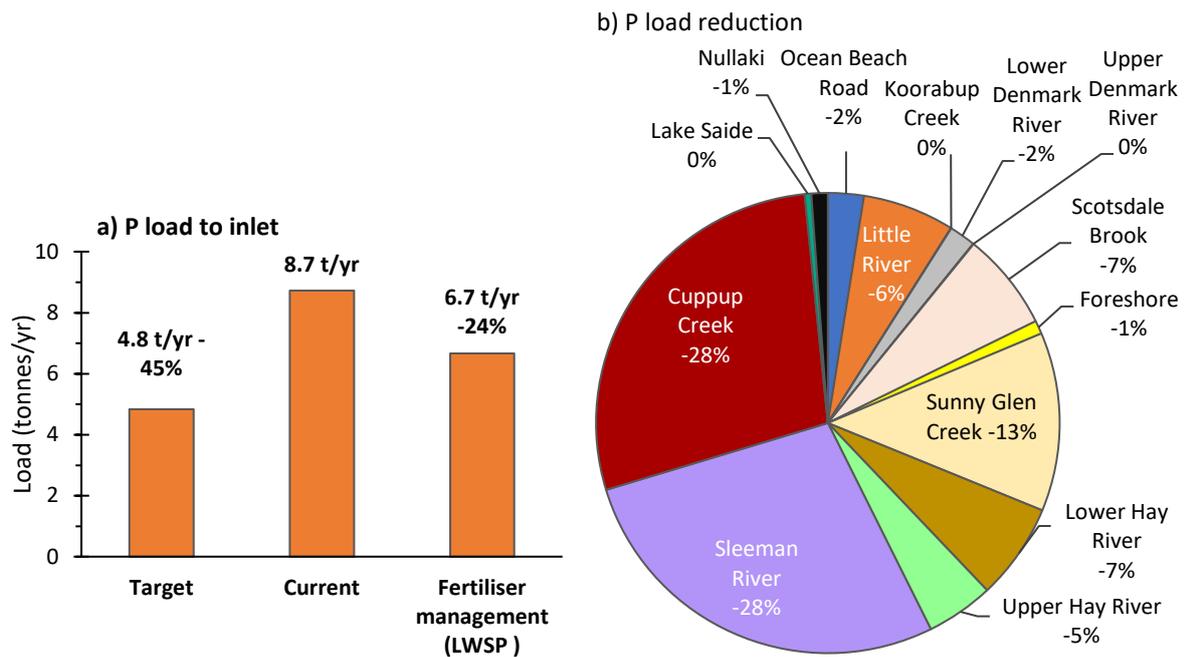
Figure 7.27: Average annual a) phosphorus load to Wilson Inlet and b) proportion of phosphorus load reduction by reporting catchment for the LWSP fertiliser scenario

Table 7.17: Phosphorus loads for the basecase and the LWSP fertiliser scenario

Reporting catchment	Low PRI beef & dairy area	Basecase	Target	Fertiliser management using LWSP fertilisers		
				Load	Difference		Reduction to meet load target
	Load	Load	Load			
	km²	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(%)	(%)
Ocean Beach Road	2	0.23	0.12	0.18	-0.05	-22%	33%
Little River	12	0.53	0.53	0.39	-0.13	-25%	-34% *
Koorabup Creek	0.3	0.13	0.10	0.13	<0.001	0%	22%
Lower Denmark River	31	0.20	0.20	0.16	-0.04	-19%	-23% *
Upper Denmark River	17	0.14	0.09	0.14	<0.001	-1%	33%
Scotsdale Brook	29	0.49	0.49	0.35	-0.14	-29%	-41% *
Foreshore	5	0.20	0.20	0.18	-0.02	-10%	-11% *
Sunny Glen Creek	16	0.69	0.21	0.43	-0.26	-38%	51%
Lower Hay River	28	0.56	0.43	0.42	-0.14	-25%	**-1%**
Upper Hay River	333	0.47	0.38	0.37	-0.10	-21%	**-1%**
Sleeman River	50	2.1	0.9	1.5	-0.57	-27%	40%
Cuppup Creek	47	2.8	1.0	2.2	-0.58	-21%	54%
Lake Saide	8	0.09	0.09	0.08	-0.01	-10%	-11% *
Nullaki	1	0.09	0.05	0.07	-0.02	-26%	23%
Wilson Inlet	**580**	**8.7**	**4.8**	**6.7**	**-2.1**	**-24%**	**27%**

* Load target met in basecase

7.3.4 Dairy effluent management

This scenario estimates the nutrient reduction to Wilson Inlet from improved dairy effluent management.

Dairy farming has a long history in the Denmark area and continues to be important to the region. Although most of the milk produced in the catchment is sold elsewhere, Denmark is known for its artisanal cheeses. At present there are nine dairy farms and eight dairy sheds in the Wilson Inlet catchment. One dairy farm has its dairy milking shed in the Torbay catchment but its dairy paddocks are in the Lower Hay catchment. All dairy farms are understood to be family run, except for the Denmark Agricultural College, which has a milking operation as part of its program.

Dairy effluent is generated daily through animal wastes, washdown and cleaning of the machinery used during the milking process. Considerable volumes of effluent are produced, which contain large concentrations of nutrients. Thus, dairy effluent is both an agronomically valuable source of fertiliser and a high risk to waterways if managed poorly.

Dairy effluent management includes the collection, conveyance, storage, treatment and reuse of solid and liquid wastes (Dairy Australia 2008). The new *Code of practice for dairy farm effluent management WA* (the code) was released in 2021 (Western Dairy 2021a). It sets the minimum industry standards and associated management actions for dairies to have acceptable social and environmental impacts. The code also provides guidelines on the siting, design and construction of new dairy sheds. Industry compliance is also supported by a nationally recognised training unit: RTE5301A Design Effluent Systems.

Photo: Dairy effluent upgrades in the Wilson Inlet catchment (Western Dairy 2020)

Compared with the previous code of practice (Western Dairy 2012), the new code is more comprehensive. There are four new standards with detailed management recommendations given for each standard. The industry standards for the 2021 code are:

- **1 Water use efficiency:** Water use is minimised and stormwater managed to reduce the volume of effluent generated.

- **2A Solid separation:** Solids in effluent are managed to optimise handling and reuse.

- **2B Solid storage (new standard):** Solids are stored in a manner that does not impact on ground or surface waters.

- **3 Laneways and crossings (new standard):** Effluent that concentrates on roads, underpasses, laneways and bridges is managed to minimise impacts on the environment and other users.

- **4A Effluent storage:** Effluent is stored in a manner that minimises impact to surface and groundwater, and people.

- **4B Effluent storage in wet periods (new standard):** Effluent is stored over periods when soils are saturated and/or precipitation exceeds evaporation.

- **5 Reuse of effluent:** Dairy effluent is reused to optimise nutrients and minimise offsite impacts.

- **6 Effluent management plan (new standard):** Western Australian dairy farms have a current effluent management plan.

- **7 Monitoring, maintenance and record keeping:** Dairy effluent systems are monitored and maintained in good working order and records kept of key management practices.

Environmental codes of practice and environmental guidelines exist in other Australian states (e.g. NSW DPI 2008) and internationally (see Dairy NZ https://www.dairynz.co.nz/).
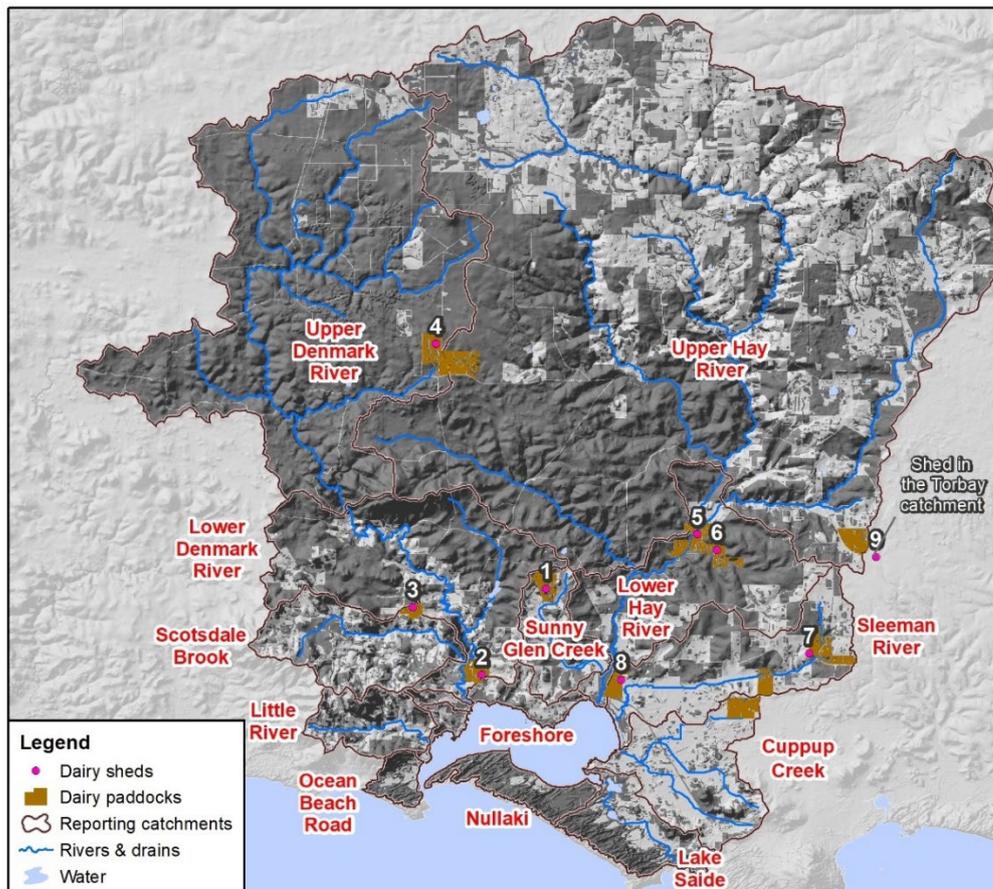
Figure 7.28: Dairy farm sheds and paddocks

Existing dairy effluent management practices

Three dairy farms have been surveyed about their effluent management practices in relation to the 2012 and/or 2021 code of practice (Table 7.18). Farm B met all aspects of the 2012 code except for solid separation. This farm was not surveyed again in 2021.

Two dairy farms (A and C) had similar results, with pond storage, effluent application, water efficiency and maintenance not meeting the 2012 code. When assessed against the 2021 code, both farms showed improvements. Farm A was meeting all aspects of the 2021 code except for 2b solids storage which was partially met (a new standard that was not part of the 2012 code). This farm received funding as part of the REI to improve effluent storage and hence met these aspects of the code, as well as effluent reuse. Farm C also partially met standard 2B solid separation but continued not to meet standards relating to effluent storage and reuse, which are a costly investment for small family-run businesses. After implementing REI funded water-use efficiency upgrades, this farm met the water efficiency standard in the 2021 code.

Surveys elsewhere in south-west Western Australia have shown that most dairy farms are not yet meeting all aspects of the code, though they found considerable improvements in 2021 compared with 2012 (Western Dairy 2021b). Therefore, it is reasonable to assume the dairy farms not surveyed would have had similar review results during the modelling period.

Table 7.18: Results of a survey of dairy farm adherence to the 2021 code of practice for farms in or adjacent to the Wilson Inlet catchment

2021 code of practice industry standard	Farm A		Farm B	Farm C	
	Survey: Pre-upgrade (2012 code)	Survey: Post-upgrade (2021 code)	Survey (2012 code)	Survey: Pre-upgrade (2012 code)	Survey: Post-upgrade (2021 code)
1. Water use efficiency	Medium	High	High	Medium	High
2A. Solid separation	High	High	Medium	High	High
2B. Solids storage	Not part of the 2012 code	Medium	Not part of the 2012 code	Not part of the 2012 code	Medium
3. Laneways & crossings	Not part of the 2012 code	High	Not part of the 2012 code	Not part of the 2012 code	High
4A. Effluent storage	Medium	High	High	Low	Low
4B. Effluent is stored in wet periods (soils are saturated with water and/or precipitation exceeds evaporation)	Not part of the 2012 code	High	Not part of the 2012 code	Not part of the 2012 code	Low
5. Reuse of effluent	Low	High	High	Low	Low
6. Effluent management plan	Not part of the 2012 code	High	Not part of the 2012 code	Not part of the 2012 code	High
7. Monitoring, maintenance & record keeping	Medium	High	High	Medium	High
REI funded upgrade	Effluent storage		None	Water use efficiency	

Assessment score

High: Meets industry standards

Medium: Partially meets industry standards

Low: Does not meet industry standards

Implementation

Ideally, we would be able to use Overseer or similar models to estimate the effect of improved dairy management practices. Overseer has a range of options for dairy effluent disposal but all assume good effluent management practices. This prevents modelling the effect of:

- dairy effluent being discharged directly to streams

- ineffective or leaking wastewater ponds

- the over-irrigation of nutrient-rich wastewater.

As such, for this scenario we relied on a review of the relevant literature and made assumptions about the efficacy of improved dairy effluent management based on the following findings:

- A literature review by Ecotones & Associates (2005) for the Peel-Harvey SSPRED model cited nutrient load reductions of 4 to 95% based on various animal industry wastewater pond intervention studies.

- The Leschenault Estuary WQIP estimated that best-practice effluent management would reduce nutrient exports from dairy sheds by 60% (Hugues-dit-Ciles et al. 2012).

- A literature review by Haine et al. (2011) found that effluent treatment ponds resulted in nutrient reductions of 0 to 73% for nitrogen and 14% for phosphorus. However, when coupled with land application, dairy effluent loads could be reduced by 90% for nitrogen and 98% for phosphorus.

On average, improved dairy effluent management is expected to reduce **dairy shed nitrogen and phosphorus exports by 60%.** Dairy sheds contribute 12% (6–32%) of all dairy farm nitrogen emissions and 8% (3–49%) of all dairy farm phosphorus emissions (Table 7.19). This scenario assumes improved dairy effluent management in all eight dairy sheds located within the Wilson Inlet catchment.

Table 7.19: Average annual (2010–19) nutrient contribution of dairy sheds as a percent of total dairy nutrient load (sheds + paddocks) and catchment nutrient load

| Reporting catchment | Dairies | Dairy shed N load | | Dairy shed P load | |
| | | % of total dairy load | % of catchment load | % of total dairy load | % of catchment load |
	(#)	(%)	(%)	(%)	(%)
Ocean Beach Road	-	-	-	-	-
Little River	-	-	-	-	-
Koorabup Creek	-	-	-	-	-
Lower Denmark River	1	9	0.8	16	2.1
Upper Denmark River	1	32	4.7	49	11.0
Scotsdale Brook	1	18	0.9	25	1.5
Foreshore	-	-	-	-	-
Sunny Glen Creek	1	28	5.8	13	2.6
Lower Hay River	2	19	3.3	16	2.2
Upper Hay River	-	-	-	-	-
Sleeman River	2	6	1.7	3	1.0
Cuppup Creek	-	-	-	-	-
Lake Saide	-	-	-	-	-
Nullaki	-	-	-	-	-
Wilson Inlet	8	12	1.0	8	0.9

Results

Improved dairy effluent management with 100% adoption has the potential to decrease nutrient loads to Wilson Inlet by 0.2% (see Figure 7.29, Table 7.20 and Table 7.21). This corresponds to a nitrogen load reduction of 0.3 tonnes and a phosphorus load reduction of 0.02 tonnes.

