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Avon Basin hydrological and nutrient modelling

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Summary

The Avon Basin, approximately 120 000 km^2 in area, is the largest river catchment in the south-west of Western Australia. The basin's waterways flow to the Swan Estuary, on which the city of Perth is located. The eastern part of the basin has low rainfall, ancient geology with little relief, slowly flowing rivers and large areas of salt lakes. The western part of the catchment has higher rainfall, steeper topographic gradients and faster flowing rivers.

Following settlement of Western Australia by Europeans, rapid agricultural expansion occurred in the Avon Valley and the hinterland in what is now called the Wheatbelt. Much of the catchment was settled within 100 years. Since the 1950s, farm productivity has increased and current wheat yields are significantly greater than historical yields. The Avon Basin produces approximately one-fifth of Australia's wheat. Clearing (from 1830) and river training (mid-1950s to the mid-1970s) in the Avon Basin have left a badly degraded catchment and river system, with severe problems of salinisation, waterlogging, wind and water erosion, soil acidity, soil structure and health decline, biodiversity loss, and waterway sedimentation and eutrophication.

Current nutrient and sediment loads are causing environmental damage to the Avon Basin's waterways and the Swan Estuary. Macroalgal and potentially toxic microalgal blooms are common in tributaries, lakes and river pools. The Northam town pool suffers from (often toxic) algal blooms most summers. In February 2013, a potentially toxic cyanobacterial bloom established itself in the 34 km stretch of the Avon River from Northam to Toodyay and persisted for approximately five weeks.

As excessive nutrient and sediment concentrations and loads in the waterways are a principal cause of their poor ecological health, the aim of this study was to develop a catchment model to quantify the flows and nitrogen, phosphorus and sediment loads in the basin's waterways. The model quantified current flows and loads, and potential flows and loads following land-use, land-management or climate changes. This information can then be used to guide catchment management, by demonstrating how practical land management changes could improve agronomic practice and farm sustainability, as well as improving water quality in streams.

eWater's Source model coupled to the **LA**rge **S**cale **Ca**tchment **M**odel (LASCAM) hydrological model were calibrated against observed river flow and nutrient concentration data from across the catchment (17 flow sites and 11 water quality sites). The model was based on 61 modelling subcatchments, and 12 reporting catchments, which were the catchments of the major rivers. As sediment modelling is not included in Source, sediment loads were calculated using LOESS-load calculations.

The average annual flow and loads to the Swan Estuary from the Avon River for the period 2001–10 were:

- 195 GL flow
- 213 tonnes (t) of nitrogen
- 5.3 t of phosphorus
- 6500 t of sediment.

Most of the flows and loads (more than 99% on average) came from the wetter catchments in the west (Lower Avon, Middle Avon, Upper Avon, Wooroloo, Brockman, Mortlock North, Mortlock East and Dale catchments) which occupy 24% of the Avon Basin. Although the catchments to the east, upstream of Yenyening Lakes (Salt, Lockhart and Yilgarn) comprise 76% of the basin area, on average they contribute less than 1% of the flow and loads. This is because the Yenyening Lakes retain on average 95% of the inflowing water and nutrients.

Accurate land-use mapping was undertaken at the beginning of the project. As land-use nutrient input and output data were available from various sources (Ovens et al. 2008; Weaver et al. 2008; Kelsey et al. 2010b; Planfarm 2011; 2012) estimation of nutrient contributions from the basin's land uses was possible. Approximately 90% of the waterway nitrogen and phosphorus loads originate from broad-acre farming (wheat & sheep and mixed grazing). Urban nutrient loads (including wastewater treatment plants) contribute approximately 2.9% of the nitrogen and 4.2% of the phosphorus loads. Even though wastewater treatment plants (WWTPs) contribute only a small percentage of the total nutrient loads of the basin, they have local detrimental impacts. Other sources, in terms of percentage of total loads, include: intensive animal uses – 2.0% of the nitrogen and 2.1% of the phosphorus; native vegetation – 3.1% of the nitrogen and 1.1% of the phosphorus; all other land uses together contribute 2.7% of the nitrogen and 3.2% of the phosphorus loads.

As broad-acre farming contributes most (90%) of the nutrient loads to the catchment's waterways, significant improvement in waterway health will not be achieved without addressing this source. Farm nutrient-use efficiency is lowered by acidic soils, drought and a tendency to overfertilise to ensure crop growth is not nutrient limited. Farm management scenarios, which were based on addressing soil acidity and managing soil nutrient stores so that nutrients were matched to agronomic need, demonstrated that there is significant potential for improved nutrient management on farms. The assumptions underpinning these scenarios were taken from extensive studies by CSIRO (Gupta et al. 2011) and the Department of Agriculture and Food Western Australia (DAFWA) (Gazey & Davies 2009; Weaver & Wong 2011; Gazey & Andrew 2013).

These initiatives would not only reduce the amounts of nutrients lost from the farm but also reduce the fertiliser inputs and thus costs to farmers. Addressing soil acidity, improving soil health and not overfertilising also promote increased root depths and thus make crops more drought resistant. If half of the basin's wheat & sheep and mixed grazing farmers treated their soil acidity, nutrient loads at the basin outlet would reduce by approximately 4% for nitrogen and 6% for phosphorus. If these farmers also implemented actions to improve their nutrient-use efficiencies the nitrogen and phosphorus loads at the basin outlet could be substantially reduced (14% for nitrogen and 28% for phosphorus).

Healthy riparian zones provide buffers between agricultural and urban land uses and waterways. Vegetated riparian zones in agricultural landscapes can be considered to have four main functions:

- Reduction of stream bank erosion
- Interception of nutrients and sediment in surface and groundwater flows from adjacent paddocks to streams

- Restoration and/or maintenance of the stream ecosystem
- Provision of biodiversity corridors to link fragmented natural landscapes and provide refuge for terrestrial fauna

There have been considerable resources invested into riparian zone rehabilitation in the Avon Basin over the past twenty or so years. Despite this, it is estimated that approximately 74% of the basin's streams (21 000 km) have no riparian zone vegetation. Different rates of riparian rehabilitation were modelled to estimate potential impacts. For example, implementation of a riparian rehabilitation program that fenced and revegetated 40 km of streamline per year, for a 20-year period could decrease, at the basin outlet, nutrient loads of nitrogen by 9% and phosphorus by 4%. Rehabilitating all of the riparian zones of the Avon Basin was estimated to reduce nitrogen and phosphorus loads by 37% and 21% respectively.

Large-scale revegetation with deep-rooted perennial plants would also decrease flows and nutrient loads. However, this would reduce the area available for farming, so is unlikely to occur, unless the profitability of the deep-rooted perennial crops was similar to current farming profitability. Revegetation with deep-rooted plants may, however, be beneficial in some locations for lowering groundwater levels, controlling salinity and for providing habitat for endangered species or for rehabilitating riparian zones.

Many other scenarios, which examined individual actions or a combination of actions, are discussed in Section 6. Ending current WWTP discharges to rivers would reduce nitrogen and phosphorus loads at the basin outlet by approximately 3% and 4% respectively. The improvement of water quality at the local scale would be much more significant. For example, it was estimated that nitrogen and phosphorus loads in the lower Avon catchment would reduce by 13% and 14% respectively once discharge from the Northam WWTP to the Avon River stopped. The future urban development proposed for the basin is estimated to increase nitrogen and phosphorus loads at the basin outlet by 5% and 3% respectively, mainly due to the increased capacity of the Northam WWTP. These scenarios highlight the impacts of disposing of WWTP effluent from inland towns into rivers and the benefits of developing detention and reuse solutions.

Recommendations

The Avon Basin has a long history of productive agricultural industry. Despite the current environmental problems, primarily of soil acidity, salinity, and the challenge of declining winter rainfall affecting profitable farming, the Avon Basin is an important agricultural region. Improving farm practices will mean that farming in the Western Australian Wheatbelt is more sustainable, that is, farms are more profitable and do not adversely affect adjacent environments.

To improve water quality in the Avon Basin:

- Increase farm nutrient use efficiencies (NUEs) to improve farm profitability and minimise nutrient leaching.
- Restore riparian zones to provide a buffer between farmed land and waterways.

- Seek alternative solutions to manage WWTP discharge both to reduce discharge to streams and to provide alternative water supplies to rural communities.

To facilitate improvements to farm practice:

- Trial various options for ameliorating soil acidity with cost-effective options made available to farmers.
- Develop and demonstrate farm management practices that ameliorate soil acidity and apply nutrients to meet crop demand so that farmers are confident that these actions will improve the sustainability and profitability of their farms, as well as reducing impacts on adjacent water environments.

To improve drought resilience of farming systems in the Avon Basin:

- Recognise that droughts drastically reduce the nutrient-use efficiency of Wheatbelt farms.
- Investigate measures that improve soil biology and rooting depths, and thus plant vigour, and establish regimes that make farms more drought tolerant.

Conclusions

Although the Avon Basin and its waterways are severely degraded, there are many actions that can be implemented to rehabilitate the basin. The solutions discussed for farming enterprises aim to improve farm sustainability as well as minimise their off-farm environmental impacts.

Rehabilitation of riparian environments improves stream water quality and contributes significantly to preservation of habitat for terrestrial and riverine fauna as well as providing enhanced amenity to adjacent landholders. Rehabilitating the riparian zones of all medium- and high-order streams in the Avon Basin will provide significant benefits. Strategic riparian rehabilitation also creates biodiversity corridors.

Ceasing WWTP effluent discharge to rivers and establishing alternative disposal methods that reuse or recycle the effluent will also provide substantial benefits.

1 Introduction

The Avon River system is the largest river system in the south-west of Western Australia, with a catchment area of approximately 120 000 km^2 (Figure 1.1). The headwaters of the Avon River originate approximately 500 km inland. The Avon River, which becomes the Swan River at its confluence with Wooroloo Brook approximately 30 km from the coast, flows through Perth, the capital city of Western Australia. The rivers of the Avon Basin and the Swan River estuary are valued assets. However, poor water quality is a major threat to their social values and ecology.

The macro-nutrients, nitrogen and phosphorus (*nutrients*), are found in low concentrations in undisturbed aquatic ecosystems. Elevated stream nutrient concentrations can result in the rapid increase of algal populations (termed *algal blooms*), with some algal species being toxic. Following large algal blooms, their collapse and decomposition can result in the depletion of dissolved oxygen in the waterbody and the release of harmful algal toxins; both can result in rapid and widespread ecosystem harm.

The aim of this study is to estimate river flows, and nitrogen and phosphorus loads within the Avon Basin under current conditions and a range of scenarios. This study complements previous hydrological and nutrient modelling of the coastal catchments of the Swan-Canning Estuary undertaken to support the Swan Canning Water Quality Improvement Plan (SCWQIP) (Kelsey et al. 2010a). Sediment loads leaving the Avon Basin have also been estimated and compared with the sediment characteristics of coastal rivers. The modelling from this study and the previous work (SQWIP) will be used to inform land management and land-use planning on the most appropriate actions to minimise nutrient pollution of the waterways.

Prior to European settlement, the Avon Basin was inhabited by the Noongar people, the Aborigines of south-west Western Australia. The Noongar people were nomadic and moved between coastal estuaries and inland rivers, depending on the season. The region from Northam in the west to Southern Cross in the east, and from Wongan Hills in the north to Narrogin in the south was inhabited by Noongar tribes that spoke the Ballardong dialect (http://www.noongarculture.org.au/ballardong/). These people moved throughout the south-west to trade with other Noongar tribes and to access coastal food sources during summer months. Other Aboriginal groups inhabited eastern areas of the basin.

The Avon River was used as a source of food and water, and was the location of important cultural ceremonies. The Avon River features in Aboriginal mythology, with the Burlong Pool (near Northam) being the summer-time resting place of Waugul, the serpent-like spirit responsible for creating all of the large rivers of the south-west (Cummins et al. 1999). The main channel of the river from Walyunga National Park to Lake Nonalling (10 km north of Yealering) has been classified as a permanent site on the Aboriginal Sites System Registry (Department of Indigenous Affairs 2009).

Following the European settlement of Perth in 1829 agri-pastoral activity commenced in the Avon Valley. Agricultural activity gradually spread eastward through the Avon Basin during the 19th and 20th centuries. Farm areas expanded faster in the periods following each of the two world wars than in other periods. Since the 1950s, farm productivity has increased

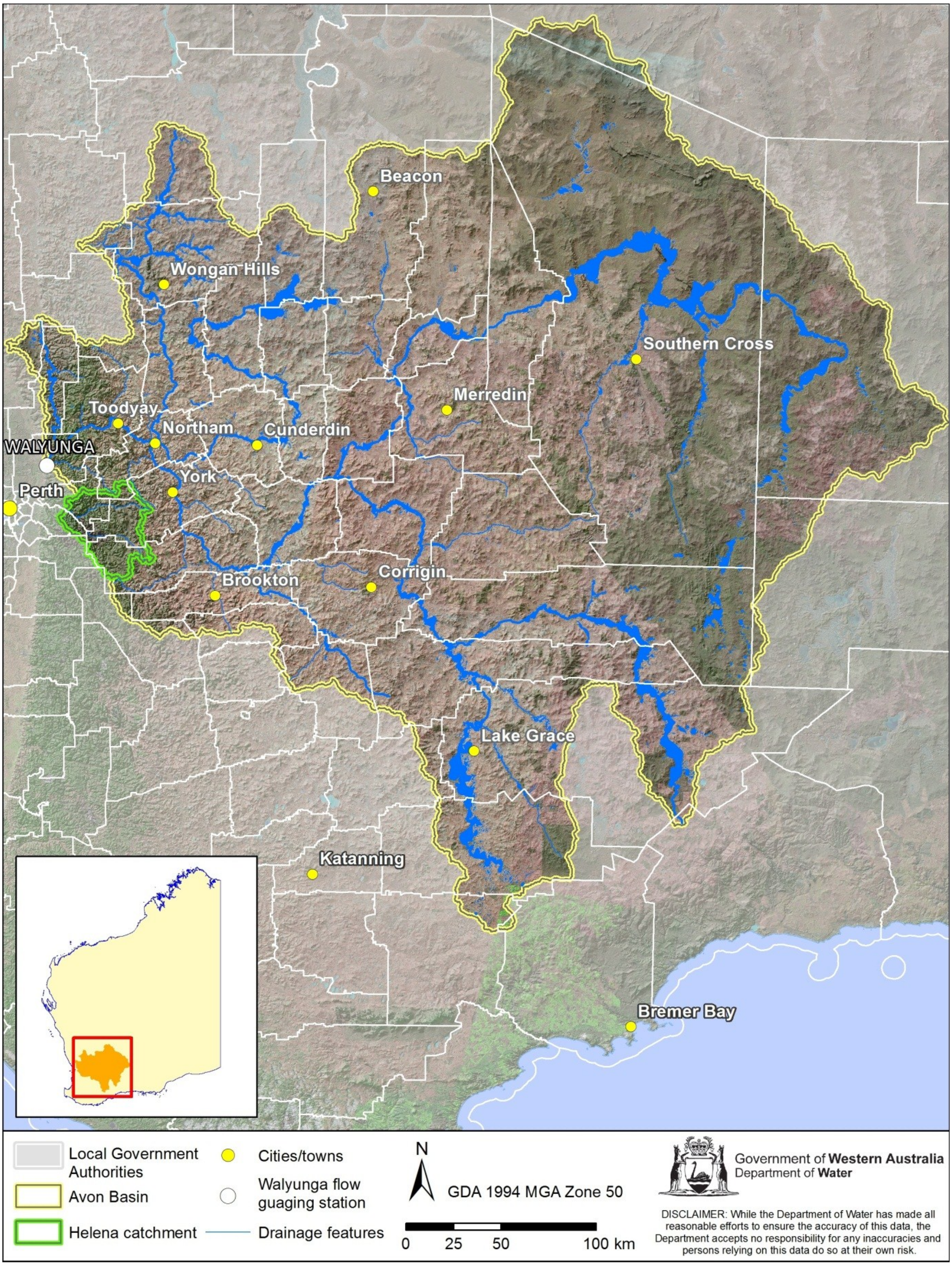


Figure 1.1: Major towns and shires of the Avon Basin

and current wheat yields are significantly greater than historical yields. The Avon Basin produces approximately one-fifth of Australia's wheat (O'Connor et al. 2004). Interesting and informative discussions of the history of the central Wheatbelt and Avon River basin can be found in many publications (e.g. Wood 1924; Harris 1996; WRC 1999; O'Connor et al. 2004).

Clearing for agriculture and the Avon River Training Scheme, undertaken in the 1950s and 1960s to prevent town-site flooding (WRC 1999), caused serious environmental damage in the catchment and rivers. Current farming practices, which use large inputs of fertilisers, contribute to poor downstream water quality. Algal blooms have occurred in the Avon River since the River Training Scheme (Hosja, pers. comm.). A bloom of the toxic cyanobacteria *Anabaenopsis* in February 2013 extended from Northam to Toodyay and had a cell count of more than 400 000 cells/mL. This bloom lasted for approximately five weeks and posed a serious threat to human and animal health.

Sections 2.1–2.6 describe the catchment in terms of its location, climate, geology, soils and land use. The environmental effects and challenges facing the catchment and river systems, including salinity, biodiversity impacts and land and water degradation are discussed in Section 2.7.

Section 3 discusses the basin's flow and nutrient data. Nutrient status, trends and loads are presented for sites across the basin. Total suspended sediment and turbidity data, and estimates of sediment loads to the upper Swan Estuary are discussed in Section 5.

eWater's Source model coupled to the **LA**rge **S**cale **Ca**tchment **M**odel (LASCAM; Sivapalan et al. 1996a, b, c; Viney et al. 2000) was used to estimate flow and nitrogen and phosphorus loads across the basin. These models, their required input data and calibrations are discussed in Section 4 and the modelling results presented in Section 5.

Scenario modelling to quantify the effects of potential future land-use and climate change and management actions on the flows and nutrient loads across the catchment is presented in Section 6. The modelling includes:

- Farm practice scenarios:
  - Soil acidity management
  - Farm nutrient management
- Riparian zone rehabilitation
- Point source management:
  - Management of WWTP and septic tank discharge through the detention and reuse of wastewater for irrigation
  - Removal of all identified point sources (WWTPs, septic tanks in towns, abattoirs, feedlots, piggeries, and stockyards)
- Urban development:
  - Effect of urban expansion in the Avon Arc Sub-Region Strategy (WAPC 2001) and the Northam Regional Centre Growth Plan (DRDL 2013)
- Large-scale revegetation
- Climate change: Projected future dry and wet climate at 2030.

2 Catchment description

2.1 Location

The Avon Basin drains an area of approximately 120 000 km^2 and is located in the south-west of Western Australia (Figure 1.1). It is approximately 480 km wide from north to south and east to west. In this study the outlet of the Avon Basin has been taken to be the flow gauging site 616011 (Swan River, Walyunga) in the Walyunga National Park, approximately 30 km inland from the coast.

The population of the Avon Basin has been declining since the peak in the 1950s at about 59 000 people and is currently about 43 000 people. The Avon Basin overlaps 48 local government authorities (Table 2.1) and includes approximately 50 towns (Figure 1.1). The largest town is Northam, with a population of 7000 people (Australian Bureau of Statistics 2011).

Table 2.1: Local government authorities in the Avon Basin

Local government authority	
City of Armadale	Shire of Lake Grace
City of Swan	Shire of Menzies
Shire of Beverley	Shire of Merredin
Shire of Brookton	Shire of Moora
Shire of Bruce Rock	Shire of Mount Marshall
Shire of Chittering	Shire of Mukinbudin
Shire of Coolgardie	Shire of Mundaring
Shire of Corrigin	Shire of Narembeen
Shire of Cuballing	Shire of Northam
Shire of Cunderdin	Shire of Nungarin
Shire of Dalwallinu	Shire of Pingelly
Shire of Dowerin	Shire of Quairading
Shire of Dumbleyung	Shire of Ravensthorpe
Shire of Dundas	Shire of Tammin
Shire of Gingin	Shire of Toodyay
Shire of Gnowangerup	Shire of Trayning
Shire of Goomalling	Shire of Victoria Plains
Shire of Jerramungup	Shire of Wandering
Shire of Kalamunda	Shire of Westonia
Shire of Kellerberrin	Shire of Wickepin
Shire of Kent	Shire of Wongan-Ballidu
Shire of Kondinin	Shire of Wyalkatchem
Shire of Koorda	Shire of Yilgarn
Shire of Kulin	Shire of York

2.2 Climate

The climate of the Avon Basin changes from temperate to semi-arid from west to east across the basin. The long-term average annual rainfall (1975–2003) ranges from 900 mm at the basin's western boundary to 300 mm in the east (Figure 2.1). More than 90% of the Avon Basin has a long-term average annual rainfall of 300–400 mm/yr. Average annual pan evaporation ranges from 1800 mm in the south to 3000 mm in the north (Figure 2.1).

The Avon Basin receives most of its rainfall in winter from frontal systems that originate in the south-west. The basin can be affected by ex-tropical cyclones in summer and autumn months. Such weather systems can cause minor–severe flooding. The most recent and notable flood-causing summer rainfall event was in January 2000.

On 15 January 2000, a thunderstorm delivered 48–109 mm of rainfall across the catchment. This was followed by 100–172 mm of rainfall from a tropical low pressure system on 22–23 January over a 200 km wide, north-east to south-west band across the basin (Muirden 2000). The rainfall caused flooding, primarily in the Lockhart River catchment and areas downstream.

