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

Hydrological and nutrient modelling of the Peel-Harvey estuary catchment

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Cover photograph: The Peel-Harvey estuary, Mandurah, Western Australia (F. Bunny)

Disclaimer

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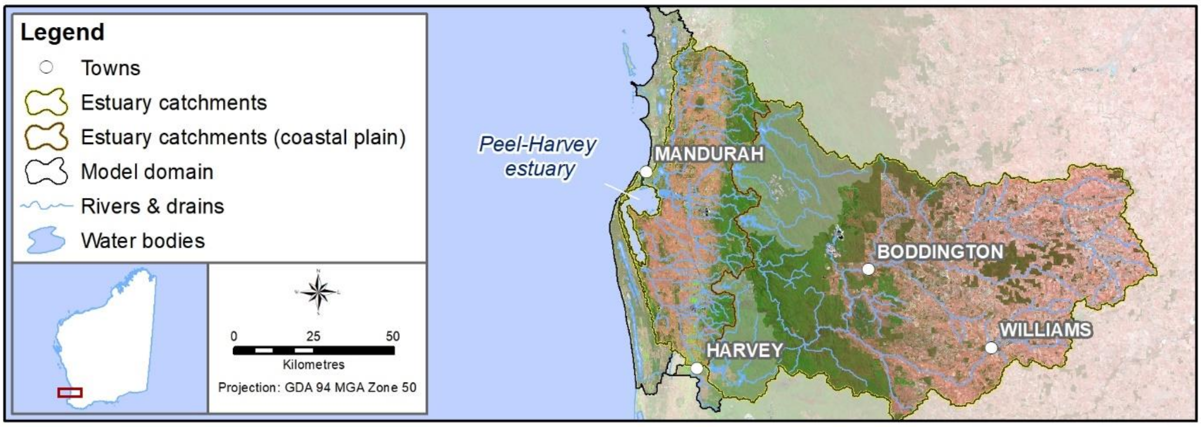
Summary

The Peel-Harvey estuary is located about 70 kilometres south of Perth, Western Australia, and is adjacent to the city of Mandurah. The estuary is internationally significant due to its Ramsar listing and is highly valued by the Bindjareb Noongar people. The estuary's two basins, the Peel Inlet and Harvey Estuary, support tourism and various recreational activities such as crabbing, fishing and boating. They also support a waterside lifestyle for the locals. Yet the estuary has a long history of ecological problems caused by excess nutrients (nitrogen and phosphorus). Actions to fix these problems began in the 1980s and continue to this day. The catchment is experiencing unprecedented drying caused by climate change, as well as land development pressures (urban and agricultural) and water abstraction.

We used a catchment model in this study to estimate the flow and nutrient loads to the Peel-Harvey estuary for the current period and a range of scenarios.



Flow and nutrient model

This study used the hydrological models GR4J and SYMHYD, as well as the Source power function model, to estimate river flow and nutrient loss (nitrogen and phosphorus) from catchments that drain to the Peel-Harvey estuary and adjacent catchments that drain to the ocean.

We calibrated the flow and nutrient models against flow and nutrient concentration data. We amalgamated 100 modelling catchments into 24 reporting catchments: four of these (Coastal North, Coastal Central, Coastal South and Harvey Diversion Drain) flow to the coast and the remainder flow to the Peel Inlet and Harvey Estuary. For the reporting period 2006–15, the average annual nitrogen and phosphorus basecase loads for these different domains for the reporting period (2006–15) were:

	Flow (GL)	Nitrogen load (t)	Phosphorus load (t)
Estuary	370	633	60
Coastal	43	134	22
Harvey Diversion Drain	12	49	7.6

We used concentration targets of 1.2 mg/L nitrogen and 0.1 mg/L phosphorus to derive load targets for rivers flowing to the estuary for the reporting period. Nutrient load targets to the estuary are 350 tonnes of nitrogen and 25 tonnes of phosphorus. The basecase 2006–15 loads – 633 tonnes of nitrogen and 60 tonnes of phosphorus – need to reduce by 284 tonnes (45%) for nitrogen and 35 tonnes (58%) for phosphorus to achieve the load targets.

Nutrient sources

Most nutrients flowing to the estuary are from the coastal plain portion of the catchment. Beef farming, which occurs almost exclusively on the coastal plain, contributes 393 tonnes (62%) of the nitrogen and 40 tonnes (67%) of the phosphorus load even though it only occupies 11% of the estuary's catchment. Cropping (12%), dairying (6.8%), intensive animal industries (3.8%) and septic tanks (3.7%) are the next-largest contributors of nitrogen load. Intensive animal industries have the largest nitrogen loads per unit area. After beef farming, the other main contributors of phosphorus load are dairy farming (8.1%), horticulture (7.3%), horses (5.5%) and septic tanks (2.6%). Horticulture has the largest phosphorus loads per unit area.

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 will use this scenario modelling to guide future planning and management decisions. The work will also support the *Peel-Harvey estuary protection plan (Bindjareb Djilba)* and the new *Water quality improvement plan for the Peel-Harvey estuary system*.

An **urban development** scenario saw little change in nutrient loads compared with the basecase (which used land use and climate for the period 2006–15). By contrast, a proposal for **agricultural development** (3,000 ha of in-ground horticulture) in the Peel Food Zone in the Nambeelup catchment saw large load increases to the estuary (18% for nitrogen and 37% for phosphorus). For Nambeelup to meet its targets, the largest load reductions of all the catchments must occur: 69% for nitrogen and 84% for phosphorus.

An increased area of horticulture or intensive animal industries in Nambeelup would further degrade the Peel-Harvey estuary. The choice of Nambeelup catchment for agricultural intensification shows poor planning and is contrary to the longstanding effort of many individuals, catchment groups and governments to improve the estuary's ecological health.

We modelled 11 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. Large-scale catchment re-vegetation
7. Intensive nutrient sources
8. Wastewater treatment plant (WWTP) management
9. Septic tank removal
10. Water sensitive urban design (WSUD) retrofitting

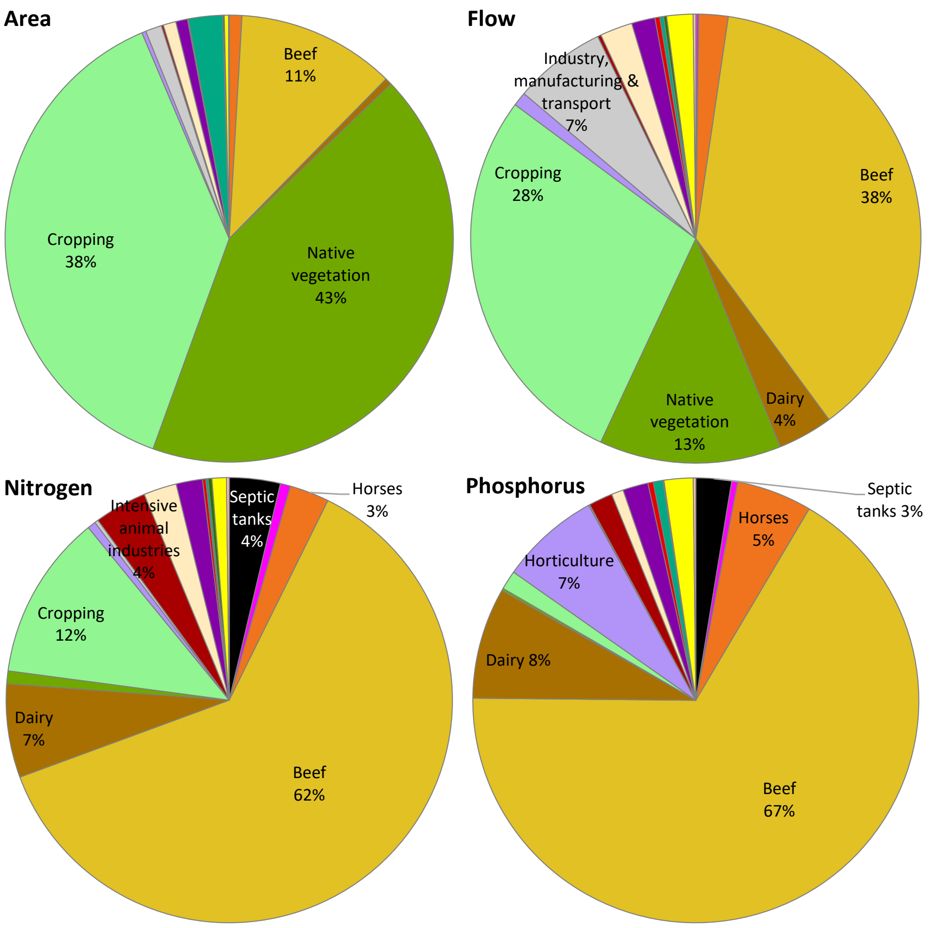
11 Constructed wetlands

No action alone could achieve the nutrient load targets.

Land-use areas and flow, and nutrient load contributions to the Peel-Harvey estuary

Land use	Colour	Area (km^2)	(%)	Flow (GL)	(%)	Nitrogen (tonnes)	(%)	Phosphorus (tonnes)	(%)
Septic tanks			-	0.2	0.1	23	3.7	1.6	2.6
Point source		1	0.0	0.5	0.1	4.7	0.7	0.3	0.4
Horses		84	0.9	7.7	2.1	18	2.9	3.3	5.5
Beef		1 073	11	139	38	393	62	40	67
Dairy		46	0.5	15	4.0	43	6.8	4.9	8.1
Native vegetation		4 008	43	48	13	5.9	0.9	0.1	0.2
Cropping		3 577	38	104	28	76	12	0.8	1.4
Horticulture		28	0.3	3.7	1.0	3.8	0.6	4.4	7.3
Industry, manufacturing & transport		110	1.2	24	6.6	1.7	0.3	0.1	0.1
Intensive animal industries		13	0.1	0.9	0.2	24.0	3.8	1.0	1.7
Lifestyle block		86	0.9	8.6	2.3	15.2	2.4	0.5	0.9
Mixed grazing		80	0.8	6.2	1.7	12.0	1.9	1.1	1.8
Offices, commercial & education		6	0.1	1.3	0.4	1.5	0.2	0.2	0.4
Plantation		231	2.5	1.0	0.3	1.0	0.2	0.4	0.7
Recreation		10	0.1	0.8	0.2	1.8	0.3	0.0	0.1
Residential		29	0.3	7.0	1.9	6.6	1.0	1.3	2.1
Viticulture		4	0.0	0.7	0.2	1.2	0.2	0.1	0.2
Total		**9 388**		**369**		**633**		**60**	

Relative land-use areas and flow, and nutrient load contributions to the Peel-Harvey estuary:



Scenarios (continued)

A farm management scenario (**best-practice agriculture**) of:

- 100% adoption of best-practice fertiliser management and use of low-water-soluble phosphorus fertilisers on low-PRI soils
- soil amendment of all low-PRI soils on beef and dairy farms (502 km^2)
- 100% dairy effluent management
- management of all intensive animal industries on the coastal plain (piggeries, poultry, abattoirs, feedlots and stockyards)

almost achieved the phosphorus load target to the estuary.

A scenario that used other management actions (**non-agricultural actions**), that is:

- re-vegetating 248 km^2 of the coastal plain with native vegetation
- stock exclusion and re-vegetation of 1,394 km of waterways
- the removal of 1,074 septic tanks adjacent to the estuary
- WSUD retrofitting to existing urban areas

did not meet either the nitrogen or phosphorus target for the estuary.

Hence we modelled an **all actions (agricultural and non-agricultural**) scenario to take in all the management actions above.

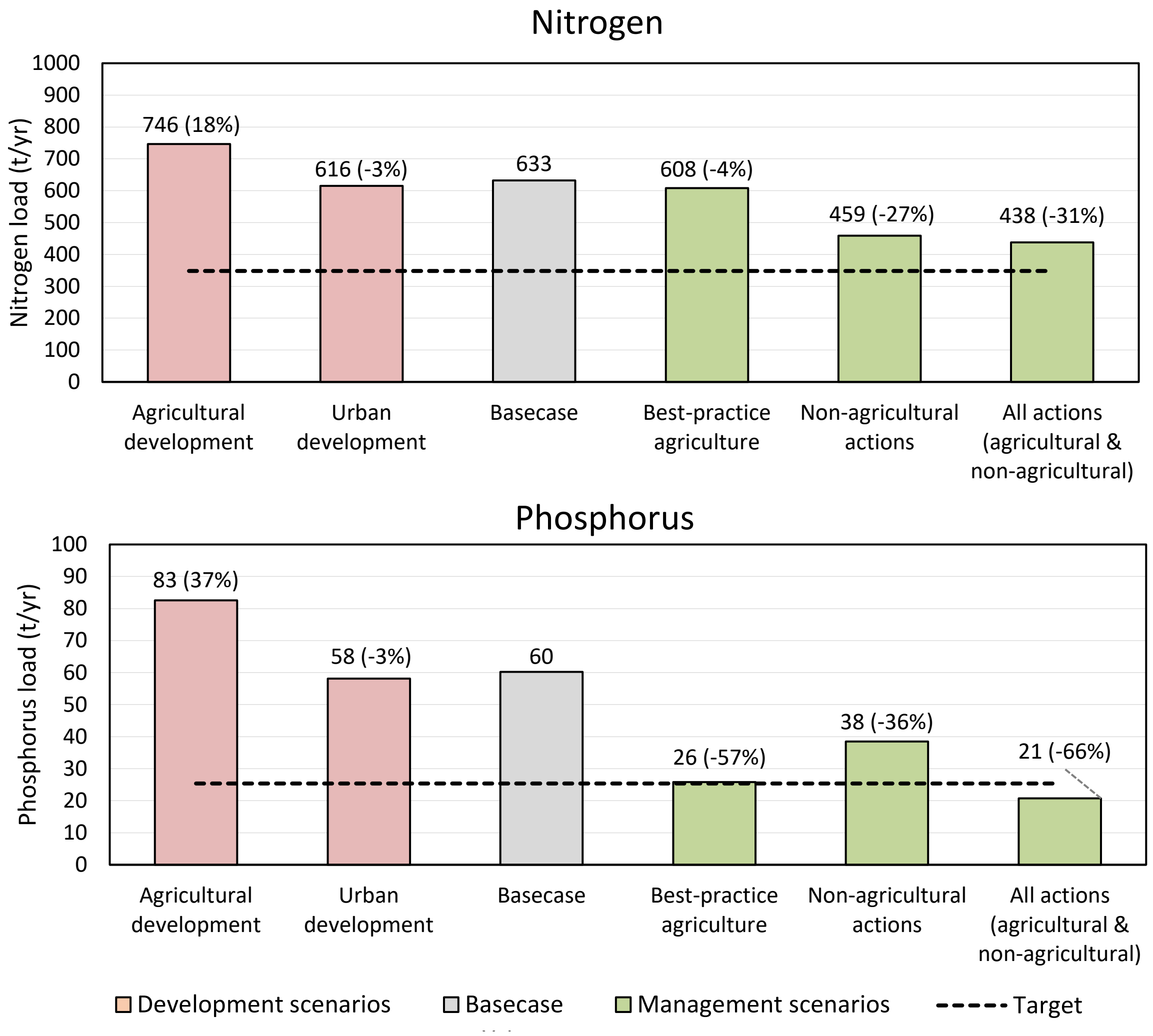
See the figure on page xiii for the nitrogen and phosphorus loads for the basecase, the urban and agricultural development scenarios and the three management scenarios. These estimated load reductions enable achievement of the phosphorus but not the nitrogen target.

The all actions (agricultural and non-agricultural) scenario achieved a 66% reduction in phosphorus load and a 31% reduction in nitrogen load.

Western Australia's south-west has a drying climate. Despite decreased flows and nutrient loads to the Peel-Harvey estuary due to decreasing rainfall, its ecological condition has not improved. A recent study shows its ecological condition may still be worsening. Of particular note is the poor condition of the estuarine portions of the Serpentine and Murray rivers, which suggests a strong link between the current catchment inputs and estuary condition.

We expect rainfall will continue to decline. Compared with the current period (2006–15), the 2050 climate is tracking to see, on average, a 25% reduction in annual rainfall and a 3% increase in annual evapotranspiration. This would result in a further 51% decrease in flow to the estuary, along with 54% and 55% decreases in nitrogen and phosphorus loads respectively. The decreased flows and loads would, compared with the current climate:

- make the estuary saltier for longer
- create a longer residence time for river inflows in the estuary
- make the nutrients in the flows more available for algal growth.



Recommendations

We recommend the following:

1. Take steps to maximise the adoption of farm best-practice fertiliser management and the use of low-water-soluble phosphorus fertilisers on sandy soils.
2. Make available and promote a range of soil amendments through government agencies, farm extension programs and other initiatives such Healthy Estuaries WA.
3. Best-practice management of dairy shed effluent. (This would substantially reduce nutrient loading to the estuary. Management of dairy shed effluent generally has a low standard in the Peel-Harvey catchment and elsewhere in south-western Australia. Recent State Government funding has improved standards, but further work is required.)
4. Implement the actions promoted in State Planning Policy (SPP) 2.1. (Rehabilitation of all riparian zones would have a large environmental benefit beyond nutrient filtering. It would help create biodiversity corridors and improve stream ecological health. We recommend re-vegetation of all riparian zones, including 50% coverage with deep-rooted vegetation. To achieve this, a 250 km^2 area in the coastal plain portion of the catchment would need re-vegetation.

5. Conduct an environmental water requirement study for the Peel-Harvey estuary to examine stresses on water. (There is increasing groundwater extraction and plans to increase surface water abstraction in the Peel-Harvey catchment while rainfall is decreasing and it is getting hotter.)
6. In response to a proposed 3,000-hectare development of in-ground annual horticulture in the Peel Food Zone:
    a. Measure the nutrient exports from greenhouse/hydroponic horticulture locally
    b. Assess and demonstrate the efficacies of nutrient removal technologies locally
    c. Develop guidelines to establish and operate greenhouse/hydroponic horticulture in sensitive Western Australian environments, such as the Peel-Harvey catchment.

    (This proposal would substantially increase phosphorus loading to the Peel-Harvey estuary. Greenhouse/hydroponic horticulture is said to have lower or no nutrient emissions (i.e. closed loop) when compared with traditional in-ground horticulture. Yet the literature suggests that greenhouse/hydroponic horticulture can have greater nutrient emissions than traditional horticulture, even when effluent recycling systems are used.)
7. Conduct further work to estimate maximum allowable loads to the Peel-Harvey estuary under different climatic conditions to improve its ecological health. (This work could use the recently developed Peel-Harvey estuary model. Once we achieve a better understanding of estuary targets, we should review the nutrient concentration and load targets for the inflowing rivers.)
8. Assess the uptake of farm best-practice to create appropriate incentives for farm extension programs, define the social or economic benefits, and put enforcement measures in place. (Note that improved land management brought about by land holders changing their practices requires ongoing education and extension programs).

1 Introduction

The Peel-Harvey estuary has two basins (the Peel Inlet and the Harvey Estuary) and includes the estuarine portions of the Serpentine, Murray and Harvey rivers. The estuary's area is about 133 km^2. It is connected to the Indian Ocean by the Mandurah Channel and the Dawesville Cut, both of which are artificial modifications and permanently open to the sea.

European settlement in the area began in 1830 and gradually the land was cleared for agriculture until the 1980s. The coastal plain portion of the catchment has been extensively drained since 1930s–40s. Phosphorus fertilisers have been used since 1850. By the 1960s, the estuary was showing severe signs of eutrophication. This caused frequent blooms of macro and microalgae, fish deaths, nuisance odours and reduced amenity. Interventions to improve the situation began in the 1980s and included catchment management actions and the creation of the Dawesville Cut, completed in 1994. Despite past interventions, poor water quality persists in the estuary and its wetlands and streams.

The estuary provides important habitat for birds and is Ramsar-listed. Residents and visitors enjoy the recreational pursuits and fishing the estuary supports. Thus, there are reasons both from a local and an international perspective to improve its ecological condition. Healthy Estuaries WA, a state-funded program through the Department of Primary Industries and Regional Development (DPIRD), supports this work.

This study uses catchment-scale models to estimate the flows, as well as the loads and concentrations of nitrogen and phosphorus, to the Peel-Harvey estuary and the ocean. We used the eWater Source modelling platform to develop the hydrological and nutrient models. These 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). This modelling updates the work of Kelsey et al. (2011), but uses different models and methodology.

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 *Peel-Harvey estuary protection plan* and the new *Water quality improvement plan for the Peel-Harvey estuary system*. We have also coupled model outputs to an estuary hydrodynamic and biogeochemical model.

2 Catchment description

This chapter briefly describes the study area's location, climate and geology. See a more detailed catchment description in Kelsey et al. (2011). See Section 3.2 for other relevant information, such as land use, soil phosphorus retention index and drainage.

2.1 Location

The study area, which we refer to as the Peel-Harvey catchment, includes all the land that drains to the Peel Inlet and Harvey Estuary and adjacent land that drains to the ocean (see Figure 2.1). The area includes:

- the catchments of the Serpentine, Murray and Harvey rivers
- the catchment of the Harvey Diversion Drain, which flows to the ocean at Myalup
- the lands on the western side of the Spearwood dune system that drain to the ocean or to local wetlands (from Fremantle to Myalup).

The catchment that drains to the Peel-Harvey estuary is about 9,390 km^2 excluding dam catchments, which total about 1,660 km^2. Catchments that drain to the Indian Ocean total about 870 km^2. The entire study area is about 11,920 km^2.

The study area overlaps 17 local government authorities (LGAs) and contains 25 towns. See Table 2.1 for the populations of the LGAs. About 542,950 people live in the catchment overall. Excluding Perth suburbs, its largest population centre is Mandurah, with almost 81 000 residents.

Table 2.1: Population of local governments

Local government authority	Estimated resident population 2016
Armadale	79 602
Boddington	1 844
Cockburn	104 473
Cuballing	863
Fremantle	28 893
Harvey	26 553
Kwinana	38 918
Mandurah	80 813
Murray	17 307
Narrogin	5 162
Pingelly	1 146
Rockingham	125 114
Serpentine-Jarrahdale	26 833
Wandering	294
Waroona	4 148
Williams	981
Total	542 944

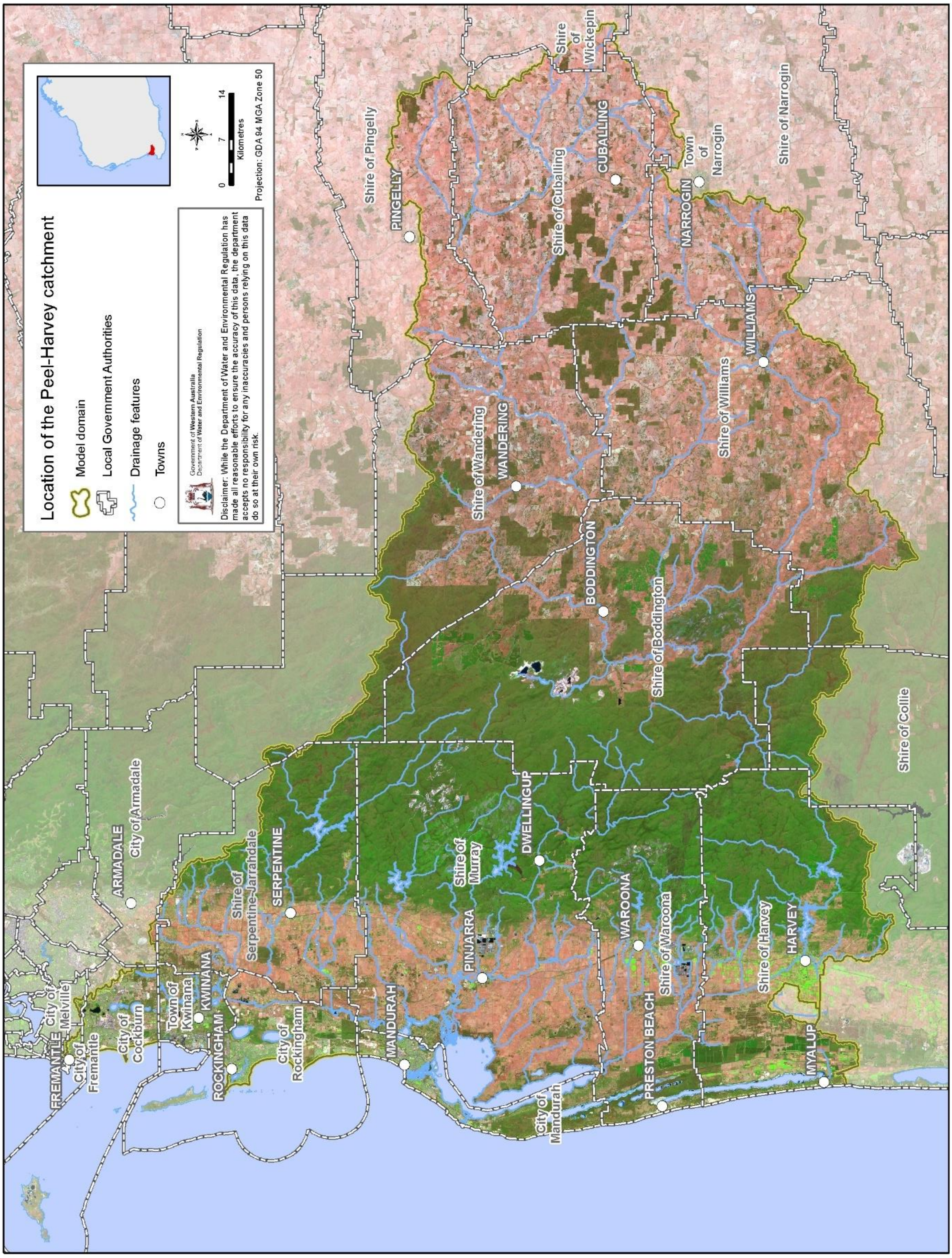


Figure 2.1: Location of the study area

2.2 Climate

The Peel-Harvey catchment has a Mediterranean climate with cool, wet winters (June–August) and hot, dry summers (December–March). Figure 2.2 shows the average annual rainfall for the period 1975 to 2003. Average annual rainfall increases from about 750 mm on the coast to 1,050 mm on the Darling Scarp, and then decreases east of the scarp to about 400 mm at the catchment's eastern boundary. About 80% of the rain falls in the May to October period. The south-west of Australia has become drier over the past few decades. Before 1975 the average annual rainfall was about 850 mm on the coast, 1,300 mm on the scarp and 450 mm at the catchment's eastern edge.

2.3 Geology, hydrogeology and soils

In brief, the study area lies across two major geological provinces: the sedimentary Perth Basin and the Yilgarn block, which has a weathered granite geology. The Darling Fault separates the two. At the surface, these are represented as the Swan Coastal Plain to the west and the Darling Plateau to the east. The Darling Scarp marks the transition between the regions.

The Perth Basin has considerable groundwater resources because of its sedimentary geology. There are three main aquifers: the unconfined superficial aquifer and the confined Leederville and Yarragadee aquifers. These aquifers comprise many different geological formations which were laid down from the Jurassic to Quaternary geological ages – see Figure 2.3 and Table 2.2. Detailed hydrogeological conceptualisation and water balance is given in Hall et al. (2010) for the Lower Murray, Marillier et al. (2011) for the Lower Serpentine and other publications such as Davidson (1995).

Table 2.3 summarises the study area's main geomorphic elements and

Figure 2.4 shows its main surface soils.

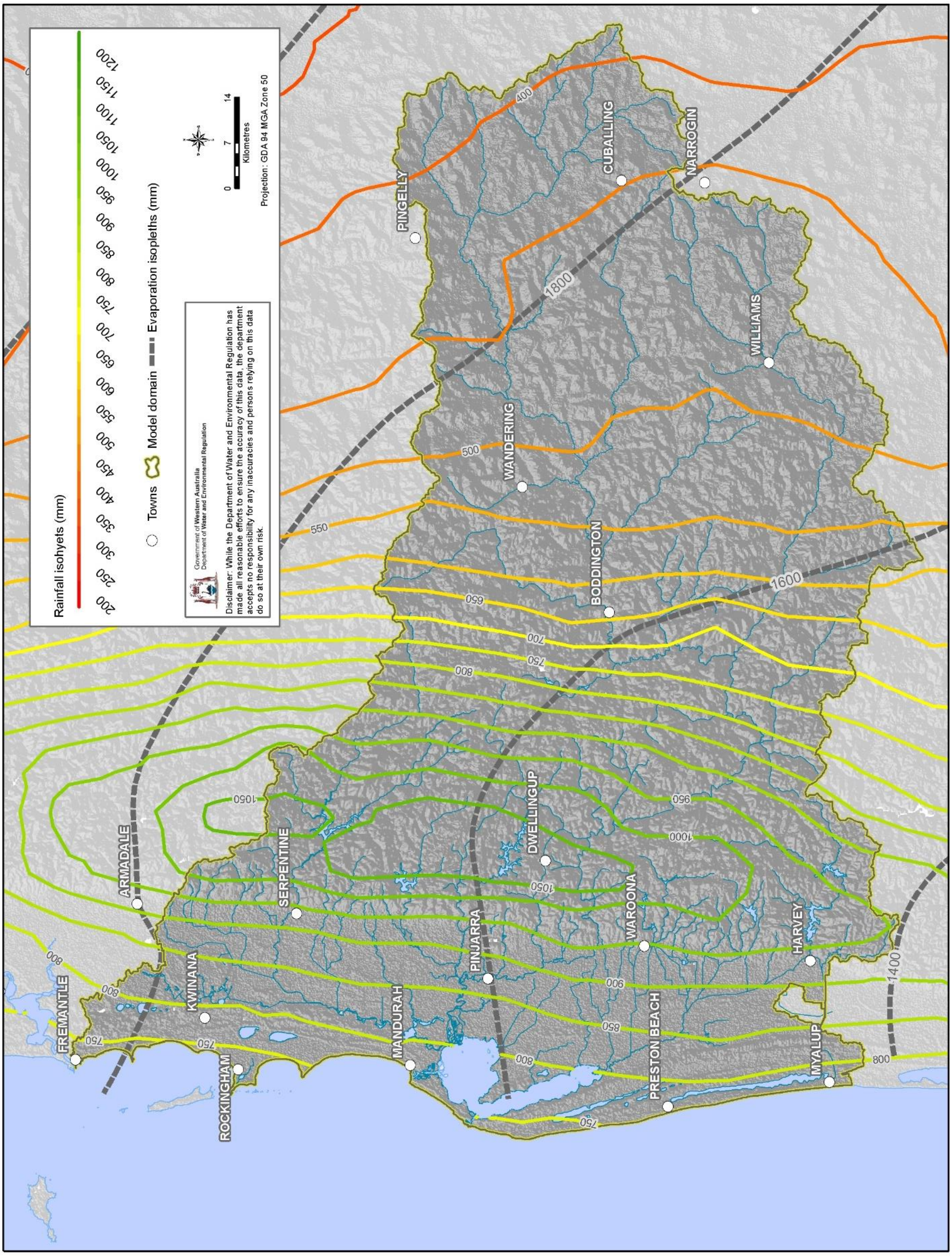


Figure 2.2: Rainfall isohyets and evaporation isopleths (1973–2003)

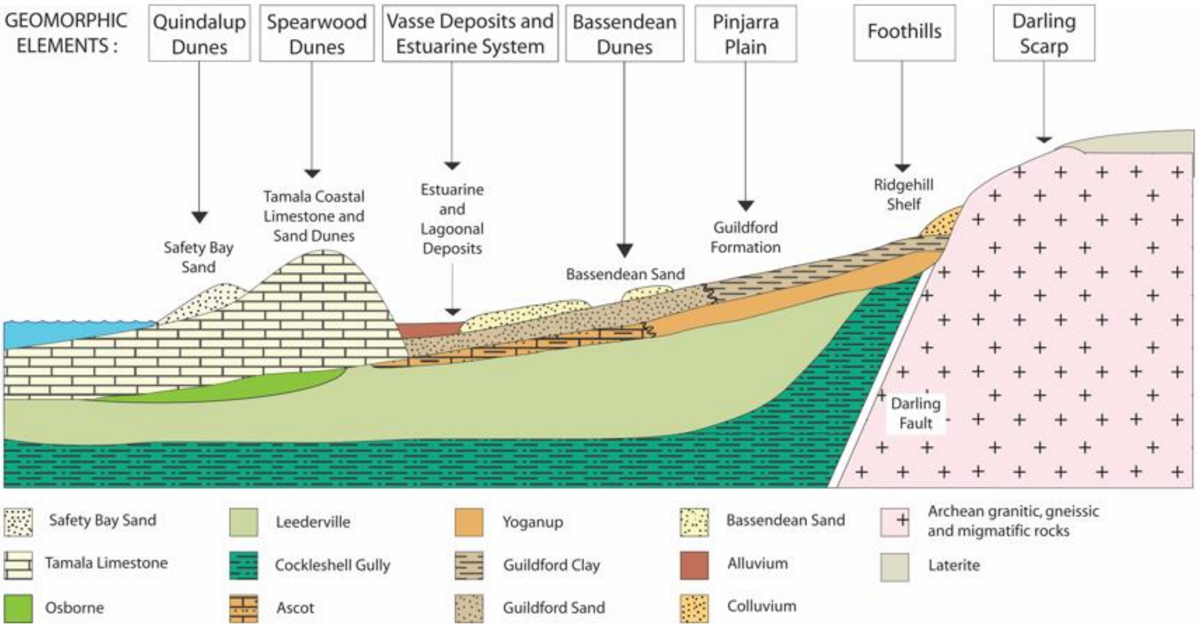


Figure 2.3: East to west schematic cross-section around Mandurah and Pinjarra

Table 2.2: Stratigraphy and lithology of the Perth Basin

Age	Stratigraphic unit and lithology		
	West	Central	East
QUATERNARY **Holocene**	Alluvium, estuarine, lagoonal and swamp deposits (15) (sand, silt, clay and peat)		
	Safety Bay Sand (50) (sand, calcareous and unlithified)		Colluvium (5) (lithic sand, silt, clay, laterite, debris)
Pleistocene Middle–late	Tamala Limestone (90) (limestone, sand, calcarenite, minor clay, minor fossils)	Bassendean Sand (15?) (sand)	
Early– middle		Guildford Formation sand (30) (sand, minor clay, calcareous sand and fossils)	Guildford Formation clay (27) (clay, sandy clay)
Early	Ascot Formation (25) (sand, silt, minor limestone, fossiliferous)		Yoganup Formation (25) (sand, clayey sand)
CRETACEOUS Early–late	Osborne Formation (siltstone and clay)		
Early	Leederville Formation (sand, siltstone, clay, shale)		
JURASSIC Early–middle	Cattamarra Coal Measures (sand, siltstone, clay, shale)		

Table 2.3: Geomorphic elements of the Peel-Harvey catchment.

Geomorphic element	Landform	Soil description
Quindalup Dunes	Low-relief coastal dune system consisting of the most recent unconsolidated aeolian deposits.	Safety Bay Sands
Vasse Deposits	Low-lying poorly-drained terraces, flats and beach ridges fringing the Peel-Harvey estuary, the coastal lakes and major river mouths.	Unconsolidated Holocene estuarine alluvium and lagoonal deposits, often highly saline and subject to inundation
Spearwood Dunes	These are intermediate in age and lie between the Quindalup and Bassendean dunes. They are more hilly and often separated from the other systems by a series of lakes or swamps. They also encompass gently undulating terrain overlying marine limestone, which is associated with coastal lakes such as Lake Clifton.	Yellowish brown siliceous sand overlying limestone
Bassendean Dunes	These are directly west of the Pinjarra Plain. They consist of low hills of leached siliceous sand interspersed with sand flats and seasonal swamps. They are the oldest dunal system on the coastal plain (Wells 1989).	Pale deep sand
Pinjarra Plain	An alluvial tract which slopes gently away towards the west. The surface is slightly undulating and consists of coalescing piedmonts and riverine deposits. Poor natural drainage has been alleviated by artificial drainage.	Mottled duplex soils and yellow-grey clays. The most productive soils on the coastal plain with good ability to hold nutrients (Weaving 1999).
Ridge Hill Shelf (foothills)	A narrow dissected strip, 1 to 3 km in width, which forms the foothills of the Darling Scarp. It slopes gently towards the west and consists of stream-deposited coalescing alluvial fans and remnants of marine terraces. The foothills are the gentle slopes (1–10%) between the Darling Scarp and Pinjarra Plain.	Alluvium and some residual laterite at the surface
Darling Scarp	Moderately steep hill slopes and valleys (20–30%) and gentle crests and upper slopes (3–10%). Deeply incised stream channels. It was formed by marine erosion along an ancient coastline and separates the coastal plain from the Darling Plateau to the east.	Variable soils formed from weathering of Archaean granitic and gneissic rocks and laterite
Darling Plateau	A gently undulating area of moderately raised land which consists of laterite, lateritic gravels and sand overlaying Mesozoic rocks. Its elevation gradually increases from about 100 m above sea level just east of the scarp to about 400 m above sea level at the catchment's eastern boundary.	Laterite, lateritic gravels and sand overlaying Mesozoic rocks

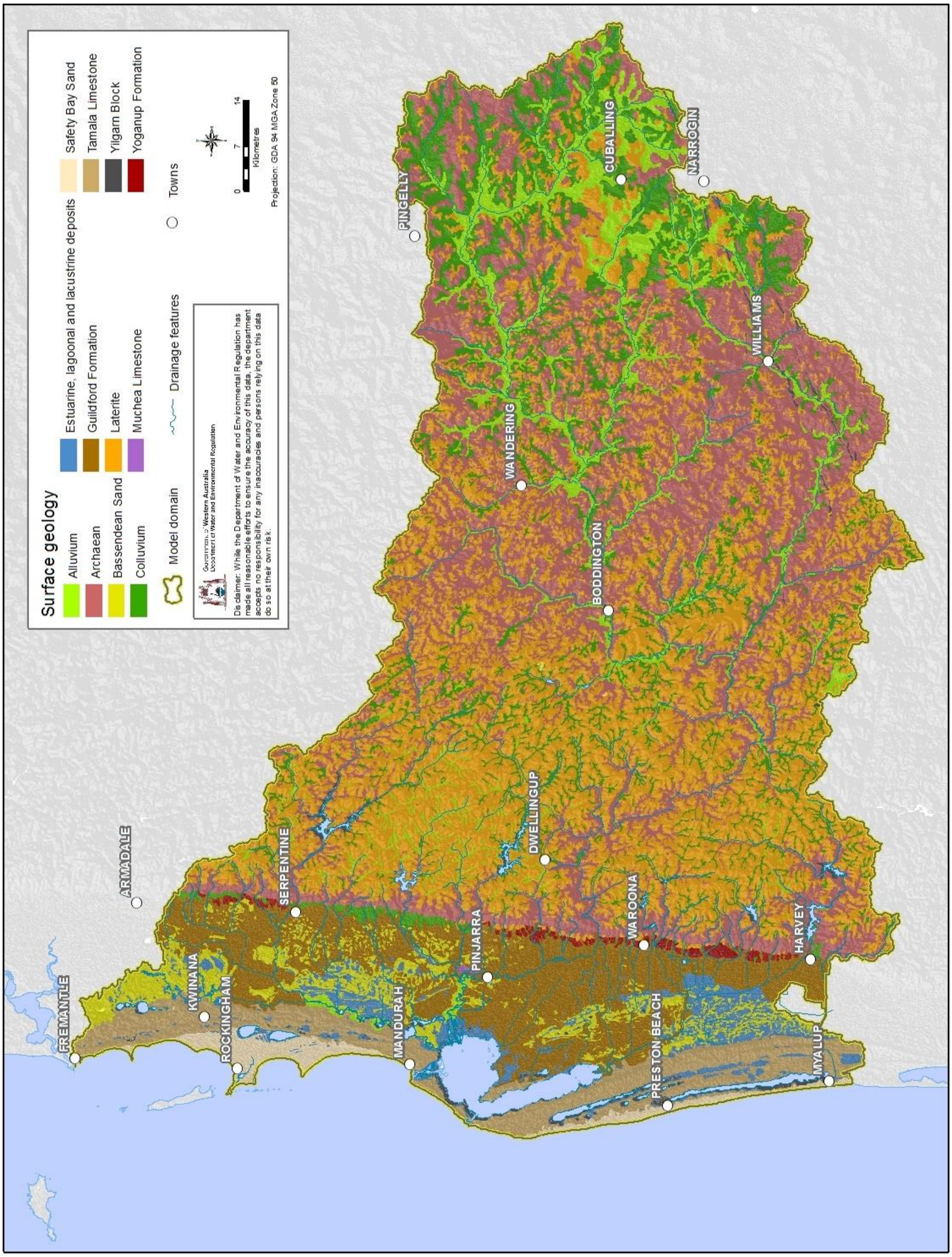


Figure 2.4: Soils of the Peel-Harvey catchment

3 Model description and data

This chapter describes the main aspects of the catchment model and input data. Section 3.1 details the modelling software we used and describes the main aspects of the hydrological and nutrient models. We also discuss model parameterisation of the gauged and ungauged[1] catchments. See Appendix A and B for a detailed description of model parameterisation and calibration performance.

Section 3.2 describes all the input data we used to construct and run the model, as well as the data we used to inform model parameterisation.

3.1 Modelling framework and model description

We used the eWater Source model framework (version 4.3.0.6541) 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 yield and nutrients that are external to the hydrological and nutrient models (e.g. dam releases, irrigation returns, point sources and septic tanks).
- **Links**: Links represent the river reaches. Within each link, users can apply a selection of models to route or delay the movement of water along the link or modify the contaminant loads due to processes occurring within the links, such as the decay of a particular constituent over time.

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).

[1] Catchments upstream of a flow gauge and/or routine water quality measurement site are defined as ‘gauged’ catchments. Catchments without measurements are termed ‘ungauged’ catchments. Catchments can be ‘gauged’ for flow but ungauged for water quality and vice versa.

3.1.1 Hydrological model

We calibrated and parameterised the GR4J and SYMHYD with routing models to represent the flow yield of cleared, vegetated and urban land uses (Figure 3.1). We attributed the parameters at the functional unit scale according to the modelling land uses in Table 3.1. We tested various hydrological models before model construction – see Appendix A for details. We calibrated and parameterised the hydrological models as follows:

- **Urban:** Urban land uses create many impervious areas and little onsite stormwater detention (e.g. stormwater detention ponds). For all urban land uses we used the SYMHYD with routing model (Chiew et. al. 2002), which we calibrated to the Bannister Creek catchment (Swan-Canning river catchment). This was necessary because no predominantly urban catchments in the study area were also measured for flow.
- **Vegetated:** Vegetated land uses include native vegetation and plantations. We calibrated the GR4J model (Perrin et al. 2003) to forested catchments east of the Darling Scarp. We then applied and fixed the calibrated model parameters from these forested catchments in all other catchments, such as those on the coastal plain or in the predominantly cleared portion of the Upper Murray.
- **Cleared:** Cleared land uses represent land without significant impervious areas or deep-rooted vegetation. For cleared land uses we calibrated the GR4J model to flow gauging stations throughout the Peel-Harvey catchment. We then applied the calibrated parameters to all upstream modelling catchments. In cases where there were one or multiple calibration sites in a river reach, we applied parameters to all upstream modelling catchments between calibration sites. Figure 3.2 shows the hydrological model parameterisation by modelling catchment.

Note that:

- Intensive animal industries such as piggeries, abattoirs, feedlots, stockyards and poultry use the cleared hydrological model. Best-practice guidelines for these land uses typically require management of stormwater runoff from impervious and hard-stand areas. We did not include these lot-scale processes, which can include stormwater infiltration and/or detention, in the model.
- We assumed lifestyle blocks have a cleared rather than urban hydrology to account for the lot sizes (>1 hectare in some areas), which tend to be larger than the typical urban residential block (<1500 m^2). This assumption may underestimate the flow yield from lifestyle blocks.
- We assumed orchards have a cleared hydrology, as previous studies have assumed leaf area index (LAI) values that were half that of native vegetation (Kelsey et al. 2011). This assumption likely overestimates the flow yield from orchards.

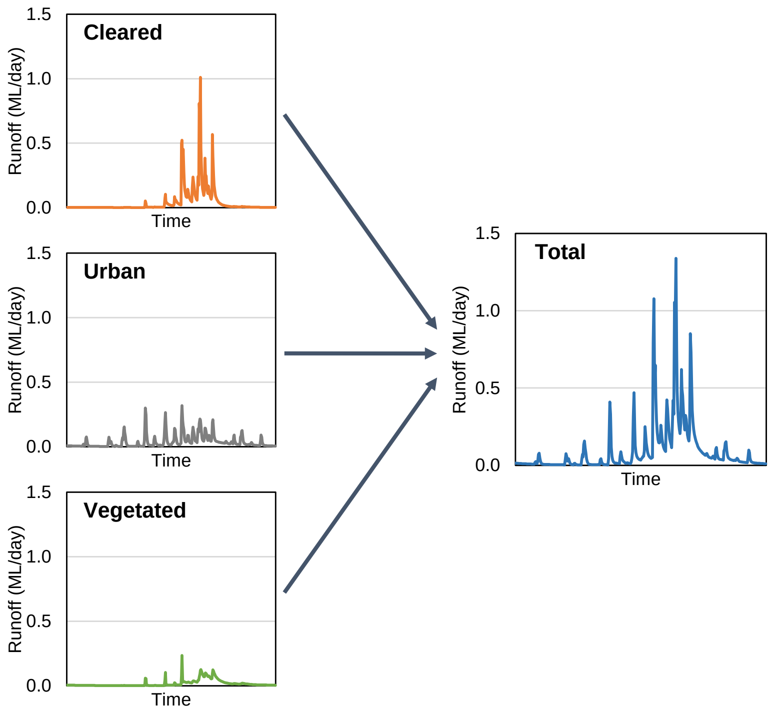


Figure 3.1: Components of the hydrological model at the modelling-catchment scale. Cleared, urban and vegetated land uses have unique hydrological models. The flow generated from these land uses amount to the flow generated by a modelling catchment, as the blue 'total' graph shows.

We calibrated 92% of the Peel-Harvey catchment (and 80% of the model domain area, which also includes catchments that drain to the ocean) to flow measurement sites. The remaining ungauged catchments are mostly located in areas that are not suitable for flow measurement.

We parameterised ungauged catchments based on catchment and hydrogeological properties.

The following describes our rationale for assigning ungauged catchment parameters:

- Coastal North and Coastal Central catchments use the cleared hydrology parameters from Hope Valley (614013). The Coastal North and Coastal Central catchments are situated on the Spearwood and Quindalup dune systems. Although substantial infiltration of rainfall would occur in these catchments, open channel drains that likely intercept groundwater are present in the Coastal North catchment. The Hope Valley catchment is similar given it is situated between the Jandakot Groundwater mound (Bassendean sands) and the Spearwood dunes. Rainfall would predominantly infiltrate, and the catchment is drained by the Peel Main Drain.
- The Coastal South catchment uses the cleared hydrology parameters of the nearby Harvey Diversion Drain (613019) gauge, as this is the closest calibrated flow site.
- The ungauged portion of the Lower Serpentine catchment uses the cleared hydrology parameters from Nambeelup Brook (614063). The Nambeelup Brook gauge generally

had good quality flow data and a long flow record. The Nambeelup catchment is adjacent to the Lower Serpentine and has comparable soils and drainage. Note we did not use the Gull Road Drain gauge (612020) to parameterise ungauged catchments due to its limited flow record (2005–07) and issues with data quality when we developed the model.

- Dam catchments we did not calibrate to flow measurement, or were ungauged, included: North Dandalup, South Dandalup, Waroona, Drakesbrook, Logue Brook and Samson. For these catchments we assigned the parameters from River Road, Big Brook, which had an average coefficient of runoff comparable to other dam flow calibration sites.

Most water supply dams are understood to have minimal water releases. We did not do any dam water balance modelling in this project. However, we included dams with published environmental water provisions in the model using inflow nodes.

See the flow calibration report (Appendix A) for further information about model parameterisation.

Table 3.1: Hydrological models used for all modelling land uses

Modelling land use	Hydrological model
Bare soil & other	Cleared
Beef	Cleared
Cropping	Cleared
Dairy	Cleared
Feedlots & stockyards	Cleared
Horses	Cleared
Horticulture	Cleared
Industry, manufacturing & transport	Urban
Lifestyle block	Cleared
Mixed grazing	Cleared
Native vegetation	Vegetated
Offices, commercial & education	Urban
Orchard	Cleared
Piggeries & abattoirs	Cleared
Plantation	Vegetated
Point source	Cleared
Poultry	Cleared
Recreation	Cleared
Rural living (bush block)	Vegetated
Turf farm	Cleared
Urban residential	Urban
Urban residential (very small)	Urban
Viticulture	Cleared

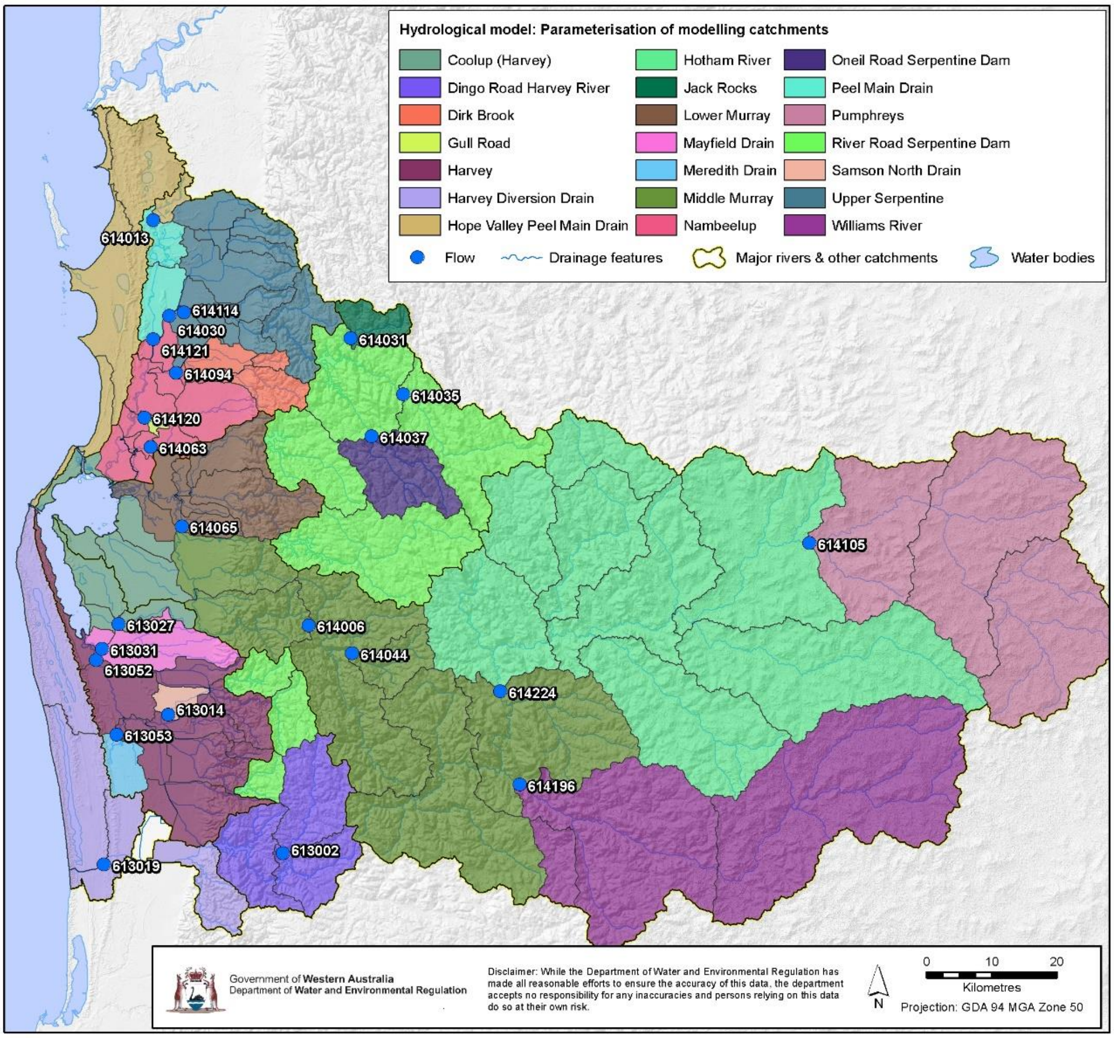


Figure 3.2: Hydrological model parameterisation

Stream routing

Model links distribute flow and constituents between modelling catchments in eWater Source. By default, Source links use a straight-through routing model, which delivers flow and constituents to downstream subcatchments with no modification to the timing or amount of flow or constituent load. Stream-routing models offer more functionality and we can use them to:

- modify the timing and amount of daily river flow and therefore nutrient concentrations and loads
- include in-stream constituent attenuation models (Note we did not explicitly model instream attenuation in this project because of insufficient data when we developed the model. Nutrient attenuation processes that occur between a nutrient source, such as paddocks, as well as water quality monitoring sites, are implicit in model calibration.)
- include additional sources of flow and constituents, such as the contributions of septic tanks.

We applied hydrological routing to subcatchments in the Murray River catchment as the time to concentration was greater than one day. We calibrated storage model parameters using the Source calibration tool – see Appendix A for details.

3.1.2 Nutrient model

We modelled nutrients in the Source framework using four modules:

- **Constituent generation models:** these determine how constituents (e.g. sediments or nutrients) are generated within a functional unit (e.g. a land-use parcel within a subcatchment) and the resulting concentrations or loads that are passed to the filter model.
- **Inflow nodes:** we used these to include point sources of nutrients, septic tanks, dam inflows and irrigation returns. The nutrients from these sources are external to the constituent generation and filtering models.
- **Filtering models**: these represent any transformation of constituents between generation within the functional unit and arrival at the subcatchment node. Filtering models process constituents within the functional units. We used filtering models to represent nutrient processes in vegetated riparian zones.
- **In-stream processing models:** we did not use explicit in-stream processing models. These processes are implicit within the catchment calibration process.

The diffuse nutrient model

The diffuse nutrient model uses the *power function (flow in mm)* constituent generation model to generate total nitrogen and total phosphorus concentrations. We selected this model due to:

- the scarcity of land-use EMC/DWC concentration data that was locally derived
- 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 (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 (not used in this model).

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

The first step requires the calibration of a single catchment-scale power function to observed data (termed the *catchment power curve*). In the second step the calibrated catchment power curves are separated 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 conducted this process for all catchments upstream of water quality monitoring sites for the nitrogen and phosphorus models. The 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[2] (LOESS) flow-weighted TP concentrations (2011–15) and the proportion of the catchment with low-PRI soils (see Figure 3.3).

About 94% of the Peel-Harvey catchment was upstream of the 14 monitoring sites that we used to calibrate the nutrient model. See Figure 3.4. for the parameterisation of the nutrient model and the location of nutrient model calibration sites. Our rationale for assigning the nutrient model parameters included the following:

- We generally used the parameters of the nearest upstream gauge for ungauged catchments downstream of water quality monitoring sites.
- The ungauged portion of the Lower Serpentine used parameters from Dog Hill (614030). We calibrated the Lower Murray to data from 6142623 and the Upper Murray to data from 614065. Thus, we calibrated the Lower Murray to water quality measurements taken on the coastal plain.

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

- We assigned nutrient parameters from 613027 to the ungauged Coolup catchments based on the similarities of catchment properties (slope, soils, drainage).
- The Coastal North, Central and South catchments are ungauged. They are unique in that they have Spearwood and Quindalup dunes, which have a greater PRI than the Bassendean sands found further inland. These catchments have large areas of urban land uses. We used the Peel Main Drain (614121) parameters for them as this was the calibrated catchment that was most similar.
- The Harvey Diversion Drain did not have recent water quality measurements at gauge 613019. For this catchment we also used the Peel Main Drain (614121) parameters due to the similarities in catchment properties. Both catchments have areas of heavy clays and sand dunes. This catchment drains to the ocean.

We calibrated the nutrient model to winter nutrient concentration data for the period 2011–15 (see Section 4 and Appendix B for calibration performance).

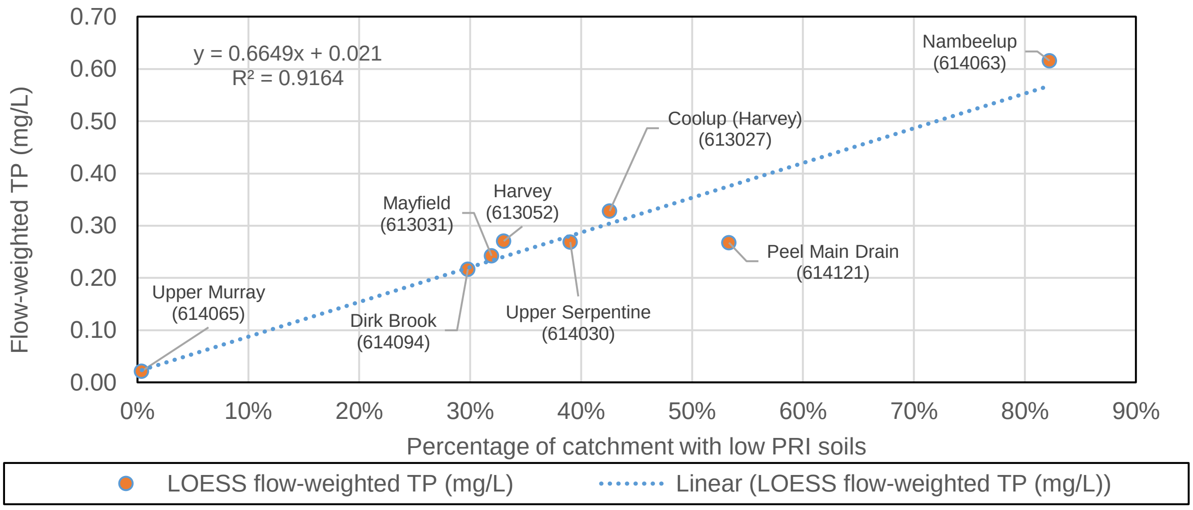


Figure 3.3: Average annual (2011–15) LOESS flow-weighted total phosphorus concentrations at eight flow and water quality monitoring sites in the Peel-Harvey catchment

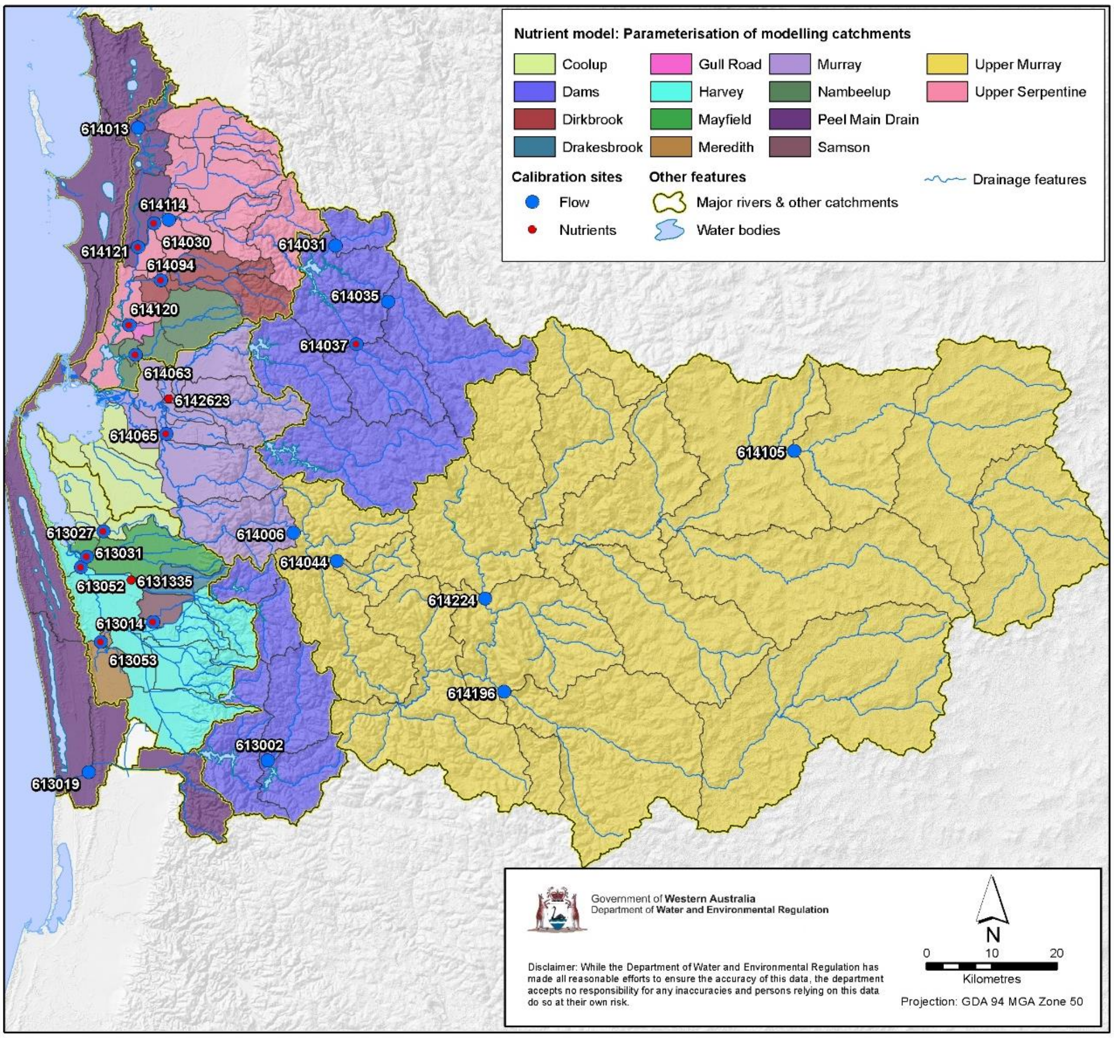


Figure 3.4: Nutrient model parameterisation

Dairy paddocks and sheds

A 2012 survey of dairy farms in the Peel-Harvey found that most did not meet the *Code of practice for dairy shed effluent Western Australia* (Western Dairy 2012; Section 7.3.4). Nutrient loss from poorly managed dairy effluent can be a significant source of nutrients (Western Dairy 2012). We modified the method for parameterising the diffuse nutrient model for dairy farms to better represent the nutrient contribution from dairy sheds (point sources) to whole-farm dairy nutrient exports. Using this modified method, nutrient exports from dairy farms change depending on the size of the milking herd. (We did this to avoid using inflow nodes to represent dairy sheds.)