Dairy farming in the Wilson Inlet catchment is less prevalent than in some other catchments. For example, the Wilson Inlet catchment has eight dairy farms with about 2,000 dairy cattle, whereas the Geographe catchment has 36 dairy farms with a total of 15,120 dairy cattle. Dairy effluent management nevertheless provides benefits at the local scale and will contribute to overall nutrient load reduction to Wilson Inlet.
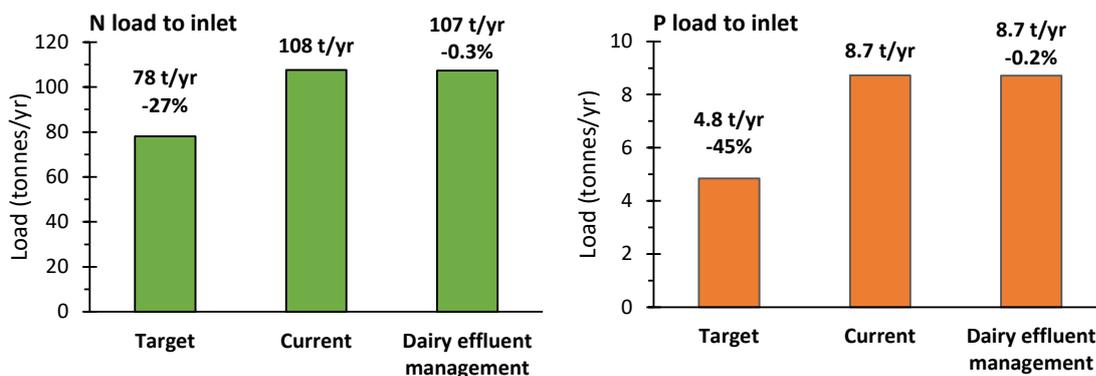
Figure 7.29: Average annual nutrient loads to Wilson Inlet from dairy effluent management

Table 7.20: Average annual nitrogen loads for the basecase and the dairy shed effluent management scenario

Reporting catchment	Dairies	Dairy shed N load	Dairy paddock N load	Total dairy N load	Catchment N load	Catchment N load	Load change	
		Basecase				Dairy effluent management: 100% adoption		
	(#)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(%)
Ocean Beach Road	-	-	-	-	2.6	2.6	-	-
Little River	-	-	-	-	6.2	6.2	-	-
Koorabup Creek	-	-	-	-	2.1	2.1	-	-
Lower Denmark River	1	0.06	0.54	0.60	7.5	7.5	-0.04	-0.5
Upper Denmark River	1	0.22	0.45	0.67	4.6	4.6	-0.04	-0.9
Scotsdale Brook	1	0.10	0.47	0.58	12	12	-0.02	-0.2
Foreshore	-	-	0.01	0.01	3.9	3.9	-	-
Sunny Glen Creek	1	0.25	0.65	0.90	4.4	4.3	-0.06	-1.5
Lower Hay River	2	0.18	0.74	0.91	5.4	5.3	-0.04	-0.7
Upper Hay River	-	-	0.78	0.78	21	21	-	-
Sleeman River	2	0.28	2.6	2.9	16	16	-0.06	-0.3
Cuppup Creek	-	-	1.5	1.5	19	19	-	-
Lake Saide	-	-	-	-	2.9	2.9	-	-
Nullaki	-	-	-	-	0.6	0.6	-	-
Wilson Inlet	8	1.1	7.8	8.8	**108**	**107**	-0.26	-0.2

Table 7.21: Average annual phosphorus loads for the basecase and the dairy shed effluent management scenario

Reporting catchment	Dairies	Dairy shed P load	Dairy paddock P load	Total dairy P load	Catchment P load	Catchment P load	Load change	
		Basecase				Dairy effluent management: 100% adoption		
	(#)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(%)
Ocean Beach Road	-	-	-	-	0.23	0.23	-	-
Little River	-	-	-	-	0.53	0.53	-	-
Koorabup Creek	-	-	-	-	0.13	0.13	-	-
Lower Denmark River	1	0.00	0.02	0.02	0.20	0.20	-0.003	-1.4
Upper Denmark River	1	0.02	0.02	0.03	0.14	0.14	-0.003	-2.2
Scotsdale Brook	1	0.01	0.02	0.03	0.49	0.49	-0.001	-0.3
Foreshore	-	-	0.00	0.00	0.20	0.20	-	-
Sunny Glen Creek	1	0.02	0.12	0.14	0.69	0.68	-0.005	-0.7
Lower Hay River	2	0.01	0.07	0.08	0.56	0.56	-0.003	-0.4
Upper Hay River	-	-	0.01	0.01	0.47	0.47	-	-
Sleeman River	2	0.02	0.42	0.44	2.1	2.1	-0.004	-0.2
Cuppup Creek	-	-	0.24	0.24	2.8	2.8	-	-
Lake Saide	-	-	-	-	0.09	0.09	-	-
Nullaki	-	-	-	-	0.09	0.09	-	-
Wilson Inlet	8	0.08	0.92	0.99	**8.7**	**8.7**	-0.018	-0.2

7.3.5   Soil amendments

Soil-amendment products improve plant growth by improving soil structure, soil water-holding capacity and/or nutrient retention. This scenario models the use of soil amendments that hold phosphorus – keeping it within the soil available for plant growth instead of leaching to ground and surface waters. Combined with good fertiliser management, soil amendments can reduce phosphorus loss, and some also have the potential to improve pasture yields.

Traditionally, the use of soil amendments for nutrient management has focused on the use of inexpensive mining by-products, such as Red Sands™, Alkaloam® and Iron Man Gypsum (IMG). See Hennig et al. (2021) for a summary of the studies supporting use of these materials.

Unfortunately, stockpiles of these materials are in Pinjarra, Wagerup and Capel. Transport from these stockpiles (>300 km) would likely make the use of these materials cost prohibitive. However, reworked onsite clays (i.e. mixing subsoil clays with sandy topsoils) and bentonite have been demonstrated by Summers et al. (2019) to reduce phosphorus loss from broadscale agriculture and annual horticulture respectively.

The effect of reworking subsoil clays into sandy topsoils was measured in glasshouse conditions. Clay was added to increase topsoil clay content from a baseline of 2.9% clay to 5.5%, 8.8%, 10.7% and 13.6%. Adding clay to achieve 8.8% clay content was found to:

- increase PRI from 0 to ~5 and phosphorus buffering index (PBI) from 5 to ~17

- require more phosphorus application to achieve the same pasture yield

- decrease the phosphate concentration in soil solution by 89%.

The few lithology logs in the sandy areas of the Wilson Inlet catchment suggest that sands can be at least 1 m deep. Some farmers have the necessary machinery to extract, spread and incorporate clays onto their paddocks or can hire contractors to undertake the task. Therefore the 'mining' of subsurface clays is plausible and being trialled on a farm in the Wilson Inlet catchment by Western Dairy. For areas where subsurface clays are closer to the surface, methods such as spading and mouldboard ploughing can invert and mix soils up to about 0.35 m below the surface.

Farmers likely already know the distribution of subsurface clays on their properties. Testing subsurface clays is necessary to determine favourable and unfavourable soil properties; the latter includes the presence of subsurface sodicity, acidity and potentially toxic subsurface minerals, as well as heavy clays that clump and are not easily mixed.

There is a need for further research on the effectiveness of reworking subsoil clays from both an agronomic and environmental perspective (reduced phosphorus leaching). Sourcing 'commercial' clays such as bentonite are another alternative to mining or reworking subsurface clays. In the Peel-Harvey catchment, bentonite clay applications at a horticultural farm were found to reduce phosphorus leaching by 68% compared with the untreated portion of the farm (Summers et al. 2019). Bentonite clay is a commonly used soil amendment but is prohibitively expensive for broadscale agriculture. Its use would be limited to more intensive operations such as annual horticulture.

Implementation

We assumed that all areas of low-PRI beef, dairy, annual horticulture and potato farming were amended to improve soil phosphorus retention through:

- using 20 tonnes/ha of IMG, Alkaloam® or bentonite clay

- increasing clay content in the topsoil so that soil PRI increased by 5 (approximate clay content of 8% and resulting PRI of 5 to 12).

We assumed that soil amendments reduced phosphorus loads from low-PRI soils by 60%, based on a review of relevant literature by Hennig et al. (2021). We also assumed nitrogen would be unaffected by soil amendments.

Results

Figure 7.30 and Table 7.22 give the potential phosphorus loads reaching Wilson Inlet after treatment of 8,690 ha of low-PRI soils with agricultural soil amendments. If all beef, dairy, annual horticulture and potato farms were amended, this could reduce phosphorus loads by about 1.8 tonnes (21% reduction). Nearly half (46%) of the phosphorus removed from this scenario was from the Sleeman catchment and a large proportion was from the Sunny Glen Creek (19%) and Lower Hay (16%) catchments. This scenario achieved catchment phosphorus targets in the Lower Hay and Nullaki catchments.
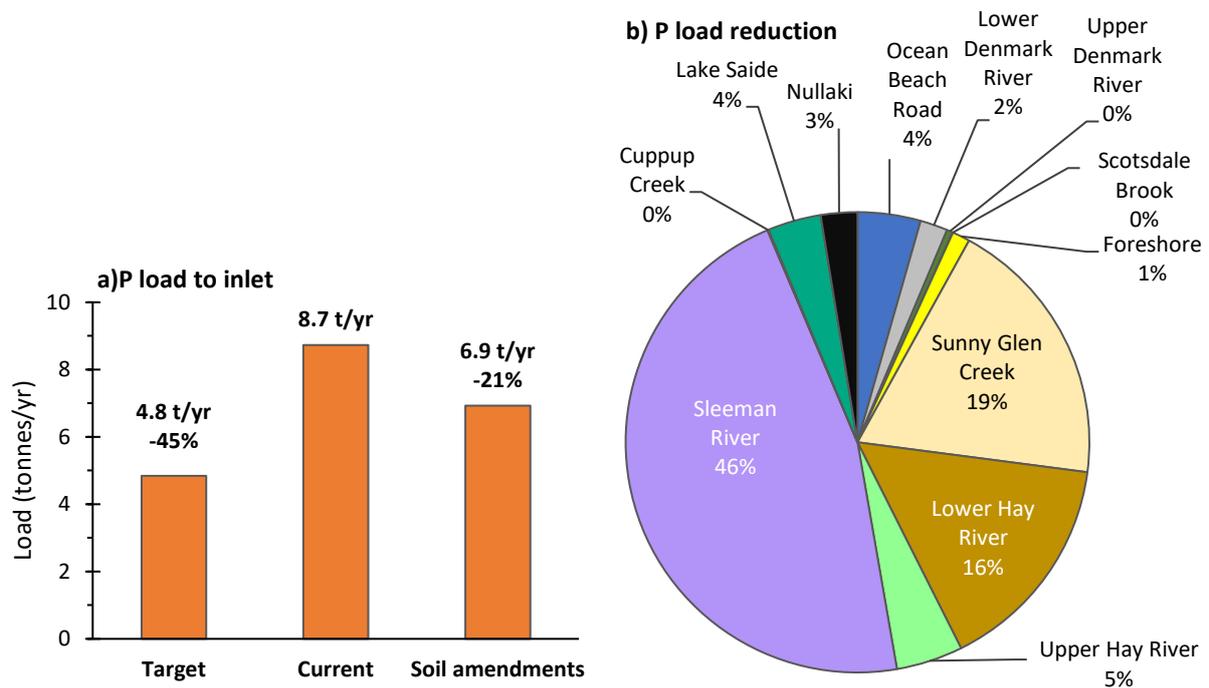
Figure 7.30: Average annual a) phosphorus load to Wilson Inlet and b) proportion of phosphorus load reduction by reporting catchment for the soil amendment scenario

Table 7.22: Average annual phosphorus loads for the basecase and soil amendment scenarios by land-use category and reporting catchment

Reporting catchment	Area							Base case	Soil amendment								Target	
	All land uses	Scenario land uses		Low PRI beef & dairy		Low PRI horticulture & potato farms		Total P load to inlet	Total P load to inlet	Load change			Load change: Low PRI beef & dairy		Load change: Low PRI horticulture & potato farms		P target	Comment
	(ha)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(t/yr)	(t/yr)	(t/yr)	(%)	(% WI)	(t/yr)	(%*)	(t/yr)	(%*)	(t/yr)	
Ocean Beach Road	1 263	115	9%	115	9%	-	-	0.23	0.15	0.08	-35%	4%	0.08	100%	-	-	0.12	*Further reduction required*
Little River	3 449	-	-	-	-	-	-	0.53	0.53	-	-	-	-	-	-	-	0.53	*Current loads acceptable*
Koorabup Creek	510	-	-	-	-	-	-	0.13	0.13	-	-	-	-	-	-	-	0.10	*No change*
Lower Denmark River	16 272	222	1%	221	1%	1	0.01%	0.20	0.17	0.03	-17%	2%	0.03	94%	0.00	6%	0.20	*Current loads acceptable*
Upper Denmark River	44 405	86	0%	86	0%	-	-	0.14	0.13	0.01	-5%	0%	0.01	100%	-	-	0.09	*Further reduction required*
Scotsdale Brook	6 726	1	0%	1	0%	-	-	0.49	0.49	0.001	-0.1%	0%	0.00	100%	-	-	0.49	*Current loads acceptable*
Foreshore	2 675	118	4%	118	4%	-	-	0.20	0.18	0.02	-11%	1%	0.02	100%	-	-	0.20	*Current loads acceptable*
Sunny Glen Creek	3 583	1 192	33%	1 192	33%	-	-	0.69	0.34	0.34	-50%	19%	0.34	100%	-	-	0.21	*Further reduction required*
Lower Hay River	12 167	1 563	13%	1 551	13%	11	0.09%	0.56	0.28	0.28	-50%	16%	0.24	87%	0.04	13%	0.43	**Target met**
Upper Hay River	112 508	3 437	3%	3 437	3%	-	-	0.47	0.39	0.08	-18%	5%	0.08	100%	-	-	0.38	*Further reduction required*
Sleeman River	9 440	1 750	19%	1 730	18%	21	0.22%	2.10	1.26	0.84	-40%	46%	0.75	89%	0.09	11%	0.92	*Further reduction required*
Cuppup Creek	7 008	1	0%	1	0%	-	-	2.80	2.80	0.00	-0.1%	0%	0.00	100%	-	-	1.02	*Further reduction required*
Lake Saide	4 014	107	3%	99	2%	8	0.19%	0.09	0.03	0.07	-72%	4%	0.04	53%	0.03	47%	0.09	*Current loads acceptable*
Nullaki	2 369	98	4%	97	4%	1	0.05%	0.09	0.05	0.05	-50%	3%	0.04	82%	0.01	18%	0.05	**Target met**
Wilson Inlet	**226 390**	**8 690**	**4%**	**8 648**	**4%**	**42**	**0.02%**	**8.73**	**6.92**	**1.80**	**-21%**	**100%**	**1.64**	**91%**	**0.17**	**9%**	**4.84**	*Further reduction required*

Note:

All percentages are given as the proportion of reporting catchment area or load change except where indicated:

% WI - gives the proportion of reporting catchment load change to total load change for the Wilson Inlet catchment,

%* - gives the proportion of the load change by land use

7.3.6 Onsite wastewater disposal (septic tanks)

In this section we identify unsewered areas to be considered for future infill sewerage initiatives (see Figure 7.31 and Table 7.23). Infill sewerage involves the connection of unsewered properties to reticulated sewerage to reduce impacts on human health and/or the environment from septic tanks.

When considering unsewered areas, we used the 'septic tanks' that were mapped and modelled in this study, their density (lot size) and modelled nutrient contributions to Wilson Inlet. We also took into account recent seagrass surveys in Wilson Inlet adjacent to Inlet Drive – this area generally had no seagrass or a greater proportion of epiphytes (Bennett et al. 2021). Epiphytes are typically macroalgae that grow on seagrass (and other surfaces) when there is an abundance of nutrients, which can lead to seagrass mortality. While the observations of Bennett et al. (2021) cannot be conclusively linked to septic tank impacts, it demonstrates that this region of the inlet is showing signs of excess nutrients.

We decided not to include the 47 unsewered lots east of the Denmark River. The potential difficulty and expense associated with installing or upgrading the sewerage lines that cross this area is unlikely to be prioritised for infill sewerage given the small number of lots relative to the likely cost and difficulty of upgrades. In addition, we did not consider recent unsewered developments as older onsite systems pose the highest risk of leaching.

The Denmark WWTP also discharges treated wastewater to Wilson Inlet, so the connection of unsewered properties to reticulated sewerage will still result in some amount of nutrient contribution to the inlet. We accounted for this in equation 4 when calculating the mass of nutrient removed (i.e. does not reach the inlet) when a septic tank is removed (i.e. connected to reticulated sewerage):

Equation 4 $Net\ septic\ load\ removed = Septic\ load - WWTP\ discharge$

where all terms are in load per person per year. Each septic tank assumes 2.2 people per dwelling. WWTP discharge is taken as the load of discharge divided by the estimated number of people connected to deep sewerage (~3,000 people, 0.14 kg N/person/yr and 0.009 kg P/person/yr).

Note that the construction of deep sewerage infrastructure to Poddy Shot in the Foreshore catchment would likely subsidise the development cost of proposed urban developments (see Figure 7.31).

We did not consider the effect of converting septic tanks to alternative treatment units in this scenario modelling. However, installing and adequately maintaining alternative treatment units with 'nutrient removal'[26] in existing unsewered areas could reduce nutrient loss.

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[26] The Government Sewerage Policy (2019) defines an alternative treatment unit with high nutrient removal as being one with maximum treated wastewater concentrations of 10 mg/L for TN and 1 mg/L for TP.
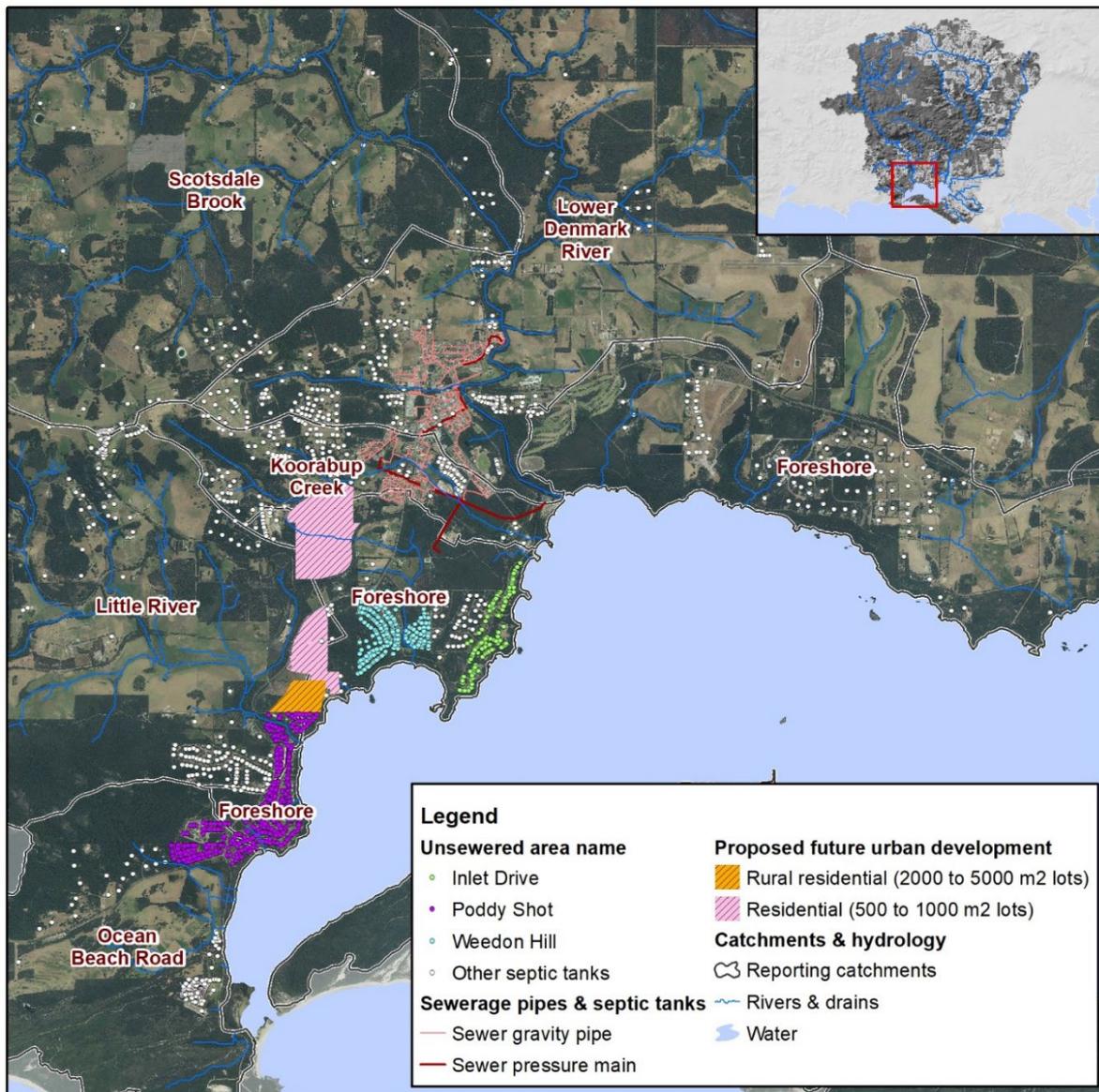
Figure 7.31: Unsewered areas where infill sewerage would improve water quality and proposed urban developments that require connection to deep sewerage. Note that private sewer pipes are not shown.