Figure 2.2 shows the average monthly rainfall for three towns that represent the rainfall zones of the west Darling Range (Wooroloo), the central Wheatbelt (Northam) and the eastern Wheatbelt (Merredin). All sites receive most of their rainfall during winter (May–September). The town of Wooroloo receives substantially more rainfall during April–November than the sites to the east. Northam and particularly Merredin have a rainfall pattern more evenly distributed throughout the year. Additionally, Merredin receives more rainfall during December–March than the other sites. Figure 2.3 shows the monthly evaporation for the same sites. Evaporation is highest in November–March, with monthly evaporation increasing from west to east in all months.

Like the rest of the south-west of Western Australia, the Avon Basin has had a drying climate over the past 40 years. For example, the average annual rainfall at Northam (10111) was 446 mm for the period 1889–1974, 421 mm for the period 1975–2000 and 367 mm for the period 2001–10 (Figure 2.4). The average annual rainfall was 18% lower during 2001–10 than during 1889–1974.

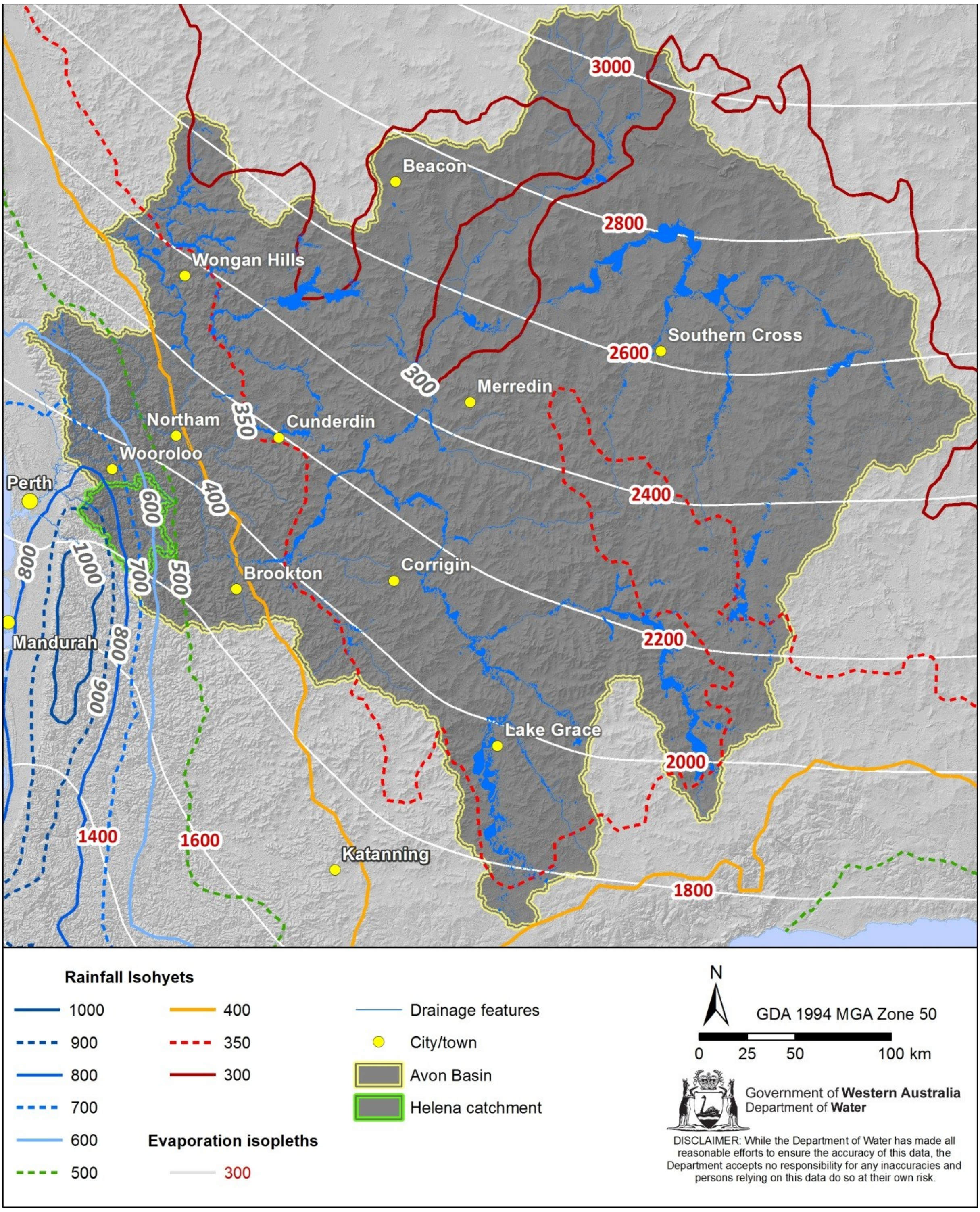


Figure 2.1: Rainfall isohyets and evaporation isopleths

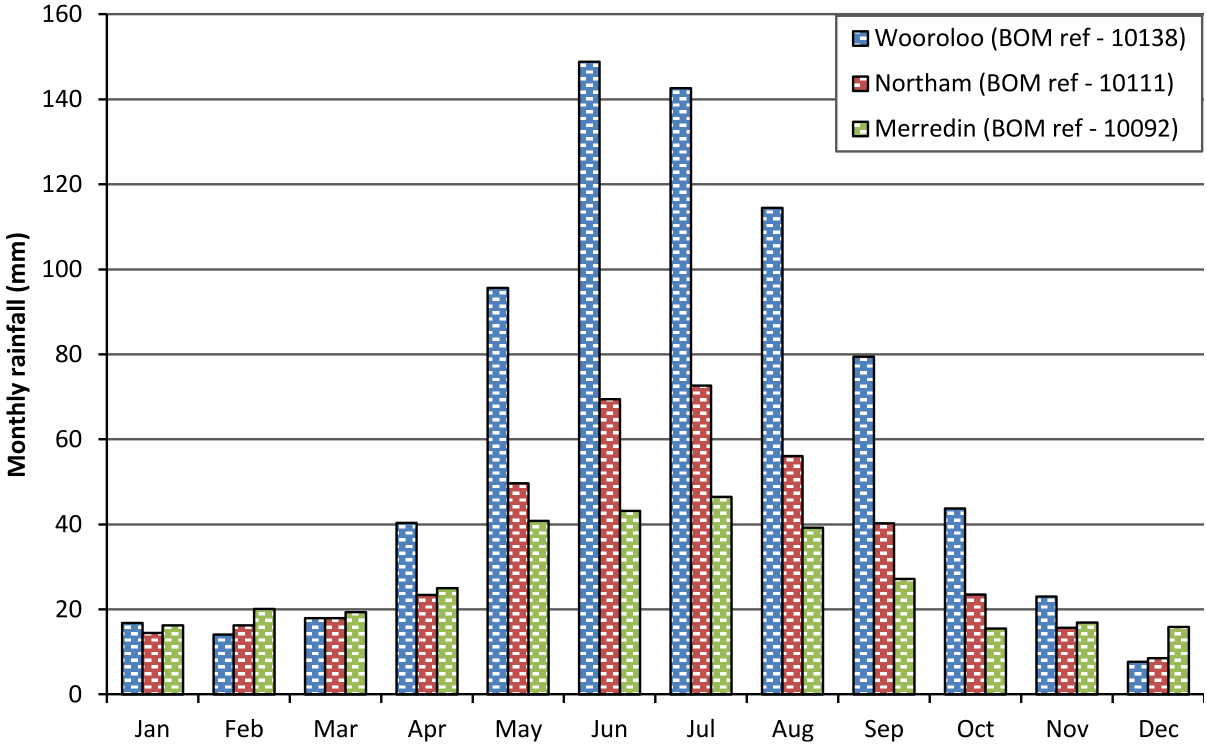


Figure 2.2: Average monthly rainfall for Wooroloo (10138), Northam (10111) and Merredin (10092)

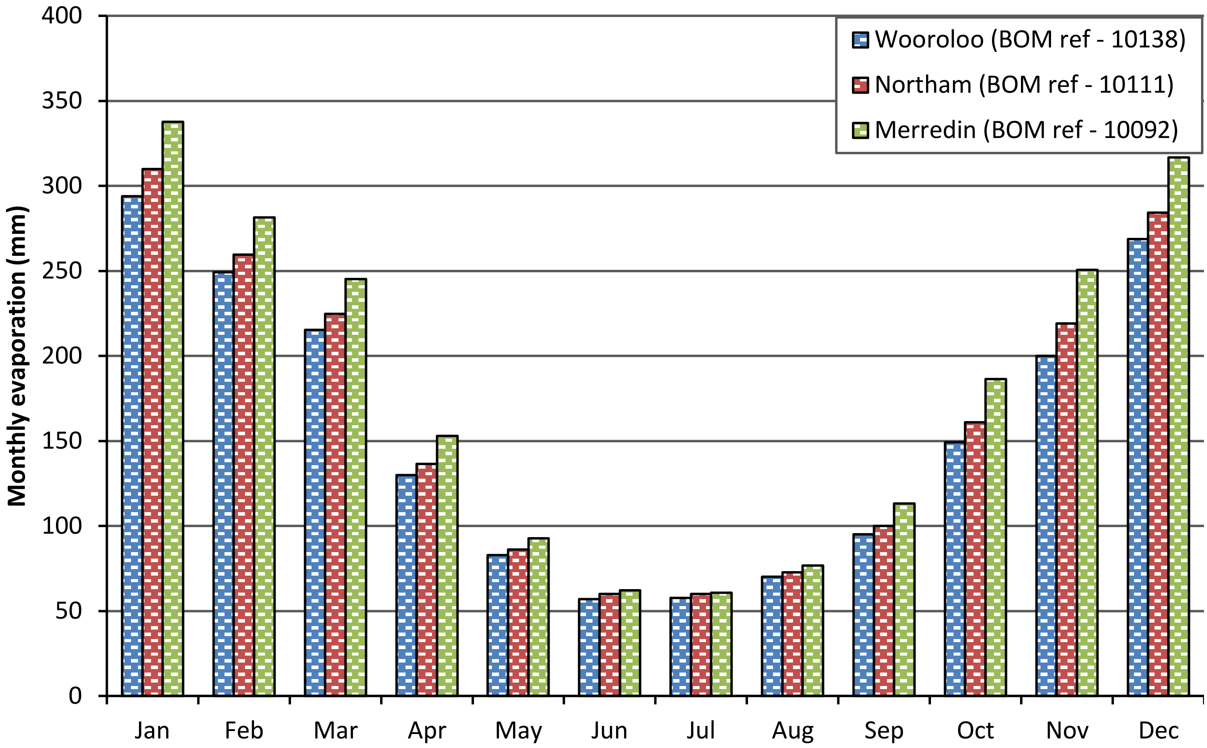


Figure 2.3: Average monthly evaporation for Wooroloo (10138), Northam (10111) and Merredin (10092)

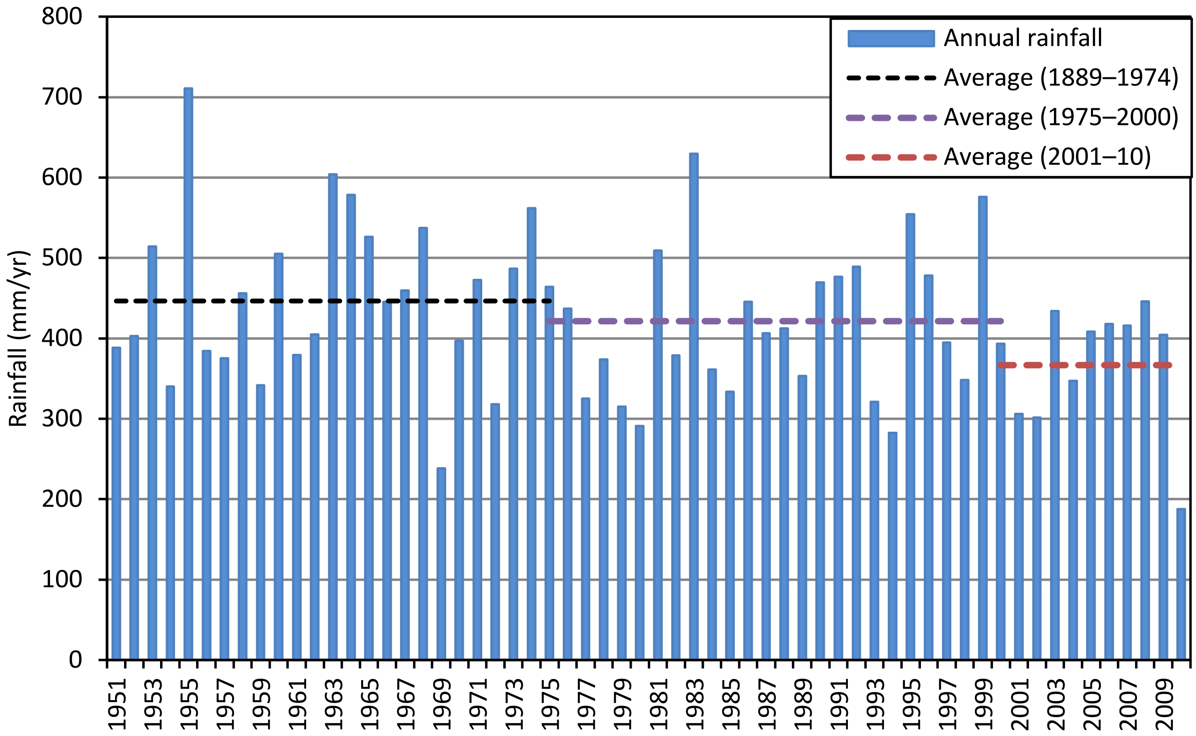


Figure 2.4: Annual rainfall at Northam (BOM ref–10111) between 1951–2010

2.3 Geology and soils

Geology and drainage

The Avon Basin is largely situated on the Yilgarn Craton, which mainly comprises granite and gneiss, with belts of metamorphic rock such as greenstone (Figure 2.5). The Yilgarn Craton is 2.6–3.3 billion years old (Geological Survey 1990), with hydrologically-relevant geological activity occurring 5–120 million years ago. This activity caused the realignment of ancient rivers, altered the topography and created the Avon Basin and its rivers in their current form. The most recent geological activity, the uplifting of the Darling Range, created two distinct drainage zones:

- The zone of ancient drainage which was unaffected by uplift of the Darling Range and is approximately 34–38 million years old.
- The zone of rejuvenated drainage which was influenced by the uplift of the Darling Range and is approximately 5–10 million years old.

The dividing line between these drainage zones is the Meckering Line (Figure 2.5). A description of the formation of these drainage zones and their soils is included in the following subsections, and their hydrology is described in Section 2.4.

Zone of ancient drainage

The separation of Antarctica from Australia (43–120 million years ago) resulted in the uplifting of the Ravensthorpe Ramp. It has been suggested that before the uplifting of the Ravensthorpe Ramp, the landscape had only a low gradient. The then south-flowing Pingrup, Lockhart, Camm and Yilgarn rivers were slow-moving and had little erosional potential (Beard 1999). Additionally, the Cowcowing Lakes may have flowed to the Mortlock River North Branch which flowed in a south-west direction, meeting the Mortlock River East Branch between Toodyay and Northam (Beard 1999).

Following the uplifting of the Ravensthorpe Ramp (38–43 million years ago) the flow direction of the Pingrup, Lockhart, Camm and Yilgarn rivers was reversed so that they flowed to the Salt River. This new drainage line flowed west through the Helena catchment and included inflows from the Dale River (Beard 1999; De Silva & Smith 2010). Additional uplift to the north of the Yilgarn Craton during this period reduced the topographic gradient of northerly-flowing rivers, such as the Lockhart River. This uplift also realigned some westerly-draining rivers in the Moore River catchment (north of the Avon Basin) to flow south through the Mortlock River North catchment (Beard 1998, cited in Commander et al. 2001; Beard 1999). The Mortlock River North Branch may have also separated from the Cowcowing Lakes during this period, with the Cowcowing Lakes joining the Mortlock East River Branch (Beard 1999). The combined Mortlock rivers flowed west through to the Perth Basin and met the Salt River at the base of the Darling Scarp on the Swan Coastal Plain (Beard 1999).

Between 5 and 10 million years ago, there was uplifting of the Darling Range, which extended from the Darling Fault to approximately 200 km inland (Commander et al. 2001). This was the last major geological event to affect the rivers of the Avon Basin. However, it is thought that areas upstream of the Yenyening Lakes have had little change since 34–38 million years ago (Beard 1999). So, areas unaffected by the uplift of the Darling Range have been termed the zone of ancient drainage.

Zone of rejuvenated drainage

Uplifting of the Darling Range caused the topography in the zone of rejuvenated drainage to steepen. This increased the topographic gradient along drainage lines by an order of magnitude, resulting in higher river velocities and higher erosional potentials (Harris 1996). The Mortlock River North Branch was pushed east and joined the Mortlock River East Branch near Northam. The uplifting of the Darling Range also caused the westerly-draining Salt River to flow in a north-westerly direction from the Yenyening Lakes to connect with the Mortlock rivers. These combined rivers then flowed west, creating the drainage features seen today (Beard 1999). Areas affected by the uplift of the Darling Range are termed the zone of rejuvenated drainage, as its topology, relief and drainage features differ markedly from areas unaffected by uplift.

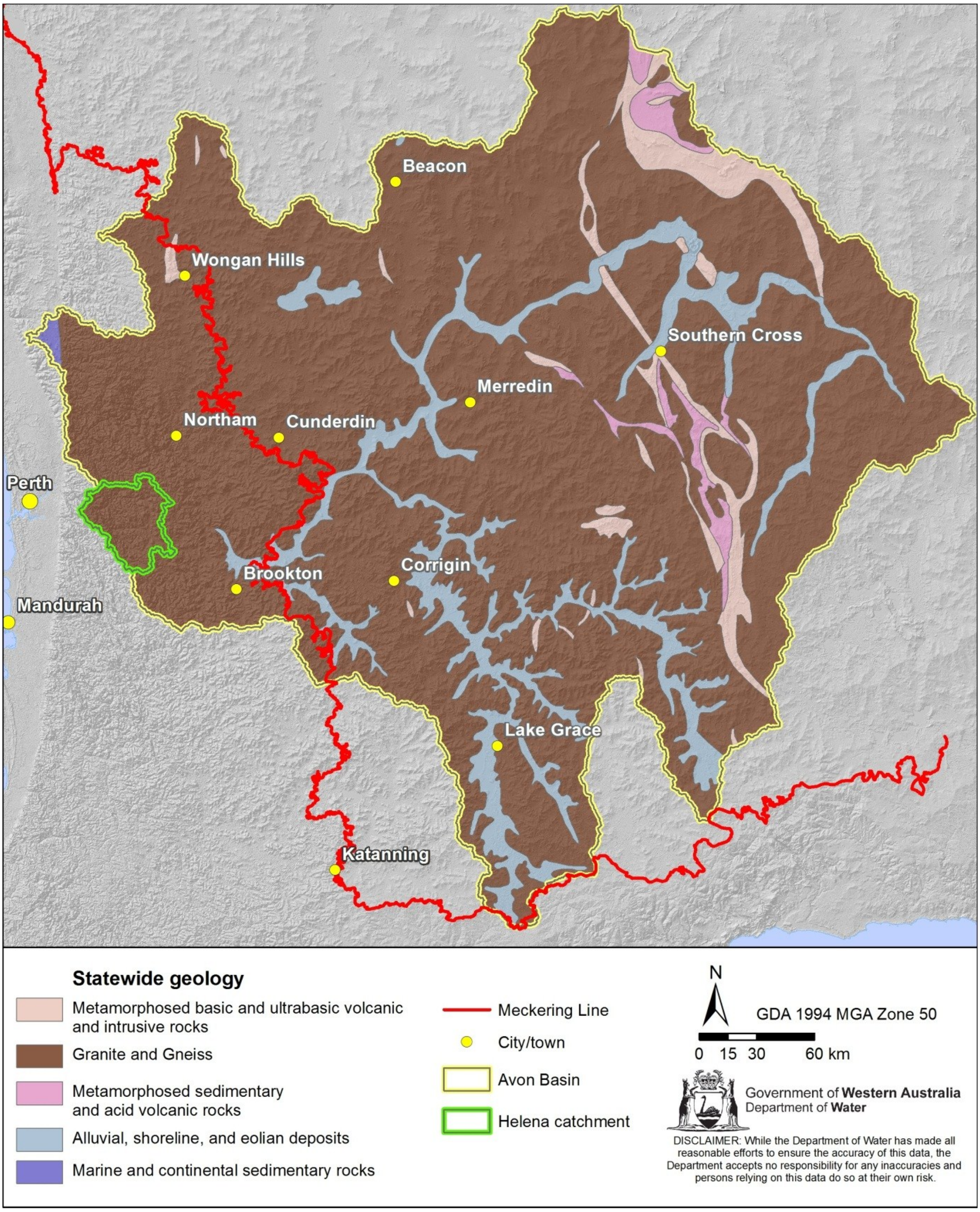


Figure 2.5: Geology of the Avon Basin

Soils

Soil mapping was sourced from the Department of Agriculture and Food, Western Australia (Schoknecht & Pathan 2013). The characteristic soils spatial dataset (Figure 2.6) is a simplified interpretation of the soil systems data set, which can have multiple soil types occurring within a single mapping unit. The characteristic soils dataset shows groupings of system-level soils that commonly coexist within a region (Table 2.2). The rangeland soils in the Great Western Woodlands (37 000 km^2) are not included in this mapping.