We used the following methodology:

1. We estimated **the nutrient loads (surplus) from dairy sheds (S_{Shed})** based on the data in Table 3.2. Western Dairy (Dan Parnell pers. comm. 2017) gave us the approximate number of milking cows per farm and we took other information from the relevant literature or ensured consistency with previous modelling.
2. We estimated **the dairy paddock nutrient surplus ($S_{Paddock}$) for each farm** by subtracting the estimated nutrient surplus for the dairy shed from the whole-farm

nutrient surplus (S_{farm}). We assumed the whole-farm nutrient surplus rates were the average rates determined from farm-gate nutrient budgets (see Table 3.7). That is, the dairy paddock nutrient surplus is: $S_{Paddock} = S_{farm} – S_{Shed}$.

3. **Dairy shed nutrient export factors (E_{Shed})** give the proportion of dairy shed nutrient surplus that is exported to surface water. In the Source model we assumed the dairy paddocks had the same nutrient export factors as other broadscale land uses. We then derived the dairy shed nutrient export factors from calibration to surface water nutrient measurements. Dairy shed nitrogen and phosphorus export factors were the same for all dairy farms in the model.

That is, for dairy farms, Equation 2 was modified:

Equation 3: $$a_{dairy\ farm} = a_{cat} \times \frac{C_{Dairy\ farm}}{C_{cat}}$$

and $$C_{Dairy\ farm} = \frac{(S_{Paddock} \times E + S_{Shed} \times E_{Shed})}{Q_{lu}}$$

See Table 3.2 for an explanation of the parameters used above.

Table 3.2: Parameters used to estimate the load of nutrients exported per cow

Parameter	Units	Value	Source
Wash-down volume per cow per day	kL/cow/day	0.060	Hall pers. comm. 2018
Number of milking days per year	# days	365	Assumption
Effluent TN concentration	mg/L	200	Hall pers. comm. 2018
Effluent TP concentration	mg/L	40	Hall pers. comm. 2018
Mass of nitrogen in dairy effluent (S_{Shed})	*kg/cow/yr*	*4.38*	*Calculated*
Mass of phosphorus in dairy effluent (S_{Shed})	*kg/cow/yr*	*0.88*	*Calculated*
Dairy shed nitrogen export (E_{Shed})	**Factor**	**0.15**	**Calibrated**
Dairy shed phosphorus export (E_{Shed})	**Factor**	**0.13**	**Calibrated**
Nitrogen load (to stream; S_{Shed} * E_{Shed})	**kg/cow/yr**	**0.66**	**Calculated**
Phosphorus load (to stream; S_{Shed} * E_{Shed})	**kg/cow/yr**	**0.11**	**Calculated**

Table 3.3: Proportion of nutrient export from dairy sheds and dairy paddocks by reporting catchment

Reporting catchment	Number of sheds	Nitrogen		Phosphorus	
		Sheds	Paddocks	Sheds	Paddocks
Upper Serpentine	4	31%	69%	50%	50%
Dirk Brook	1	3%	97%	31%	69%
Nambeelup	2	8%	92%	8%	92%
Lower Murray	2	15%	85%	63%	37%
Coolup (Peel)	1	26%	74%	45%	55%
Coolup (Harvey)	1	15%	85%	39%	61%
Mayfield Drain	2	13%	87%	38%	62%
Harvey	12	8%	92%	54%	46%
Harvey Diversion Drain	6	8%	92%	53%	47%
Peel-Harvey estuary	**25**	**10%**	**90%**	**33%**	**67%**
Total	**31**	**9%**	**91%**	**37%**	**63%**

Dam releases and irrigation returns

We calculated water and nutrients from dam releases and irrigation returns separately (see Section 3.2) and included them as inflow nodes.

Riparian zone nutrient model

We used a filtering model to represent nutrient removal by vegetated riparian zones. We parameterised the filtering model to reduce the daily load of nutrient generated by a modelling catchment based on the amount of riparian vegetation within it.

We calculated riparian zone nutrient removal linearly, with 0% removal for modelling catchments with 0% riparian zone vegetation and the maximum nutrient removal for catchments with 100% riparian zone vegetation (Table 3.4 Hugues-dit-Ciles et al. 2012, medium efficacy). We assumed the nutrient removal of riparian zones on the Swan Coastal Plain would be less effective than catchments in the Upper Murray and dam catchments (Hugues-dit-Ciles et al. 2012).

Section 3.2 describes how we estimated riparian zone vegetation. See Appendix B for the filtering model parameters derived from the model calibration.

Table 3.4: Riparian zone nutrient reduction for modelling catchments with 100% riparian vegetation (Hugues-dit-Ciles et al. 2012)

Category	Nitrogen load reduction		Phosphorus load reduction	
	Upland (%)	Coastal plain (%)	Upland (%)	Coastal plain (%)
Moderately vegetated riparian zone	40	12	15	2.5

Towards the end of this study, Hall (2019) did an in-depth review of riparian zone nutrient removal efficiency and deduced different removal rates (Table 3.5) for different levels of riparian management. We used these removal rates in the scenario modelling.

Table 3.5: Riparian management nutrient removal efficacy for different levels of management (taken from Hall 2019)

Category	Description	Nitrogen load reduction	Phosphorus load reduction	
		Upland & coastal plain (%)	Upland (%)	Coastal plain (%)
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 & re-vegetation	Fencing with stock exclusion, off-stream watering points and stream crossings. Re-vegetated using native canopy and understory vegetation (8,000 plants/ha).	30	30	5

3.2 Input data

Meteorological data

We derived meteorological data from the Australian Water Availability Project (AWAP), which provides daily rainfall, temperature, vapour pressure and solar exposure data (amount of solar radiation reaching the earth's surface). We extracted daily rainfall and calculated potential evapotranspiration (PET) data for the centroids of the modelling catchments for 1/1/1960 to 31/12/2015. We calculated PET using the FAO56 methodology (Allen et al. 1998; Ladson 2008), with missing data infilled as following:

- Solar exposure data was not available before 1990. We substituted pre-1990 global exposure data.
- Vapour pressure was not available before 1971. We infilled using average monthly vapour pressure from 1971–2015.

Land-use data

We updated the land-use mapping dataset from Kelsey et al. (2011) to represent the 2015 land use (Figure 3.5). We used the following datasets to do so:

- the state cadastre dataset (Landgate)
- aerial photography from 2010–15
- upper storey vegetation data calculated from the Swan Coastal Plain one-metre Light Detection and Ranging (LIDAR) data (Department of Water and Environmental Regulation)
- native vegetation data (DPIRD).

The land-use mapping update includes new urban developments, large-scale changes to agricultural land uses and practices, intensive agriculture and riparian zone re-vegetation. We put the land-use data to an internal review and sought advice from DPIRD and the Peel-Harvey Catchment Council (PHCC).

We kept the detailed land-use mapping nomenclature from Kelsey et al. (2011) but simplified it into modelling and reporting land-use categories (Table 3.6). We based the aggregation of land-use categories on their expected hydrological response (i.e. urban, cleared or vegetated) and nutrient surplus rates.

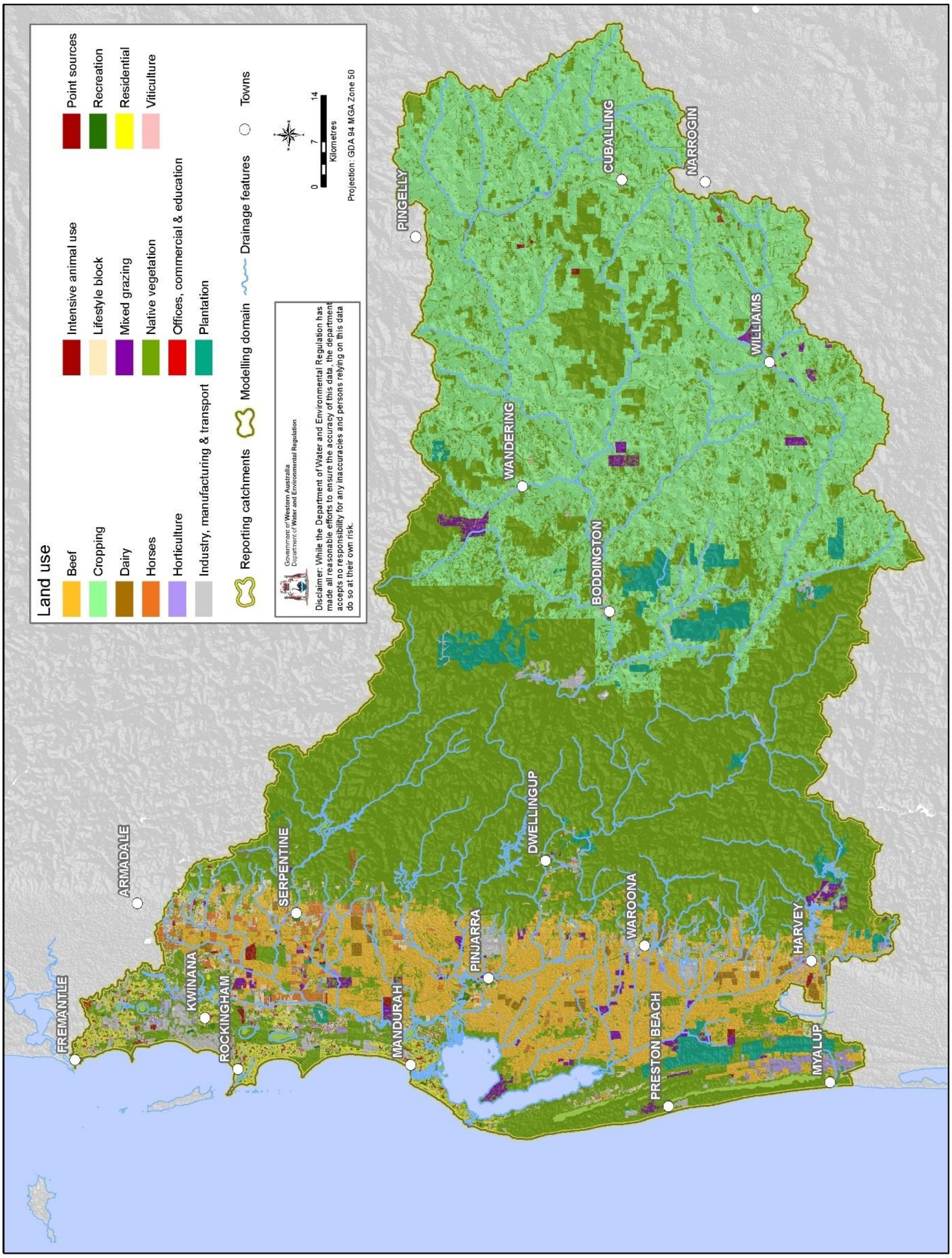


Figure 3.5: Land use

Table 3.6: Land-use classification and aggregation into modelling and reporting land uses

Land-use mapping classification	Reporting land use	Modelling land use	Hydrological model
Cattle for beef	Beef	Beef	Cleared
Hay and Silage	Beef	Beef	Cleared
Cropping	Cropping	Cropping	Cleared
Cattle for dairy	Dairy	Dairy	Cleared
Animal keeping - non-farming (horses)	Horses	Horses	Cleared
Annual horticulture	Horticulture	Horticulture	Cleared
Garden centre / nursery	Horticulture	Orchard	Cleared
Perennial horticulture	Horticulture	Orchard	Cleared
Turf Farm	Horticulture	Turf farm	Cleared
Aquaculture	Industry, manufacturing & transport	Bare soil & other	Cleared
Quarry / extraction	Industry, manufacturing & transport	Bare soil & other	Cleared
Transport access - airport	Industry, manufacturing & transport	Bare soil & other	Cleared
Unused - cleared - bare soil	Industry, manufacturing & transport	Bare soil & other	Cleared
Unused - cleared - grass	Industry, manufacturing & transport	Bare soil & other	Cleared
Water storage and treatment	Industry, manufacturing & transport	Bare soil & other	Cleared
Manufacturing / processing	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Sewerage - non-treatment plant	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Storage / distribution	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Transport access - non-airport	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Utility	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Yacht facilities	Industry, manufacturing & transport	Industry, manufacturing & transport	Urban
Feedlot	Intensive animal industries	Feedlots & stockyards	Cleared
Intensive animal farming	Intensive animal industries	Piggeries & abattoirs	Cleared
Piggery	Intensive animal industries	Piggeries & abattoirs	Cleared
Poultry	Intensive animal industries	Poultry	Cleared
Lifestyle block	Lifestyle block	Lifestyle block	Cleared
Mixed grazing	Mixed grazing	Mixed grazing	Cleared
Sheep	Mixed grazing	Mixed grazing	Cleared
Recreation / conservation - trees / shrubs	Native vegetation	Native vegetation	Vegetated
Unused - uncleared - trees / shrubs	Native vegetation	Native vegetation	Vegetated
Water body	Native vegetation	Native vegetation	Vegetated
Rural residential / bush block	Native vegetation	Rural living (bush block)	Vegetated
Caravan park	Offices, commercial & education	Offices, commercial & education	Urban
Commercial / service - centre	Offices, commercial & education	Offices, commercial & education	Urban
Commercial / service - residential	Offices, commercial & education	Offices, commercial & education	Urban
Community facility - education	Offices, commercial & education	Offices, commercial & education	Urban
Community facility - non-education	Offices, commercial & education	Offices, commercial & education	Urban
Office - with parkland	Offices, commercial & education	Offices, commercial & education	Urban
Office - without parkland	Offices, commercial & education	Offices, commercial & education	Urban
Tree plantation	Plantation	Plantation	Vegetated
Landfill	Point sources	Point source	Cleared
Sewerage - treatment plant	Point sources	Point source	Cleared
Cemetery	Recreation	Recreation	Cleared
Recreation - grass	Recreation	Recreation	Cleared
Recreation - turf	Recreation	Recreation	Cleared
Residential - aged person	Residential	Urban residential	Urban
Residential - temporary accommodation	Residential	Urban residential	Urban
Urban (>600-730m^2)	Residential	Urban residential	Urban
Urban (>730m^2)	Residential	Urban residential	Urban
Urban (400-600m^2)	Residential	Urban residential	Urban
Residential - multiple dwelling	Residential	Urban residential (very small)	Urban
Residential - single/duplex dwelling	Residential	Urban residential (very small)	Urban
Urban (<400m^2)	Residential	Urban residential (very small)	Urban
Viticulture	Viticulture	Viticulture	Cleared

Land-use nutrient surveys

Table 3.7 gives the assigned nutrient input and surplus rates for all modelling land uses. We sourced this data from the relevant literature and used the assumptions described below. We took the terms nutrient inputs and surplus from the farm-gate nutrient budgeting framework (Ovens et al. 2008, Weaver et al. 2008; Figure 3.6):

- **Nutrient inputs:** mass of nutrient flowing into a property or parcel of land. Nutrient inputs include fertiliser, animals, feed, atmospheric inputs, nitrogen fixation, disinfectants, detergent wastes and other chemicals.
- **Nutrient outputs:** mass of nutrients leaving a property or parcel of land. Nutrient outputs include animals, produce and wastes disposed of offsite (e.g. dairy effluent 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 from the land parcel. Nutrient losses can occur though leaching to groundwater, in surface water, or to the atmosphere (wind erosion, fire, denitrification, volatilisation). Note that the nutrient model uses nutrient surplus to estimate land-use nutrient concentrations.
- **Nutrient use efficiency (NUE)** is nutrient out divided by nutrient in, expressed as a percentage. Land uses with 100% NUE convert all nutrient inputs to nutrient outputs and therefore have a nutrient surplus of zero.

Figure 3.7 ranks land uses by their nutrient surplus and gives their nutrient-use efficiency

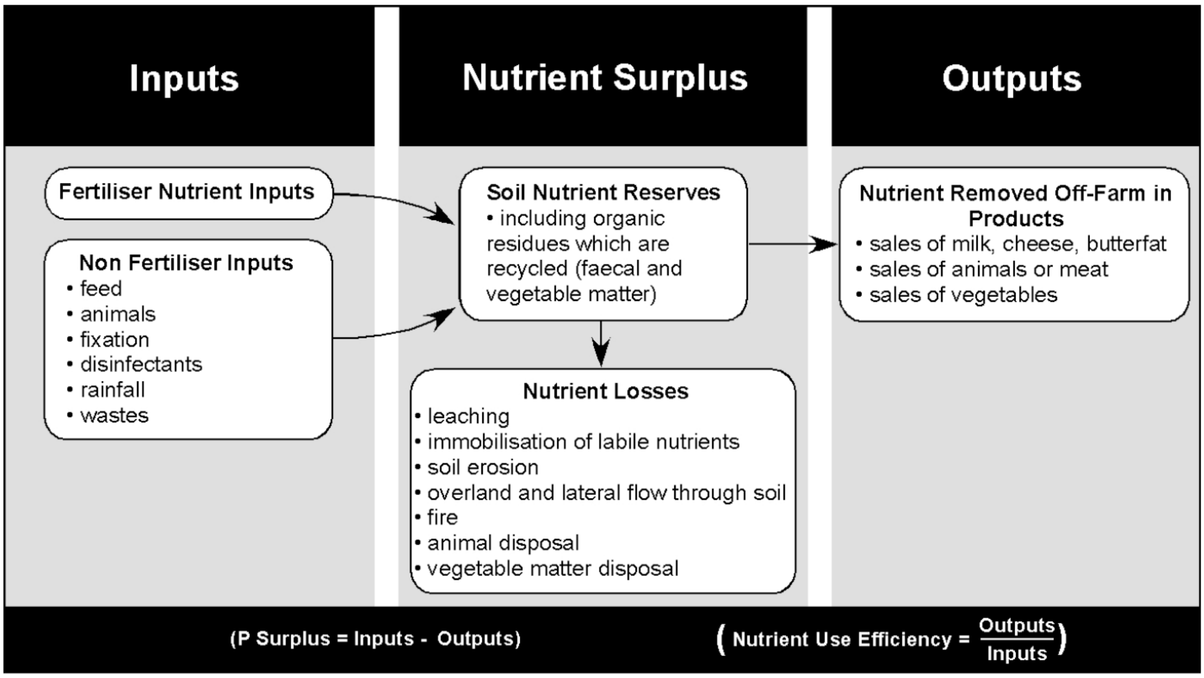


Figure 3.6: The farm-gate nutrient budget framework (Ovens et al. 2008)

Table 3.7: Nutrient input and surplus rates for modelling land uses

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	90	90	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	142.6	126.9	45.8	116.2	32	92	3
Industry, manufacturing & transport	Urban	5.2	0.2	4.7	0.2	90	90	1, 2
Lifestyle block	Cleared	49.2	3.4	49.2	2.4	100	70	3
Mixed grazing	Cleared	79.5	9.9	61.6	7.7	78	78	3
Native vegetation	Vegetated	9.2	0.2	0.5	0.0	5	5	1, 2, 5
Offices, commercial & education	Urban	106.2	20.3	95.6	18.3	90	90	1, 2, 6
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	Vegetated	12.6	8.2	9.5	6.2	75	75	1, 7
Poultry	Cleared	3343.2	411.1	1224.5	21.7	37	5	3
Recreation	Cleared	71.2	2.2	64.1	2.0	90	90	1, 2, 8
Rural living (bush block)	Vegetated	9.2	0.2	8.3	0.2	90	90	1, 2, 5
Turf farm	Cleared	505.2	124.2	90.0	26.6	18	21	9
Urban residential	Urban	89.7	17.8	80.7	16.0	90	90	1, 10
Urban residential (very small)	Urban	28.6	7.1	25.7	6.4	90	90	1, 11
Viticulture	Cleared	54.5	15.9	47.1	13.5	86	85	3

Notes

¥ Surplus as a percentage of nutrient inputs

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

1. Nutrient surplus is assumed to be capped at 90% of nutrient inputs
2. Data taken from the UNDO tool nutrient input fact sheets for atmospheric deposition
3. DPIRD farm gate nutrient budget
4. Hennig & Kelsey 2015
5. Nutrient input rates taken from the UNDO tool nutrient input fact sheets for native vegetation (natural).
6. Data taken from the UNDO tool nutrient input fact sheets for schools
7. Kelsey et al. 2011
8. Krupa 2014
9. Douglas et al. 2010
10. Median of all lots > 400 m^2 from the Urban Nutrient Survey (Kelsey et al. 2010b) primary data.
11. < 400 m^2 lots Kelsey et al. 2010b.

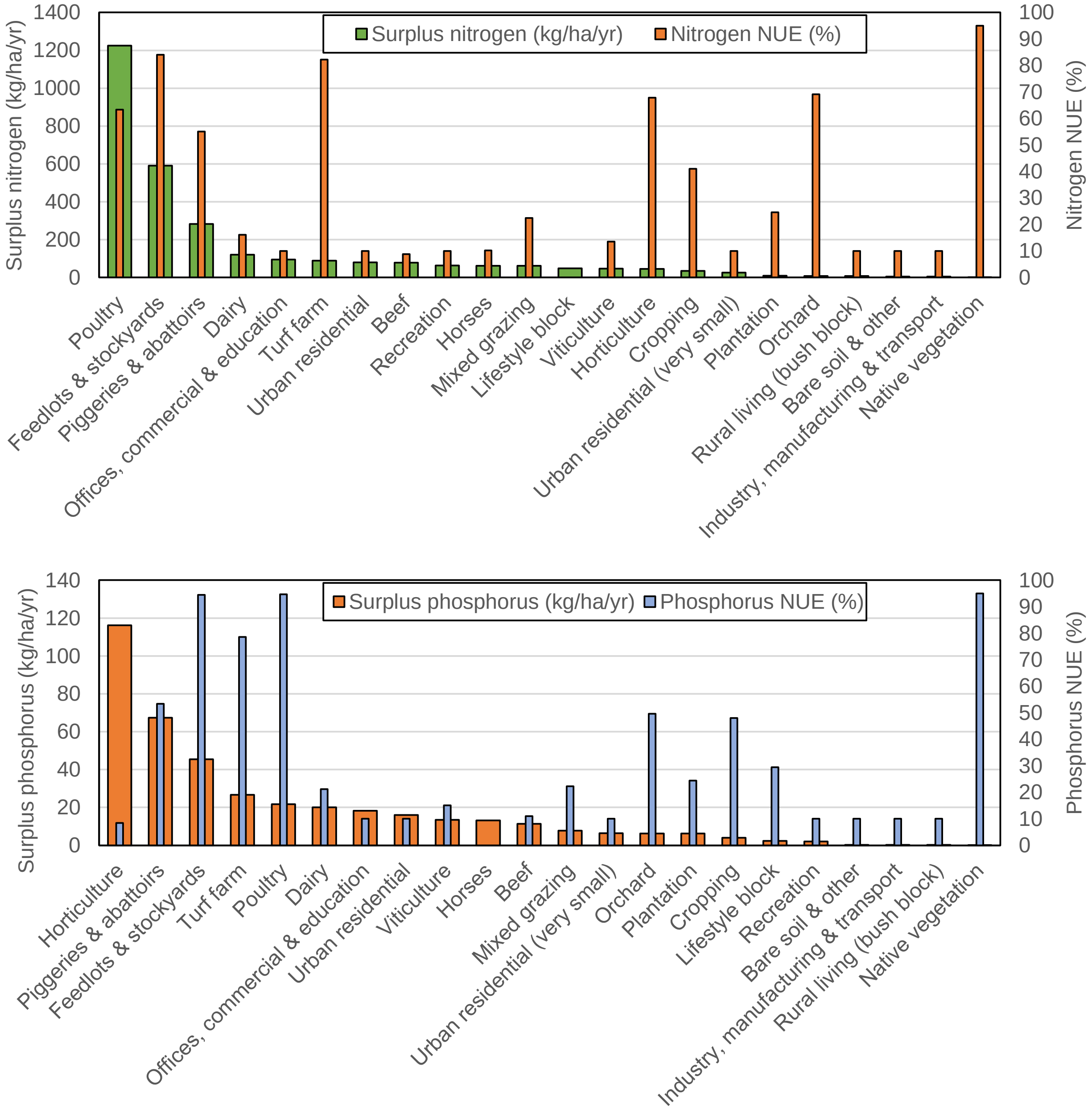


Figure 3.7: Ranked land use nitrogen (top) and phosphorus (bottom) surplus and nutrient use efficiency (NUE)

Modelling and reporting catchments

We derived the modelling catchments using the one-metre-resolution LIDAR dataset for areas on the Swan Coastal Plain, and the 3 arc second Digital Surface Model for inland areas (Geoscience Australia 2011). We needed the higher resolution LIDAR dataset to identify the flow paths and catchment boundaries on the low-lying areas of the Swan Coastal Plain.

We then compared the derived catchments with the Hydrographic Subcatchments dataset (Department of Water and Environmental Regulation) and these largely agreed. Thus we edited the Hydrographic Subcatchments dataset to resolve catchment boundary errors. We then aggregated these catchments to minimise the number of subcatchments, ensuring:

- rainfall changes across the subcatchment were small
- flow and water quality measurement sites aligned with catchment outflow points
- the catchments of major rivers and drains were preserved
- where possible the subcatchment contained similar land uses.

We called the resulting 100 subcatchments the modelling catchments – see Figure 3.8. We then further aggregated the modelling catchments into 24 reporting catchments. We aligned the reporting catchments with those given in Kelsey et al. (2011). Punrak Drain was the only reporting catchment we did not replicate from Kelsey et al. (2011) as we merged it with the Dirk Brook reporting catchment. This was due to its small size and the relocation of the flow and water quality gauging station. Figure 3.9 identifies the reporting catchments we used in this report.

Riparian zone vegetation

We obtained riparian zone vegetated and non-vegetated areas using the ArcMap™ geographical information system (GIS). We applied a 15-metre buffer to first- and second-order[3] streams (i.e. 30 metres wide) and a 30-metre buffer to higher-order[3] streams (i.e. 60 metres wide). The buffered areas represent riparian zones. We then intersected the buffered areas with the land-use dataset. We classed as vegetated riparian zone the areas containing native vegetation and the areas mapped as water. We classed all other land uses as cleared riparian zone.

We calculated the proportion of cleared and vegetated riparian zone by modelling catchment for use in the riparian filtering model parameterisation (see Section 3.1.2). Table 3.8 gives the proportion of riparian vegetation by reporting catchment.

[3] We used Strahler stream ordering (lower-order streams are smaller than higher-order streams). We ordered watercourses using the Stream Order tool in ArcMap™ with the minimum catchment area threshold set to one square kilometre. The highest stream order was 7 (Figure 3.8).

Table 3.8: Riparian zone vegetation by reporting catchment

Reporting catchment	Vegetated area within riparian zone (ha)	Total area within riparian zone (ha)	Vegetated (%)
Serpentine Dam	1 686	1 690	100
North Dandalup Dam	406	406	100
South Dandalup Dam	790	790	100
Drakesbrook & Waroona Dams	120	138	87
Samson Brook Dam	132	132	100
Logue Brook Dam	87	93	94
Harvey Reservoir & Stirling Dam	780	981	80
Coastal North	1	2	40
Coastal South	7	10	68
Peel Main Drain	170	403	42
Upper Serpentine	711	1 686	42
Dirk Brook	213	493	43
Nambeelup	143	484	30
Lower Serpentine	213	350	61
Upper Murray	8 716	17 594	50
Lower Murray	1 510	2 316	65
Coolup (Peel)	98	455	22
Coolup (Harvey)	55	222	25
Mayfield Drain	101	396	26
Harvey	633	1 863	34
Meredith Drain	38	171	22
Harvey Diversion Drain	174	548	32
Total	**16 784**	**31 221**	**54**
Swan Coastal Plain	**3 656**	**8 874**	**41**
Upland	**13 127**	**22 347**	**59**

Dam catchments
Drains to ocean
Peel Inlet
Harvey Estuary

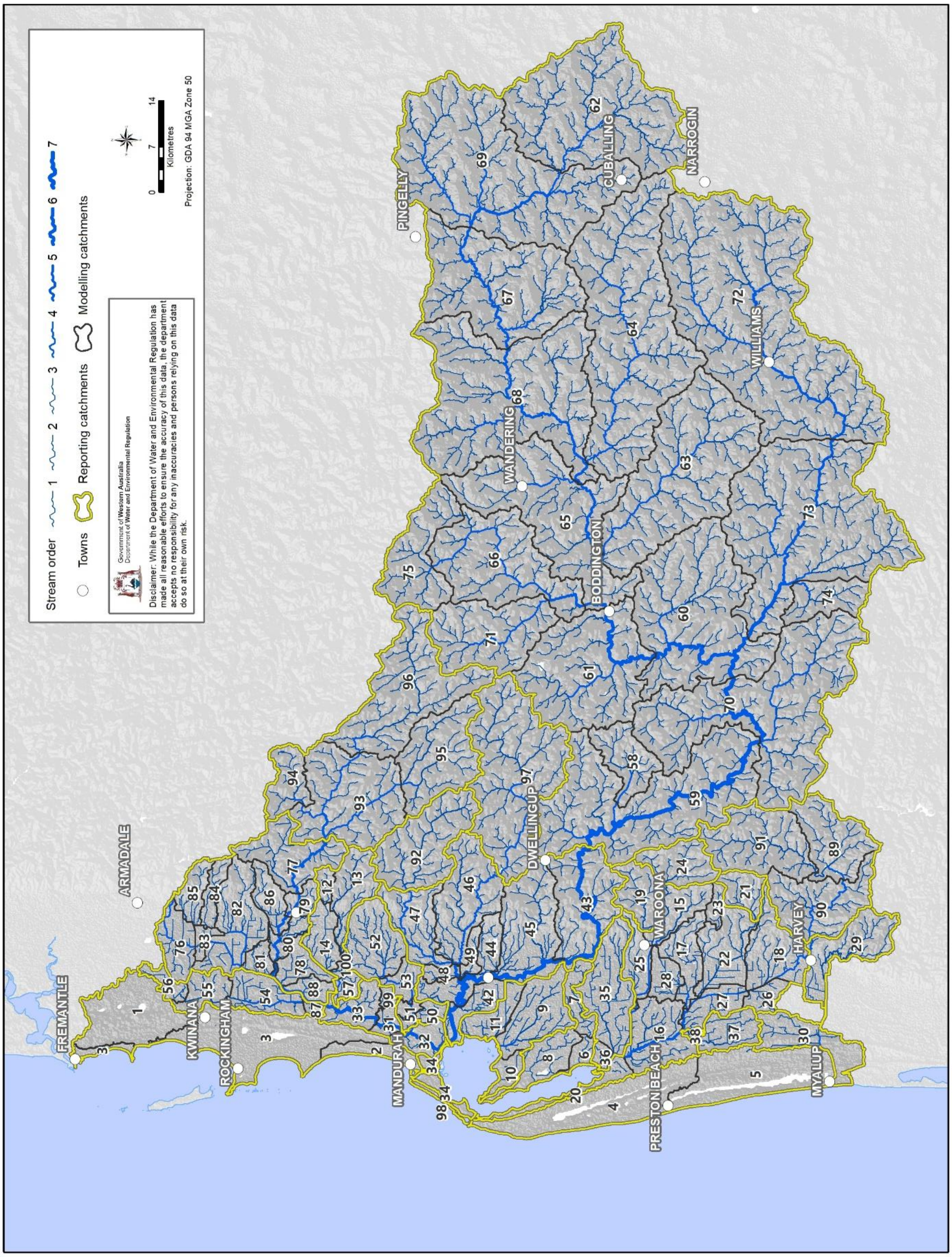


Figure 3.8: Catchments and stream order

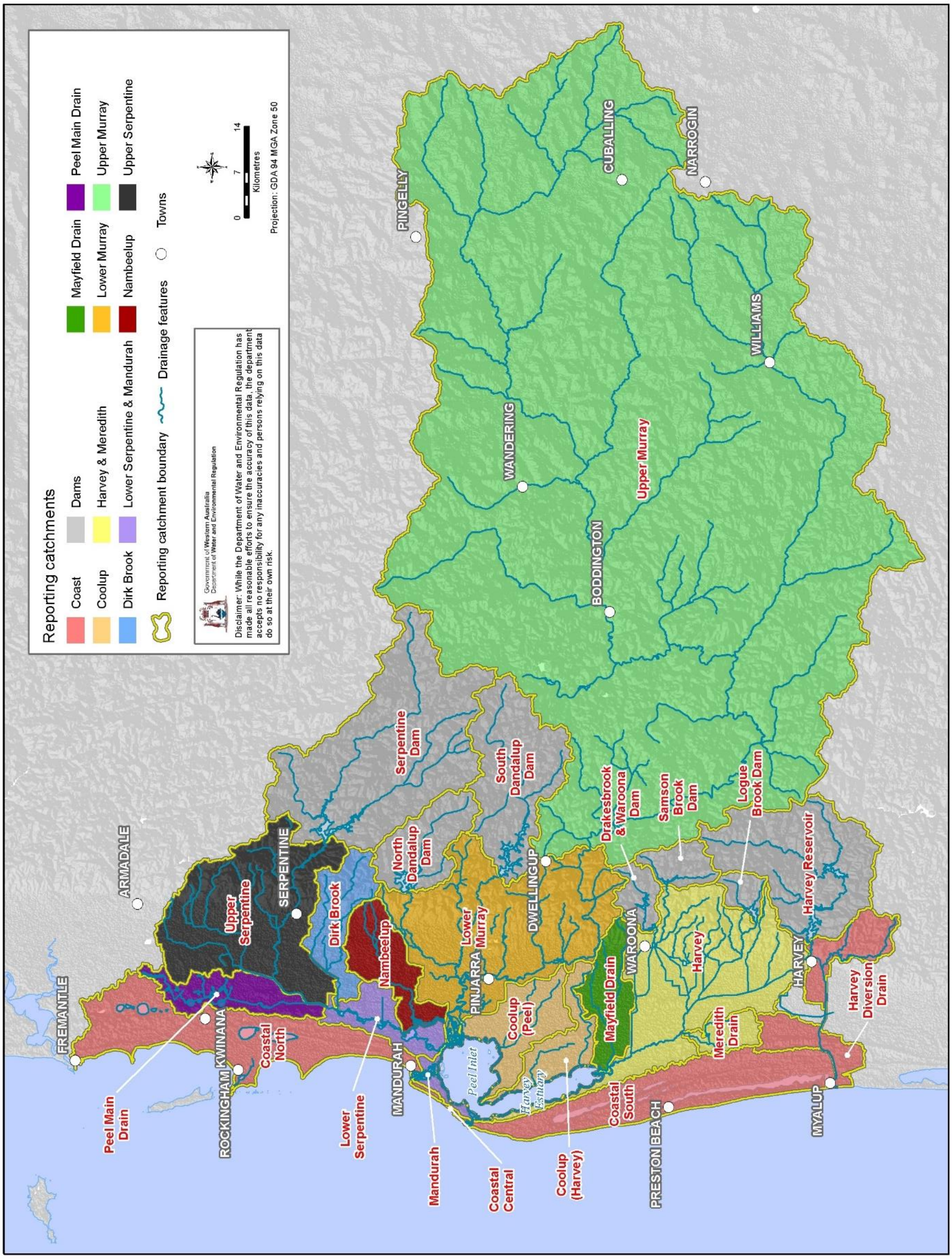


Figure 3.9: Reporting catchments

Soil phosphorus retention index (PRI)

Soil phosphorus retention index (PRI) is a measure of a soil's capacity to retain phosphorus (Allen & Jeffery 1990). Soil with a PRI of zero would have no capacity to retain phosphorus. We used DPIRD soil mapping to find soil PRI – the same data that Kelsey et al. (2011) used.

We used soil PRI as a variable in the phosphorus model. We created two soil PRI classifications: soils with a PRI of < 7 being 'low PRI' and soils with a PRI of ≥ 7 being 'high PRI' (Figure 3.10). We merged the land-use mapping data (23 categories) with the DPIRD soil PRI data (two categories) to create the primary modelling functional units for Source, which resulted in a maximum of 46 functional units per subcatchment.

Dam releases and irrigation returns

The major dams in the catchment supply both potable water (Serpentine main and pipehead dams, North Dandalup, South Dandalup, Samson and Stirling dams) and agricultural water (Waroona, Drakesbrook, Logue, Wokalup dams and Harvey Reservoir). The Water Corporation owns all the dams. Harvey Water delivers agricultural water supply through a network of pipe and channel infrastructure. Releases from dams can occur by way of overflow events, environmental water provisions and irrigation supply.

Our reasoning for the dam and irrigation inputs into the model included:

- **Dam overflows:** None of the dams in the Peel-Harvey catchment have overflowed in recent years. Therefore we did not include dam overflows in the model.
- **Environmental water provisions/releases:** We included environmental water provisions from the Larson's Cut (Harvey Diversion Drain to the Harvey River) and Logue and Drakesbrook dams in the model according to the *Harvey-Waroona irrigation water resource management operating strategy* (Strategen 2013). Note we did not include the environmental water provisions from Wokalup Dam in the model. This dam is in the Harvey Diversion Drain catchment and does not contribute to the Peel-Harvey estuary through Larson's Cut, because its releases are in winter and the Cut only operates in summer. There are no long-term nutrient concentration measurements from dams or dam releases. Thus, we assumed dam releases had nutrient concentrations of 0.35 mg/L TN and 0.01 mg/L TP based on nutrient measurements from the stream that flows into the Serpentine Dam (O'Neil Road, Big Brook, AWRC ref 614037, Figure 3.11).
- **Irrigation returns:** We followed the same approach as Marillier et al. (2009) to calculate excess irrigation water – using irrigation supply point data from Harvey Water. We assumed half of the average daily irrigation water (1998–2008) supplied to each modelling catchment then flowed to the adjacent stream/drain. We calibrated the nutrient concentrations of irrigation returns to measurements at 613052, 613031 and 6131335 with fixed concentrations of 0.75 mg/L nitrogen and 0.08 mg/L phosphorus. As dairy farms are the main irrigated land use, we apportioned water and nutrient loads from irrigation returns to dairy farms in the source separation of nutrients.

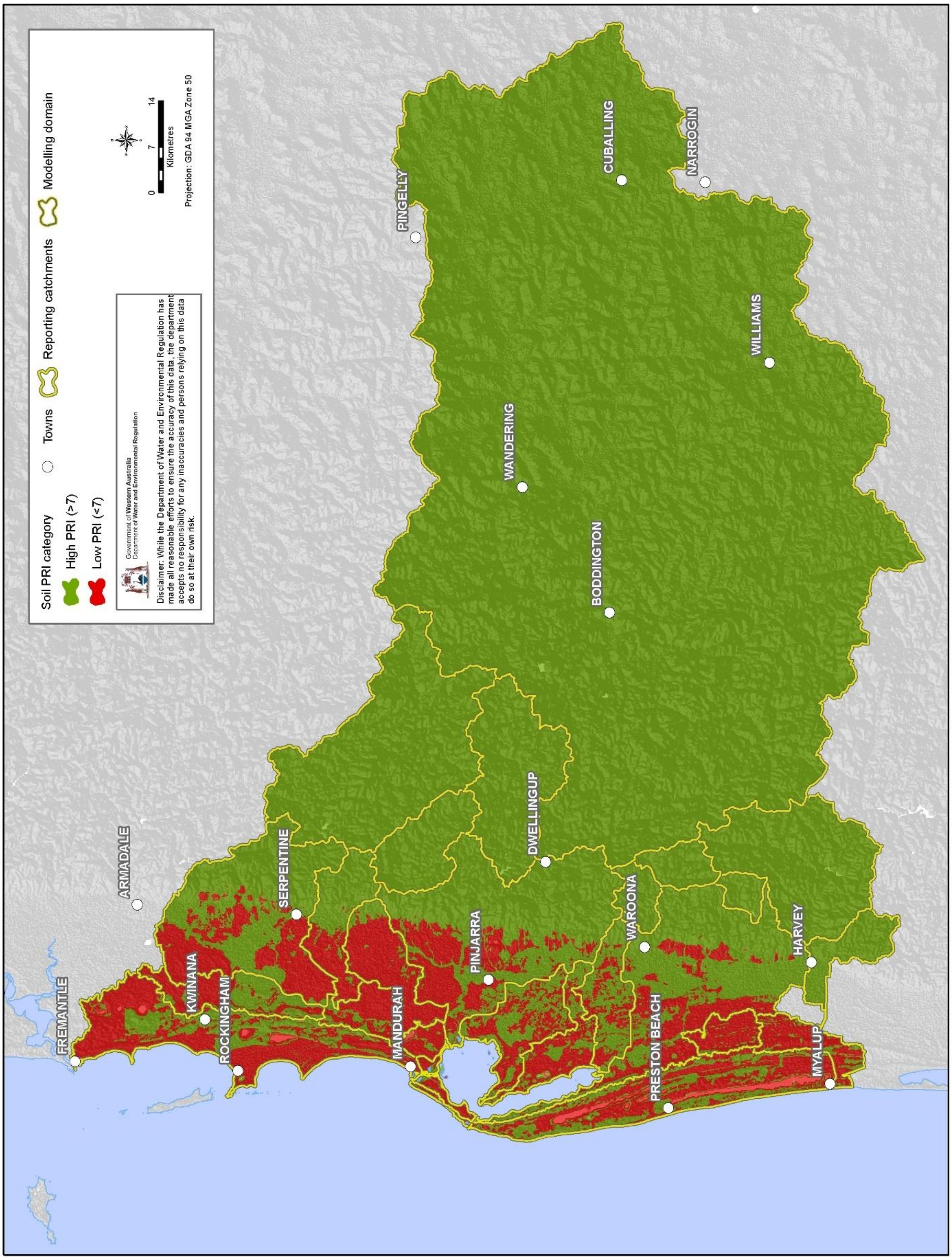


Figure 3.10: High (>7) and low (<7) soil phosphorus retention index categories

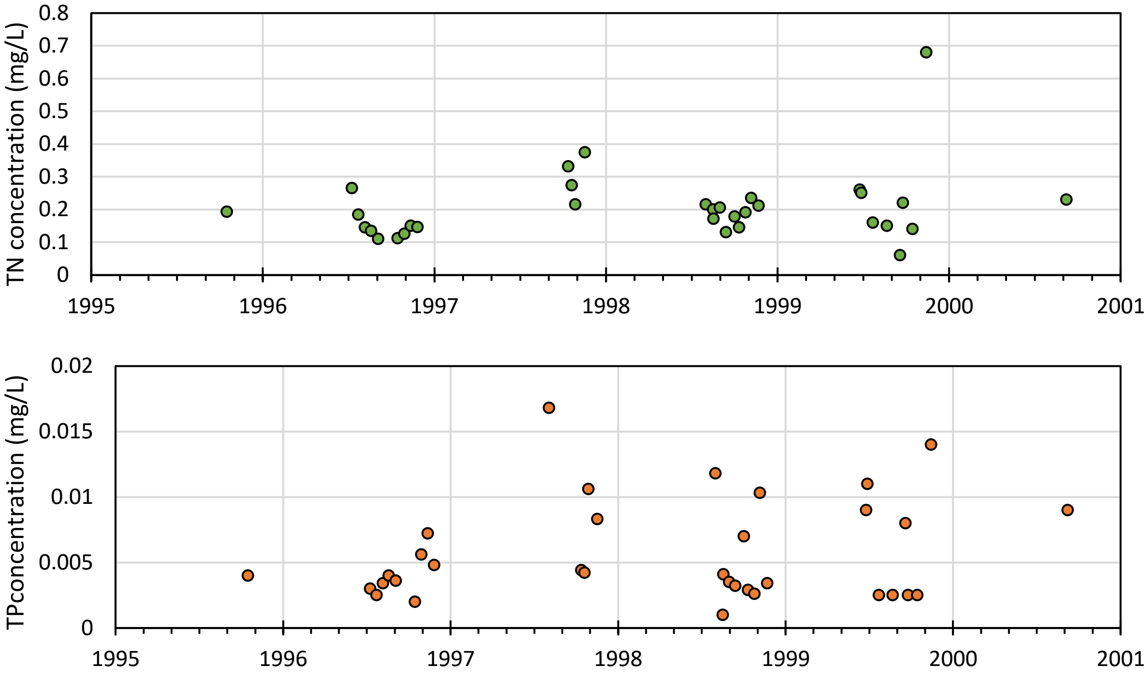


Figure 3.11: Measured total nitrogen (top) and total phosphorus concentrations at O'Neill Road, Big Brook (AWRC ref 614037). See Figure 4.2 for the location of this site.

Point sources and septic tanks

Figure 3.12 gives the locations of the septic tanks and point sources we put in the model. Appendix C details our methodology for point source inclusion, while Table 3.9 summarises the point sources and nutrient emissions by reporting catchment.

We assumed all onsite wastewater systems were septic tanks because no known mapping exists of alternative/aerobic treatment units. See Table 3.10 for the number of septic tanks and their emissions to surface water. We calculated septic tank nutrient emissions separately from the diffuse model – see Appendix C.

Table 3.9: Number of point sources and estimated average annual (2006–2015) nutrient emissions to surface water

Reporting catchment	Feedlots & stockyards			Piggeries & abattoirs			Poultry			Other industries			WWTP			**Total**		
	#	N load (t/yr)	P load (t/yr)	#	N load (t/yr)	P load (t/yr)	#	N load (t/yr)	P load (t/yr)	#	N load (t/yr)	P load (t/yr)	#	N load (t/yr)	P load (t/yr)	**#**	**N load (t/yr)**	**P load (t/yr)**
Coastal North							4	0.2	0.00	3	42	5				**7**	**42**	**5.3**
Coastal Central																		
Coastal South	1	0.3	0.03													**1**	**0.3**	**0.03**
Peel Main Drain	1	0.5	0.02				3	0.4	0.01				1	1.4	0.03	**5**	**2.3**	**0.06**
Upper Serpentine	4	5.4	0.15	1	0.2	0.01	13	3.5	0.11	1	0.3	0.05				**19**	**9.5**	**0.32**
Dirk Brook	1	0.2	0.02	1	0.4	0.12	3	3.7	0.08							**5**	**4.3**	**0.22**
Nambeelup	1	0.2	0.02		0.02	0.01										**1**	**0.2**	**0.02**
Lower Serpentine				1	0.8	0.19	3	0.1	0.005							**4**	**0.9**	**0.20**
Upper Murray	3	0.1	0.00	3	0.1	0.00	1	0.0	0.000				2	0.1	0.04	**9**	**0.4**	**0.04**
Lower Murray	1	0.1	0.01				2	6.8	0.05							**3**	**6.9**	**0.06**
Coolup (Peel)	1	0.1	0.01	1	0.1	0.02										**2**	**0.1**	**0.03**
Coolup (Harvey)				1	0.1	0.02										**1**	**0.1**	**0.02**
Mayfield Drain	1	0.1	0.00													**1**	**0.1**	**0.00**
Harvey	1	0.2	0.03							1	0.6	0.52	1	2.8	0.14	**3**	**3.6**	**0.69**
Meredith Drain				1	0.9	0.18										**1**	**0.9**	**0.18**
Harvey Diversion Drain				1	3.2	0.13							1	7.9	0.28	**2**	**11**	**0.42**
Peel-Harvey estuary	**14**	**6.8**	**0.25**	**9**	**2.6**	**0.55**	**25**	**15**	**0.25**	**2**	**0.9**	**0.57**	**4**	**4.3**	**0.22**	**54**	**29**	**1.8**
Total	**15**	**7.1**	**0.28**	**10**	**5.8**	**0.68**	**29**	**15**	**0.25**	**5**	**43**	**5.9**	**5**	**12**	**0.50**	**64**	**83**	**7.6**

Table 3.10: Number of septic tanks and average annual (2006–15) nutrient exports to surface water by reporting catchment

Reporting catchment	People (#)	Septic tanks (#)	Average annual discharge to surface water (2006–15) Volume (ML/yr)	N load (t/yr)	P load (t/yr)
Harvey Reservoir & Stirling Dam	5	2	-	-	-
Coastal North	22 669	4 838	613	60	4.0
Coastal Central	1 795	744	49	4.8	0.3
Coastal South	3 775	1 340	17	1.7	0.04
Peel Main Drain	4 267	1 632	31	3.0	0.2
Upper Serpentine	11 079	4 187	78	7.6	0.4
Dirk Brook	429	175	3.1	0.3	0.01
Nambeelup	758	316	0.9	0.1	0.02
Lower Serpentine	3 492	1 206	38	3.7	0.1
Mandurah	1 850	746	32	3.1	0.2
Upper Murray	3 738	781	-	-	-
Lower Murray	4 670	1 172	35	3.4	0.1
Coolup (Peel)	238	99	0.5	0.05	0.001
Coolup (Harvey)	284	115	0.6	0.06	0.001
Mayfield Drain	151	63	0.5	0.05	0.01
Harvey	6 275	2 229	20	2.0	0.6
Meredith Drain	29	12	0.1	0.01	0.002
Harvey Diversion Drain	805	234	9.5	0.9	0.1
Peel-Harvey estuary	37 259	12 733	240	23	1.6
Total	66 308	19 891	930	90	6.0

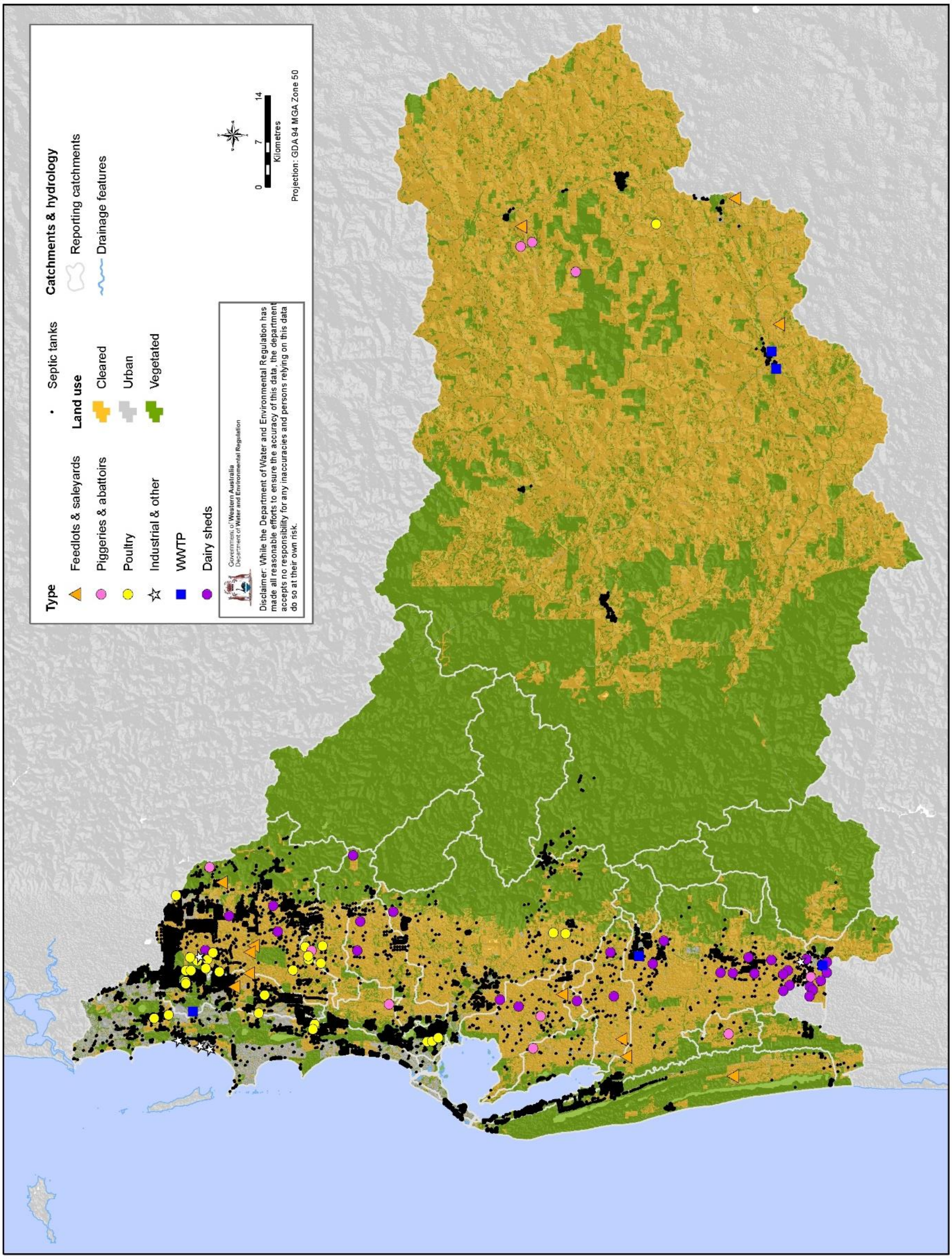


Figure 3.12: Point sources, dairy sheds and septic tanks

4 Model calibration, model use and limitations

4.1 Calibration process and performance

This chapter summarises the calibration, parameterisation and model performance statistics. See Appendix A and B for additional information.

The Department of Water and Environmental Regulation has many flow gauges in the Peel-Harvey catchment. Of these, we used 23 to calibrate the hydrological model parameters for cleared, urban and vegetated land uses. The Peel-Harvey catchment did not have any flow monitoring in the catchments with a large proportion of urban land uses. Thus, we parameterised the urban land uses using model parameters from the Bannister Creek catchment (Canning River catchment). Table 4.1 summarises the flow gauging stations and the hydrological calibration and validation statistics.

We calibrated the hydrological models with the Source automatic calibration tool, which uses the shuffle complex evolution algorithm and the Nash-Sutcliffe daily bias (NSE bias) as the objective function. Our secondary calibration objectives were to replicate base flow, high flow, no-flow conditions, cumulative frequency plots and visual comparison of modelled and observed hydrographs. We accepted the NSE daily bias statistic at a score of 0.65, with good and very good being >0.80 and >0.90 respectively.

Where possible, we calibrated the hydrological models over the period 2000–15 and validated these against data from 1980–99. We did this so that the hydrological model would produce accurate results for the period in which most results were derived (2006–15). The 2000–15 period had substantially lower flow than previous years due to reduced rainfall. As a result, the model consistently underestimated larger flow events that were present in the validation period of 1980–1999. Calibrating to recent data was also important to align with the model land use, which was mapped using 2010–15 aerial photography.

We calibrated the nutrient models against five-year (generally 2011–15) winter median nutrient concentrations from 14 monitoring sites. 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 4.1 show the nutrient calibration statistics and Figure 4.2 shows the flow and water quality monitoring sites we used for model calibration. Two sites did not meet these criteria:

- Yangedi Swamp (614094) had an annual NSE score of 0.55. The annual flow in 2003 was poorly replicated. The annual NSE excluding this year was 0.79. We did not adjust the model as this year was outside the reporting period of 2006–15.
- Serpentine River (614035) is located in the Serpentine Dam catchment. This site had a daily NSE of 0.61, which was due to the substantial over-prediction of baseflow post-2009. We did not adjust the model as flows from this catchment are detained by the Serpentine Dam and therefore do not affect the primary study area (catchments that actively discharge to the Peel-Harvey estuary).

Figure 4.3 compares the average annual (2006–15) nutrient load estimated by LOESS and the Source model at nine sites (613027, 613031, 613052, 614030, 614063, 614065, 614094, 614121, 613031). The Source model typically estimated higher nitrogen loads than the LOESS model. Phosphorus loads were more closely correlated.

Catchments without flow and/or nutrient calibration have greater uncertainty. There was no nutrient model calibration within the Upper Murray catchment. As such, there is greater uncertainty about the source of nutrients in the Upper Murray. However, the nutrient contribution from the entire Upper Murray catchment calibrated well at 614065.