Results

The removal of 714 septic tanks from selected unsewered areas near Poddy Shot, Weedon Hill and Inlet Drive could reduce nitrogen loads to the inlet by 1.7% (1.7 tonnes/yr) and phosphorus loads by 0.9% (0.09 tonnes/yr) (see Figure 7.32 and Table 7.23).
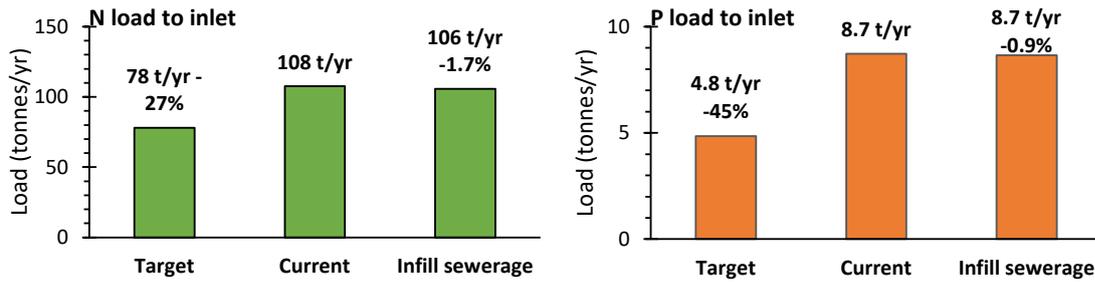
Figure 7.32: Average annual nutrient loads to Wilson inlet after infill sewerage

Table 7.23: Average annual net nutrient load reduction after infill sewerage in selected areas

Unsewered area name	Reporting catchment	# septic tanks	Net N load removed (kg/yr)	N load reduction: Wilson Inlet (%)	Net P load removed (kg/yr)	P load reduction: Wilson Inlet (%)
Poddy Shot	Foreshore, Little River, Ocean Beach Road	368	1348	1.3%	52	0.6%
Inlet Drive*	Foreshore	113	149	0.1%	8	0.1%
Weedon Hill	Foreshore	233	293	0.3%	16	0.2%
Total		**714**	**1790**	**1.7%**	**77**	**0.9%**

Net nutrient load is the load produced by the septic tanks minus the approximate load produced by diverting this sewage to the Denmark WWTP which discharges treated wastewater to the Wilson Inlet.

* 104 lots with an equivalent of 113 septic tanks due to accommodation

7.3.7 Wastewater treatment plant: treated wastewater management

This section summarises all modelling results related to the Denmark wastewater treatment plant (WWTP) and the Mount Barker WWTP disposal site. No new scenario modelling is presented in this section.

Denmark WWTP

Denmark WWTP disposes of treated wastewater via subsurface infiltration galleries adjacent to an unnamed creek in the Koorabup catchment (modelling catchment 79). This wastewater disposal site is less than 1 km from Wilson Inlet.

Before it was upgraded in February 2015, the WWTP used an intermittently decant extended aeration (IDEA) treatment system with alum dosing and had the capacity to treat 0.35 ML of sewage per day (Water Corporation 2015). The upgrade consisted of an oxidation ditch treatment system, which has a treatment capacity of about 1.2 ML of sewage per day. At present the WWTP receives about 0.13 ML of sewage per day. Total phosphorus concentrations remained high until at least June 2015. Thus, we have assumed the WWTP remained in a transitional phase until the start of 2016 and have excluded 2015 from some of the calculations given in this section.

Compared with the old WWTP, the new one has nutrient loads about 5 to 6 times lower (Figure 7.33). For the period 2010–14, the old WWTP had nutrient loads greater than the new WWTP running at maximum capacity, as assumed in the urban expansion scenario.
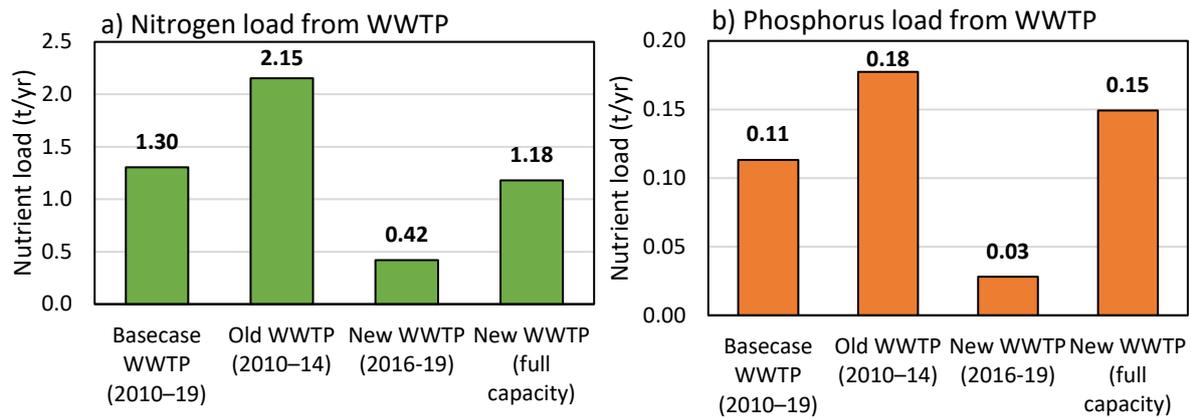
Figure 7.33: Nutrient loads from the Denmark WWTP

Basecase nutrient loads from the Denmark WWTP are an average of pre and post upgrades to the WWTP. **In the basecase period (2010–19):**

- Average annual nutrient loads from the Denmark WWTP are:

    - **nitrogen:**   **1.30** tonnes/yr (1.2% of load to the inlet)

    - **phosphorus:**   **0.11** tonnes/yr (1.3% load to the inlet)

- The Koorabup reporting catchment had loads of 2.08 tonnes/yr of nitrogen and 0.13 tonnes/yr of phosphorus. These loads **exceed targets by 40% for nitrogen and 22% for phosphorus** (1.25 tonnes/yr and 0.10 tonnes/yr respectively).

- Discharge from the Denmark WWTP (2010–19, with the pre-upgrade WWTP nutrient loads from 2010–16) contributed 63% of the nitrogen load and 85% of the phosphorus load from the Koorabup catchment.

However, if the post-upgrade nutrient loads (2016–19) are assumed to apply for the entire 2010–19 period, then:

- Average annual nutrient loads from the Denmark WWTP would be:

    - **nitrogen:**   **0.42** tonnes/yr (0.4% of load to the inlet)

    - **phosphorus:**   **0.03** tonnes/yr (0.3% of load to the inlet)

- The Koorabup reporting catchment would have loads of 1.19 tonnes/yr of nitrogen and 0.05 tonnes/yr of phosphorus, which are **below targets** (1.25 tonnes/yr and 0.10 tonnes/yr respectively).

- Discharge from the Denmark WWTP contributes about 35% of the nitrogen load and 60% of the phosphorus load from the Koorabup reporting catchment.

The urban expansion scenario assumes the Denmark WWTP would be running at capacity (1.2 ML/day) with discharge concentrations from 2019–20. In addition to the increased area of urban land uses, **the Denmark WWTP could have the following impact by 2050:**

- Average annual nutrient loads from the Denmark WWTP would be:

    - **nitrogen:**   **1.18** tonnes/yr (1.1% of load to the inlet, 10% lower than basecase WWTP loads)

- **phosphorus: 0.15** tonnes/yr (1.7% of load to the inlet, 32% greater than basecase WWTP loads).

- The Koorabup reporting catchment would have loads of 2.19 tonnes/yr of nitrogen and 0.18 tonnes/yr of phosphorus and flow of 1.37 GL/yr (a 32% increase from the basecase). Flow-weighted concentrations from the Koorabup catchment would be 1.6 mg/L TN and 0.13 mg/L TP which **would require reductions of 25% (0.55 tonnes/yr) and 23% (0.04 tonnes/yr) respectively**. Note that load targets would now be 1.64 tonnes/yr nitrogen and 0.14 tonnes/yr for the Koorabup catchment due to the additional flow in the urban expansion scenario.

- Discharge from the Denmark WWTP contributes about 54% of the nitrogen load and 84% of the phosphorus load from the Koorabup reporting catchment, which is similar to the basecase.

Figure 7.34: The Denmark WWTP and treated wastewater discharge site

The Great Southern Development Commission's 2015 regional investment blueprint envisaged that 100% of all treated wastewater would be reused in the region by 2040. At present 94% of all treated wastewater is reused in the Great Southern region. Until recently, the Denmark WWTP was one of the few treatment plants in the region without a wastewater reuse scheme.

From March 2024, the Shire of Denmark has been able to irrigate the 2.15 ha McLean Oval with up to 30 ML/yr of treated wastewater. Under this arrangement, the Water Corporation provides treated wastewater to the park, with the shire being responsible for its management. Typically, irrigation is required from October to April. Based on the information available to us at the time, we estimate that:

- Nutrient loading rates to the oval would be about 47 kg/ha/yr of nitrogen and 6.5 kg/ha/yr of phosphorus, which are below input targets.

- About 0.1 tonnes/yr of nitrogen and 0.01 tonnes/yr of phosphorus would not be discharged to Wilson Inlet via the Koorabup catchment. This would be insufficient for mitigating the WWTP's impact in the 2050 urban expansion scenario, which requires load reductions of 0.55 tonnes/yr of nitrogen and 0.04 tonnes/yr of phosphorus.

At this stage, it is unclear if the use of treated wastewater will be expanded elsewhere in the town; for example, to irrigate the golf course (~29 ha of turf) or the grassed areas of Denmark Primary School (1.5 ha), which is less than 1 km from Mclean Oval. If all treated wastewater were reused at 8 to 14 ML/ha/yr (the range proposed for McLean Oval), this would mean:

- An additional 8 to 14 ha of irrigation area would be required for reusing 110 ML/yr; that is, the current annual treated wastewater (140 ML/yr) less the volume proposed at McLean Oval (30 ML/yr).

- At maximum capacity, the Denmark WWTP would produce about 441 ML/yr. Accounting for the 30 ML/yr proposed for McLean Oval, an additional 29 to 51 ha irrigation area (equal to 410 ML/yr) would be required.

There appears to be sufficient area of turf in or near Denmark to irrigate the treated wastewater that would be produced by the WWTP at maximum capacity. However, if the rate of irrigation is constrained (i.e. less than the proposed 14 ML/ha/yr) there may still be an excess of treated wastewater, which would be discharged to Wilson Inlet. Also, this assumes there is enough storage capacity to detain treated wastewater during periods when irrigation is not required (e.g. during winter). If the storage capacity is insufficient, then treated wastewater would continue to be discharged to the inlet.

Mount Barker WWTP

The Mount Barker WWTP is located north-east of the town in the King River catchment. Treated wastewater is pumped to a storage dam before being used to irrigate a woodlot south-west of the town in the Hay River catchment. This woodlot is within the Ooranggatup Creek catchment which is part of modelling catchment 42.

The Mount Barker WWTP treats wastewater to a secondary standard using three treatment ponds that can accommodate inflows of up to 1.28 ML/day, but averaged 0.31 ML/day in 2015–16. There have been unlicensed overflows from the WWTP in every annual

environmental report that was reviewed as part of this project (2014–15, 2015–16, 2018–19). Overflows occurred in winter due to high rainfall and were discharged to a tributary of the upper Kalgan River catchment which flows to Oyster Harbour.
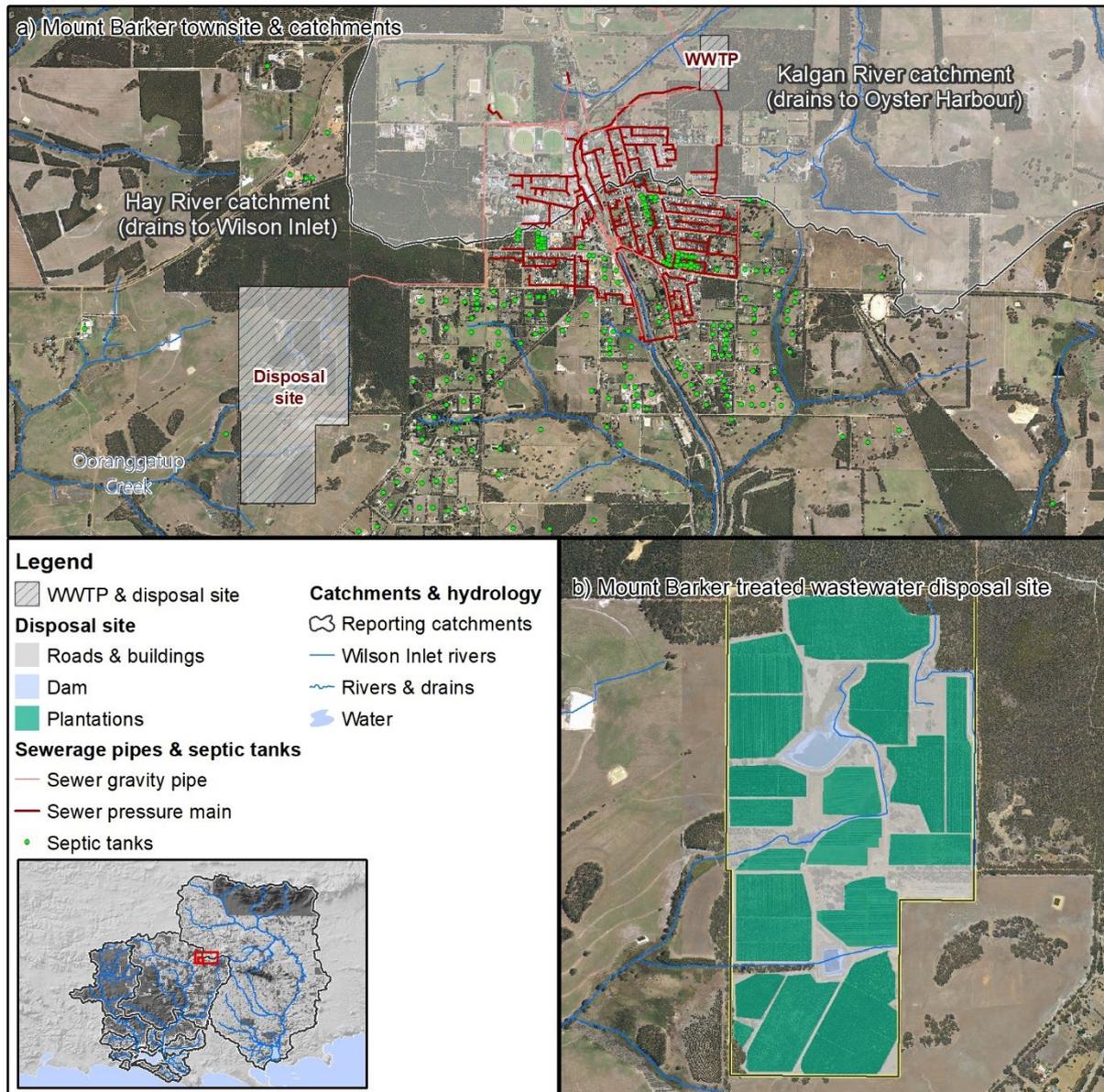
Figure 7.35: Mount Barker WWTP and disposal site

The 126 ha Mount Barker disposal site was historically used as grazing land until the year 2000 when it was converted to a vineyard. Treated wastewater was used to supplement the irrigation at this vineyard, however it is not known when this began. In 2013 the Water Corporation took ownership of the vineyard and converted 126 ha of the site to a woodlot. In 2015–16 about 101 ML of treated wastewater was used to irrigate this woodlot. Nutrient inputs to the woodlot from treated wastewater irrigation were about 22 kg/ha/yr for nitrogen and 5 kg/ha/yr for phosphorus.

In the urban expansion scenario, we assumed no increase in sewage inflow to the plant. Most of the planned future development near Mount Barker will be unsewered rural residential and industrial lots that use onsite wastewater systems.

The Mount Barker disposal site contributed about 0.2% of the nitrogen load and 0.1% of the phosphorus load to Wilson Inlet. However, at the small scale, nutrient emissions from this site may be more concerning. Modelled surface water nutrient concentrations from the disposal site were 5 mg/L for TN and 0.3 mg/L for TP. About 13% of the nitrogen load and 28% of the phosphorus load in the Ooranggatup Creek catchment came from diffuse losses from the WWTP disposal site.