Of the 83 700 km^2 of available soil data within the Avon Basin and Helena catchment, 44 400 km^2 (53%) are *texture contrast soils* (termed duplex soils in this report). Duplex soils can be defined as soils with a surface layer of loam or sand underlain by soils of contrasting texture, often with low permeability. Duplex soils east of the Meckering Line are more commonly sodic than the duplex soils west of the Meckering Line. *Deep sandy and deep sandy earth soils* are the next most abundant (16 500 km^2 or 20% of the area with soil data) and are mostly found in the northern areas of the Avon Basin, particularly in the Mortlock and Yilgarn catchments. *Gravelly soils* (5700 km^2 or 7% of the area with soil data) are commonly found to the west of the catchment adjacent to the Darling Scarp, with some areas in the Lockhart River catchment. *Deep sandy soils* (2000 km^2 or 2% of the area with soil data) are found in the Mortlock River catchments and the Brockman River catchment. *Soils with shallow watertables* are only found east of the Meckering Line, mostly in areas with salt lakes.

Table 2.2: Characteristic soils of the Avon Basin and Helena catchment

Soil ID	Soil Group	Characteristics	Area† (km^2)	Area† (%)
1	*Deep sandy and sandy earth soils*	Yellow deep sands, yellow and brown sandy earths (often with gravelly subsoil)	16 483	20
2	*Deep sandy soils*	Siliceous Coloured sands (yellow, brown and minor red), some gravelly soils	1 953	2
3	*Gravelly soils*	Gravels in a sandy or loamy matrix – Sandy gravels, loamy gravels and shallow gravels	4 028	5
4		Gravels, usually in a loamy matrix – Loamy gravels, common also duplexes, loamy earths	1 676	2
5	*Loamy earth soils*	Calcareous – Calcareous loamy earths	10 208	12
6		Non-calcareous – Non-calcareous brown to red loamy earths	212	0
7	*Soils with shallow watertables*	Saline watertables – Saline and salt lake soils	4 671	6
8	*Texture contrast soils*	Grey sandy duplexes over non-alkaline clay, often with gravel	1 194	1
9		Coloured sandy duplexes – non-alkaline subsoils	2 981	4
10	*Texture contrast soils: usually sodic*	Loamy duplexes – Red loamy duplexes	1 154	1
11		Sandy and loamy duplexes – Alkaline subsoils (usually calcareous)	16 706	20
12		Sandy and loamy duplexes – Non-alkaline subsoils	13 459	16
13		Complex of alkaline and non-alkaline (often highly sodic) subsoils	7 416	9
14		Sandy duplexes – Grey sandy duplexes and saline wet soils	1 529	2
	Rangeland soils	Not mapped	36 952	

Note: Characteristic soil areas include both the Avon Basin and the Helena catchment
† The percentage area of soils excludes rangeland soils

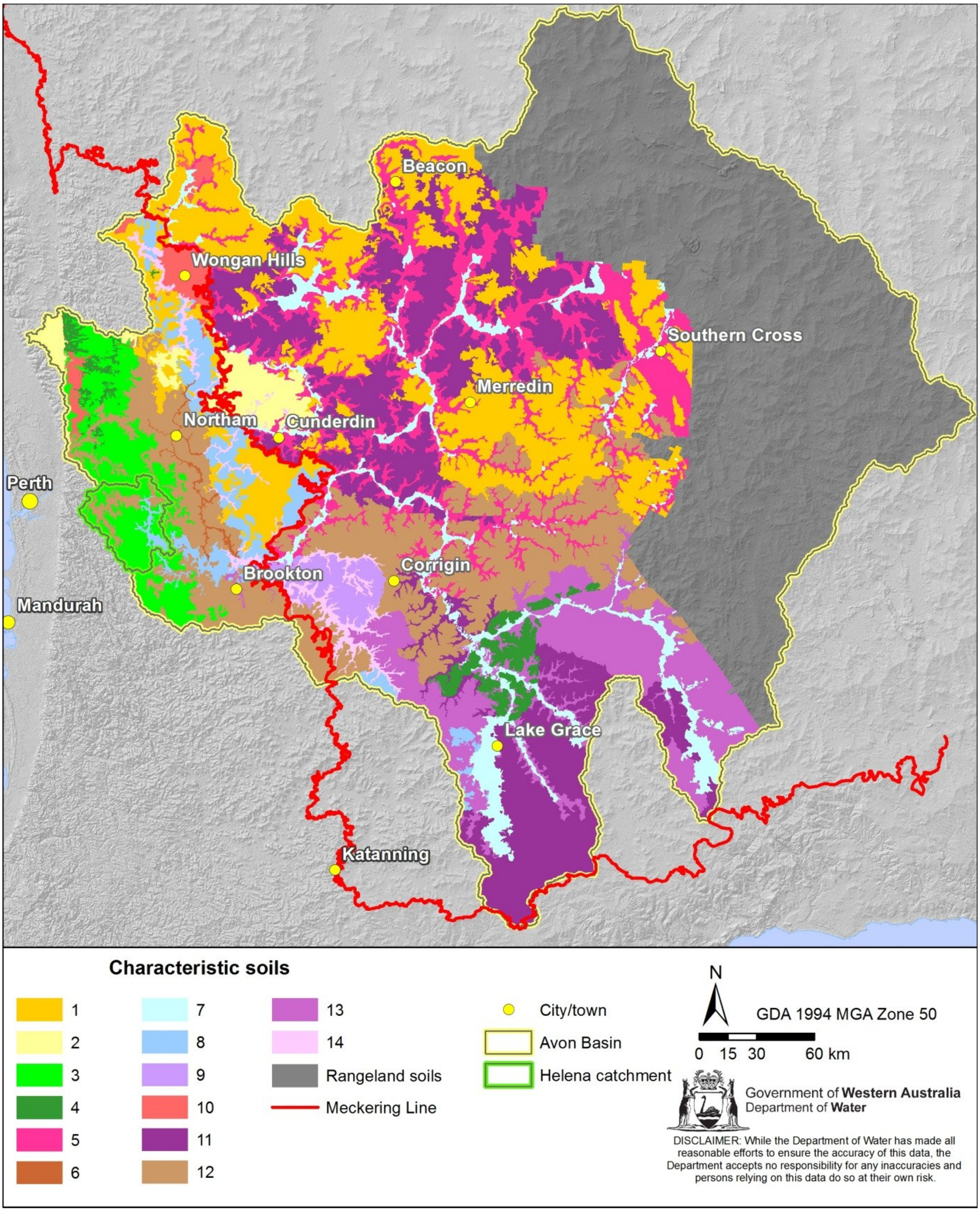


Figure 2.6: Characteristic soils of the Avon Basin (refer to Table 2.2 for characteristic soil names)

Phosphorus retention index

The soil phosphorus retention index (PRI) is a measure of the phosphorus adsorption (binding) capacity of a unit of soil. This capacity increases with increasing reactive iron, aluminium and calcium carbonate content. However, successive additions of phosphorus can exhaust the soil adsorption capacity so subsequent applications of phosphorus can readily leach to waterways.

Soil PRI mapping was provided by the Department of Agriculture and Food Western Australia (Figure 2.7). This mapping has a coarse spatial resolution.

The PRI of the Avon Basin is generally above 12 as soils are high in phosphorus-adsorbing minerals. Thus these soils have a large capacity to bind phosphorus and have a low risk of leaching phosphorus to waterways. Soils with low PRI values (less than 7) have a low binding capacity and so have a substantial risk of leaching phosphorus to waterways. There are areas of low PRI soils (less than 7) in the Mortlock East and North catchments as well as in the Dale, Upper Avon and Brockman river catchments. So, these areas will have a high risk of leaching phosphorus. The low PRI estimates in the upper reaches of the Lockhart and Yilgarn catchments may be underestimated due to the coarse nature of the mapping.

2.4 Hydrology

The Avon Basin has nine major rivers and a number of significant streams, lakes and smaller watercourses (Table 2.3). The Helena catchment, which also drains to the Swan River, has two major rivers and includes Darkin Swamp, as well as a number of smaller lakes/swamps. The hydrology of the Avon Basin changes greatly from its headwaters in the east to the basin outlet in the west. This is due to differences in geology, which were discussed in Section 2.3. The differences in hydrology between the ancient and rejuvenated zones of drainage are discussed below.

Zone of ancient drainage

The zone of ancient drainage includes shallow, saline playa lakes connected by a series of narrow preferential flow paths. Some lake systems are disconnected from the drainage network except in very wet years. The storage capacity of most lakes is typically 2–65 GL, although there are three larger lakes: Cowcowing Lakes (675 GL), Lake Wallambin (208 GL) and Lake Grace (275 GL; Ali et al. 2010). The combination of large lake storage volumes, low rainfall and low river gradients results in little river discharge from the zone of ancient drainage. For instance, the Yilgarn River (catchment area 58 400 km^2) regularly has annual flows under 83 ML, the median daily flow of the Avon River at the basin's outlet (catchment 119 100 km^2).

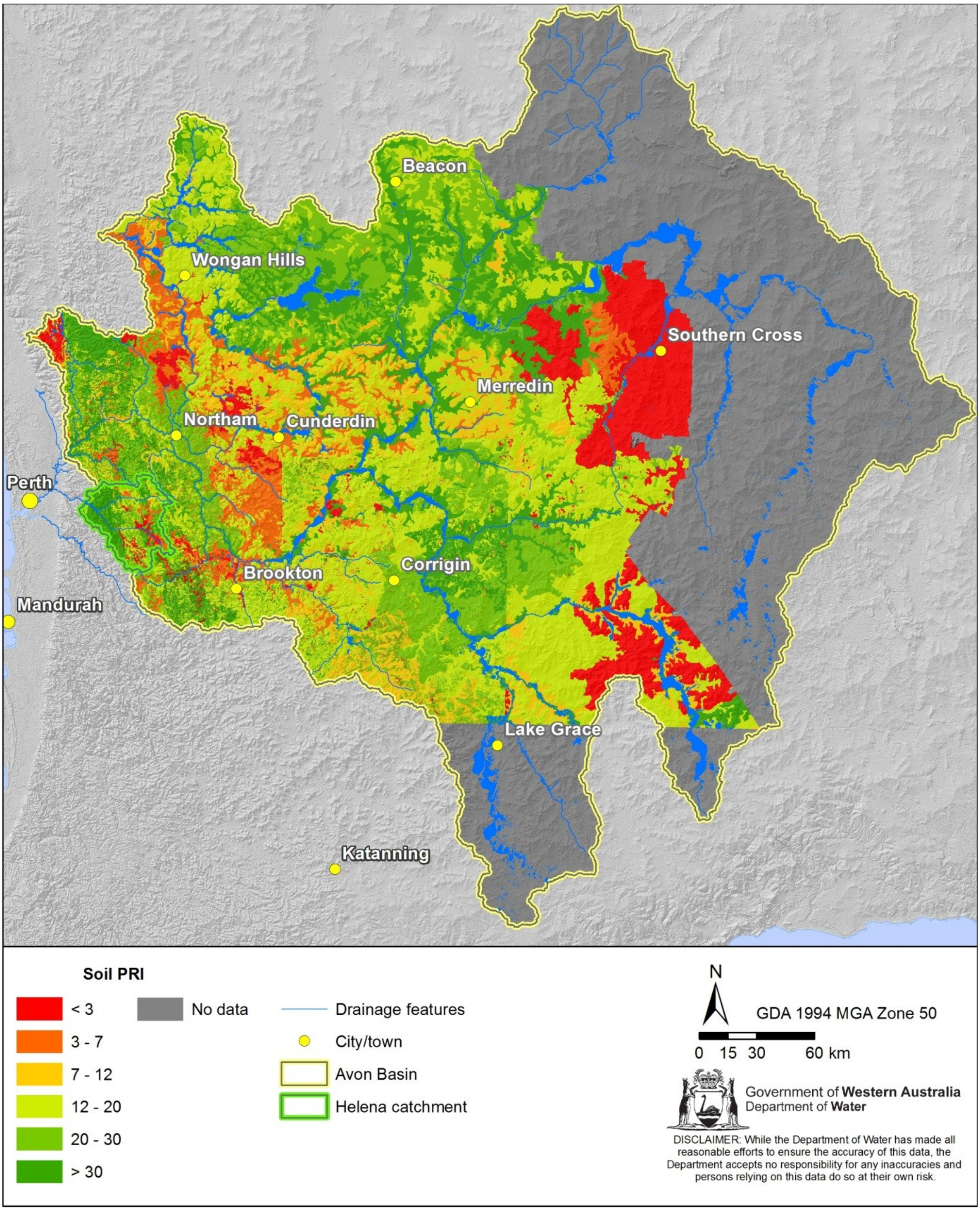


Figure 2.7: Estimated soil phosphorus retention index (PRI) for the Avon Basin

Table 2.3: Major rivers, significant watercourses and lakes in the Avon Basin

Reporting catchment	Major River	Significant watercourse	Lakes/swamps
Lower Avon	Avon river	Julimar Brook Toodyay Brook Wongamine Brook	
Middle Avon	Avon River	Spencer Brook Mackie River Avon River South	
Upper Avon	Avon River	Wongalin Gully	Lake Yealering
Wooroloo	Wooroloo Brook	Coates Gully	
Brockman	Brockman River	Woortra Brook	Lake Chittering
Mortlock North	Mortlock River North Branch	Chitbin Brook	Lake Hinds
Mortlock East	Mortlock River East Branch	Mortlock River South Branch	Cowcowing Lakes Lake Wallambin Walyirmouring Lake
Dale	Dale River	Dale River South	Maitland Swamp
Salt	Salt River	Kunjin Creek	Yenyening Lakes
Lockhart	Lockhart River	Pingrup River Camm River Wakeman River	Chinconup Lake Lake Grace North Lake Grace South Kondinin Lake Lake Kurrenkutten Lake King Lake Camm
Yilgarn	Yilgarn River	Muka River Belka River	Lake Brown Lake Deborah North Lake Deborah East Lake Polaris Baker Lake Lake Cronin
Helena†	Darkin River Helena River		Darkin Swamp

† Drains to the Swan-Canning coastal catchments

The largest river systems in the zone of ancient drainage are the Salt, Lockhart and Yilgarn rivers. These flow into the Yenyening Lakes, which have been artificially dammed to allow for recreation, to provide bird breeding habitat and to protect the downstream rivers from highly saline waters (WRC 2002; Kelly pers. comm.). The damming has created an important hydrological feature as most of its river inflows (from 76% of the Avon Basin by land area) are stored within the lakes or are lost through evaporation. The Yenyening Lakes Management Group regulates outflows from the lakes in consultation with the Department of Water. However, no accurate estimates of managed outflows from the Yenyening Lakes are available.

Before extensive land clearing, the hydrology and ecological character of the Yenyening Lakes were very different (Viney et al. 2000). Flows from the lakes were less sporadic and the water had lower salinity and nutrient concentrations.

The Mortlock River North and East branches have a portion of their catchments in the zone of ancient drainage. In the Mortlock River North catchment, the zone of ancient drainage begins upstream of Lake Hinds and is approximately 54% (3704 km^2) of the catchment area (6901 km^2). In the Mortlock East catchment, the zone of ancient drainage begins halfway between Northam and Cunderdin, and is approximately 83% (8227 km^2) of the catchment area (9889 km^2). The Mortlock East catchment also includes the Cowcowing Lakes and Lake Wallambin which have a combined dead storage capacity of 883 GL.

Land clearing has significantly altered the hydrology of the Avon Basin, particularly within the zone of ancient drainage. The removal of deep-rooted vegetation and its replacement with shallow-rooted crops has resulted in rising groundwater across the catchment, and increased river flows relative to the uncleared condition. Groundwater rises have resulted in the secondary salinisation of many low-lying areas. Modelling by the CSIRO (Ali et al. 2010) has shown that groundwater levels have not yet reached equilibrium and will likely stabilise over the next 60 years, thus further increasing the area of land affected by secondary salinisation.

In an attempt to manage rising, saline and often acidic groundwater, deep groundwater interception drains have been constructed. These drains either convey water to natural waterways and lakes or to specifically designed evaporation basins (Shand & Degens 2008). In 2000, it was estimated that there were 4540 km of constructed deep-drainage channels, with that number likely to have increased in recent years (Shand & Degens 2008). Acidic groundwater has also been shown to be an issue in the region, particularly in the Yilgarn River and Lockhart River catchments where surface water pH values of 3.9–4.7 have been observed (Degens et al. 2012).

Zone of rejuvenated drainage

In the zone of rejuvenated drainage, the chains of salt lakes grade to a series of broad river channels (Beverley to Toodyay) then to narrow and steeply-incised channels in the area east of the Darling Scarp (Harris 1996). There are 51 named pools which act as refuges for aquatic life during summer (Pinder 2009).

During winter, continuous river flows can extend from Wickepin to the basin outlet for a short period (Harris 1996). In low flows, the Avon River has thin (approximately 1–3 m wide) braided flows amongst sediment mounds and vegetation. However, in flood conditions the Avon River can spill onto its large flood plains, creating a river over 100 m wide in places.

A series of devastating floods before 1958 motivated the government to invest in flood abatement. During 1958–70 the Public Works Department carried out a *River Training Scheme* between Toodyay and Aldersyde including the Avon River South Branch as far upstream as Brookton (Harris 1996). The river training scheme involved removing in-stream vegetation and obstructions with the aim of increasing flow velocities and thus alleviating flooding. Flood velocity estimates pre- and post-river training (Binnie and Partners 1985) are shown in Table 2.4.

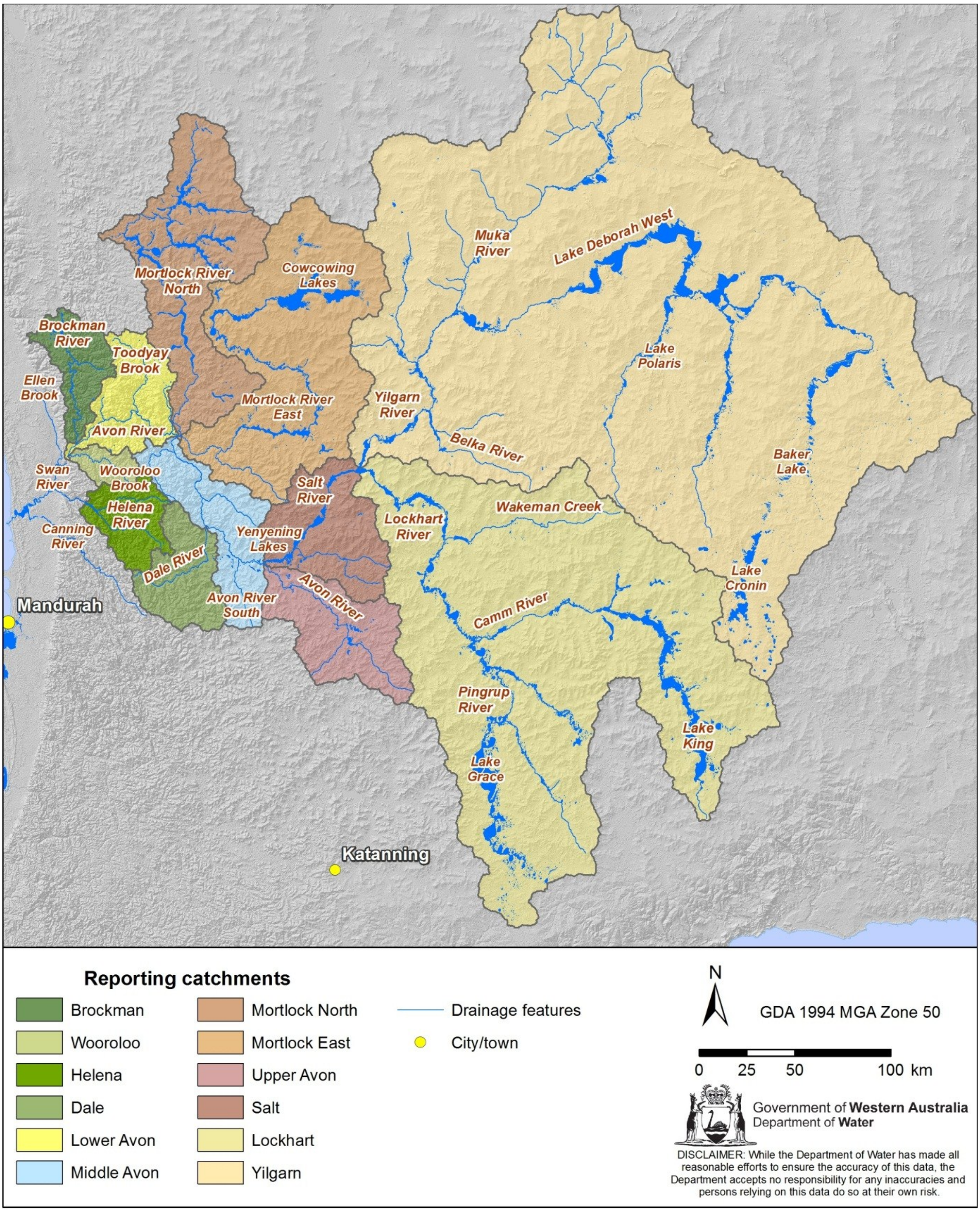


Figure 2.8: Hydrology of the Avon Basin

Table 2.4: Estimated flow velocities as a result of the river training scheme

	Pre-training		Post-training	
Flow (m^3/sec)	Depth (m)	Velocity (m/sec)	Depth (m)	Velocity (m/sec)
200	2.5	0.80	1.5	1.22
400	3.8	1.05	2.2	1.82
600	4.9	1.22	2.8	2.14

Apart from the Avon River, other significant rivers include the Dale River (2026 km^2 catchment), Brockman River (1519 km^2 catchment) and Wooroloo Brook (537 km^2 catchment). The Dale River meets the Avon River downstream of Beverley. Its headwaters lie in the 500–700 mm/yr rainfall zone, and thus it is a significant source of flow to the middle sections of the Avon River. The Brockman River flows into the Avon River 8 km from the basin outlet, its catchment rainfall is 600–700 mm/yr and it has similar total flow volumes to the Dale River. However, the Brockman River flows through Lake Chittering and so has less intense peak flows and more base flow than the Dale River. Wooroloo Brook discharges to the Avon River approximately 1 km upstream of the basin outlet. Although Wooroloo Brook has a much smaller catchment area than the Brockman and Dale River catchments, it is located in the 700–900 mm/yr rainfall zone and as a result contributes more flow than the Brockman and Dale rivers.