Table 4.1: Hydrological model calibration and validation statistics

AWRC ref	River name	Calibration					Validation				
		Period	Daily NSE	Monthly NSE	Annual NSE	MB error (%)	Period	NSE daily	Monthly NSE	Annual NSE	MB error (%)
616134	Bannister Creek	2000–15	0.84	0.94	0.66	-1	-	-	-	-	-
614031	39 Mile Brook	1990–2015	0.79	0.79	0.64	3	-	-	-	-	-
614035	Serpentine River	1990–2015	0.61	0.76	0.74	13	-	-	-	-	-
614037	Big Brook	1990–2015	0.66	0.74	0.67	7	-	-	-	-	-
613002	Harvey River	1990–2015	0.85	0.88	0.69	1	-	-	-	-	-
614030	Serpentine Drain	2000–15	0.91	0.94	0.92	4	1980–99	0.76	0.74	-0.21	-40
614063	Nambeelup Brook	2000–15	0.88	0.94	0.94	7	1990–99	0.68	0.75	0.49	-31
614094	Dirk Brook	2000–15	0.84	0.83	0.55	0	1995–99	0.84	0.92	0.75	-14
614114	Serpentine River	2000–15	0.85	0.91	0.79	3	1998–99	0.83	0.95	0.81	-9
614120	Gull Road drain	2005–07	0.82	0.90	0.91	3	-	-	-	-	-
614013	Peel Main Drain	1990–99	0.74	0.82	0.45	-4	-	-	-	-	-
614121	Peel Main Drain	2005–15	0.75	0.84	0.72	11	-	-	-	-	-
614030	Murray River	2000–15	0.90	0.94	0.90	5	1980–99	0.86	0.91	0.79	-16
614044	Yaragil Brook	2000–15	0.69	0.75	0.81	7	1980–99	0.49	0.53	0.20	-42
614065	Murray River	2000–15	0.90	0.94	0.90	1	1992–99	0.89	0.91	0.73	-19
614105	Hotham River	2000–15	0.57	0.77	0.73	-5	1996–99	0.71	0.77	0.66	-30
614196	Williams River	2000–15	0.78	0.91	0.90	-2	1980–99	0.87	0.96	0.90	-5
614224	Hotham River	2000–15	0.86	0.90	0.87	1	1980–99	0.83	0.91	0.80	-17
613014	Samson North Drain	2000–15	0.82	0.90	0.97	-2	1980–98	0.67	0.71	-0.22	-20
613027	South Coolup Drain	2005–15	0.82	0.85	0.82	12	1990–98	0.78	0.90	0.83	-9
613031	Mayfield Drain	2005–15	0.77	0.86	0.80	5	1991–99	0.81	0.93	0.87	0
613052	Harvey River	2000–15	0.87	0.93	0.85	4	1982–99	0.82	0.84	0.25	-28
613053	Meredith Drain	2000–10	0.85	0.88	0.89	2	1982–99	0.75	0.75	0.16	-37
613019	Harvey Diversion Drain	2014–15	0.96	0.99	0.99	-3	1980–99	0.23	0.09	-2.48	-76

NSE: Nash-Sutcliffe Efficiency

MB error: Total period mass balance error

Table 4.2: Nutrient model calibration statistics

Nutrient	Gauging station reference	Reporting catchment	Nutrient model	No. samples	Observed winter median (mg/L)	Modelled winter median (mg/L)	Diff (%)	Annual NSE
TN	613014	Harvey	Samson	48	1.60	1.66	3.4	0.88
	613027	Coolup (Harvey)	Coolup	46	2.15	2.22	3.1	1.00
	613031	Mayfield Drain	Mayfield Drain	48	1.45	1.47	1.5	0.98
	613052	Harvey	Harvey	48	1.70	1.76	3.2	0.99
	613053	Meredith Drain	Meredith	46	2.60	2.68	3.2	0.99
	614030	Upper Serpentine	Upper Serpentine	48	1.20	1.23	2.5	0.98
	614063	Nambeelup	Nambeelup	45	3.60	3.77	4.7	1.00
	614065	Lower Murray	Upper Murray	48	0.63	0.63	-0.5	0.84
	614094	Dirk Brook	Dirk Brook	47	1.90	1.94	2.2	0.69
	614120	Lower Serpentine	Gull Road	36	4.90	5.00	2.0	0.99
	614121	Peel Main Drain	Peel Main Drain	47	1.50	1.53	2.1	0.99
	6131335	Harvey	Harvey	48	1.60	1.67	4.3	0.95
	6142623	Lower Murray	Murray	47	0.92	0.93	1.3	0.91
	614037	Serpentine Dam	Dams	27	0.18	0.19	1.2	0.95
TP	613014	Harvey	Samson	48	0.165	0.171	3.3	0.67
	613027	Coolup (Harvey)	Coolup	46	0.275	0.283	3.0	0.97
	613031	Mayfield Drain	Mayfield Drain	48	0.130	0.133	2.7	0.97
	613052	Harvey	Harvey	48	0.165	0.168	1.5	0.98
	613053	Meredith Drain	Meredith	46	0.385	0.396	2.8	0.98
	614030	Upper Serpentine	Upper Serpentine	48	0.150	0.156	3.7	0.99
	614063	Nambeelup	Nambeelup	45	0.580	0.601	3.6	0.99
	614065	Lower Murray	Upper Murray	48	0.013	0.014	4.6	0.83
	614094	Dirk Brook	Dirk Brook	47	0.190	0.194	2.1	0.54
	614120	Lower Serpentine	Gull Road	36	1.000	1.025	2.5	0.95
	614121	Peel Main Drain	Peel Main Drain	47	0.190	0.195	2.4	0.69
	6131335	Harvey	Harvey	48	0.073	0.075	4.1	0.96
	6142623	Lower Murray	Murray	47	0.082	0.084	1.9	0.68
	614037	Serpentine Dam	Dams	27	0.004	0.004	1.2	0.86

Note that all sites were calibrated to the period of 2011–2015 except for 614037 which was calibrated to the period of 1995–2000 due to limited data

NSE = Nash-Sutcliffe efficiency

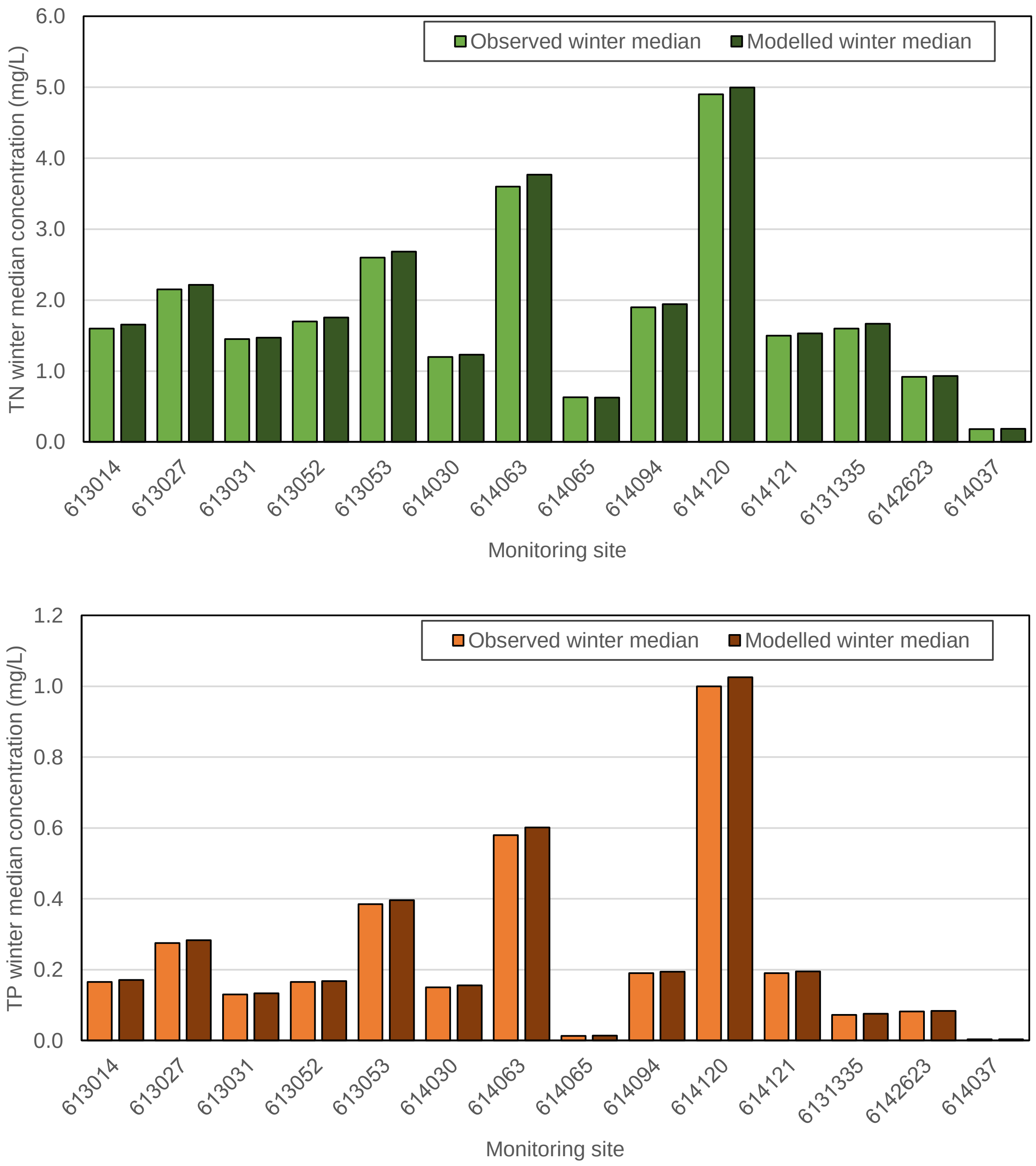


Figure 4.1: Winter median observed and modelled total nitrogen (top) and total phosphorus (bottom) concentrations. All sites represent the period of 2011–2015 except 614037, which represents the period of 1995–2000.

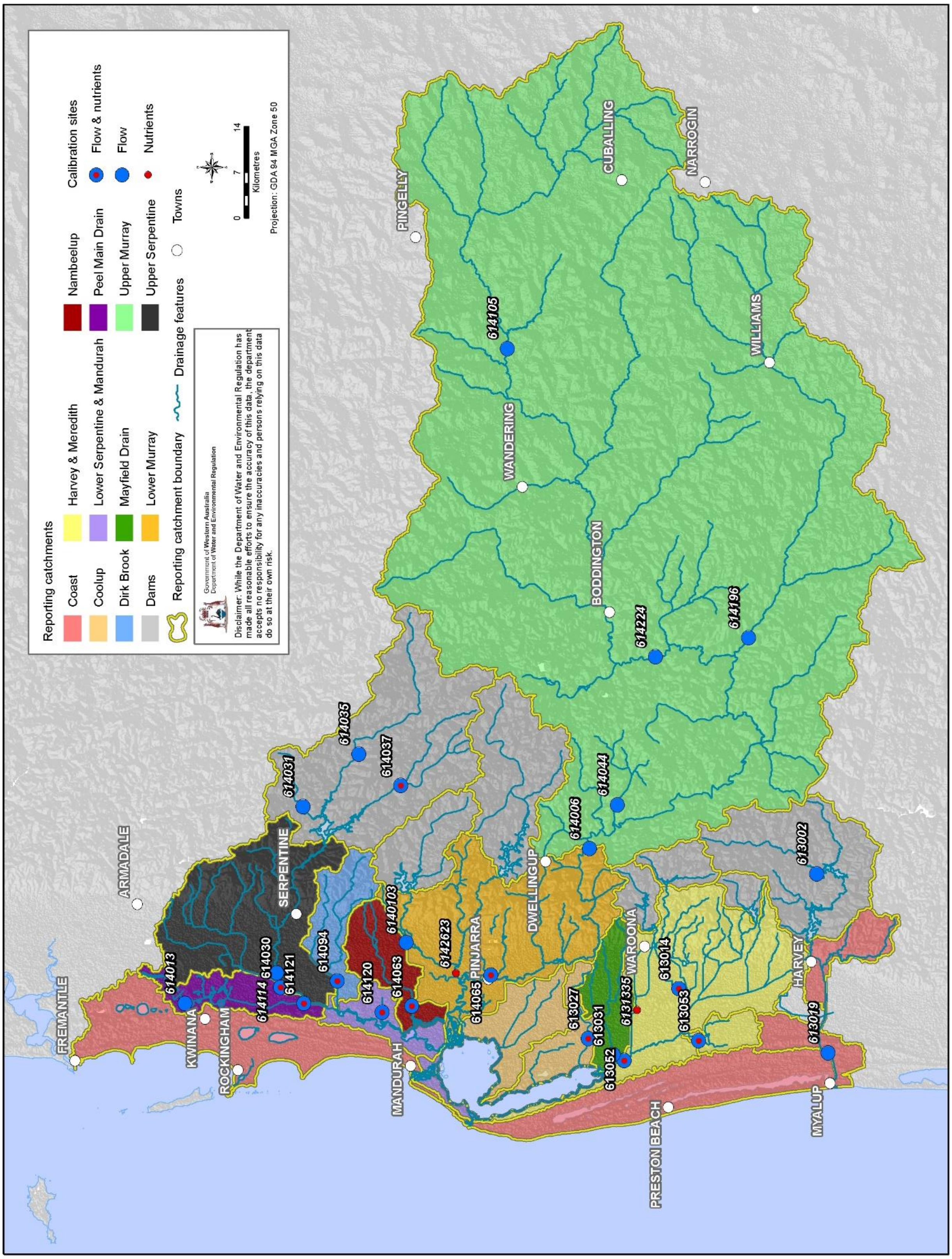


Figure 4.2: Flow and nutrient calibration sites

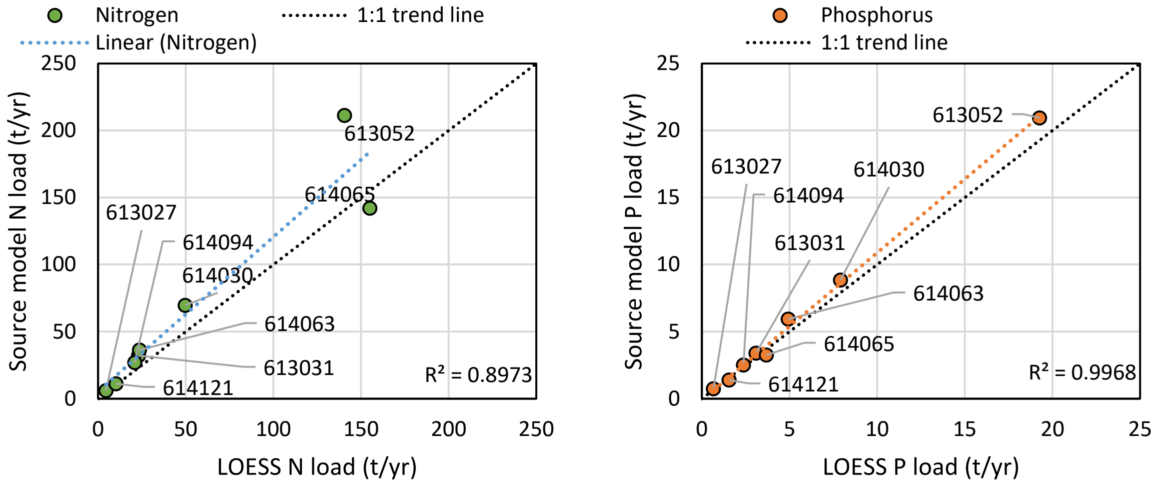


Figure 4.3: Comparison of the average annual (2006–15) nutrient loads estimated by LOESS and the Source model

4.2 Comparison to previous modelling

The flows and loads that SQUARE estimated for 1997–2007 (Kelsey et al. 2011) are different to those that Source estimated for 2006–15 (see Figure 4.4). The differences are due to:

- change in climate (rainfall and evaporation)
- different models, model calibration and model performance
- land-use and land-management changes.

Decreased rainfall due to the changing climate generally results in a much greater percentage reduction in streamflow than rainfall. For example, the 7% reduction in average annual rainfall at Dog Hill (614030) between 1997–2007 and 2006–15 resulted in a 39% reduction in flow and a similar (if not greater) reduction in nutrient loads (see Figure 4.5).

See Figure 4.4 for the reporting catchment loads for SQUARE and Source for the 1997–2007 period. The model methodology differences and the reasons for the different load estimations are discussed below.

- We re-defined some catchments for the Source modelling. This contributes to differences in the reporting of catchment flow and load results between the Source and SQUARE models (see Table 4.3).
- More data was available for the Source model calibration compared with the SQUARE calibration (Kelsey et al. 2011).
- The Source nutrient model is a flow-concentration relationship model. We derived land-use nutrient concentrations using observed flow and concentration data, land-use nutrient surplus and land-use flow yield. The Source nutrient model is steady-state: it has one set of land-use and management inputs, and gives estimated flows and nutrients loads for these inputs. The SQUARE model is a physically-based lumped conceptual model which accounts for changing land uses and physical

processes. The build-up or rundown of soil nutrients is accounted for. Thus the basecase flows and loads for Source are an average of 10 years of modelled flows and loads which are generated by the different annual climates, but the same land use. We derived the basecase flows and load for SQUARE by averaging 11 years of model outputs which have different annual climates, and changing land uses.

- This Source model used separate rainfall-runoff models for urban, cleared and vegetated land uses within a modelling subcatchment, rather than a single lumped hydrological model – as was used in Kelsey et al. (2011). This modelling approach tended to predict greater flow yield (and therefore nutrient loads) in highly urbanised ungauged catchments, namely the Lower Serpentine, Mandurah, Coastal North and Coastal Central catchments.
- Models will produce more accurate flow and load estimations for periods with similar climates to their calibration period, compared with periods that have different climates. We mostly calibrated the Source hydrological model to the 2000–2015 period, which was dryer and had less river flow than pre-2000. Thus, in the 1997–2007 period the Source model better replicated average to lower-flow years and under-predicted higher flow years such as the year 2000 (the wettest year in the calibration period) and years before 2000 (uncalibrated). We mostly calibrated the SQUARE model to pre-2000 data: thus it better represents higher flow years and can over-estimate lower flow years.
- There were differences in model performance in some catchments (Figure 4.4):
  - We found a 60% discrepancy in average annual flow and nitrogen load to the estuary for the 1997–2007 period between the SQUARE and Source models. Most of this discrepancy was due to differences in the Upper Murray flow estimations, which were primarily due to the Source model's under-estimation of flow (and hence nitrogen load) in 1999 and 2000. In other years in the period 1997–2015 the Source model flows compared well with observed data, particularly for the model reporting period 2006–15 (mass balance error of -2%, annual NSE of 0.97 at site 614006).
  - Large differences in phosphorus load for the Upper Serpentine, Coolup (Peel), Coolup (Harvey), Harvey and Meredith catchments are due to 1) the flow bias from the different calibration periods of the two models; 2) very poor SQUARE flow calibration at site 613027 due to the small amount of data – this affected both Coolup reporting catchments which used parameters from this calibration; and 3) an error in the SQUARE Meredith phosphorus model.

Table 4.3 outlines the following differences between the SQUARE and Source models: changes to catchment area, data availability, model calibration performance, land-use changes and changes in the number of septic tanks.

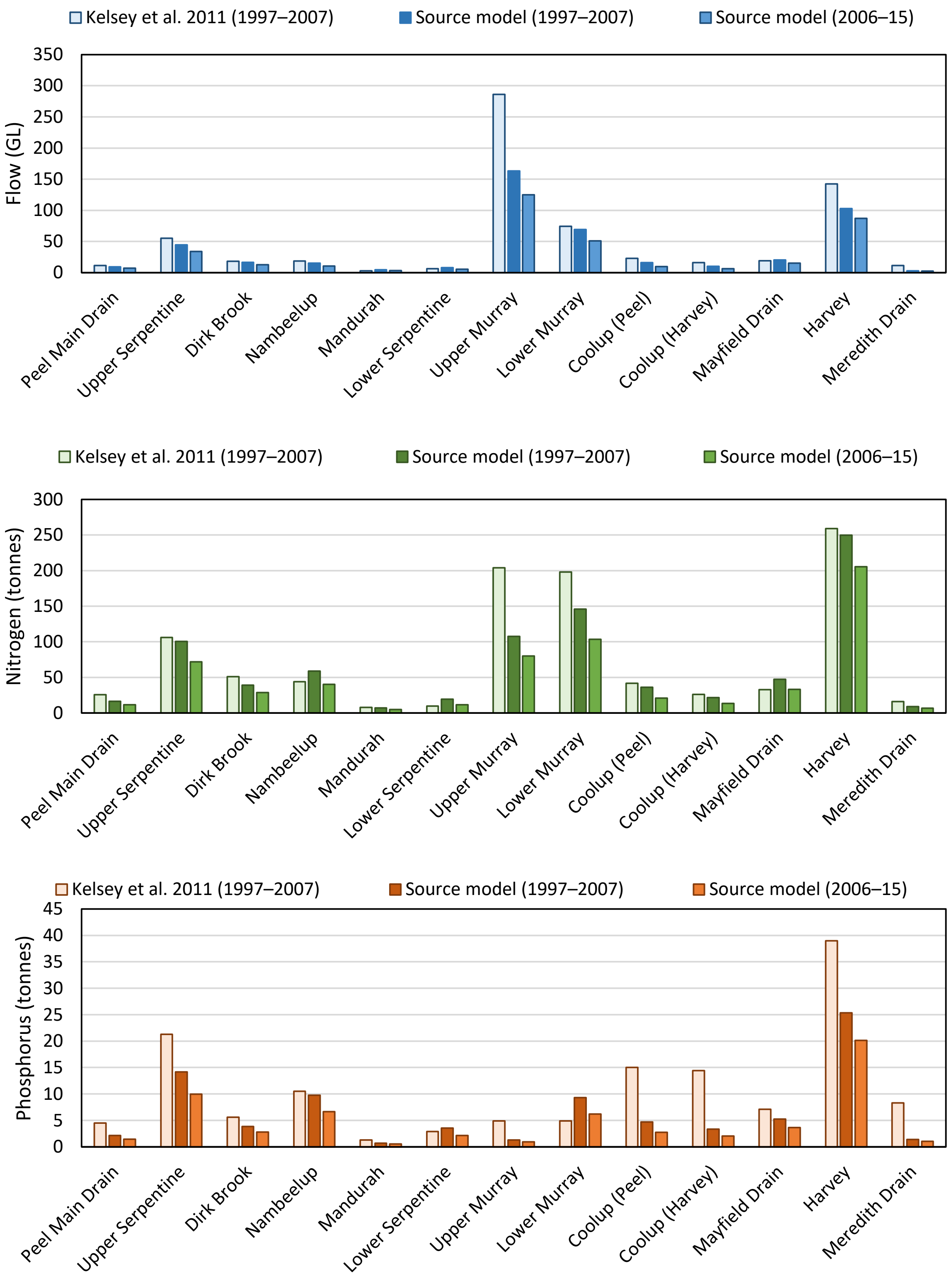


Figure 4.4: SQUARE and Source modelled average annual flows and loads for calibrated catchments

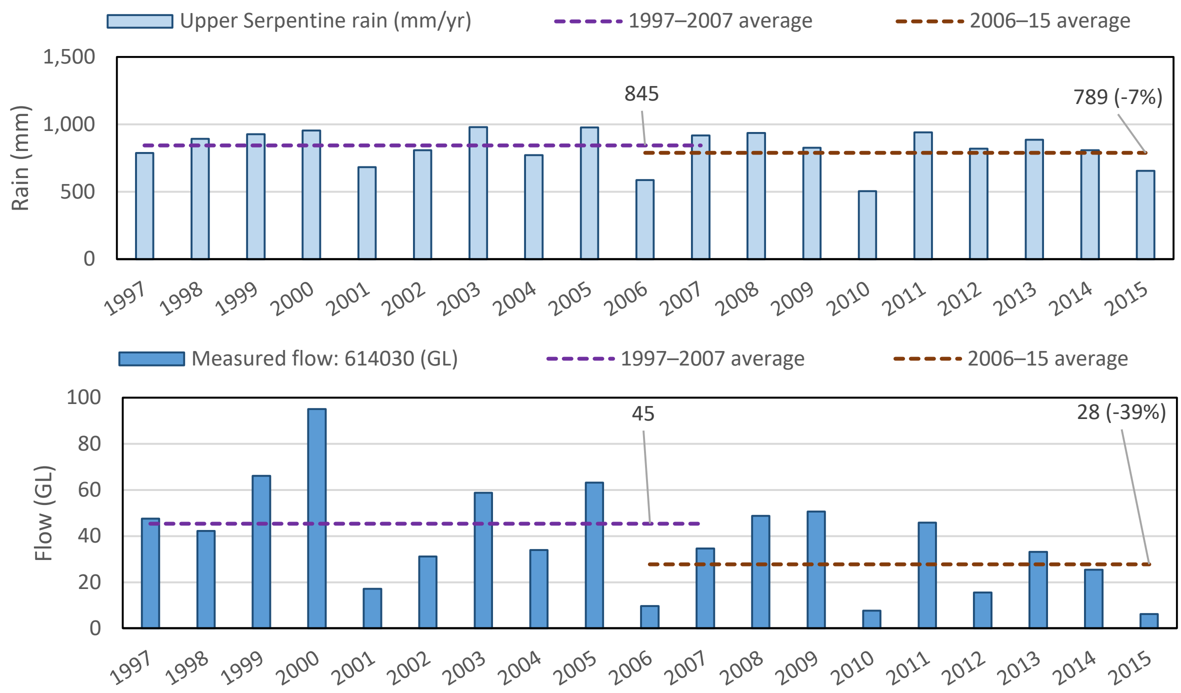


Figure 4.5: Annual rainfall (top) and measured annual flows at Dog Hill (Serpentine Drain, AWRC ref 614030). The average annual rain and flow for 1997–2007 (reporting period of the SQUARE modelling) and 2006–15 (reporting period of this model) are given. The per cent change in rain and flow is shown in brackets.

Table 4.3: Summary of reporting catchment changes between the SQUARE and Source models. Note: positive area increases mean that the Source model had a greater reporting catchment area than the SQUARE model.

Reporting catchment	Comment
Coastal North	**Area:** +8%. Includes all coastal draining catchments between the Peel-Harvey and Swan-Canning catchments **Land-use change:** Increased area of urban land use and the inclusion of additional point sources of nutrients **Septic tanks**: SQUARE (7454), Source (4838)
Coastal Central	**Area:** +7% **Land-use change:** Negligible **Septic tanks**: SQUARE (1171), Source (744)
Coastal South	**Area:** +32%. Inclusion of catchments from Harvey Diversion Drain catchment. **Land-use change:** Additional catchment has large areas of horticulture **Septic tanks**: SQUARE (1223), Source (1340)
Peel Main Drain	**Area:** +4% additional area **Land-use change:** Increases in urban land uses and decreases in horticulture and animal grazing land uses **Calibration:** Better accuracy in Source flow model as no data was available for calibration in the SQUARE model **Septic tanks**: SQUARE (1471), Source (1632)
Upper Serpentine	**Area:** -2% **Land-use change:** Increased urban land uses **Septic tanks**: SQUARE (4076), Source (4187)
Dirk Brook (includes Punrak Drain catchment)	**Area:** +4%. Inclusion of entire Punrak catchment **Land-use change:** Increased horticulture and intensive animal industries **Septic tanks**: SQUARE (80), Source (175)

Reporting catchment	Comment
Nambeelup	**Area:** -3% **Land-use change:** Decrease in dairy area **Septic tanks**: SQUARE (294), Source (316)
Mandurah	**Area:** +1% **Land-use change:** Negligible **Septic tanks**: SQUARE (1660), Source (746)
Lower Serpentine	**Area:** +6% **Land-use change:** Decrease in plantation and mixed grazing land uses and increase in beef grazing and native vegetation land uses **Septic tanks**: SQUARE (1229), Source (1206)
Upper Murray	**Area:** 0% **Land-use change:** Increase in native vegetation and plantation land uses and decrease in cropping land uses **Septic tanks**: SQUARE (832), Source (781)
Lower Murray (Includes Dandalup catchments)	**Area:** 0% **Land-use change:** Increase in horticulture and native vegetation land uses and decrease in dairy and plantation land uses **Septic tanks**: SQUARE (1159), Source (1172)
Coolup (Peel)	**Area:** 0% **Land-use change:** Decrease in dairy land uses **Septic tanks**: SQUARE (-), Source (99)
Coolup (Harvey)	**Area:** -9% **Land-use change:** Decrease in dairy land uses **Septic tanks**: SQUARE (-), Source (115) **Calibration:** More flow data post 2000
Mayfield Drain	**Area:** +2% **Land-use change:** Increase in native vegetation land uses and decrease in dairy land uses **Septic tanks**: SQUARE (12), Source (63).
Harvey	**Area:** -22%. The Logue Brook, Waroona, Drakes Brook and Samson Brook dams are now reported individually **Land-use change:** Increase in plantation and decrease in dairy land uses **Septic tanks**: SQUARE (2221), Source (2229)
Meredith Drain	**Area:** -5% **Land-use change:** Increase in intensive animal industries **Calibration:** SQUARE model greatly overestimated flow **Septic tanks**: SQUARE (2), Source (12)
Harvey Diversion Drain	**Area:** -39%. The Lake Preston subcatchment was reported as part of the Coastal South catchment **Land-use change:** Decrease in dairy land uses **Septic tanks**: SQUARE (337), Source (234)

4.3 Model uses and limitations

The Source model is a large-scale catchment model designed to support catchment management decisions. However, results and output data from the model are produced at a daily time-step at many locations within the model (i.e. results are potentially available for each functional unit within each modelling subcatchment), and as such can be interpreted and used to inform a variety of projects for which the model was not specifically developed. It is not possible to anticipate forthcoming projects that require daily nutrient data, but if they are using the model results at small temporal or spatial scales, caution should be exercised.

See below for a list of recommended uses and limitations of the model, based on the method of construction and accuracy of calibration.

The Peel-Harvey water quality model is suitable to be used for estimating:

- **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 in waterways with flow gauging and nutrient sampling data, and less certainty in waterways with no flow gauging (but only a sampling location), and less certainty again for waterways without sampling or flow gauging data.
- **Land-use and long-term climate change impacts.** The model reports the change in relative and absolute nutrient loads and concentrations that would result from land use or climate change in the catchment, if these are reported as average annual loads or concentrations. Reporting changes in load or nutrient load that result from land use and climate change impacts at a lower temporal or spatial scale are subject to the constraints and cautionary notes provided below.
- **The change in relative and absolute flows and 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 a lower temporal or spatial scale are subject to the constraints and cautionary notes provided below.
- **The source of nutrient loads by land-use class 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, in catchments with flows and nutrient loads that have been calibrated against observed data.
- **Data for receiving estuary models.** The minimum time-step of this model is daily. This limitation should be well understood before model outputs are used as input estuary models.

In the following cases, it may 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 the low-flow response is adequately represented. If the low-flow data are too poorly represented, we recommend that the rainfall-runoff model be re-calibrated with an objective function that specifically targets low flows.
- **Seasonal 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. We observed elevated summer concentrations at several calibration sites. However, flows during the summer are generally small and thus nutrient load is also generally small. The focus of this modelling was to replicate nutrient concentrations that have the largest effect on nutrient load (i.e. moderate to high flows).

- **Loads from catchment outlets that are not gauged or sampled.** As mentioned above, these are likely to have significant uncertainty, and researchers should exercise caution when using this data. This applies to all subcatchments that do not have water quality or flow gauging data for calibration, which includes a significant number of the small modelling catchments. Thus, using modelled data at a small spatial scale will have high levels of uncertainty in loads and flows. 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 the local (Davies et al. 2000) and national literature (Duncan 1999). The underestimation of both road reserve nutrient input rates and their assumed nutrient export factor (Equation 2, Section 3.1.2) caused this issue. This arose from a misunderstanding of the amount of fertilised area in urban road reserves. Roads can also collect debris from adjacent land uses, and road runoff can cause erosion of roadside drains.
  - In future modelling of roads, it may be more appropriate to assume fixed-event mean concentration/dry weather concentrations or to lump roads with adjacent land uses and use a modified nutrient input rate.
- **In-stream assimilation:** When we constructed and calibrated this model, there were few measurements and limited knowledge of in-stream nutrient assimilation for the Peel-Harvey catchment. In this model, in-stream nutrient attenuation is inherent in the nutrient calibration process. The University of Southern Cross is in the process of finalising a snapshot study of in-stream nutrient assimilation in the Peel-Harvey catchment and estuary. Thus, there is the potential to develop empirical in-stream assimilation relationships that are suitable for explicitly representing in-stream nutrient assimilation in future catchment models.
- **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.

The following processes and applications were not simulated by the model:

- **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 nutrient:** The Source nutrient model is steady-state 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). Section 7.3.5 discusses a local example where the application of soil amendment resulted in a gradual decrease in the stream phosphorus concentration over an eight-year period.
- The models are not set up to determine the time it takes for the stores of nutrient to ‘run-down’ once a management practice is implemented. So the Source framework will not inform managers about how long it might take for a water quality response due to a

specific management action. Some paddock-scale models, such as the Agricultural Production Systems Simulator (APSIM) can help with this process.

- **Flood or other sub-daily outputs:** The Source model is simulated at a daily time-step, and results can be aggregated but not disaggregated. Therefore, sub-daily outputs, which are generally used for flood applications, are not possible in this model.
- **Detailed ecological processes (or estuary processes):** Our models do not include nutrient species other than total nitrogen (TN) and total phosphorus (TP). Potential ecological effects may be inferred but we did not model them explicitly.
- **Groundwater dynamics:** Groundwater is an important driver of hydrological and nutrient processes in the Peel-Harvey catchment, particularly within the Swan Coastal Plain catchment. Groundwater is only considered a conceptual store within the rainfall-runoff and nutrient-generation models. Therefore this model does not simulate explicit groundwater dynamics. We have calibrated the model to the climatic and groundwater abstraction impacts of 2000–15.
- **Channel hydraulics or estuary hydrodynamics:** This model is a coupled hydrological and nutrient model and does not simulate water levels or flow dynamics in the Serpentine lakes.

5 Modelling results

5.1 Catchment condition 2006–15

5.1.1 Average annual flows and loads

Table 5.1 gives the average annual flows and nutrient loads for reporting catchments for the period 2006–15. We have aggregated the results into major rivers, coastal catchments and catchments that drain to the Peel-Harvey estuary.

On average, the nutrient load from all catchments in the modelling domain is about 830 tonnes per year of nitrogen and 90 tonnes per year of phosphorus. We estimated the loads to the Peel-Harvey estuary to be 630 tonnes of nitrogen and 60 tonnes of phosphorus, with 550 tonnes of the nitrogen and 59 tonnes of the phosphorus coming from the coastal plain portion of the catchment.

Table 5.1: Average annual (2006–15) reporting catchment nutrient loads and flows

Reporting catchment	Area		Flow		Nitrogen		Phosphorus	
	(km^2)	(%)ǂ	(GL)	(%)ǂ	(tonnes)	(%)ǂ	(tonnes)	(%)ǂ
Serpentine Dam	664		18		3.0		0.1	
North Dandalup Dam	151		6.5		1.0		0.0	
South Dandalup Dam	313		3.5		0.6		0.0	
Drakesbrook & Waroona Dams	53		2.3		0.5		0.0	
Samson Brook Dam	64		3.3		0.5		0.0	
Logue Brook Dam	37		2.0		0.3		0.0	
Harvey Reservoir & Stirling Dam	380		52		8.1		0.1	
Coastal North	366		34		116		13	
Coastal Central	7		1.1		5.4		0.4	
Coastal South	326		8		13		8.9	
Peel Main Drain	125	1	7	2	12	2	1.4	2
Upper Serpentine	490	5	34	9	72	11	10	17
Dirk Brook	139	1	13	3	29	5	2.8	5
Nambeelup	139	1	11	3	40	6	6.7	11
Mandurah	24	0	3.2	1	5.0	1	0.5	1
Lower Serpentine	100	1	5.3	1	12	2	2.1	4
Upper Murray	6 752	72	125	34	80	13	1.0	2
Lower Murray	636	7	51	14	103	16	6.2	10
Coolup (Peel)	150	2	10	3	21	3	2.7	5
Coolup (Harvey)	103	1	6	2	13	2	2.1	3
Mayfield Drain	122	1	15	4	33	5	3.6	6
Harvey	553	6	87	24	205	32	20	33
Meredith Drain	53	1	2.3	1	6.7	1	1.0	2
Harvey Diversion Drain	172	2	12	3	49	8	7.6	13
Subtotals:								
Dam catchments	1 662		88		14		0.3	
Drains to ocean	871		55		183		30	
Serpentine River	1 018	11	72	20	169	27	23	39
Murray River	7 539	80	185	50	205	32	10	16
Harvey River	832	9	111	30	259	41	27	45
Peel Inlet	8 556	91	258	70	374	59	33	55
Harvey Estuary	832	9	111	30	259	41	27	45
Estuary coastal plain catchment	**2 636**	**28**	**244**	**66**	**552**	**87**	**59**	**98**
Peel-Harvey estuary catchment	**9 388**	**100**	**369**	**100**	**633**	**100**	**60**	**100**
Total	**11 921**		**511**		**830**		**90**	

ǂ Percentage of area/flow /nutrient reaching the Peel-Harvey estuary

Each year on average about 14 tonnes of nitrogen and 0.3 tonnes of phosphorus flow into the seven dam catchments. Dams generally do not contribute flows to downstream catchments, except for the few that supply irrigation water or provide environmental flows (see Section 3.2).

The Coastal North, Central, North and Harvey Diversion Drain catchments drain to the ocean and discharge about 183 tonnes of nitrogen and 30 tonnes of phosphorus each year on average.

5.1.2 Annual flows and loads

See Figure 5.1 for the annual flow and nutrient loads to the Peel-Harvey estuary for 2006–15. We have aggregated the flow and nutrient loads by major rivers in Figure 5.2, Table 5.2 and Table 5.3. We have summed the flows and loads from the Mandurah catchment with those of the Serpentine catchment. Likewise, we have summed the flow and load contributions from the Coolup (Peel) with those of the Murray River, as well as contributions from the Coolup (Harvey) with those of the Harvey River (Harvey, Mayfield, Meredith).

Table 5.4 contains annual flow-weighted nitrogen and phosphorus concentrations to the estuary. The flow-weighed nutrient concentration is the annual nutrient load divided by the annual flow.

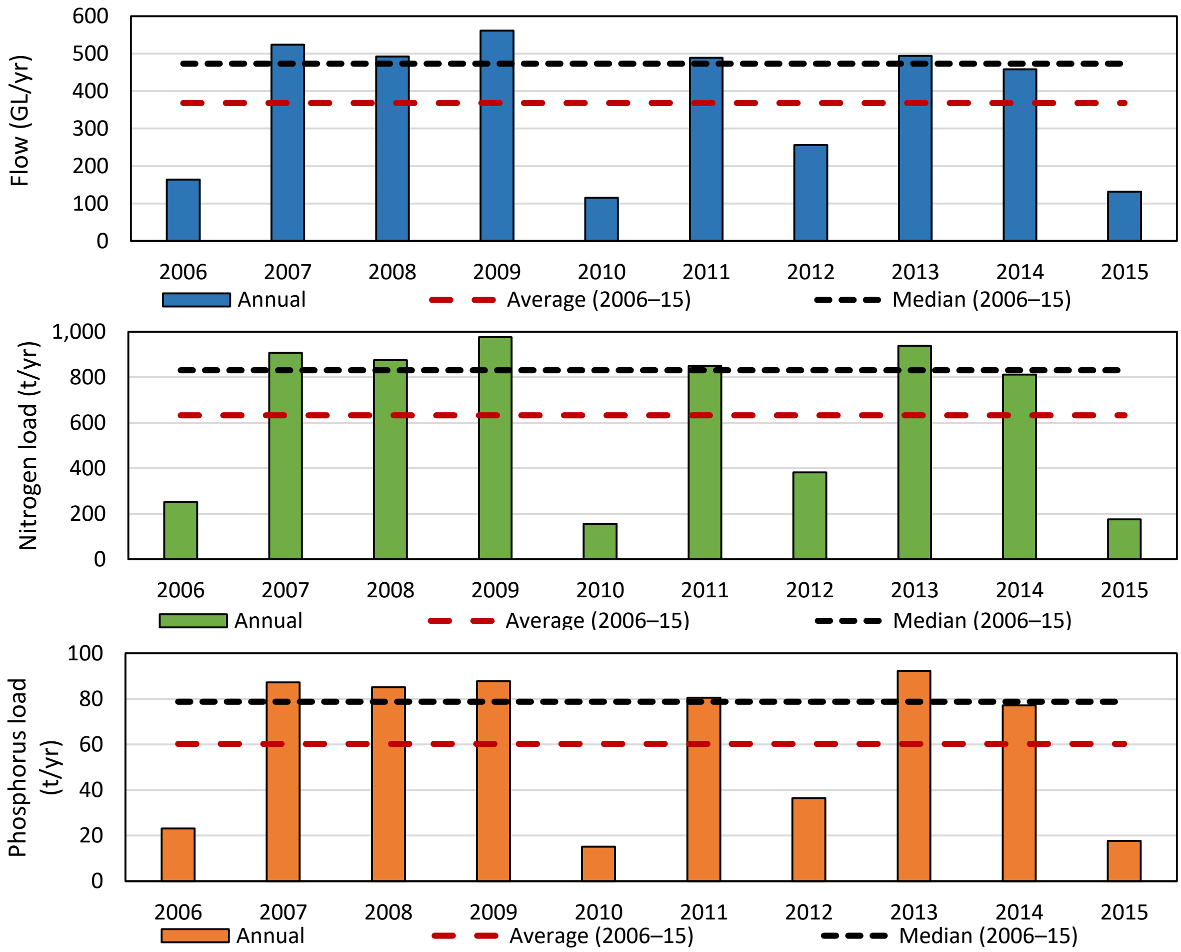


Figure 5.1: Annual flow (top), nitrogen (middle) and phosphorus (bottom) inflows to the Peel-Harvey estuary

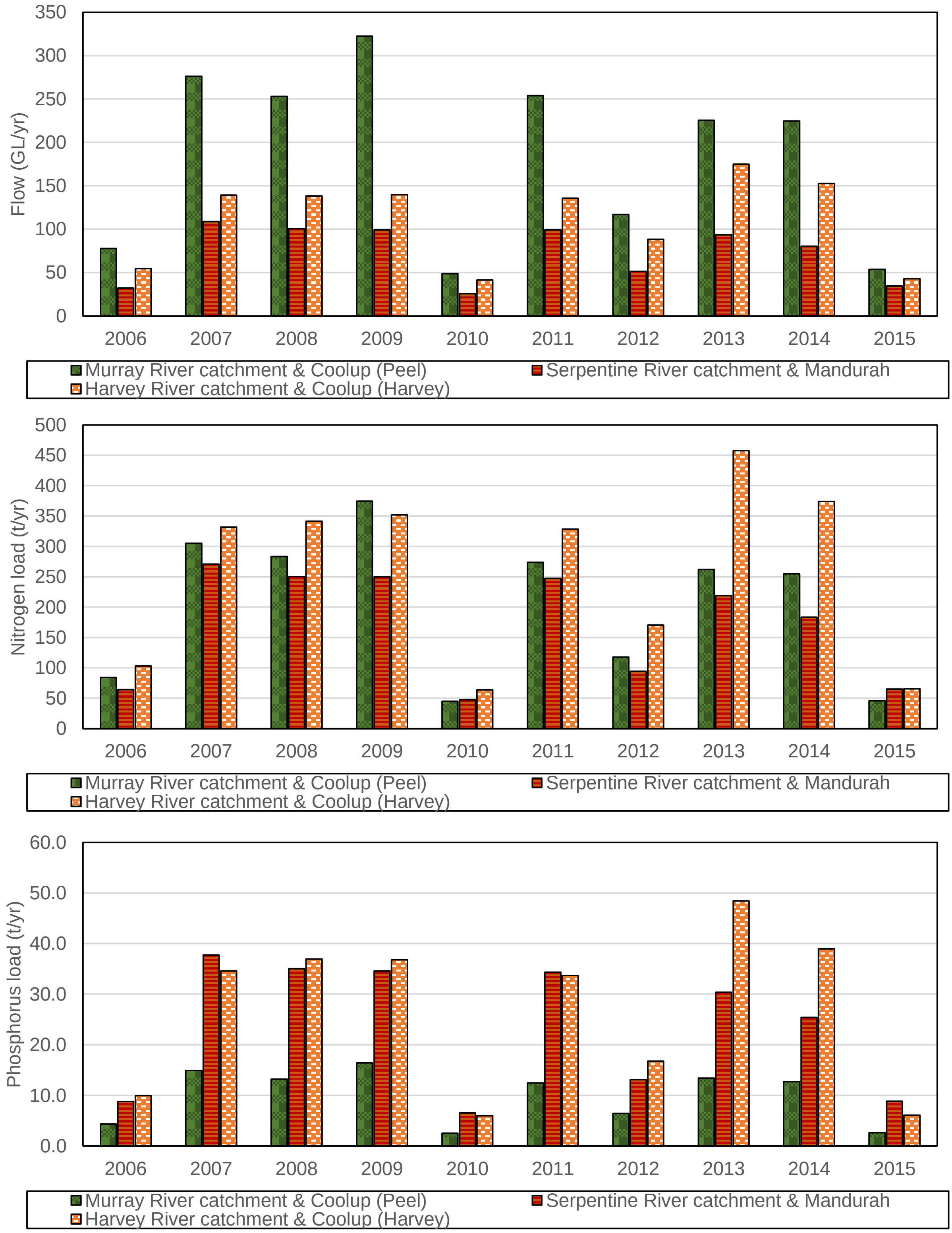


Figure 5.2: Annual flow and nitrogen and phosphorus loads from the major river catchments to the Peel-Harvey estuary

Table 5.2: Annual flow from the Serpentine, Murray and Harvey river catchments (including local drains) to the Peel-Harvey estuary from 2006–15

Year	Serpentine River catchment		Murray River catchment		Harvey River catchment		Total
	(GL)	(% total)	(GL)	(% total)	(GL)	(% total)	(GL)
2006	32	20%	78	47%	55	33%	164
2007	109	21%	276	53%	139	27%	524
2008	100	20%	253	51%	138	28%	492
2009	99	18%	323	57%	140	25%	561
2010	26	22%	49	42%	41	36%	116
2011	99	20%	254	52%	136	28%	489
2012	51	20%	117	46%	88	34%	256
2013	94	19%	226	46%	175	35%	494
2014	80	18%	225	49%	153	33%	458
2015	34	26%	54	41%	43	33%	131
Median (2006–15)	**87**	**19%**	**225**	**50%**	**137**	**31%**	**449**
Average (2006–15)	**72**	**20%**	**185**	**50%**	**111**	**30%**	**369**

Table 5.3: Annual nitrogen and phosphorus loads from the Serpentine, Murray and Harvey river catchments from 2006–15

Year	Serpentine River catchment		Murray River catchment		Harvey River catchment		Total
	(tonnes)	(% total)	(tonnes)	(%)	(% total)	(%)	(% total)
			Nitrogen load				
2006	64	25%	84	34%	103	41%	252
2007	271	30%	305	34%	332	37%	907
2008	250	29%	283	32%	342	39%	875
2009	250	26%	374	38%	352	36%	976
2010	48	30%	45	29%	64	41%	156
2011	247	29%	274	32%	329	39%	850
2012	94	25%	118	31%	171	45%	383
2013	219	23%	262	28%	458	49%	938
2014	183	23%	255	31%	374	46%	812
2015	65	37%	46	26%	66	37%	176
Median (2006–15)	**201**	**24%**	**258**	**31%**	**330**	**40%**	**831**
Average (2006–15)	**169**	**27%**	**205**	**32%**	**259**	**41%**	**633**
			Phosphorus load				
2006	8.8	38%	4.3	19%	10	43%	23
2007	38	43%	15	17%	35	40%	87
2008	35	41%	13.2	16%	37	43%	85
2009	35	39%	16	19%	37	42%	88
2010	6.6	43%	2.5	17%	6.0	40%	15
2011	34	43%	12.5	16%	34	42%	80
2012	13	36%	6.5	18%	17	46%	36
2013	30	33%	13.4	15%	48	53%	92
2014	25	33%	12.7	17%	39	51%	77
2015	8.9	50%	2.6	15%	6.1	35%	18
Median (2006–15)	**34**	**43%**	**12.6**	**16%**	**34**	**43%**	**79**
Average (2006–15)	**23**	**39%**	**9.9**	**16%**	**27**	**45%**	**60**

Table 5.4: Modelled flow-weighted nitrogen and phosphorus concentrations of the major river catchments that flow to the Peel-Harvey estuary. The contributions with and without the Upper Murray are given to highlight the poor water quality of estuary catchments on the coastal plain.

Year	Serpentine River catchment		Murray River catchment		Murray River catchment (excluding Upper Murray)		Harvey River catchment		Total	
	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)	N (mg/L)	P (mg/L)
2006	2.0	0.28	1.1	0.056	2.0	0.13	1.9	0.18	1.5	0.14
2007	2.5	0.35	1.1	0.054	2.1	0.16	2.4	0.25	1.7	0.17
2008	2.5	0.35	1.1	0.052	2.1	0.16	2.5	0.27	1.8	0.17
2009	2.5	0.35	1.2	0.051	2.3	0.17	2.5	0.26	1.7	0.16
2010	1.9	0.26	0.9	0.052	1.6	0.11	1.5	0.14	1.4	0.13
2011	2.5	0.35	1.1	0.049	2.1	0.16	2.4	0.25	1.7	0.16
2012	1.8	0.26	1.0	0.055	1.7	0.12	1.9	0.19	1.5	0.14
2013	2.3	0.32	1.2	0.060	2.1	0.15	2.6	0.28	1.9	0.19
2014	2.3	0.32	1.1	0.057	2.1	0.15	2.5	0.26	1.8	0.17
2015	1.9	0.26	0.8	0.049	1.4	0.10	1.5	0.14	1.3	0.13
Average (2006–15)	**2.3**	**0.32**	**1.1**	**0.054**	**2.1**	**0.15**	**2.3**	**0.24**	**1.7**	**0.16**

Note: Flow-weighted concentrations were calculated from average annual (2006–15) nutrient load and flow.

5.1.3 Seasonal delivery of nutrients

Figure 5.3 shows the average monthly flow and nutrient loads from the major rivers and the Coolup catchments. All catchments have most (> 90%) of their flow and nutrient load discharged during winter and spring months (June–October). The Harvey catchment receives irrigation excess and has persistent (albeit small) flows and nutrient loads during the summer months.

Generally wet years have higher flow-weighted nutrient concentrations than dry years. This may be due to:

- nutrients being more readily mobilised from their sources in the catchment
- decreased travel times reducing the opportunity for assimilation or processing.

This means that the difference between annual loads in wet and dry years is relatively greater in per cent terms, than the difference in the annual flows.

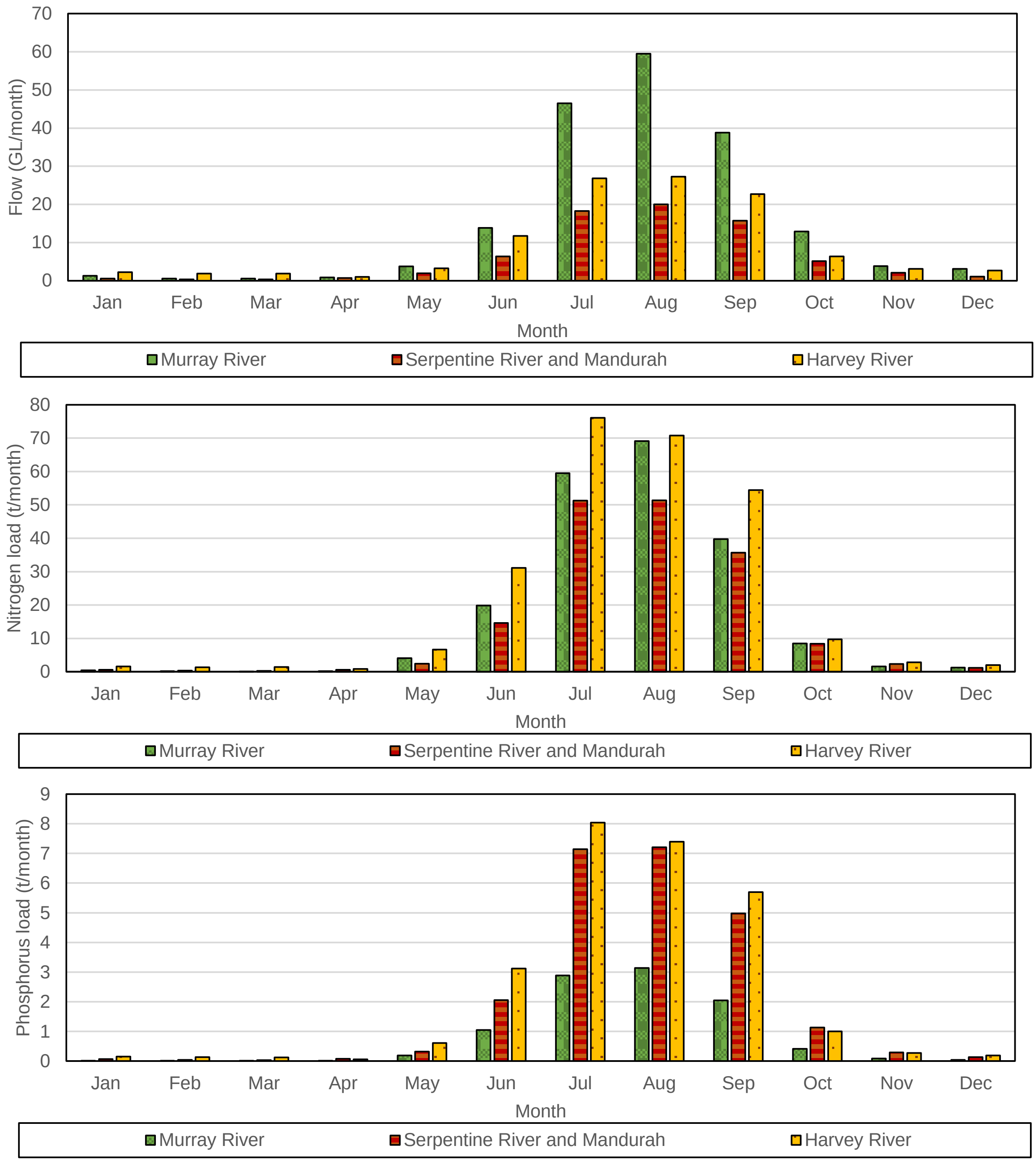


Figure 5.3: Average monthly (2006–15) flow and nitrogen and phosphorus load outflows from the major river catchments to the Peel-Harvey estuary

5.2 Sources of nutrients

5.2.1 Reporting catchments

This section discusses two measures to identify sources of nutrients at a catchment scale:

- nutrient loads per cleared area (kg/cleared hectare/year)
- absolute nutrient loads (tonnes/year)

Generally, larger catchments have larger nutrient loads than smaller catchments. We have used nutrient loads per cleared area to highlight the relative nutrient loss intensity of land uses. We have excluded native vegetation areas as their nutrient loss is much smaller than other land uses. As shown in Section 5.2.1, native vegetation makes up 43% of the Peel-Harvey catchment area yet contributes <1% of the nutrient load to the estuary.

See Table 5.5 and Figure 5.4 for the average annual (2006–15) reporting catchment nutrient loads and loads per cleared area.

In all tables and figures, for dam catchments we have given nutrient load per catchment area rather than per cleared area, as these catchments have very small cleared areas. In other catchments, the cleared area is taken as the total catchment area minus the area of native vegetation.

Load per cleared area

The loads per cleared area represent the intensity of nutrient loss over a catchment. The catchments with the greatest average annual nutrient loads per cleared area that drain to the estuary are:

Nitrogen:

1. Harvey (6.1 kg/cleared ha)
2. Dirk Brook (4.1 kg/cleared ha)
3. Nambeelup (3.7 kg/cleared ha)

Phosphorus:

1. Nambeelup (0.61 kg/cleared ha)
2. Harvey (0.59 kg/cleared ha)
3. Lower Serpentine (0.42 kg/cleared ha)

Of the major river catchments, the Harvey River catchment (Harvey, Meredith, Mayfield and the Coolup (Harvey) catchments) has the largest nutrient loads per cleared area followed by the Serpentine River catchment (Upper Serpentine, Peel Main Drain, Dirk Brook, Nambeelup, Lower Serpentine and Mandurah) and the Murray catchment (Upper Murray, Lower Murray and Coolup (Peel)).

About 50% of the Serpentine River catchment has low-PRI soils compared with 37% of the Harvey River catchment. Thus we would expect the phosphorus export from the Serpentine River catchment to be greater, on a per area basis. However, the flow yield in the Harvey River catchment is nearly double (133 mm/yr) the flow yield of the Serpentine River catchment (71 mm/yr). Also, the surplus mass of phosphorus is slightly higher in the Harvey

River catchment (0.76 kg/ha/yr) than the Serpentine River catchment (0.67 kg/ha/yr), which means there is a larger pool of nutrients that could be lost to surface waters.

The Upper Murray is the largest estuary catchment and has nutrient loads per cleared area of 0.2 kg N/cleared ha/yr and 0.002 kg P/cleared ha/yr. The nutrient loads from estuary catchments on the coastal plain are an order of magnitude greater for nitrogen (3.6 kg N/cleared ha/yr) and two orders of magnitude greater for phosphorus (0.39 kg P/cleared ha/yr). The small loads from the Upper Murray are due to:

a. lower rainfall and flow yield
b. the soils generally being much more nutrient retentive, particularly for phosphorus
c. cropping (the predominant land use) having moderate nutrient inputs and substantially better nutrient-use efficiency than other agricultural and urban land uses.

The Coastal North, Coastal Central, Coastal South and Harvey Diversion Drain catchments all have large nutrient loads per cleared area. The Coastal North catchment had large point source and septic tank nutrient emissions. Most (>75%) of the nutrient emissions from the Coastal Central catchment are from septic tanks. More than 60% of the phosphorus load from the Coastal South and Harvey Diversion Drain catchments are from horticulture.

Absolute nutrient loads

The catchments that delivered the greatest loads of nutrients to the Peel-Harvey estuary were:

Nitrogen:

1. Harvey (205 tonnes, 32%)
2. Lower Murray (103 tonnes, 16%)
3. Upper Murray (80 tonnes, 13%)
4. Upper Serpentine (72 tonnes, 11%).

Phosphorus:

1. Harvey (20 tonnes, 33%)
2. Upper Serpentine (10 tonnes, 17%)
3. Nambeelup (6.7 tonnes, 11%)
4. Lower Murray (6.2 tonnes, 10%).

Figure 5.4 ranks estuary catchments by absolute nutrient load and gives the nutrient load per cleared area.