7.3.8 Management actions not modelled

The following management actions were not modelled, but may have the potential to mitigate nutrient loss:

- **Perennial pastures** have the potential to reduce phosphorus loss if managed appropriately (Rogers pers. comm. 2019). The current extent of their use is not mapped or known in sufficient detail to allow modelling of this management action.

- **Constructed wetlands for nutrient removal.** Constructed wetlands can be used to reduce nutrient loads when applied in suitable locations (Kadlec & Wallace 2009). This management action was not a priority for investigation for this project's reference group.

- **Large-scale deep-rooted vegetation:** A scenario looking at the expansion of plantations in existing farmland or large-scale revegetation was not modelled. We did not consider it likely the plantation area would increase given the current profitability of pasture grazing. Although an increase in deep-rooted vegetation may be of interest for salinity management, there are better-suited models and previous work in this area (see Ward et al. 2011).

- **Dung beetles** have been demonstrated to improve soil nutrients (Bertone et al. 2006), and decrease surface runoff (Browne et al. 2010), and are a proposed management action for improving catchment water quality (Doube et al. 2003). However, recent nutrient leachate trials with and without dung beetles were not significantly different (Aislabie et al. 2020).

7.4   Climate change

Climate assessment framework

The department has developed a new climate assessment framework for applying climate projection data in water resource planning and decision-making exercises (DWER 2024b). The framework comprises three stages: understanding the water system and climate context, assessing climate change impact to a water system, and communication. The diagram below summarises each step in the framework.
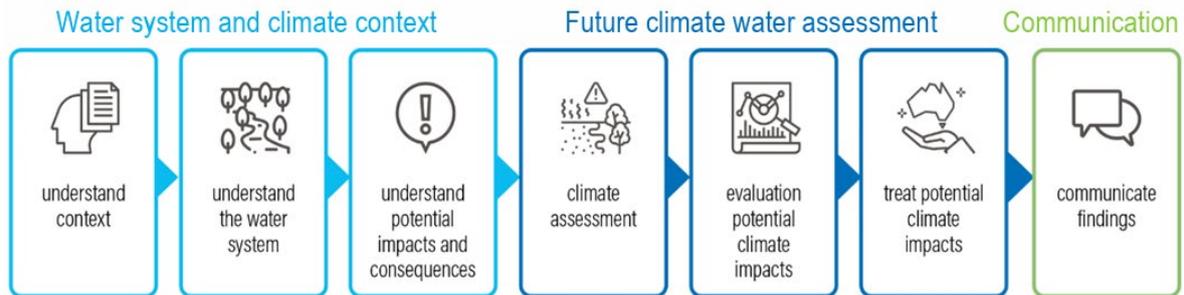
Figure 7.36: The climate assessment framework to apply climate projections in decision-making processes for water management (DWER 2024b)

The underlying principle of the framework is that climate change should be incorporated into water planning and decision-making by acknowledging the range of plausible future climate projections and assessing the climate risk to the water resource.

Context for climate assessment

The main purpose of the modelling exercise is to guide catchment management activities to reduce nutrient export in the Wilson Inlet catchment. This will aid decision-makers by prioritising where management actions need to be undertaken, for which land uses, and how much needs to be done to achieve water quality objectives. These can then be used in a cost-benefit analysis to determine which activities provide best value for money. The recommended actions required to meet the load reduction targets in each of the reporting catchments are summarised in a water quality improvement plan. This plan is used for investment planning and as a basis for detailed subcatchment implementation planning.

Photo: Rainfall north of Mount Lindesay 2019

The model achieves this by estimating nutrient loads that are delivered from various catchments and land uses. The model is then used to estimate load reduction targets for each catchment, and subsequently undertakes scenario simulations to identify management activities (i.e. what sort of management is required, and at what scale) to meet these reductions.

The WQIP is intended to be reviewed and revised every 10 years to ensure it aligns with contemporary science and technology. A 10-yearly review-and-revise framework forms an adaptive management process for WQIPs, which is important not only to ensure the WQIP's recommendations adapt to a changing climate, but also to incorporate changes in other factors such as land use and land management, as well as technologies, research and science related to nutrient-reduction activities. Hence a 2040 future climate is appropriate for assessing the impact of future climate in this instance (i.e. forward 10 years and round up to the nearest decade).

Understanding the water system

Climate change has the potential to impact both flow and nutrient export to receiving waterways. This means that nutrient loads and load reduction targets are a function of the climate for which the model was assessed and will change depending on the future climate.

In the face of reduced river flows from a drying climate, a set (i.e. unchanging) nutrient load target for estuaries is no longer appropriate. This was evident in the Peel-Harvey catchment, which previously had phosphorus load targets set as part of an Environmental Protection Policy in 1992. These formed the basis for a water quality improvement plan for phosphorus that was released in 2008 (EPA 2008). However, when these targets were reviewed in 2020 (DWER 2023), it was found the load targets had been achieved in most recent years, yet phosphorus concentrations remained significantly elevated, and water quality issues in the receiving waterways had persisted. The reason the load targets had been achieved was primarily because flow had reduced but concentrations had not.

More recent WQIPs (e.g. the Vasse-Wonnerup, Leschenault and updated Peel-Harvey plans) use concentrations, expressed as water quality objectives, to develop load reduction targets. It is explicit that these load reduction targets are relevant only for a given time-period. In the context of modelling the impact of climate change, load reductions have the following caveats and uses:

- Load reduction targets are based on water quality objective concentrations in waterways. They are modelled average annual loads for a specific climate sequence and for specific target concentrations.

- Load reduction targets are only valid for the climate sequence for which they were derived. Therefore, these loads are not valid to assess against any future climate scenarios. In these instances, maximum acceptable loads would need to be recalculated for the alternative climate sequence.

- Load reduction targets are not suitable for assessing whether a catchment has met a load target using year-by-year measurement, again due to the climate sequence used to derive the load target, and due to the highly variable nature of interannual flow.

- Load reduction targets are useful for catchment management planning, to estimate how much intervention is required in a catchment to produce a reasonable water quality outcome. This is the context for which they are used in a WQIP.

The management decisions are based on the proportion of nutrient reduction that each of the catchments require to meet their load reduction targets. Ideally, this would mean that if the target percentage reduction in load was met for the waterway (for a given climate sequence), the waterway would meet its concentration target. This method is much more resilient to climate: a load reduction expressed as a percentage of total load required to meet a concentration target will be more consistent in future climate sequences that result in both greater or less flow compared with an absolute load target.

However, there is still a risk that climate change will affect the percentage load reduction required to meet a water quality objective concentration due to the non-linear response of nutrient concentrations to changing climate and flow. For example, runoff from forested areas, which is generally low in nutrient concentration and dilutes the nutrient concentration in waterways, may be more heavily impacted by a drier climate than runoff from cleared areas – and this could mean that dry periods produce higher nutrient concentrations in waterways. Conversely, for cleared land uses the relationship between flow and nutrient concentration generally presents higher nutrient concentrations for higher flows, and this could mean that a dry sequence may have lower nutrient concentrations.

If we undertake our assessment using the historical climate and recommend a suite of actions to meet a nutrient-reduction target – and the future climate sequence is not consistent with the historical sequence (yielding either greater or less flow) – there is a risk we may not meet our water quality objectives should we undertake the desired work recommended in the WQIP. This could lead to investment planning which does not achieve a desired outcome, and continued water quality impacts in the rivers and estuary.

Future climate projection data, used in conjunction with the Wilson Inlet catchment model, can evaluate this risk: we can use climate projections to analyse a range of plausible future scenarios, to estimate the percentage reduction in nutrients required to meet a load target for each of these scenarios.

Climate characteristics that drive the system

Nutrient load delivery to Wilson Inlet is driven by flow quantity, and the primary climatic driver for the quantity of flow delivered to the inlet is precipitation (rainfall). Total annual precipitation is heavily correlated with the annual flow, and annual flow is heavily correlated with total annual nutrient load (Figure 7.37).

The climate of Wilson Inlet catchment has been steadily becoming hotter and drier since the 1960s, however the declines in rainfall are not as pronounced as those observed in other areas of the state's south-west. There is uncertainty in the direction and magnitude of change for the future climate in this region.

Many scenarios from the Bureau of Meteorology's National Hydrological Projections (NHP) suggest this drying trend is likely to continue, and in some cases the drying trend is projected to increase over the next 50 years (Figure 7.38). While some projections predict a future climate with more rainfall than we have seen over the past two decades, and some have a

similar rainfall to our historical period (1950–2023), most predict a future with reduced average annual rainfall. No projections predict a climate that will return to pre-1980 rainfall averages over the next four decades.

To assess the potential impact of future climate on the decision-making processes in the Wilson Inlet catchment, we do not need to simulate all 32 scenarios from the NHP – as this would be time consuming, data-intensive, and unlikely to yield a greater understanding of this issue than a smaller suite of models. Rather, we need a scenario that represents the stable-to-wetter end of the NHP rainfall projections, and one that represents a significantly drier end. This approach captures the range of NHP projections, excluding outliers.

Thirty-year assessment periods for future climate are recommended where possible, as they capture both short- and long-term (i.e. decadal) climate variability. Hence we have used a 30-year climate period for this assessment. Figure 7.39: Scatter plot of average annual rainfall versus potential evapotranspiration (PET) for all National Hydrology Projection climate scenarios (2025–54) and historical Australian Water Availability Project data (1991–2019) -34.95 latitude and 117.30 longitude.

 shows the range of average annual rainfall over the 30-year period 2025–54 for each of the NHP scenarios, as well as the average annual Penman potential evapotranspiration (which is related to air temperature). Most NHP scenarios are warmer (higher PET) over the assessment period than the historical rainfall. There are some outliers that predict a cooler and drier future climate, and some that predict extreme drying conditions with less than 800 mm average annual rainfall (representing an 18% reduction in rainfall from the previous 30 years).

We have selected two scenarios to use in the climate assessment to estimate the percentage reduction in nutrients required to meet a load target (see Figure 7.40):

- The **stable rainfall** scenario, which has slightly higher average annual rainfall and is warmer than the past two decades. The **CRNM-MRNBC-85**[27] future climate sequence represents this scenario. Note that although we refer to this scenario as being stable, we are referring to its rainfall being comparable with the historical average. This scenario does not necessarily result in stable catchment flow.

- The **drier climate** scenario is warmer and has substantially less rainfall than the past. Evapotranspiration (and therefore temperature) is slightly higher than the stable rainfall scenario. The **GFDL-QME-45**[28] future climate sequence represents the drier climate scenario.

Both climates represent warmer futures. We did not include the outliers or climate extremes in this analysis. We acknowledge it is possible the two scenarios selected do not represent the full range of plausible futures. However, the selected scenarios are adequate to assess the potential risks that climate change poses to decision-making processes.

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[27] Centre National de Recherches Météorologiques Coupled Global Climate Model – multivariate recursive nesting bias correction – Representative Concentration Pathway 8.5 (high emissions)

[28] Geophysical Fluid Dynamics Laboratory – quantile matching extremes – Representative Concentration Pathway 4.5 (intermediate emissions)
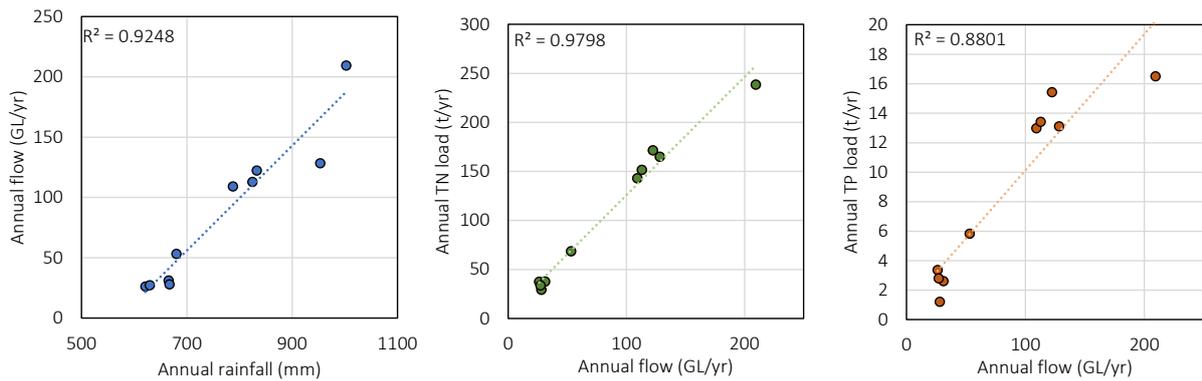
Figure 7.37: Relationships between a) annual rainfall and flow, b) annual flow and nitrogen load, and c) annual flow and phosphorus load. All plots use data from 2010–19.
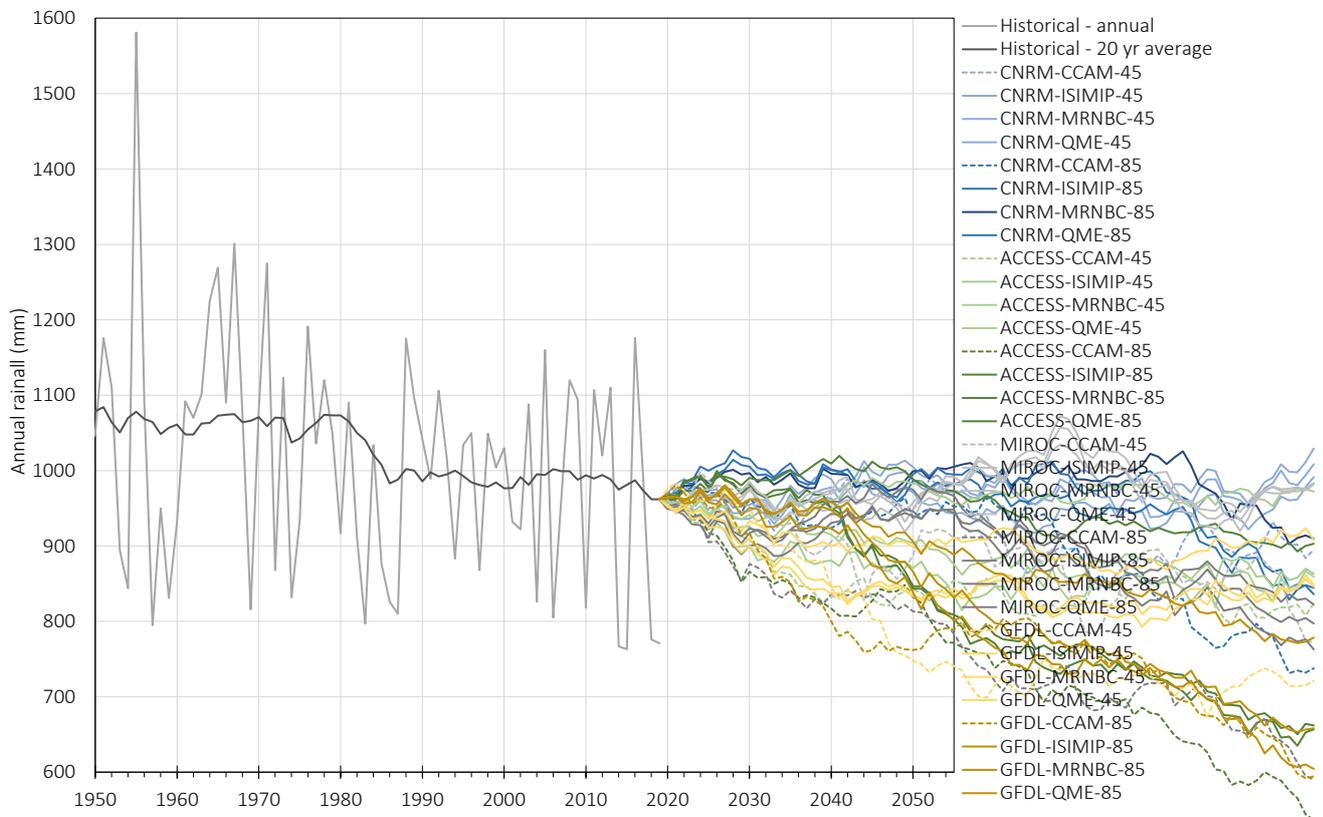
Figure 7.38: Historical annual and 20-year moving average rainfall at Denmark and from the suite of National Hydrology Projection scenarios from 2020–55.
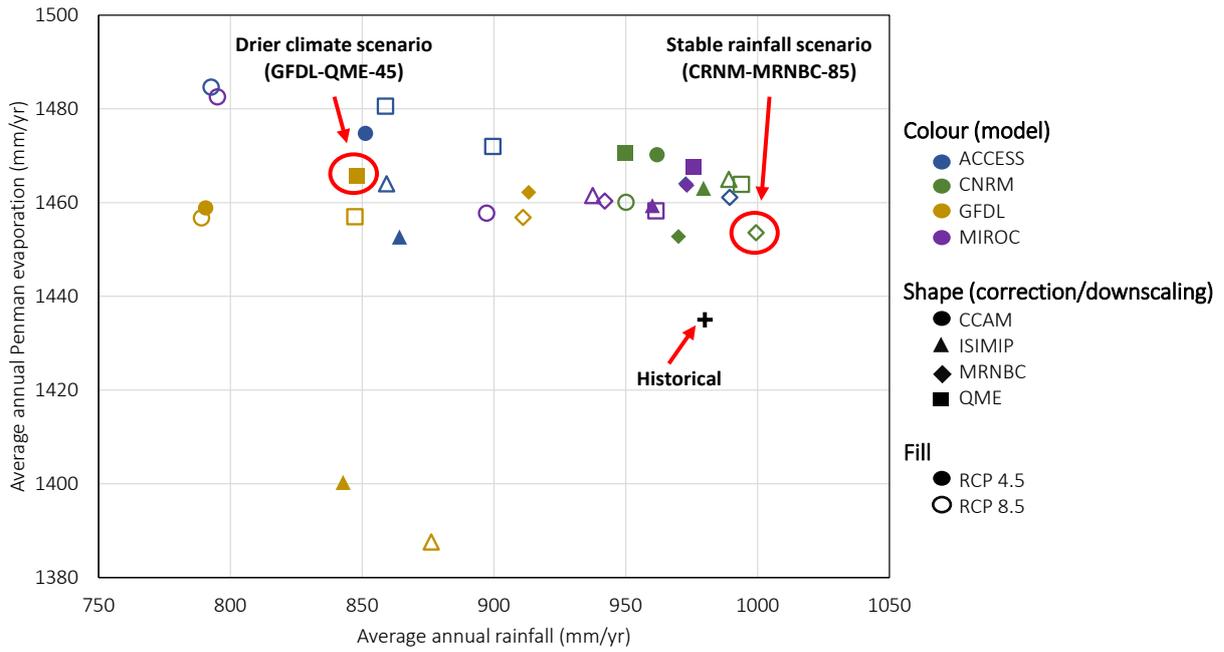
Figure 7.39: Scatter plot of average annual rainfall versus potential evapotranspiration (PET) for all National Hydrology Projection climate scenarios (2025–54) and historical Australian Water Availability Project data (1991–2019) -34.95 latitude and 117.30 longitude.
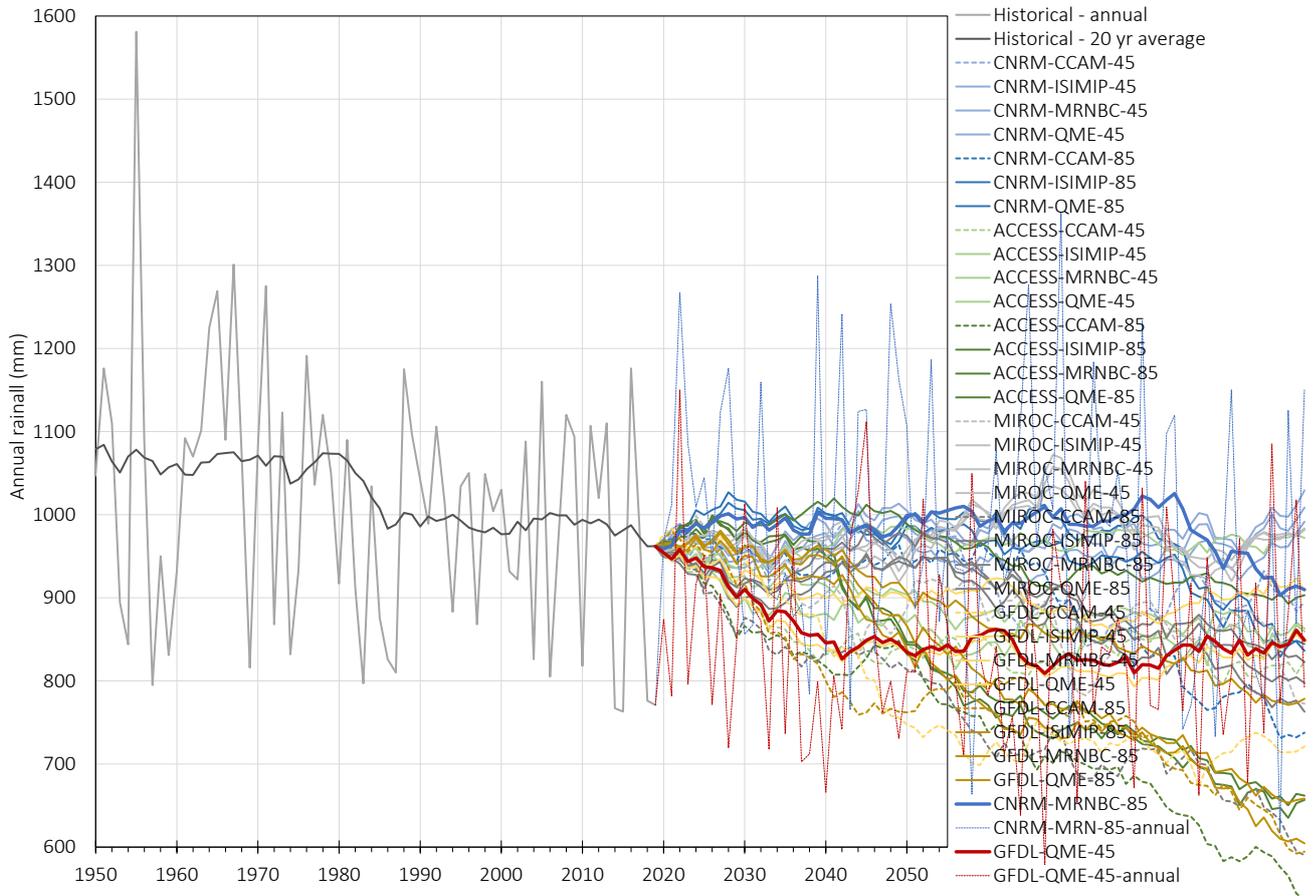
*Figure 7.40: Historical and future annual and 20-year mean rainfall of all 32 NHP climate scenarios. The CNRM-MRNBC-85 (representing our **stable rainfall** scenario) is highlighted*