2.5 Land use

Automated and manual mapping methods were employed to map the land use of the Avon Basin. The State Cadastre (2011), the DAFWA remnant vegetation and the Department of Water's hydrography data were used to create a base land-use map. Checking was done to validate the automated mapping. For areas within 5 km of towns, as well as the entire Brockman and Wooroloo catchments, the mapping was compared with aerial photography and adjusted as required. Ground-truthing of the land-use mapping was done for the Dale catchment. Fifty-three different land-use categories were mapped and then aggregated into the 14 modelling categories shown in Table 2.5 and Table 2.6 which were similar to categories used in past modelling projects (Kelsey et al. 2011).

Figure 2.9 shows the land use of the Avon Basin. The largest land uses by area are wheat & sheep (54%) and native vegetation (43%). Wheat & sheep occupies most of the area between Northam and Southern Cross. Most of the basin's native vegetation is located east of Southern Cross in the Great Western Woodlands. However, there are also considerable areas of native vegetation to the west of the catchment adjacent to the Darling Scarp and small, fragmented areas of native vegetation remain amongst the wheat & sheep farms.

Mixed grazing, which represents an unknown assemblage of livestock grazing and cropping, occupies 1.1% of the total area of the Avon Basin. Mixed grazing is located exclusively within the high rainfall areas (> 500 mm/yr) in the west of the catchment. Water bodies make up 1.4% of the total area of the Avon Basin, with most of this area being salt lakes in the zone of ancient drainage. Apart from industry & transport, all other land uses occupy less than 0.2% of the basin area (Table 2.5). Urban and peri-urban land uses (lifestyle blocks, residential and recreation) occupy only 0.04% of the basin area.

Table 2.5: Land-uses used for nutrient modelling of the Avon Basin and Helena catchment

Land-use category	**Avon Basin**		**Helena**		**Total**	
	(km^2)	**(%)**	**(km^2)**	**(%)**	**(km^2)**	**(%)**
Native vegetation	50 099	42	1 422	96	51 521	43
Wheat & sheep	64 619	54	0.004	<0.01	64 619	54
Animal keeping	47	0.04	1.2	0.08	49	0.04
Horticulture	3.3	<0.01	-	-	3.3	<0.01
Orchard	13	0.01	0.18	0.01	14	0.01
Industry & transport	1 238	1.0	4.9	0.33	1 243	1.0
Lifestyle block	90	0.08	0.6	0.04	90	0.07
Mixed grazing	1 261	1.1	43	2.9	1 303	1.1
Plantation	28	0.02	1.5	0.1	29	0.02
Recreation	16	0.01	0.06	<0.01	16	0.01
Residential	22	0.02	0.03	<0.01	22	0.02
Point sources	2.0	<0.01	-	-	2.0	<0.01
Intensive animal use	10	0.01	-	-	10	0.01
Water	1 693	1.4	6.0	0.4	1 699	1.4
Total	**119 141**		**1 479**		**120 620**	

Table 2.6: Aggregation of initial land-use categories into modelling categories for the Avon Basin and Helena catchment

Modelling land-use categories	Initial land-use mapping categories	Total		Avon Basin		Helena	
		(ha)	%	(ha)	%	(ha)	%
Point sources	Sewerage – treatment plant	43	<0.01	43	<0.01		
	Sewerage – non-treatment plant	43	<0.01	43	<0.01		
	Landfill	115	<0.01	115	<0.01		
Horticulture	Annual horticulture	299	<0.01	299	<0.01		
	Turf farm	15	<0.01	15	<0.01		
	Garden centre / nursery	14	<0.01	14	<0.01		
Animal keeping	Animal keeping – non-farming	20	<0.01	18	<0.01	1	<0.01
	Horses	4 832	0.0	4 717	0.0	115	0.1
Native vegetation	Rural residential / bush block	5 968	0.05	5 962	0.05	5	<0.01
	Recreation / conservation – trees / shrubs	904 536	7.5	869 952	7.5	34 584	23
	Unused – uncleared – trees / shrubs	3 804 306	32	3 696 668	32	107 638	73
	Unused – cleared – grass	2 225	0.0	2 217	0.0	8	<0.01
	Unused – cleared – bare soil	738	<0.01	734	<0.01	4	<0.01
	Livestock grazing - rangelands	434 321	3.6	434 321	3.6		<0.01
Wheat & sheep	Cropping	6 461 844	54	6 461 844	54	0.4	<0.01
	Hay and silage	45	<0.01	45	<0.01		
Orchard	Perennial horticulture – trees	1 134	<0.01	1 126	<0.01	9	<0.01
	Viticulture	222	<0.01	213	<0.01	9	<0.01
Industry & transport	Quarry/extraction	2 175	0.02	2 155	0.02	19	0.01
	Manufacturing / processing	113	<0.01	112	<0.01	0.5	<0.01
	Storage / distribution	791	<0.01	781	<0.01	10	<0.01
	Transport access – roads and paths	109 347	0.91	108 887	0.91	459	0.31
	Transport access – airport	600	<0.01	600	<0.01		
	Utility	26	<0.01	25	<0.01	1	<0.01
	Water storage and treatment	242	<0.01	242	<0.01		
	Transport access – railway	11 014	0.09	11 014	0.09		
Intensive animal use	Piggery	565	<0.01	565	<0.01		
	Intensive animal farming	249	<0.01	249	<0.01		
	Feedlot	150	<0.01	150	<0.01		
	Aquaculture	16	<0.01	16	<0.01		
Lifestyle block	Lifestyle block	**9 030**	0.07	**8 968**	0.07	**62**	0.04
Mixed grazing	Cattle for beef	139	<0.01	139	<0.01		
	Cattle for dairy	1 870	0.02	1 870	0.02		
	Mixed grazing	128 328	1.1	124 065	1.1	4 263	2.9
	Sheep	0	<0.01	0	<0.01		
Plantation	Tree plantation – softwood	1 873	0.02	1 858	0.02	14	<0.01
	Tree plantation – hardwood	400	<0.01	339	<0.01	61	0.04
	Tree plantation – rehabilitation	629	<0.01	554	<0.01	74	0.05
Recreation	Recreation – grass	1 484	0.01	1 478	0.01	6	<0.01
	Recreation – turf	107	<0.01	107	<0.01		
Residential	Residential – single / duplex dwelling	1 362	0.01	1 359	0.01	3	<0.01
	Residential – multiple dwelling	31	<0.01	31	<0.01		
	Residential – aged person	20	<0.01	20	<0.01		
	Residential – temporary accommodation	33	<0.01	33	<0.01	<0.1	<0.01
	Caravan park	43	<0.01	43	<0.01		
	Commercial / service – centre	9	<0.01	9	<0.01		
	Commercial / service – residential	56	<0.01	56	<0.01	0.4	<0.01
	Office – without parkland	63	<0.01	63	<0.01		
	Office – with parkland	32	<0.01	32	<0.01		
	Community facility – education	275	<0.01	275	<0.01		
	Community facility – non-education	318	<0.01	318	<0.01		
Water	Water body	169 910	1.4	169 313	1.4	597	0.4
Total		**12 062 021**		**11 914 076**		**147 944**	

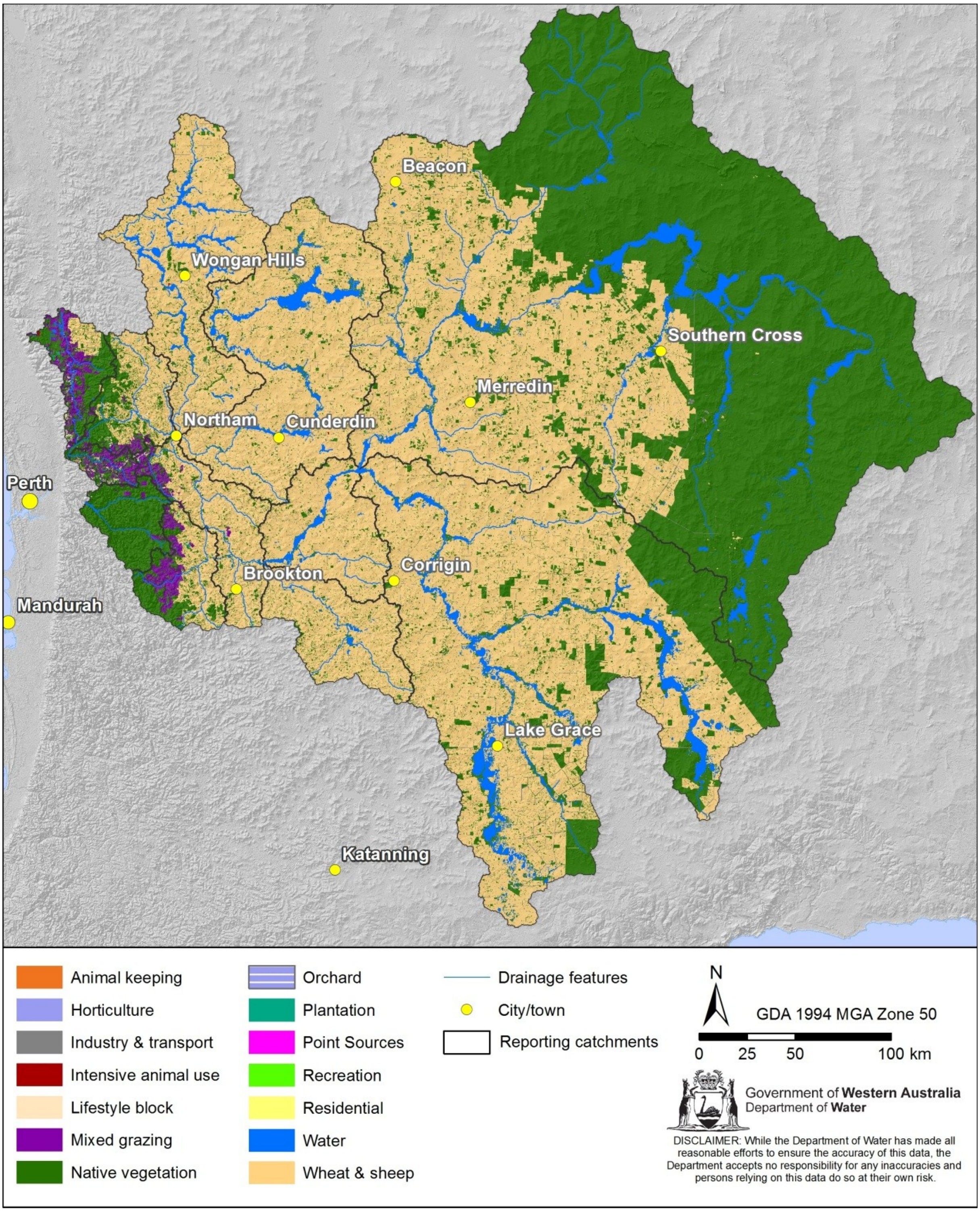


Figure 2.9: Land use of the Avon Basin

2.6 Point sources

Forty-two point sources were included in the Avon Basin modelling (Figure 2.10). Point sources were identified from land-use mapping, advice from the former Department of Environment and Conservation (DEC), the Water Corporation and from a past report (Department of Water 2007). Seven types of point sources were identified:

- Wastewater Treatment plants (WWTP)
- Towns with septic tanks
- Abattoirs
- Feedlots
- Stockyards
- Piggeries
- Landfill.

Landfill sites were not included in the modelling as there was insufficient data to reliably estimate the amount of nutrients they leach to the environment. Additionally, nutrient loads from landfill sites are thought to be small.

Piggeries and abattoirs are required to treat all wastewater generated to comply with their DEC works approval licences. Maximum wastewater irrigation rates of 640 kg/ha/yr of nitrogen and 120 kg/ha/yr phosphorus are permitted to be irrigated over set areas which were taken from the DEC works approval licenses (L7728/2001/6; L7930/2004/4; L6010/1989/11) or interpreted from aerial photography.

Stockyards and feedlots were assumed to have nitrogen and phosphorus input rates of 2884 kg/ha/yr and 746 kg/ha/yr respectively. These rates were derived using the following methodology:

1) The National Consultative Committee on Animal Welfare (National Consultative Committee on Animal Welfare 1990) recommended maximum feedlot stock densities of 20 m^2 per animal. Since Department of Water staff, who are familiar with feedlots and stockyards in the Avon Basin found that these land uses typically had lower stocking rates than the National Consultative Committee on Animal Welfare (1990) recommendations (Allen *pers. comm.*), it was assumed that feedlots and stockyards had stocking rates of 30 m^2 per animal or 333 animals per hectare.
2) The nutrient input rates of cattle were taken as 8.66 kg/cow/yr of nitrogen and 2.24 kg/cow/yr of phosphorus (Fahrner 2002; DOE 2004; Hall 2011a).
3) The nutrient input rate was derived from the stocking rate and the nutrient inputs per animal.
4) The areas of stockyards and feedlots were derived from DEC works approval licences (L8547/2011/1) or interpreted from aerial photography.

Piggeries, abattoirs, stockyards and feedlots are reported together as ‘intensive animal use’.

Three WWTPs were identified by the Water Corporation as discharging wastewater directly to waterways: Northam, Cunderdin and Meckering. Flow and nutrient concentration data from which annual loads were calculated were provided by the Water Corporation.

Local government authorities operate a number of WWTPs, two of which (Brookton and Lake Grace) discharge treated wastewater to waterways. Wastewater discharge from these plants was estimated from the licenced maximum operating capacity of their DEC works approval license (L7994/2003/3) or from their town population (assuming wastewater generation of 0.04 ML/person/yr). Annual wastewater discharge volumes of 23 ML and 20 ML were assumed for Brookton and Lake Grace respectively. Outflow concentrations of 32 mg/L of nitrogen and 12 mg/L of phosphorus were estimated from Cunderdin and Meckering data and used to calculate loads for the Brookton and Lake Grace WWTPs.

Three towns were identified as having septic tanks that could have problematic nutrient loads: Bruce Rock, Chidlow and Bakers Hill. Nutrient input rates of 5.5 kg/person/yr of nitrogen and 1.1 kg/person/yr of phosphorus were assumed (Whelan et al. 1981). Town populations were taken from the 2011 census data (Australian Bureau of Statistics 2011). Other septic tanks (e.g. farms) were assumed to contribute negligible nutrient loads to streams and rivers and were not included in the modelling. The remaining towns within the Avon Basin either had deep-sewerage systems that did not discharge nutrients to waterways or were excluded as their impacts were assumed to be small.

For the point sources that discharged to land (all point sources except for WWTPs), it was assumed that a maximum of 10% of the discharged nutrients reached waterways. All point sources were assumed to discharge nutrients to waterways only when local river flow exceeded 10 ML/day. These assumptions were used to account for the relatively low nutrient export (i.e. the small percentage of nutrients applied to land that reaches waterways) of the Avon Basin, and to prevent discharge at times when point sources would be hydrologically disconnected from waterways. It should be noted that these assumptions may underestimate the contributions from point sources. Table 2.7 shows the estimated nutrient loads from point sources that reach waterways.

2.7 Environmental degradation

The main Avon River channel between Toodyay and Aldersyde (including the Avon River South Branch up to Brookton) was originally braided, with many small channels interweaving between thickly-vegetated islands, and punctuated by numerous deep, shady pools. The river and its adjacent woodlands abounded with animal and bird life. Further east in the catchment, beautiful lakes were surrounded by wooded hills. The river (like all rivers) contained sediment and a bedload of sand and silt, but prior to European settlement this material was in equilibrium, with natural gains (through erosion of stream banks etc.) and losses (through downstream transport) in balance. The river's original bedload was largely intact until about the 1940s or 1950s. Since then the rivers have been seriously degraded as a result of the impacts of land clearing, river training, farming and salinisation (WRC 1999).

Western Australia's first inland agricultural settlement was at York on the Avon River in 1830. Rapid development followed with the opening up of the Avon Valley and then the hinterland

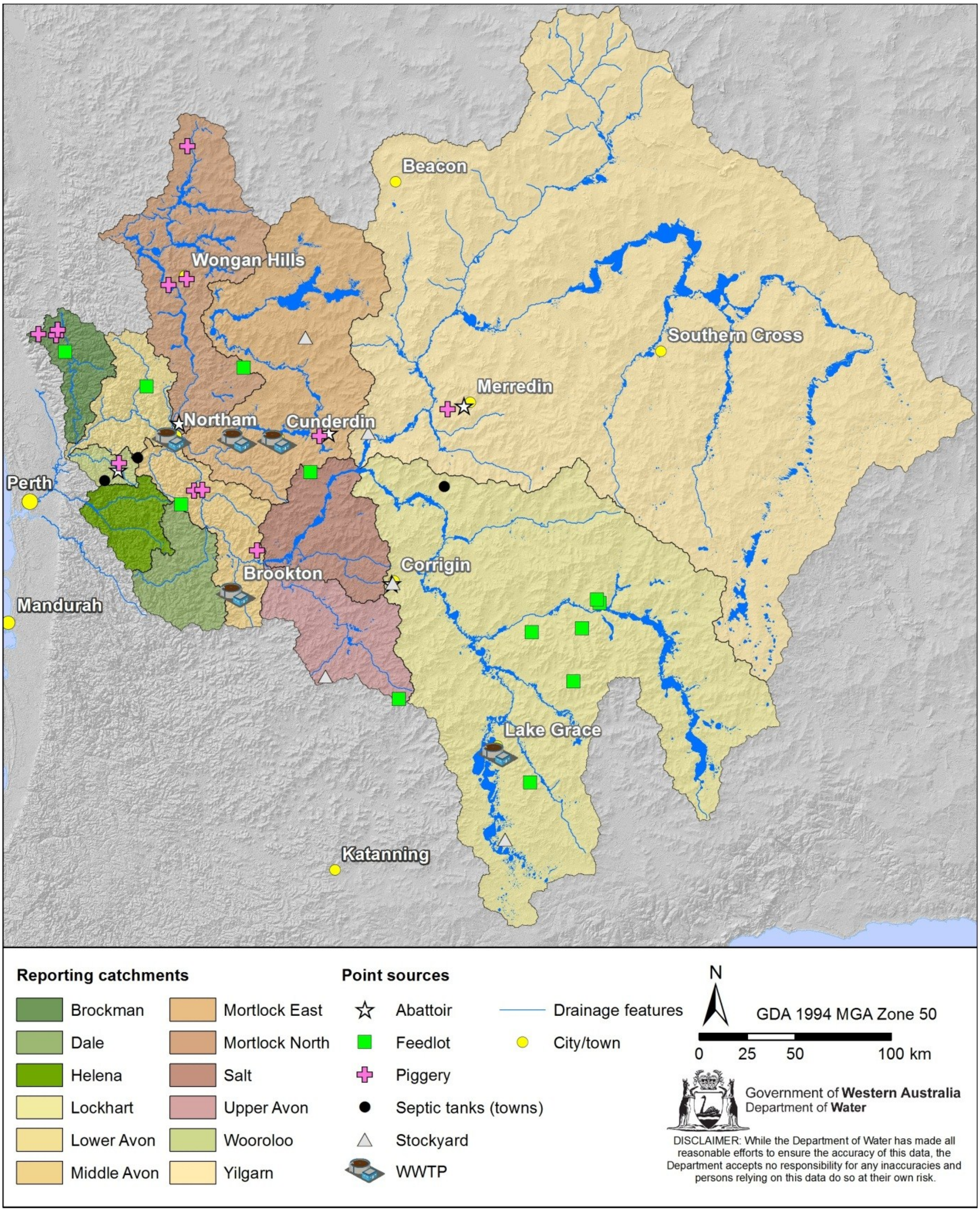


Figure 2.10: Point sources of nitrogen and phosphorus in the Avon Basin

Table 2.7: Annual nutrient loads exported to waterways from point sources

Reporting catchment	Point source type	Number of point sources	Load exported to the environment Nitrogen kg/yr	Load exported to the environment Phosphorus kg/yr
Brockman	Feedlot	1	106	5.7
	Piggery	3	1 238	51
Lockhart	Abattoir	1	1. 3	0.02
	Feedlot	6	177	2.3
	Septic tanks (towns)	1	1	0.01
	Stockyard	2	7	0.1
	Lake Grace WWTP	1	19	6.9
Lower Avon	Feedlot	1	100	1.3
	Northam WWTP	1	5 553	62
Middle Avon	Feedlot	1	58	0.8
	Piggery	3	73	0.8
	Septic tanks (towns)	1	102	0.5
	Brookton WWTP	1	433	148
Mortlock East	Abattoir	1	34	0.4
	Feedlot	1	514	6.6
	Piggery	1	129	1.5
	Stockyard	1	34	0.4
	Meckering WWTP	1	45	13
	Cunderdin WWTP	1	255	77
Mortlock North	Abattoir	1	3	0.4
	Feedlot	1	236	3.1
	Piggery	3	122	1.4
Upper Avon	Feedlot	1	1 130	29
	Stockyard	1	48	1.3
Wooroloo	Abattoir	1	146	1.8
	Piggery	1	34	0.6
	Septic tanks (towns)	1	145	2.8
Yilgarn	Abattoir	1	21	0.3
	Piggery	1	11	0.1
	Stockyard	1	23	0.3
Avon Basin	All abattoirs	5	205	2. 9
	All feedlots	12	2 321	49
	All septic tanks (towns)	3	248	3. 3
	All stockyards	5	113	2. 1
	All piggerys	12	1 607	56
	All WWTPs	5	6 305	306
	All point sources	**42**	**10 799**	**419**

of the Wheatbelt. Much of the catchment was settled within 100 years and easily accessible land cleared (O'Connor et al. 2004). There was further clearing throughout the catchment after WWII due to land releases to returned servicemen and the availability of cheap inorganic phosphorus fertiliser which made farming more profitable. Land clearing and establishing agriculture resulted in the degradation of land and water resources.