Table 5.5: Average annual (2006–15) reporting catchment flows, flow yields, nutrient loads and nutrient loads per cleared area

Reporting catchment	Area			Flow		Nitrogen		Phosphorus	
	Total	Cleared		Volume	Yield	Load	Load per cleared area	Load	Load per cleared area
	(km²)	(km²)	(%)ᵻ	(GL)	(mm)¥	(tonnes)	(kg/ha)	(tonnes)	(kg/ha)
Serpentine Dam*	664	3	0	18	28	3.0	0.05	0.1	0.001
North Dandalup Dam*	151	0	0	6.5	43	1.0	0.07	0.0	0.001
South Dandalup Dam*	313	0	0	3.5	11	0.6	0.02	0.0	0.000
Drakesbrook & Waroona Dams*	53	9	16	2.3	42	0.5	0.1	0.0	0.001
Samson Brook Dam*	64	0	0	3.3	51	0.5	0.08	0.0	0.001
Logue Brook Dam*	37	0	0	2.0	53	0.3	0.08	0.0	0.002
Harvey Reservoir & Stirling Dam*	380	34	9	52	136	8.1	0.2	0.1	0.004
Coastal North	366	181	49	34	94	116	6.4	13	0.71
Coastal Central	7	5	71	1.1	159	5.4	10.8	0.4	0.87
Coastal South	326	86	26	8	24	13	1.5	8.9	1.03
Peel Main Drain	125	67	54	7	55	12	1.7	1.4	0.21
Upper Serpentine	490	250	51	34	69	72	2.9	10	0.40
Dirk Brook	139	70	50	13	90	29	4.1	2.8	0.40
Nambeelup	139	109	78	11	76	40	3.7	6.7	0.61
Mandurah	24	15	61	3.2	134	5.0	3.4	0.5	0.35
Lower Serpentine	100	51	51	5.3	53	12	2.3	2.1	0.42
Upper Murray	6 752	3 857	57	125	18	80	0.2	1.0	0.002
Lower Murray	636	294	46	51	80	103	3.5	6.2	0.21
Coolup (Peel)	150	121	80	10	63	21	1.7	2.7	0.23
Coolup (Harvey)	103	70	68	6	61	13	1.9	2.1	0.29
Mayfield Drain	122	100	82	15	123	33	3.3	3.6	0.36
Harvey	553	339	61	87	158	205	6.1	20	0.59
Meredith Drain	53	37	69	2.3	42	6.7	1.8	1.0	0.28
Harvey Diversion Drain	172	107	62	12	69	49	4.6	7.6	0.71
Subtotals:									
Serpentine River	1 018	562	55	72	71	169	3.0	23	0.42
Murray River	7 539	4 271	57	185	25	205	0.5	10	0.02
Harvey River	832	546	66	111	133	259	4.7	27	0.49
Estuary coastal plain catchment	**2 636**	**1 523**	**58**	**244**	**93**	**552**	**3.6**	**59**	**0.39**
Peel-Harvey estuary catchment	**9 388**	**5 379**	**57**	**369**	**39**	**633**	**1.2**	**60**	**0.11**
Total	**11 921**	**5 804**	**49**	**511**	**43**	**830**	**1.4**	**90**	**0.16**

Note:

ᵻ The per cent of the catchment that is cleared

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

* Nutrient load per catchment area

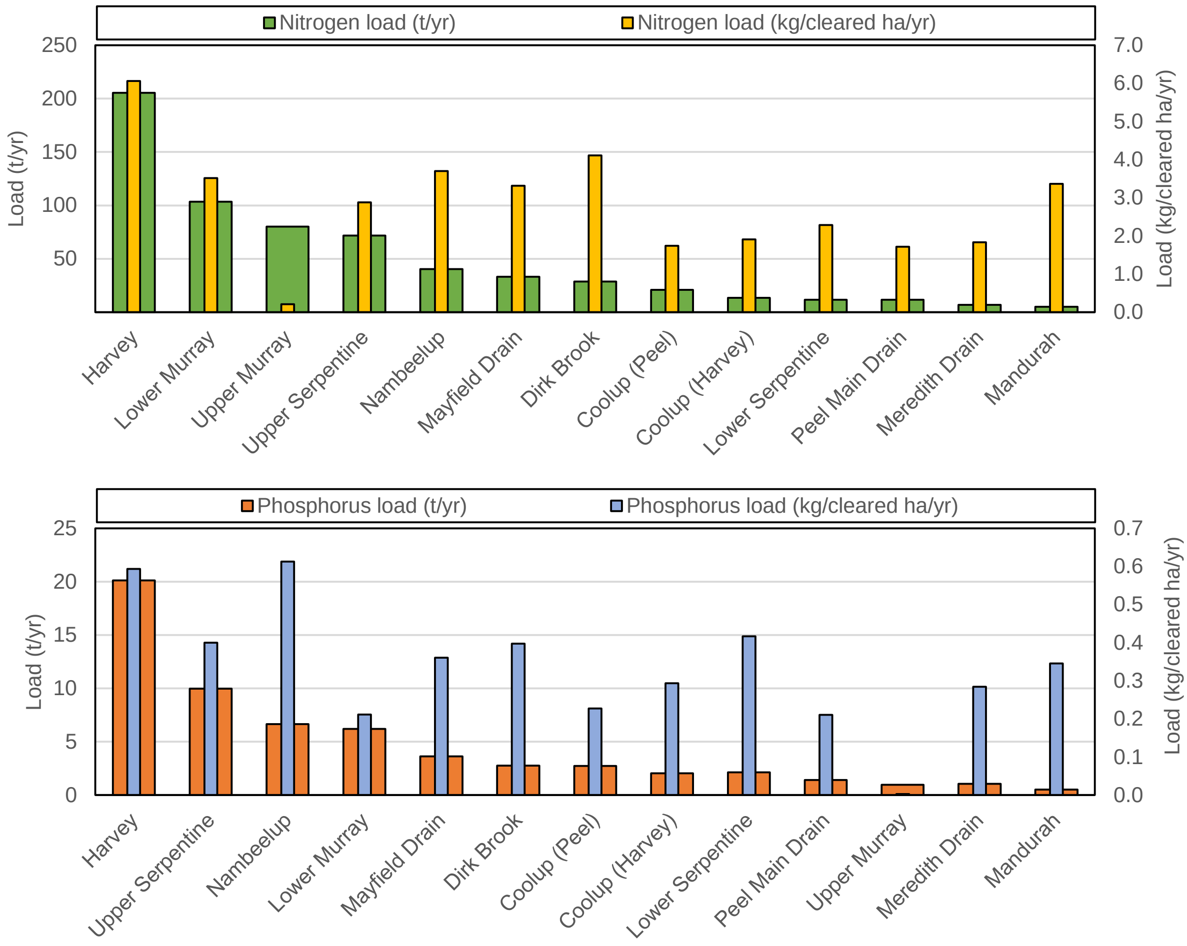


Figure 5.4: Average annual (2006–15) reporting catchment loads and loads per cleared area. Catchments are ranked based on the catchment load from highest (left) to lowest (right).

5.2.2 Nutrient loads by land use

This section gives the average annual (2006–15) nutrient loads from the land uses in catchments that drain to the Peel-Harvey estuary. See Appendix D for the results of all other reporting catchments in the model domain.

For all estuary catchments, the major sources of nutrients by land use are:

> **Nitrogen**: beef (62% of total load), cropping (12%) and dairy (6.8%).
>
> **Phosphorus**: beef (67%), dairy (8.1%) and horticulture (7.3%).

See Table 5.6 and

Figure 5.5.

Excluding the Upper Murray, the major sources of nutrients by land use are:

> **Nitrogen**: beef (71% of total load), dairy (7.8%) and intensive animal industries (4.3%).
>
> **Phosphorus**: beef (68%), dairy (8.2%) and horticulture (7.3%).

See Table 5.7 and Figure 5.6.

The land uses listed above account for about 80% of the nitrogen and phosphorus loads delivered to the Peel-Harvey estuary. Beef farming is clearly the largest nutrient source. This is primarily due to its large area, high nutrient surplus and poor nutrient-use efficiency (<10%, see Table C.2, Appendix C), as well as its location on the Swan Coastal Plain (high rainfall and large areas of low PRI soils).

Intensive animal industries (piggeries, abattoirs, poultry, feedlots and stockyards) contribute <5% of the total nutrient load. This may be considered small at the whole-of-catchment scale. However at the local scale, contributions from point sources are more significant. For instance, we estimate that 17% of the phosphorus load from the Meredith catchment originates from intensive animal industries (piggeries).

Point sources (WWTPs, industry, composting facilities) contribute <1% of the nutrient load. Septic tank nutrient contributions are much larger, accounting for 4.2% of the nitrogen load and 2.6% of the phosphorus load from estuary catchments on the coastal plain (see Table 5.7).

Table 5.6: Average annual (2006–15) catchment flow and nutrient load contributions from land uses in the Peel-Harvey catchment

Land use	**Colour**	**Area** (km^2)	(%)	**Flow** (GL)	(%)	**Nitrogen** (tonnes)	(%)	**Phosphorus** (tonnes)	(%)
Septic tanks			-	0.2	0.1	23	3.7	1.6	2.6
Point source		1	0.0	0.5	0.1	4.7	0.7	0.3	0.4
Horses		84	0.9	7.7	2.1	18	2.9	3.3	5.5
Beef		1 073	11	139	38	393	62	40	67
Dairy		46	0.5	15	4.0	43	6.8	4.9	8.1
Native vegetation		4 008	43	48	13	5.9	0.9	0.1	0.2
Cropping		3 577	38	104	28	76	12	0.8	1.4
Horticulture		28	0.3	3.7	1.0	3.8	0.6	4.4	7.3
Industry, manufacturing & transport		110	1.2	24	6.6	1.7	0.3	0.1	0.1
Intensive animal industries		13	0.1	0.9	0.2	24.0	3.8	1.0	1.7
Lifestyle block		86	0.9	8.6	2.3	15.2	2.4	0.5	0.9
Mixed grazing		80	0.8	6.2	1.7	12.0	1.9	1.1	1.8
Offices, commercial & education		6	0.1	1.3	0.4	1.5	0.2	0.2	0.4
Plantation		231	2.5	1.0	0.3	1.0	0.2	0.4	0.7
Recreation		10	0.1	0.8	0.2	1.8	0.3	0.0	0.1
Residential		29	0.3	7.0	1.9	6.6	1.0	1.3	2.1
Viticulture		4	0.0	0.7	0.2	1.2	0.2	0.1	0.2
Total		**9 388**		**369**		**633**		**60**	

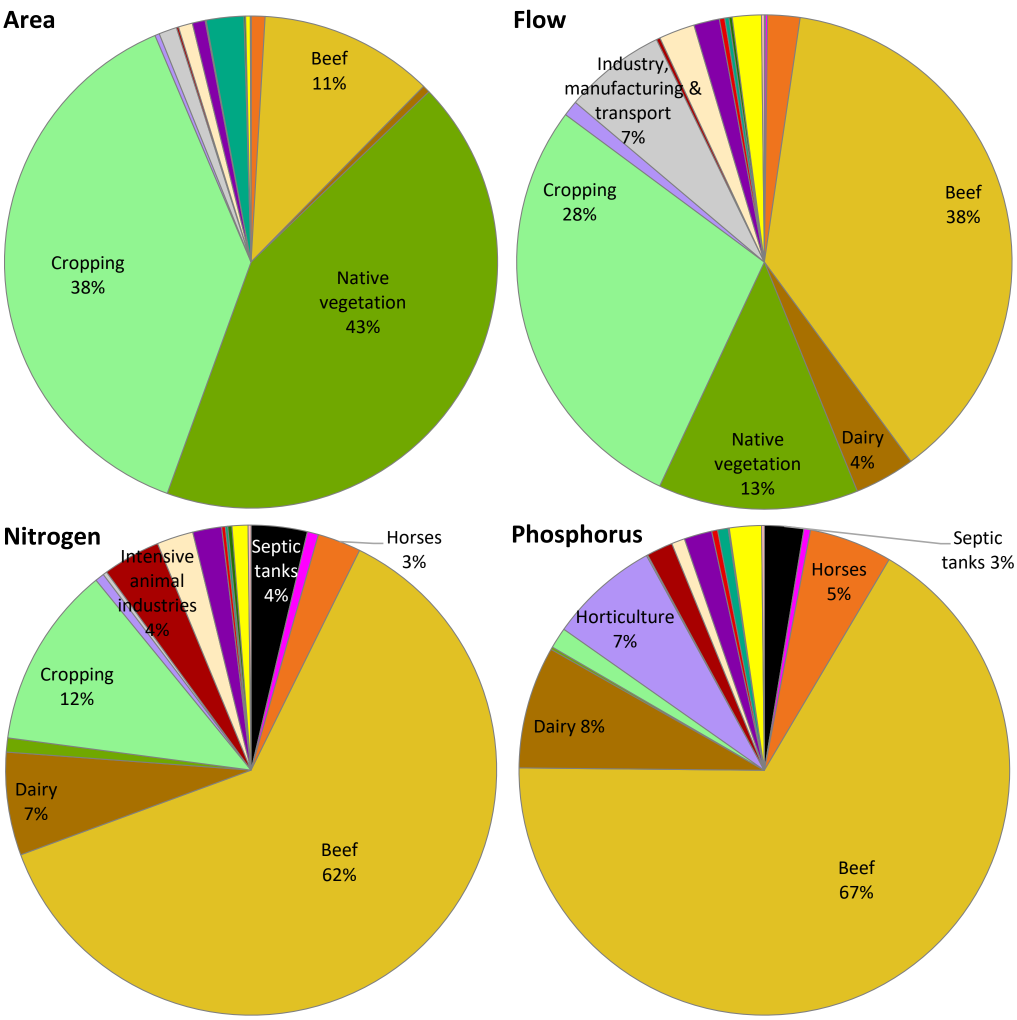


Figure 5.5: Land-use source separation for catchments draining to the Peel-Harvey estuary

Table 5.7: Average annual (2006–15) land-use area, flow and nutrient loads for all estuary catchments, excluding the Upper Murray

Landuse	**Colour**	**Area**		**Flow**		**Nitrogen**		**Phosphorus**	
		(km^2)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic tanks			-	0.2	0.1	23	4.2	1.6	2.6
Point source		1	0.0	0.5	0.2	4.5	0.8	0.2	0.4
Horses		84	3.2	7.7	3.2	18	3.3	3.3	5.6
Beef		1 072	41	139	57	393	71	40	68
Dairy		46	1.7	15	6.0	43	7.8	4.9	8.2
Native vegetation		1 113	42	35	14	5.1	0.9	0.1	0.2
Cropping									
Horticulture		26	1.0	3.6	1.5	3.7	0.7	4.3	7.3
Industry, manufacturing & transport		75	2.9	20	8.1	1.5	0.3	0.1	0.1
Intensive animal industries		11	0.4	0.9	0.4	23.8	4.3	1.0	1.8
Lifestyle block		82	3.1	8.3	3.4	14.8	2.7	0.5	0.9
Mixed grazing		46	1.7	4.8	2.0	10.3	1.9	1.1	1.8
Offices, commercial & education		5	0.2	1.1	0.5	1.4	0.3	0.2	0.4
Plantation		35	1.3	0.5	0.2	0.6	0.1	0.4	0.7
Recreation		9	0.3	0.7	0.3	1.7	0.3	0.0	0.1
Residential		28	1.1	6.8	2.8	6.5	1.2	1.3	2.1
Viticulture		3	0.1	0.6	0.3	1.2	0.2	0.1	0.2
Total		**2 636**		**244**		**552**		**59**	

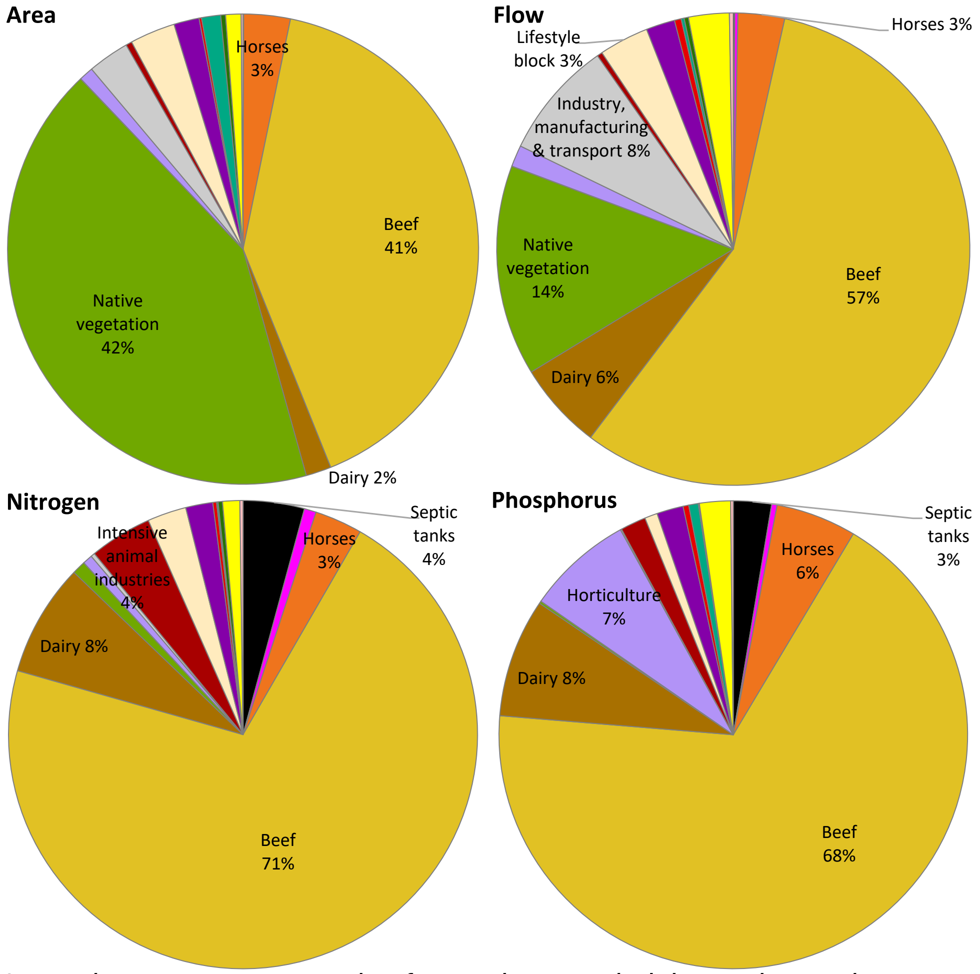


Figure 5.6: Land-use source separation for catchments draining to the Peel-Harvey estuary, excluding the Upper Murray

6 Water quality targets

All waterbodies need water and nutrient inflow to support their ecosystems. In eutrophic waterbodies, such as the Peel-Harvey estuary, load targets specify an estimated maximum load they can assimilate without unacceptable ecological impacts. The *Environmental (Peel Inlet - Harvey Estuary) Protection Policy 1992* (EPA 1992) set a median annual phosphorus load target for the Peel-Harvey estuary of 75 tonnes. This target was derived to limit *Nodularia spumigena* growth in the estuary before the Dawesville Channel was opened.

When this target was set, the impact of south-west Western Australia’s drying climate was not well understood. Since the 1970s rainfall and flows have decreased, and because nitrogen and phosphorus stream concentrations have not changed very much, nutrient loads have also decreased. Figure 6.1 shows the annual phosphorus loads for the Murray River for 1970 onwards. (Note that due to the *Source* modelling methodology and limited calibration data, the flows and loads pre-2000 are an underestimation, so decreases are actually more than depicted).

Under the current rainfall regime, the phosphorus load target in the Environmental Protection Policy (EPP) is being met (Table 6.1). Despite this, the estuary’s condition has not improved, and a recent study has found that its ecological condition may still be worsening (DPC 2015b). The nitrogen and phosphorus concentrations of most of the estuary’s tributaries have not improved since the EPP target was set (Appendix E). Of particular note is the poor condition of the estuarine portions of the Serpentine and Murray rivers (Thomson 2019), which suggests a strong link between the current catchment inputs and estuary condition. The EPP phosphorus load target is no longer relevant and a different approach is required.

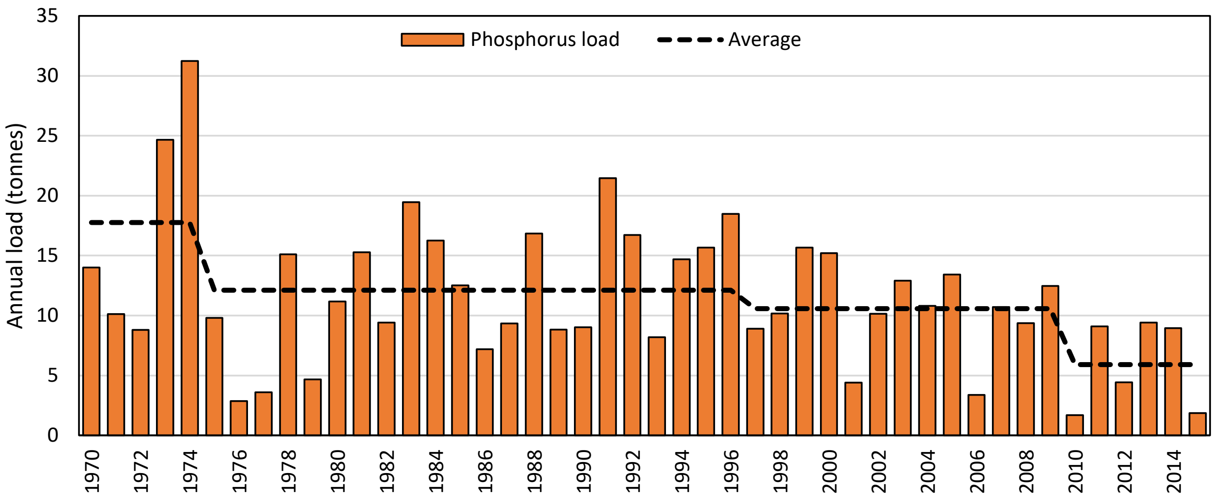


Figure 6.1: Phosphorus loads to the Peel Inlet from the Murray River

Table 6.1: Estimation of phosphorus load to the Peel-Harvey estuary from the Serpentine, Murray and Harvey rivers

Period	Average annual phosphorus load (tonnes)	Reference
Pre-1988	143	Kinhill Engineers (1988)
1990–2004	193	EPA (2008)
1997–2007	140	Kelsey et al. (2011)
2006–2015	60	This study

The impact of nutrient inflows on the estuary's ecological condition depends on their concentrations and loads, and also the fate and residence time of the nutrients in the estuary. Nutrients in large flows may be carried out to sea, whereas nutrients in low flows will stay in the estuary for longer. Nutrients attached to soil particles (particulate phosphorus) are likely to settle on the estuary bed, while algae are likely to use labile nutrients – and add to the internal nutrient loading.

Ideally, catchment nutrient targets would be derived to account for varying catchment flow regimes. This would likely require a coupled catchment-estuary hydrodynamic and ecological model, which was not available when we did this study.

The catchment targets for this study are based on flow-weighted nutrient concentrations, which aim to balance the relative impacts of nutrient loads in high and low flows. We define the flow-weighted concentration as the annual nutrient load divided by the annual flow. The flow-weighted concentration targets are for both nitrogen and phosphorus.

6.1 Catchment nutrient targets

We compared flow-weighted nutrient concentrations at Peel-Harvey reporting catchment outlets with the following:

- **Nitrogen**: 1.2 mg/L for all coastal catchments and 0.45 mg/L for the Upper Murray catchment. We based these targets on the ANZECC guidelines (ANZECC & ARMCANZ 2000) for slightly to moderately disturbed systems for lowland and upland rivers respectively.
- **Phosphorus**: 0.1 mg/L for all coastal catchments and 0.02 mg/L for the Upper Murray catchment. Our concentration target for the coastal catchments is consistent with the previous *Peel-Harvey water quality improvement plan* (EPA 2008). We based the concentration target for the Upper Murray catchment on the ANZECC guidelines (2000) for slightly to moderately disturbed systems for upland rivers.

When we compare the flow-weighted nutrient concentrations with these targets, this finds the maximum acceptable nutrient load and load reduction (defined in Table 6.2) that each reporting catchment needs. The main purpose of the targets is to identify catchments where interventions are necessary to reduce nutrient export to the estuary. Different management scenarios can then be modelled to determine optimum combinations of actions for different subcatchments.

Table 6.2: Definition of flow-weighted concentrations and maximum acceptable nutrient loads.

	Calculation
Flow-weighted concentration	$= \frac{Mean\ Annual\ load\ (2006-15)}{Mean\ Annual\ flow\ (2006-15)}$
Maximum acceptable load	$= Nutrient\ Concentration\ Target * Mean\ Annual\ Flow\ (2006-15)$

Table 6.3 gives the flow-weighted nutrient concentrations, targets and load reductions needed for the reporting catchments flowing to the Peel-Harvey estuary. Figure 6.2, Figure 6.3 and Figure 6.4 show the flow-weighted nutrient concentration and nutrient concentration targets for the coastal plain catchments. Nitrogen and phosphorus loads must reduce for all reporting catchments, except the Upper Murray for phosphorus – which has a flow-weighted concentration of more than half the target value. When a catchment meets its target, the aim is to maintain its water quality, so the phosphorus load target for the Upper Murray catchment is its current phosphorus load (on an average annual basis).

Appendix E discusses other catchment targets for the Peel-Harvey estuary and other catchments in Western Australia.

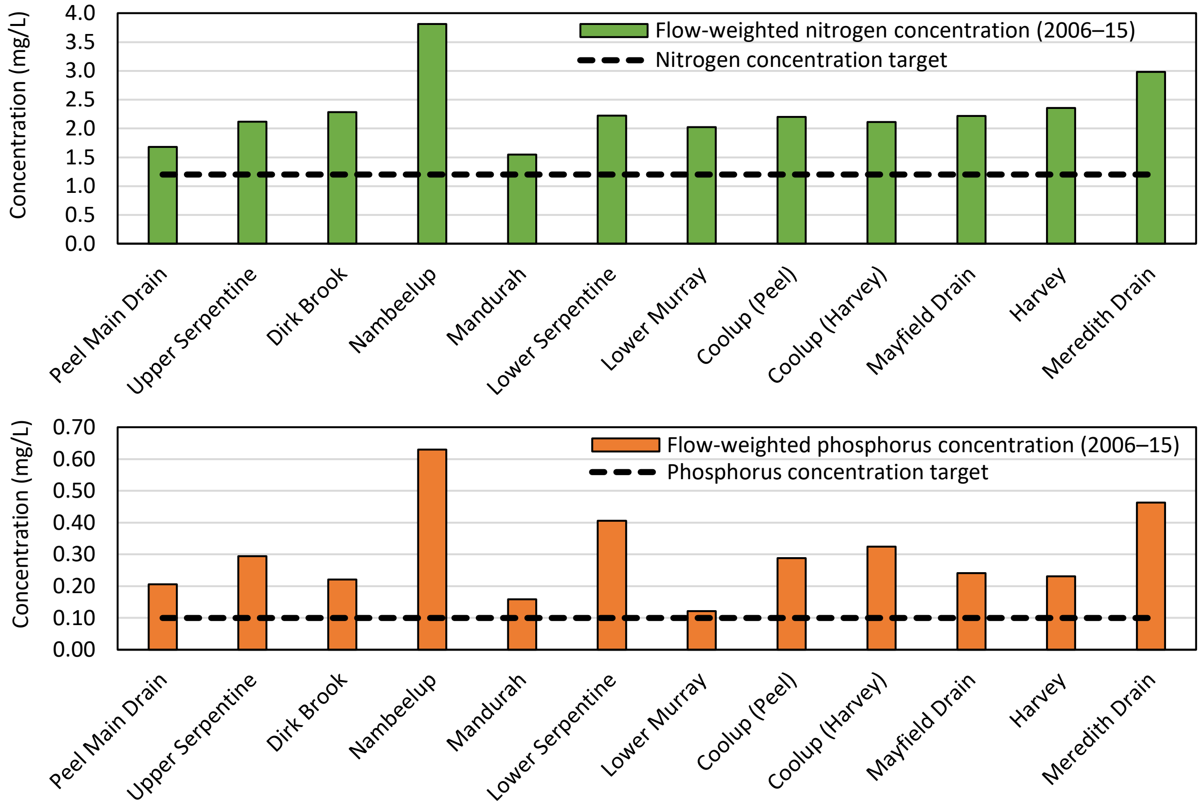


Figure 6.2: Nitrogen and phosphorus flow-weighted concentrations and targets for the coastal plain reporting catchments flowing to the Peel-Harvey estuary

Table 6.3: Reporting catchment nitrogen and phosphorus targets for 2006–15

Reporting catchment	Average annual flow (2006–15) (GL/yr)	Average annual nutrient load (2006–15) (t/yr)	Flow-weighted nutrient concentration (2006–15) (mg/L)	Nutrient concentration target (mg/L)	Nutrient reduction required to meet target (%)	Maximum acceptable load (2006–15) (t/yr)
Nitrogen						
Peel Main Drain	6.9	12	1.7	1.2	29	8.3
Upper Serpentine	34	72	2.1	1.2	43	41
Dirk Brook	13	29	2.3	1.2	48	15
Nambeelup	11	40	3.8	1.2	69	13
Mandurah	3.2	5.0	1.5	1.2	23	3.9
Lower Serpentine	5.3	12	2.2	1.2	46	6.3
Upper Murray	125	80	0.6	0.45	30	56
Lower Murray	51	103	2.0	1.2	41	61
Coolup (Peel)	9.5	21	2.2	1.2	46	11
Coolup (Harvey)	6.3	13	2.1	1.2	43	7.6
Mayfield Drain	15	33	2.2	1.2	46	18
Harvey	87	205	2.4	1.2	49	105
Meredith Drain	2.3	6.7	3.0	1.2	60	2.7
Estuary coastal plain	244	552	2.3	1.2	47	293
Peel-Harvey estuary	369	633	1.7	0.9	45	349
Phosphorus						
Peel Main Drain	6.9	1.4	0.21	0.10	51	0.7
Upper Serpentine	34	10	0.29	0.10	66	3.4
Dirk Brook	13	2.8	0.22	0.10	55	1.3
Nambeelup	11	6.7	0.63	0.10	84	1.1
Mandurah	3.2	0.5	0.16	0.10	37	0.3
Lower Serpentine	5.3	2.1	0.41	0.10	75	0.5
Upper Murray	125	1.0	0.01	0.02	Target met	1.0
Lower Murray	51	6.2	0.12	0.10	18	5.1
Coolup (Peel)	9.5	2.7	0.29	0.10	65	1.0
Coolup (Harvey)	6.3	2.1	0.32	0.10	69	0.6
Mayfield Drain	15	3.6	0.24	0.10	59	1.5
Harvey	87	20	0.23	0.10	57	8.7
Meredith Drain	2.3	1.0	0.46	0.10	78	0.2
Estuary coastal plain	244	59	0.24	0.10	59	24
Peel-Harvey estuary	369	60	0.16	0.07	58	25

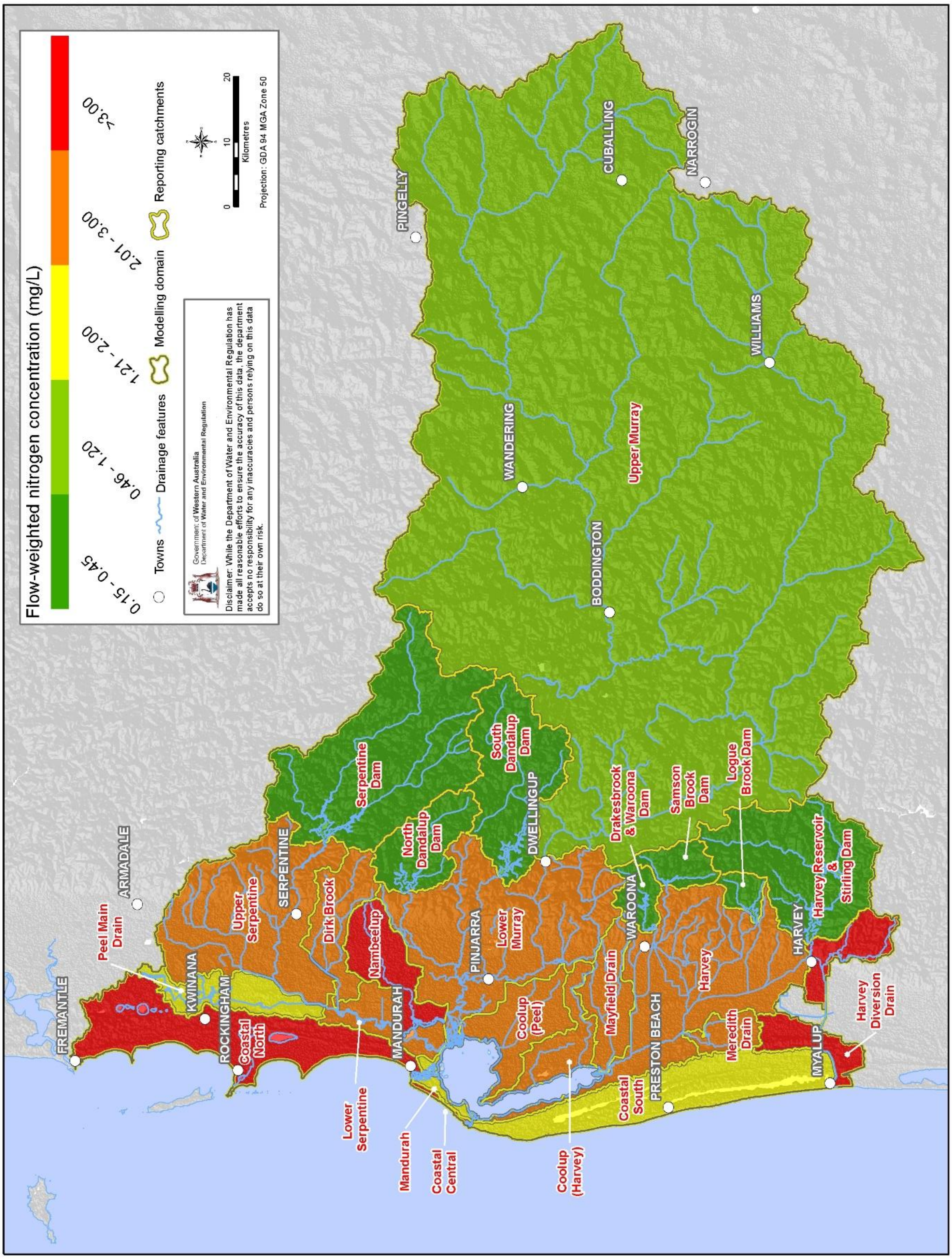


Figure 6.3: Flow-weighted nitrogen concentrations

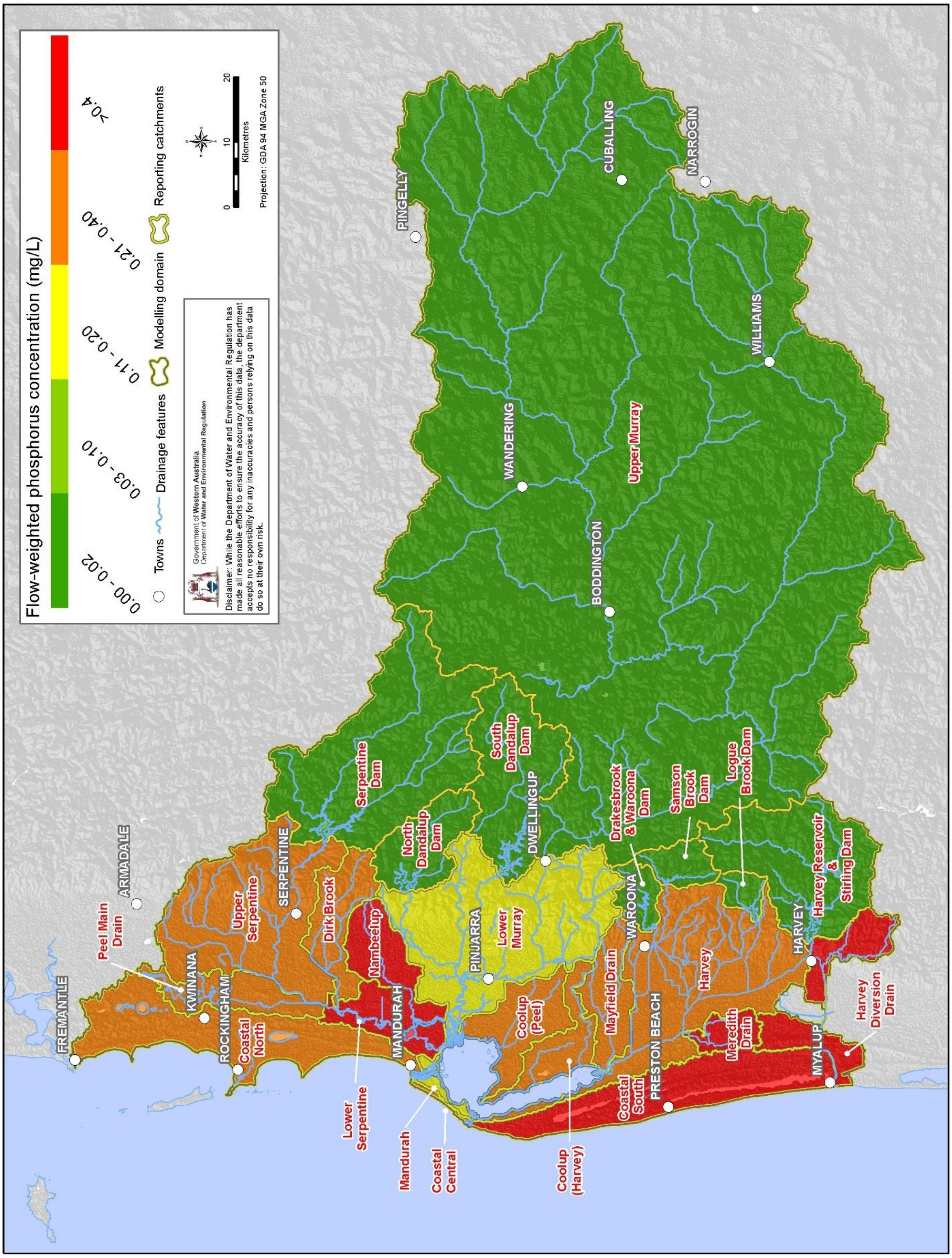


Figure 6.4: Flow-weighted phosphorus concentrations

6.2 Nutrient input targets

This section discusses the maximum amount of nutrient[4] on a per area basis which, when applied to the land, would still achieve the nutrient load targets. By limiting the amount of nutrient applied, the amount reaching the estuary would decline over time. 'Input targets' (mass of nutrient applied per unit area) were estimated in the previous modelling by Kelsey et al. (2011; Table 6.4).

The nutrient input targets are derived from the Source model (Table 6.4) by:

Equation 4

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

where

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

Export target: The maximum acceptable nutrient load per unit area from estuary catchments on the coastal plain (kg/cleared ha/year). We calculate this by dividing the maximum acceptable load by the cleared catchment area.

Current export: The average annual (2006–15) nutrient load per cleared area from estuary catchments on the coastal plain (kg/cleared ha/year).

This simple approach assumes that current nutrient inputs require the same proportional reduction as catchment outputs (loads) to meet targets. In contrast, Kelsey et al. (2011) calculated nutrient input targets using a process-based conceptual model that accounted for a range of processes in the nutrient cycle – from the application of nutrients to land to their loss from a catchment outlet. Despite the difference in methodology, both approaches gave similar input targets for phosphorus but had a greater discrepancy for nitrogen.

Table 6.4: Comparison of the nutrient input targets

Study	**Nitrogen input target** (kg/cleared ha/year)	**Phosphorus input target** (kg/cleared ha/year)
Kelsey et al. (2011)	45	6.5
This study	55	6.8

We recommend the nutrient input targets from Kelsey et al. (2011) be used in place of the nutrient input targets calculated in this study because:

- the calculated nutrient input targets are similar
- Kelsey et al. (2011) used a process-based nutrient model that is likely better suited to estimating this target.

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

The recommended nutrient input targets for estuary catchments on the coastal plain are:

Nitrogen: **45** kg N/cleared ha/ year

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

We derived these input targets from broadscale catchment models (Source and SQUARE) and they may not be appropriate for the lot scale. At the lot scale, the distance from the receiving waterbodies, transport pathways and the lot characteristics must be considered. We recommend further work to derive lot-scale input targets for different land uses in different locations. This would contribute to achieving the catchment targets in this study.

7 Scenario modelling

Scenario modelling examines the potential impacts of land use and climate change in the study area. This section discusses:

- potential urban development in the catchment to 2050
- the agricultural development that the *Transform Peel* initiative proposes
- better land-use management to reduce nitrogen and phosphorus loads to the estuary
- future climate change.

This study's scenario modelling results will inform the new water quality improvement plan (WQIP) for the Peel-Harvey estuary, which will focus on management efforts in estuary catchments on the coastal plain (see Figure 5.1). All scenario tables gives subtotal results for the following:

- **Estuary coastal plain:** these are the catchments the WQIP will target for improvement. They are Peel Main Drain, Upper Serpentine, Dirk Brook, Nambeelup, Mandurah, Lower Serpentine, Lower Murray, Coolup (Peel), Coolup (Harvey), Mayfield Drain, Harvey and Meredith Drain.
- **Peel-Harvey estuary:** these are all the catchments that drain to the Peel-Harvey estuary, excluding dam catchments; that is, all estuary coastal plain catchments listed above and the Upper Murray catchment.

We excluded catchments that drain directly to the ocean (Coastal North, Coastal Central, Coastal South and Harvey Diversion Drain) from all scenario modelling. However we did include the urban expansion scenario (see Section 7.1) and previous infill sewerage projects (see Section 7.3.8) because these scenarios had a large effect in these catchments.

Dam catchments are unaffected by all scenario modelling.

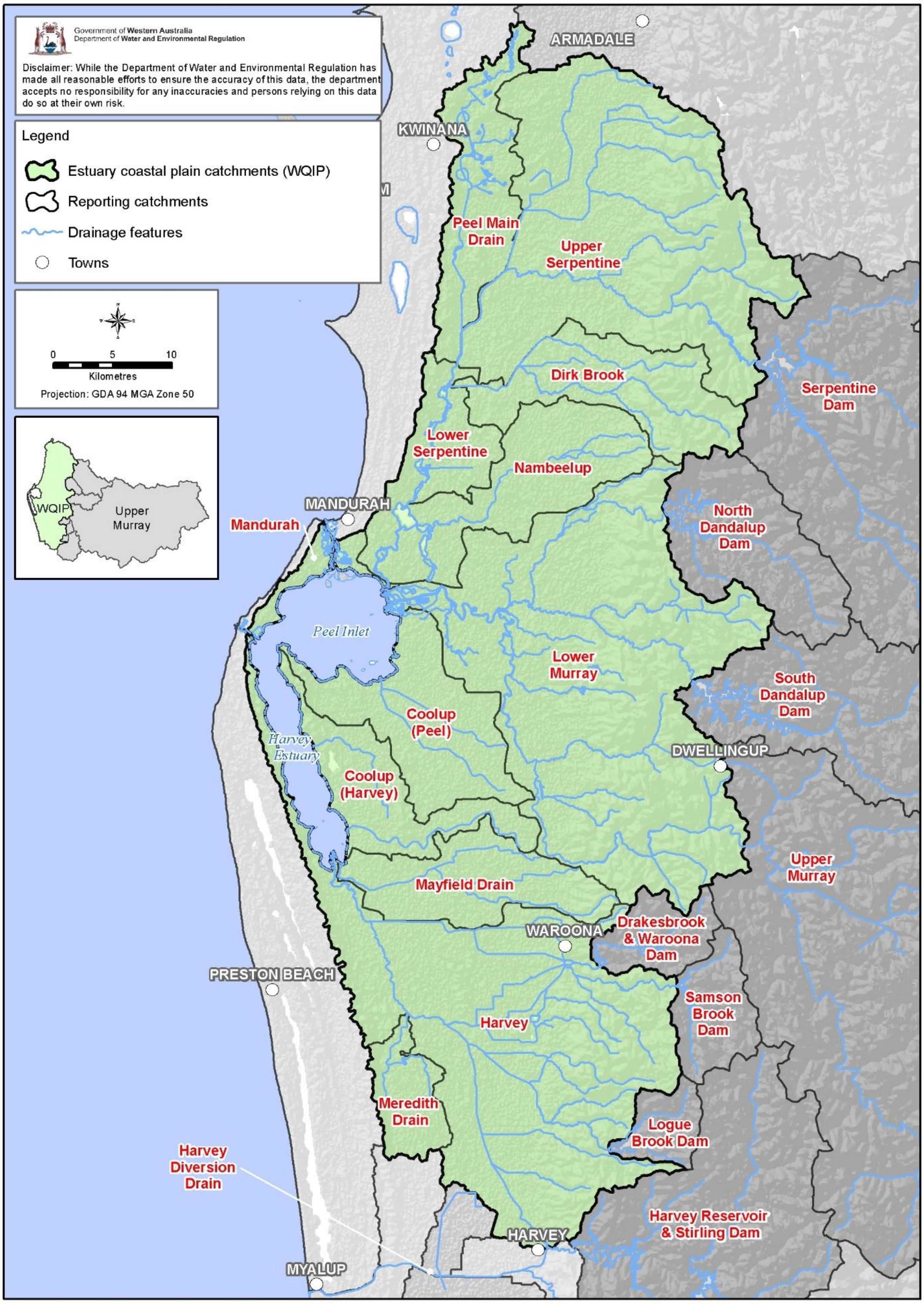


Figure 7.1: Estuary coastal plain catchments that will be managed as part of the revised water quality improvement plan for the Peel-Harvey estuary

7.1 Urban expansion

This scenario models the effect of planned urban expansion by 2050 on flows and nutrient loads. The future urban area includes areas that are undeveloped at present, but zoned for urban, industrial, rural residential and nature reserves (termed 'zoned undeveloped'), as well land that may be rezoned to account for the planned urban expansion by 2050. We used the following datasets to create our 2050 post-development land-use map.

For zoned and undeveloped areas:

- *Regional schemes and zones spatial dataset* (DPLH 2017)
- *Urban growth monitor spatial dataset* (DoP 2015) to identify undeveloped urban areas and areas of potential urban infill
- *Industrial land development outlook spatial dataset* 2013/14 (DOP 2014a)
- *Proposed and approved rural residential developments spatial dataset* (DoP 2014b).

For land that may be rezoned to account for urban expansion by 2050:

- *Industrial class of action spatial dataset* (DPLH 2018a)
- *Framework land use spatial dataset* (DPLH 2018b)
- *Rural residential class of action spatial dataset* (DPLH 2018c)
- *Urban class of action spatial dataset* (DPLH 2018d).

See Table 7.1 and Figure 7.2 for the urban expansion we predict for 2050.

Table 7.1: Areas of future (2050) urban expansion. These mostly replace cleared farmland.

	Urban expansion area				
Catchment	**Urban** (ha)	**Industrial** (ha)	**Rural residential** (ha)	**Nature reserves** (ha)	**Total** (ha)
Coastal North	1 108	1 249	370	814	3 540
Coastal Central	0	0	0	5	5
Coastal South	14	0	64	509	587
Peel Main Drain	2 115	178	550	118	2 961
Upper Serpentine	2 512	204	1 122	507	4 346
Dirk Brook	0	0	33	11	44
Nambeelup	192	331	2 154	66	2 743
Mandurah	0	0	0	9	10
Lower Serpentine	485	330	97	378	1 290
Upper Murray	1	0	78	0	78
Lower Murray	1 737	1 237	1 324	165	4 463
Coolup (Peel)	272	0	299	239	810
Coolup (Harvey)	8	0	149	31	188
Mayfield Drain	93	0	0	0	93
Harvey	365	787	886	177	2 216
Meredith Drain	0	0	0	0	0
Harvey Diversion Drain	158	0	0	0	158
Estuary coastal plain	7 780	3 067	6 614	1 702	19 162
Peel-Harvey estuary	7 780	3 067	6 692	1 702	19 241
Total	**9 060**	**4 316**	**7 126**	**3 030**	**23 531**

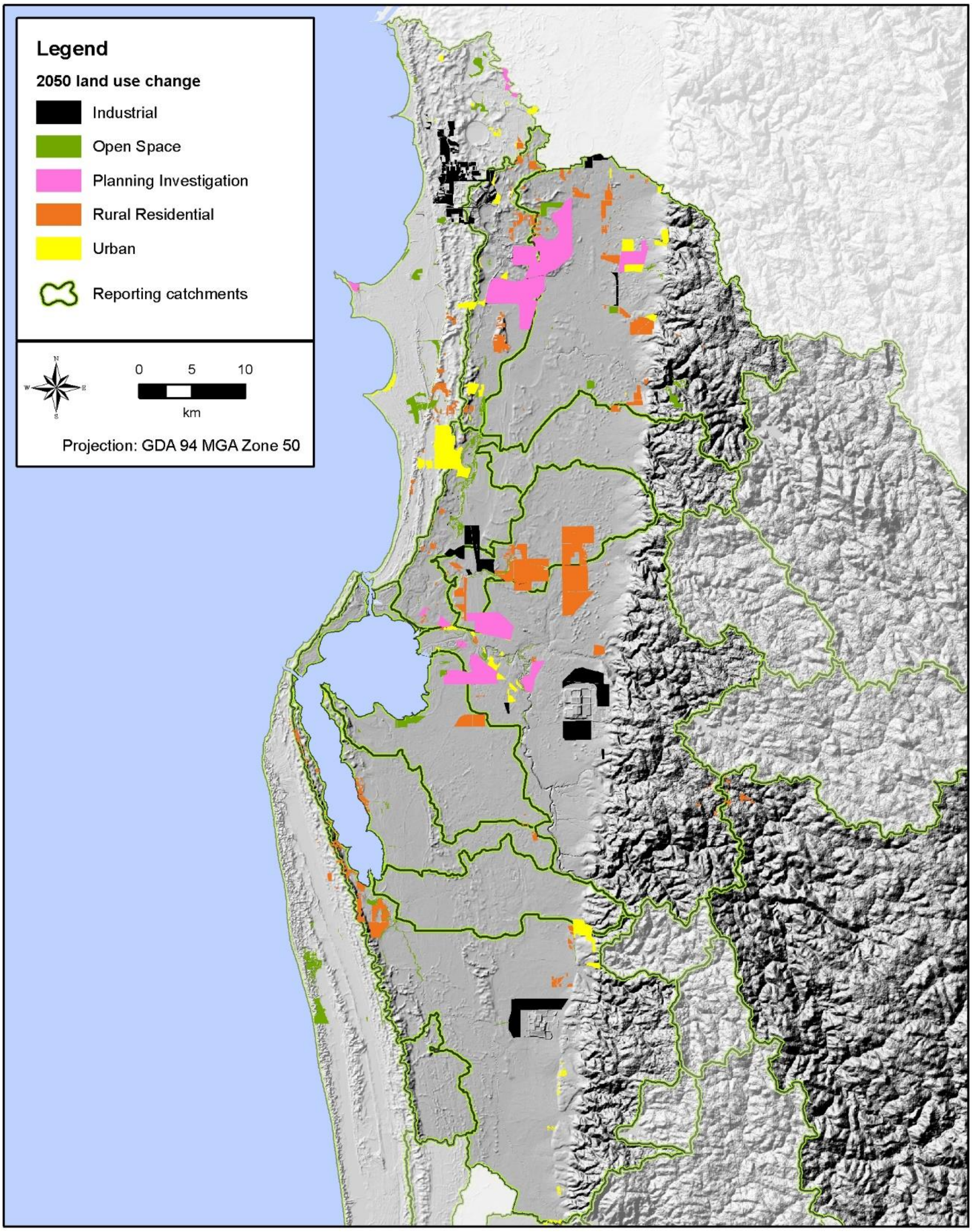


Figure 7.2: Planned urban expansion at 2050

Modelling approach

We used the planning classifications within these datasets to represent post-development land uses. These post-development land uses replace existing land uses, except for residential, recreation, sewerage treatment plants, roads, offices, commercial, schools and community facilities. We decided that these areas were unlikely to change as a result of development.

We assumed the post-development areas would retain the basecase soil-PRI categories. Urban development typically requires imported fill, which is first sourced onsite by cut-and-fill operations when enough material is available. If not, fill is imported and may have substantial phosphorus retention (e.g. Spearwood Sands). But where PRI is concerned, no minimum standard exists and fill type is selected according to availability and cost. We did not model the effect of soil-amendment inclusion within the fill or drainage system.

We used the mapping of two recent urban developments to inform the composition of urban developments in this scenario (Figure 7.3). We assumed residential post-development land uses comprised 10% recreation (i.e. public open space), 10% roads, 66% urban residential lots (> 400 m^2) and 14% very small urban residential lots (<400 m^2). We lumped offices, commercial & educational land uses (1–4% of the development area, see Figure 7.3) with small urban residential lots due to their similar nutrient inputs.

The Peel Business Park may eventually host intensive animal industries or food processing. Thus, we assumed industrial post-development land uses were 90% ‘industrial, manufacturing & roads’ and 10% ‘piggeries & abattoirs’.

We assumed post-development residential and industrial land uses were connected to reticulated sewerage systems.

Typical rural residential land-use planning categories include special rural, rural residential, small rural holdings or special use. We assumed that rural residential developments comprised the following land uses:

- Horses: permitted in 45% of the area
- Lifestyle blocks: small rural pursuits permitted in 45% of the area
- Bush blocks: lots with mostly native vegetation would take up 10% of the area.

We assumed all rural residential land uses were unsewered and serviced by septic tanks at a lot density of 0.5 septic tanks/ha.

Table 7.2 and Table 7.3 give the assumed post-development composition of new urban areas in the hydrological and nutrient models respectively.

We assumed all urban expansion scenarios were completely developed under steady-state conditions using the basecase (2006–15) model drivers. This was necessary to isolate the impacts of land-use change from climate and other impacts, such as increased groundwater abstraction.

Urban development generally increases water yield because large areas of impervious surfaces are introduced and deep-rooted vegetation is removed. In ‘traditionally drained’ urban catchments, deep drainage and subsurface drainage networks are often used to lower and maintain the groundwater level.

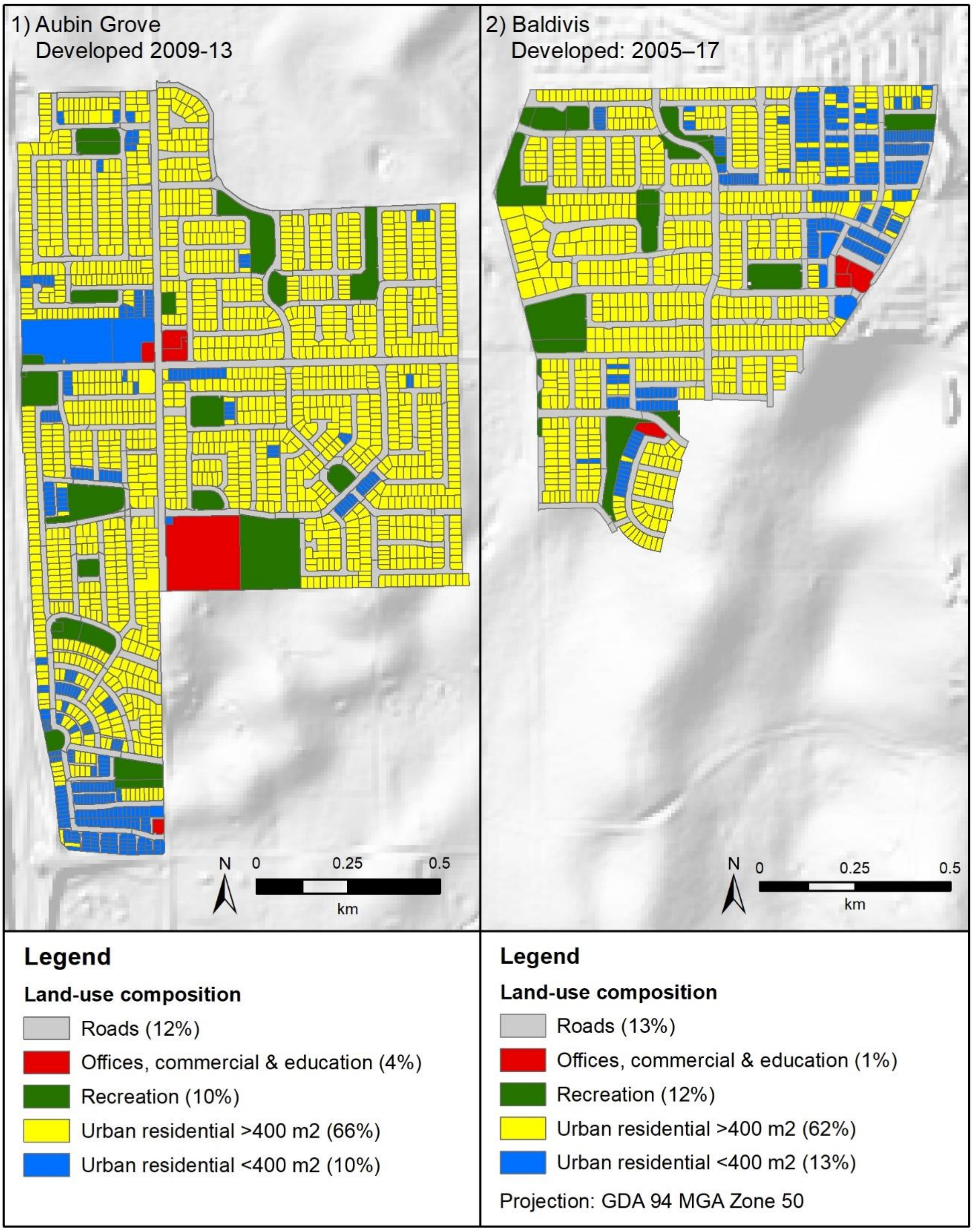


Figure 7.3: Composition of urban developments in the study area

Table 7.2: Assumed percentages of cleared, urban and vegetated areas for post-development land uses for hydrological model parameterisation

Post-development landuse	Cleared	Urban	Vegetated
Industrial expansion	10%	90%	0%
Industrial investigation	10%	90%	0%
Industrial undeveloped	10%	90%	0%
Nature reserve/passive recreation	0%	0%	100%
Proposed nature reserve/passive recreation	0%	0%	100%
Planning investigation	10%	90%	0%
Rural residential	90%	0%	10%
Urban expansion	10%	90%	0%
Urban investigation	10%	90%	0%
Urban undeveloped	10%	90%	0%

Table 7.3: Assumed percentage area breakdown of post-development land uses for nutrient model parameterisation

Post-development landuse	Urban residential	Urban residential (very small)	Lifestyle block	Rural living (bush block)	Horses	Recreation	Native vegetation	Industry, manufacturing & transport	Piggeries & abattoirs
Industrial expansion								90%	10%
Industrial investigation								90%	10%
Industrial undeveloped								90%	10%
Nature reserve/passive recreation							100%		
Proposed nature reserve/passive recreation							100%		
Planning investigation	66%	14%				10%		10%	
Rural residential¥			45%	10%	45%				
Urban expansion	66%	14%				10%		10%	
Urban investigation	66%	14%				10%		10%	
Urban undeveloped	66%	14%				10%		10%	

¥ Assumes the addition of septic tanks at a density of 0.5 per hectare

Water sensitive urban design (WSUD) principles encourage the management of stormwater quantity and quality. The *Decision process for stormwater management in Western Australia* (DWER 2017) gives an approach for the planning and design of stormwater management systems for urban developments. It puts forward some desirable outcomes, which are to:

- protect public health and safety
- protect public and private infrastructure and buildings from flooding
- protect and enhance sensitive receiving environments by managing the water cycle, water quality, habitat diversity and biodiversity
- enable economically sustainable construction, maintenance and renewal/replacement costs

- achieve good urban amenity.

These outcomes can be achieved by:

- designing urban stormwater management systems that reduce risk to people and property from flooding to within acceptable levels
- designing urban stormwater management systems that mimic natural hydrological processes
- retaining natural waterbodies as the receiving environments for runoff of suitable quality from minor and major rainfall events
- retaining and planting vegetation (preferably local native species) wherever possible to reduce stormwater runoff volumes and peak flow rates, reduce urban temperatures, improve water quality, increase urban biodiversity, and improve aesthetics and urban amenity
- implementing stormwater management systems and site management, maintenance and other practices to prevent, reduce and treat pollutants
- designing urban stormwater management systems that achieve good urban amenity and provide multiple functions.

We modelled two urban development scenarios to estimate a range of possible hydrological and nutrient impacts (see below).

- **Traditional drainage:** when post-development hydrology is not managed to maintain pre-development hydrology. This is the worst-case scenario for urban development.
- **Maintain pre-development hydrology:** when post-development land uses have the same water yield as the basecase land uses, but have the post-development land-use nutrient concentrations from the 'traditional drainage' scenario.

Scenario results

SeeTable 7.4, Table 7.5 and Table 7.6. for the potential impacts of urban development on flows, and nitrogen and phosphorus loads.

We estimated urban expansion would see up to 16.7 GL (5%) of additional flow, assuming traditional drainage. Nitrogen and phosphorus loading to the estuary would likely remain unchanged or decrease by 0.2 to 3.5%, depending on the extent of urban nutrient management. This decrease in load is due to the increased area of roads and small urban lots, which have lower nutrient exports than beef and other more intensive agricultural land uses (Figure 7.4). It is likely this model underestimates nutrient exports from roads, as detailed in Section 4.3.

Table 7.4: Estimated average annual flow volumes for the basecase and the urban expansion scenario with traditional drainage. Note: in the WSUD scenario, flow is the same as the basecase.