*in blue. The GFDL-QME-45 scenario (representing our **drier climate** scenario) is highlighted in red.*

Other climate impacts on receiving waterways

Climate change may impact water quality in Wilson Inlet and its associated waterways in many ways – with changes to nutrient delivery only one of these potential impacts. A drier climate could increase the number of years the sandbar does not open. This would lead to a higher residence time for nutrients and increased stagnation in the estuary. A hotter future climate would encourage more rapid algal growth than we have seen historically. If the climate is wetter compared with the past two decades, which is also a plausible future, higher nutrient loads will be delivered to the estuary.

The interplay between higher loading with higher flows versus lower loading and lower flows, from a water quality perspective is not well understood. These issues are not in scope for the catchment model or WQIP to address specifically. However, the department has been developing an estuary model for Wilson Inlet, which will support the assessment of future climate impacts on estuary circulation, residence time and salinity. Models are not yet advanced enough to provide predictive capability for biogeochemistry or ecology. Much of this understanding of potential ecological impacts has been captured in the *Nullaki (Wilson Inlet) sandbar opening decision framework* (Kelsey et al. in prep).

A dry and hot future climate will also affect the water quality of rivers – there will be less flow, more stagnation of summer pools (later start and earlier end to the flow season), and longer periods with no flow. This, combined with hotter summers, is likely to worsen water quality issues. Addressing environmental flows is not within the scope of this study. However, riparian zone rehabilitation not only provides some nutrient attenuation, but also shades and cools waterways, which will help limit the impacts of a hotter, drier climate on water quality. Riparian revegetation provides a climate adaptation measure for waterway health.

Climate assessment

Implementation

The following summarises how we implemented the future climate scenarios in the catchment model:

- **Data extraction:** daily NHP climate data was extracted from the four points shown in Figure 7.41.

- **PET conversion:** the data provided by NHP uses the Penman (1948) evaporation method[29], whereas our catchment model uses the Penman-Monteith method (FAO56), which is an output from the SILO dataset. We derived an annual linear relationship between FAO56 and Penman evapotranspiration values for both future climate scenarios across all four NHP climate data points for the period 2006–20.

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[29] Penman evaporation accounts for evaporation from open water, soil and grassed surfaces. It does not explicitly account for the physiological processes of plants. FAO56, which uses the Penman-Monteith equations for potential evapotranspiration, explicitly accounts for the physiological processes of a hypothetical reference crop that closely resembles large areas of actively growing green grass (Allen et al. 1998).

> This relationship enabled the conversion of daily Penman data into FAO56 equivalent data.

- **Pan evaporation conversion:** the basecase model uses pan evaporation as a data input for dams and wetlands. We derived an annual conversion factor between SILO FAO56 and pan evaporation (70% of daily value). We used a factor of 0.944 for all future climate points.

- **Updating modelling datasets:** point source, septic tank and dairy shed model inputs were extended. To enable automated running of the future climate scenarios, we automated septic tank and dairy shed discharge using functions, which meant the timing of discharge was offset by one day. We assumed the Denmark WWTP had the effluent discharge and nutrient concentrations of the 2019–20 financial year. We further assumed that plantations were harvested and replanted every 10 years, and modified their leaf area index timeseries to reflect this.

We compared the results from the 30-year simulated future climate with the 10-year basecase period (2010–19), as this was the period we used to determine the plan's loads and load targets. We acknowledge the inherent differences in variability between these periods and their impact on the results. A 30-year period will encapsulate greater variability and will tend to have larger flows and nutrient loads than the 10-year basecase period, which is substantially drier and less variable. Hence, we have qualified some results by comparing results from the past 30 years with the 30-year future climate scenarios.

Impact of future climate on nutrient loads and target loads at a whole-of-catchment scale

We simulated the Wilson Inlet catchment model for both climate scenarios – see the summary results presented as box and whisker plots of annual rainfall, flows and nutrient loads in Figure 7.42. There is significant variability in flow and nutrient load for each of the climate scenarios (interannual variability), and the stable rainfall scenario generally shows a similar variability to the previous 30 years' rainfall data, with similar nutrient load and flow distributions. The dry scenario has reduced variability, and significantly lower average mean and median nutrient loads than the basecase, previous 30 years, or stable rainfall scenario. These results show the changes in rainfall have a significant impact on the change in flow and nutrient load. Thus the nutrient export load is highly variable from year to year, and is also highly dependent on the total rainfall amount.

See Table 7.24 and Figure 7.43 for a summary of the average annual rainfall, PET, flow and nutrient export loads for the basecase and future climate scenarios.

For the basecase, nutrient load reductions of 27% and 45% were required to meet nitrogen and phosphorus targets respectively. In the future climate scenarios, reductions of 31% are required to meet nitrogen targets for both the stable and dry climates. A phosphorus load reduction of 46% is required for the drier climate, and 47% for the stable climate scenario (an increase of 1 to 2% compared with the basecase).

These results show that although there is some risk a future climate will underestimate the amount of management required by a relatively small amount, the approach to setting nutrient-reduction requirements using concentrations is relatively robust regardless of

changes to climate, and in the absence of targets derived from a suitable estuary model. The results also provide some indication of the uncertainty around the target reduction figures, and can help catchment managers understand the level of precision that might reasonably be expected when planning for future nutrient load reductions.

Table 7.24: Summary of rainfall, flow, nutrient loads and concentrations in the basecase and future climate scenarios

Result	Unit	Basecase 2010–19	Last 30 years 1994–2023	Stable rainfall 2025–54	Dry climate 2025–54
Rainfall	mm/yr	766	779	808	672
Potential Evapotranspiration	mm/yr	1059	1040	1094	1096
Flow	GL/yr	85	102	92	37
Nitrogen load	t/yr	107	130	111	48
Phosphorus load	t/yr	8.7	10.9	9.0	4.3
Nitrogen load target	t/yr	78	94	77	33
Phosphorus load target	t/yr	4.8	5.9	4.9	2.3
Current nitrogen concentration	mg/L	1.27	1.28	1.20	1.29
WQO: nitrogen concentration	mg/L	0.92	0.92	0.83	0.90
Current phosphorus concentration	mg/L	0.103	0.107	0.097	0.116
WQO: phosphorus concentration	mg/L	0.057	0.057	0.053	0.062
Nitrogen reduction target	%	27%	28%	31%	31%
Phosphorus reduction target	%	45%	46%	46%	47%

Note: All concentrations are flow-weighted

WQO: Water quality objective
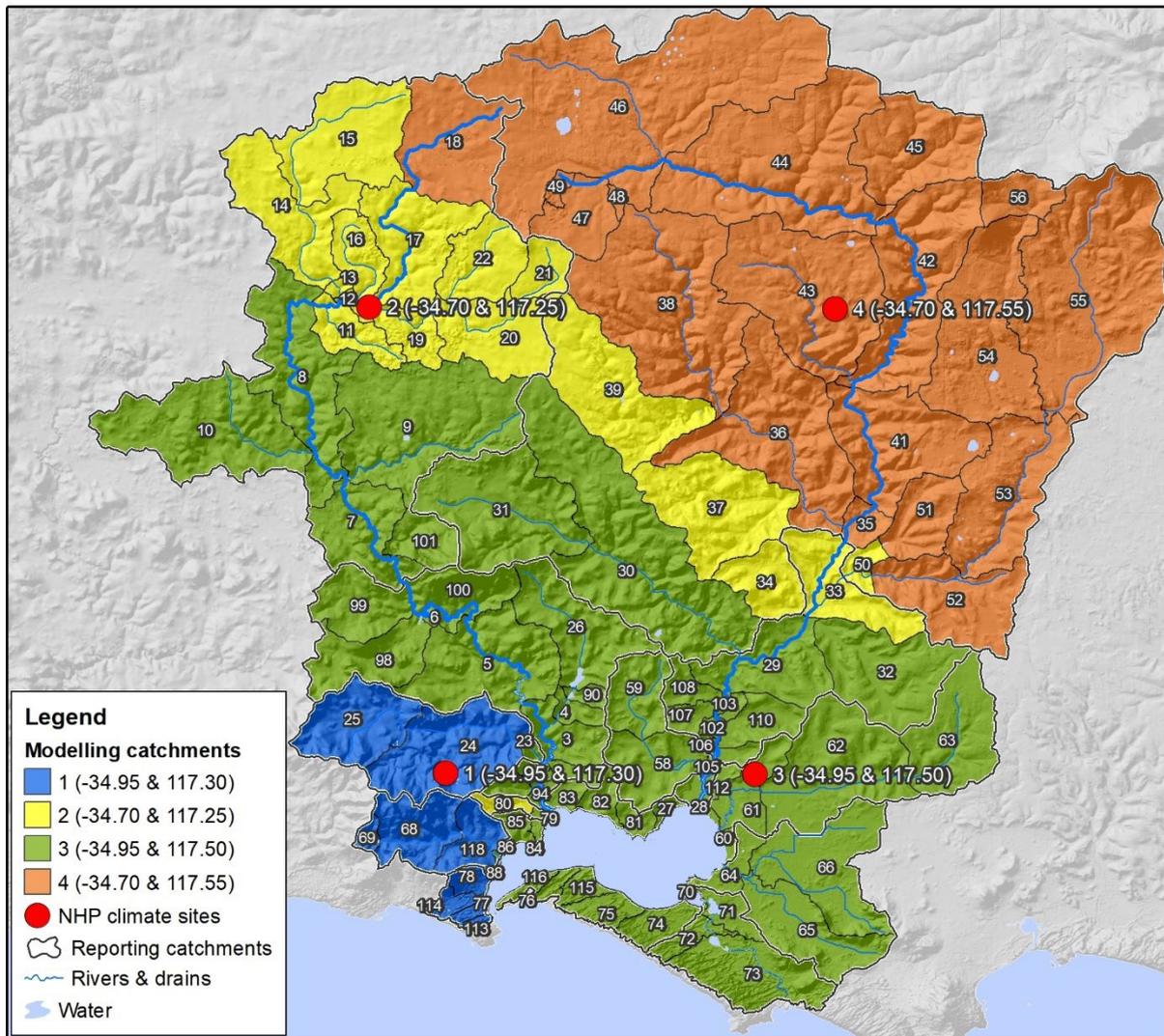
Figure 7.41: NHP climate data extraction points and their attribution to modelling catchments
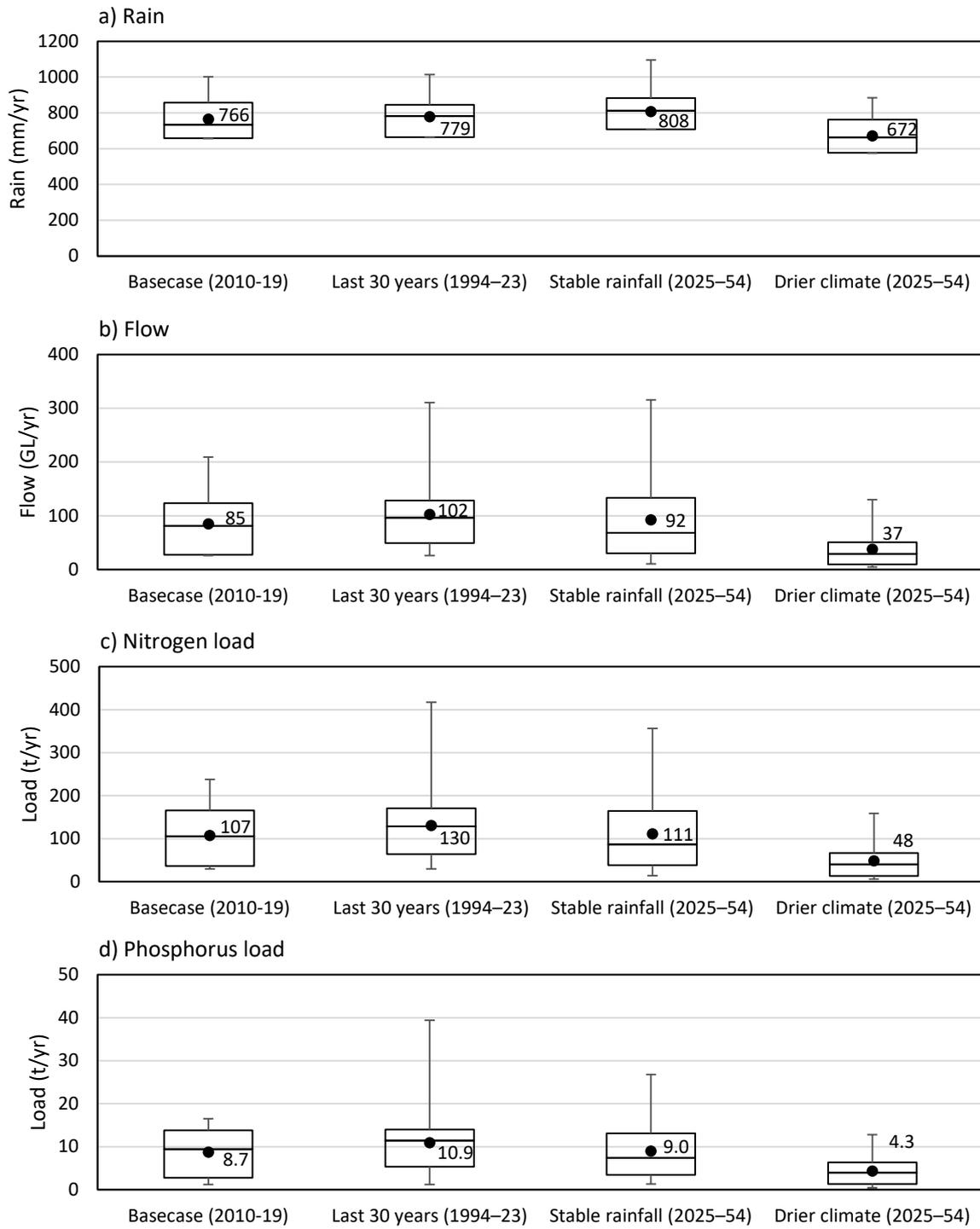
Figure 7.42: Box and whisker plots showing the 20th, 50th and 80th percentiles and mean of catchment-weighted rainfall, flow and nutrient loads for the basecase, last 30 years and the stable and drier future climate scenarios.
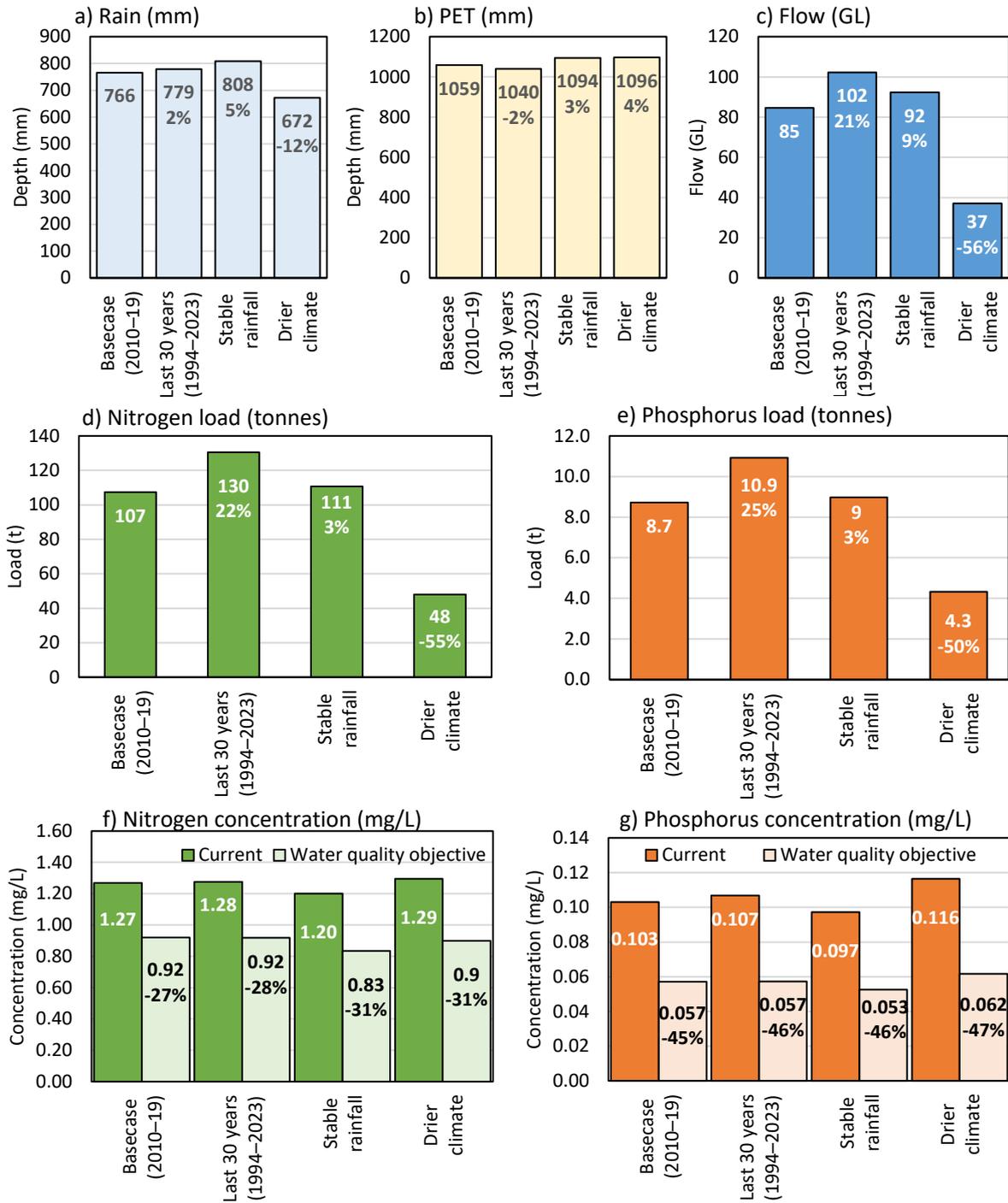
Figure 7.43: Average annual a) rain, b) potential evapotranspiration, c) modelled flow, d & e) nutrient loads, and f & g) flow-weighted nutrient concentrations of catchment discharge to Wilson Inlet in the basecase, last 30 years and future climate scenarios