The Avon is a highly disturbed river; its hydrology and ecology have been altered by clearing, establishing towns along its banks, clearing the river banks and deepening the river channel for flood mitigation. The broad-acre cropping systems of the catchment result in 1) erosion of surface soils by wind and water and the movement of these soils into watercourses; and 2) leaching of phosphate and nitrogenous fertilisers down the landscape to enter streams and the river.

Over the last 150 years most river environs have been heavily grazed, mostly by sheep but also in some places by cattle, horses and goats. This has resulted in a gradual replacement of many native grass species by introduced grasses, a loss of regeneration of native trees and shrubs, compaction of the soil and damage to river banks.

2.7.1 Land degradation

The area in the west of the basin downstream of Yenyening Lakes is 82% cleared and the area upstream of Yenyening Lakes (Salt, Lockhart and Yilgarn catchments) is 48% cleared. The percentage cleared area in the west agrees well with Pen's (1999) observation that over 75% of the original woodlands and heath vegetation on the catchment have been cleared (Pen 1999). Upstream of Yenyening Lakes the uncleared areas are primarily the very dry and unsuitable for agriculture rangelands in the far east of the catchment (Great Western Woodlands). The farmed areas of the Salt, Lockhart and Yilgarn catchments have percentages of cleared area similar to the farmed areas in the west. The wide-scale clearing of the natural bushland and its conversion to pasture and cropland has resulted in rising groundwater and the movement of salt from stores deep in the soil to the surface where it degrades the land's ecological values and renders it unsuitable for agriculture (Mayer et al. 2005a). The rising watertable also promotes soil erosion and waterlogging of farmland. Table 2.8 lists the catchment's major land management issues (salinity, soils structure decline, soil acidification, compaction, water erosion, waterlogging, water repellence and wind erosion) and the areas of potentially arable land with risk categories ranging from low to extreme.

Secondary salinity (i.e. human-induced salinity) was first noticed about 1897 (Wood 1924) but remediation was limited until the early 1980s. The 2002 *Land Management and Salinity Survey* (Australian Bureau of Statistics 2004) found that the Avon River Basin was the National Action Plan for Salinity and Water Quality (NAPSWQ) region with the most extensive challenge: 450 000 ha on 2279 farms affected

Inundation and salinisation of low-lying land in the Avon Basin (T Sparks) by salinity. Over 63% of the salinised land is estimated to be unproductive at present (O'Connor et al. 2004). CSIRO (2009) estimated that 5% of the Avon Basin is currently affected by secondary salinity and waterlogging. If pre-2000 trends in climate continue, about 25–30% of the basin may develop shallow watertables and be at risk of salinisation. If rainfall keeps declining as a result of climate change, the time to equilibrium is likely to be longer and the final areas at risk of salinity will be smaller (CSIRO 2009).

Acidity is the second highest degradation risk to land and soil, with all cleared and farmed areas having potential to acidify. Eighty-five per cent of topsoils are already acidic (pH < 5.5; (Andrew & Gazey 2010).

Table 2.8: Arable land area subject to degradation risk in the Avon River basin (Avon Catchment Council 2005)

Threat	Soil structure decline		Subsurface acidification†		Subsurface compaction		Water erosion		Waterlogging & inundation		Water repellence		Wind erosion	
Risk	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Extreme			1130	15			64	< 1					<0.5	< 1
Very high			45	< 1			92	1	213	3			251	4
High	10	< 1			3000	42	178	2	132	2	978	14	1204	17
Moderate	716	10			2883	40	1147	16	1346	19	2517	35	2225	31
Low	6362	89			1200	17	2652	37	898	13	317	4	3440	48
Very low							2945	41	1263	18				
Presently acid			6483	85										
Nil									3225	45	3177	44		
Not applicable	76	1			82	1	87	1	87	1	175	2	45	< 1
Total	**7165**		**7658**		**7165**		**7165**		**7165**		**7165**		**7165**	

† Subsurface acidification data was taken from Andrew & Gazey (2010)

Subsurface compaction affects 42% of agricultural land. Soil structure decline affects up to 40% of the Carrabbin and Southern Cross Interim Biogeographical Regionalisation for Australia (IBRA) subregions (Department of Environment 2000) and up to 20–30% of the Mortlock, SE Lakes and Northern Sandplain IBRA subregions.

Waterlogging is significant and occurs frequently in areas of low relief and where annual rainfall is greater than 400 mm (western areas). As a result, 24% of soils in the region are prone to waterlogging in an average year.

Water erosion is significant in areas of shallow duplex soils and loamy soils in the eastern Wheatbelt. These areas are susceptible to erosion because of the high frequency of intense widespread and cyclonic rain events. Sheet erosion and rill erosion are evident in western areas. Average soil losses through sheet erosion range are 6.6–9.8 t/ha/yr. Wind erosion occurs in small areas during most years although it can be widespread under exceptional conditions.

2.7.2 Biodiversity loss

Weeds, feral animals and other biosecurity issues are significant across the whole catchment and greatly contribute to biodiversity degradation and loss.

The clearing of the natural bushland for agriculture has resulted in major disturbances to the natural hydrological cycle and greatly affected flora and fauna. The south-west of WA (including the whole of the Avon River basin) is one of 25 global biodiversity hotspots based on exceptional endemism undergoing exceptional threat (Myers et al. 2001). Based on exceptional species richness forty hotspots have been identified within the basin (O'Connor et al. 2004).

During the 19th and early 20th centuries, 14 of the estimated 43 mammal species in the catchment became extinct (Figure 2.11; from Short 1999) and local extinctions of bird, mammal and reptile species and communities continue. An estimated 340–400 plant species are at risk of extinction due to salinity (Keighery et al. 2002; Table 2.9).

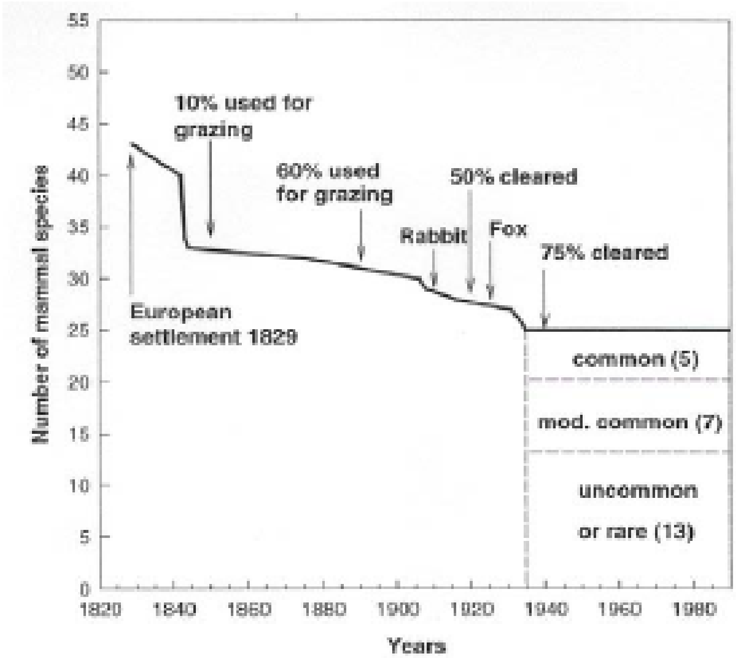


Figure 2.11: Decline in mammal species across the Wheatbelt since European settlement and possible causes (from Short 1999)

Table 2.9: Estimates of numbers of species in 1829, endemic species and threatened species in the Avon River basin (Avon Catchment Council 2005). Note that estimated number of mammal species is greater than number estimated by Short (1999).

Natural Taxa	Species in 1829	Endemic species[1]	Threatened species
Plants	>4850	60–80%	343
Mammals	62	59	23
Birds	203	94	14
Fish	10		1
Frogs	16	12	0
Reptiles	110		4
Invertebrates		Unknown	

1. An endemic species is a plant or animal species with a habitat restricted to one area

2.7.3 Water degradation

From the earliest days of observations the Avon River has been subjected to heavy floods about one year in ten (WRC 1999). The largest flood ever recorded was in 1872, well before the impact of clearing in the catchment had become pronounced. With the growth of towns along the river, especially Northam, Toodyay and York, and also with the development of valuable agricultural land on the river flats, floods took an increased toll. Following 'the great flood' of 1955, which caused serious problems in Northam, York and Toodyay, it was decided to 'train the river'; that is, to employ bulldozers to remove the braided channels, clear and deepen the main river channel and remove riverine vegetation, to allow floodwaters to move faster through the Avon Valley. The River Training Scheme operated from the mid-1950s to the mid-1970s, with bulldozing from near Cobbler's Pool (downstream of Toodyay) to Aldersyde, including the Avon River South branch up to Brookton (WRC 1999; Kelly pers. comm.). This involved:

- Removal of channel vegetation and debris to a width of 60 m
- Removal of dead trees, logs and debris which impaired the river flow
- Ripping of the river bed to induce erosion to create a deeper watercourse
- Removal of minor kinks and bends in the river.

The Avon River upstream of Beverley showing the denudation of stream vegetation and subsequent sedimentation resulting from the river training scheme (P Kelsey)

The scheme was deemed a partial success with flood levels reduced by 60% and flood velocities increased by 70%, although these were well below the expected targets (Binnie and Partners 1985). The main impacts of the river training scheme were the speeding up of the river flows and the mobilisation of sediments along the riverbed which resulted in filling the deep pools between Beverley and downstream of Toodyay with sediment. The scheme has also had disastrous effects on the river and riparian vegetation.

Boyagarra Pool, Avon River: Turbid water and algal growth after a storm event (Department of Water)

Between Cobblers Pool to the west and the Yenyening Lakes to the south-east there were originally (before the River Training Scheme) 26 major pools in the Avon River, some said to be more than 10 m deep. The pools were characteristically about 70 m wide, and 370 m to 2 km long. The pools were spaced down the river 16 to 20 times the width of the river. This is a low density of pools compared with many rivers elsewhere. Before the river training these pools had high aesthetic, nature conservation and recreational values. All the pools were affected by sedimentation after the river training. Some pools like Gwambygine Pool and Beverley Town Pool have been recently excavated, and sand has been excavated from Burlong Pool for many years (WRC 1999).

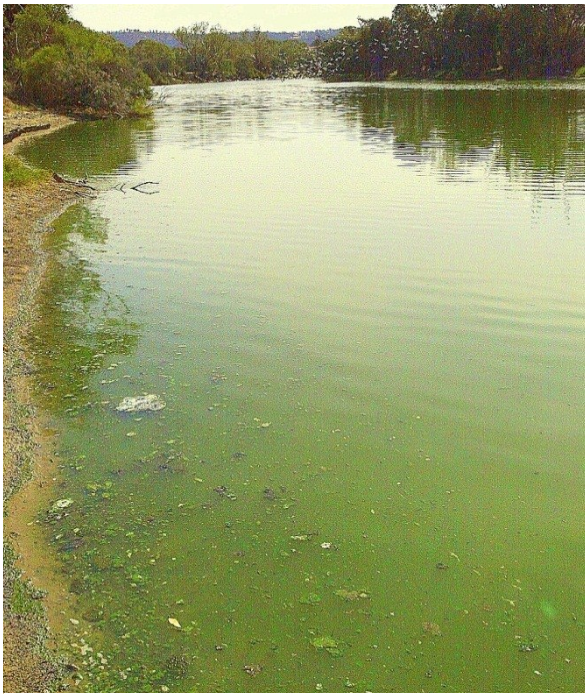
Gully erosion of farm land in the Avon Basin (Department of Water)

The wide-scale clearing of the natural bushland and its conversion to pasture and cropland has resulted in rising groundwater levels and the movement of salt from stores deep in the soil to the surface where it has entered streams and rivers. This has turned the Avon from a marginally-fresh river to a permanently brackish–saline river.

Excess water on farmland is a problem because of rising saline groundwater, soil erosion and waterlogging of cropland. An approach to dealing with this problem, favoured by some landowners, is to construct deep drains which carry water directly into watercourses or lakes. If not managed carefully, this practice can lead to increased salinisation and sedimentation of streams, rivers and lakes, and to unsightly scars on the landscape. Deep drains and their management are becoming one of the most important issues in the catchment.

Ali et al. (2010) modelled various deep-drainage scenarios with the Large Scale Catchment Model. They estimated increased streamflows and salt loads at the catchment outlet in the first quarter of the 21st century if artificial drains are installed, though the impacts of the drying climate are expected to reduce flows and loads by larger amounts. The flow-weighted salt concentrations are expected to increase if extensive artificial drains are installed.

Although most groundwater aquifers in the Avon River Basin are saline, there are localised fresh aquifers at risk of nitrogen pollution due to leaching from fertilising farmland. This could affect water quality in natural waterways as well as farm water supplies. For example, farm dams maintained by groundwater seepage are likely to experience summer algal blooms due to excess nutrients in groundwater (DOW 2009).



The Avon River during a potentially toxic blue-green algal bloom upstream of Toodyay in February 2013 (Department of Water)

In addition to sedimentation and salinity, the Avon River and its tributaries are also adversely affected by eutrophication. Nutrient inputs come from fertiliser, animal waste, sewage and organic matter. Algal activity is a regular occurrence in the Avon River pools between Beverley and Toodyay during summer and autumn, as well as in the catchment's tributaries and lakes. Algal blooms degrade ecological, recreational and scenic values and necessitate shut down of swimming, boating and other activities in the river pools.

The Northam town pool suffers from algal blooms (often toxic) most summers. In February 2013, a potentially toxic cyanobacterial bloom established itself in the 34 km stretch of the Avon River from Northam to Toodyay and persisted for approximately five weeks.

The Avon River: (left) algal growth upstream of the Northam Town Pool (Department of Water)

2.8 Impacts on the Swan Estuary

The inflows from the Avon River carry large amounts of sediment, organic matter, nutrient and algae, which adversely affect the Swan Estuary. Under most flow regimes these adverse impacts are only evident in the upper estuary. However, under exceptional circumstances, such as the large summer flow event of January 2000, the inflows can have damaging effects on the whole estuary.

Sediment inflows

The ANZECC guidelines (ANZECC & ARMCANZ 2000) give trigger values for turbidity for slightly disturbed ecosystems of 10–20 NTU for lowland and upland rivers, and 1–2 NTU for estuaries. Most sites in the east of the catchment have turbidity > 10 NTU and many have turbidity > 20 NTU. The average turbidity in the Swan (Avon) River flowing to the Upper Swan Estuary is 11 NTU (at 616011).

The large amounts of sediment in the Swan (Avon) River inflows are deposited on the estuary bed as the flows slow when they reach the coastal plain. Ellen Brook which also flows to the upper reaches of the Swan Estuary has very high soluble phosphorus concentrations (~0.4 mg/L) which adsorb onto the sediments suspended in Avon River flows and so deposits large amounts of particulate phosphorus in the upper estuary. It is not certain how much of the deposited phosphorus is available for algal growth or what is its ultimate fate; that is, whether it is cycled along the estuary bed towards the ocean or largely remains in the upper estuary.

Organic matter and oxygen

Most natural waters contain small quantities of organic compounds. Aquatic microorganisms use dissolved oxygen to convert the organic compounds into energy for growth and reproduction (food), also incorporating other nutrients such as nitrogen and phosphorus. Populations of these microorganisms tend to increase in proportion to the amount of food available. When excessive amounts of organic matter are available, and growth is not limited by other necessary nutrients, light, temperature or salinity, microbial metabolism can consume dissolved oxygen faster than atmospheric oxygen can dissolve into the water or the autotrophic community (algae, cyanobacteria and macrophytes) can produce it. Fish and aquatic insects can die when oxygen is depleted by microbial metabolism. Dissolved oxygen depletion can become evident during the initial aquatic microbial population explosion in response to inputs of large amounts of organic material (or other nutrients) or can be a chronic condition in a water body which receives large inputs of organic matter over a long period, as is the case in the Swan Estuary.

Over the last 20 years low dissolved oxygen conditions in the Swan Estuary have been common and are exacerbated by the presence of saltwater stratification. In summer and autumn, seawater intrudes up the Swan Estuary to approximately 50 km upstream of the estuary mouth. At the interface of the fresh and salt water, the denser saltwater underlies the freshwater as a ‘wedge’. Winter inflows push the salt wedge seaward. Tidal excursions of the salt wedge are typically of the order of 1–3 km although synoptic forcing may displace the salt wedge by up to 10 km, corresponding to the duration of the passage of low- and high-barometric pressure systems (Hamilton et al. 2000). There are several mechanisms by which the saline water may induce hypoxia or anoxia:

- The different chemical properties of salt water compared with freshwater decrease the solubility of oxygen and increase the coagulation and settling of suspended particles. As the organic matter in these settled particles decomposes it consumes oxygen.
- In the area of the salt wedge, the water column is salinity stratified. That is, the lighter freshwater floats on the denser saline water. This stratification inhibits mixing of the water column and the bottom water may become anoxic as oxygen consumed by aquatic fauna and plant decomposition is not replaced.

- Dense saline water also displaces oxygen-poor and nutrient-rich fresh water from the sediments.

To improve the ecological health of the upper Swan Estuary two oxygenation plants have been built, the first at Guildford (started operation in March 2009) and then one at Caversham, 5.5 km upstream of the Guildford plant (started operation in April 2012; Figure 2.12). When oxygen concentrations in the water are high, aerobic decomposition and recycling processes can function efficiently and organic matter is rapidly mineralised and nutrients removed from the system.

The oxygenation plants pump oxygen-depleted water from near the estuary bed, supersaturate it with oxygen, and return it to the bottom waters of the estuary. In the presence of oxygen, carbon in organic matter is converted to carbon dioxide by aerobic respiration, and is then lost to the atmosphere. Additionally, in oxygenated water phosphorus bound to sediment particles is less soluble and oxygenation of ammonium to nitrate is promoted. The nitrate can then be de-nitrified, given the appropriate conditions.

The effectiveness of the oxygenation plants was assessed for the 2010–11 period (DoW 2013). The 2010 winter had the second lowest flows on record, which meant 1) that the salt wedge remained in the oxygenation area most of the time, 2) that low flows had a limited 'flushing' effect on the accumulation of organic matter in the upper estuary, and 3) high water temperatures diminished the solubility of oxygen while increasing the rate of metabolism. All these factors increase oxygen demand. The challenging conditions contributed to several extended periods during which the oxygenation plants were unable to adequately supplement the high oxygen demand of the estuary. However there were repeated examples of periods during which plant operation markedly improved oxygen conditions over a substantial stretch of the estuary (DoW 2013)

River oxygenation plant in the Swan River, Guildford (Department of Water)

Nutrients and algal blooms

Most algae and cyanobacteria use the sun's energy and carbon dioxide dissolved in water to photosynthesise the carbohydrates required for their growth. Algae also extract microscopic amounts of necessary elements (nitrates and phosphates) from the surrounding water. Thus algal growth is limited by light, temperature, salinity and nutrient availability. Other elements are also important to some algae. For instance, diatoms require silicate to form their complex structures, and in many marine environments low iron concentrations have been shown to limit algal growth. Fresh, brackish and marine water support different algal species.

Algal blooms upset the delicate natural balance of plant and animal ecosystems in wetlands, rivers, estuaries and marine environments and can have many consequences. In the Swan Estuary, these include:

- Direct toxicity. *Karlodinium veneficum* blooms in the Swan Estuary have been shown to kill fish, most likely through damage to their gills. They are also toxic to mussels. Cyanobacterial blooms such as the bloom in the Avon River in February 2013 can be toxic to aquatic organisms and mammals (neurotoxins, liver toxin).
- Smothering of benthic habitat. An over-abundance of algae can choke a waterway, and block out the light other plants, such as seagrasses, need to produce food. Excessive and sustained algal growth will eventually kill seagrass beds.
- De-oxygenation following algal bloom collapse. When an algal bloom dies the process of decay can use up all the available oxygen in the water, effectively suffocating other aquatic life. This can kill fish, crabs and other animals, especially those that are attached or sedentary (do not move around).

The highly seasonal hydrology of the Swan River estuary is reflected in a well-documented succession of phytoplankton taxa (John 1994; Thompson & Hosja 1996). The high flow period of winter and early spring is dominated by freshwater diatoms, which are typically succeeded by a short-lived bloom of freshwater chlorophytes. In summer and autumn, estuarine and marine assemblages are dominant and typically show transitions between dinoflagellates (e.g. *Gymnodinium spp*. and *Prorocentrum spp.*) and the cosmopolitan coastal diatom *Skeletonema costatum*. Blooms of blue-green alga *Microcystis aeruginosa* (Hamilton 2000) and more recently (autumn 2012) dinoflagellates such as *Karlodinium veneficum* (Thompson 2013) are of particular concern in terms of biodiversity, amenity and long-term impacts on the estuary ecosystem due to their potential toxicity, and the ability to trigger rapid oxygen consumption and depletion upon their decay.

The Avon River contributes more than two-thirds of the nitrogen and one-third of the phosphorus load to the Swan Estuary (Section 5). Kalnejais et al. (2006) showed that most of this phosphorus remains in the estuary and is available for algal growth while most of the nitrogen from the Avon River is in soluble organic form (Figure 2.13) and flows to the ocean. This is in contrast to the estuary's coastal catchments which have a greater proportion of their nitrogen in inorganic form which is readily available for algal growth.