Catchment	**Flow**			
	Basecase	**Urban expansion traditional drainage**		
	Average annual	**Average annual**	**Difference**	
	(GL/yr)	(GL/yr)	(GL/yr)	(%)
Coastal North	34.3	38.0	3.7	11%
Coastal Central	1.1	1.1	0.0	0%
Coastal South	7.8	7.7	-0.1	-2%
Peel Main Drain	6.9	11.0	4.1	59%
Upper Serpentine	33.9	38.2	4.3	13%
Dirk Brook	12.6	12.5	0.0	0%
Nambeelup	10.6	11.5	0.9	8%
Mandurah	3.2	3.2	0.0	0%
Lower Serpentine	5.3	6.3	1.1	20%
Upper Murray	124.8	124.8	0.1	0%
Lower Murray	51.0	55.5	4.5	9%
Coolup (Peel)	9.5	9.8	0.2	2%
Coolup (Harvey)	6.3	6.3	0.0	0%
Mayfield Drain	15.0	15.1	0.1	1%
Harvey	87.2	88.6	1.4	2%
Meredith Drain	2.3	2.3	0.0	0%
Harvey Diversion Drain	11.9	12.3	0.4	3%
Estuary coastal plain	244	260	16.6	7%
Peel-Harvey estuary	369	385	16.7	5%
Total	424	444	20.6	5%

Drains to Peel Inlet
Drains to Harvey estuary
Drains to coast

Table 7.5: Estimated average annual nitrogen loads for the basecase and the urban expansion scenario

	Nitrogen load						
	Basecase	**Urban expansion traditional drainage**			**Urban expansion WSUD**		
Catchment	**Average annual**	**Average annual**	**Difference**		**Average annual**	**Difference**	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Coastal North	116	114	-1.8	-1.6%	112	-4.0	-3.4%
Coastal Central	5.4	5.4	0.0	0.0%	5.4	0.0	0.0%
Coastal South	12.6	12.3	-0.3	-2.7%	12.3	-0.3	-2.8%
Peel Main Drain	11.6	12.2	0.6	5.3%	9.6	-2.0	-17.3%
Upper Serpentine	71.8	70.5	-1.3	-1.8%	66.1	-5.7	-8.0%
Dirk Brook	28.7	28.8	0.0	0.0%	28.8	0.0	0.0%
Nambeelup	40.3	39.1	-1.2	-3.0%	38.1	-2.2	-5.5%
Mandurah	5.0	5.0	0.0	0.0%	5.0	0.0	0.0%
Lower Serpentine	11.7	11.3	-0.4	-3.2%	10.5	-1.2	-10.0%
Upper Murray	80.2	80.2	0.0	0.0%	80.2	0.0	0.0%
Lower Murray	103	103	-0.7	-0.7%	99.7	-3.7	-3.6%
Coolup (Peel)	21.0	20.6	-0.4	-2.0%	20.3	-0.7	-3.5%
Coolup (Harvey)	13.3	13.4	0.0	0.2%	13.3	0.0	0.0%
Mayfield Drain	33.3	33.5	0.2	0.5%	33.3	0.0	0.0%
Harvey	205	206	0.9	0.4%	204	-1.5	-0.8%
Meredith Drain	6.7	6.7	0.0	0.0%	6.7	0.0	0.0%
Harvey Diversion Drain	49.1	49.0	-0.1	-0.2%	48.6	-0.5	-1.0%
Estuary coastal plain	552	550	-2.3	-0.4%	535	-17.1	-3.1%
Peel-Harvey estuary	633	630	-2.3	-0.4%	616	-17.1	-2.7%
Total	816	811	-4.6	-0.6%	794	-21.9	-2.7%

Table 7.6: Estimated average annual phosphorus loads for the basecase and the urban expansion scenario

Catchment	Phophorus load						
	Basecase	Urban expansion traditional drainage			Urban expansion WSUD		
	Average annual	Average annual	Difference		Average annual	Difference	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Coastal North	12.8	12.6	-0.20	-1.5%	12	-0.4	-3.4%
Coastal Central	0.4	0.4	0.00	0.0%	0.4	0.0	0.0%
Coastal South	8.9	8.8	-0.04	-0.5%	8.8	0.0	-0.5%
Peel Main Drain	1.4	1.3	-0.09	-6.0%	1.1	-0.3	-19.4%
Upper Serpentine	10.0	9.8	-0.14	-1.4%	9.1	-0.9	-9.1%
Dirk Brook	2.8	2.8	-0.01	-0.2%	2.8	0.0	-0.2%
Nambeelup	6.7	6.4	-0.25	-3.7%	6.2	-0.4	-6.6%
Mandurah	0.5	0.5	0.00	0.0%	0.5	0.0	0.0%
Lower Serpentine	2.1	2.2	0.02	1.0%	2.0	-0.2	-7.7%
Upper Murray	1.0	1.0	-0.01	-0.6%	1.0	0.0	-0.6%
Lower Murray	6.2	6.2	-0.03	-0.4%	5.9	-0.3	-5.1%
Coolup (Peel)	2.7	2.7	-0.08	-3.1%	2.6	-0.1	-3.8%
Coolup (Harvey)	2.1	2.1	0.01	0.5%	2.1	0.0	0.2%
Mayfield Drain	3.6	3.6	0.01	0.2%	3.6	0.0	0.0%
Harvey	20.1	20.6	0.46	2.3%	20	0.1	0.5%
Meredith Drain	1.0	1.0	0.00	0.0%	1.0	0.0	0.0%
Harvey Diversion Drain	7.6	7.6	0.00	-0.1%	7.6	0.0	-0.2%
Estuary coastal plain	59.3	59.2	-0.10	-0.2%	57	-2.1	-3.5%
Peel-Harvey estuary	60.2	60.1	-0.10	-0.2%	58	-2.1	-3.5%
Total	89.9	89.6	-0.35	-0.4%	87	-2.6	-2.9%

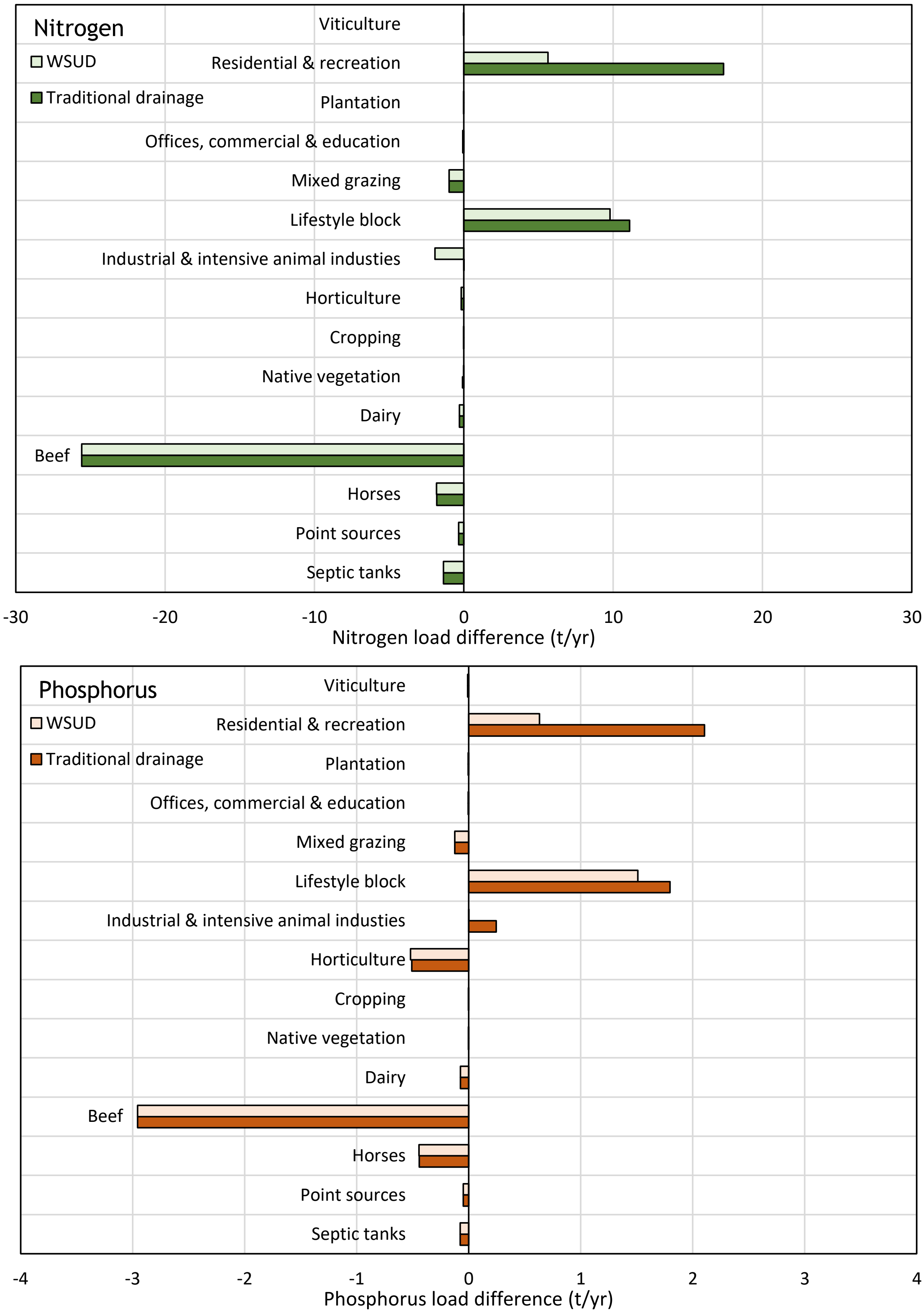


Figure 7.4: The difference between the basecase and urban expansion scenario nitrogen and phosphorus loads for different land uses

7.2 Agricultural development

Transform Peel is a program that aims to create 33,000 new jobs in the Mandurah region by 2050. The program comprises:

- **Peel Business Park:** This 1,000 ha light industrial area would host businesses that service the Peel Food Zone, such as food processing facilities and logistics.
- **Peel Food Zone:** This would require about 3,000 ha of intensive agriculture to be developed within the 42,000 ha investigation area. Agricultural industries such as in-ground annual horticulture, perennial horticulture, cattle feedlots and piggeries would be considered. Greenhouse horticulture would also be endorsed.
- **Peel Integrated Water Initiative (PIWI):** The Peel Food Zone's development is constrained by the availability of fresh water. The PIWI project will quantify water resources in the zone, identify the demand for alternative water sources and help develop nutrient management measures.

This scenario models the Peel Food Zone as 3,000 ha of annual horticulture at 2050, using the climate and model parameters for 2006–15. The development would be located in modelling catchment 52, which is in Nambeelup Brook catchment. We converted beef farms to in-ground annual horticulture, preferencing high-PRI areas. Table 7.7 gives the resulting land-use areas.

Greenhouse/hydroponic horticulture has been put forward as a favourable land use in the Peel Food Zone because of its higher water-use efficiency than in-ground horticulture. There is a perception that greenhouse/hydroponic horticulture can be engineered to have environmentally acceptable or zero nutrient emissions to the environment (Safstrom & Short 2012). We do not know of any published studies that quantify the nutrient exports from greenhouse/hydroponic horticulture locally. Haine et al. (2011) found that hydroponic horticulture had large offsite nutrient losses (1560 kg N/ha/yr and 111 kg P/ha/yr), even when effluent recycling systems were used. Thus, we did not model greenhouse/hydroponic horticulture in this scenario given the lack of local data and the excessively high nutrient exports that Haine et al. (2011) reported.

We modified the model parameters for annual horticulture in the Nambeelup catchment to reflect DPIRD's recommendations. We did this by using the median recommended fertiliser input and surplus nutrient rates from Table 7.8. For all other land uses in the Nambeelup catchment we used the parameters from the basecase model. All other catchments were unaffected by this scenario.

Table 7.7: Land-use areas in the Nambeelup modelling catchment ID 52 for the basecase and the agricultural development scenario

Modelling land use	Nambeelup modelling catchment 52 land use areas		
	Basecase (ha)	Agricultural development (ha)	Change (ha)
Bare soil & other (high PRI)	18	18	0
Bare soil & other (low PRI)	45	45	0
Beef (high PRI)	682	0	-682
Beef (low PRI)	4 860	2 542	-2 318
Dairy (high PRI)	134	134	0
Dairy (low PRI)	768	768	0
Horses (high PRI)	507	507	0
Horses (low PRI)	285	285	0
Horticulture (high PRI)	0	682	682
Horticulture (low PRI)	2	2 320	2 318
Industry, manufacturing & transport (high PRI)	45	45	0
Industry, manufacturing & transport (low PRI)	90	90	0
Lifestyle block (high PRI)	40	40	0
Lifestyle block (low PRI)	73	73	0
Native vegetation (high PRI)	292	292	0
Native vegetation (low PRI)	964	964	0
Total	**8 803**	**8 803**	**0**

Table 7.8: Summary of the annual fertiliser inputs, crop outputs and nutrient surplus of various crops. These rates were derived from DPIRD data.

Crop type		Crops per year	Fertiliser inputs		Output from crops			Surplus nutrient			
			N input	P input	Crop yield per year	N removed	P removed	N surplus		P surplus	
		(#)	(kg/ha/yr)	(kg/ha/yr)	(t/ha)	(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(%)	(kg/ha/yr)	(%)
Celery	1, 2	3	2 230	470	270	513	100	1 717	77%	371	79%
English spinach	3	7	1 612	182	21	40	8	1 572	98%	174	96%
Sweet potatoes: Sand	4	2	368	70	40	120	17	248	67%	53	76%
Sweet potatoes: Loam	4	2	552	175	40	120	17	432	78%	158	90%
Pumpkin: Sand	5	2	1 006	177	52	109	29	897	89%	148	84%
Pumpkin: Loam	5	2	840	165	52	109	29	731	87%	135	82%
Average			1 101	206	79	169	33	933	85%	173	84%
Median			**923**	**176**	**46**	**115**	**23**	**814**	**88%**	**153**	**87%**

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

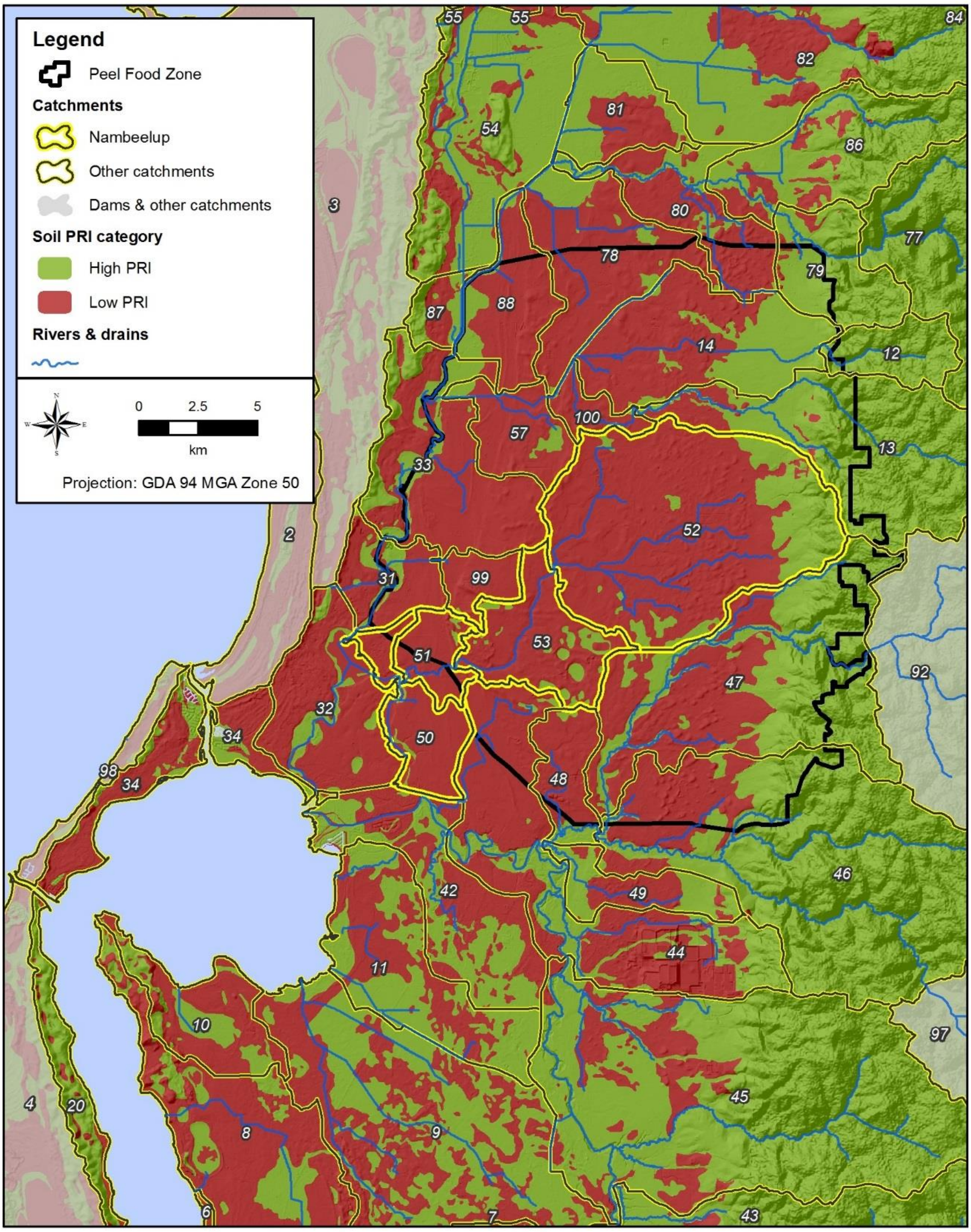


Figure 7.5: Catchments and soil phosphorus retention index categories for the Peel Food Zone investigation area

Results

We estimated the 3,000 ha in-ground horticulture development would increase average annual phosphorus loads from the Nambeelup catchment by 22 tonnes (336%) (see sTable 7.9). Of all the catchments, this would make Nambeelup the largest contributor of phosphorus to the Peel-Harvey estuary (see sTable 7.9, Figure 7.6 and Figure 7.7). Phosphorus loading to the estuary would increase from 60 tonnes to 83 tonnes, a 37% increase. Horticulture would become the second-largest source of phosphorus load to the Peel-Harvey estuary (35%), with beef farming the largest (46%) (see Figure 7.7). We estimated the nitrogen loads from the Nambeelup catchment would increase by 114 tonnes (282%).

sTable 7.9: Average annual nutrient loads for the agricultural development scenario

Reporting catchment	Nitrogen				Phosphorus			
	Basecase	**Agricultural development**	**Load change**		**Basecase**	**Agricultural development**	**Load change**	
	(tonnes)	(tonnes)	(tonnes)	(%)	(tonnes)	(tonnes)	(tonnes)	(%)
Peel Main Drain	11.6	11.6	-	-	1.4	1.4	-	-
Upper Serpentine	71.8	71.8	-	-	10.0	10.0	-	-
Dirk Brook	28.7	28.7	-	-	2.8	2.8	-	-
Nambeelup	40.3	153.9	113.6	282	6.7	29.0	22.4	336
Mandurah	5.0	5.0	-	-	0.5	0.5	-	-
Lower Serpentine	11.7	11.7	-	-	2.1	2.1	-	-
Upper Murray	80.2	80.2	-	-	1.0	1.0	-	-
Lower Murray	103.4	103.4	-	-	6.2	6.2	-	-
Coolup (Peel)	21.0	21.0	-	-	2.7	2.7	-	-
Coolup (Harvey)	13.3	13.3	-	-	2.1	2.1	-	-
Mayfield Drain	33.3	33.3	-	-	3.6	3.6	-	-
Harvey	205.5	205.5	-	-	20.1	20.1	-	-
Meredith Drain	6.7	6.7	-	-	1.0	1.0	-	-
Estuary coastal plain	552.4	666.1	113.6	21	59.3	81.6	22.4	38
Peel-Harvey estuary	**632.7**	**746.3**	113.6	18	**60.2**	**82.6**	22.4	37

Table 7.10: Agricultural development scenario land-use areas and average annual (2006–15) flow and nutrient loads from all catchments that flow to the Peel-Harvey estuary

Land use	Colour	Area		Runoff		Nitrogen		Phosphorus	
		(km²)	(%)	(GL)	(%)	(tonnes)	(%)	(tonnes)	(%)
Septic (#)		12 967	-	0.2	0.1	23	3.1	1.6	1.9
Point sources		1	0.0	0.5	0.1	4.7	0.6	0.3	0.3
Horses		84	0.9	7.7	2.1	18	2.4	3.3	4.0
Beef		1 043	11	139	38	381	51	38	46
Dairy		46	0.5	15	4.0	43	5.8	4.9	5.9
Native vegetation		4 008	43	48	13	5.9	0.8	0.1	0.1
Cropping		3 577	38	104	28	76	10	0.8	1.0
Horticulture		58	0.6	3.7	1.0	130	17	29	35
Industry, manufacturing & transport		110	1.2	24	6.6	1.7	0.2	0.1	0.1
Intensive animal industries		13	0.1	0.9	0.2	24	3.2	1.0	1.3
Lifestyle block		86	0.9	8.6	2.3	15	2.0	0.5	0.6
Mixed grazing		80	0.8	6.2	1.7	12	1.6	1.1	1.3
Offices, commercial & education		6	0.1	1.3	0.4	1.5	0.2	0.2	0.3
Plantation		231	2.5	1.0	0.3	1.0	0.1	0.4	0.5
Recreation		10	0.1	0.8	0.2	1.8	0.2	0.0	0.1
Residential		29	0.3	7.0	1.9	6.6	0.9	1.3	1.5
Viticulture		4	0.0	0.7	0.2	1.2	0.2	0.1	0.1
Total		**9 388**		**369**		**746**		**83**	

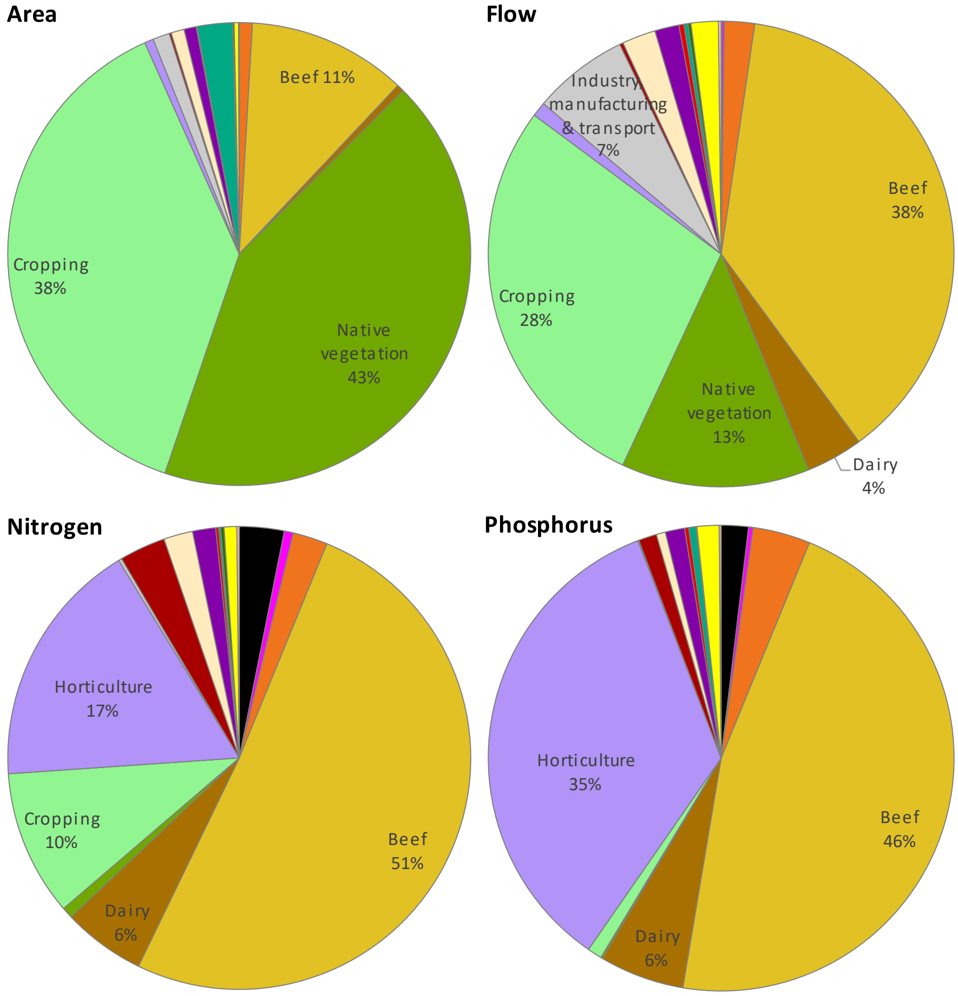


Figure 7.6: Agricultural development scenario land-use source separation for catchments draining to the Peel-Harvey estuary

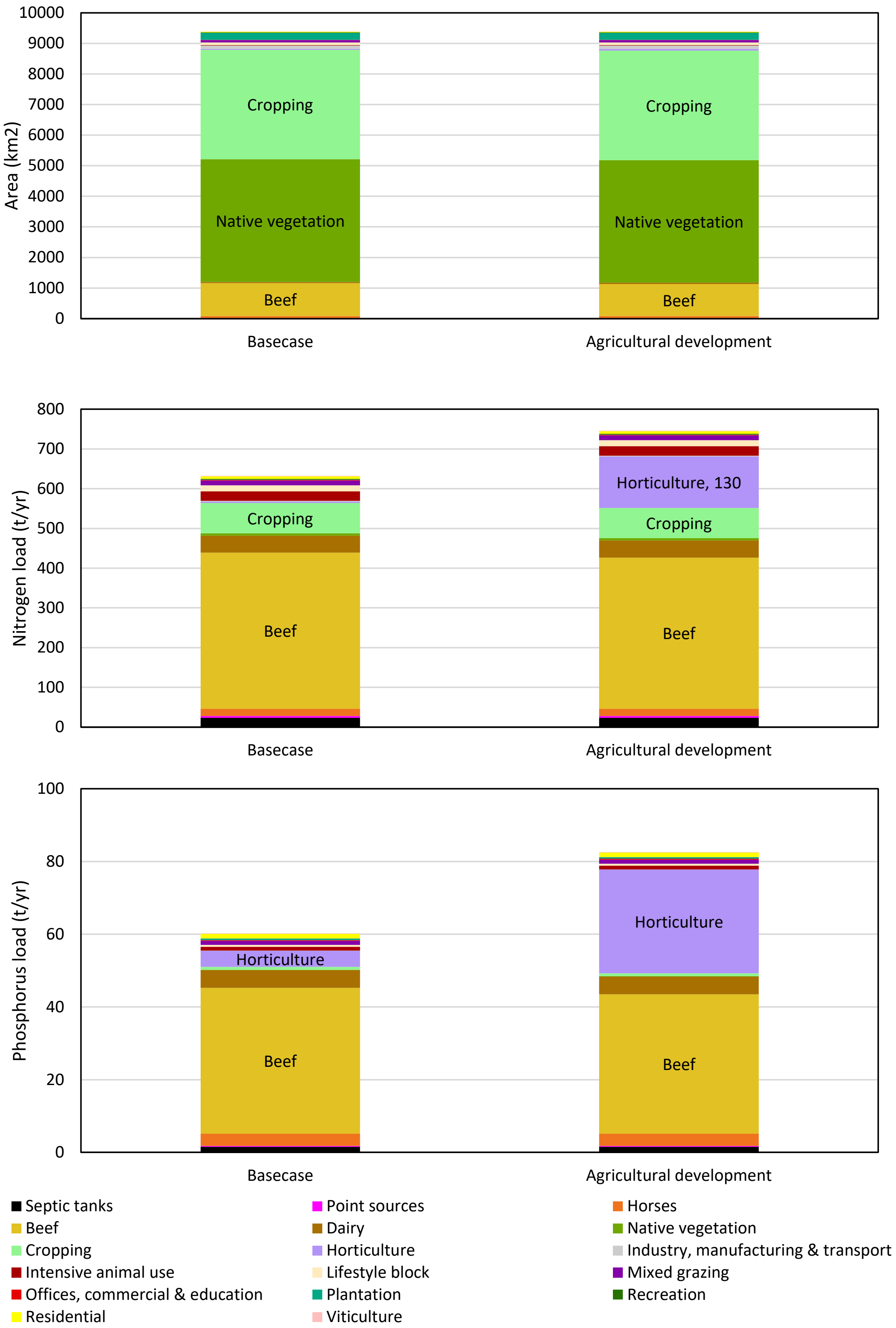


Figure 7.7: Land-use area and average annual (2006–15) nutrient loads to the Peel-Harvey estuary for the basecase and agricultural development scenario

7.3 Management scenarios

We modelled several management scenarios to estimate their potential contribution to decreasing nutrient loads and achieving targets (see Section 6.1).

We examined the effect of 11 management actions to determine their relative impacts on nutrient loads to the Peel-Harvey estuary:

1. Riparian zone rehabilitation (stock exclusion and re-vegetation)
2. Best-practice fertiliser management on farms
3. Use of low-water-soluble phosphorus fertilisers
4. Dairy effluent management
5. Soil-amendment application on farms
6. Intensive nutrient sources (point sources)
7. Wastewater treatment plant (WWTP) effluent management
8. Septic tank removal (rural and urban)
9. Water sensitive urban design (WSUD) retrofitting in existing urban areas
10. Constructed wetlands (rural)
11. Catchment re-vegetation

We adapted the modelling approach from the *Leschenault water quality improvement plan* (Hugues-dit-Ciles et al. 2012). Where possible, we used the farm-scale model Overseer® to estimate the efficacies of agricultural management practices. We adapted other scenarios from the best-available information, and these are largely consistent with previous modelling (Kelsey et al. 2011; Ecotones & Associates 2005; Zammit et al. 2006). We did not model some of the recommended management actions for water quality improvement, but we discuss these at the end of this section. We ran all the scenarios using the land use, climate and other model inputs of the basecase period (2006–15). We have reported the scenario results as nutrient load reductions relative to the basecase loads.

See Table 7.11 for the assumed efficacies of the management practices. The following sections discuss the implementation of each of the management actions. See Appendix F for the load reductions of all the management actions.

Table 7.11: Estimated efficacy of management practices

Management practice	Scenario, category or land use	Nitrogen load reduction	Phosphorus load reduction	Reference[1]
Riparian zone management: coastal plain[3]	Fencing and revegetation	30%	5%	Hall 2019 (Section 7.3.1)
	Fencing only	15%	5%	
Best practice fertiliser management[2]	Beef (low PRI)	0%	44%	Overseer modelling (Section 7.3.2)
	Dairy (low PRI)	0%	36%	
	Beef (high PRI)	0%	50%	
	Dairy (high PRI)	0%	23%	
Best practice fertiliser management using low water soluble phosphorus fertilisers[¥2]	Beef (low PRI)	0%	56% (+12%)	Overseer modelling (Section 7.3.3)
	Dairy (low PRI)	0%	41% (+5%)	
Dairy effluent management[2]	Dairy sheds	60%	60%	Literature review (Section 7.3.4)
Soil amendment[2]	20 t/ha of amendment	0%	60%	Literature review (Section 7.3.5)
Intensive nutrient sources (point sources)[2]	Intensive animal industries, point sources, annual horticulture, turf farms	95%	95%	Assumption (Section 7.3.6)
WWTP management[2]	Improved treated wastewater discharge quality	30%	50%	PHCC data (Section 7.3.7)
Infill sewerage[2]	Infill sewerage recommendations	100%	100%	Manipulation of basecase model (Section 7.3.8)
	Expanded infill sewerage	100%	100%	
	Remove all septics	100%	100%	
Water sensitive urban design retrofitting[2]	Existing urban	45%	45%	Assumption (Section 7.3.9)
Constructed wetlands[3]	0.5% of catchment area	30%	50%	UNDO tool (Section 7.3.10)
Catchment revegetation[3]	Plantations or native vegetation	0–42%	0–72%	Manipulation of basecase model (Section 7.3.11)

¥ Values in brackets indicate the additional phosphorus load reduction from the best practice fertiliser management scenario.

[1] The primary reference used to support the nutrient removal efficacy and the section of this report which details the modelling scenario.

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

[3] Load reduction relative to catchment.

7.3.1 Riparian management

Riparian management may include:

- fencing waterways
- re-vegetating the riparian zone
- modifying the physical form of a waterway (typically drains).

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 on the effectiveness of riparian re-vegetation to remove, attenuate or prevent the export of nutrients, with a focus on Western Australian south coastal plain catchments. See below for a summary of the outcomes.

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, inhibit plant regrowth and add nutrients directly to waterways and the riparian zone (faeces and urine).
- Re-vegetating riparian zones:
  - stabilises waterway banks and reduces erosion
  - traps sediment and particulate nutrients in overland flow
  - utilises 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 re-vegetation is likely to help reduce phosphorus loads to waterways in the upland catchments due to steep catchment slopes, finer textured soils, lower infiltration rates, and hence overland flow being the dominant hydrological pathway. Riparian zones efficiently trap and process particulate nutrients in overland flow.

Phosphorus removal is likely to be small in the riparian zones of the flat sandy waterways of the Swan Coastal Plain. 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. Given the above, the primary mechanisms for phosphorus load reduction due to riparian zone rehabilitation on the Swan Coastal Plain 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.

However, the conditions in riparian zones on the Swan Coastal Plain are mostly ideal for nitrogen removal. 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 the Western Australian setting generally involves:

- Fencing programs that are implemented by land holders, 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 land holder.
- In some instances, drains are modified to better represent natural streams. This can involve the flattening and widening of the drain 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. Recently, the Peel Harvey Catchment Council (PHCC) funded the development of temporary weirs to detain water within degraded and artificially drained wetlands. This was done to increase the period of standing water and to promote wetland nutrient attenuation processes.

- 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.

The width of riparian management varies and depends on the land holder. In general, it occurs within 5 to 15 m of the stream.

Historically, natural resource management (NRM) groups such as the PHCC have done riparian zone rehabilitation in conjunction with land holders. Rates of riparian zone re-vegetation depend on funding (state and/or federal government), the priorities of NRM groups and the capacity for NRM groups to implement rehabilitation.

The PHCC provided spatial data relating to the following management activities:

- streamlining (stream fencing, with revegetation in some locations)
- catchment re-vegetation
- wetland rehabilitation
- shelterbelts on farms (see Section 7.3.11)
- other on-ground works including weeding and perennial pastures.

The streamlining dataset gave the length of waterways that were fenced and the year completed. During 1992–2008 streamlining averaged 21 km per year with an approximate maximum of 40 km per year in 1992–97. From 2004–08 the rate of streamlining slowed to about 1 km per year.

A survey of 70 land owners in the Peel-Harvey catchment found that 75% of respondents had fenced one or more sides of watercourses (Lavell et al. 2004). The role of Landcare groups in providing the education and resources were noted as an incentive for undertaking these works (Lavell et al. 2004).

Implementation

This scenario modifies the parameters we used in the riparian filtering component of the nutrient model (see Section 3.1.2).

We modelled two categories of riparian zone management: one with fencing and the other with fencing and revegetation. Each category has different efficacies in upland and coastal plain locations – see Table 7.12. For phosphorus, we assumed load attenuation was greater in upland areas than coastal plain areas.

We defined waterways from DEM mapping, assuming a minimum catchment area of 1 km^2 (see Section 3.2). That is, if a watercourse’s catchment was less than 1 km^2, we considered it too small to warrant riparian zone rehabilitation. This resulted in total waterway length for the Peel-Harvey estuary catchment of 7,105 km. We identified cleared riparian zones (3,929 km) from the dataset used in the riparian filtering model (see Section 3) and took fenced riparian zones from the PHCC dataset. We also estimated the proportion of drains owned by the Water Corporation at a coarse scale (see Table 7.13).

This scenario models 100% uptake of the two categories of riparian zone rehabilitation and assumes that:

1. All unfenced riparian zone is fenced
2. All cleared and unfenced riparian zone is fenced and re-vegetated

It is likely there are already more fenced riparian areas than the PHCC dataset captures; hence we have likely overestimated the load reductions of the first (fencing only) scenario. Note that re-vegetation of all cleared riparian zone (3,929 km) would take hundreds of years using the recent riparian rehabilitation rates.

Table 7.12: Riparian management nutrient removal efficacy (taken from Hall 2019)

Category	Description	Nitrogen load reduction	Phosphorus load reduction	
		Upland & coastal plain	Upland	Coastal plain
		(%)	(%)	(%)
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 & revegetation	Fencing with stock exclusion, off-stream watering points and stream crossings. Re-vegetated using native canopy and understory vegetation (8,000 plants/ha).	30	30	5

Table 7.13: Length of fenced and cleared riparian zones

Reporting catchment	Total waterway length	Previous fencing programs	Cleared riparian zone	Water Corporation owned	Length of stream treated: Fencing only		Fencing & revegetation	
	(km)	(km)	(km)	(%)	(km)	(%)	(km)	(%)
Peel Main Drain	108	0.4	66	75–100%	66	61	66	61
Upper Serpentine	451	75	266	50%	191	42	266	59
Dirk Brook	130	17	73	25%	56	43	73	56
Nambeelup	134	26	100	0%	75	56	100	75
Mandurah	-	-	-	-	-	-	-	-
Lower Serpentine	86	2	39	< 25%	37	43	39	46
Upper Murray	4 744	-	2 535	0%	2 535	53	2 535	53
Lower Murray	595	65	237	25–50%	173	29	237	40
Coolup (Peel)	130	32	102	100%	70	54	102	78
Coolup (Harvey)	74	17	56	75–100%	39	52	56	75
Mayfield Drain	109	59	83	100%	24	22	83	76
Harvey	497	48	337	75–100%	288	58	337	68
Meredith Drain	48	10	36	50%	25	53	36	74
Estuary coastal plain	**2 361**	**351**	**1 394**	**50%**	**1 043**	**44**	**1 394**	**59**
Peel-Harvey estuary	**7 105**	**351**	**3 929**	**<25%**	**3 578**	**50**	**3 929**	**55**

Results

See the nutrient removal from 100% implementation of riparian zone management in Table 7.14 and Table 7.15. We estimated riparian zone management would reduce nutrient loading to the Peel-Harvey estuary by 7 to 18% for nitrogen and 2.7 to 3.6% for phosphorus, depending on management effort. Most (> 85%) of the nitrogen load reduction came from interventions on the coastal plain.

Apart from the Upper Murray, which is already achieving its phosphorus target, this scenario did not reduce nutrient loads below catchment targets (see Figure 7.8). However, the riparian zone management scenario – fencing and re-vegetation – was one of the most effective management actions for nitrogen management of the 11 management actions we modelled.

Riparian zone rehabilitation was less effective for phosphorus management on the coastal plain. In the Upper Murray catchment, phosphorus reduced by 9 to 16%. However, the Upper Murray phosphorus load is small relative to its catchment area, making riparian zone management less effective (load removed per km of management) than in other catchments. Catchments on the coastal plain had phosphorus reductions of 1.1 to 3.9%.

The Mayfield catchment had the highest proportion of fenced waterways (54%), which resulted in the smallest benefit from the fencing only scenario. If all the waterways in the Mayfield catchment were fenced and vegetated, then the nitrogen and phosphorus loads would reduce by 23% and 3.8% respectively.

Table 7.14: Reporting catchment nitrogen loads for the basecase and the riparian management scenario

Reporting catchment	Basecase	Fencing only			Fencing & revegetation		
	N load	N load	N load change		N load	N load change	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Peel Main Drain	12	11	-1.0	-8.8	10	-1.9	-17
Upper Serpentine	72	67	-5.0	-7.0	58	-14	-20
Dirk Brook	29	27	-1.9	-6.7	24	-5.0	-17
Nambeelup	40	37	-3.5	-8.7	31	-9.3	-23
Mandurah	5.0	5.0	-	-	5.0	-	-
Lower Serpentine	12	11	-0.6	-5.5	11	-1.1	-9.6
Upper Murray	80	73	-7.0	-8.8	67	-13	-16
Lower Murray	103	99	-4.1	-4.0	94	-9.8	-9.5
Coolup (Peel)	21	19	-1.7	-8.1	16	-4.9	-24
Coolup (Harvey)	13	12	-1.0	-7.8	10	-3.0	-23
Mayfield Drain	33	32	-1.1	-3.2	26	-7.6	-23
Harvey	205	187	-18	-8.8	164	-41	-20
Meredith Drain	6.7	6.2	-0.6	-8.7	5.2	-1.6	-23
Estuary coastal plain	**552**	**514**	**-39**	**-7.0**	**453**	**-100**	**-18**
Peel-Harvey estuary	**633**	**587**	**-46**	**-7.2**	**520**	**-113**	**-18**

Table 7.15: Reporting catchment phosphorus loads for the basecase and the riparian management scenario

Reporting catchment		Fencing only			Fencing & revegetation		
	P load	P load	P load change		P load	P load change	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Peel Main Drain	1.4	1.4	-0.04	-2.7	1.4	-0.04	-2.6
Upper Serpentine	10	10	-0.26	-2.6	10	-0.35	-3.5
Dirk Brook	2.8	2.7	-0.06	-2.3	2.7	-0.09	-3.1
Nambeelup	6.7	6.5	-0.19	-2.9	6.4	-0.25	-3.8
Mandurah	0.5	0.5	-	-	0.5	-	-
Lower Serpentine	2.1	2.1	-0.04	-1.9	2.1	-0.04	-1.7
Upper Murray	1.0	0.9	-0.08	-8.5	0.8	-0.15	-16.0
Lower Murray	6.2	6.1	-0.09	-1.4	6.1	-0.11	-1.8
Coolup (Peel)	2.7	2.7	-0.07	-2.7	2.6	-0.11	-3.9
Coolup (Harvey)	2.1	2.0	-0.05	-2.7	2.0	-0.08	-3.7
Mayfield Drain	3.6	3.6	-0.04	-1.1	3.5	-0.14	-3.8
Harvey	20	19	-0.65	-3.2	19	-0.77	-3.8
Meredith Drain	1.0	1.0	-0.03	-2.9	1.0	-0.04	-3.9
Estuary coastal plain	**59**	**58**	**-1.5**	**-2.6**	**57**	**-2.0**	**-3.4**
Peel-Harvey estuary	**60**	**59**	**-1.6**	**-2.7**	**58**	**-2.2**	**-3.6**

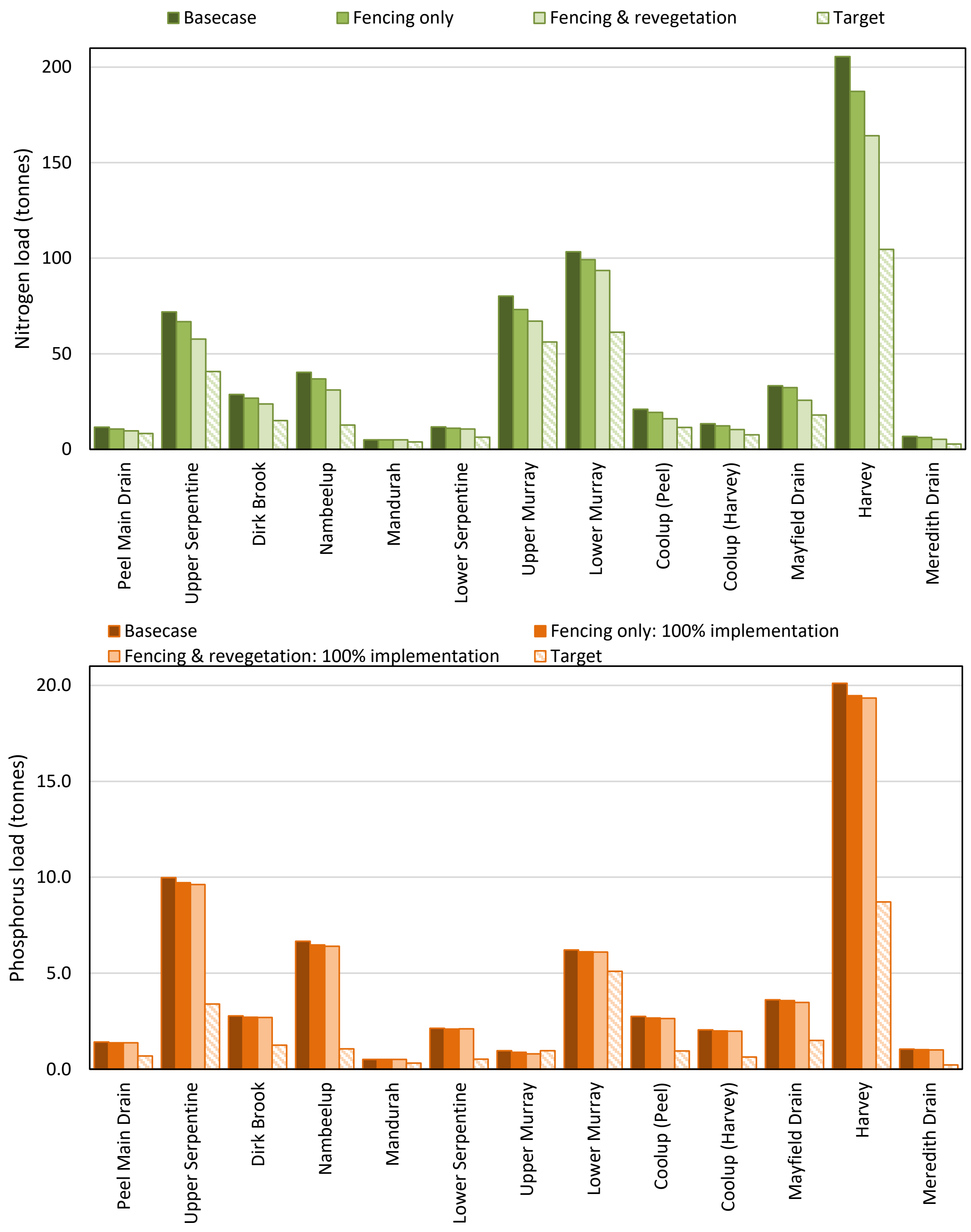


Figure 7.8: Reporting catchment nitrogen and phosphorus loads for the basecase and the riparian management scenario

7.3.2 Best-practice fertiliser management

Beef and dairy farms are the largest sources of nutrients to the Peel-Harvey estuary (see Section 5.2). Most beef and dairy farms have phosphorus content in their soil that exceeds what productive pasture growth requires. This is due to a long history of excessive phosphorus fertiliser use. It is common for farmers to apply fertiliser according to tradition rather than using soil and tissue test results to inform the correct dosage. In some cases, farmers apply excessive phosphorus fertiliser when other nutrients, such as potassium and sulfur, are deficient and limit pasture productivity.

Local and international literature has discussed phosphorus fertiliser reduction and its impact on phosphorus leaching or runoff and soil phosphorus content:

- Schofield et al. (1985) did a local study that 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 phosphorus runoff concentration over the two-year period.
- Silberstein & Schofield (1990) did a similar study to Schofield et al. (1985) but ran the experiment for four years and used a smaller study site on 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 (1995) and Vadas et al. (2005) to develop a linear relationship between dissolved reactive phosphorus in runoff, and phosphorus saturation (which is Colwell P as a percentage of the soil P sorption capacity). 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 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 tool phosphorus soil-loss model.

Best-practice fertiliser management requires farmers to 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 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).

Figure 7.9: The four Rs (source: https://nutrientstewardship.org/4rs/)

To determine the right rate of fertiliser, farmers need to work out their target pasture productivity. Beef and dairy farms typically aim to achieve maximum pasture production of 85% and 95% respectively, as this is generally the most profitable. However, this target will vary from farm to farm and could differ between paddocks of a single farm. We have assumed these productivity targets in this scenario modelling.

Farmers will then need to undertake paddock soil testing to determine the content of soil nutrients, soil properties such as phosphorus buffering index, 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** (https://www.agric.wa.gov.au/climate-land-water/land-use/high-rainfall-pastures), which includes:

- methods of soil and tissue testing
- phosphorus, sulfur and potassium fertiliser 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** (https://www.bfdc.com.au/interrogator/frontpage.vm). The Better Fertiliser Decisions 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.

Implementation

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

1. **The potential effect of soil test programs on phosphorus loss:** We assumed beef and dairy farms that joined the Regional Estuaries Initiative (REI) soil testing program adopted best-practice farm fertiliser management (3.7% of total beef and dairy farm area). We assumed all beef and dairy farms in the DPIRD whole-farm nutrient

mapping database adopted best-practice farm fertiliser management (26% of total beef and dairy farm area).

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

We modelled scenario 1 to estimate the potential long-term water quality benefit of programs that aim to improve farm nutrient-use efficiency. Note that further study is needed to determine the effectiveness of these programs in changing farm management behaviour.

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). Note that nitrogen was unaffected in this scenario as most farm nitrogen input is from nitrogen-fixing pastures rather than fertiliser. See Appendix F for a full description of this modelling and the summary below.

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 F). We used a greater proportion of the dataset to find the potential effect of government-funded programs that aim to improve the efficiency of farm fertiliser practices in high-rainfall estuary catchments. A total of 247 km^2 was soil tested (114 km^2 from REI funded programs and 133 km^2 from other programs).

A ‘fertility index’ is used to indicate if soil plant-available phosphorus content is above or below the agronomic optimum for a given pasture productivity target. 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 maximum) and would not require phosphorus fertiliser. A fertility index of less than 1 means that a farm is deficient in plant-available soil phosphorus and would require fertiliser to maintain the pasture productivity target. 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.

Figure 7.10 shows the fertility index of beef and dairy farms that DPIRD measured. On average, beef and dairy farms had fertility indices of about 2.

We used Overseer to determine the fertiliser regime needed to maintain a soil fertility index of 1, and the corresponding farm phosphorus load exports that would result for:

1. Beef farms on low-PRI soils
2. Beef farms on high-PRI soils
3. Dairy farms on low-PRI soils
4. Dairy farms on high-PRI soils

We compared these Overseer models with the Overseer models of basecase farm-fertiliser-management behaviour. This modelling showed that optimal fertiliser management and maintenance of soil fertility at 1 would result in phosphorus load reductions of:

- Beef (low PRI): **44%**
- Beef (high PRI): **50%**
- Dairy (low PRI): **36%**
- Dairy (high PRI): **23%**

It is important to note that this modelling assumed steady-state conditions. In reality, some farms may have enough soil phosphorus to sustain pasture production for many years, even with zero phosphorus fertiliser application (Summers pers. comm. 2018). See more details about the Overseer modelling in Appendix F.

Results: 1) The potential effect of soil testing programs on phosphorus loss

Table 7.16 gives the estimated phosphorus load reductions for best-practice fertiliser management on farms in the REI-funded soil testing program (2016–20) and all data from the WFNM database (2009–20).

The REI-funded soil testing program covered 10% of all beef and dairy farm areas. If these farms continued to use best-practice fertiliser management in the long term, then phosphorus loss to the estuary could reduce by 4% (2.2 tonnes per year). The entire WFNM database (including REI-funded projects) tested 26% of all beef and dairy farm areas in the Peel-Harvey catchment. If the management practices were adopted in the long term, phosphorus loss to the estuary would reduce by 8% (4.9 tonnes per year).

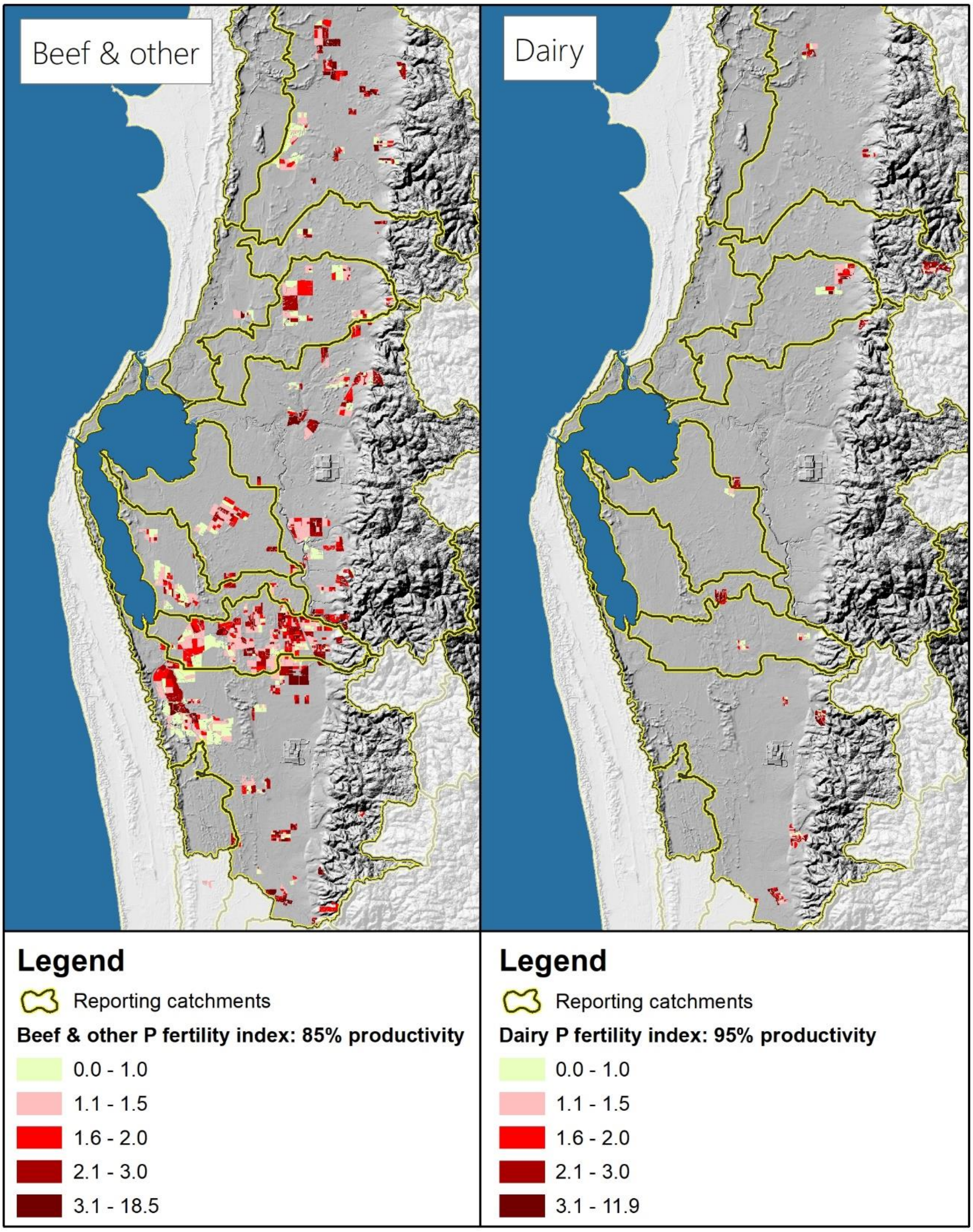


Figure 7.10: Fertility index of beef and dairy farms from soil testing programs (2009–20)

Table 7.16: Potential average annual phosphorus load reductions that could result from farm soil-testing programs in the Peel-Harvey catchments. Farmers are assumed to adopt best-practice fertiliser management practices but continue to use highly-soluble phosphorus fertilisers on low-PRI soils.

Reporting catchment	Basecase				REI soil testing 2016–20				All soil testing programs 2009–20 (including REI)			
	Beef and dairy		All land uses									
	Area	P load	Area	P load	Area tested		Load change		Area tested		Load change	
	(km²)	(t/yr)	(km²)	(t/yr)	(km²)	(%)¥	(t/yr)	(%)*	(km²)	(%)¥	(t/yr)	(%)*
Peel Main Drain	14	0.1	125	1.4	-	-	-	-	-	-	-	-
Upper Serpentine	127	4.4	491	10.0	19	15	-0.29	-2.9	27	22	-0.46	-4.6
Dirk Brook	45	1.7	139	2.8	3.2	7.0	-0.02	-0.7	4.6	10.1	-0.05	-1.9
Nambeelup	92	6.2	139	6.7	12	13	-0.35	-5.2	22	24	-0.70	-10
Mandurah	-	-	24	0.5	-	-	-	-	-	-	-	-
Lower Serpentine	27	1.1	100	2.1	1.4	5.2	-0.03	-1.4	1.4	5	-0.03	-1.4
Upper Murray	0.4	< 0.1	6752.4	1.0	-	-	-	-	-	-	-	-
Murray	249	5.4	636	6.2	18	7.3	-0.18	-3.0	39	16	-0.36	-5.8
Coolup (Peel)	109	2.5	150	2.7	10.8	9.9	-0.11	-4.0	13	12.2	-0.14	-5.1
Coolup (Harvey)	62	1.8	103	2.1	10.0	16	-0.15	-7.1	16	25	-0.21	-10
Mayfield Drain	89	3.3	122	3.6	14.8	17	-0.24	-6.6	56	63	-0.82	-23
Harvey	282	17	553	20	23	8.3	-0.80	-4.0	65	23	-2.08	-10.4
Meredith Drain	21	0.6	53	1.0	0.5	2.6	-0.01	-0.7	1.2	5.5	-0.02	-1.5
Estuary coastal plain	**1 118**	**44**	**2 637**	**60**	**114**	**10**	**-2.2**	**-3.6**	**247**	**22**	**-4.9**	**-8.1**
Peel-Harvey estuary	**1 119**	**44**	**9 389**	**60**	**114**	**10**	**-2.2**	**-3.6**	**247**	**22**	**-4.9**	**-8.1**

¥ Percent of beef and dairy area

* Percent of basecase load from all land uses

Results: 2) All farmers adopting best-practice fertiliser management

Table 7.17 and Figure 7.11 give the estimated phosphorus load reduction from 100% adoption of best-practice farm fertiliser management. If all beef and dairy farms applied fertiliser based on the agronomic requirement for optimal pasture production, the phosphorus load to the Peel-Harvey estuary would reduce by 32%. We estimated the Lower Murray catchment had phosphorus loads below the catchment target (Figure 7.11). (The Upper Murray already meets its phosphorus load target and was mostly unaffected by this scenario.) All other catchments would continue to exceed their phosphorus load targets. (Note the Mandurah catchment did not have any beef or dairy land uses and was thus unaffected by this scenario.)

Figure 7.12 shows the nutrient load reductions by land use and soil-PRI category. Most (75%) of the phosphorus load reduction was from beef farms with low-PRI soils, followed by beef farms on high-PRI soils (19%). Catchments with a large proportion of beef farms on low-PRI soils therefore had the greatest phosphorus reductions.