Impact of future climate on individual reporting catchments

See Table 7.25 for rainfall and PET changes for each reporting catchment, Table 7.26 for modelled flows, and Table 7.27 for nitrogen and Table 7.28 for phosphorus loads, concentrations and targets.

Table 7.25: Average annual rainfall and potential evapotranspiration of the basecase climate (2010–19) and 2040 climate scenarios (2025–54)

Reporting catchment	Rainfall							Potential evapotranspiration						
	Base case	Stable rainfall	Diff		Drier climate	Diff		Base case	Stable rainfall	Diff		Drier climate	Diff	
	(mm)	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(mm)	(mm)	(%)	(mm)	(mm)	(%)
Ocean Beach	1057	1017	-40	-4%	851	-205	-19%	1053	1054	2	0%	1056	3	0%
Little River	1028	1016	-12	-1%	850	-178	-17%	1060	1055	-5	0%	1056	-4	0%
Koorabup	989	809	-180	-18%	663	-326	-33%	1069	1096	28	3%	1102	34	3%
Lower Denmark	932	904	-28	-3%	753	-179	-19%	1083	1093	10	1%	1086	4	0%
Upper Denmark	766	831	66	9%	686	-79	-10%	1071	1095	25	2%	1097	27	2%
Scotsdale	1149	1014	-135	-12%	849	-300	-26%	1053	1055	3	0%	1057	4	0%
Foreshore	933	908	-25	-3%	757	-176	-19%	1073	1091	18	2%	1085	12	1%
Sunny Glen	862	904	42	5%	753	-109	-13%	1065	1093	28	3%	1086	21	2%
Lower Hay	836	881	45	5%	731	-104	-13%	1080	1094	13	1%	1090	10	1%
Upper Hay	673	731	58	9%	608	-65	-10%	1049	1098	49	5%	1105	56	5%
Sleeman	856	904	48	6%	753	-103	-12%	1048	1093	45	4%	1086	38	4%
Cuppup	886	904	18	2%	753	-133	-15%	1068	1093	25	2%	1086	19	2%
Lake Saide	903	904	1	0%	753	-150	-17%	1061	1093	31	3%	1086	25	2%
Nullaki	920	904	-16	-2%	753	-167	-18%	1068	1093	25	2%	1086	18	2%
Wilson Inlet	766	808	42	5%	672	-94	-12%	1059	1094	35	3%	1096	37	4%

For the stable rainfall scenario, the upper Denmark and Hay catchments collectively contribute 12% more nitrogen load than the basecase. Although this is a substantial increase, these upper catchments cover a large area and hence have a lower potential for nitrogen removal per unit area. Monitoring suggests that inorganic nitrogen in the Upper Hay catchment is being converted to dissolved organic nitrogen, which breaks down more slowly and cannot be effectively managed other than through large-scale planting of deep-rooted vegetation or prohibiting extensions of drainage (i.e. a preventative measure only). Also, less than 10% of the excess phosphorus originates from these upper catchments in the scenario. Hence, even with increased nutrient loads in the scenario, a higher prioritisation for management in the Upper Hay and Denmark river catchments is not warranted.

Table 7.26: Average annual reporting catchment flow in the basecase and 2040 climate scenarios

Reporting catchment	Flow						
	Basecase	Stable rainfall			Drier climate		
	Volume	Volume	% of total	% diff	Volume	% of total	% diff
	(GL/yr)	(GL/yr)	(%)	(%)	(GL/yr)	(%)	(%)
Ocean Beach	1.2	0.9	1%	-24%	0.4	1%	-68%
Little River	6.1	5.7	6%	-7%	3.5	9%	-43%
Koorabup	1.0	0.6	1%	-42%	0.4	1%	-60%
Lower Denmark	8.4	6.9	7%	-18%	1.9	5%	-77%
Upper Denmark	5.3	11	12%	112%	2.6	7%	-51%
Scotsdale	11	6	6%	-48%	2.5	7%	-78%
Foreshore	2.1	1.7	2%	-20%	0.8	2%	-63%
Sunny Glen	2.1	2.3	2%	8%	0.7	2%	-66%
Lower Hay	4.3	5.7	6%	34%	2.4	6%	-44%
Upper Hay	21	29	32%	36%	10	27%	-54%
Sleeman	9.2	10	11%	13%	5.5	15%	-41%
Cuppup	10	10	11%	0%	6.1	16%	-40%
Lake Saide	1.6	1.2	1%	-21%	0.3	1%	-79%
Nullaki	0.5	0.4	0%	-28%	0.1	0%	-75%
Wilson Inlet	**85**	**92**	**100%**	**9%**	**37**	**100%**	**-56%**

The Lower Hay catchment exceeded its nitrogen target in the basecase, but met its nitrogen targets in both 2040 climate scenarios. Phosphorus targets were met in all cases. The basecase scenario required a nitrogen reduction of 4% as it had a flow-weighted nitrogen concentration of 1.25 mg/L. The stable future climate had a flow-weighted nitrogen concentration of 1.10 mg/L. This was because of a greater proportion of flow from areas of native vegetation in this scenario. A stable or wetter future climate will affect the way we recommend nitrogen management in the Lower Hay catchment.

The Koorabup reporting catchment exceeded targets in both future climate scenarios. In the future climate scenarios, we assumed the volumes of treated wastewater and concentrations of discharge from the treatment plant in 2019–20 continued. A drier future climate would see the Denmark WWTP contribute a greater proportion of the water volume and nutrient load to the Koorabup catchment.

In the drier climate scenario, the upper catchments contribute a smaller proportion of excess nutrients and hence greater focus is placed on lowland catchments, especially the Sleeman, Cuppup and Sunny Glen catchments (Figure 7.45). Of these three catchments, Sunny Glen would have greater flow reductions (66%) than the Sleeman (41%) and Cuppup (40%) catchments. This demonstrates that under declining future rainfall scenarios, management should focus on the Cuppup, Sleeman and Sunny Glen catchments, despite the latter having a relatively smaller impact in the drier climate scenario. This is consistent with recommendations from the basecase.
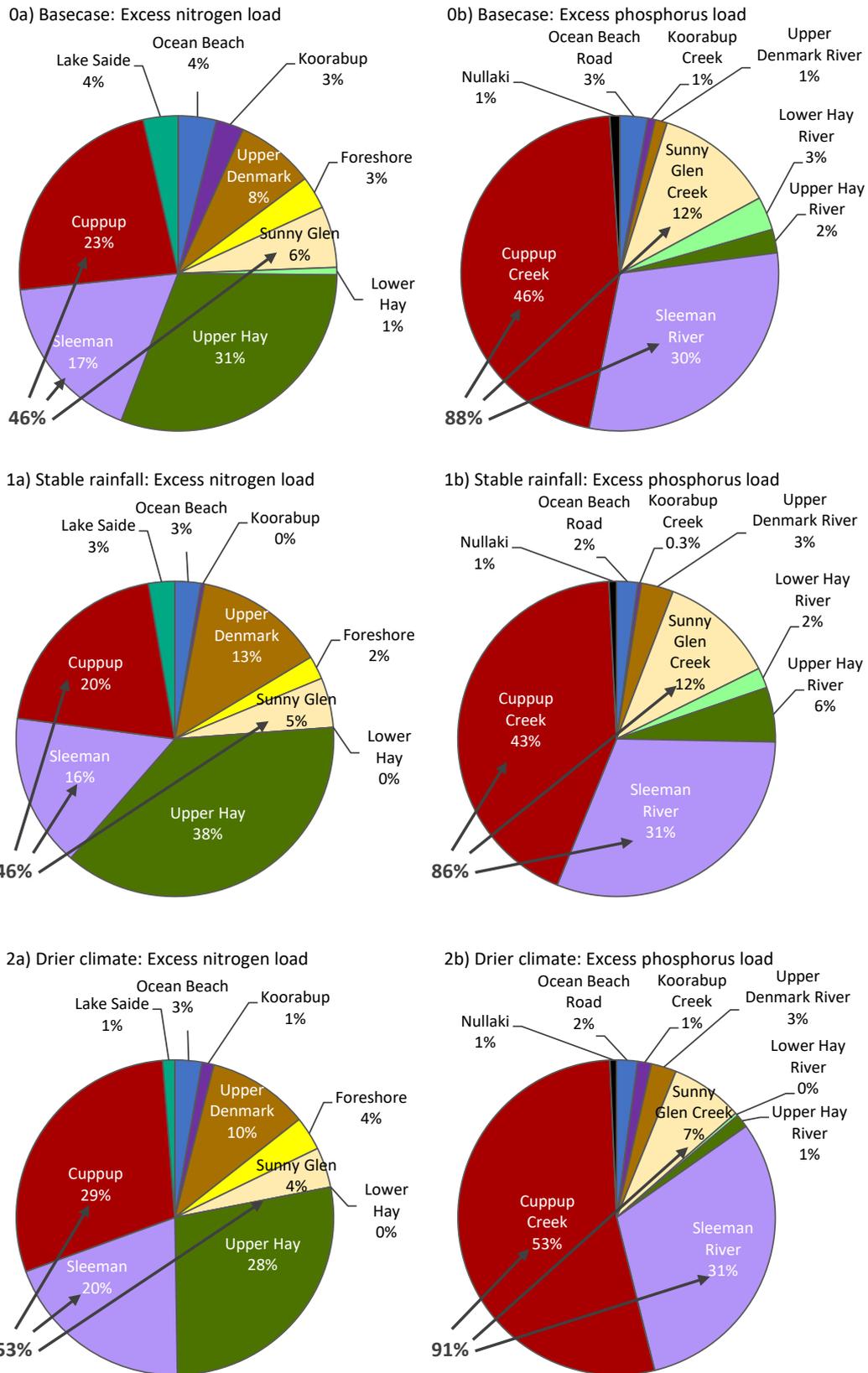
Figure 7.44: Proportion of excess nitrogen (a) and phosphorus (b) loads in the basecase (0), 2040 stable rainfall (1) and drier climate (2) scenarios

Table 7.27: Average annual reporting catchment nitrogen loads, flow-weighted concentrations (FWC) and nutrient-reduction targets in the basecase and 2040 climate scenarios