Robson & Hamilton (2004) modelled the February 2000 *Microcystis* bloom. Their modelling confirmed that *Microcystis* grew strongly in the high-temperature, high-nutrient, low-salinity conditions that followed the heavy inflow, as observed. Seeding from tributaries was also significant and the bloom could not have been sustained if the cell counts in the inflows had been low. This work highlights the role of algae in tributaries of the estuary in initiating and sustaining algal blooms. The *Microcystis* bloom of February 2000 was (most likely) ‘seeded’ by *Microcystis* in Avon River inflows as these were the dominant inflows.

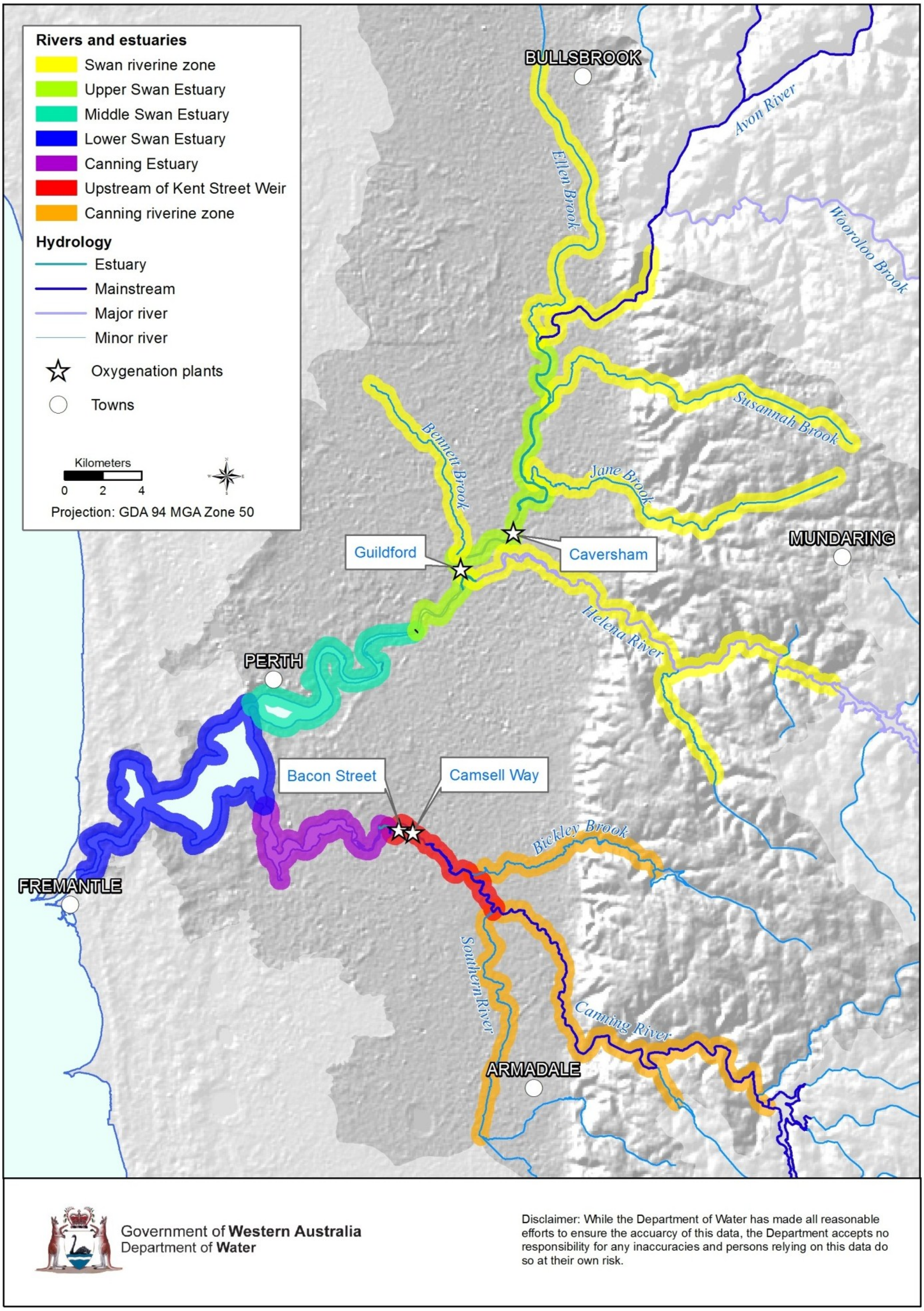


Figure 2.12: Location of the Swan and Canning river oxygenation plants

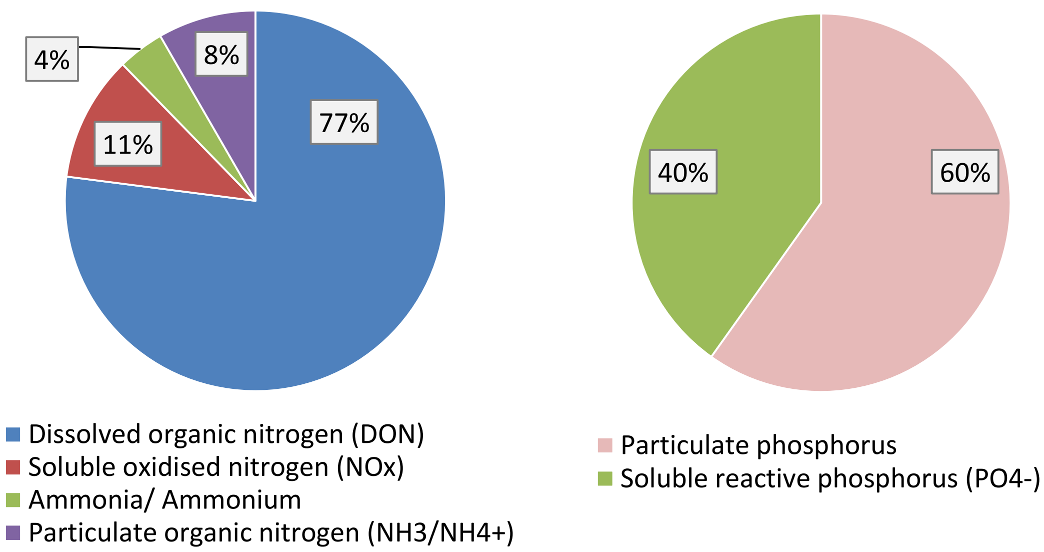


Figure 2.13: Average nutrient fractions in water samples from site 616076 (Swan River, Great Northern Highway)

2.9 Recent management initiatives

Under Western Australia's *Waterways Conservation Act 1976,* the 'inner catchment' of the Avon River was declared a *Management Area* and the Avon River Management Authority (ARMA) was created to undertake its management. The management area contained the land in the basin to the west of the eastern boundaries of the Koorda, Trayning, Kellerberrin, Quairading, Corrigin and Wickepin shires, but did not include the Brockman, Wooroloo and Helena catchments. The ARMA powers were limited to the *Management Area*, and ARMA had no power to undertake actions in the broader Avon catchment to the east.

In 1999 the ARMA provided a vision for the Avon River for 2020, with actions concentrated on the western one-third of the basin (the management area). This area was identified as being the part of the catchment most in need of initial attention. Furthermore, the problems of the Yilgarn and Lockhart catchments are primarily related to land management, rather than to river management. The ARMA's vision for 2020 included:

1. The river and its tributaries have significantly improved naturally functioning ecosystems.
2. The main river channel from Brookton and Wickepin down to the Avon Valley National Park is fenced on both sides and fencing of the major tributaries is well advanced.
3. Management agreements on riparian zone management are in place with landholders with properties adjoining the river.
4. Riverine and riparian rehabilitation is underway, with 75% of the original pools rehabilitated.
5. Sustainable agricultural systems are in place on 50% of the Avon River Basin.
6. Remnant vegetation is protected and managed for long-term sustainability.

7. Revegetation programmes and farming practices aimed at controlling discharge of saline groundwater and protecting surface soils are being implemented in 100% of the subcatchments of the basin.
8. Point source discharges to the river are either eliminated or their impacts minimised.
9. The town pools at Beverley, York and Northam are a source of pride and pleasure to local communities and attractions to tourists. Recreational sites along the river have been chosen with care, are properly designed, and are managed to ensure the river environment is not degraded.
10. The river wildlife (including terrestrial and aquatic) has also recovered according to measurable indicators. Feral and pest animals, especially foxes, cats, corellas and rabbits, and invasive exotic weeds, have been largely eliminated from the riverine bushland.
11. A fire management regime aimed at protecting both the environment and human assets has been developed and is being implemented.
12. Research and monitoring programmes continue to supply new information and progress reports on river recovery, both to ARMA and the public.
13. Rural and urban communities have learned to respect the river and to share responsibility for its recovery and conservation. Community interests are coordinated through an efficient communications network, based on resource centres and modern communication technology.
14. Finally, integrated purposeful management of the river and the catchment are accepted as the responsibility of all government agencies and community groups, and these parties share a common vision and goals, and enjoy working together to achieve them.

The ARMA then proposed a comprehensive prioritised management program to work towards its vision. However, Western Australian management authorities were disbanded in the 2000s and the ARMA was replaced by the community-based advisory committee, Avon Waterways Committee in December 2001. Natural resource management of the Avon Basin has continued primarily through the Avon Catchment Council, which became the Wheatbelt NRM in 2009.

Rehabilitation of the Avon catchment has continued over the past 30 years supported by management authorities, committees and community groups (e.g. ARMA, Avon Waterways Committee (AWC) and various committees established to develop plans for the river recovery sections, Avon Catchment Council, Wheatbelt NRM, York River Conservation Society, Avon Valley Environmental Society, Toodyay Friends of the River), government agencies (DEC (now DER and DPaW), WRC [now Department of Water], SRT, DAFWA), and other organisations (Greening WA, WWF). Major achievements, using an extensive array of external funds including NHT and State NRM Office funding, outlined in Revell et al. 2006 and DoW (2007), include:

- *Avon River riparian zone rehabilitation*
    - Fencing of approximately 500–600 km of the basin's riparian zones – about 170 km of the main river channel is fenced both sides (340 km of fence) and the remainder is on tributaries. The fencing involved 230 landholders (Kelly pers. comm.; DoW 2007).
    - Revegetation and/or regeneration of fenced areas
    - Establishment of a riparian plant herbarium collection for the Avon River Basin as both specimens and electronic data
    - Construction of demonstration waterway riffles for sediment control at Burlong Pool, Gwambygine, Bolgart, York, Toodyay and Beverley town pools
    - Monitoring and evaluation.
- *Rehabilitation of Avon River pools*

  This involved the preparation of sediment management plans for major river pools:
    - Katrine Pool
    - Boyagarra Pool
    - Northam Town Pool
    - Beverley Town Pool
    - Gwambygine Pool
    - Burlong Pool.

  and ongoing monitoring and evaluation of sediment inflows to pools. This project also involved the removal of approximately 71 600 m^3 of sediments from
    - Boyagarra Pool
    - Gwambygine Pool
    - Railway Pool
    - Katrine Pool
    - Northam Town Pool
    - Ballardong Pool
    - Beverley Town Pool.

- *Management surveys of major tributaries*

  Foreshore and channel surveys of major tributaries to map current condition and identify management options were completed for:

  - Toodyay Brook, approximately 45 km long (WRC, Water Resource Management Series [WRM] 22)
  - Mackie River, approximately 46 km long (WRC, WRM 26)
  - Spencers Brook, approximately 29 km long (WRC, WRM 28)
  - Talbot Brook, approximately 35 km long (WRC, WRM29)
  - Magnolia Creek, approximately 10 km long (WRC, WRM 38)
  - Mortlock River North, approximately 76 km (WRC, WRM 39)
  - Mortlock River East, approximately 82 km (WRC, WRM 41).

- *Assessing salinity risk to rural towns and infrastructure*

  Salinity risk survey of rural towns was done by Department of Agriculture and Food WA under its Rural Towns – Liquid Assets Project (George et al. 2005).

- *River section management*

The primary output from this project was the production of River Recovery Plans (RRP). The Avon River was divided into 19 management sections; this allowed local landholders to focus on the river closest to their properties. These section plans each started with the establishment of a group of landholders with properties in the section and other interested people to form the group to drive the planning over a period of 6–12 weeks along with a consultant. The planning included river walks and one-on-one interviews with landholders. The resulting draft publication was reviewed by the group prior to publication and alterations negotiated with the project team. The results produced an action plan for future work by either the community or government. This project also tied in with other projects mentioned above, like fencing, revegetation and sediment management. River recovery plans were produced for the following river sections:

- Section 1 & 2 Avon Gorge and Deepdale (WRC, RRP7)
- Section 3 Toodyay Townsite (WRC, RRP1)
- Section 4 & 5 Northam to Toodyay (WRC, RRP8)
- Section 6 Northam Townsite (WRC, RRP2)
- Section 7,8 & 9 Mile Pool to Spencers Brook (WRC, RRP9)

  - Section 10 York Townsite (WRC, RRP3)
  - Section 11 & 12 Gwambygine to Edwards Crossing (WRC, RRP6)
  - Section 13, Beverley Townsite to Edwards Crossing (WRC, RRP4)
  - Section 14 ,15,16 Beverley to Qualandary Crossing (WRC, RRP5)
  - Section 17 Yenyening Lakes Management Strategy 2002–2012 (WRC, WRM32)
  - Section 18 Avon River South Branch (unpublished).

- *Communication Strategy for the Avon River and Associated Land Management*
  - The output was the Communication Strategy and eight Rivercare workshops to present to the community waterways management techniques, including how to implement them: *Avon River Communication Strategy* (WRC, WRM3).

In the hiatus between NHT and NHT2 funding, further projects completed a lot of the work started using NHT funding and River Recovery Plans were produced for:

  - Dale River (including Foreshore and Channel Assessment; DoE, RRP10)
  - Section 19 Aldersyde to Kweda (including Foreshore and Channel Assessment) (DoW, RRP11)
  - Section 20 Yealering Lakes (DoW, RRP 12).

Foreshore and channel assessments were also completed for:

  - Mortlock River and Mortlock River South, approximately 75 km (DoE, WRM 42).

A plant identification book: *Riparian Plants of the Avon Catchment* (Oversby 2004) resulted from the electronic herbarium collection. The NHT funded the distribution of the book to 80 Avon community organisations and individuals. Other works included the removal of 2000 cubic metres of sediments from Long Pool.

Subsequent major investment plans were coordinated by the Wheatbelt NRM in 2005–08 (Avon Catchment Council 2005; $13.8M in 2005/06, $12.1M in 2006/07 and $10.6M in 2007/08) with funding from NHT2 and NAPSWQ and included projects to:

- Manage surface water
- Improve and monitor water quality
- Plant trees for salinity management
- Protect natural diversity and biosecurity
- Promote soil health and ameliorate acidity
- Enable stakeholders engagement and develop partnerships.

The Wheatbelt NRM's 2008–09 (Wheatbelt NRM 2009) annual report summarised work done in the catchment, which included:

- River dredging of priority pools
- Community fencing of waterways
- Riparian revegetation
- Water quality monitoring.

Specifically, foreshore and channel assessments were completed for:

  - Christopher Brook (WRM 52)
  - Dale River South (WRM 50)
  - Jimperding Brook (WRM 48)
  - Monjerducking Gully (WRM 53).

During the period 2005–10, river pool dredging removed large volumes of river sediments. In addition to the dredging outlined by Revell et al. (2006), sediment (~180 000 m^3) was removed from other pools:

- Cobblers Pool
- Long Pool
- Jimperding Pool
- Burlong Pool
- Kokeby Pool, Eyres Pool
- Dwarlaking Pool
- Reserve Pool (Dale R)
- Mile Pool (Avon R South)
- Neuralgin pool
- Sandy Pool.

Some pools, Gwambygine Pool, Katrine Pool and Railway Pool, have had sediment cleared more than once. Burlong Pool, 5–6 km upstream of Northam, has sediments removed regularly, primarily to protect the Northam Town Pool from sedimentation.

Management plans for Dwarlacking, Neuralgin and Beardlucking pools were completed. A nutrient management manual entitled '*Nutrient management for the Avon River Basin* – a *toolkit for managing nutrient loss to the environment from a range of land uses*' was written (DOW 2009) and widely distributed, and workshops held with managers. Waterways assessments in the Lockhart and Yilgarn rivers were undertaken, and community education continued with the Ribbons of Blue Program and a Rivercare workshop. Solutions to acid saline drainage were investigated.

There has been a large investment in natural resource management in the Avon Basin and a lot of work contributed by many concerned organisations and individuals. Much progress has been made with respect to items 2, 3, 4 and 13 of the ARMA's vision for 2020, described at the beginning of this section. The improvements to river health are primarily due to the fencing and re-establishment of riparian zone vegetation and the clearing of sediment from river pools. However, the Avon catchment covers a huge area, approximately 120 000 km^2 (bigger than the state of Tasmania), and immense resources and continued effort will be required to mitigate the cumulative impacts of land clearing and the historic river training scheme in this fragile landscape. Based on the evidence from this study the ARMA's 1999 vision for the Avon River for 2020 is still to be realised.

3 Data analysis

3.1 Flow data

Although there were 35 sites across the basin with flow data, only 17 had sufficient data and/or were suitably located to be included in the analyses. General criteria for selecting flow sites for analysis were:

- Located close to the catchment outlet of major rivers
- Good quality data and data quality control
- Ideally having more than five years of daily data
- Water quality sampled at the same location.

Flow data from these sites were examined and the following extracted:

- Data quality
- Minimum, maximum, average and median daily flow
- Flow duration.

Appendix D gives site flow and data quality statistics and flow duration curves for all 17 sites.

Three sites are discussed here: Swan River, Walyunga (616011), Dale River, Waterhatch Bridge (615027) and Yilgarn River, Gairdners Crossing (615015) for the period of 2001–10. Walyunga (616011) is at the catchment outlet. The other sites, Waterhatch Bridge (615027) and Gairdners Crossing (615015) are in the zone of rejuvenated drainage and the zone of ancient drainage respectively (Figure 3.3). Both Walyunga and Waterhatch Bridge have 95% of their flows during winter (May–October; Table 3.1). Gairdners Crossing discharges only 63% of its average annual flow during winter. However, the large proportion of summer flow at Gairdners Crossing was a result of a summer storm in February 2003, which was the largest flow event of the record, and thus skewed the average monthly summer flow at this site.

Figure 3.1 shows the average monthly flow per cent for 2001–10 for the three sites. It is clear that both Walyunga and Waterhatch Bridge are hydrologically similar whereas Gairdners Crossing is quite different with a greater proportion of its flow in summer and a shorter duration of winter flow. Figure 3.2 shows the flow duration curves for the sites. Waterhatch Bridge has over an order of magnitude more flow per unit catchment area than Walyunga and several orders of magnitude more than Gairdners Crossing, and flows more than 90% of the time. Gairdners Crossing only flows 18% of the time, and the flow quickly falls from high flow to no flow.