Table 7.17: Average annual phosphorus loads for the basecase and 100% adoption of fertiliser management scenario on beef and dairy farms

Reporting catchment	**Basecase (all land uses)**	**Fertiliser management: 100% adoption by beef and dairy farms**		
	P load	**P load**	**Load change**	
	(t/yr)	(t/yr)	(t/yr)	(%)
Peel Main Drain	1.4	1.4	-0.05	-3.3
Upper Serpentine	10	8	-1.9	-20
Dirk Brook	2.8	2.0	-0.7	-27
Nambeelup	6.7	4.0	-2.6	-39
Mandurah	0.5	0.5	-	-
Lower Serpentine	2.1	1.6	-0.5	-23
Upper Murray	1.0	1.0	< -0.1	-0.1
Lower Murray	6.2	3.8	-2.4	-39
Coolup (Peel)	2.7	1.6	-1.1	-40
Coolup (Harvey)	2.1	1.3	-0.8	-39
Mayfield Drain	3.6	2.2	-1.5	-41
Harvey	20	13	-7.4	-37
Meredith Drain	1.0	0.8	-0.3	-26
Estuary coastal plain	**59**	**40**	**-19**	**-33**
Peel-Harvey estuary	**60**	**41**	**-19**	**-32**

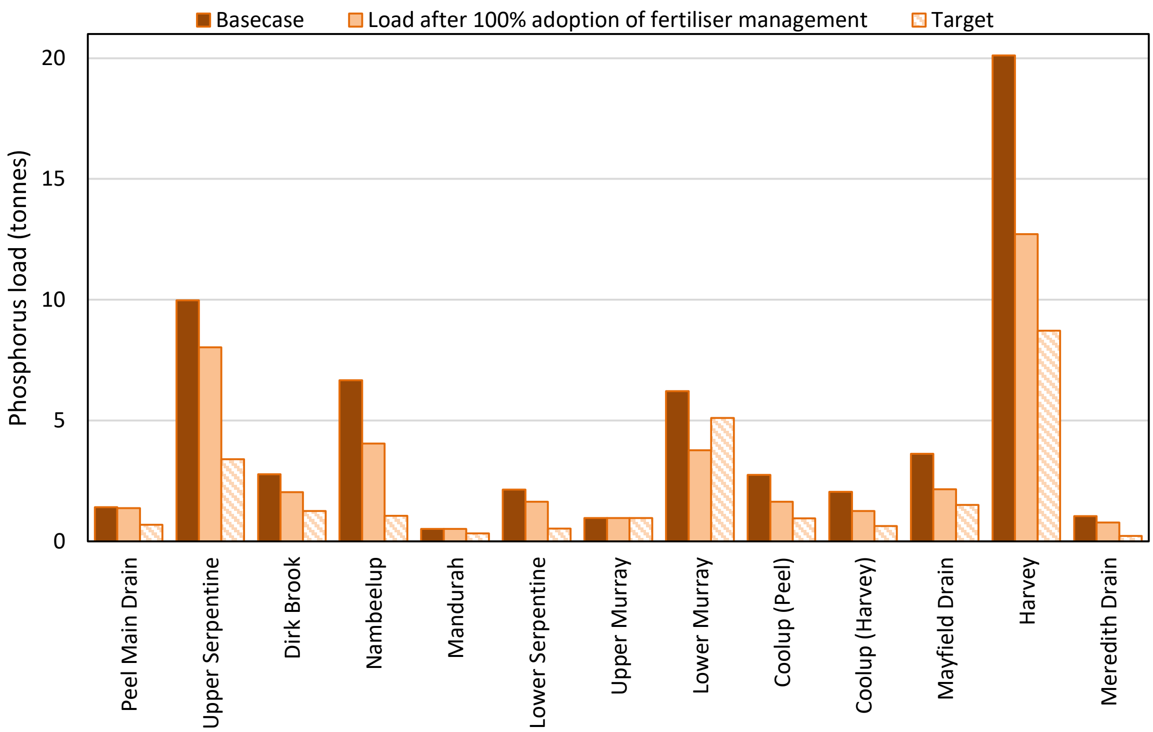


Figure 7.11: Phosphorus loads for the basecase and the 100% adoption of best-practice fertiliser management scenario

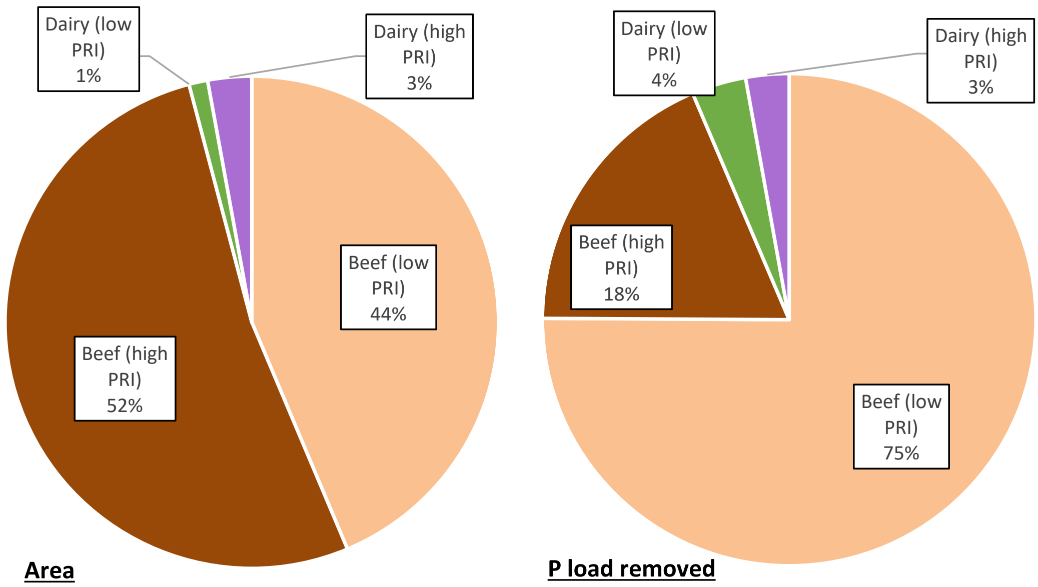


Figure 7.12: The proportion of beef and dairy area and the proportion of load removed for the fertiliser management scenario for all estuary catchments

7.3.3 Low-water-soluble phosphorus fertilisers

Single superphosphate is the most common type of phosphorus fertiliser used by grazing farms in Western Australia. About 80% of the phosphorus in single superphosphate fertiliser is water soluble. When used on sandy acidic low-PRI soils, highly water-soluble phosphorus fertilisers are susceptible to leaching. 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.

A variety of low-water-soluble phosphorus (LWSP) fertilisers have been trialled locally since the 1980s. The water solubility of these fertilisers is typically 0 to 40%, compared with 77% for single superphosphate, however some newer fertilisers may have a water solubility of about 50% (Table 7.18). Pasture yield studies have shown that use of low-water-soluble phosphorus fertilisers generally results in similar pasture yields to single superphosphate fertilisers when used on sandy acidic soils.

However, it has been shown that when farmers apply low-water-soluble phosphorus fertilisers at rates greatly in excess of plant requirements, phosphorus leaching equivalent to that of single superphosphate occurs. Thus, use of low-water-soluble phosphorus fertiliser will only cause phosphorus export to decrease if paired with a sound fertiliser management program that includes:

- soil and tissue testing
- phosphorus application at rates that maintain soil critical phosphorus values.

Low-water-soluble phosphorus fertilisers are not generally recommended for use on heavier soils such as loamy and clayey soils. This is because these soils usually have a large capacity to store phosphorus. Fertiliser management alone is recommended to reduce phosphorus export from these heavier soils.

Table 7.18: 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

*Data taken from Maddern 2016. All other data was taken from the Fertiliser Action Plan (Joint Government & Fertiliser Industry Working Party 2007)

Implementation

For this scenario we used the same modelling approach as the best-practice fertiliser management scenario, except that we included LWSP fertilisers on low-PRI soils. On high-PRI soils, the modelling (and results) are the same as for the previous scenario. On 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). The reduction in phosphorus export loads were:

- **Beef farms on low-PRI soils**: 44% reduction from farm fertiliser management plus **12%** reduction from replacing single superphosphate with LWSP fertiliser (total reduction of 56%).
- **Dairy farms on low-PRI soils**: 36% reduction from farm nutrient management plus **5%** reduction from replacing single superphosphate with LWSP fertiliser (total reduction of 41%).

See Appendix F for further information on the modelling approach and a review of the relevant literature.

This scenario models 100% adoption of best-practice fertiliser management on beef and dairy farms, with LWSP fertilisers being used on all low-PRI farm areas.

Results

Table 7.19 and Figure 7.13 give the estimated phosphorus load reduction from 100% adoption of best-practice fertiliser management with LWSP fertilisers applied to low-PRI soils. This scenario shows a reduction in phosphorus loading to the estuary of 39%, which is a further 7% reduction because of LWSP fertilisers being used rather than traditional phosphorus fertilisers. The Lower Murray was the only catchment that went below catchment targets with a 48% phosphorus load reduction (see Figure 7.13).

This scenario also achieved 48 to 49% phosphorus reductions in several other catchments – the Nambeelup, Coolup (Peel), Coolup (Harvey) and Mayfield Main Drain catchments.

Table 7.19: Phosphorus loads for the basecase and the LWSP fertiliser scenario

Reporting catchment	Basecase	Fertiliser management with LWSP fertilisers: 100% adoption by beef and dairy farms		
	P load (t/yr)	P load (t/yr)	Load change (t/yr)	(%)
Peel Main Drain	1.4	1.4	-0.05	-3.8
Upper Serpentine	10	8	-2.4	-24
Dirk Brook	2.8	1.9	-0.9	-33
Nambeelup	6.7	3.4	-3.3	-49
Mandurah	0.5	0.5	0.0	-
Lower Serpentine	2.1	1.5	-0.6	-29
Upper Murray	1.0	1.0	< -0.1	-0.1
Lower Murray	6.2	3.3	-3.0	-48
Coolup (Peel)	2.7	1.4	-1.4	-49
Coolup (Harvey)	2.1	1.1	-1.0	-48
Mayfield Drain	3.6	1.8	-1.8	-49
Harvey	20	11	-8.7	-43
Meredith Drain	1.0	0.7	-0.3	-33
Estuary coastal plain	**59**	**36**	**-23**	**-39**
Peel-Harvey estuary	**60**	**37**	**-23**	**-39**

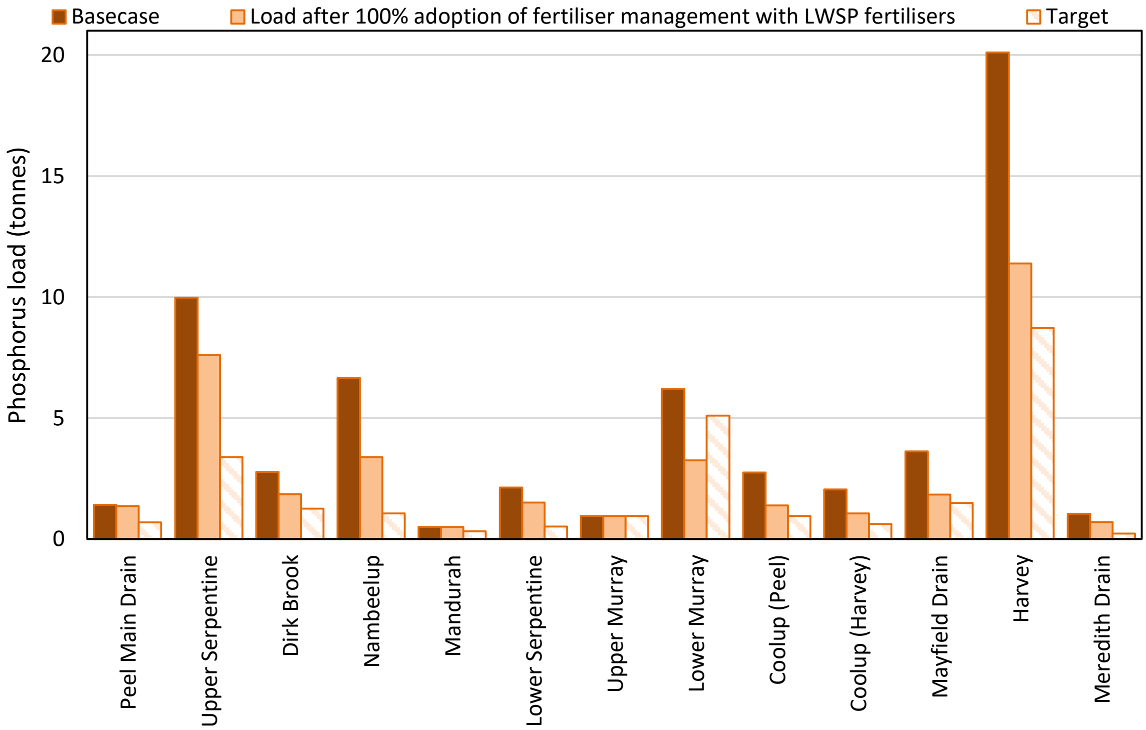


Figure 7.13: Phosphorus loads for the basecase and the LWSP fertiliser scenario

7.3.4 Dairy effluent management

Dairy farming in the Peel-Harvey catchment is an important industry for the region and the state. The environmental risks associated with dairy farms and dairy effluent management are a national and international issue. Environmental codes of practice and environmental guidelines exist in other Australian states (for example, NSW DPI 2008) and internationally (see Dairy NZ https://www.dairynz.co.nz/).

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 re-use of solid and liquid wastes (Dairy Australia 2008). The *Code of practice for dairy shed effluent Western Australia* (Western Dairy 2012) is the basis for this management action, given it sets out the expected minimum industry standards. 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. The code recognises benefits to the farmer, the dairy industry and the environment and is a cooperative venture between Dairy Australia, Western Dairy, the Government of Western Australia and GeoCatch.

The code of practice says:

1. **Effluent from diary sheds will be prevented from entering surface water or groundwater**
    - Dairy shed effluent will not be discharged into any river, creek, wetland or drain.
    - Dairy shed effluent will not be stored or discharged onto land where it is likely to enter any river, creek, wetland, drain, dam or groundwater.
    - Where there are waterways, wetlands or other sensitive water resources close to a dairy shed, vegetative buffers should be maintained and/or revegetated (where degraded) with native species sourced from local provenance.
2. **All dairy sheds will have effective effluent management systems**
    - Effluent management systems will collect, contain and re-use all effluent generated from dairy shed premises and adjoining stock-holding yards.
    - Any new effluent management systems or upgrades to existing systems will be designed by a suitably qualified specialist or practitioner with proven experience and knowledge.
    - A system should provide storage/treatment of effluent in suitably lined ponds for application at a suitable time.
    - It is recognised that even in well-designed systems there is potential for accidents (e.g. large rainfall events) that will lead to inadvertent runoff or spills.

- Dairy sheds will have contingency procedures in place to respond to emergencies that disrupt normal operation of the effluent management system.

3. **Effluent management systems will be monitored, maintained and reviewed regularly**
    - A maintenance program will be developed and followed to ensure the system operates effectively and efficiently.
    - Ongoing monitoring is required for all aspects of the effluent management system including structures, equipment and processes.
    - New technology (where appropriate) may be integrated into existing effluent management systems to improve practices.
    - If there is an increase in milking herd numbers or in the amount of organic material collected, a review of the effluent system will occur to ensure the system copes with increased volumes of effluent.
4. **All dairies will maximise water-use efficiency**
    - Dairy sheds will undertake operations to minimise water use and the generation of wastewater.
    - Where practical washdown water will be re-used.
    - All uncontaminated stormwater collected from the dairy shed roof (and where possible also the areas/yards surrounding the shed) will be diverted away from the effluent system.
5. **Dairy shed effluent will be re-used on-farm**
    - Effluent re-use should be undertaken at controlled rates to minimise any leaching into groundwater systems.
    - Regular soil testing will be undertaken at application sites to monitor soil health and nutrient requirements and to prevent excessive nutrient build-up.
    - Sensitive areas such as waterways, drainage lines and property boundaries will be avoided when applying effluent.
    - At least a two-week grazing withholding period is often recommended after effluent has been applied to pastures. The *Effluent and manure management database for the Australian dairy industry* (Dairy Australia 2008) discusses circumstances where longer withholding periods may be required.

Improved dairy effluent management typically requires substantial initial investment, ongoing costs and farmer commitment. However, investments in effluent capture, storage and re-use infrastructure can reduce fertiliser use and therefore nutrient losses to the environment.

Existing dairy effluent management practices

Several dairy farms were surveyed about their effluent management practices as part of the REI and compared with criteria in the *Code of practice for dairy shed effluent Western Australia* (see Appendix F). Of the dairies surveyed, nine were in the Peel-Harvey and one was in the Harvey Diversion Drain catchment (see Table 7.20). Most farms scored low to medium for the five management areas and only one farm met all criteria for pond and effluent application.

A previous survey of agricultural best-management practice adoption in the Peel-Harvey catchment (Lavell et al. 2004) found:

- 80% of enterprises that produced effluent had management systems which included ponds, tanks, land application and spray irrigation.
- The efficacy of management systems varied and one-third of respondents directly discharged effluent to waterways and a further third indicated that effluent ponds leaked or overflowed.

No information was given about the rate of effluent irrigation or nutrient loading to pastures.

Table 7.20: Results of a recent dairy survey in the Peel-Harvey catchment

Farm ID	Reporting Catchment	Cows (2017)	Dairy water efficiency maximisation	Solid separation	Pond (storage)	Application of effluent	Management Maintenance
1	Lower Murray	50	Medium	Medium	Low	Low	High
2	Coolup (Peel)	400	Medium	Medium	Medium	Low	Low
3	Harvey	400	Medium	High	Medium	Medium	Medium
4	Harvey	170	Medium	Medium	Low	Medium	Medium
5	Harvey	180	Medium	Medium	High	High	High
6	Harvey Diverson Drain	230	Medium	Medium	Medium	High	High
7	Harvey	260	Medium	High	Medium	Low	Medium
8	Harvey		Medium	High	Low	Low	Medium
9	Harvey	250	Medium	Medium	High	Medium	Medium
10	Upper Serpentine	300	Medium	High	Medium	Low	Medium

Assessment score
High: Meets industry standards in Code of Practice
Medium: Partially meets industry standards in Code of
Low: Does not meet industry standards in Code of Practice

Implementation

This scenario considers water quality improvement as a result of improved dairy effluent management. Ideally we would be able to use Overseer or something similar to model the effect of improved dairy management practices. Unfortunately Overseer assumes that dairy effluent management is done according to best practice. 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 have relied on a review of the relevant literature and made assumptions about the efficacy of improved dairy effluent management (see Appendix F).

On average, improved dairy effluent management is expected to reduce **dairy shed nitrogen and phosphorus exports by 60%.** Dairy sheds contribute 3 to 31% of all dairy farm nitrogen emissions and 8 to 63% of all dairy farm phosphorus emissions. This scenario assumes improved dairy effluent management in all 25 dairies in the Peel-Harvey catchment (nine surveyed farms plus 16 farms not surveyed).

Results

Improved dairy effluent management with 100% adoption has the potential to decrease the nitrogen and phosphorus loads to the estuary by 2.3 and 1.0 tonnes/yr respectively (see Table 7.21; Table 7.22). Figure 7.14 shows the catchment basecase and dairy effluent management scenario average annual loads. We found that improved dairy effluent management would reduce reporting catchment nutrient loads by less than 1% for nitrogen and 0.2 to 3.3% for phosphorus.

Dairy farming in the Peel-Harvey is less prevalent than in some other catchments. For example, the Peel-Harvey catchment has 25 dairy farms with a total of 5,770 dairy cattle, whereas the Geographe catchment has 36 dairy farms with a total of 15,120 dairy cattle. Despite the industry's smaller size, dairy effluent management is important. It provides benefits at the local scale, and will contribute to overall nutrient load reduction to the Peel-Harvey estuary.

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

Reporting catchment	Basecase					Dairy effluent management: 100% adoption		
	Dairies	Dairy shed N load	Dairy Paddock N load	Total dairy N load	Catchment N load	Catchment N load	Load change	
	(#)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(%)
Peel Main Drain	-	-	-	-	12	12	-	-
Upper Serpentine	4	0.7	1.6	2.3	72	71	-0.4	-0.6
Dirk Brook	1	0.1	2.8	2.9	29	29	-0.1	-0.2
Nambeelup	2	0.5	5.5	5.9	40	40	-0.3	-0.7
Mandurah	-	-	-	-	5.0	5.0	-	-
Lower Serpentine	-	-	-	-	12	12	-	-
Upper Murray	-	-	-	-	80	80	-	-
Lower Murray	2	0.1	0.4	0.5	103	103	0.0	0.0
Coolup (Peel)	1	0.2	0.7	0.9	21	21	-0.1	-0.7
Coolup (Harvey)	1	0.2	1.1	1.3	13	13	-0.1	-0.9
Mayfield Drain	2	0.2	1.3	1.5	33	33	-0.1	-0.4
Harvey	12	1.9	21	23	205	204	-1.1	-0.5
Meredith Drain	-	-	-	-	6.7	6.7	-	-
Estuary coastal plain	**25**	**3.8**	**34**	**38**	**633**	**630**	**-2.3**	**-0.4**
Peel-Harvey estuary	**25**	**3.8**	**34**	**38**	**633**	**630**	**-2.3**	**-0.4**

Table 7.22: Average annual phosphorus loads for the basecase and the dairy effluent management scenario

Reporting catchment	Basecase					Dairy effluent management: 100% adoption		
	Dairies	Dairy shed P load	Dairy Paddock P load	Total dairy P load	Catchment P load	Catchment P load	Load change	
	(#)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(t/yr)	(%)
Peel Main Drain	-	-	-	-	1.4	1.4	-	-
Upper Serpentine	4	0.2	0.2	0.5	10	9.8	-0.1	-1.4
Dirk Brook	1	0.0	0.1	0.1	2.8	2.8	0.0	-0.7
Nambeelup	2	0.1	1.0	1.1	6.7	6.6	-0.1	-0.8
Mandurah	-	-	-	-	0.5	0.5	-	-
Lower Serpentine	-	-	-	-	2.1	2.1	-	-
Upper Murray	-	-	-	-	1.0	1.0	-	-
Lower Murray	2	0.0	0.0	0.0	6.2	6.2	0.0	-0.2
Coolup (Peel)	1	0.1	0.1	0.2	2.7	2.7	0.0	-1.7
Coolup (Harvey)	1	0.1	0.1	0.2	2.1	2.0	0.0	-1.9
Mayfield Drain	2	0.1	0.1	0.2	3.6	3.6	0.0	-1.3
Harvey	12	1.1	0.9	2.1	20	19	-0.7	-3.3
Meredith Drain	-	-	-	-	1.0	1.0	-	-
Estuary coastal plain	**25**	**1.7**	**2.6**	**4.3**	**60.2**	**59**	**-1.0**	**-1.7**
Peel-Harvey estuary	**25**	**1.7**	**2.6**	**4.3**	**60.2**	**59**	**-1.0**	**-1.7**

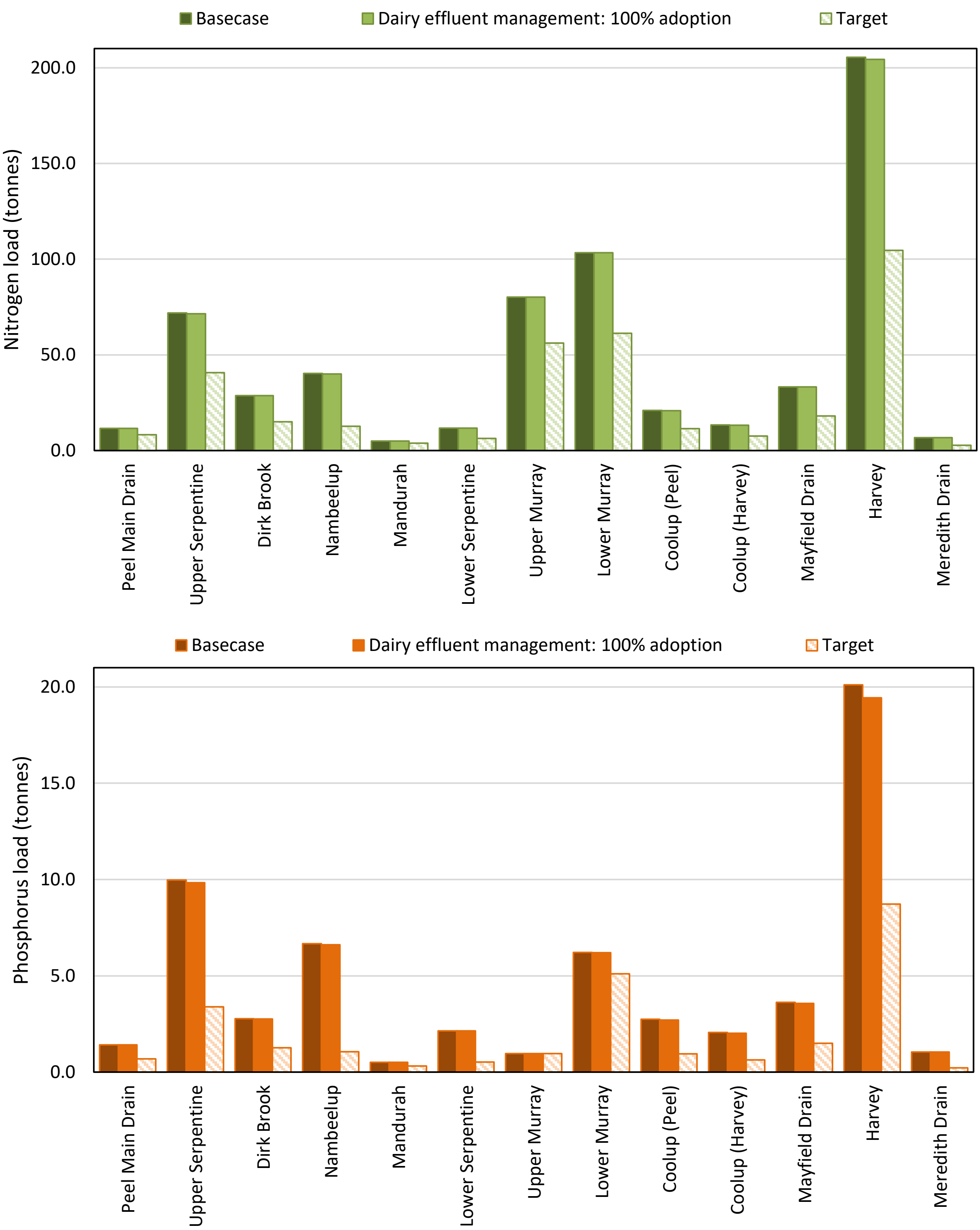


Figure 7.14: Average annual nitrogen and phosphorus loads for the basecase and the dairy effluent management scenario

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 soil amendments that bind with 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 significantly reduce phosphorus loss, and 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 IronMan Gypsum (IMG). However, reworked onsite clays (i.e. mixing subsoil clays with sandy topsoils) and bentonite have been more recently investigated. These products are discussed below.

IMG is a residue from mineral-sands processing and has previously been referred to as neutralised unused acid (NUA). The residue is formed through the chemical refinement of ilmenite ($FeTiO_3$) into rutile (TIO_3). The refinement process uses sulfuric acid (H_2SO_4), which is later neutralised with lime (CaO) post-refinement. The resulting residue is mostly comprised of gypsum ($CaSO_4$) but also contains iron and manganese. An estimated 450,000 tonnes of IMG is stockpiled at the Capel refinery, which has an annual production rate of 40,000 tonnes (Degens pers. comm. 2020).

The properties of IMG (and other materials such as Red Sands™ and Alkaloam®) have been investigated using column trials and leachate toxicity tests (Wending et al. 2009; Wendling et al. 2010). The laboratory studies (column trials) found that IMG reduced phosphate and total phosphorus concentrations in leachate by more than 99% and total nitrogen concentrations by 61% over a 373-day period (Wendling et al. 2010). Field trials of IMG applications at a turf farm, which used a rate of 150 tonnes/ha, found that leaching of phosphate, ammonium and nitrate reduced by 97%, 82% and 40% respectively over four years (Douglas et al. 2010). Laboratory testing found that IMG had low environmental toxicity and radioactivity that was comparable to concrete and clay bricks (Wendling et al. 2009). Measured radioactivity dose rates of IMG blended with topsoil were about half that of guideline values (Douglas et al. 2010). A radiological assessment by the ChemCentre (2018) found that IMG and Alkaloam® complied with the *Radiation Safety Act 1975* (WA).

IMG, as well as Alkaloam® and lime amended biosolids (LABC), were investigated using plot-scale top-dress trials on pasture in Ellen Brook. IMG applications of 2 to 50 tonnes/ha were tested and the total phosphorus in leachate was reduced by up to 90% (ChemCentre 2018). No significant attenuation of nitrogen leaching was observed in IMG-treated plots. However the IMG plots (and Alkaloam® and LABC plots) did not initially leach nitrogen.

In urban drainage applications IMG has been found to reduce phosphate concentrations in subsurface drains (Degens & Shackleton 2016).

In the 1980s Alkaloam® (also known as Red Mud™), a residue from bauxite processing, was suggested for use as soil-amendment material for reducing phosphorus leaching from sandy agricultural soils (Barrow 1982). Residue stockpiles consist of about equal proportions of Alkaloam® (a finer textured material) and Red Sand™ (a coarser, more sandy textured material).

Initial field trials demonstrated the effectiveness of Alkaloam® at reducing phosphorus leachate, but used large application rates of soil amendment (0–2,000 tonnes/ha) and phosphorus fertiliser (0–270 kg P/ha/yr) (Vlahos et al. 1989).

These studies led to the first major catchment-scale intervention in the Meredith Drain catchment. In 1991 about 1,400 ha of a total of 4,300 ha of agricultural land was amended with Alkaloam® at rates of 20 tonnes/ha. A catchment-scale water quality response was observed, with phosphate concentrations dropping 67% (from 0.7 to 0.23 mg/L) from 1991 to 2000 (Figure 7.15). Field trials and laboratory studies continued:

- Summers et al. 1996 investigated plot-scale phosphorus leaching in response to 0 to 80 tonnes/ha Alkaloam® applications. A 20-tonne/ha application reduced phosphate leachate by about 60%, while increasing PRI from 0 to 2, soil pH from ~4.0 to 5.5, Colwell P from ~3 to 15 mg/kg and total soil phosphorus from 20 to 60 mg/kg. The 5 and 10 tonne/ha applications reduced phosphate leaching by ~37% and ~53% respectively.
- The effects of Alkaloam® application rate and phosphorus fertiliser application rate on pasture yields and soil properties were investigated (Summers et al. 2001). Alkaloam® applications of 20 tonnes/ha had greater pasture yields than the unamended plots for the same phosphorus application.

However later work by Wendling et al. (2009) investigated the environmental toxicity of a number of soil-amendment materials, including Alkaloam®, Red Sand™, reduced Red Sand™ and IMG. Of the three environmental toxicity tests undertaken, Alkaloam® had high toxicity for two tests and low toxicity for the third. Red Sand™ and IMG had low environmental toxicity for all three tests and reduced Red Sand™ did not demonstrate any environmental toxicity.

Summers et al. (2019) recently investigated the effect of reworking subsoil clays into sandy topsoils. The pasture response and phosphorus content in soil solution were 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%. The addition of 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%.

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 typically much more expensive than the other amendments mentioned in this section.

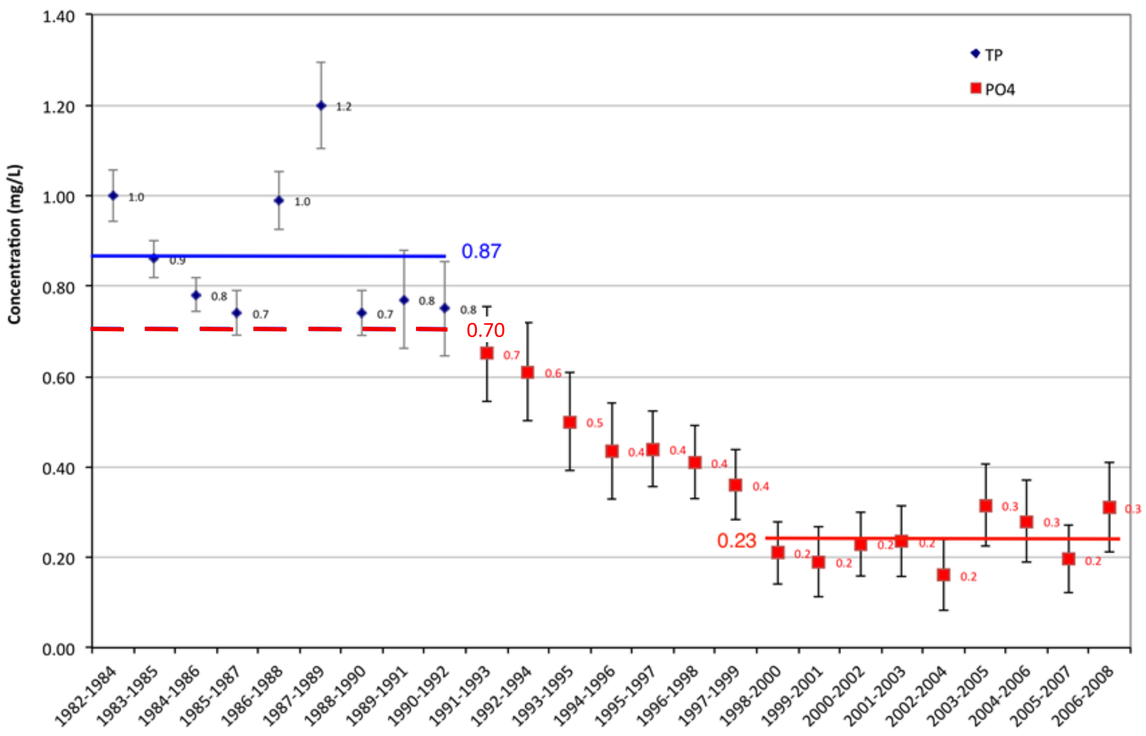


Figure 7.15: Three-year median TP and PO_4 concentrations at Johnston Road – Meredith drain (613053) for 1982–2008

Implementation

To model this scenario, we applied soil amendments to all beef and dairy farms with low-PRI soils at rates of 20 tonnes/ha. This equates to about 1 million tonnes of soil amendment applied to a 502 km^2 area. We assumed a 20 tonne/ha amendment would reduce phosphorus export by 60%, based on IMG and Alkaloam® experiments. We assumed nitrogen would be unaffected by soil amendments. Although IMG was found to attenuate nitrogen in some studies (Wendling et al. 2010; Douglas et al. 2010), this was not replicated convincingly in other studies (ChemCentre 2018).

Results

Table 7.23 and Figure 7.16 give the basecase and scenario phosphorus loads for catchments draining to the Peel-Harvey estuary. If soil amendments were applied to all low-PRI beef and dairy areas, phosphorus loading to the estuary would reduce by about 21 tonnes (35% reduction). This scenario reduced phosphorus loading in the Lower Murray catchment below the catchment target (Figure 7.16). However this action alone did not meet the phosphorus load target in other catchments.

The Nambeelup catchment had a large reduction in phosphorus load (3.6 tonnes or a 54% reduction), along with the Coolup and Lower Murray catchments (41–49% reductions). All other catchments had reductions of 22 to 35%, except for the Peel Main Drain which had a small area of low-PRI beef and dairy land uses. The Upper Murray and Mandurah catchments were unaffected by this scenario as these catchments did not have any low-PRI beef and dairy land uses.

Table 7.23: Phosphorus loads for the basecase and the soil-amendment scenario

	Basecase				Soil amendments: 100% adoption on low PRI beef and dairy farms		
Reporting catchment	**Low PRI beef and dairy**			**Catchment P load**	**Catchment P load**	**P load change**	
	Area	**P load**					
	(km²)	(t/yr)	(%)	(t/yr)	(t/yr)	(t/yr)	(%)
Peel Main Drain	1.9	0.1	4	1.4	1.4	-0.03	-2
Upper Serpentine	54	3.7	37	10	7.8	-2.2	-22
Dirk Brook	27	1.5	53	2.8	1.9	-0.9	-32
Nambeelup	83	6.0	90	6.7	3.0	-3.6	-54
Mandurah	-	-	-	0.5	0.5	-	-
Lower Serpentine	24	1.1	52	2.1	1.5	-0.7	-31
Upper Murray	-	-	-	1.0	1.0	-	-
Lower Murray	100	4.3	69	6.2	3.7	-2.6	-41
Coolup (Peel)	51	2.1	78	2.7	1.5	-1.3	-47
Coolup (Harvey)	36	1.7	82	2.1	1.0	-1.0	-49
Mayfield Drain	30	2.7	74	3.6	2.0	-1.6	-44
Harvey	76	11	56	20	13	-6.7	-33
Meredith Drain	20	0.6	58	1.0	0.7	-0.4	-35
Estuary coastal plain	**502**	**35**	**58**	**59**	**38**	**-21**	**-35**
Peel-Harvey estuary	**502**	**35**	**58**	**60**	**39**	**-21**	**-35**

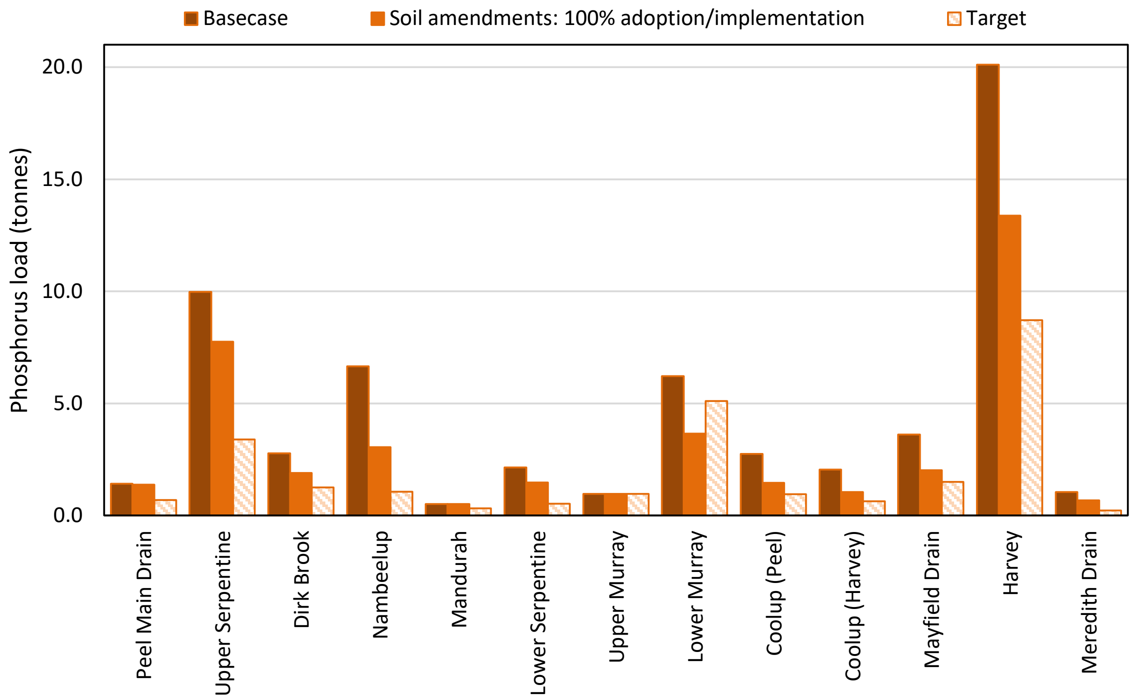


Figure 7.16: Phosphorus loads for the basecase and the soil-amendment scenario

7.3.6 Intensive nutrient sources (point sources)

The intent of this scenario is to highlight the nutrient contribution of point and other intensive sources, and identify catchments where detailed investigation would be beneficial. We consider the nutrient emissions from 50 intensive facilities and 16 km^2 of intensive horticulture in this scenario. We report results for:

> **Intensive animal industries:** piggeries, abattoirs, feedlots, stockyards and poultry.
>
> **Intensive horticulture:** annual horticulture and turf farms.
>
> **All intensive sources:** includes the animal industries and intensive horticulture described above and two other industries (a beverage-making and a composting facility).

See the basecase nutrient emissions from these intensive sources by catchment in Table 7.24 for nitrogen and Table 7.25 for phosphorus.

We consider other point sources – wastewater treatment plants and septic tanks – in sections 7.3.7 and 7.3.8 respectively.

Table 7.24: Basecase average annual nitrogen loads from intensive nutrient sources

Reporting catchment	Basecase catchment N load	Basecase N load													
		Other industries		Feedlots & stockyards		Piggeries & abattoirs		Poultry		In-ground horticulture		Turf farm		All intensive sources	
	(t/yr)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)
Peel Main Drain	12	-	-	0.5	4.6	-	-	0.4	3.2	0.2	2.1	0.0	<0.1	1.2	10.0
Upper Serpentine	72	0.3	0.5	5.4	7.6	0.2	0.3	3.5	4.9	1.1	1.5	0.0	<0.1	10.6	14.8
Dirk Brook	29	-	-	0.2	0.6	0.4	1.5	3.7	13.0	0.2	0.6	0.4	1.3	4.9	17.0
Nambeelup	40	-	-	0.2	0.4	0.0	<0.1	-	-	0.0	<0.1	-	-	0.2	0.5
Mandurah	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lower Serpentine	12	-	-	-	-	0.8	6.8	0.1	1.1	0.0	0.2	-	-	1.0	8.1
Upper Murray	80	-	-	0.1	0.1	0.1	0.1	0.005	<0.1	0.1	<0.1	-	-	0.3	0.3
Lower Murray	103	-	-	0.1	0.1	-	-	6.8	6.6	0.1	<0.1	-	-	7.0	6.8
Coolup (Peel)	21	-	-	0.1	0.3	0.1	0.4	-	-	-	-	-	-	0.1	0.7
Coolup (Harvey)	13	-	-	-	-	0.1	0.4	-	-	0.0	0.1	0.1	0.4	0.1	1.0
Mayfield Drain	33	-	-	0.1	0.2	-	-	-	-	0.0	<0.1	-	-	0.1	0.3
Harvey	205	0.6	0.3	0.2	<0.1	-	-	-	-	0.4	0.2	-	-	1.2	0.6
Meredith Drain	7	-	-	-	-	0.9	13.5	-	-	0.0	0.2	-	-	0.9	13.7
Estuary coastal plain	**552**	**0.9**	**0.2**	**6.8**	**1.2**	**2.5**	**0.5**	**14.6**	**2.6**	**2.1**	**0.4**	**0.5**	**<0.1**	**27.4**	**5.0**
Peel-Harvey estuary	**633**	**0.9**	**0.1**	**6.8**	**1.1**	**2.6**	**0.4**	**14.6**	**2.3**	**2.2**	**0.3**	**0.5**	**<0.1**	**27.6**	**4.4**

Note: All percentages are the proportion of intensive source load to catchment load

Table 7.25: Basecase average annual phosphorus loads from intensive nutrient sources

Reporting catchment	Basecase catchment P load	Basecase P load													
		Other industries		Feedlots & stockyards		Piggeries & abattoirs		Poultry		In-ground horticulture		Turf farm		All intensive sources	
	(t/yr)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)
Peel Main Drain	1.4	-	-	0.02	1.4	-	-	0.01	0.4	0.68	48.1	0.001	<0.1	0.71	49.9
Upper Serpentine	10.0	0.05	0.5	0.15	1.5	0.01	0.1	0.11	1.1	2.00	20.1	0.01	<0.1	2.33	23.4
Dirk Brook	2.8	-	-	0.02	0.5	0.12	4.4	0.08	2.9	0.16	5.9	0.14	4.9	0.52	18.6
Nambeelup	6.7	-	-	0.02	0.3	0.01	0.1	-	-	0.02	0.4	-	-	0.05	0.7
Mandurah	0.5	-	-	-	-	-	-	-	-	-	-	-	-	0.00	<0.1
Lower Serpentine	2.1	-	-	-	-	0.19	8.9	0.00	0.2	0.07	3.3	-	-	0.27	12.4
Upper Murray	1.0	-	-	0.001	<0.1	0.003	0.3	-	-	0.02	1.9	-	-	0.02	2.3
Lower Murray	6.2	-	-	0.01	0.2	-	-	0.05	0.8	0.20	3.2	-	-	0.26	4.1
Coolup (Peel)	2.7	-	-	0.01	0.3	0.02	0.7	-	-	-	-	-	-	0.03	1.0
Coolup (Harvey)	2.1	-	-	-	-	0.02	1.1	-	-	0.07	3.3	0.02	0.9	0.11	5.3
Mayfield Drain	3.6	-	-	0.001	<0.1	-	-	-	-	0.08	2.3	-	-	0.08	2.3
Harvey	20.1	0.52	2.6	0.03	0.1	-	-	-	-	0.21	1.1	-	-	0.76	3.8
Meredith Drain	1.0	-	-	-	-	0.18	16.8	-	-	0.03	3.2	-	-	0.21	20.0
Estuary coastal plain	**59.3**	**0.57**	**1.0**	**0.25**	**0.4**	**0.55**	**0.9**	**0.25**	**0.4**	**3.54**	**6.0**	**0.16**	**0.3**	**5.32**	**9.0**
Peel-Harvey estuary	**60.2**	**0.57**	**0.9**	**0.25**	**0.4**	**0.55**	**0.9**	**0.25**	**0.4**	**3.56**	**5.9**	**0.16**	**0.3**	**5.34**	**8.9**

Note: All percentages are the proportion of intensive source load to catchment load

State and national environmental guidelines and codes of practice have been developed for most of the industries listed above. These standards help them to design and manage their operations to reduce environmental impacts. Nevertheless, the standards may be insufficient in very sensitive environments, including some areas of the Peel-Harvey catchment. In these locations land-use planning controls must guide the appropriate location of intensive industries. See below for some relevant guidelines and documents.

The Department of Water and Environmental Regulation regulates environmental discharge. See our website for more information and guidelines and guidance statements.

Piggeries:

- *Western Australian guidelines for new and existing piggeries* (Latto et al. 2000)
- National environmental guidelines for indoor (Tucker 2018) and outdoor (Tucker et al. 2011) piggeries (http://australianpork.com.au/industry-focus/environment/national-environmental-guidelines-for-piggeries/)

Abattoirs:

- Environmental code of practice: Environmental Protection (Abattoirs) Regulations 2001
- *Rural abattoirs, Water quality protection note (WQPN) no. 98* (DoW 2007)

Feedlots & stockyards:

- *National guidelines for beef cattle feedlots in Australia* (Meat & Livestock Australia 2012a; Meat & Livestock 2011)
- *National environmental code of practice* (Meat & Livestock Australia 2012b)
- *Western Australian environmental guidelines* (Department of Agriculture 2004)

Poultry:

- *Western Australian environmental code of practice* (Department of Environment 2004)
- *National environmental guidelines for the egg industry* (McGahan et al. 2018)

Intensive horticulture:

- *Horticulture in the Peel-Harvey: a guide for investors and growers* (Peel-Harvey Catchment Council 2017)
- *Guidelines for environmental assurance in Australian horticulture* (Horticulture for Tomorrow 2014)

Wastewater irrigation:

- *Technical guidelines for the disposal of effluent using irrigation* (Tennakoon & Ramsay 2020)

Implementation

We used a simplistic modelling approach to represent the effect of intensive point source management. In reality, in very sensitive environments, it is impossible to reduce nutrient pollution from some intensive land uses to acceptable levels. In these environments the 95% reduction in nutrient exports from intensive industries discussed below may be unachievable and, even if they were achieved, might still be unacceptable. See Section 6 for more information about catchment nutrient input targets.

These scenarios assume that nutrient emissions from intensive sources would reduce by 95%. Yet we acknowledge that this modelling approach would not apply to some industries, such as in-ground horticulture and turf farms. However, nutrient reductions of this order of magnitude are mentioned in the guidelines and documents above. For example:

- The *National guidelines for beef cattle feedlots* specifies that effluent evaporation ponds should have an average spill frequency that is no greater than once every 20 years.
- The technical guidelines for effluent irrigation (Tennakoon & Ramsay 2020) typically require 95% of all effluent to be stored and available for re-use, with a 5% allowance for environmental releases because of extreme weather events and/or infiltration.

In these scenarios, we consider the 5% of basecase nutrient emissions emitted to surface water to represent accidental emissions due to unexpected equipment failure or unavoidable emissions due to extreme meteorological events. That is, these scenarios assume near-zero nutrient emissions from intensive sources under normal operating conditions. We do not explicitly define or model the management actions required to achieve a 95% reduction in nutrient export.

Results

See the catchment nutrient load reductions for this scenario in Table 7.26 for nitrogen and Table 7.27 for phosphorus. The scenario that affected all intensive sources reduced nutrient loads to the estuary by 26 tonnes (4%) for nitrogen and 5 tonnes (8%) for phosphorus. For intensive animal industries only, the load reduction was 23 tonnes (3.6%) for nitrogen and 1.0 tonnes (1.6%) for phosphorus, and for intensive horticulture only, the load reduction was

2.5 tonnes (0.4%) for nitrogen and 3.5 tonnes (5.9%) for phosphorus. These load reductions are significant and demonstrate the need to manage these nutrient sources appropriately.

The catchments that would benefit the most from future management were the Peel Main Drain, Upper Serpentine, Dirk Brook, Lower Serpentine, Lower Murray and Meredith Drain. These catchments had nutrient reductions that were greater than 5%.

Most of the nutrient emissions from intensive sources were from poultry farms, feedlots & stockyards and horticulture (see Table 7.24 and Table 7.25). However, in the Lower Serpentine and Meredith Drain catchments, piggeries contributed the largest proportion of nutrient load of all intensive source types. In Meredith Drain, we estimated a single piggery contributed 13% of the nitrogen load and 17% of the phosphorus load. Thus, further investigation and potential management actions should be a priority for this site.

Table 7.26: Nitrogen loads for the basecase and the intensive nutrient sources scenarios

		Intensive animal industries			Intensive horticulture			All intensive sources		
Reporting catchment	**Basecase catchment N load**	**Catchment N load**	**N load change**		**Catchment N load**	**N load change**		**Catchment N load**	**N load change**	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Peel Main Drain	12	11	-0.9	-7.4	11	-0.2	-2.1	10	-1.1	-9.5
Upper Serpentine	72	63	-8.7	-12	71	-1.0	-1.4	62	-10.1	-14
Dirk Brook	29	25	-4.1	-14	28	-0.5	-1.9	24	-4.7	-16
Nambeelup	40	40	-0.2	-0.5	40	-0.01	-0.02	40	-0.2	-0.5
Mandurah	5	5	-	-	5	-	-	5	-	-
Lower Serpentine	12	11	-0.9	-7.5	12	-0.02	-0.2	11	-0.9	-7.7
Upper Murray	80	80	-0.2	-0.2	80	-0.1	-0.1	80	-0.3	-0.3
Lower Murray	103	97	-6.6	-6.4	103	-0.1	-0.1	97	-6.7	-6.4
Coolup (Peel)	21	21	-0.1	-0.6	21	-	-	21	-0.1	-0.6
Coolup (Harvey)	13	13	-0.1	-0.4	13	-0.1	-0.5	13	-0.1	-0.9
Mayfield Drain	33	33	-0.1	-0.2	33	-0.02	-0.1	33	-0.1	-0.3
Harvey	205	205	-0.2	-0.1	205	-0.4	-0.2	204	-1.2	-0.6
Meredith Drain	7	6	-0.9	-13	7	-0.01	-0.2	6	-0.9	-13
Estuary coastal plain	**552**	**530**	**-23**	**-4.1**	**550**	**-2.5**	**-0.4**	**526**	**-26**	**-4.7**
Peel-Harvey estuary	**633**	**610**	**-23**	**-3.6**	**630**	**-2.5**	**-0.4**	**606**	**-26**	**-4.1**

Table 7.27: Phosphorus loads for the basecase and the intensive nutrient sources scenarios

Reporting catchment	Basecase catchment P load	Intensive animal industries			Intensive horticulture			All intensive sources		
		Catchment P load	P load change		Catchment P load	P load change		Catchment P load	P load change	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Peel Main Drain	1.4	1.4	-0.02	-2	0.8	-0.65	-46	0.7	-0.67	-47
Upper Serpentine	10.0	9.7	-0.26	-3	8.1	-1.91	-19	7.8	-2.21	-22
Dirk Brook	2.8	2.6	-0.20	-7	2.5	-0.29	-10	2.3	-0.49	-18
Nambeelup	6.7	6.6	-0.02	-0.3	6.6	-0.02	-0.3	6.6	-0.05	-0.7
Mandurah	0.5	0.5	-	-	0.5	-	-	0.5	-	-
Lower Serpentine	2.1	2.0	-0.19	-8.7	2.1	-0.07	-3.1	1.9	-0.25	-12
Upper Murray	1.0	1.0	-0.003	-0.3	0.9	-0.02	-1.8	0.9	-0.02	-2.2
Lower Murray	6.2	6.2	-0.05	-0.9	6.0	-0.19	-3.1	6.0	-0.24	-3.9
Coolup (Peel)	2.7	2.7	-0.03	-0.9	2.7	-	-	2.7	-0.03	-0.9
Coolup (Harvey)	2.1	2.0	-0.02	-1.1	2.0	-0.08	-4.0	1.9	-0.10	-5.1
Mayfield Drain	3.6	3.6	-0.001	0.0	3.5	-0.08	-2.2	3.5	-0.08	-2.2
Harvey	20.1	20	-0.03	-0.1	20	-0.20	-1.0	19	-0.72	-3.6
Meredith Drain	1.0	0.9	-0.17	-16	1.0	-0.03	-3.0	0.8	-0.20	-19
Estuary coastal plain	**59.3**	**58**	**-1.0**	**-1.7**	**56**	**-3.5**	**-5.9**	**54**	**-5.0**	**-8.5**
Peel-Harvey estuary	**60.2**	**59**	**-1.0**	**-1.6**	**57**	**-3.5**	**-5.9**	**55**	**-5.1**	**-8.4**

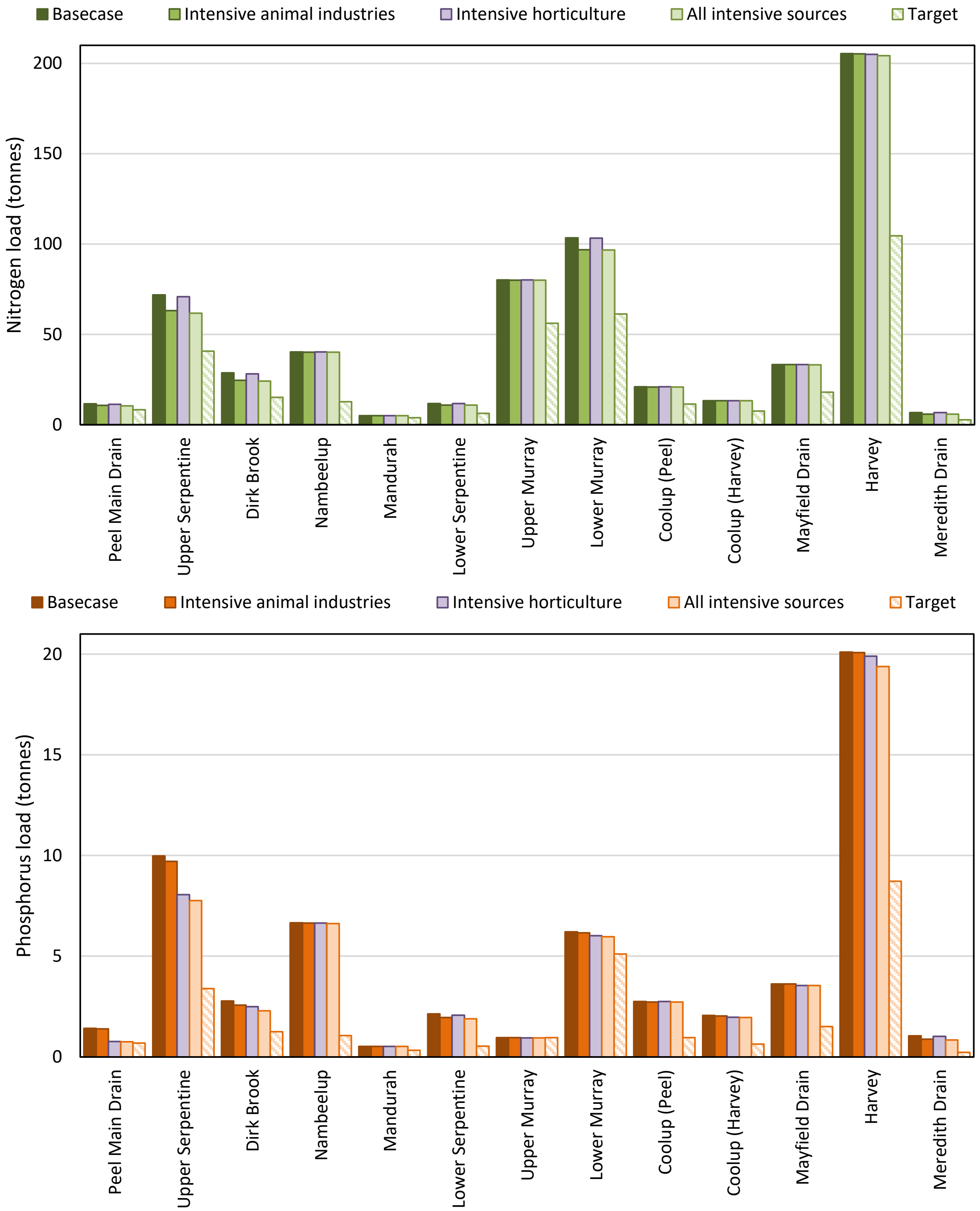


Figure 7.17: Nitrogen and phosphorus loads for the basecase and the intensive nutrient sources scenarios

7.3.7 Wastewater treatment plant (WWTP) management

We assumed the following WWTPs emitted nutrients to Peel-Harvey catchments in the basecase model:

- **Waroona:** located in the Harvey catchment. Discharges treated wastewater to a clay-lined treatment swale or a woodlot before direct or indirect discharge to Drakesbrook Drain. Currently treats about 100 ML/yr of wastewater.
- **Kwinana:** located in Coastal North catchment but contributes nutrients to the Spectacles wetlands (Peel Main Drain) via groundwater discharge. Currently treats 2,050 ML/yr of wastewater.
- **Williams:** located in the Upper Murray catchment. Detains and re-uses treated wastewater on public open space in the town. (This WWTP was built to replace the old Williams WWTP which was decommissioned in 2012. By 2015 the new WWTP began operations and treated wastewater was used to irrigate about 4 ha of public open space. We estimated and included the nutrient contributions from the old Williams WWTP in the model. We assumed the new Williams WWTP had no nutrient discharge in the model.) Currently treats 36 ML/yr of wastewater.

We did not include the following WWTPs in the basecase model, but they are currently operating in the Peel-Harvey or could contribute nutrients to the estuary:

- **Gordon Road:** located in the Coastal North catchment. Treated wastewater is infiltrated onsite and can flow to Goegrup Lake (Serpentine River). However, the nutrient loading to Goegrup Lake is unknown. Thus, we did not include nutrient emissions from the Gordon Road WWTP in this model. Currently treats about 3,750 ML/yr of wastewater.
- **Halls Head WWTP (Mandurah no. 2):** located in the Coastal Central catchment. All treated wastewater is infiltrated onsite. We assumed this WWTP did not contribute nutrients to the estuary in this model. Currently treats about 1,200 ML/yr of wastewater.
- **Pinjarra:** sends all treated wastewater to the Alcoa Refinery for industrial re-use. We assumed this WWTP did not contribute nutrients to the Peel-Harvey catchment in this model. Currently treats about 350 ML/yr of wastewater.
- **Boddington:** located in the Upper Murray catchment and sends treated wastewater to the Boddington Gold Mine for industrial re-use. We assumed this WWTP did not contribute nutrients to the Peel-Harvey catchment in this model. Currently treats about 56 ML/yr of wastewater.

See Appendix C for all the WWTPs identified in the model domain and our modelling assumptions.

Implementation

This scenario includes the effect of improved wastewater treatment at the Waroona WWTP. The Waroona WWTP discharges to the Drakesbrook Drain. In 2014, the PHCC, the Water Corporation and this department funded and implemented a nutrient stripping swale. The swale was observed to reduce the nutrient concentrations in discharge after the trial’s first year. The long-term effectiveness of this treatment system is not known. However, for this scenario, we assumed the effectiveness of the trial's first year endured as a result of careful maintenance and management. We estimated a nitrogen load reduction of 30% and phosphorus load reduction of 50% at the Waroona WWTP.

We also took into account the nutrient emissions after decommissioning of the old Williams WWTP. We did not model improvements to the Kwinana WWTP in this scenario.

Results

Table 7.28 gives the estimated nutrient load reduction from the WWTP management scenario. We estimated that loads to the estuary reduced by 1 tonne (0.2%) for nitrogen and 0.1 tonnes (0.2%) for phosphorus. The only catchments affected are Harvey (Waroona WWTP) and Upper Murray (old Williams WWTP).