Reporting catchment	Current nitrogen — Basecase Load (t/yr)	% of total (%)	FWC (mg/L)	Stable rainfall Load (t/yr)	% of total (%)	% diff (%)	FWC (mg/L)	Drier climate Load (t/yr)	% of total (%)	Diff (%)	FWC (mg/L)	Target nitrogen — Base case Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Stable rainfall Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Drier climate Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Excess N — Basecase Excess of target (t/yr)	% of total (%)	Stable rainfall Excess of target (t/yr)	% of total (%)	% diff (%)	Drier climate Excess of target (t/yr)	% of total (%)	% diff (%)
Ocean Beach	2.6	2%	2.16	2.0	2%	-23%	2.20	0.9	2%	-67%	2.26	1.4	45%	2%	1.20	1.1	45%	1%	1.20	0.5	47%	1%	1.20	1.1	4%	0.9	3%	-22%	0.4	3%	-65%
Little River	6.2	6%	1.02	5.7	5%	-8%	1.00	3.5	7%	-44%	1.00	6.2	Maintain	8%	1.02	5.7	Maintain	7%	1.00	3.5	Maintain	10%	1.00	-	-	-	-	-	-	-	-
Koorabup	2.1	2%	2.00	0.8	1%	-60%	1.39	0.7	1%	-67%	1.63	1.2	40%	2%	1.20	0.7	13%	1%	1.20	0.5	26%	2%	1.20	0.8	3%	0.1	0%	-86%	0.2	1%	-79%
Lower Denmark	7.5	7%	0.89	6.1	6%	-19%	0.88	1.9	4%	-75%	1.00	7.5	Maintain	10%	0.89	6.1	Maintain	8%	0.88	1.9	Maintain	6%	1.00	-	-	-	-	-	-	-	-
Upper Denmark	4.6	4%	0.87	9.7	9%	109%	0.85	2.6	5%	-43%	1.00	2.3	51%	3%	0.43	5.2	47%	7%	0.45	1.1	58%	3%	0.42	2.4	8%	4.5	13%	91%	1.5	10%	-36%
Scotsdale	12	11%	1.05	5.1	5%	-56%	0.88	1.8	4%	-84%	0.74	12	Maintain	15%	1.05	5	Maintain	7%	0.88	1.8	Maintain	5%	0.74	-	-	-	-	-	-	-	-
Foreshore	3.6	3%	1.66	2.9	3%	-20%	1.67	1.5	3%	-59%	1.85	2.6	28%	3%	1.20	2.1	28%	3%	1.20	0.9	35%	3%	1.20	1.0	3%	0.8	2%	-18%	0.5	3%	-49%
Sunny Glen	4.4	4%	2.08	4.4	4%	2%	1.96	1.5	3%	-67%	2.05	2.5	42%	3%	1.20	2.7	39%	4%	1.20	0.8	42%	3%	1.20	1.8	6%	1.7	5%	-7%	0.6	4%	-67%
Lower Hay	5.4	5%	1.25	6.5	6%	21%	1.13	2.6	5%	-51%	1.10	5.2	4%	7%	1.20	6.5	Maintain	8%	1.13	2.6	Maintain	8%	1.10	0.2	1%	-	-	-	-	-	-
Upper Hay	21	19%	0.96	28	25%	35%	0.96	9.3	19%	-55%	0.94	15	44%	15%	0.52	15	46%	20%	0.52	5.2	44%	16%	0.53	9.0	31%	13	38%	40%	4.1	28%	-55%
Sleeman	16	15%	1.71	18	16%	10%	1.71	9.5	20%	-42%	1.73	11	32%	14%	1.20	13	30%	16%	1.20	6.6	30%	20%	1.20	5.1	17%	5	16%	3%	2.9	20%	-44%
Cuppup	19	18%	1.87	19	17%	0%	1.87	12	24%	-39%	1.90	12	36%	16%	1.20	12	36%	16%	1.20	7.4	37%	22%	1.20	6.8	23%	7	20%	0%	4.3	29%	-37%
Lake Saide	2.9	3%	1.87	2.4	2%	-18%	1.94	0.6	1%	-80%	1.75	1.9	36%	2%	1.20	1.5	38%	2%	1.20	0.4	31%	1%	1.20	1.0	4%	0.9	3%	-13%	0.2	1%	-83%
Nullaki	0.6	1%	1.16	0.4	0%	-27%	1.17	0.2	0%	-74%	1.22	0.6	Maintain	1%	1.16	0.4	Maintain	1%	1.17	0.2	Maintain	0.5%	1.22	-	-	-	-	-	-	-	-
Wilson Inlet	**107**	**100%**	**1.27**	**111**	**100%**	**3%**	**1.20**	**48**	**100%**	**-55%**	**1.29**	**78**	**27%**	**100%**	**0.92**	**77**	**31%**	**100%**	**0.83**	**33**	**31%**	**100%**	**0.90**	**29**	**100%**	**34**	**100%**	**15%**	**15**	**100%**	**-50%**

Table 7.28: Average annual reporting catchment phosphorus loads, flow-weighted concentrations (FWC) and nutrient-reduction targets in the basecase and 2040 climate scenarios

Reporting catchment	Current phosphorus — Basecase Load (t/yr)	% of total (%)	FWC (mg/L)	Stable rainfall Load (t/yr)	% of total (%)	% diff (%)	FWC (mg/L)	Drier climate Load (t/yr)	% of total (%)	Diff (%)	FWC (mg/L)	Target phosphorus — Base case Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Stable rainfall Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Drier climate Target (t/yr)	Reduction target (%)	% of total (%)	FWC (mg/L)	Excess P — Basecase Excess of target (t/yr)	% of total (%)	Stable rainfall Excess of target (t/yr)	% of total (%)	% diff (%)	Drier climate Excess of target (t/yr)	% of total (%)	% diff (%)
Ocean Beach	0.23	3%	0.192	0.18	2%	-22%	0.199	0.08	2%	-64%	0.213	0.12	48%	2%	0.100	0.09	50%	2%	0.100	0.04	53%	2%	0.100	0.11	3%	0.09	2%	-19%	0.04	2%	-61%
Little River	0.53	6%	0.086	0.47	5%	-10%	0.083	0.29	7%	-45%	0.083	0.53	Maintain	11%	0.086	0.47	Maintain	10%	0.083	0.29	Maintain	13%	0.083	-	-	-	-	-	-	-	-
Koorabup	0.13	2%	0.129	0.07	1%	-44%	0.123	0.07	2%	-47%	0.168	0.10	22%	2%	0.100	0.06	19%	1%	0.100	0.04	41%	2%	0.100	0.03	1%	0.01	0.3%	-52%	0.03	1%	-3%
Lower Denmark	0.20	2%	0.024	0.16	2%	-18%	0.024	0.05	1%	-74%	0.027	0.20	Maintain	4%	0.024	0.16	Maintain	3%	0.024	0.05	Maintain	2%	0.027	-	-	-	-	-	-	-	-
Upper Denmark	0.14	2%	0.026	0.34	4%	137%	0.030	0.10	2%	-30%	0.037	0.09	34%	2%	0.018	0.20	40%	4%	0.018	0.05	53%	2%	0.018	0.05	1%	0.14	3%	185%	0.05	3%	10%
Scotsdale	0.49	6%	0.044	0.22	2%	-55%	0.038	0.08	2%	-84%	0.032	0.49	Maintain	10%	0.044	0.22	Maintain	5%	0.038	0.08	Maintain	3%	0.032	-	-	-	-	-	-	-	-
Foreshore	0.19	2%	0.088	0.15	2%	-18%	0.091	0.07	2%	-64%	0.087	0.19	Maintain	4%	0.088	0.15	Maintain	3%	0.091	0.07	Maintain	3%	0.087	-	-	-	-	-	-	-	-
Sunny Glen	0.69	8%	0.326	0.72	8%	4%	0.315	0.22	5%	-68%	0.312	0.21	69%	4%	0.100	0.23	68%	5%	0.100	0.07	68%	3%	0.100	0.48	12%	0.49	12%	3%	0.15	7%	-68%
Lower Hay	0.56	6%	0.131	0.66	7%	17%	0.115	0.25	6%	-56%	0.103	0.43	24%	9%	0.100	0.57	13%	12%	0.100	0.24	3%	10%	0.100	0.13	3%	0.09	2%	-36%	0.01	0%	-95%
Upper Hay	0.47	5%	0.022	0.74	8%	56%	0.025	0.20	5%	-57%	0.020	0.38	20%	8%	0.018	0.51	31%	10%	0.017	0.17	14%	8%	0.017	0.09	2%	0.23	6%	146%	0.03	1%	-70%
Sleeman	2.10	24%	0.227	2.32	26%	10%	0.221	1.18	27%	-44%	0.215	0.92	56%	19%	0.100	1.05	55%	22%	0.100	0.55	53%	24%	0.100	1.17	30%	1.27	31%	8%	0.63	31%	-46%
Cuppup	2.80	32%	0.275	2.80	31%	0%	0.274	1.69	39%	-40%	0.277	1.02	64%	21%	0.100	1.02	64%	21%	0.100	0.61	64%	27%	0.100	1.78	46%	1.78	43%	0%	1.08	53%	-39%
Lake Saide	0.09	1%	0.060	0.08	1%	-14%	0.066	0.02	0%	-80%	0.056	0.09	Maintain	2%	0.060	0.08	Maintain	2%	0.066	0.02	Maintain	1%	0.056	-	-	-	-	-	-	-	-
Nullaki	0.09	1%	0.175	0.07	1%	-24%	0.184	0.03	1%	-71%	0.207	0.05	43%	1%	0.100	0.04	46%	1%	0.100	0.01	52%	1%	0.100	0.04	1%	0.03	1%	-19%	0.01	1%	-65%
Wilson Inlet	**8.72**	**100%**	**0.103**	**8.98**	**100%**	**3%**	**0.097**	**4.32**	**100%**	**-50%**	**0.116**	**4.83**	**45%**	**100%**	**0.057**	**4.86**	**46%**	**100%**	**0.053**	**2.29**	**47%**	**100%**	**0.062**	**3.89**	**100%**	**4.12**	**100%**	**6%**	**2.04**	**100%**	**-48%**

8   Discussion

Priority catchments for future management

Highest priority: Cuppup, Sleeman and Sunny Glen Creek

The Cuppup, Sleeman and Sunny Glen catchments contribute 37% of the nitrogen load and 64% of the phosphorus load to Wilson Inlet. Of the nutrient load **in excess of targets**, about 47% of the excess nitrogen load and 88% of the excess phosphorus load come from these catchments.

Thus, meeting the nutrient load targets for Wilson Inlet is not possible unless these catchments are effectively managed. Flow and water quality are measured in these catchments, hence it is possible to track the long-term efficacy of their management.

Fertiliser management should be promoted to manage phosphorus in these catchments. The reworking of subsoil clays and other soil amendments should then be investigated and implemented in these catchments if feasible. Dairy effluent management would have the greatest benefit in the Sunny Glen catchment and is worth considering in the Sleeman catchment.

High priority

The **Ocean Beach Road** catchment has the greatest intensity of nutrient loss per cleared area. Rainfall in this catchment is among the highest over the entire Wilson Inlet catchment and it has large areas of soils with poor phosphorus retention. However, due to its small size (10 km^2 or 0.4% of the Wilson Inlet catchment area) and large area of native vegetation (75% of the catchment area), it only contributes about 2% and 3% of the nitrogen and phosphorus load to Wilson Inlet respectively. In terms of excess nutrient loads, about 4% and 3% of the excess nitrogen and phosphorus come from the Ocean Beach catchment. Although small, the catchment has a similar excess phosphorus load (0.11 tonnes/yr) as the Upper Hay catchment (0.09 tonnes/yr), which has a cleared catchment area 250 times greater than Ocean Beach.

We estimated that about 38% of the nitrogen and 61% of the phosphorus load in the Ocean Beach catchment came from a limited number of beef farms. Working with these farms through future soil-testing programs would benefit water quality by reducing offsite nutrient losses and might also boost farm profitability. This catchment would also benefit from the use of suitable low-water-soluble phosphorus fertilisers and soil amendments, given that 72% of the area of beef farming has low-PRI soils.

Ocean Beach is a lower priority than the Cuppup, Sleeman and Sunny Glen catchments because improvements to it would reduce absolute nutrient loads by only a small amount. In addition, it is an unmeasured catchment and ideally, the investment in management actions should be targeted at catchments where improvements can be detected.

Macroalgae is commonly seen growing in the shallow areas of Wilson Inlet adjacent to catchment drains (see Figure 8.1). This suggests that nutrients from the Ocean Beach catchment are having a localised impact in the inlet. Therefore, managing nutrient loss from

this catchment could see local improvements, thus strengthening the case for targeted management in this catchment.

Although not explicitly modelled, the exclusion of livestock and revegetation of the Wilson Inlet floodplain where it is used for grazing adjacent to Ocean Beach Road should be considered (see Figure 8.1). This area is essentially part of Wilson Inlet given it floods each year. The surface elevation of this land grades from about 0.1 to 1.2 mAHD from Ocean Beach Road to 175 m to the west. Use of this area for cattle grazing contributes nutrients through animal excretions to standing water, as well as the loss of fertilisers (if used).

Figure 8.1: Farmland adjacent to Ocean Beach Road where fencing and revegetation would be beneficial (although these were not modelled). The top figure shows areas < 1.2 m AHD. The bottom photo shows the water quality issues common to the adjacent area of Wilson Inlet.

Koorabup: As discussed in Section 7.3.7, upgrades to the WWTP have resulted in nutrient loads below catchment targets. However, as the population grows, increases in the volume of discharge from the Denmark WWTP will eventually exceed catchment nutrient-load targets. While constraints exist, there are likely enough recreational and public open space areas to use current and future volumes of treated wastewater for their irrigation. This would require the construction of additional water storage. If all environmental discharge were to cease, storage volumes of about 150 to 200 ML would be needed. For context, this would require a dam that is at least about a third of the volume of the Denmark dam (~450 ML), or 1.4 times the volume of the private dam (2) in the Little River catchment (estimated volume of 109 ML). Alternatively, the town could consider becoming the first town to recycle treated wastewater for potable uses. This would, however, raise the issue of the disposal of concentrated brine from the reverse osmosis process.

Moderate priority

Nutrient management is required in the following catchments, but would be less impactful for reducing nutrient inflows to Wilson Inlet than the catchments discussed thus far:

- **Lower Hay:** nitrogen and phosphorus loads exceed targets. About 56% of the area of beef and dairy farms has low-PRI soils. This catchment is the next most important location to invest in management actions after those previously discussed.

- **Foreshore:** nitrogen exceeds targets and nitrogen loss intensity is the third highest. About half the nutrient load is estimated to be derived from septic tanks. Although management actions targeted at agriculture and riparian zones would be beneficial, substantial improvements would come from connecting septic tanks to reticulated sewerage or replacing septic tanks with onsite sewerage systems that have improved nutrient removal.

- **Lake Saide:** nitrogen exceeds targets but makes up 3% of the nitrogen load to Wilson Inlet. However, we have not considered the water quality and ecological benefit of management actions for Lake Saide (Eungedup wetlands) and Nenamup Inlet.

- **Upper Denmark** and **Upper Hay**: nitrogen and phosphorus loads exceed targets. However, because these catchments have a low intensity of nutrient loss and are the largest by area, management here would remove less nutrients than other catchments.

Investing in nutrient management actions would be beneficial in these *moderate-priority* catchments. However, if resources are limited, nutrient management in these catchments should be prioritised only if:

- Intensive sources of nutrients are being managed, such as intensive animal industries, point sources or there is evidence to suggest that soil phosphorus content could be excessive (e.g. soil test results, excessive fertiliser use considering the soils of the farm).

- Landowners in higher-priority catchments are unwilling to participate.

- Management actions could result in multiple beneficial effects, such as habitat restoration for threatened riverine biota, the provision of biodiversity corridors and the protection of existing habitat.

- Implementing soil-testing programs more broadly could help build a community of practice and normalise its widespread use for environmental and economic benefits.

- Investigations into the fate and impacts of nutrients in the inlet provide new information that warrants management attention. Note that studies could also find that the fate and impacts of nutrients from some catchments are acceptable, thus lowering their priority for management.

Note that the above is intended to serve as a high-level guide and does not exhaust all possible criteria that could justify nutrient management in these catchments when resources are limited.

Other catchments

The following catchments have a lower and more nuanced priority for management. Management in these catchments can be pursued using the same reasoning described for moderate-priority catchments.

- **Little River:** nitrogen and phosphorus are below targets. Little River has the highest flow yield (flow per unit area) and thus has a moderate to high intensity of nutrient loss, despite nutrients being below targets. About 45% of the beef farm area in the Little River catchment has been part of the REI soil-testing program. Ideally, government and natural resource managers would continue to work collaboratively with farmers in the catchment toward best-practice fertiliser use given soil-test results warrant further action. Improvements in farm fertiliser use would further reduce nutrient loss below targets, thus offsetting nutrient loss elsewhere in the Wilson Inlet catchment.

- **Lower Denmark** and **Scotsdale**: nitrogen and phosphorus are below targets.

- **Nullaki:** phosphorus exceeds targets but makes up 1% of the phosphorus load to Wilson Inlet. There are several landowners in the cleared areas of the Nullaki catchment. Management actions such as fertiliser management could be effective if these landowners were receptive. WICC fenced all of the drains in this catchment, supported by REI funding.

The impacts of future land-use change

See Section 7.1 for a scenario that modelled the impacts of possible urban expansion by 2050. Using the same climate drivers as 2010–19, urban expansion increased average annual flow and loads of nitrogen and phosphorus to Wilson Inlet by 0.5%, 4% and 3% respectively. About 1,552 ha of land was developed in the scenario, which is about 0.6% of the Wilson Inlet catchment area. This small area of development resulted in higher intensities of nutrient loss, which were about six times greater than the pre-development land uses. The impacts of future urban development can be mitigated by good practice informed by models such as the UNDO tool, including adopting the principles of water sensitive urban design.

A separate scenario examined the effect of large-scale reversion of plantations to beef grazing. The reversion of 14,400 ha of plantations (6.4% of the Wilson Inlet catchment) increased average annual flow and loads of nitrogen and phosphorus by 11%, 15% and 23% respectively. This scenario had a large impact on flows and nutrient loads but also affected a

larger area than the urban expansion scenario. Comparing the nutrient loss per unit area of land-use change, nitrogen and phosphorus loss in the urban expansion scenario were 2.6 and 1.4 times greater respectively than the basecase.

Combined management actions

Extensive implementation of combined management actions

We modelled six land-management scenarios to estimate their potential for nutrient removal and individual impact towards achieving the catchment nutrient targets (see Figure 8.2). We modelled the management scenarios at or near maximum adoption and found that no individual management action could reduce nutrients enough to meet targets for Wilson Inlet. Therefore, multiple catchment-wide actions are required to improve water quality in the inlet and its catchment. We have modelled the following management actions assuming a treatment train[30]:

1. Agricultural actions:

   a. All beef and dairy farms adopt best-practice fertiliser management.

   b. All beef, dairy and horticulture farms with low-PRI soils apply soil amendments or incorporate suitable subsurface clays into topsoils to increase soil P retention and decrease nutrient losses.

   c. All dairy sheds use best-practice effluent management.

2. Non-agricultural actions:

   a. Fencing and re-vegetation of the 1,776 km of streams and drains that potentially require management.

   b. The targeted removal of 714 septic tanks in the areas around Ocean Beach, Weedon Hill and along Inlet View Drive.

   c. Long-term discharge from the Denmark WWTP (post 2015 upgrade) is assumed.