Table 3.1: Flow statistics for the Swan River, Walyunga (616011) at the Avon Basin outlet, Dale River, Waterhatch Bridge (615027) in the zone of rejuvenated drainage and Yilgarn River, Gairdners Crossing (615015) in the zone of ancient drainage

Site name	**Walyunga**	**Waterhatch Bridge**	**Gairdners Crossing**
Site context	Avon River	Dale River	Yilgarn River
Drainage zone	outlet	rejuvenated	ancient
AWRC reference	616011	615027	615015
Period	2001–10	2001–10	2001–10
Average Annual flow (GL/yr)	154	26	0.3
% of Walyunga flow		*17%*	*0.2%*
Average summer Flow (GL/yr)	8.4	1.2	0.1
% of annual flow	*5%*	*5%*	*37%*
% of Walyunga flow		*14%*	*2%*
Average winter Flow (GL/yr)	145	25	0.2
% of annual flow	*95%*	*95%*	*63%*
% of Walyunga flow		*17%*	*0.1%*
Average daily flow (ML/yr)	421	70	0.9
Minimum daily flow (ML/day)	0.0	0.0	0.0
25^{th} percentile (ML/day)	0.4	0.7	0.0
Median daily flow (ML/day)	43	9	0.0
75^{th} percentile (ML/day)	319	52	0.0
Maximum daily flow (ML/day)	12 480	5 520	277

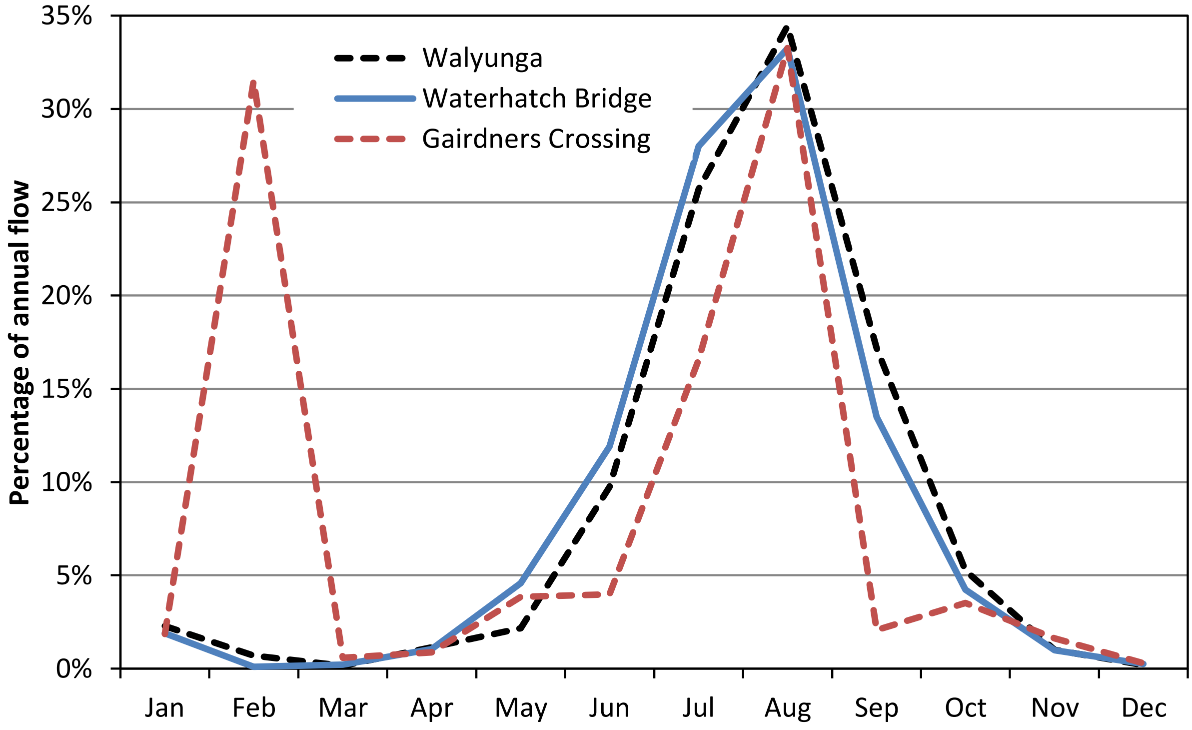


Figure 3.1: Average monthly flow per cent for Swan River, Walyunga (616011), Dale River, Waterhatch Bridge (615027) and Yilgarn River, Gairdners Crossing (615015) for 2001–10

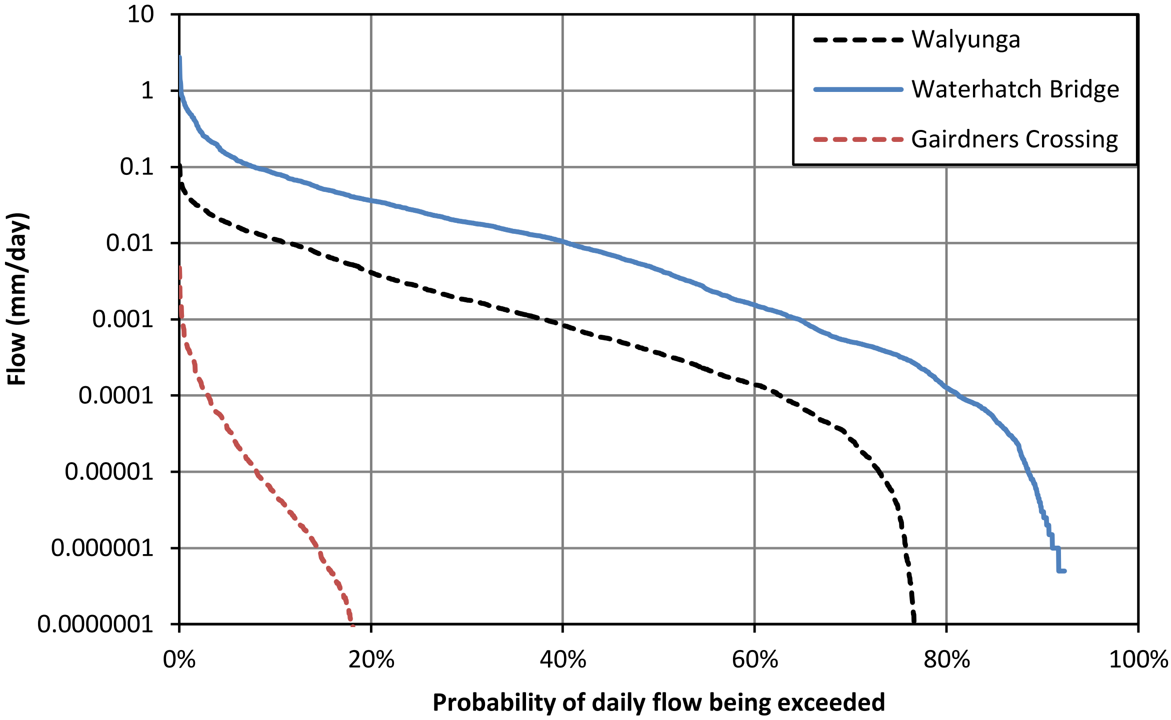


Figure 3.2: Flow duration curves for Swan River, Walyunga (616011), Dale River, Waterhatch Bridge (615027) and Yilgarn River, Gairdners Crossing (615015) during 2001–10

3.2 Nutrient data collection and analysis

Nutrient data in the Avon Basin has been collected intermittently since the 1970s at a multitude of sites across the catchment. Since the 1990s, nutrient sampling has been more frequent, long-term monitoring sites have been established, and sampling and laboratory methods documented. Between 2003 and 2005, many long-term monitoring sites were not sampled due to budget cuts but from 2006 sampling at these sites resumed.

Nutrient statistics were calculated for 31 sites throughout the Avon Basin (Figure 3.3 & Figure 3.4). These statistics, which include status, trends and loads, allow comparisons of nutrient data across the catchment and examination of changes (trends) in nutrient concentrations. This information aided the understanding of nutrient processes and model conceptualisation, and was compared with the modelled loads for model validation. Sites were selected based on their sample size and position within the catchment. Water quality status classifications were done for all sites but only 16 sites had sufficient data for trends analyses and 12 sites for load calculations.

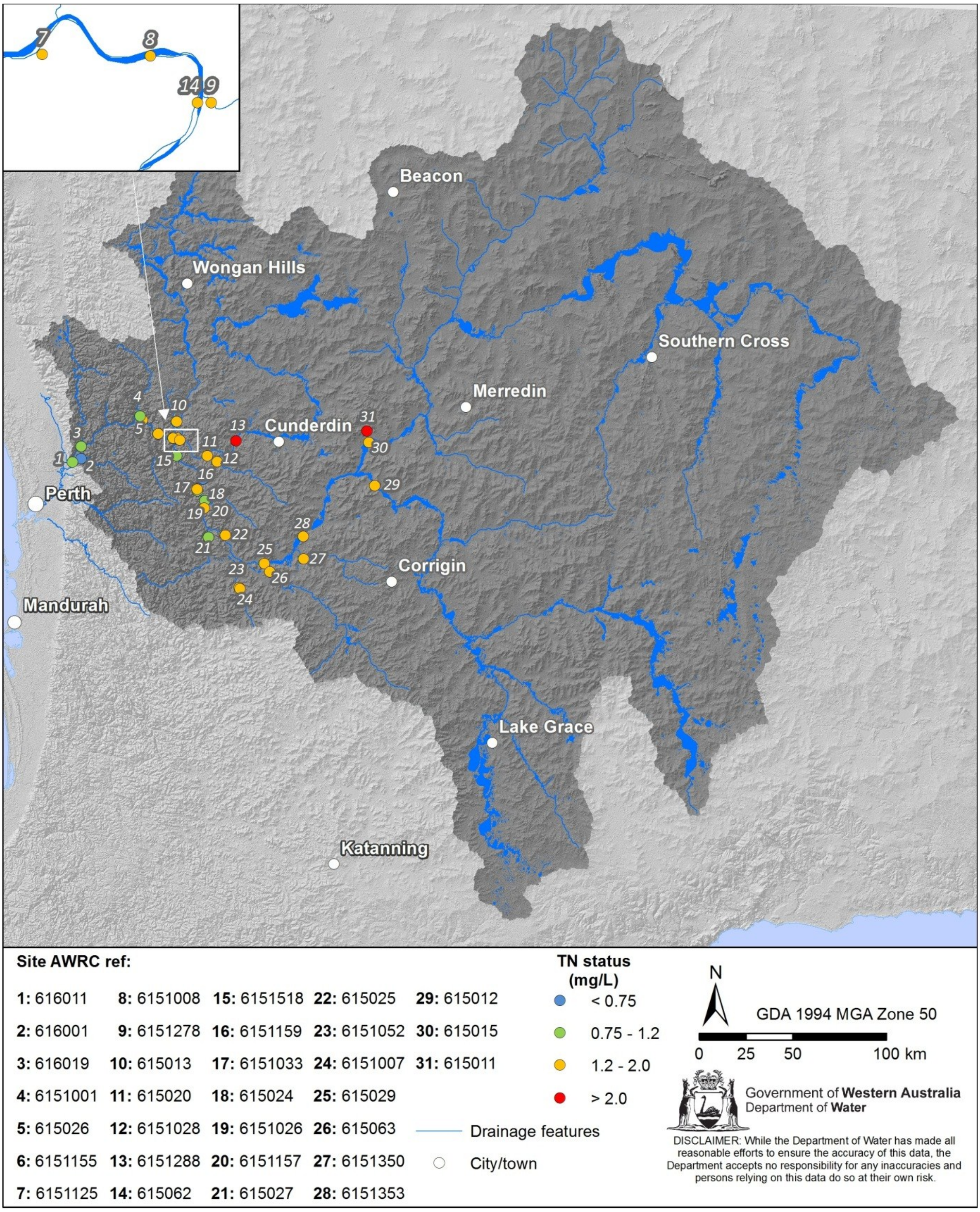


Figure 3.3: Three-year median total nitrogen concentration status

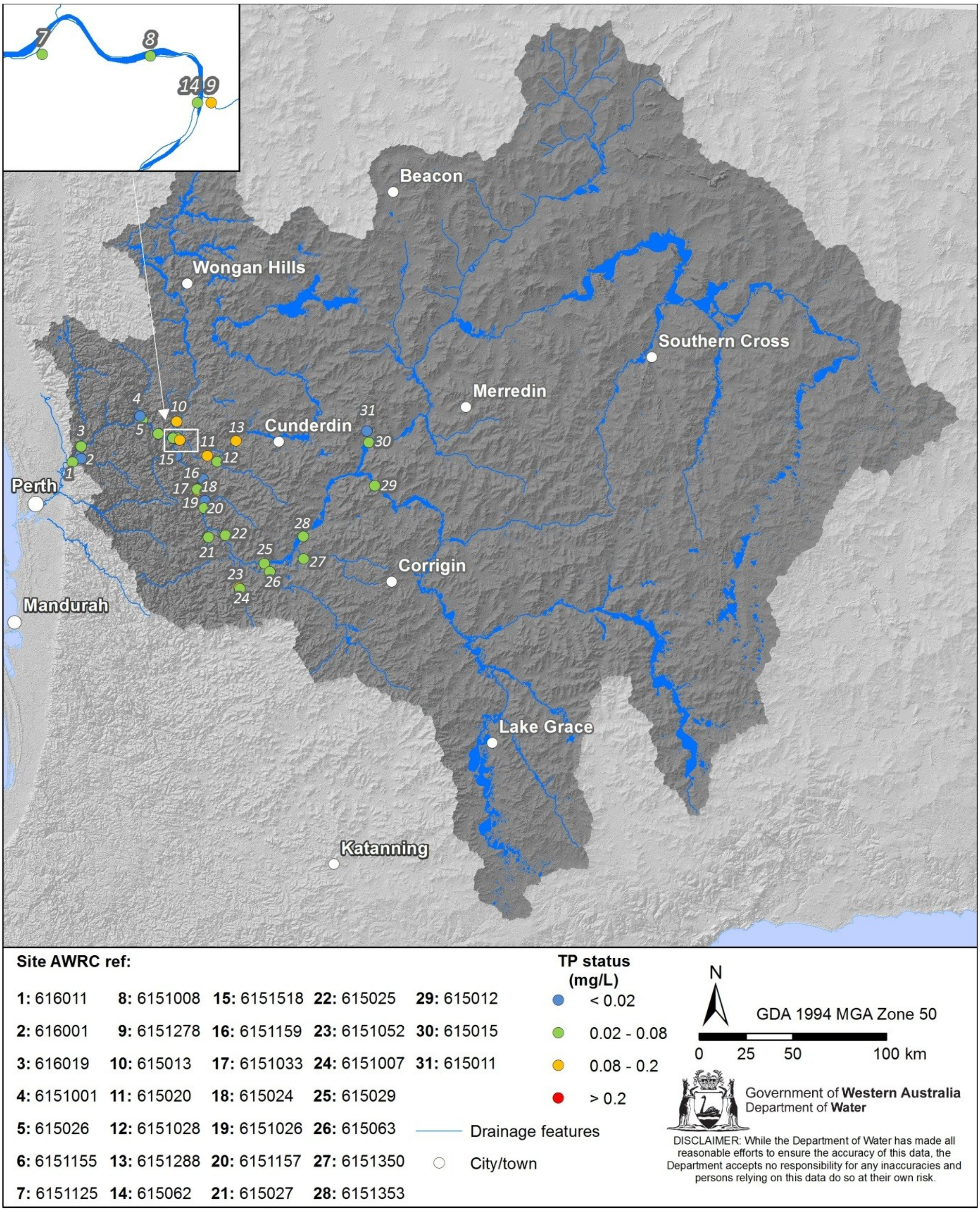


Figure 3.4: Three-year median total phosphorus concentrations status

3.2.1 Nutrient status

The nutrient status is a method for classifying and reporting the total nitrogen (TN) and total phosphorus (TP) concentrations. The classifications are listed in Table 3.2, and are the same as those used in the Statewide River Water Quality Assessment webpage on the Department of Water's website <www.water.wa.gov.au/idelve/srwqa/>.

Table 3.2: Classifications used to assess the status of TN and TP concentrations in monitored waterways

Status		TN three-year winter median concentration (mg/L)	TP three-year winter median concentration (mg/L)
Very high	🔴	> 2.0	> 0.2
High	🟡	1.2 – 2.0	0.08 – 0.2
Moderate	🟢	0.75 – 1.2	0.02 – 0.08
Low	🔵	< 0.75	< 0.02

Nutrient status is based on the median of the three most recent consecutive years of water quality data. When sampling commences at a site, the status is given initially as the median of the first year of data, then at the end of the second year, as the median of the two previous years of data, and at the end of three years as the three-year median value. This is done so that status can be reported during the first three years of monitoring. Following the first three years of sampling, changes in nutrient status are made if both the three-year median and the whole 90% confidence interval move to a new classification category. This methodology reduces the effect that natural variability has on reporting of nutrient concentration data. Thus, a change in status indicates a significant change in water quality. An example of a status calculation is given in Appendix B.

Water quality data in the Avon Basin is sparse and intermittent, with most data for the period 2006–09. Ideally, the water quality status should reflect the most recent three-year period; however, only 19 of the 31 sites had sufficient data in 2010 to calculate three-year medians for the 2008–10 period. Thus, in order to effectively report and compare water quality status between sites, the period 2007–09 was used for most sites. Four sites had insufficient TN data and six sites insufficient TP data to calculate medians for 2007–09 so medians for these sites were calculated using 2006–08 data.

TN concentrations in the Avon Basin were generally high. Of the 31 sites (Table 3.3 & Figure 3.3), two sites had 'very high' status, 21 sites 'high' status, six sites 'moderate' status and two sites had 'low' status. The TP status was quite different: no sites with 'very high', seven with 'high', 18 with 'moderate' and six with 'low' status (Table 3.3 & Figure 3.4).

Figure 3.3 and Figure 3.4 give a spatial representation of site nutrient status within the Avon Basin. Median TN concentrations ranged from 0.52 mg/L at Wooroloo Brook, Karls Ranch (616001) to 2.35 mg/L at Mooranoppin Creek, Mooranoppin Rock (615011).There was a progressive increase in the TN status across the catchment from the west to the east (Figure 3.3). There was little difference between tributaries and main river channel concentrations, except in the high rainfall areas, where tributaries had lower TN concentrations than the main channels.

Median TP concentrations ranged from 0.007 mg/L at Wooroloo Brook, Karls Ranch (616001) to 0.14 mg/L at Mooranoppin Creek, Mooranoppin Rock (615011). High TP concentrations were found in the North and East branches of the Mortlock River, as well as the Avon River at Toodyay (615024). Note that the Mortlock catchments have lower soil PRI values than other areas of the catchment (see Figure 2.7).

Table 3.3: Three-year median TN and TP concentrations, with status shown as: low (🔵), moderate (🟢), high (🟡), very high (🔴). The status period is 2007-09 unless otherwise indicated.

AWRC ref	Site context	Site Name	TN			TP		
			mg/L	Status		mg/L	Status	
615024	Avon River	Balladong Street York	1.10	🟢	*	0.086	🟡	*
615025	Avon River	Beverley Bridge	1.70	🟡		0.040	🟢	
615063	Avon River	Boyagarra Road	1.70	🟡		0.044	🟢	
6151052	Avon River South	Brookton Highway	1.40	🟡		0.037	🟢	
6151008	Avon River	Clark Street	1.30	🟡		0.036	🟢	
6151007	Avon River South	Downstream Brookton WWTP	1.75	🟡		0.090	🟡	
6151125	Avon River	Downstream of (Northam WWTP) inflow	1.90	🟡		0.053	🟢	
6151157	Avon River	Gwambygine	1.30	🟡		0.028	🟢	
6151155	Avon River	Katrine Bridge	1.30	🟡	*	0.035	🟢	*
6151159	Avon River	Mackies Crossing	0.64	🔵	*	0.011	🔵	*
615062	Avon River	Northam Weir	1.20	🟡		0.025	🟢	
615026	Avon River	Stirling Terrace Toodyay	1.30	🟡		0.032	🟢	
616011	Avon River	Walyunga	0.89	🟢		0.022	🟢	
615029	Avon River	Yenyening Confluence	1.65	🟡		0.037	🟢	
6151033	Avon River	YTP4	1.20	🟡		0.026	🟢	
616019	Brockman River	Yalliawirra	0.91	🟢	*	0.024	🟢	*
615027	Dale River	Waterhatch Bridge	0.95	🟢		0.032	🟢	*
6151350	Kunjin Creek	Kunjin Creek Dangin Mears Road	1.30	🟡		0.030	🟢	
615012	Lockhart River	Kwolyn Hill	2.00	🟡		0.023	🟢	
6151026	Mackie River	Top of Beverley - York Road	1.00	🟢		0.017	🔵	
615011	Mooranoppin Creek	Mooranoppin Rock	2.35	🔴		0.140	🟡	
6151288	Mortlock River East	Great Eastern Highway - D/S Meckering	2.10	🔴		0.064	🟢	
615020	Mortlock River East	O'Driscolls Farm	1.70	🟡		0.093	🟡	
6151028	Mortlock River East	Quellington Road	1.60	🟡		0.120	🟡	
6151278	Mortlock River East	Taylor Street Weir	1.70	🟡		0.091	🟡	
615013	Mortlock River North	Frenches	1.70	🟡		0.086	🟡	
6151353	Salt River	Dangin Mears Road	1.40	🟡		0.037	🟢	
6151518	Spencers Brook	Spencers Brook	0.77	🟢		0.014	🔵	
6151001	Toodyay Brook	Toodyay West Road	0.86	🟢		0.019	🔵	
616001	Wooroloo Brook	Karls Ranch	0.52	🔵		0.007	🔵	
615015	Yilgarn River	Gairdners Crossing	1.30	🟡		0.032	🟢	*

* Sites with nutrient status from 2006–08 due to insufficient data

3.2.2 Trends in nutrient concentrations

Stream water quality will vary due to changes or disturbances within the catchment. Changes in TN and TP concentrations can be caused by:

- changes in flow
- seasonal variations
- changes in land use
- land management practices
- relative timing of fertiliser application, rainfall and data collection
- stream bank erosion following floods or clearing in the riparian zone
- fires in the catchment.

Changes brought about by human activity will usually be superimposed on natural sources of variation. In this project the influences of flow and seasonal variation were examined and were corrected for before trend analysis. Thus, the observed trends in nutrient concentration are likely to be linked to human intervention or other changes within the catchment.

Non-parametric tests are used to identify statistically-significant trends in the nutrient data; they are used because they are not affected by non-normal data distribution, are not sensitive to outliers and are not affected by missing or censored data (Loftis et al. 1991). An assumption of the non-parametric (Mann-Kendall) trend tests is that the trends are monotonically increasing or decreasing (Helshel & Hirsch 1992). Further explanation for the methodology is included in Appendix B.

The results of the statistical trends analysis are shown in Table 3.4 and Table 3.5. To detect a statistically significant trend the statistical *p-value* must be below 0.05, and the number of independent samples (n^*) must be larger than the number of independent samples required to detect a trend ($n^\#$). That is, if $p < 0.05$ and $n^* > n^\#$, then there is a statistically significant trend. If $p < 0.05$ and $n^* < n^\#$, then it is likely that a trend will emerge if more samples are collected. In this case the trend is labelled an ‘emerging’ increasing or decreasing trend. If $p > 0.05$ no trend is reported.

There were no statistically significant tends in TN and TP concentrations in any of the data examined. However, Dale River, Waterhatch Bridge (615027) displayed an emerging increasing TN trend (0.03 mg/L/yr) and emerging increasing TP trends were observed at Toodyay West Road, Toodyay Brook (6151001; 0.001 mg/L/yr) and Top of Beverley – York Road, Mackie River (6151026; 0.002 mg/L/yr). An emerging decreasing TP trend was observed at Downstream Brookton WWTP, Avon River South (6151007; 0.015 mg/L/yr).