Table 7.28: Nitrogen and phosphorus loads for the basecase and the WWTP management scenario

Reporting catchment	Nitrogen					Phosphorus				
	Basecase		WWTP management			Basecase		WWTP management		
	WWTP N load (t/yr)	Catchment N load (t/yr)	Catchment N load (t/yr)	N load change (t/yr)	N load change (%)	WWTP P load (t/yr)	Catchment P load (t/yr)	Catchment P load (t/yr)	P load change (t/yr)	P load change (%)
Peel Main Drain	1.4	11.6	11.6	-	-	0.03	1.4	1.4	-	-
Upper Serpentine	-	71.8	71.8	-	-	-	10.0	10.0	-	-
Dirk Brook	-	28.7	28.7	-	-	-	2.8	2.8	-	-
Nambeelup	-	40.3	40.3	-	-	-	6.7	6.7	-	-
Mandurah	-	5.0	5.0	-	-	-	0.5	0.5	-	-
Lower Serpentine	-	11.7	11.7	-	-	-	2.1	2.1	-	-
Upper Murray	0.14	80.2	80.1	-0.14	-0.2	0.04	1.0	0.9	-0.04	-4.3
Lower Murray	-	103.4	103.4	-	-	-	6.2	6.2	-	-
Coolup (Peel)	-	21.0	21.0	-	-	-	2.7	2.7	-	-
Coolup (Harvey)	-	13.3	13.3	-	-	-	2.1	2.1	-	-
Mayfield Drain	-	33.3	33.3	-	-	-	3.6	3.6	-	-
Harvey	2.77	205.5	204.6	-0.83	-0.4	0.14	20.1	20.0	-0.07	-0.4
Meredith Drain	-	6.7	6.7	-	-	-	1.0	1.0	-	-
Estuary coastal plain	**4.17**	**552.4**	**551.6**	**-0.83**	**-0.2**	**0.17**	**59.3**	**59.2**	**-0.07**	**-0.1**
Peel-Harvey estuary	**4.31**	**632.7**	**631.7**	**-0.97**	**-0.2**	**0.22**	**60.2**	**60.1**	**-0.11**	**-0.2**

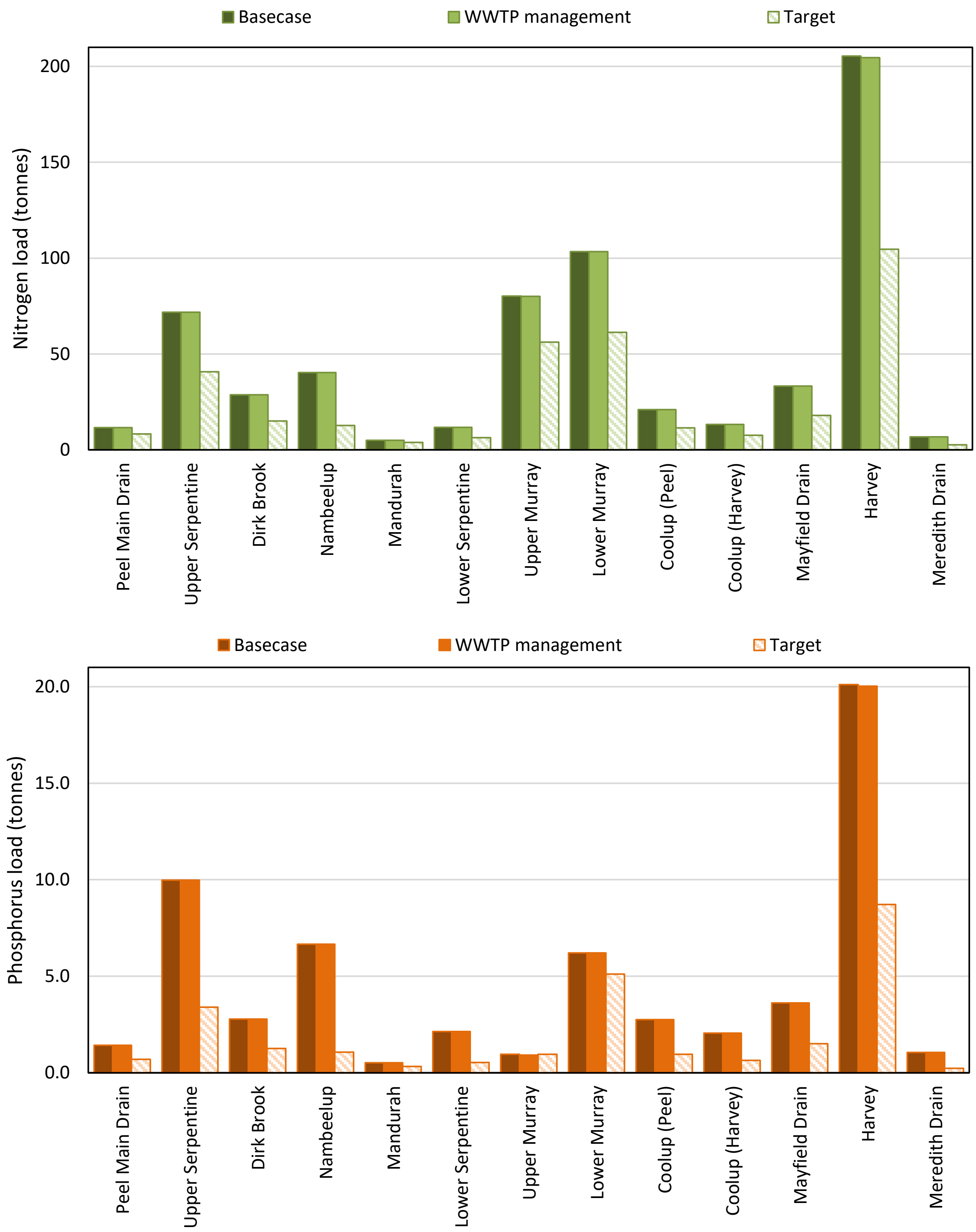


Figure 7.18: Nitrogen and phosphorus loads for the basecase and the WWTP management scenario

7.3.8 Septic tank removal

In 1996 the State Government initiated the infill sewerage program to connect unsewered properties to reticulated sewerage. From 2000–15 the Water Corporation connected about 1,960 properties in estuary catchments to reticulated sewerage. There are still about 11,950 unsewered properties in the coastal plain portion of the Peel-Harvey catchment.

The G*overnment Sewerage Policy* (DPLH 2019) says residential developments in sensitive environments (which includes the coastal plain portion of the Peel-Harvey catchment) must have reticulated sewerage connection for lots less than 1 ha. Lots that are 1 ha or more must have nutrient-attenuating alternative treatment units. Similar measures are included in SPP 2.1 (WAPC 1992).

Implementation

In the model, we assumed that septic tanks were present on unsewered properties. This scenario removes septic tanks from the coastal plain portion of the Peel-Harvey catchment. We did not include unsewered sites in the Upper Murray catchment (~780).

We modelled the effect of the past infill sewerage program (2000–15) and the following septic tank removal scenarios:

1. **Targeted removal:** we removed 1,075 septic tanks from unsewered lots adjacent to the Peel-Harvey estuary and the estuarine portion of the Serpentine River. This included septic tanks from the suburbs of Falcon (525), Coodanup (123), Park Ridge-Bouvard (229) and Pleasant Grove (197).
2. **Small lots close to waterways:** expands on scenario 1 and assumes the removal of an additional 852 septic tanks (1,926 total) in estuary catchments on the coastal plain. We removed septic tanks in the suburbs of Greenfields (215) and Wellard (290). This scenario also includes the 347 septic tanks removed by infill sewerage programs after 2015, which is outside of the model reporting period.
3. **Lots less than 1 hectare:** we removed all septic tanks in unsewered lots with areas less than 1 ha in estuary catchments on the coastal plain (3,840 septic tanks total). This scenario includes all septic tanks in scenario 2.
4. **Remove all septic tanks:** we removed all septic tanks from estuary catchments on the coastal plain (~11,950 septic tanks). This scenario would not be economically or practically feasible as it includes isolated rural dwellings.

Figure 7.19 and Figure 7.20 give the location of septic tanks removed during the former infill sewerage program and the septic tanks removed in the above scenarios.

The basecase model assumes septic tank inputs from 2016 mapping. We estimated the average annual nutrient loads exported per septic tank from the basecase model for each reporting catchment. We then used these to determine the impact of septic tank removal for the past infill sewerage program and the above scenarios.

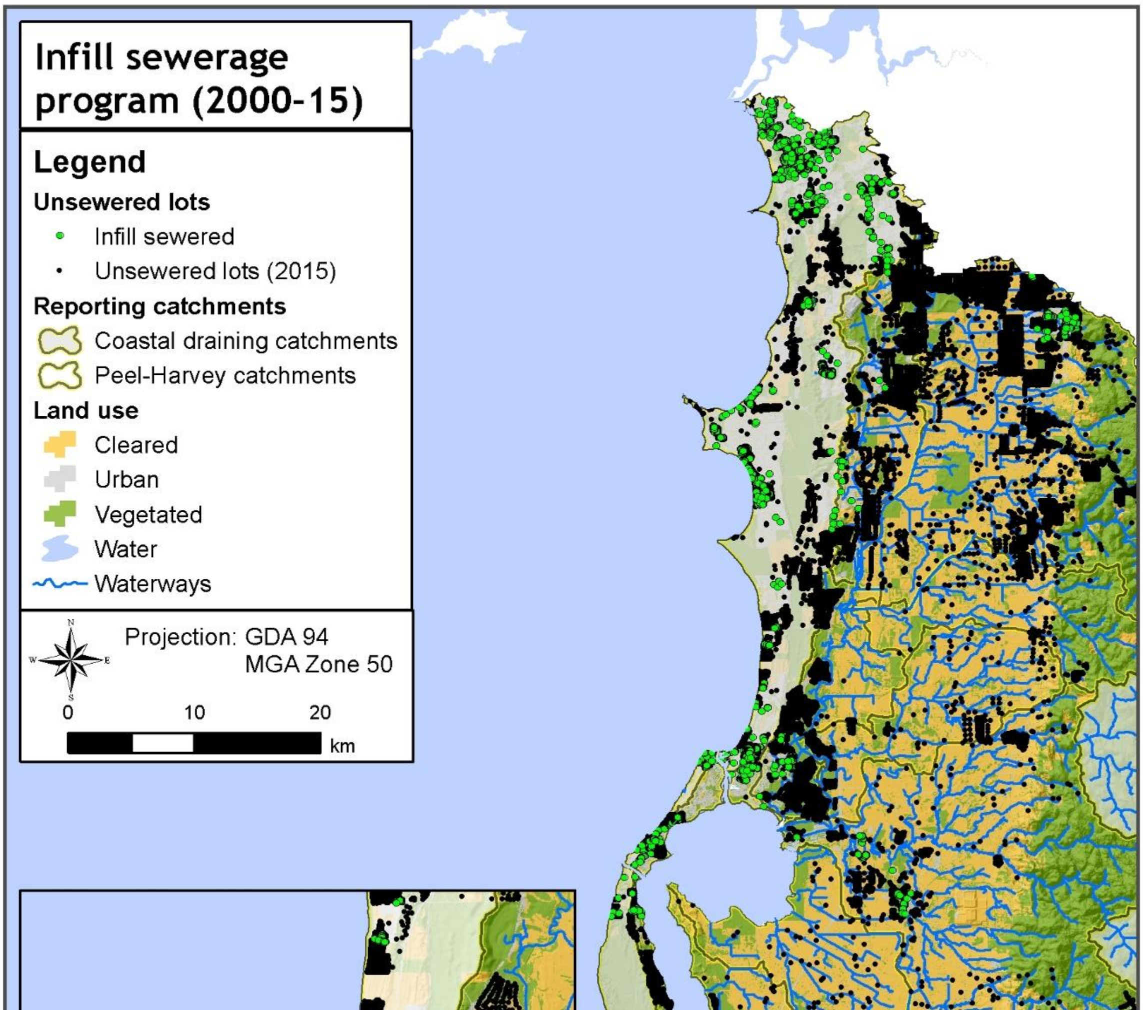


Figure 7.19: Septic tanks removed by infill sewerage program projects between 2000–15 are coloured green

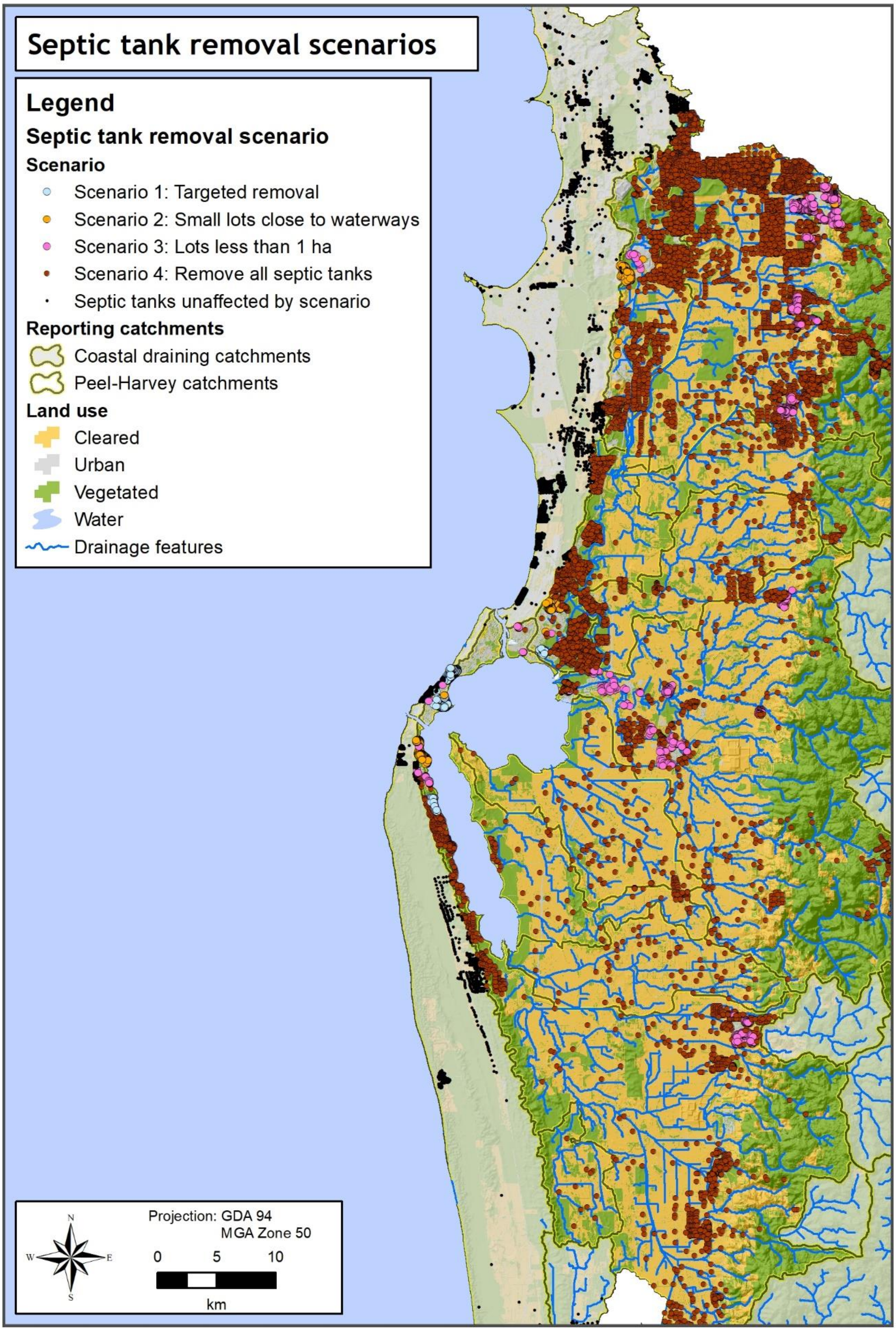


Figure 7.20: Septic tank removal scenarios

Results: Infill sewerage program projects (2000–15)

The infill sewerage program removed about 1,960 septic tanks from estuary catchments and 7,700 septic tanks from catchments draining to the ocean (total of 9,660 – see Figure 7.19 and Table 7.29).

We estimated the infill sewerage program reduced nutrient loading to the estuary by 6.6 tonnes of nitrogen and 0.33 tonnes of phosphorus (see Table 7.29). Most of this load reduction (~75%) was from infill projects in the Mandurah catchment.

Table 7.29: Estimated reduction in nutrient export load from infill sewerage projects between 2000–15

Reporting catchment	Septic tanks removed	Nitrogen load		Phosphorus load	
	(#)	(t/yr)	(%)	(t/yr)	(%)
Coastal North	7 229	-89		-6.0	
Coastal Central	452	-2.9		-0.20	
Coastal South	14	-0.02		-0.0004	
Peel Main Drain	21	-0.04	-1	-0.003	-1
Upper Serpentine	325	-0.6	-9	-0.03	-9
Dirk Brook					
Nambeelup					
Lower Serpentine	276	-0.9	-13	-0.03	-8
Mandurah	1 214	-5.1	-76	-0.25	-75
Lower Murray					
Upper Murray	23	-		-	
Coolup (Peel)					
Coolup (Harvey)					
Mayfield Drain					
Harvey	101	-0.1	-1	-0.03	-8
Meredith Drain					
Harvey Diversion Drain	6	-0.02		-0.002	
Draining to ocean	7 701	-92		-6.2	
Estuary coastal plain	**1 937**	**-6.6**	-100	**-0.33**	-100
Peel-Harvey estuary	**1 960**	**-6.6**	-100	**-0.33**	-100
Total	**9 661**	**-99**		**-6.6**	

Results: Septic tank removal

Table 7.30 and Table 7.31 give the estimated nitrogen and phosphorus load reductions for the four septic tank removal scenarios. We estimated the nitrogen loading to the estuary reduced by 4 to 23 tonnes (0.6–3.7% reduction), while the phosphorus loading reduced by 0.2 to 1.6 tonnes (0.4–2.6% reduction).

We estimated the targeted septic tank removal:

- reduced nutrient loads from the Mandurah catchment by 60% for nitrogen and 29% for phosphorus
- enabled the catchment’s nitrogen target of 3.9 tonnes to be met (see Figure 7.21).

However, nutrient load targets were not met in any other catchment for any of the four scenarios.

Table 7.30: Nitrogen loads for the basecase and the septic tank removal scenarios

	Basecase	Scenario 1: Targeted septic tank removal				Scenario 2: Small lots close to waterways			
Reporting catchment	**N load** (t/yr)	**N load** (t/yr)	**N load change** (t/yr)	(%)	**Septics removed** (#)	**N load** (t/yr)	**N load change** (t/yr)	(%)	**Septics removed** (#)
Peel Main Drain	12	12	-	-	-	11	-0.5	-4.7	296
Upper Serpentine	72	72	-	-	-	72	0.0	0.0	3
Dirk Brook	29	29	-	-	-	29	-	-	-
Nambeelup	40	40	-	-	-	40	-	-	-
Mandurah	5	2	-3.0	-60.1	722	2	-3.0	-60.4	725
Lower Serpentine	12	11	-0.4	-3.2	123	11	-1.0	-8.9	339
Upper Murray	80	80	-	-	-	80	-	-	-
Lower Murray	103	103	-	-	-	103	-	-	-
Coolup (Peel)	21	21	-	-	-	21	-	-	-
Coolup (Harvey)	13	13	-	-	-	13	-	-	-
Mayfield Drain	33	33	-	-	-	33	-	-	-
Harvey	205	205	-0.2	-0.1	229	205	-0.5	-0.2	563
Meredith Drain	7	7	-	-	-	7	-	-	-
Estuary coastal plain	**552**	**549**	**-3.6**	**-0.7**	**1 074**	**547**	**-5.1**	**-0.9**	**1 926**
Peel-Harvey estuary	**633**	**629**	**-3.6**	**-0.6**	**1 074**	**628**	**-5.1**	**-0.8**	**1 926**

	Basecase	Scenario 3: Lots less than 1 ha				Scenario 4: Remove all septic tanks			
Peel Main Drain	12	11	-0.6	-5.0	312	9	-3.0	-26	1 632
Upper Serpentine	72	70	-2.1	-2.9	1 162	64	-7.6	-11	4 187
Dirk Brook	29	29	-	-	-	28	-0.3	-1	175
Nambeelup	40	40	-	-	-	40	-0.1	-0.2	316
Mandurah	5	2	-3.1	-61.9	743	2	-3.1	-62	746
Lower Serpentine	12	11	-1.1	-9.0	341	8	-3.7	-32	1 206
Upper Murray	80	80	-	-	-	80	-	-	-
Lower Murray	103	102	-1.0	-1.0	351	100	-3.4	-3	1 172
Coolup (Peel)	21	21	-	-	-	21	0.0	-0.2	99
Coolup (Harvey)	13	13	-	-	-	13	-0.1	-0.5	115
Mayfield Drain	33	33	-	-	-	33	0.0	-0.1	63
Harvey	205	205	-0.8	-0.4	931	204	-2.0	-1.0	2 229
Meredith Drain	7	7	-	-	-	7	0.0	-0.1	12
Estuary coastal plain	**552**	**544**	**-8.7**	**-1.6**	**3 840**	**529**	**-23.3**	**-4.2**	**11 952**
Peel-Harvey estuary	**633**	**624**	**-8.7**	**-1.4**	**3 840**	**609**	**-23.3**	**-3.7**	**11 952**

Table 7.31: Phosphorus loads for the basecase and the septic tank removal scenarios

	Basecase	Scenario 1: Targeted septic tank removal				Scenario 2: Small lots close to waterways			
Reporting catchment	**P load** (t/yr)	**P load** (t/yr)	**P load change** (t/yr)	(%)	**Septics removed** (#)	**P load** (t/yr)	**P load change** (t/yr)	(%)	**Septics removed** (#)
Peel Main Drain	1.4	1.4	-	-	-	1.4	-0.04	-2.8	296
Upper Serpentine	10.0	10.0	-	-	-	10.0	0.00	0.0	3
Dirk Brook	2.8	2.8	-	-	-	2.8	-	-	-
Nambeelup	6.7	6.7	-	-	-	6.7	-	-	-
Mandurah	0.5	0.4	-0.15	-28.7	722	0.4	-0.15	-28.9	725
Lower Serpentine	2.1	2.1	-0.01	-0.5	123	2.1	-0.03	-1.4	339
Upper Murray	1.0	1.0	-	-	-	1.0	-	-	-
Lower Murray	6.2	6.2	-	-	-	6.2	-	-	-
Coolup (Peel)	2.7	2.7	-	-	-	2.7	-	-	-
Coolup (Harvey)	2.1	2.1	-	-	-	2.1	-	-	-
Mayfield Drain	3.6	3.6	-	-	-	3.6	-	-	-
Harvey	20.1	20.0	-0.06	-0.3	229	20.0	-0.15	-0.7	563
Meredith Drain	1.0	1.0	-	-	-	1.0	-	-	-
Estuary coastal plain	**59.3**	**59.1**	**-0.22**	**-0.4**	**1 074**	**58.9**	**-0.37**	**-0.6**	**1 926**
Peel-Harvey estuary	**60.2**	**60.0**	**-0.22**	**-0.4**	**1 074**	**59.9**	**-0.37**	**-0.6**	**1 926**
	Basecase	**Scenario 3: Lots less than 1 ha**				**Scenario 4: Remove all septic tanks**			
Peel Main Drain	1.4	1.4	-0.04	-2.9	312	1.2	-0.22	-15.4	1 632
Upper Serpentine	10.0	9.9	-0.10	-1.0	1 162	9.6	-0.38	-3.8	4 187
Dirk Brook	2.8	2.8	-	-	-	2.8	-0.01	-0.5	175
Nambeelup	6.7	6.7	-	-	-	6.6	-0.02	-0.3	316
Mandurah	0.5	0.4	-0.15	-29.6	743	0.4	-0.15	-29.7	746
Lower Serpentine	2.1	2.1	-0.03	-1.5	341	2.0	-0.11	-5.1	1 206
Upper Murray	1.0	1.0	-	-	-	1.0	-	-	-
Lower Murray	6.2	6.2	-0.02	-0.3	351	6.2	-0.06	-0.9	1 172
Coolup (Peel)	2.7	2.7	-	-	-	2.7	-0.001	-0.03	99
Coolup (Harvey)	2.1	2.1	-	-	-	2.1	-0.001	-0.1	115
Mayfield Drain	3.6	3.6	-	-	-	3.6	-0.01	-0.4	63
Harvey	20.1	19.9	-0.25	-1.2	931	19.5	-0.59	-2.9	2 229
Meredith Drain	1.0	1.0	-	-	-	1.0	0.00	-0.2	12
Estuary coastal plain	**59.3**	**58.7**	**-0.6**	**-1.0**	**3 840**	**57.7**	**-1.56**	**-2.6**	**11 952**
Peel-Harvey estuary	**60.2**	**59.6**	**-0.59**	**-1.0**	**3 840**	**58.7**	**-1.56**	**-2.6**	**11 952**

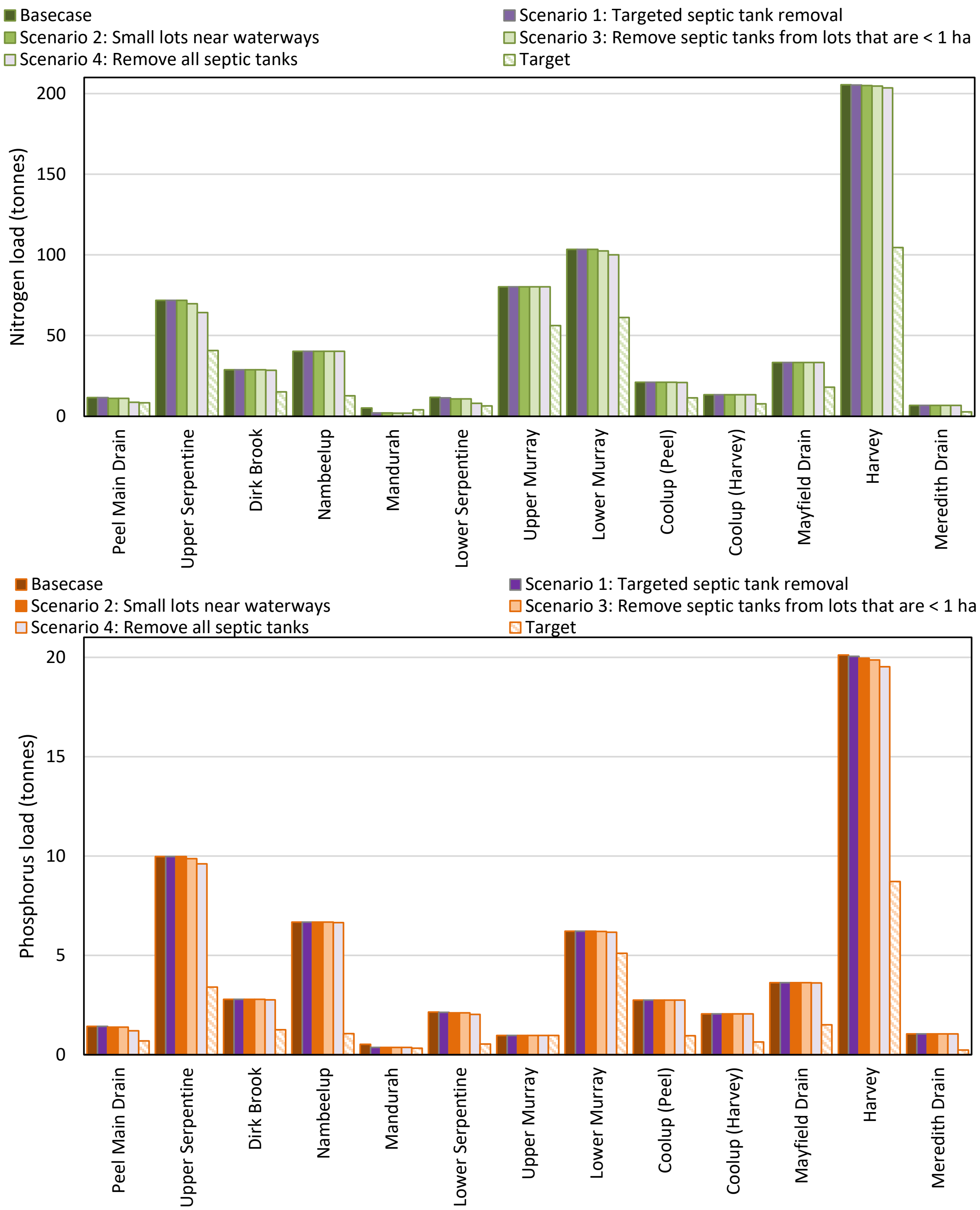


Figure 7.21: Nitrogen and phosphorus loads for the basecase and the septic tank removal scenarios

Recommendations: Future infill sewerage programs

Table 7.32 shows the unsewered areas we recommend for further infill sewerage programs. This modelling suggests that septic tank removal would benefit estuary water quality, particularly in the Falcon area.

We have used unsewered areas from scenario 1 as the basis for infill sewerage recommendations. Although all the areas below would ideally be included in future programs, Falcon and Coodanup would be higher priority than Pleasant Grove and Park Ridge-Bouvard. This is because Falcon and Coodanup have high lot densities and are close to existing sewerage infrastructure. Infill sewerage would be more cost-effective in both these areas than Pleasant Grove (lower lot density) and Park-Ridge Bouvard (no sewerage infrastructure nearby). Figure 7.22 shows the location of these unsewered areas and Table 7.32 gives estimated nutrient emissions from each of them.

We recommend nutrient-stripping alternative treatment units in areas where infill sewerage is not practical.

Table 7.32: Recommended infill sewerage priorities

Priority of unsewered area	Reporting catchment	# properties	N load from septics (kg/yr)	P load from septics (kg/yr)	Average lot size (m2)
1. Falcon	Mandurah	**525**	2190	107	850
1. Coodanup	Lower Serpentine	**123**	380	11	1050
2. Pleasant Grove	Mandurah	**197**	822	40	4000
2. Park Ridge - Bouvard	Harvey	**229**	201	60	1200
Total recommended		**1074**	**3593**	**218**	**1800**

Figure 7.22: Location of unsewered areas recommended for inclusion in the infill sewerage program

7.3.9 Water sensitive urban design retrofitting in urban areas

This scenario examines the effect of implementing water sensitive urban design (WSUD) in existing urban areas. We consider WSUD in future urban areas in the urban expansion scenario (see Section 7.1).

Existing urban land uses (‘offices, commercial & education’, ‘recreation’ and ‘residential’) encompass about 1.6% of the of the Peel-Harvey coastal plain catchment area. This relatively small area contributes about 3.5% of the flow, 1.7% of the nitrogen load and 2.6% of the phosphorus load to the estuary. As such, the management of nutrient exports from existing urban areas (excluding septic tanks) has a small potential benefit to the estuary as a whole. However, urban areas are often located very close to waterways and the estuary, and the model may underestimate their impacts due to no local data being available for calibration. WSUD in urban areas would help to mitigate nutrient and non-nutrient pollution.

WSUD retrofitting changes stormwater management in an existing urban area (DOW 2004–2007). Opportunities for retrofitting arise when upgrading or redeveloping existing structures, and can occur at the lot, street or suburb scale.

Many urban areas have pipes and straight trapezoidal drains (traditional drainage) to manage flooding and groundwater tables. This type of system conveys flows quickly and efficiently to receiving waterbodies. Floods are generally managed appropriately with traditional drainage infrastructure, however the natural flow regime is altered and peak flow and total flow volumes are increased. These drainage systems allow little nutrient assimilation of nutrient-rich water from urban areas and their stream ecology is poor compared with natural streams due to their larger flow rates, lack of sinuosity, lack of woody debris in the stream, and little or no shading and carbon input from riparian vegetation.

Retrofitting traditional drainage infrastructure aims to restore natural flow rates to the receiving waterbodies, improve water quality in receiving waterbodies and provide enhanced amenity in public spaces. Retrofitting techniques (examples in Figure 7.23) include:

- increasing temporary storage of stormwater to reduce peak flows and increase infiltration
- using storage areas to remove pollutants by including bio-retention systems or garden beds with amended soil
- reducing impervious areas by installing permeable surfaces (e.g. in roads and car parks)
- disconnecting impervious areas piped to streams/drains, and instead directing stormwater to bioretention basins, swales or soakwells
- capturing and re-using water onsite with rainwater tanks or soakwells and garden bores
- rehabilitating open drainage or piped systems, replacing them with vegetated swales or ‘living streams’.
- using end-of-pipe treatment solutions that capture, treat and release water, such as constructed wetlands.

As well as improving water quality, retrofitting can achieve many other objectives such as:

- reduced potable water use through re-use of stormwater
- improved public health and safety
- catchment repair and restoration
- creation of more attractive and liveable neighbourhoods and public spaces
- reduced irrigation requirement in public open spaces
- retention or enhancement of cultural values
- increased community awareness of the need for better management of the water cycle.

WSUD structures may also intercept/treat other urban contaminants before they enter waterways, such as heavy metals and hydrocarbons.

Nutrient and non-nutrient pollution is most effectively managed when a combination of actions and structures are implemented in a ‘treatment train’. These include minimising generation of pollutants (at source), disconnecting pollutant transport pathways (in transit) and capture or treatment of pollutants before they reach the main drain or receiving waterbody (end-of-pipe).

All re-developments and infill/brownfield developments should include WSUD features consistent with *State Planning Policy 2.9: Water resources* (WAPC 2006). Provision of training and awareness-raising forums for local government staff and councillors is essential.

Specific advice for implementation includes:

- developing stormwater management plans for local government areas to help identify opportunities and priorities for undertaking WSUD retrofitting projects
- strategic monitoring to evaluate the structural and non-structural interventions in retrofitting projects
- identifying opportunities to address other urban contaminants such as heavy metals and hydrocarbons.

How much nutrient load reduction that urban retrofitting with WSUD infrastructure might make possible depends on the scale of the works undertaken. Large treatment trains, for example, which include bio-retention systems, living streams and constructed wetlands have the potential to greatly reduce the nutrient load from most urban areas.

The department’s Urban Nutrient Decision Outcomes (UNDO) tool is a conceptual decision-support tool that evaluates WSUDs in urban developments on the sandy coastal plain in Western Australia. The tool enables users to estimate the benefit of a range of structural designs or retrofitting options that reduce nutrient loads exported from an urban development.

Implementation

UNDO is designed to assess potential nutrient load reductions in urban areas for a specific retrofitting project. It is not appropriate for a whole-of-catchment or reporting-subcatchment scale.

However, we used previous UNDO development-scale modelling and interstate studies (Melbourne Water 2013) to estimate potential nutrient reductions from urban retrofitting: 45% for both nitrogen and phosphorus.

This scenario modelled 100% adoption of WSUD retrofit in all existing urban areas in both the coastal plain portion of the catchment and the Upper Murray catchment.

Figure 7.23: Examples of WSUD providing water quality and amenity benefits

Results

See the nutrient load reductions for this scenario in Figure 7.24, Table 7.33 for nitrogen and Table 7.34 for phosphorus. We estimated that loads to the estuary reduced by 4.5 tonnes (0.7%) for nitrogen and 0.7 tonnes (1%) for phosphorus. The small impact of this scenario is due to the small urban area in the Peel-Harvey catchment relative to its large size.

In highly urbanised catchments such as Mandurah, we estimated the scenario would have a large benefit. Nitrogen loads reduced by 16% and phosphorus loads by 31%. Catchments such as the Peel Main Drain and Lower Serpentine also have large urban areas relative to their size: we estimated these would have nitrogen load reductions of 4 to 5% and phosphorus load reductions of 6 to 9% . Nutrient load reductions in all other catchments were typically <1%.

Table 7.33: Nitrogen loads for the basecase and the WSUD retrofitting scenario

Reporting catchment	Basecase			WSUD retrofit in existing urban		
	N load from urban (t/yr)	Urban N load as % of catchment N load (%)	Catchment N load (t/yr)	Catchment N load (t/yr)	N load change (t/yr)	N load change (%)
Peel Main Drain	1.2	10.5	11.6	11.0	-0.5	-4.7
Upper Serpentine	2.1	2.9	71.8	70.9	-0.9	-1.3
Dirk Brook	0.0	0.0	28.7	28.7	0.0	0.0
Nambeelup	0.0	0.0	40.3	40.3	0.0	0.0
Mandurah	1.8	36.3	5.0	4.2	-0.8	-16.3
Lower Serpentine	1.1	9.5	11.7	11.2	-0.5	-4.3
Upper Murray	0.3	0.3	80.2	80.1	-0.1	-0.1
Lower Murray	1.5	1.4	103.4	102.7	-0.7	-0.7
Coolup (Peel)	0.0	0.1	21.0	21.0	0.0	0.0
Coolup (Harvey)	0.1	0.5	13.3	13.3	0.0	-0.2
Mayfield Drain	0.0	0.0	33.3	33.3	0.0	0.0
Harvey	1.8	0.9	205.5	204.6	-0.8	-0.4
Meredith Drain	-	-	6.7	6.7	-	-
Estuary coastal plain	**9.6**	**1.7**	**552.4**	**548.1**	**-4.3**	-0.8
Peel-Harvey estuary	**9.9**	**1.6**	**632.7**	**628.2**	**-4.5**	-0.7

Table 7.34: Phosphorus loads for the basecase and the WSUD retrofitting scenario

Reporting catchment	Basecase			WSUD retrofit in existing urban		
	P load from urban (t/yr)	Urban P load as % of catchment P load (%)	Catchment P load (t/yr)	Catchment P load (t/yr)	P load change (t/yr)	P load change (%)
Peel Main Drain	0.18	12.4	1.4	1.3	-0.08	-5.6
Upper Serpentine	0.24	2.4	10.0	9.9	-0.11	-1.1
Dirk Brook	0.00	0.0	2.8	2.8	0.00	0.0
Nambeelup	0.00	0.0	6.7	6.7	0.00	0.0
Mandurah	0.36	69.7	0.5	0.4	-0.16	-31.3
Lower Serpentine	0.42	19.7	2.1	1.9	-0.19	-8.9
Upper Murray	0.00	0.4	1.0	1.0	0.00	-0.2
Lower Murray	0.18	3.0	6.2	6.1	-0.08	-1.3
Coolup (Peel)	0.00	0.0	2.7	2.7	0.00	0.0
Coolup (Harvey)	0.02	0.7	2.1	2.0	-0.01	-0.3
Mayfield Drain	0.00	0.0	3.6	3.6	0.00	0.0
Harvey	0.15	0.7	20.1	20.0	-0.07	-0.3
Meredith Drain	-	-	1.0	1.0	-	-
Estuary coastal plain	**1.54**	**2.6**	**59.3**	**58.6**	**-0.69**	-1.2
Peel-Harvey estuary	**1.55**	**2.6**	**60.2**	**59.5**	**-0.70**	-1.2

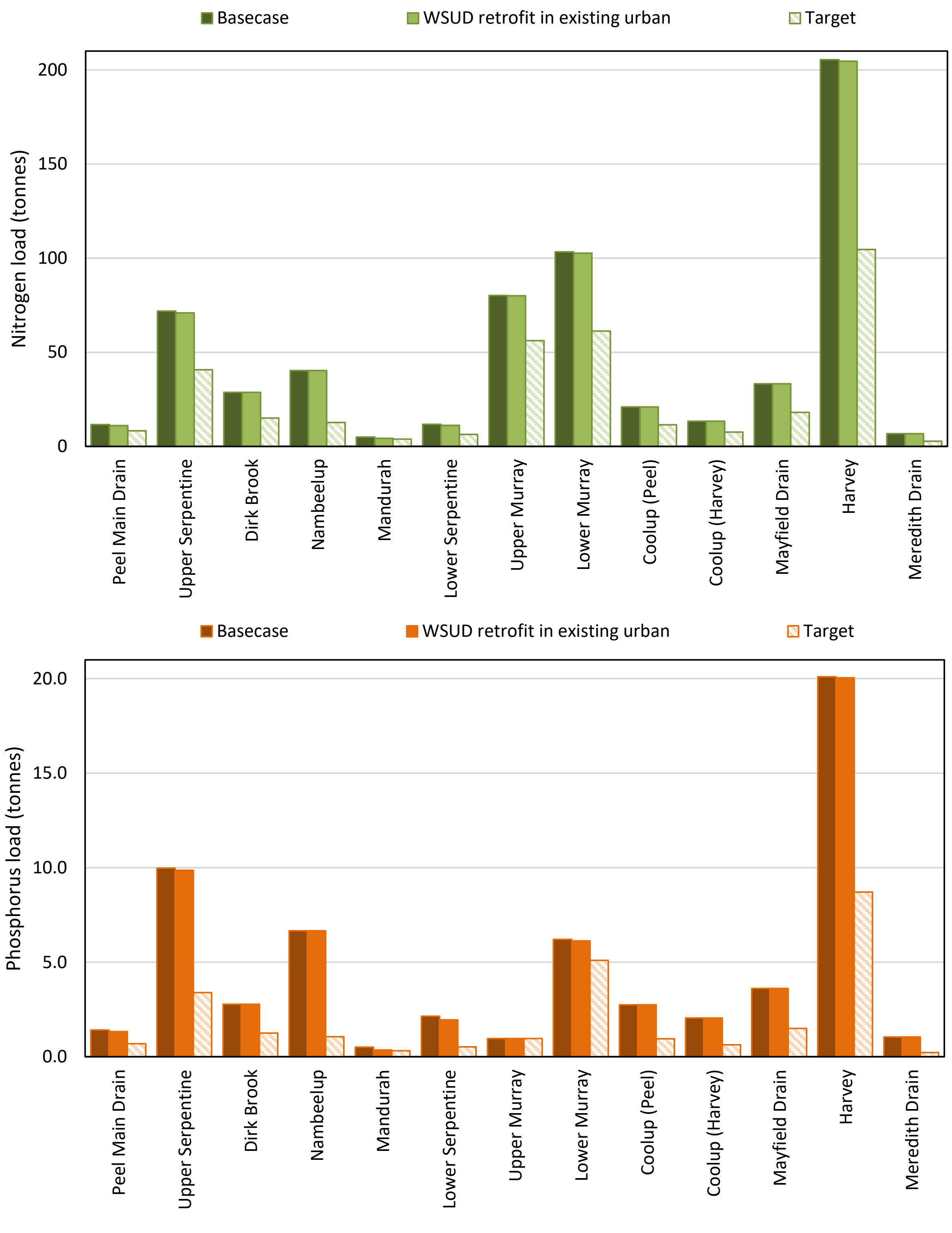


Figure 7.24: Nitrogen and phosphorus loads for the basecase and the WSUD retrofitting scenario

7.3.10 Constructed wetlands

Constructed wetlands are artificial wetlands that are specifically designed for water quality treatment. In Western Australia, constructed wetlands have primarily been used to treat urban stormwater or treated wastewater before discharge to the environment. The largest artificial wetland on the Swan Coastal Plain treats flows from Ellen Brook, which is predominantly an agricultural catchment. We could not find any published reports on the Ellen Brook wetland's efficacy when we conducted this modelling.

The Peel-Harvey Catchment Council (PHCC) has been investigating adjustable weirs to detain or divert water in drained and degraded wetlands. In 2011, it diverted agricultural drainage water to Lake Mealup to maintain water levels and manage the oxidation of acid sulfate soils. Although not quantified, this drainage diversion project would likely have substantially reduced the nutrient loading to the Peel-Harvey estuary, due to the trapping and assimilation of nutrients in the wetland. Similar drainage diversions are being investigated for Lake McLarty due to the same issues (water-level decline and acidity).

The PHCC installed an adjustable weir in a drained and degraded wetland at the Jenkins farm in the Mayfield Drain catchment. Ocampo et al. (2018) measured inflow and outflow nutrient concentrations from this wetland. Outflows from the wetland had consistently lower TP concentrations than inflows. However, TN concentrations were only substantially reduced during periods of low flow, when long retention times would have promoted de-nitrification. See Hall (2019) for a more detailed discussion of this study.

Implementation

This scenario only considers constructed wetlands. We did not model the effects of large-scale wetland drainage diversions (e.g. Lake Mealup) or paddock-scale wetland water retention (e.g. Jenkins Weir).

We used the constructed wetland treatment module in the UNDO tool to assess the efficacy of constructed wetlands. We assumed the wetland area was 0.5% of the upstream catchment area and reduced average annual loads by about 30% for nitrogen and 50% for phosphorus.

We assumed the wetlands treated seven reporting catchments: Peel Main Drain, Upper Serpentine, Dirk Brook, Nambeelup, Mayfield Drain, Harvey and Meredith. We placed the constructed wetlands at the end of each catchment and assumed that they treated all upstream land areas. We did not identify suitable land for constructed wetlands in these catchments. Our modelling approach likely overstates the proportion of the catchment that constructed wetlands could treat.

We did not model constructed wetlands in the:

- Upper and Lower Murray catchments due to the required wetland area
- Lower Serpentine due to the current large area of estuarine wetlands
- Mandurah catchment due to the lack of large drains
- both Coolup catchments based on their low nutrient loads.

Results

See Table 7.35 and Figure 7.25 for the nutrient load reductions for the constructed wetland scenario. We estimated that loads to the estuary reduced by 119 tonnes (19%) for nitrogen and 23 tonnes (38%) for phosphorus. Although this scenario would underpin large nutrient removal, significant cost would be associated with constructing about 800 ha of wetlands.

Table 7.35: Average annual nitrogen and phosphorus loads for the basecase and the constructed wetland scenario

		Basecase		**Constructed wetlands**						
Reporting catchment	Area	N load	P load	N load after treatment	N load Change		P load after treatment	P load Change		Constructed wetland area
	(km2	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(%)	(tonnes)	(tonnes)	(%)	(ha)
Peel Main Drain	125	12	1.4	8	-3	-30	0.7	-0.7	-50	63
Upper Serpentine	491	72	10.0	50	-22	-30	5.0	-5.0	-50	245
Dirk Brook	139	29	2.8	20	-9	-30	1.4	-1.4	-50	70
Nambeelup	139	40	6.7	28	-12	-30	3.3	-3.3	-50	69
Mandurah	24	5	0.5	5	0	0	0.5	0.0	0	-
Lower Serpentine	100	12	2.1	12	0	0	2.1	0.0	0	-
Upper Murray	6 752	80	1.0	80	0	0	1.0	0.0	0	-
Lower Murray	636	103	6.2	103	0	0	6.2	0.0	0	-
Coolup (Peel)	150	21	2.7	21	0	0	2.7	0.0	0	-
Coolup (Harvey)	103	13	2.1	13	0	0	2.1	0.0	0	-
Mayfield Drain	122	33	3.6	23	-10	-30	1.8	-1.8	-50	61
Harvey	553	205	20.1	144	-62	-30	10.1	-10	-50	277
Meredith Drain	53	7	1.0	5	-2	-30	0.5	-0.5	-50	27
Estuary coastal plain	**2 637**	**552**	**59**	**433**	**-119**	**-22**	**36.5**	**-23**	**-38**	**811**
Peel-Harvey estuary	**9 389**	**633**	**60**	**513**	**-119**	**-19**	**37.4**	**-23**	**-38**	**811**

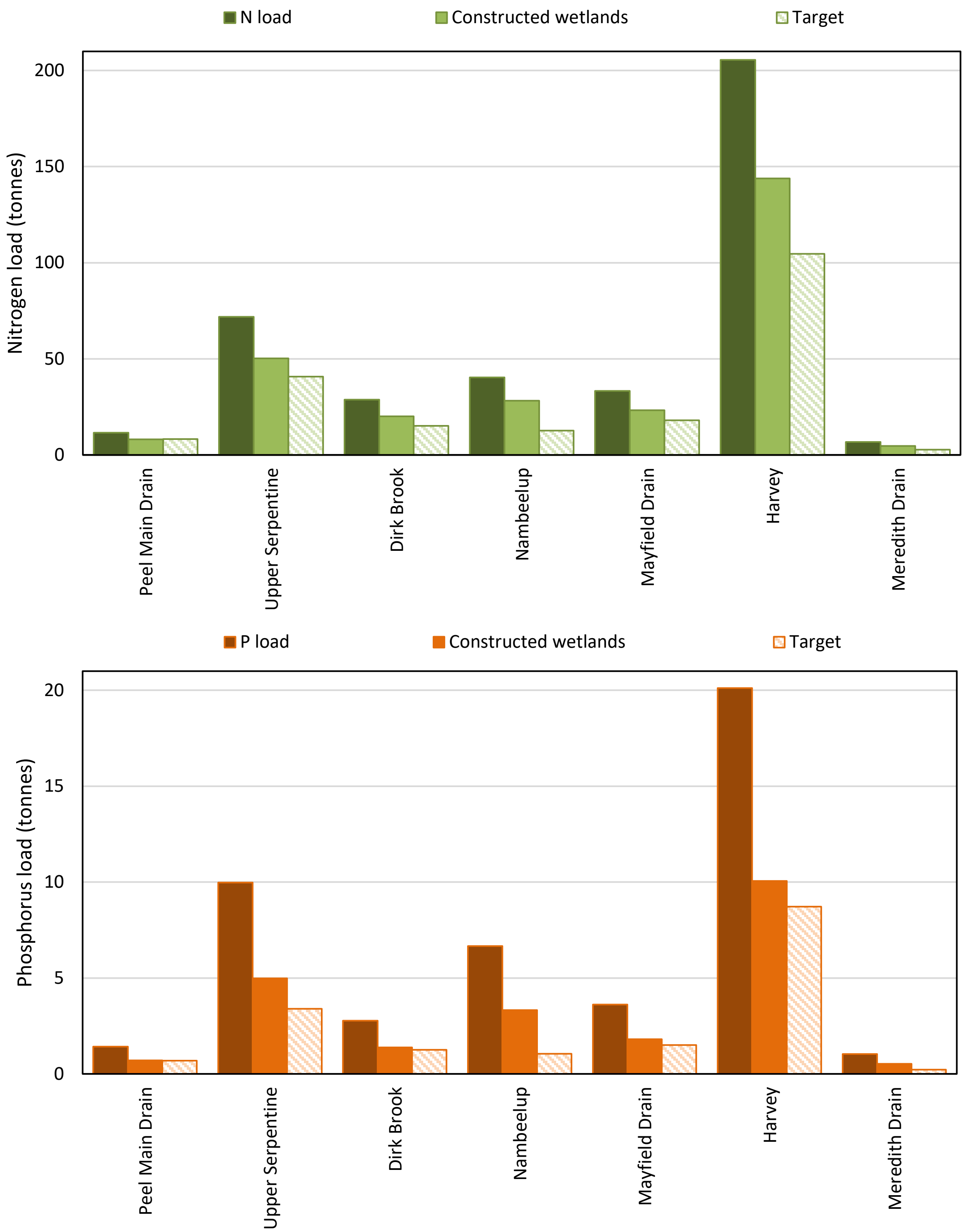


Figure 7.25: Average annual nitrogen and phosphorus loads for the basecase and the constructed wetland scenario

7.3.11 Re-vegetation with deep-rooted plants

Nutrient inputs in areas of native vegetation are from atmospheric deposition and a small amount of nitrogen fixation by some native plants. The clearing and replacement of native vegetation with shallow-rooted crops and pasture increases nutrient inputs by one or more orders of magnitude, due to fertiliser application, fodder and animal inputs, and nitrogen fixation. In addition, shallow-rooted crops and pasture has resulted in increased groundwater levels, surface runoff and secondary salinisation in some areas (Schofield & Bari 1991; Ruprecht & Schofield 1991). This increase in flow also increases the mobilisation of nutrients from agricultural land. Cleared land is also more susceptible to erosion.

When cleared land is re-planted with deep-rooted vegetation, this greatly reduces nutrient inputs and helps control groundwater rise and stream salinity. A notable example is the Denmark River catchment, where salinity has reduced because of the large-scale conversion of pasture to agroforestry (Ward et al. 2011).

Statement of Planning Policy (SPP) 2.1 outlines a general policy provision for deep-rooted vegetation targets:

> 5.4 The retention and rehabilitation of existing remnant vegetation is to be encouraged. A catchment target of 50% of land area established to deep rooted perennial plants, preferably local indigenous species but including high water using and suitable exotic species, shall be attempted. Remnant vegetation shall be retained along watercourses, or the margins shall be replanted to higher water-using vegetation, to maintain the stability of banks and exert some control on sediment and nutrient movement.

Achieving this catchment target would require the conversion of large areas of farmland to agroforestry or native vegetation plantings. The widespread adoption of shelterbelts on farms could increase the area of deep-rooted vegetation by as much as 56 km^2 in estuary catchments on the coastal plain (Kelsey et al. 2011). Shelterbelts are strips of deep-rooted vegetation within crops or pastures. Shelterbelts provide many benefits to agricultural enterprises including shelter for pasture, crops and livestock; control of soil erosion; and better productivity and sustainability (Bird et al. 1992). The PHCC has used shelterbelts as part of its catchment interventions.

Implementation

This scenario aims to increase the area of deep-rooted vegetation in each reporting catchment to 50% of their area. Catchments with more than 50% deep-rooted vegetation (Dirk Brook, Lower Murray and Meredith Drain) are not affected by this scenario and neither was the urban Mandurah catchment (see Table 7.36). Beef and cropping lands were converted to either native vegetation or plantations. We preferenced low-PRI soils on the coastal plain for conversion. We ran the model with the same drivers as the basecase model and give all scenario results as an average annual for the period of 2006–15.

This scenario does not completely fulfil the 50% deep-rooted vegetation requirement of SPP 2.1 because the coastal plain reporting catchments have vegetated upland areas that contribute to the 50% deep-rooted vegetation target. If the upland areas of the coastal plain catchments were not included, the amount of re-vegetation on the coastal plain would need to be greater. This scenario also implements 50% deep-rooted re-vegetation in the Upper

Murray catchment. The area re-vegetated in this scenario is 248 km^2 on the coastal plain and 316 km^2 in the Upper Murray catchment.

Table 7.36: Basecase catchment deep-rooted vegetation area and area converted to deep-rooted vegetation in this scenario

	Basecase			Area converted to deep-rooted vegetation			
Reporting catchment	**Catchment area**	**Area of deep-rooted vegetation**		**Beef (low PRI)**	**Beef (high PRI)**	**Cropping (high PRI)**	**Total change**
	(km^2)	(km^2)	(%)	(km^2)	(km^2)	(km^2)	(km^2)
Peel Main Drain	125	53	43	2	7	-	9
Upper Serpentine	491	223	45	22	-	-	22
Dirk Brook	139	70	51	-	-	-	-
Nambeelup	139	29	21	41	-	-	41
Mandurah	24	8	33	-	-	-	-
Lower Serpentine	100	49	49	1	-	-	1
Upper Murray	6 752	3 060	45	-	-	316	316
Lower Murray	636	326	51	-	-	-	-
Coolup (Peel)	150	29	19	46	-	-	46
Coolup (Harvey)	103	32	31	19	-	-	19
Mayfield Drain	122	20	16	30	11	-	41
Harvey	553	209	38	67	-	-	67
Meredith Drain	53	26	50	-	-	-	-
Estuary coastal plain	2 637	1 075	41	229	19	-	248
Peel-Harvey estuary	9 389	4 135	44	229	19	316	564

Results

See the effects of the deep-rooted vegetation scenario on flow in

Table 7.37, nitrogen in Table 7.38 and phosphorus in Table 7.39. The scenario (for both plantation and native vegetation) resulted in 10% less flow to the estuary. We estimated that nitrogen loads to the estuary reduced by 89 and 91 tonnes (14% reduction) from increased areas of plantations and native vegetation respectively. Phosphorus loads to the estuary reduced by 18 and 20 tonnes (30% and 33% reduction) from increased areas of plantations and native vegetation respectively. The amount of land required to achieve this is about 248 km^2 in the coastal plain catchments and 316 km^2 in the Upper Murray catchment.

The largest percentage reductions in flow and nutrient export were for the Mayfield Drain catchment, along with considerable reductions in the Coolup and Nambeelup catchments. These catchments all had low proportions of deep-rooted vegetation in the basecase model. Phosphorus load targets were met in the Mayfield and Coolup (Peel) catchments (see Figure 7.26).

Even though there is only a small difference between native vegetation and plantations in terms of reduced nutrient pollution, native re-vegetation would benefit terrestrial and stream ecosystems much more than plantations. Plantations also cause large offsite impacts when they are harvested and replanted.