3. All actions described above (agricultural and non-agricultural).

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[30] A **treatment train** of management actions sequentially treats nutrients by actions that operate at the source of nutrient loss (e.g. fertiliser management) and actions that operate in the transport pathways (e.g. riparian zone rehabilitation).
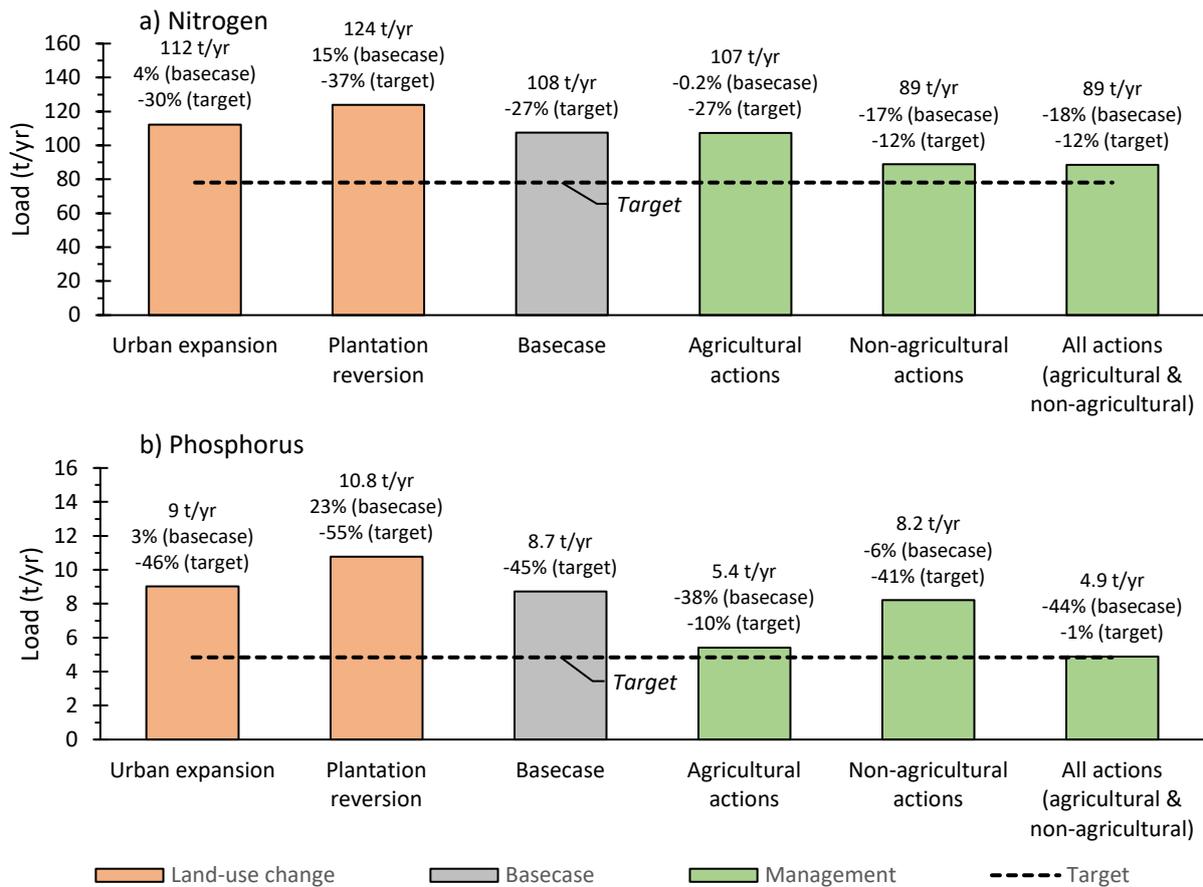
Figure 8.2: Average annual nitrogen and phosphorus loads to Wilson Inlet for the basecase, target and land-use change scenarios and combined management action scenarios

Agricultural actions reduced nitrogen loads by **0.2%** (0.3 tonnes/yr) and phosphorus loads by **38%** (3.3 tonnes/yr). Dairy effluent management was the only management action that affected nitrogen loads, which had a small impact at the catchment scale. The fertiliser management scenario focused only on phosphorus, with nitrogen being unaffected. Farm-gate nutrient surveys show that nitrogen fertiliser is only 2% of beef inputs and 17% of dairy inputs (see Table E.1 in Appendix E). In addition, guidelines for nitrogen fertiliser use may result in greater nitrogen fertiliser use than indicated by farm-gate surveys, to the benefit of productivity but not necessarily the environment. These guidelines also give valuable strategies to reduce offsite losses of nitrogen fertilisers, which were not modelled in this project.

Phosphorus management was much more impactful. Although the phosphorus target for Wilson Inlet catchment was not achieved (reduction of 45%), reporting catchment targets were met in three catchments (Lower Hay, Upper Hay and Nullaki) with another three being within 1% of the target (Ocean Beach Road, Sunny Glen Creek and Sleeman). Importantly, the Sunny Glen and Sleeman catchments are two of the three catchments with the highest loads of phosphorus. Further reductions of 6% (0.57 tonnes/yr) would be required to meet the phosphorus target for Wilson Inlet.

Non-agricultural actions reduced nitrogen loads by **17%** (18.8 tonnes/year) and phosphorus loads by **6%** (0.5 tonnes/year). Most of the nitrogen load removal was from riparian management, which is the most effective management action for nitrogen

management. Although the nitrogen targets for Wilson Inlet (27%) were not met, reporting catchment targets were met in the Foreshore and Lower Hay catchments.

All management actions reduced nitrogen loads by **18%** (19.0 tonnes/year) and phosphorus loads by **44%** (3.8 tonnes/year), which is within 1% of the phosphorus target. The scenario did not meet the overall target for nitrogen, although it did meet the nitrogen targets in the same two reporting catchments as the non-agricultural scenario (Foreshore and Lower Hay). For phosphorus, seven reporting catchments met their targets (Ocean Beach Road, Koorabup, Sunny Glen, Lower Hay, Upper Hay, Sleeman and Nullaki).

Regional Estuaries Initiative management actions

We modelled the combined effect of REI-funded management actions in Wilson Inlet:

- **Best-practice fertiliser management**: 133 km^2 of beef and dairy farms were part of the REI-funded soil-testing program (see Table 7.14). This program helped farmers adopt best-practice fertiliser management – it included soil testing, results mapping, fertiliser recommendations and farmer workshops to explain the process and encourage long-term adoption.

- **Dairy effluent management:** upgrades to a dairy farm in the Sunny Glen catchment.

- **Riparian management:** 26 km of fencing (see Table 7.9).

We estimate that these actions reduced nitrogen loads by **0.3%** (0.3 tonnes/year) and phosphorus loads by **4%** (0.37 tonnes/year). The selection of farms and fencing sites for REI-funded management actions generally required farmers to reply to an expression of interest and co-fund a portion of the management action. A minimum of 40 ha of arable land was also required for a farm to take part in the soil-testing program. Farmers who had never been part of a farm extension program were encouraged to apply. Yet some were reluctant to be part of a government-funded program and/or employed their own agronomists.

Targeted actions in the Sleeman, Cuppup and Sunny Glen Creek catchments

To highlight the importance of the Sleeman, Cuppup and Sunny Glen catchments, we modelled the impact of undertaking a similar magnitude of actions as the REI. However, actions were implemented exclusively in these three catchments. This involved:

- **Best-practice fertiliser management**: all beef and dairy farms in the Cuppup (47 km^2), Sleeman (86 km^2) and Sunny Glen catchments (16 km^2) were assumed to adopt best-practice fertiliser management in the long-term. This area is 114 km^2, which is about 86% of the area of REI-funded soil testing (133 km^2).

- **Dairy effluent management:** upgrades to a dairy farm in the Sunny Glen catchment.

- **Riparian management:** 26 km of fencing in the Cuppup catchment.

The long-term effect of the combined management actions above reduced nitrogen loads by an estimated 0.5% (0.5 tonnes/yr) and phosphorus loads by 15% (1.3 tonnes/yr). Most of the phosphorus reduction came from best-practice fertiliser management. By targeting the latter, larger reductions in nutrient export are possible on a per hectare basis than what was observed in the REI program.

Engaging as many farmers as possible from the priority catchment areas in fertiliser extension programs would result in the greatest reduction in phosphorus loss to the inlet. Riparian management results in modest reductions in nutrient export, however it provides multiple benefits to water quality and ecology.

In the Sunny Glen catchment, a dairy effluent upgrade was funded through the REI. There is merit to pursuing future dairy effluent upgrades in the Sleeman catchment. However, dairies that are closest to Wilson Inlet (e.g. Lower Denmark, Lower Hay) could also be considered. Any future incentives for dairy effluent upgrades could be targeted at any of these dairies, if their standard of dairy effluent management was found to be low.

Further investigation: soil amendments and soil mapping

Amending sandy topsoils with local clays

There is merit in investigating the feasibility, benefits (environmental and agronomic) and costs of amending sandy agricultural topsoils with subsurface or extracted[31] soils with high phosphorus retention. In the absence of suitable low-cost soil amendments (e.g. IMG), utilising subsoil or locally extracted clays are the only viable methods for improving soil phosphorus retention in the Wilson Inlet catchment. The maximum phosphorus load removal under the 'all management actions' scenario would be 29% without soil amendments compared with 44% when it is included (see 'all actions' in Figure 8.2).

Preliminary trials are underway on a dairy farm in the Sunny Glen catchment. Further investigations may be required, such as:

- Identify and assess potential soil amendments that could have agronomic and environmental benefits in the lower Wilson Inlet catchment. Emphasis should be on the catchment's lower east region.

- Assess the agronomic and environmental (phosphorus loss) feasibility of incorporating subsurface or local clays into topsoils, as well as their likely costs. The context of such studies relate to its application on beef, dairy and horticulture farms.

- Map the location and depth of soils that are suitable for use as amendments. If required, map the associated risks of such soils if they are identified.

Soil-phosphorus-retention mapping

We found disparities between the soil-phosphorus-retention mapping and the whole-farm nutrient mapping (see Section 7.3.2). We used the former to represent soils with greater phosphorus loss in the model – see Figure 2.24 and Figure 3.17.

These disparities were most noticeable in the Cuppup and Sleeman catchments, where less than 1% and 7% of their catchment area has low-PRI soils respectively. About 20% (Cuppup) and 30% (Sleeman) of the whole-farm nutrient mapping area indicated low-PRI

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[31] Ploughing to mix subsoils into sandy topsoils or the extraction of soils elsewhere on the farm or locally that are top-dressed and mixed into sandy topsoils.

soils (i.e. PBI values < 35). Visually, the topsoils in some areas of these catchments seem sandy, based on aerial photography and site visits (see photos in Figure 2.23).

If these discrepancies are caused by errors in the soil PRI mapping, then the basecase model may be affected. Differences in the source separation are possible depending on the location of low-PRI soils and land uses. However, it is unlikely the basecase nutrient loads, concentrations or targets would be substantially different – if the model were recalibrated – as they are based primarily on measured data.

A larger area of low-PRI soils allows for broader implementation of management actions that target low-PRI soils, particularly soil amendments. Hence, the potential phosphorus reductions for these scenarios (individually and combined) may be greater than reported, and the phosphorus targets may be slightly easier to achieve.

Given the importance of these catchments to nutrient management, efforts to investigate and revise existing mapping are warranted. However, discrepancies in the PRI mapping were present elsewhere in the Wilson Inlet catchment. Therefore, reviewing the soil PRI mapping more broadly may be beneficial.

The impacts of future climate

In Section 7.4 we detail our process to assess the impact of future climate and its impact on nutrient concentration targets compared with the basecase (and hence its impact on management recommendations). Our assessment followed the department's climate assessment framework and used future climate data from the Bureau of Meteorology's National Hydrological Projections (NHP). Out of 32 NHP future climate sequences, we used two scenarios that bookended the range of plausible future climates. These were from 2025–54 (i.e. centred around 2040) and represented:

- **A stable rainfall scenario** with similar rainfall totals to the past 30 years. This is one of the higher rainfall projections in the NHP dataset for the region.

- **A drier future climate** that is hotter and dryer than the past 30 years, with about 13% less rainfall than the past decade. This is one of the drier projections from the NHP dataset.

From the range of potential future climates we assessed, we found relatively small changes to nutrient reduction would be required to meet targets in the future. The nitrogen load reduction target was 31% for both future climate scenarios (although a reduction of 27% was required for the basecase) and the phosphorus reduction target was between 46 and 47%. These results show that while there is some risk a future climate will require slightly greater nutrient load reductions, the approach (setting nutrient-reduction targets using concentrations rather than loads) is relatively robust irrespective of changes to climate.

If the climate is wetter compared with the past two decades, which is also a plausible future, higher nutrient loads will be delivered to the inlet, with larger contributions from the Upper Denmark and Hay catchments. If the climate is drier, then lower nutrient loads will be delivered to the inlet, with the Sleeman and Cuppup catchments contributing a greater proportion of nutrients.

Climate change, particularly a drier climate, could impact water quality in Wilson Inlet in other ways that were not part of our assessment:

- Less estuary flushing and the potential for a greater number of years that the sandbar does not open at all.

- Higher residence time for nutrients and increased stagnation of the estuary waterbody.

- A hotter future climate (which is likely) will encourage more rapid algal growth than we have seen historically.

Climate change adaptation

The results of our modelling demonstrate the range of potential impacts to streamflow that may arise from future climate scenarios. Nevertheless, we have not assessed the reliability of supply for town water supply schemes, private dams or groundwater resources. Adapting to climate change is a multifaceted challenge that presents numerous risks to a region, such as sea-level rise, bushfires, extreme weather events and the reliability of water resources. Local governments can use the following resources as part of their efforts to address climate change:

- The Western Australia Local Government Association (WALGA) Climate Change Action Framework and supporting action planning templates.

- Climate change risk management guide (interim), Climate risk assessment tool, and Western Australian climate projections summary – note these resources are intended for public sector agencies but may also provide a useful guide for local governments.

- In development: WALGA is finalising a climate risk assessment manual specific to the local government sector – please contact WALGA for more information.

- Guidelines for natural resource managers in adapting to climate change can be found here.

9   Conclusions

Catchment flow volumes and nutrient loads have shown increasing variability since 2000, marked by numerous drought and high-flow years. Despite this, several catchments still have nutrient concentrations far exceeding the target levels needed to support a healthy river and estuarine ecology. While some catchments are below nutrient targets, during 2010–19 the total catchment inflow to Wilson Inlet had excess nitrogen and phosphorus loads of 27% and 45% respectively.

This study estimated nutrient loads to Wilson Inlet for the period 2010–19. We derived load targets based on nutrient concentration targets in the inflowing rivers. For lowland rivers (<150 mAHD elevation), the concentration targets were a flow-weighted nitrogen concentration of 1.2 mg/L and a flow-weighted phosphorus concentration of 0.1 mg/L. For upland rivers (≥150 mAHD), the flow-weighted concentration targets were 0.45 mg/L for nitrogen and 0.02 mg/L for phosphorus. These concentration targets led to maximum acceptable loads to the inlet of about 78 tonnes for nitrogen and 4.8 tonnes for phosphorus during the 2010–19 modelling period. To achieve the targets, current loads – 108 tonnes of nitrogen and 8.7 tonnes of phosphorus – must be reduced by 30 tonnes (27%) for nitrogen and 3.9 tonnes (45%) for phosphorus.

Three catchments – Cuppup, Sleeman and Sunny Glen – contribute roughly 37% of the nitrogen load and 64% of the phosphorus load to Wilson Inlet. About 47% of the excess nitrogen load and 88% of the excess phosphorus load originate from these three catchments. These catchments should therefore be prioritised for future management actions to reduce nutrient loss.

Our scenario modelling examined the relative benefits of land-use and management changes. This determined that no management action alone or combined would achieve the required load reductions for Wilson Inlet, although some would be able to meet nutrient targets within some reporting catchments.

As most of the nutrient load to the inlet originates from beef and dairy farms (accounting for about 75% of the nitrogen and phosphorus load), implementing better management practices on these farms would result in the most significant load reductions. A scenario incorporating soil amendments (reworking subsurface clays) and managing dairy effluent fertilisers achieved a 39% reduction in phosphorus load; however, nitrogen reduction was less than 1%. Nitrogen was not significantly affected as these measures primarily targeted phosphorus fertiliser usage or aimed to retain phosphorus. When all possible management actions were combined, including stream rehabilitation and septic tank removal, the phosphorus reduction target of 45% was met. The nitrogen load was reduced by 18% due to extensive fencing and stream rehabilitation efforts, but was still short of the reduction target of 27%. Therefore, like other investigated catchments such as the Peel-Harvey and Geographe/Vasse-Wonnerup, the phosphorus target can be achieved through substantial collective effort and investment, while the nitrogen target remains unattainable with the management actions available at present.

The State Government has funded farm soil testing and fertiliser management programs in the Wilson Inlet catchment through programs including Regional Estuaries Initiative (REI)

and Healthy Estuaries WA. These programs support farmers to make informed fertiliser decisions to reduce excessive fertiliser use and offsite losses of nutrients, particularly phosphorus. Soil-testing programs (including those funded through the REI) have tested nearly 180 ha of farmland (31%). If all the participants followed advice from the programs, long-term phosphorus loss to the inlet would be reduced by 6%. If 100% of beef and dairy farms adopted appropriate fertiliser management, phosphorus loads would decrease by about 29%.

Shire town planning schemes specify where future development may occur. Using the local schemes, we estimated the urban and industrial (light industry or abattoirs) development by 2050 that would be realistically allowed given the current supply of dwellings and the development of new land uses. We accounted for the ability to connect to deep sewerage or the use of onsite wastewater disposal. We estimated that by 2050, nitrogen and phosphorus loads could increase by 3 and 4% because of the development of 0.6% of the catchment (1,554 ha). Therefore, although future development made a relatively small increase in nutrient loads, the affected area was also small. Nitrogen and phosphorus loss per hectare of developed area increased seven to eight fold. This large increase in nutrient loss per unit area was primarily due to the removal of low-nutrient-exporting land uses (e.g. native vegetation in 21% of development area) and the use of septic tanks.

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