Table 7.37: Average annual flow for the basecase and the deep-rooted vegetation scenario

Reporting catchment	Basecase Flow (GL/yr)	50% deep-rooted vegetation Flow (GL/yr)	Flow change (GL/yr)	Flow change (%)
Peel Main Drain	7	7	-0.2	-3
Upper Serpentine	34	32	-1.6	-5
Dirk Brook	13	13	-	-
Nambeelup	11	7	-3.5	-33
Mandurah	3	3	-	-
Lower Serpentine	5	5	-0.1	-1
Upper Murray	125	116	-8.4	-7
Lower Murray	51	51	-	-
Coolup (Peel)	10	6	-3.3	-35
Coolup (Harvey)	6	5	-1.4	-23
Mayfield Drain	15	9	-5.8	-38
Harvey	87	76	-11	-13
Meredith Drain	2	2	-	-
Estuary coastal plain	244	217	-27	-11
Peel-Harvey estuary	369	333	-35	-10

Table 7.38: Average annual nitrogen loads for the basecase and the deep-rooted vegetation scenario

Reporting catchment	Basecase	50% deep-rooted vegetation					
		Plantation			Native vegetation		
	N load (t/yr)	N load (t/yr)	N load change (t/yr)	N load change (%)	N load (t/yr)	N load change (t/yr)	N load change (%)
Peel Main Drain	12	10	-1.2	-10	10	-1.3	-11
Upper Serpentine	72	67	-5.0	-7	67	-5.3	-7
Dirk Brook	29	29	-	-	29	-	-
Nambeelup	40	26	-15	-37	26	-15	-36
Mandurah	5	5	-	-	5	-	-
Lower Serpentine	12	12	-0.2	-1	12	-0.2	-2
Upper Murray	80	74	-6.0	-8	74	-6.7	-8
Lower Murray	103	103	-	-	103	-	-
Coolup (Peel)	21	13	-8.2	-39	13	-8.1	-39
Coolup (Harvey)	13	10	-3.5	-27	10	-3.5	-26
Mayfield Drain	33	19	-14	-42	19	-14	-42
Harvey	205	169	-37	-18	168	-38	-18
Meredith Drain	7	7	-	-	7	-	-
Estuary coastal plain	552	469	-83	-15	468	-84	-15
Peel-Harvey estuary	633	543	-89	-14	542	-91	-14

Table 7.39: Average annual phosphorus loads for the basecase and the deep-rooted vegetation scenario

	Basecase	50% deep-rooted vegetation					
		Plantation			Native vegetation		
Reporting catchment	P load	P load	P load change		P load	P load change	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(%)
Peel Main Drain	1.4	1.4	-0.05	-3	1.3	-0.08	-6
Upper Serpentine	10	9.0	-1.0	-10	8.5	-1.4	-14
Dirk Brook	2.8	2.8	-	-	2.8	-	-
Nambeelup	6.7	3.9	-2.7	-41	4.0	-2.7	-41
Mandurah	0.5	0.5	-	-	0.5	-	-
Lower Serpentine	2.1	2.1	-0.03	-1	2.1	-0.05	-2
Upper Murray	1.0	0.9	-0.02	-2	0.9	-0.07	-8
Lower Murray	6.2	6.2	-	-	6.2	-	-
Coolup (Peel)	2.7	0.8	-1.9	-70	0.8	-1.9	-70
Coolup (Harvey)	2.1	1.2	-0.8	-41	1.2	-0.8	-41
Mayfield Drain	3.6	1.0	-2.6	-72	1.0	-2.6	-72
Harvey	20	11	-9.0	-45	10	-9.9	-49
Meredith Drain	1.0	1.0	-	-	1.0	-	-
Estuary coastal plain	59	41	-18	-31	40	-20	-33
Peel-Harvey estuary	60	42	-18	-30	41	-20	-33

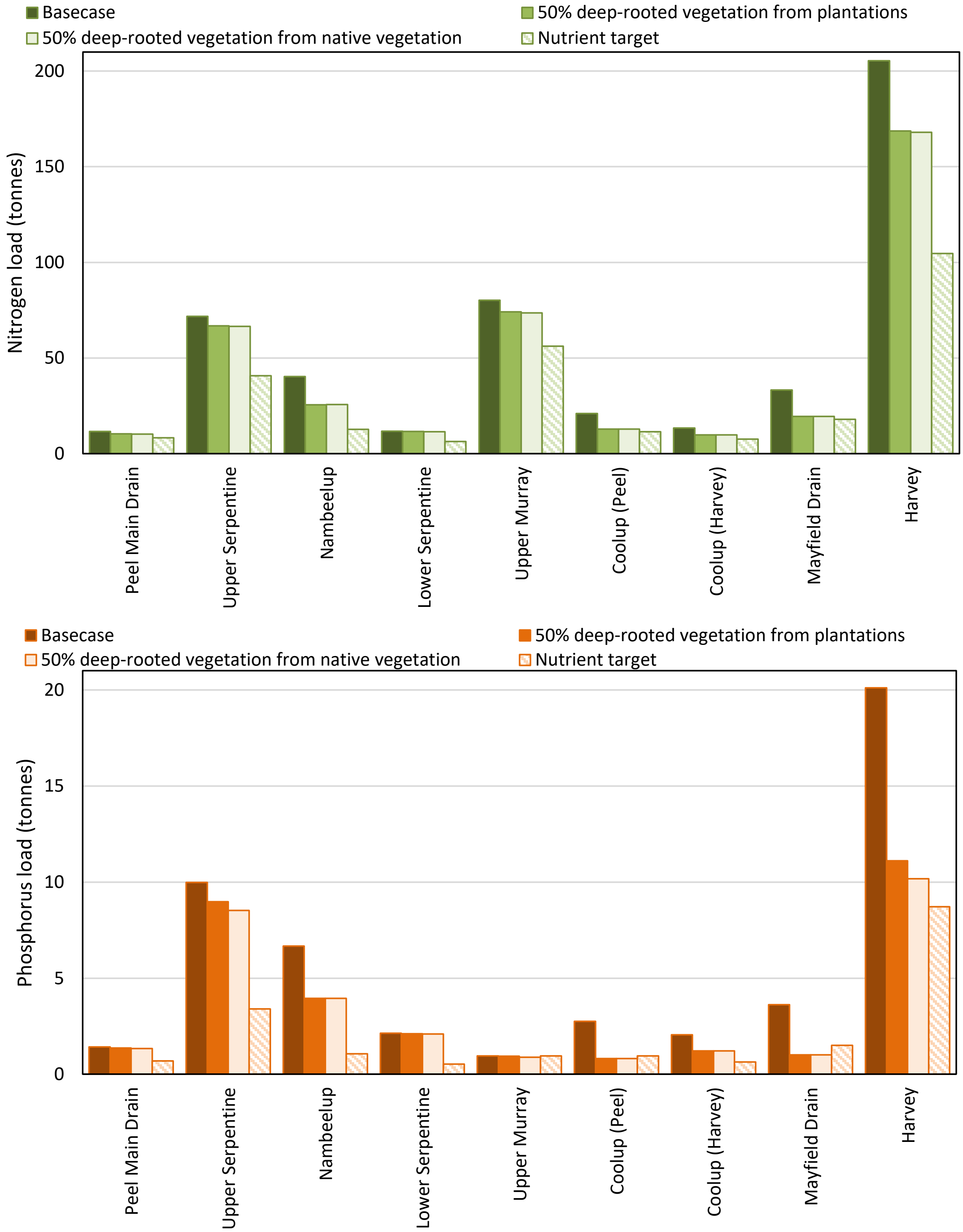


Figure 7.26: Nutrient loads for the basecase and the deep-rooted vegetation scenario. Catchments that were unaffected by this scenario are not shown.

7.3.12 Management practices that were not modelled

Perennial pastures

Perennial pastures provide summer feed for grazing animals, increase land carrying capacity and improve farm profitability. Compared with annual pasture, perennial pastures are slower growing and need to be managed differently for maximum agronomic benefit. Farmers can grow many different perennial pasture species to maximise farm profitability: these vary with the climate, type of pasture (dryland or irrigated), soil characteristics and type of livestock (Moore et al. 2006). Perennial pastures can be used for beef grazing on the coastal plain and for sheep grazing in the wheatbelt.

With careful management, perennial pastures can potentially reduce nutrient exports from grazing lands. The mechanisms for reducing nutrient export are:

- Perennial pastures have deeper root systems that allow for greater water and nutrient utilisation. This has the potential to reduce groundwater recharge and possibly reduce agricultural drainage volumes.
- Perennial pastures, such as kikuyu, require less phosphorus fertilisation to grow yields similar to an annual pasture.
- The extended growing period of perennial grasses has been found to reduce nitrogen excretion by dairy cattle without affecting milk quality.

Previous surveys of the adoption of best-management practices (Lavell et al. 2004) found that about 28 respondents (40% of 70) used perennial pastures, most commonly kikuyu or couch grass. However, unpublished work suggests these pastures are typically not managed for improved nutrient removal (Rogers pers. comm. 2020). Apart from the surveys by Lavell et al. (2004), no other studies describe the extent of perennial pastures on farmland in the Peel-Harvey nor how they are managed. Because of this uncertainty, we did not include perennial pastures in the scenario modelling.

Improved irrigation practices

Flood irrigation is common in the Harvey and Waroona irrigation districts. This method involves the release of water to flat and typically laser-levelled irrigation bays to grow pasture from October to April. Flood irrigation is less water efficient than other methods such as centre-pivot or subsurface irrigation. Drains remove the excess flood irrigation water, which contains high concentrations of nutrients, and direct flow to the Peel-Harvey estuary (Rivers 2012).

Excess irrigation water from the Waroona and Harvey irrigation districts contributed on average about 2% of the annual flow (7 GL), and less than 1% of the nutrient load (5 tonnes N and 0.56 tonnes P) to the Peel-Harvey estuary during 2006–15. Although the estimated volume and loads from excess irrigation water are small, they are delivered to the estuary during spring, summer and autumn when conditions are optimal for algal growth (high temperatures and long water-retention times).

Better irrigation water-use efficiency, such as use of centre-pivot rather than flood irrigation, has the potential to substantially reduce the volume of flow and nutrient loads in irrigation returns (Rivers 2012). However, we did not model this scenario because:

- the maximum effect of improved irrigation efficiency was nutrient load reductions to the estuary of less than 1%
- the method of irrigation could not be changed in the Source catchment model.


Figure 7.27: Flood irrigated paddocks (left) and centre-pivot sprinkler irrigation (right) in Benger (photos: J. Hugues-Dit-Ciles).

7.4 Climate change

South-west Western Australia is experiencing a drying climate (IOCI 2012; Charles et al. 2010) as a result of global human-induced changes (IPCC 2007). We have estimated the effects of the projected 2050 climate on flows in this scenario.

We used the climate change in Australia (CCIA) tool to model projected climate at 2050. We chose this tool because the seasonality of recent rainfall – which affects the timing and magnitude of flow estimated by the catchment model – is well represented in the future projections. The tool uses pattern-scaling to derive monthly climate anomalies from a 30-year baseline period (1981–2010) using the results from eight global climate models (GCMs). These GCMs were selected from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model dataset (as used in IPCC 2015) based on their performance over Australia.

The CCIA scenarios: dry, median and wet represent the 10th, 50th and 90th percentiles of 26 future climate scenarios generated using the monthly anomalies, derived from the eight GCMs, and various representative (greenhouse gas) concentration pathways (RCPs). The catchment model used rainfall and potential evapotranspiration (PET) anomalies from the dry scenario (Hadley Global Environment Model 2 – Carbon Cycle and the RCP 8.5 pathway) [5].

We derived monthly rainfall and climate anomalies for the locations given in Figure 7.28 and applied them to the modelling catchments. On average, the projected 2050 climate shows a

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[5] Detailed climate change modelling was undertaken by Hennig et al. (2019) using the CCIA tool and DoW (2015). This work supports the choice of the dry climate scenario used in this project.

25% reduction in annual rainfall and a 3% increase in annual PET compared with the current period (2006–15) (see Table 7.40).

This climate change scenario shows the long-term average effects of future climate on flow and nutrient loading to the Peel-Harvey estuary. We have not included the compounding effect of land-use change and increased groundwater and surface water abstraction in this scenario.

Table 7.40: Average annual rainfall and PET for the current climate (2006–15) and the projected 2050 climate

Catchment	Rainfall				Potential evapotranspiration			
	Current (mm/yr)	2050 (mm/yr)	Difference (mm/yr)	Difference (%)	Current (mm/yr)	2050 (mm/yr)	Difference (mm/yr)	Difference (%)
Peel Main Drain	691	539	-152	-22%	1430	1468	37	3%
Upper Serpentine	763	584	-179	-23%	1429	1463	35	2%
Dirk Brook	799	607	-192	-24%	1394	1429	35	2%
Nambeelup	706	558	-148	-21%	1414	1453	39	3%
Mandurah	668	537	-130	-20%	1397	1436	40	3%
Lower Serpentine	684	545	-139	-20%	1416	1456	40	3%
Upper Murray	555	412	-143	-26%	1366	1412	46	3%
Lower Murray	779	606	-173	-22%	1379	1416	38	3%
Coolup (Peel)	695	559	-136	-20%	1386	1431	45	3%
Coolup (Harvey)	714	568	-146	-20%	1380	1425	45	3%
Mayfield Drain	735	576	-159	-22%	1376	1421	45	3%
Harvey	813	620	-193	-24%	1350	1393	43	3%
Meredith Drain	760	586	-173	-23%	1358	1405	46	3%
Serpentine River	741	573	-168	-23%	1420	1456	36	3%
Murray River	577	431	-146	-25%	1368	1413	45	3%
Harvey River	786	605	-181	-23%	1358	1402	44	3%
Peel Inlet	597	448	-148	-25%	1374	1418	44	3%
Harvey estuary	786	605	-181	-23%	1358	1402	44	3%
Estuary coastal plain	762	590	-171	-23%	1389	1428	39	3%
Peel-Harvey estuary	613	462	-151	-25%	1372	1417	44	3%

Results

See Table 7.41 for the average annual flow and nutrient loads for the current climate (2006–15) and the future dry climate (a 10-year period centred around 2050). We estimate that the 25% rainfall decrease and the 3% PET increase (on average) results in a 51% decrease in flow to the Peel-Harvey estuary, and 54% and 55% decreases in nitrogen and phosphorus loads respectively. The Meredith and Upper Murray catchments are the most affected – we predict these would have 64% and 59% decreases in average annual flow volume.

The decreased flows and loads would make the estuary saltier for longer compared with the current climate regime, the river inflows would have a longer residence time in the estuary and the nutrients in the flows would likely be more available for algal growth. To examine the effects of climate change, a fully calibrated estuary hydrodynamic and ecological model is required. These results also underline the need for robust water quality target-setting criteria, which considers both flows and nutrient concentrations/loads.

Table 7.41: Average annual flow and nutrient loads under the current climate (2006–15) and the projected 2050 climate

	Flow				Nitrogen load				Phosphorus load			
Catchment	**Current**	**2050**	**Difference**		**Current**	**2050**	**Difference**		**Current**	**2050**	**Difference**	
	(GL/yr)	(GL/yr)	(GL/yr)	(%)	(t N/yr)	(t N/yr)	(t N/yr)	(%)	(t P/yr)	(t P/yr)	(t P/yr)	(%)
Peel Main Drain	6.9	4.1	-2.8	-40%	11.6	7.8	-3.8	-33%	1.4	0.7	-0.7	-49%
Upper Serpentine	33.9	15.5	-18.4	-54%	71.8	33.1	-38.7	-54%	10.0	4.2	-5.8	-58%
Dirk Brook	12.6	5.7	-6.8	-54%	28.7	12.6	-16.2	-56%	2.8	1.3	-1.5	-54%
Nambeelup	10.6	5.1	-5.4	-51%	40.3	18.7	-21.6	-54%	6.7	3.1	-3.6	-54%
Mandurah	3.2	2.2	-1.0	-31%	5.0	4.9	-0.1	-2%	0.5	0.4	-0.1	-17%
Lower Serpentine	5.3	2.9	-2.3	-44%	11.7	8.2	-3.5	-30%	2.1	1.1	-1.0	-49%
Upper Murray	125	51.4	-73.4	-59%	80.2	28.3	-51.9	-65%	1.0	0.3	-0.6	-66%
Lower Murray	51.0	27.2	-23.9	-47%	103	47.9	-55.5	-54%	6.2	2.8	-3.5	-56%
Coolup (Peel)	9.5	4.8	-4.7	-49%	21.0	10.0	-11.0	-52%	2.7	1.3	-1.4	-52%
Coolup (Harvey)	6.3	3.1	-3.2	-51%	13.3	6.2	-7.2	-54%	2.1	1.0	-1.1	-53%
Mayfield Drain	15.0	7.8	-7.2	-48%	33.3	14.4	-18.9	-57%	3.6	1.5	-2.1	-59%
Harvey	87.2	49.7	-37.5	-43%	205	95	-110.3	-54%	20.1	9.0	-11.1	-55%
Meredith Drain	2.3	0.8	-1.4	-64%	6.7	2.0	-4.7	-70%	1.0	0.3	-0.8	-73%
Serpentine River	72.5	36	-36.8	-51%	169	85	-83.9	-50%	23.5	10.8	-12.7	-54%
Murray River	185	83	-101.9	-55%	205	86	-118.4	-58%	9.9	4.4	-5.5	-56%
Harvey River	111	61	-49.4	-45%	259	118	-141.0	-54%	26.8	11.7	-15.1	-56%
Peel Inlet	258	119	-138.7	-54%	374	172	-202.2	-54%	33.4	15.2	-18.2	-55%
Harvey estuary	111	61	-49.4	-45%	259	118	-141.0	-54%	26.8	11.7	-15.1	-56%
Estuary coastal plain	244	129	-115	-47%	552	261	-291	-53%	59.3	26.6	-32.7	-55%
Peel-Harvey estuary	369	181	-188	-51%	633	289	-343	-54%	60.2	26.9	-33.3	-55%

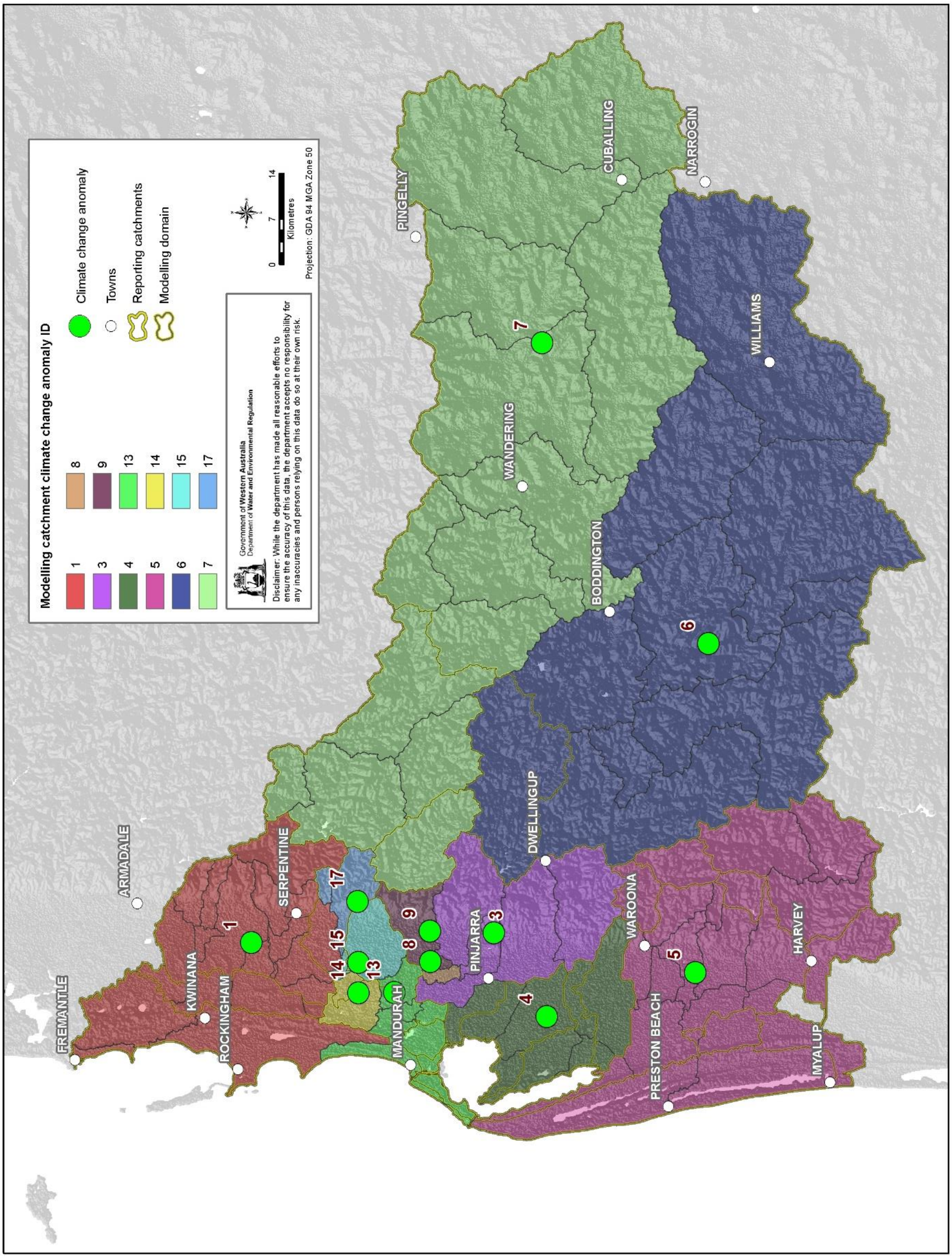

Figure 7.28: Point locations used to derived the down-scaling parameters that were applied to catchment climates to derive the 2050 climate

8 Discussion

We modelled 11 land-management scenarios to estimate their potential for nutrient removal and achievement of nutrient targets (Section 7.3). We modelled the management scenarios at or near maximum adoption. No individual management action reduced nutrients enough to meet targets for the estuary, although some actions met reporting catchment targets and substantially reduced nutrient loads reaching the estuary. Multiple catchment-wide actions are required to improve water quality in the Peel-Harvey estuary, as decreed in the Environment Protection Policy 1992 (EPA 1992).

Significant nutrient load reductions would result from:

1. Best-practice fertiliser use on farms
2. Application of soil amendments to low-PRI soils
3. Catchment re-vegetation with deep-rooted plants
4. Best-practice dairy shed effluent management
5. Riparian zone rehabilitation (stock exclusion and re-vegetation)
6. Reticulated sewerage, and WSUD to enable treatment and assimilation of nutrients onsite in all existing urban areas
7. Appropriate location and land-use restrictions on the keeping of livestock or horses on rural residential and lifestyle lots
8. No horticulture or intensive animal industries in areas with high watertables and large density of artificial drains.

We modelled combinations of different management actions to examine potential nitrogen and phosphorus load reductions to the estuary. We modelled the management actions using a treatment train[6]. These scenarios aim to show the maximum effect of selected management actions at a high level of adoption.

We modelled the following combinations of management actions for estuary catchments on the coastal plain:

- Best-practice agriculture:
    1. All beef and dairy farms adopt best-practice fertiliser management, including use of LWSP fertiliser on low-PRI soils
    2. All beef and dairy farms with low-PRI soils apply soil amendments to increase soil P retention and decrease nutrient losses
    3. All dairy sheds use best-practice effluent management
    4. All intensive animal industries reduce nutrient discharge by 95%. These industries include piggeries, abattoirs, feedlots, stockyards and poultry.

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[6] A **treatment train** of management actions sequentially treats nutrients by actions that operate at the source of nutrient loss (e.g. soil amendment), actions that operate in the transport pathways (e.g. riparian zone rehabilitation) and actions that act at the end of catchment (e.g. constructed wetlands).

- Non-agricultural actions:
    1. Large-scale revegetation with deep-rooted vegetation (native vegetation and plantation) so that 50% of the catchment area has deep-rooted vegetation. In coastal catchments that drain to the estuary this requires replanting 248 km^2 with native vegetation (a 9.4% area increase from current area). The following catchments are unaffected: Dirkbrook (51% deep-rooted vegetation), Mandurah (urban catchment), Lower Murray (51% deep-rooted vegetation), Meredith Drain (50% deep-rooted vegetation) and the Upper Murray (upland catchment with 45% deep-rooted vegetation).
    2. Fencing and re-vegetation of the 1,394 km of streams and drains that potentially require management.
    3. The targeted removal of 1,074 septic tanks in the following suburbs: Falcon, Coodanup, Park Ridge-Bouvard and Pleasant Grove.
    4. Water sensitive urban design (WSUD) retrofitting of all existing urban areas.
- All actions described above (best-practice agriculture and non-agricultural).

See Figure 8.1 for the nitrogen and phosphorus loads for these different management combinations, as well as the estimated loads for the urban expansion (Section 7.1) and agricultural development (Section 7.2) scenarios. Figure 8.1 also distinguishes the nutrient load from estuary catchments on the coastal plain (affected by management actions) and the Upper Murray (unaffected by management actions).

The coastal catchment best-practice agriculture scenario reduced nitrogen and phosphorus loads by 4% and 57% respectively. This scenario nearly met the phosphorus target but had a small effect on nitrogen loads. The non-agricultural management actions in the coastal catchment reduced nitrogen and phosphorus loads to the estuary by 27% and 36% respectively. Neither target was met in this scenario, although nitrogen load reductions were much greater due to large-scale re-vegetation and riparian zone management actions. The combination of agricultural and non-agricultural management actions in the coastal catchments reduced phosphorus loads to the estuary below the target and had a load reduction of 66%. Nitrogen loads were reduced by 31% in this scenario but did not achieve the target.

Our modelling shows that with significant effort, phosphorus loads can be managed to achieve targets. The same is not true for nitrogen management, as the nitrogen target was not met in any scenario. Of the 11 scenarios we modelled, only two had a significant effect on nitrogen loads. Dissolved organic nitrogen makes up most of the nitrogen in measurements taken in the Peel-Harvey. This form of nitrogen is recalcitrant and difficult to treat in the catchment but can contribute to estuary eutrophication (Seitzinger & Sanders 1997; Petrone et al. 2009). Thus, further work is required to:

a) understand the fate and importance of dissolved organic nitrogen on eutrophication in the Peel-Harvey

b) develop management actions for dissolved organic nitrogen treatment if required.

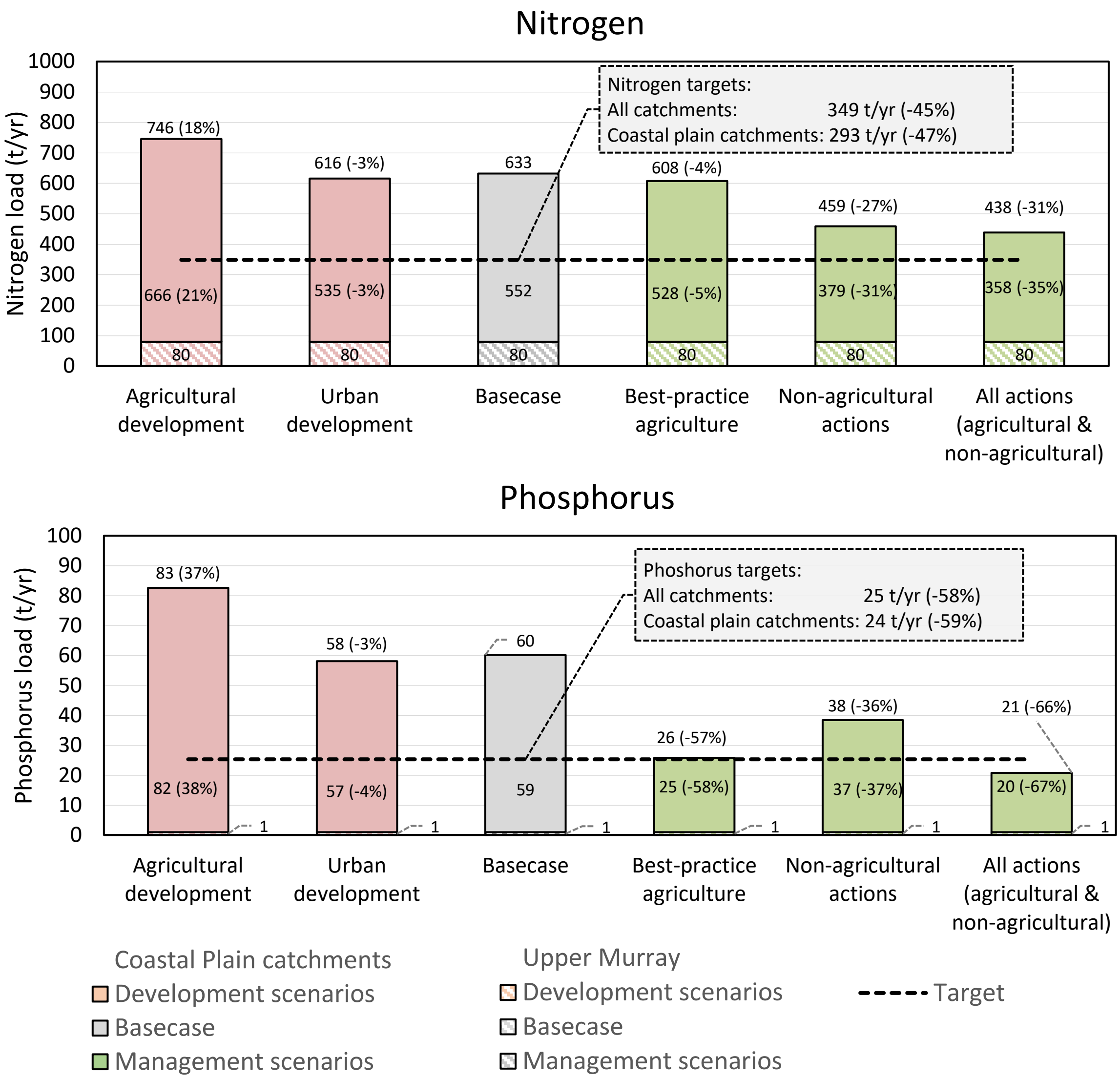

Figure 8.1: Nitrogen and phosphorus loads to the Peel-Harvey estuary for different combinations of management actions implemented in estuary coastal plain catchments. The top, middle and bottom labels represent nutrient loads from all estuary catchments, estuary coastal plain catchments and the Upper Murray catchment respectively. The percentages in the brackets are the differences between the basecase load and the scenario load.

In Figure 8.1 the urban and agricultural development scenarios are contrasted against the management scenarios. The urban development scenario, which includes WSUD (Section 7.1), results in reductions of 17 tonnes (3%) and 2 tonnes (3%) in average annual nitrogen and phosphorus loads to the estuary respectively. The agricultural development scenario (Section 7.2) results in increases in the average annual nitrogen and phosphorus loads of 114 tonnes (18%) and 22 tonnes (37%) respectively.

In the agricultural development scenario, we modelled the development proposed for the Peel Food Zone as 3,000 ha of in-ground horticulture in the Nambeelup catchment. We did not include any intensive animal industries. The Nambeelup catchment has soil and landscape characteristics (see Figure 7.5) that promote offsite nutrient export. For Nambeelup to meet its targets, the largest load reductions of all the catchments must occur:

69% for nitrogen and 84% for phosphorus. An increased area of horticulture or intensive animal industries in Nambeelup would further degrade the Peel-Harvey estuary. This represents poor planning, which:

a) is contrary to the EPP 1992 (EPA 1992) and SPP 2.1 (Western Australian Planning Commission 1992)

b) conflicts with the longstanding effort of many individuals, catchment groups and governments to improve the estuary's ecological health

c) would be expensive to mitigate.

Enclosed greenhouse/hydroponic horticulture could only be considered 'closed loop' if all liquid and solid wastes were removed or isolated from the estuary and its catchment.

9 Conclusions and recommendations

Conclusions

Despite decreased flows and nutrient loads to the Peel-Harvey estuary due to decreasing rainfall, the Peel-Harvey estuary's ecological condition has not improved. A recent study shows its ecological condition may still be worsening (Section 6; DPC 2015b). Of particular note is the poor condition of the estuarine portions of the Serpentine and Murray rivers (Thompson 2019), which suggests a strong link between the current catchment inputs and estuary condition.

This study estimated nutrient loads to the Peel-Harvey estuary for the period of 2006–15. We derived estuary load targets based on nutrient concentration targets in the inflowing rivers. The concentration targets are a flow-weighted nitrogen concentration of 1.2 mg/L and a flow-weighted phosphorus concentration of 0.1 mg/L. These concentration targets resulted in maximum acceptable loads to the estuary of about 350 tonnes for nitrogen and 25 tonnes for phosphorus for the modelling period 2006–15. The current loads – 633 tonnes of nitrogen and 60 tonnes of phosphorus – must decrease by 284 tonnes (45%) for nitrogen and 35 tonnes (58%) for phosphorus to achieve the targets.

Our scenario modelling examined the relative benefits of land use and management changes. This determined that no management action alone would achieve the required load reductions. A large amount of intervention is required to achieve the nutrient targets, especially for nitrogen.

As most of the nutrient load to the estuary comes from beef and dairy farms (69% of the nitrogen and 75% of the phosphorus) in the coastal plain portion of the catchment, better management practices on those farms would achieve the largest load reductions. A scenario that included fertiliser and effluent management, as well as application of soil amendments to low-PRI soils on all beef and dairy properties, almost achieved the phosphorus target. This scenario did not greatly affect nitrogen loads because fertiliser management focuses on phosphorus fertiliser, and soil amendments reduce phosphorus but not nitrogen leaching.

The government has funded farm soil testing and fertiliser management programs in the Peel-Harvey catchment. 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 250 ha of farmland (22%). If all the participants followed the advice from the programs, long-term phosphorus loss to the estuary would be reduced by 8%. If 100% of beef and dairy farms adopted appropriate fertiliser management, phosphorus loads would decrease by about 32%.

Some land-use planning agencies promote urban and agricultural development in the Peel-Harvey coastal plain catchment given its proximity to Perth and a growing population. An urban development scenario resulted in little change to nutrient loads to the estuary, but the impact of urban development depends on whether it displaces areas with low nutrient inputs (such as native vegetation) or areas of high nutrient input (such as intensive animal industries or horticulture).

Our agricultural development scenario, which modelled 3,000 ha of horticultural development proposed for the Peel Food Zone, resulted in an 18% increase in nitrogen load and a 38% increase in phosphorus load to the estuary. This development would make achieving the estuary's phosphorus target impossible using source control measures, such as fertiliser management and soil-amendment application on low-PRI soils. With this amount of in-ground horticulture in the Nambeelup catchment, even with expensive end-of-catchment interventions and a large amount nutrient offset, it is unlikely that estuary load targets would be achieved. We also note that the Peel Food Zone's location in the Nambeelup catchment is a poor decision due to its soil and landscape characteristics (see Figure 7.5). Other locations in the Peel-Harvey catchment may be more suited to intensive agricultural development.

An alternative to in-ground horticulture is fully enclosed glasshouse horticulture. Glasshouses can be more efficient in terms of water use, but the Australian literature (Haine et al. 2011) suggests that glasshouse wastewater poses a substantial risk to surface water eutrophication and should not be discharged to the environment.

Our scenario modelling shows that management of intensive nutrient sources (industry, intensive animal industries and intensive horticulture) is required and would substantially reduce nutrient loading both locally and to the estuary.

By 2050, we expect average annual flow to the Peel-Harvey estuary to decrease by about 51% compared with the modelling period 2006–15, while nitrogen and phosphorus loads would decrease by 54% and 55% respectively. The Peel-Harvey estuary will be saltier for longer, and nutrient inflows are likely to have longer residence times in the lower estuarine river reaches and the estuary. The nutrients in the inflows may be more available for algal growth and the ecology may be stressed by the changed salinity regime.

Recommendations

We recommend the following:

1. Take steps to maximise the adoption of farm best-practice fertiliser management and the use of low-water-soluble phosphorus fertilisers on sandy soils.
2. Make available and promote a range of soil amendments through government agencies, farm extension programs and other initiatives such Healthy Estuaries WA.
3. Best-practice management of dairy shed effluent. (This would substantially reduce nutrient loading to the estuary. Management of dairy shed effluent generally has a low standard in the Peel-Harvey catchment and elsewhere in south-western Australia. Recent State Government funding has improved standards, but further work is required.)
4. Implement the actions promoted in SPP 2.1. (Rehabilitation of all riparian zones would have a large environmental benefit beyond nutrient filtering. It would help create biodiversity corridors and improve stream ecological health. We recommend re-vegetation of all riparian zones, including 50% coverage with deep-rooted vegetation. To achieve this, a 250 km^2 area in the coastal plain portion of the catchment would need re-vegetation.

5. Conduct an environmental water requirement study for the Peel-Harvey estuary to examine stresses on water. (There is increasing groundwater extraction and plans to increase surface water abstraction in the Peel-Harvey catchment while rainfall is decreasing and it is getting hotter.)
6. In response to a proposed 3000 ha development of in-ground annual horticulture in the Peel Food Zone:
    a. Measure the nutrient exports from greenhouse/hydroponic horticulture locally
    b. Assess and demonstrate the efficacies of nutrient removal technologies locally
    c. Develop guidelines to establish and operate greenhouse/hydroponic horticulture in sensitive Western Australian environments, such as the Peel-Harvey catchment.

    (This proposal would substantially increase phosphorus loading to the Peel-Harvey estuary. Greenhouse/hydroponic horticulture is said to have lower or no nutrient emissions (i.e. closed loop) when compared with traditional in-ground horticulture. Yet the literature suggests that greenhouse/hydroponic horticulture can have greater nutrient emissions than traditional horticulture, even when effluent recycling systems are used.)
7. Conduct further work to estimate maximum allowable loads to the Peel-Harvey estuary under different climatic conditions to improve its ecological health. (This work could use the recently developed Peel-Harvey estuary model. Once we achieve a better understanding of estuary targets, we should review the nutrient concentration and load targets for the inflowing rivers.)
8. Assess the uptake of farm best-practice to create appropriate incentives for farm extension programs, define the social or economic benefits, and put enforcement measures in place. (Note that improved land management brought about by land holders changing their practices requires ongoing education and extension programs).

References

Allen, R, Pereira, L, Raes, D & Smith, M 1998, *Crop evapotranspiration – Guidelines for computing crop water requirements*, FAO irrigation drainage paper 56, Food and Agriculture Organization of the United Nations, Rome.

Allen, DG & Jeffery, JC 1990, *Methods of analysis of phosphorus in Western Australia,* Agricultural Chemistry Laboratory, report no. 37, Chemistry Centre, Perth, Western Australia.

ANZECC & ARMCANZ 2000, *Australian and New Zealand guidelines for fresh and marine water quality*, Australia and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand.

APrince Consulting 2006, *Market development study: used glass*, report for the Western Australian Waste Management Board, Perth, Western Australia.

Asselman, NEM 2000, 'Fitting and interpretation of sediment rating curves', *Journal of Hydrology*, vol. 234, pp 228–248.

Barrow 1982, 'Possibility of using caustic residue from bauxite for improving the chemical and physical properties of sandy soils', *Australian Journal of Agricultural Research*, vol. 33, pp 275–285.

Bird, PR, Bicknell, D, Bulman, PA, Burke, SJA, Leys, JF, Parker, JN, Van der Sommen, FJ & Voller, P 1992, 'The role of shelter in Australia for protecting soils, plants and livestock', *Agroforestry Systems*, vol. 20, pp 59–86.

Bradby K 1997, *Peel-Harvey: the decline and rescue of an ecosystem*.

Carr, R & Podger, G 2012, 'eWater Source – Australia's next generation IWRM modelling platform', *34th Hydrology and Water Resources Symposium*, ISBN 978-1-922107-62-6.

Charles, S, Silberstein, R, Teng, J, Fu, G, Hodgson, G, Gabrovsek, C, Crute, J, Chiew F, Smith, I, Kirono, D, Bathols, J, Li, L, Yang, A, Donohue, R, Marvanek, S, McVicar, T, Van Niel, T & Cai, W 2010, *Climate analyses for south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project*, CSIRO, Australia, 83p.

ChemCentre 2018, *Ellen Brook soil amendment trial: Ellen Brook, Western Australia*, ChemCentre project T233, Perth, Western Australia.

Chiew, FHS, Peel, MC & Western, AW, 2002, 'Application and testing of the simple rainfall-runoff model SIMHYD', In: Singh, VP & Frevert, DK, (eds.), *Mathematical Models of Small Watershed Hydrology and Applications,* Water Resources Publications, Littleton, USA, pp 335–367.

Davidson, WA 1995, *Hydrogeology and groundwater resources of the Perth region Western Australia*, Department of Minerals and Energy, Geological Bulletin of Western Australia, Bulletin 142.

Davies, J, Vukomanovic, S, Yan, M & Goh, J 2000, 'Stormwater quality in Perth, Western Australia', In: Hydro 2000, 3rd International Hydrology and Water Resources Symposium, Institution of Engineers Australia, *Interactive Hydrology*, pp 271–276, Perth, Nov 2000.

Dairy Australia 2008, *Effluent and manure management database for the Australian dairy industry*, Australia.

Dairy Australia 2016, *Dairy farm monitor project Western Australia annual report 2015–16*, Australia.

Degens, BP & Shackleton, M 2016, *Iron man gypsum amendment of subsoil drains to treat nutrients in urban groundwater discharge*, Water Science Technical Series, report no. 78, Department of Water, Western Australia.

Degens, BP 2020, Personal communication, Senior Environmental Officer, Department of Water and Environmental Regulation, Western Australia.

Department of Agriculture 2004, *Guidelines for the environmental management of beef and cattle feedlots in Western Australia*, Bulletin 4550 ISSN 1326-415X, Perth, Western Australia.

Department of Environment 2004, *Environmental code of practice for poultry farms in Western Australia*, ISBN – 1 920947 24 8, Perth, Western Australia.

DoP – see Department of Planning

Department of Planning 2014a, *Industrial land development outlook spatial dataset*, Department of Planning, Perth, Western Australia.

—2014b, *Proposed and approved rural residential developments spatial dataset*, Department of Planning, Perth, Western Australia.

—2015, *Urban growth monitor spatial dataset*, Department of Planning, Perth, Western Australia.

DPLH – see Department of Planning, Lands and Heritage

Department of Planning, Lands and Heritage 2017, *Regional schemes and zones spatial dataset,* Department of Planning, Lands and Heritage, Perth, Western Australia.

—2018a, *Industrial class of action spatial dataset,* Department of Planning, Lands and Heritage, Perth, Western Australia (accessed 27/3/2018).

—2018b, *Framework land use spatial dataset*, Department of Planning, Lands and Heritage, Perth, Western Australia (accessed 27/3/2018).

—2018c, *Rural residential class of action spatial dataset*, Department of Planning, Lands and Heritage, Perth, Western Australia (accessed 27/3/2018).

—2018d, *Urban class of action spatial dataset*, Department of Planning, Lands and Heritage, Perth, Western Australia (accessed 27/3/2018).

—2019, *Government Sewerage Policy 2019*, Department of Planning, Lands and Heritage, Perth, Western Australia (accessed 6/5/2021 https://www.dplh.wa.gov.au/government-sewerage-policy).

DPC – see Department of Premier and Cabinet

Department of Premier and Cabinet 2015a, *Perth and Peel Green Growth Plan for 3.5 million – Draft strategic conservation plan for the Perth and Peel regions*, Western Australia.

—2015b, *Perth and Peel Green Growth Plan for 3.5 million – Draft EPBC Act strategic impact assessment report Appendix D: Ramsar condition statements*, Western Australian Government, December 2015.

DPI – see Department of Primary Industries

Department of Primary Industries 2007, *Making better fertiliser decisions for grazed pastures in Australia*, Victorian Government, Melbourne.

DPIRD – see Department of Primary Industries and Regional Development.

Department of Primary Industries and Regional Development 2018, *Using soil test results to calculate phosphorus rate for high rainfall clover pastures*, Government of Western Australia, Perth (accessed 6/5/21 https://www.agric.wa.gov.au/soil-nutrients/phosphorus-high-rainfall-clover-pastures).

DoW – see Department of Water

Department of Water 2007a, *Hydrographic catchments – subcatchments spatial dataset*, Department of Water, Perth, Western Australia.

—2007b, *Rural abattoirs*, Water quality protection note (WQPN) no. 98, Perth, Western Australia.

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

DWER – see Department of Water and Environmental Regulation

Department of Water and Environmental Regulation 2017, *Decision process for stormwater management in Western Australia*, Department of Water and Environmental Regulation, Perth.

Douglas, G, Wendling, L, Adeney, J, Johnston, K & Coleman, S 2010, *Investigation of mineral-based by-product use as a soil amendment: Results from the Bullsbrook turf farm*, CSIRO: Water for a Healthy Country National Research Flagship.

Duncan HP 1999, *Urban stormwater quality: a statistical overview*, Cooperative Research Centre for Catchment Hydrology, Technical Report 99/3.

Ecotones & Associates 2005, *SSPRED: the support system for phosphorus reduction decisions – model framework development report*, Department of Agriculture Peel-Harvey CCI Project, Denmark, Western Australia.

EPA – see Environmental Protection Authority

Environmental Protection Authority 1992, Environmental Protection (Peel Inlet-Harvey Estuary) Policy 1992, approved by Minister under section 31(d) of *Environmental Protection Act 1986, Government Gazette*, WA 5969 11 December 1992.

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

Geoscience Australia 2011, *Peel LiDAR spatial dataset,* Geoscience Australia.

Haine, B, Coade G & McSorley A, 2011, *Nutrient export monitoring: agricultural nutrient exports and mitigation in the Hawkesbury-Nepean*, report prepared by the New South Wales Office of Environment and Heritage for the Australian Government, New South Wales, Australia.

Hall, J, Kretschmer, P, Quinton, B & Marillier, B, 2010, *Murray hydrological studies: surface water, groundwater and environmental water, conceptual model report,* Water Science Technical Series, report no. WST 16, Department of Water, Western Australia.

Hall, J 2009, *Nutrient modelling in the Vasse Geographe catchment,* Water Science Technical Series, report no. 2, Department of Water, Western Australia.

—2018, Personal communication, Principal Environmental Officer, Department of Water and Environmental Regulation, Western Australia.

—2019, *Managing rural drains to facilitate the removal of nutrients on the Swan Coastal Plain: draft report*, Department of Water and Environment, Western Australia.

Helshel, DR & Hirsch, RM 1992, *Statistical methods in water resources*, Elsevier, Amsterdam, 522p.

Hennig, K & Kelsey, P 2015, *Avon Basin hydrological and nutrient modelling*, Water Science Technical Series, report no. 74, Department of Water, Perth, Western Australia.

Hennig, K, Kelsey, P & Hall, J, 2019, Peel Integrated Water Initiative (PIWI) hydrological and nutrient modelling, Aquatic Science Branch internal report, Department of Water and Environmental Regulation, Perth, Western Australia.

Hirschberg, 1991, *Inventory of known and inferred point sources of groundwater contamination in the Perth Basin, WA,* Geological Survey of Western Australia, Record 1991/7.

—1992, *Municipal waste disposal in Perth and its impact on groundwater quality,* Hydrogeology report no. 1992/30, Geological Survey of Western Australia, Perth.

Horowitz, JA 2003, 'An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations', *Hydrological Processes*, vol. 177, pp. 3387–3409

Horticulture for Tomorrow 2014, *Guidelines for environmental assurance in Australian horticulture: second edition*, managed by Horticulture Australia Limited.

Hugues-dit-Ciles, J, Kelsey, P, Marillier, B, Robb, M, Forbes, V& McKenna, M 2012, *Leschenault water quality improvement plan*, Department of Water, Western Australia.

IOCI – see Indian Ocean Climate Initiative

Indian Ocean Climate Initiative 2012, *Western Australia's weather and climate: a synthesis of Indian Ocean Climate Initiative stage 3 research*, CSIRO and BoM, Australia.

IPCC – see Intergovernmental Panel on Climate Change

Intergovernmental Panel on Climate Change 2007, 'Climate change 2007: physical science basis', in S Solomon, D Qin, M Manning, Z Chen, M Marquis, K Averyt, M Tignor & H Miller (eds), *Contribution of Working Group I to the Fourth Assessment Report of the* Intergovernmental Panel on Climate Change, ISBN 978-0-521-88010-7.

—2015, 'Climate change 2014: synthesis report'*, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core writing team, RK Pachauri & LA Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jakeman, AJ, Littlewood IG, & Whitehead, PG, 1990, 'Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments', *Journal of Hydrology* vol. 117, pp 275–300.

Joint Government and Fertiliser Industry Working Party 2007, *Fertiliser Action Plan: phasing-out the use of highly water soluble phosphorus fertilisers in environmentally sensitive areas of southwest Western Australia,* Perth, Western Australia.

Kelsey, P, Hall, J, Kitsios, A, Quinton, B & Shakya, D 2010a, *Hydrological and nutrient modelling of the Swan-Canning coastal catchments*, Water Science Technical Series, report no. 14, Department of Water, Western Australia.

Kelsey, P, King, L & Kitsios, A 2010b, *Survey of urban nutrient inputs on the Swan Coastal Plain*, Water Science Technical Series, report no. 24, Department of Water, Western Australia.

Kelsey, P, Hall, J, Kretschmer, P, Quinton, B & Shakya, D 2011, *Hydrological and nutrient modelling of the Peel-Harvey catchment*, Water Science Technical Series, report no. 33, Department of Water, Western Australia.

Kinhill Engineers 1988, *Peel Inlet and Harvey Estuary management strategy: environmental review and management programme – stage 2*, Kinhill Engineers, Western Australia.

Krupa, A 2014, *Annual nutrient survey for local government authorities – results 2014*, SERCUL, Western Australia.

Ladson, A 2008, *Hydrology, an Australian introduction*, Oxford University Press, Melbourne.

Latto, A, Noonan, J, & Taylor, RJ 2000, *Environmental guidelines for new and existing piggeries,* Department of Agriculture and Food, Bulletin 4416, Perth, Western Australia.

Lavell, KM, Summers, RN, Weaver, DM & Clarke MF 2004, 'The Peel Harvey coastal catchments initiative: preliminary findings on the adoption of water quality best management practices', *Nutrient management forum April 2004*, Albany, Western Australia.

Lobry-de-Bruyn, L & Andrews, S 2016, 'Are Australian and United States farmers using soil information for soil health management?', *Sustainability*, vol. 8 (4), 304.

Loftis, JC, McBride, GB & Ellis, JC 1991, 'Considerations of scale in water quality monitoring and data analysis', *Water Resources Research*, vol. 12, no. 5, pp. 1037–1046.

Maddern, RJ 2016, *Low water-soluble super phosphate fertiliser for pasture production in south-western Australia*, PhD thesis, Curtin University, Western Australia.

Marillier, B, Hall, J & Shakya, D 2009, *Water-balance modelling of the Leschenault catchment*, Water Science Technical Series, report no. 10, Department of Water, Perth, Western Australia.

Marillier, B, Kretschmer, P, Hall, J & Quinton, B 2012, *Lower Serpentine hydrological studies – conceptual model report*, Water Science Technical Series, report no. 45, Department of Water, Western Australia.

McDowell R & Condron L, 2004, 'Estimating phosphorus loss from New Zealand grassland soils', *New Zealand Journal of Agricultural Research*, vol. 47:2, pp 137–145.

McDowell, RW, Monaghan, RM & Wheeler, D 2005, 'Modelling of phosphorus losses from pastoral farming systems in New Zealand', *New Zealand Journal of Agricultural Research*, vol. 48, Iss. 1, pp. 131–141.

McGahan, E, Wiedemann, SG & Gould, N 2018, *Egg industry environmental guidelines*, Australian Eggs Limited publication no. 1PS701AA, Sydney, New South Wales.

Meals, DW, Dressing, SA & Davenport, TE 2010, 'Lag time in water quality response to best management practices: a review', *Journal of Environmental Quality*, vol. 39, pp. 85–96.

Meat & Livestock Australia 2011, *National procedures and guidelines for intensive sheep and lamb feeding systems*, prepared by Productive Nutrition Pty Ltd June 2011, Sydney, New South Wales.

Meat & Livestock Australia 2012a, *National guidelines for beef cattle feedlots in Australia – third edition*, Sydney, New South Wales.

Meat & Livestock Australia 2012b, *National beef cattle feedlot environmental code of practice – second edition*, Sydney, New South Wales.

Melbourne Water 2013, *Water sensitive urban design: south eastern councils*, Victorian Government, Melbourne.

Moore, GA, Sanford, P & Wiley, T 2006, *Perennial pastures for Western Australia,* Bulletin 4690, Department of Agriculture and Food, Western Australia, Perth.

NSW DPI – see New South Wales Department of Primary Industries

New South Wales Department of Primary Industries 2008, *Environmental management guidelines for the dairy industry*, New South Wales.

Ocampo, C, Kidd, D & Ryan, M 2018, *Jenkins' weir study (2013–2015) final report*, School of Plant Biology, University of Western Australia, 129pp.

Ovens, R, Weaver, D, Keipert, N, Neville, S, Summers, R & Clarke, M 2008, 'Farm-gate nutrient balances in south west Western Australia – an overview', *12th International Conference on Integrated Diffuse Pollution Management*, Thailand, August 2008.

Overseer Limited 2018a, *How the Overseer engine works.* (Accessed 2/5/2019 https://www.overseer.org.nz/how-overseer-engine-works)

Overseer Limited 2018b, *What is Overseer?* (Accessed 2/5/2019 https://www.overseer.org.nz/what-is-overseer)

Parnell, D 2017, Personal communication, Project Officer, Western Dairy.

Pavlov, VR 2015, *Hydrogeological impact assessment of infiltrated treated wastewater at the Gordon Road wastewater treatment plant*, University of Western Australia Master of Hydrogeology thesis, Perth, Western Australia.

Perrin, C, Michel, C & Andréassian, V, 2003, 'Improvement of a parsimonious model for streamflow simulation', *Journal of Hydrology*, vol. 279, pp 275–289.

Petrone, KC, Richards, JS & Grierson, PF, 2009, 'Bioavailability and composition of dissolved organic carbon and nitrogen in a near coastal catchment of south-western Australia', *Biogeochemistry*, vol. 92, pp 27–40.

Peel-Harvey Catchment Council 2017, *Horticulture in the Peel-Harvey: a guide for investors and growers*, an initiative of the Peel Regional Leaders Forum and Peel Sustainable Agriculture Technical Working Group 2015, Mandurah, Western Australia.

Phillips, JM, Webb, BW, Walling, DE and Leeks, GJL 1999, 'Estimating the suspended sediment loads of rivers in the LOIS study area using infrequent samples', *Hydrological Processes*, vol. 13, pp. 1035–1050.

Rivers 2012, Spatial and temporal variations and patterns in water and nutrient dynamics within agriculturally-dominated watersheds in south west Australia, University of Western Australia PhD thesis.

Ritchie, GSP, Weaver, DM & Anderson GC 1985, 'Long-term phosphorus losses from deep grey sands and duplex soils', *Department of Conservation and Environment Western Australia Bulletin No 195*, pp 45–57.

Ritchie, GSP & Weaver, DM 1993, 'Phosphorus retention and release from sandy soils of the Peel-Harvey catchment', *Fertiliser Research*, vol. 36, pp 115–122.

Robinson, B, Shaw, M, Silburn, M, Roberts, A, Viagak, O, Thornton, C, McClymont, D 2011, 'An improved model for linking phosphorus loads in runoff to climate, soil and agricultural management', *19th International Congress on Modelling and Simulation*, Perth, Australia, 12–16 December 2011.

Rogers, D 2019, Personal communication, Officer, Research Scientist, Department of Primary Industries and Regional Development, Western Australia.

Ruprecht, JK & Schofield, NJ 1991, *The effect of partial clearing on the hydrology and salinity of the Lemon catchment*, report no. WS 74, Surface Water Branch of the Water Authority, Perth, Western Australia.

Safstrom, R &, Short, N 2012, *Agriculture futures: potential rural land uses on the Palusplain*, Department of Agriculture and Food, report 372, Western Australia.

Seitzinger, S & Samders, RW 1997, 'Estuarine eutrophication: the contribution of dissolved organic nitrogen', *Marine Ecology Progress Series,* vol. 159, pp 1–12.

Selbie D, Watkins, NL, Wheeler, DM & Shepard, MA 2013, 'Understanding the distribution and fate of nitrogen and phosphorus in Overseer ®', *Proceedings of the New Zealand Grassland Association*, vol. 75, pp113–118.

Schofield, NJ & Bari, MA 1991, 'Valley reforestation to lower saline groundwater tables: results from Stene's Farm, Western Australia', *Australian Journal of Soil Research,* vol. 29, pp 635–50.

Shams, R 2000, *Hydrogeological and nutrient balance of Spectacles wetlands*, Hydrogeology report no. HR 168, Perth, Western Australia.

Steele, J 2008, *Management of diffuse water quality pollution in the Peel-Harvey coastal drainage system: a strategic approach to implantation of best management practices*, Peel-Harvey Catchment Council, Mandurah, Western Australia.

Strategen 2013, *Harvey-Waroona irrigation water resource management operating strategy,* report prepared for Harvey Water, Western Australia.

Summers, RN 2018, Personal communication, Research Scientist, Department of Primary Industries and Regional Development, Western Australia.

Summers, RN, Smirk, DD & Karafilis, D 1996, ‘Phosphorus retention and leachates from sandy soil amendment with bauxite residue (red mud)’, *Australian Journal of Soil Research*, vol. 34, pp 555–567.

Summers, RN, Bolland, MDA & Clarke MF 2001, ‘Effect of application of bauxite residue (red mud) to very sandy soils on subterranean clover yield response’, *Australian Journal of Soil Research*, vol. 39, pp 979–990.

Summers, RN, Richards, P, Weaver, D & Rowe, D 2019, Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative, Resource Management Technical Report, internal report, Department of Primary Industries and Regional Development, Western Australia.

SRT – see Swan River Trust.

Swan River Trust 2008, *Healthy Rivers Action Plan*, Swan River Trust, Perth, Western Australia.

–2009, Swan Caning Water Quality Improvement Plan. Swan River Trust, Perth Western Australia.

Tennakoon, S & Ramsay, I 2020, *Disposal of effluent using irrigation: technical guideline*, Department of Environment and Science, Brisbane, Queensland.

Thomson, CE 2019, *Regional Estuaries Initiative, Estuary condition report: Peel-Harvey 2016/17*, Department of Water and Environmental Regulation, Western Australia.

Tucker, RW & O’Keefe, MF 2011, *National environmental guidelines for rotational outdoor piggeries*, Project 2011/1039 (2013), Australian Pork Ltd, Barton, ACT (revised).

Tucker, RW 2018, *National environmental guidelines for indoor piggeries – third edition*, APL Project 2015-2221, Australian Pork Ltd, Kingston, ACT.

Viney, NR, Sivapalan, M & Deeley, D 2000, ‘A conceptual model of nutrient mobilisation and transport applicable at large catchment scales’, *Journal of Hydrology*, vol. 240, pp 23–44.

Vlahos, S, Summers, KJ, Bell, DT & Gilkes, RJ 1989, ‘Reducing phosphorus leaching from sandy soils with red mud bauxite processing residues’, *Australian Journal of Soil Research*, vol. 27, pp 651–662.

Ward, B, Sparks, T & Blake, G 2011, *Denmark River water resource recovery plan,* Salinity and land use impacts series, report no. SLUI 40, Department of Water, Perth.

Watkins, N & Selbie, D 2015, *Technical description of Overseer for regional councils*, AgResearch contract report RE500/2015/084.

Weaver, D, Neville, S, Ovens, R, Keipert, N, Summers, R & Clarke, M 2008, ‘Farm gate nutrient balances in south west Western Australia – understanding nutrient loss risk within agricultural land uses', *12th International Conference on Integrated Diffuse Pollution Management*, Thailand, August 2008.

Welsh, WD, Vaze, J, Dutta, D, Rassam, D, Rahman, JM, Jolly, ID, Wallbrink, P, Podger, GM, Bethune, M, Hardy, MJ, Teng, J & Lerat, J 2013, 'An integrated modelling framework for regulated river systems', *Environmental Modelling and Software*, vol. 39, Issue C, January 2013, pp 81–102.

Wegner S, 1999, *A review of the scientific literature on riparian buffer width, extent and vegetation*, Office of Public Service and Outreach, Institute of Ecology, University of Georgia.

Wegner, S & Fowler, L 2000, *Protecting streams and river corridors, creating effective local riparian buffer ordinances*, Public Policy Research Series, Carl Vinson Institute of Government, University of Georgia.

Wendling, L, Douglas, G & Coleman, S 2009, *Characterisation of mining and industrial by-products with potential for use as environmental amendments*, CSIRO: Water for a Healthy Country National Research Flagship.

Wendling, L, Douglas, G, Coleman, S, Yuan, Z & Klauber, C 2010, *Nutrient and DOC removal from Ellen Brook waters: evaluation of mining by-products*, CSIRO: Water for a Healthy Country National Research Flagship, Perth, Western Australia, 78 pp.

WAPC – see Western Australian Planning Commission

Western Australian Planning Commission,1992, *Statement of Planning Policy no. 2.1 The Peel-Harvey coastal plain catchment*, gazetted 21 February 1992, Special Gazette no. 25, amended as per *Statement of Planning Policies 2003*, gazetted 19 September 2003.

Western Australian Planning Commission, 2006, *Statement of Planning Policy no. 2.9 Water Resources,* gazetted no. 227, 19 December 2006.

Western Dairy 2012, *Code of practice for dairy shed effluent Western Australia*, Western Australia (accessed 1/12/2020: https://content-prod.dairyaustralia.com.au/western-dairy/resources-repository/2020/07/09/code-of-practice-for-dairy-shed-effluent-in-wa#.X8b5HlUzZhE).

Wheeler, D, Legard, SF, De Klein, CAM, Monagahn, RM, Carey, PL, McDowell, RW & Johns, KL 2003, 'Overseer® nutrient budgets – moving towards on-farm resource accounting', in*: Proceedings of the New Zealand Grassland Association*, pp 191–194.

Wheeler, D et al. 2009, 'Overseer® nutrient budget model – what it is, what it does', *Implementing Sustainable Nutrient Management Strategies in Agriculture*, Occasional report no. 19: Currie, LD, Hanly, JA (Eds.), Massey University, Palmerston North, New Zealand.

Wheeler, D & Read, C 2016, 'Spotlight on Overseer: perspectives and approaches to addressing nutrient management challenges using an integrated farm systems model', *Proceedings of the 2016 International Nitrogen Initiative Conference*, Melbourne, pp 2–5.

Whelan, BR, Barrow, NJ & Carbon, BA 1981, 'Movement of phosphate and nitrogen from septic tank effluent in sandy soils near Perth, Western Australia', in *Proceedings of Groundwater Pollution Conference 1979*, Australian Water Resources Council, Department National Development, Perth, CSIRO Publishing, pp 226–233.

White, KS 2012, *Hardy Inlet water quality improvement plan: Stage one – the Scott River catchment,* Department of Water, Western Australia.

Zammit, C, Bussemaker, P & Hall, J 2006, *Establishment of a decision support system for the protection of the Peel Inlet and Harvey estuary*, Department of Environment, Aquatic Science Branch, Perth, Western Australia.

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