Table 3.4: TN trend results (p-values and other statistics are included in Appendix B)

AWRC ref	Site Name	Context name	Test	Period	Trend (mg/L/yr)	Trend
615024	Balladong Street York	Avon River	MK	2003–10	-	No trend
615025	Beverley Bridge	Avon River	S	2000–10	-	No trend
615026	Stirling Terrace Toodyay	Avon River	S	2006–10	-	No trend
615062	Northam Weir	Avon River	S	2003–10	-	No trend
616011	Walyunga	Avon River	S	2006–10	-	No trend
6151008	Clark Street	Avon River	S	2006–10	-	No trend
6151033	YTP4	Avon River	S	2006–10	-	No trend
6151007	Downstream Brookton WWTP	Avon River South	S	2006–10	-	No trend
6151052	Brookton Highway	Avon River South	S	2006–10	-	No trend
615027	Waterhatch Bridge	Dale River	MK	2002–10	0.03	Emerging increasing
6151026	Top of Beverley - York Road	Mackie River	S	2006–10	-	No trend
615020	Odriscolls Farm	Mortlock River East	MK	1999–10	-	No trend
6151028	Quellington Road	Mortlock River East	MK	2006–10	-	No trend
6151278	Taylor Street Weir	Mortlock River East	MK	2006–10	-	No trend
615013	Frenches	Mortlock River North	S	2003–10	-	No trend
6151001	Toodyay West Road	Toodyay Brook	S	2006–10	-	No trend

S: Seasonal Kendall test for trend

MK: Mann-Kendall test for trend

Table 3.5: TN trend results (p-values and other statistics are included in Appendix B)

Site	Site Name	Context name	Test	Period	Trend (mg/L/yr)	Trend
615024	Balladong Street York	Avon River	S	2003–10	-	No trend
615025	Beverley Bridge	Avon River	S	2000–10	-	No trend
615026	Stirling Terrace Toodyay	Avon River	MK	2006–10	-	No trend
615062	Northam Weir	Avon River	MK	2003–10	-	No trend
616011	Walyunga	Avon River	S	2006–10	-	No trend
6151008	Clark Street	Avon River	S	2006–10	-	No trend
6151033	YTP4	Avon River	S	2006–10	-	No trend
6151007	Downstream Brookton WWTP	Avon River South	S	2006–10	-0.015	Emerging decreasing
6151052	Brookton Highway	Avon River South	MK	2006–10	-	No trend
615027	Waterhatch Bridge	Dale River	MK	2002–10	-	No trend
6151026	Top of Beverley - York Road	Mackie River	S	2006–10	0.002	Emerging increasing
615020	Odriscolls Farm	Mortlock River East	MK	1999–2010	-	No trend
6151028	Quellington Road	Mortlock River East	MK	2006–10	-	No trend
6151278	Taylor Street Weir	Mortlock River East	MK	2006–10	-	No trend
615013	Frenches	Mortlock River North	MK	2003–10	-	No trend
6151001	Toodyay West Road	Toodyay Brook	MK	2006–10	0.004	Emerging increasing

S: Seasonal Kendall test for trend

MK: Mann-Kendall test for trend

3.2.3 Loads

In order to calculate nutrient loads (without catchment models), sites must have both flow and nutrient concentration data taken on the same day, with more than 4 samples per year. Ideally, nutrient concentration data also needs to be taken over a range of flows, in order to develop a representable flow-concentration relationship. Of the 17 sites that were found to be suitable for flow analysis (Section 3.1), 12 sites had sufficient flow, TN and TP data for load calculations. Loads were calculated using a LOESS technique (Cleveland 1979; Helshel & Hirsch 1992) with further details on the LOESS load calculation methodology given in Appendix B. The 1997–2010 loads are also listed in Appendix B and the average annual nitrogen and phosphorus loads for each site are listed in Table 3.6.

Table 3.6: Average annual nitrogen and phosphorus loads for Avon Basin monitoring sites

Site name	Context	AWRC ref	Nitrogen load (t/yr)	Number of years of data	Phosphorus load (t/yr)	Number of years of data
Walyunga	Avon River	616011	210	10	7.7	10
Karls Ranch	Wooroloo Brook	616001	21	10	0.27	10
Yalliawirra	Brockman River	616019	33	10	0.75	10
Stirling Tce Toodyay	Avon River	615026	133	9	3.7	9
Frenches	Mortlock North	615013	13	10	0.61	10
Odiscrolls Farm	Mortlock East	615020	13	10	0.72	10
Northam Weir	Avon River	615062	89	10	1.8	10
Waterhatch Bridge	Dale River	615027	52	10	1.1	10
Boyagarra Road	Avon River	615063	21	3	1.0	3
Kwolyn Hill	Lockhart River	615012	3.0	10	0.08	10
Gairdners Crossing	Yilgarn River	615015	0.6	10	0.01	10
Mooranoppin Rock	Mooranoppin Creek	615011	0.3	10	0.02	10

4 Model selection, data and calibration

Large-scale flow and nutrient catchment models have large data requirements which can be roughly divided into the following categories:

- Spatial data
  - Drainage network
  - Lake and reservoir mapping
- Model drivers
  - Rainfall
  - Evaporation/evapotranspiration
  - Leaf area index (LAI)
  - Impervious area
  - Land use and associated nutrient data (e.g. fertilisation, nitrogen fixation, nutrient surplus)
- Calibration data
  - Streamflow
  - Stream nutrient (TN and TP) concentrations.

The data requirements vary with the model used. This section discusses the choice of hydrological and nutrient model for this project, the input data used and the model calibration.

4.1 Model selection

The modelling platform chosen was the Source Integrated Modelling System (IMS; referred to as Source in this report). Source facilitates whole-of-catchment models and was developed by eWater (Carr & Podger 2012). It is the latest of the EMSS, E2 and WaterCast model evolution.

Two of the six hydrological models available with Source, the Large Scale Catchment Model (LASCAM; Sivapalan et al. 1996a, b, c) and Gènie Rural à 4 paramètres Journalier (GR4J; Perrin et al. 2003) were compared in the Brockman River catchment. LASCAM was developed by the University of Western Australia's Centre for Water Research and has been used to estimate flows in many Western Australian catchments. LASCAM was coded as a 'plug-in' to Source by Department of Water staff (Hall 2011b).

Both models were run at a daily time step with the same climatic input data, and calibrated between 6/7/1985 and 1/1/2002 (5293 days) and validated between 2/1/2000 and 30/10/2004 (1764 days). Both models were calibrated to the Brockman River, Yalliawirra (616019) and Brockman River, Tanamerah (616006) flow gauging stations. The objective function used was the Nash-Sutcliffe Efficiency (NSE) daily log-bias.

The calibration results (Table 4.1) show that LASCAM had a better NSE and a lower bias for both the calibration and validation, and also replicated summer flows more accurately than GR4J. So, LASCAM was chosen to model the hydrology of the Avon Basin.

Table 4.1: Calibration and validation statistics for LASCAM and GR4J

Parameter	Tanamerah (AWRC ref–616006)					Yalliawirra (AWRC ref–616019)				
	Observed	GR4J		LASCAM		Observed	GR4J		LASCAM	
		value	Bias	value	Diff		value	Diff	value	Diff
Calibration										
NSE daily	-	0.87	-	0.88	-	-	0.85	-	0.91	-
NSE monthly	-	0.91	-	0.94	-	-	0.88	-	0.93	-
NSE annual	-	0.85	-	0.91	-	-	0.62	-	0.82	-
Total runoff (GL)	370	376	-2%	355	4%	787	802	-2%	780	1%
Summer runoff (GL)	12	31	<-100%	8	30%	25	54	<-100%	12	51%
Winter runoff (GL)	350	346	1%	465	-33%	762	748	2%	768	-1%
75 percentile flow (ML/day)	77	74	5%	65	16%	165	183	-11%	178	-8%
90 percentile flow (ML/day)	227	200	12%	242	-7%	478	430	10%	521	-9%
Max flow (ML/day)	2296	2096	9%	1649	28%	2588	3055	-18%	2486	4%
Period	6/7/1985–01/01/2000					6/7/1985–01/01/2000				
Number of days	5293					5293				
Validation										
NSE daily	-	0.69	-	0.75	-	-	0.80	-	0.81	-
NSE monthly	-	0.72	-	0.81	-	-	0.84	-	0.83	-
NSE annual	-	0.37	-	0.52	-	-	0.59	-	0.61	-
Total runoff (GL)	75	64	14%	71	6%	169	162	4%	178	-5%
Summer runoff (GL)	14	31	<-100%	7	53%	5	13	<-100%	2	64%
Winter runoff (GL)	355	345	3%	348	2%	163	149	9%	176	-7%
75 percentile flow (ML/day)	58	46	21%	51	11%	124	128	-4%	137	-11%
90 percentile flow (ML/day)	129	106	18%	141	-9%	314	276	12%	372	-18%
Max flow (ML/day)	707	463	35%	610	14%	1349	899	33%	1090	19%
Period	2/1/2000–30/10/2004					2/1/2000–30/10/2004				
Number of days	1764					1764				

4.2 Source model description

Source was set up as a semi-distributed model using a node and link system to define subcatchments and flow paths. Nodes can take on a variety of functions, including sources of flow, storages, allocation points, flow splitters and confluences. A confluence node joins the flows from more than one catchment into a single stream. Storages, another common node property, accumulate water, which subsequently discharges to the downstream link. Storage node discharge can be set at a defined interval and/or based on the overfilling of the storage. Links are transport pathways for flow and nutrients between nodes. Links also support routing models that adjust the timing and volume of flows.

Flow routing becomes necessary if a parcel of water travelling between two points in a river (e.g. headwater and catchment outlet) exceeds the time step of the model. If flow routing is not included in the model of a large catchment, the timing and magnitude of flows can have large errors. The flow-routing model used in this project was Muskingum routing which infers the storage and subsequent delay in flows within a section of river from the outflow and inflow of two points along a river.

An important aspect of Source is the *functional unit*. A functional unit represents a region of land with unique hydrological and/or nutrient runoff characteristics. For example, native vegetation would yield less runoff and nutrient load than wheat & sheep farms. In this study, the functional units were defined in terms of land-use type. The variations due to rainfall and soil type were accounted for by using different parameters for different locations (Section 4.5.2).

4.2.1 LASCAM hydrological model

LASCAM was originally developed for the large, temperate-to-arid catchments of the Western Australian Wheatbelt and has been applied to the Avon Basin in other studies (Viney et al. 2000; Ali et al. 2010). As such, physical processes specific to this region (e.g. subsurface runoff from duplex soils) are included in the model. The result is a model tailored to the sparse and intermittent hydrology of the Avon Basin.

Because LASCAM is partially based on conceptual parameters, it requires calibration to observed flow data, such as river flows. The hydrological component of LASCAM has five fixed parameters and 23 parameters that require calibration.

LASCAM has six core computational components as illustrated in Figure 4.1 and Figure 4.2:

- Canopy interception: A proportion of rainfall is intercepted by vegetation (based on leaf density) and is lost through evaporation.
- Infiltration and runoff: This component distributes water into the F and A stores or to the stream. When the F and A stores become saturated, or when rain falls at an intensity that exceeds the infiltration rate of the soil, runoff to the stream is generated.
- The A store: This store represents the riparian zone of a stream or a perched aquifer. Inputs to this store are: infiltration, subsurface runoff (i.e. groundwater flow) and discharge from the deeper B groundwater store. Outputs occur through evaporation, discharge to stream or infiltration to the B store. Note that streamflow cannot enter the A store.
- The F store: This store represents the unsaturated soil zone. Water enters this store from upslope perching infiltration and surface infiltration. Outputs from this store include infiltration to the B store and evaporation.
- The B store: The B store represents the deep groundwater. Water enters this zone from the F and A stores. Water is lost from the B store by discharge to the A store and through evaporation.
- Upslope perching (subsurface saturation): This element accounts for the saturated land that is largely disconnected from stream networks (Figure 4.2).

The LASCAM model generated flows for each modelling subcatchment. The flow routing through subcatchments was done using Source's routing module (Muskingum routing).

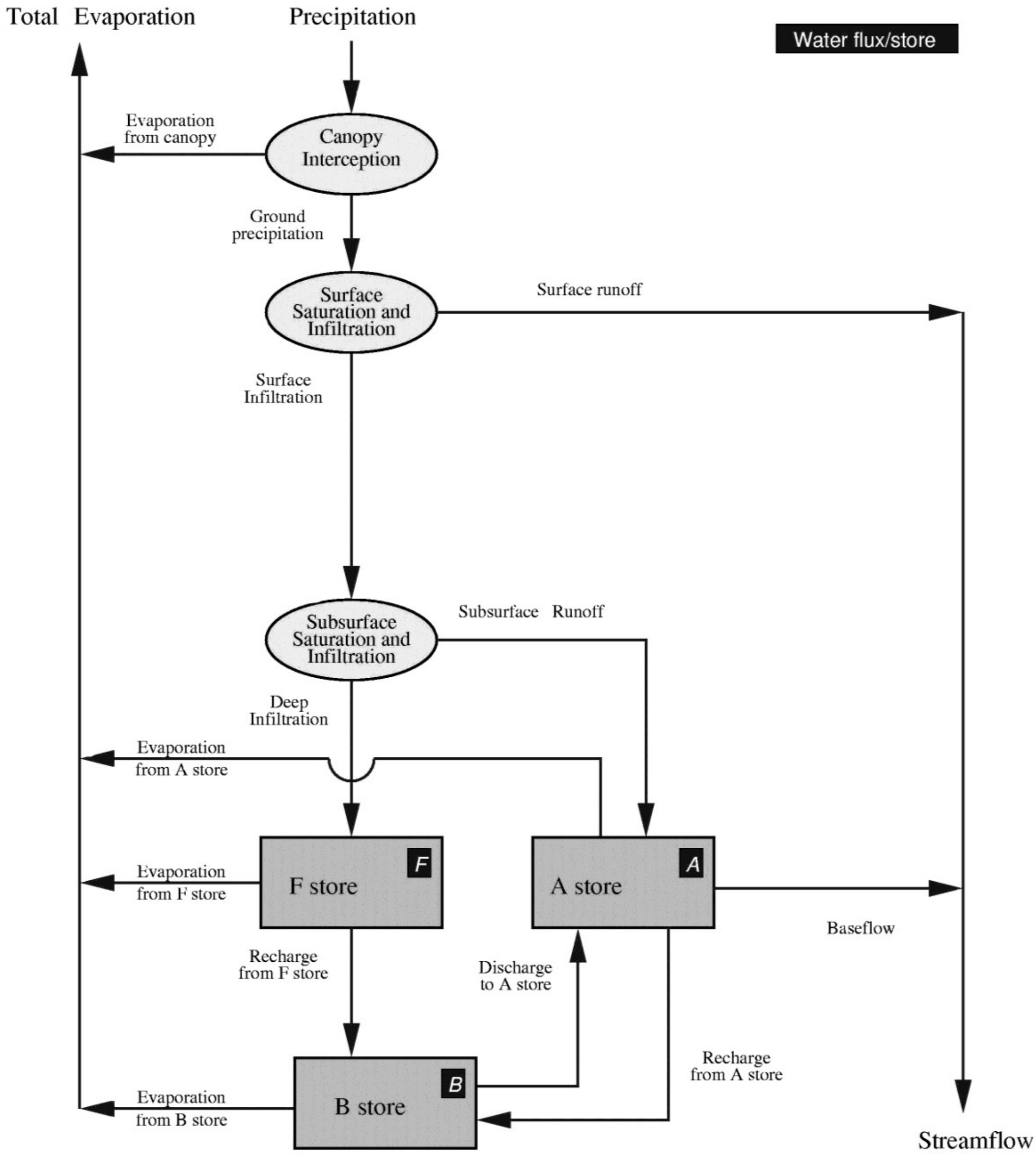
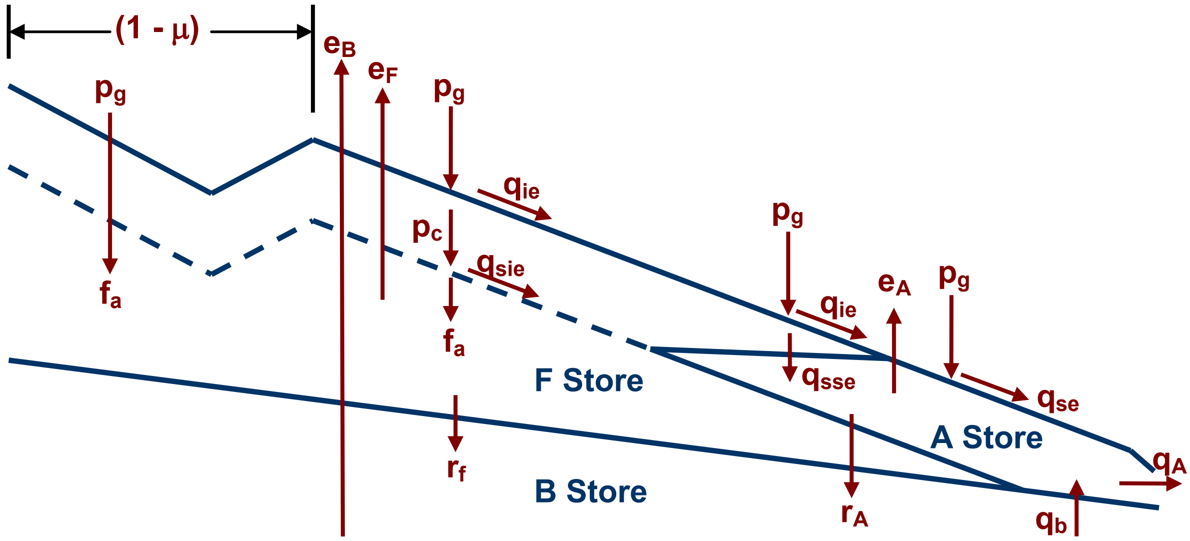


Figure 4.1: Storages and processes in LASCAM (Viney et al. 2000)



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

Figure 4.2: Hill-slope hydrological processes in LASCAM (Viney et al. 2000)

Storages include in the model

As discussed in Section 2.4, the Avon Basin has a large network of intermittently connected natural lakes mostly in the Upper Avon, Mortlock East, Mortlock North, Yilgarn and Lockhart catchments. Storages are accounted for implicitly in the model by the Muskingum routing and the model calibration. However, the Yenyening Lake system and the Mundaring Weir were included explicitly in the model.

The Helena catchment flows to the Mundaring Reservoir. The model calculates the inflows to the Mundaring Reservoir but it does not report dam spills. The dam overflowed twice in the modelling period, in 1977 and in1996, and so it rarely discharges flow and nutrient loads to the Swan Estuary.

The Yenyening Lakes comprise a natural lake system that has been artificially dammed by surface water management gates since the 1980s (Figure 4.3). These gates hold back the flows from the Salt, Lockhart and Yilgarn catchments (~76% of the Avon Basin area) and are periodically opened by the Yenyening Lakes Management Group. As opening dates and discharge volumes are not available, the Yenyening Lakes has been modelled as a simple fill-and-spill bucket model, represented as a storage node within Source. This assumes that flow out of the system is only related to overspilling and not by manipulation of the weir gates.

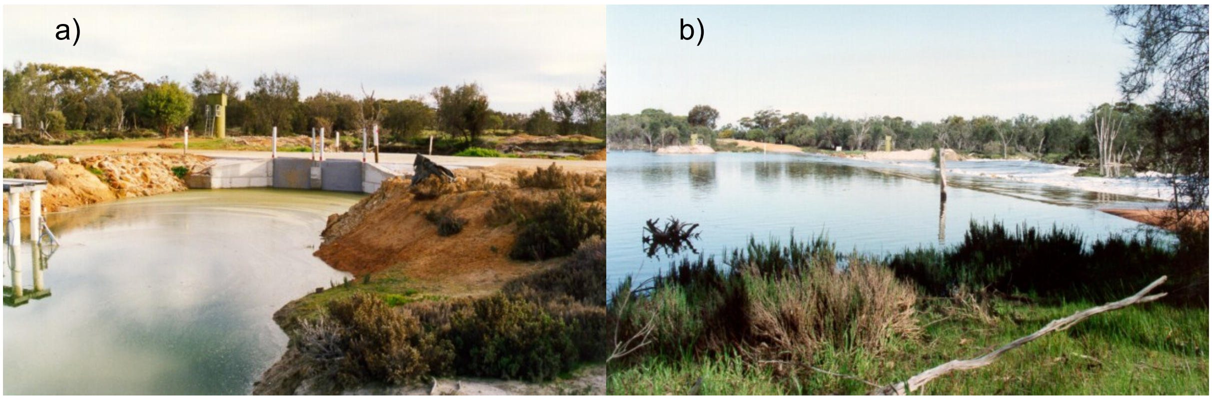


Figure 4.3: a) Weir gates at the bottom of the Yenyening Lake system, b) 1990 flood event illustrating the system overtopping, photos by Ingrid Bell and Bernard Kelly (Department of Water)

Data inputs for the Yenyening Lakes were modelled flows, evaporation, dead storage, surface area and a stage-discharge relationship. A dead storage volume of 10 000 ML (Water and Rivers Commission 2002), a surface area of 2098 ha and evaporation taken as the potential evapotranspiration data from the adjacent modelling subcatchment (ID: 36) were used. Outflows from the (ungated) spillway were derived assuming a linear relationship, where there was zero outflow at the dead storage level of 10 m and a flow of 5000 ML/day at 10.01 m. Modelling overflow at Yenyening Lakes in this way improved the flow calibration at the downstream gauge (615062) and gave reasonable outflow volumes. The modelled volumes (1980–2010) of the Yenyening Lakes storage node are given in Figure 4.4.

Storage nodes accumulate constituent mass. For Yenyening Lakes, a decay model was used to account for nutrient assimilation in years without outflow, with a decay time (D) of one day being used for both nitrogen and phosphorus (i.e. $load(t+1) = load\,(t).2^{-Dt}$). This produced overflow loads that were consistent with inflow loads for large events, such as January 2000.

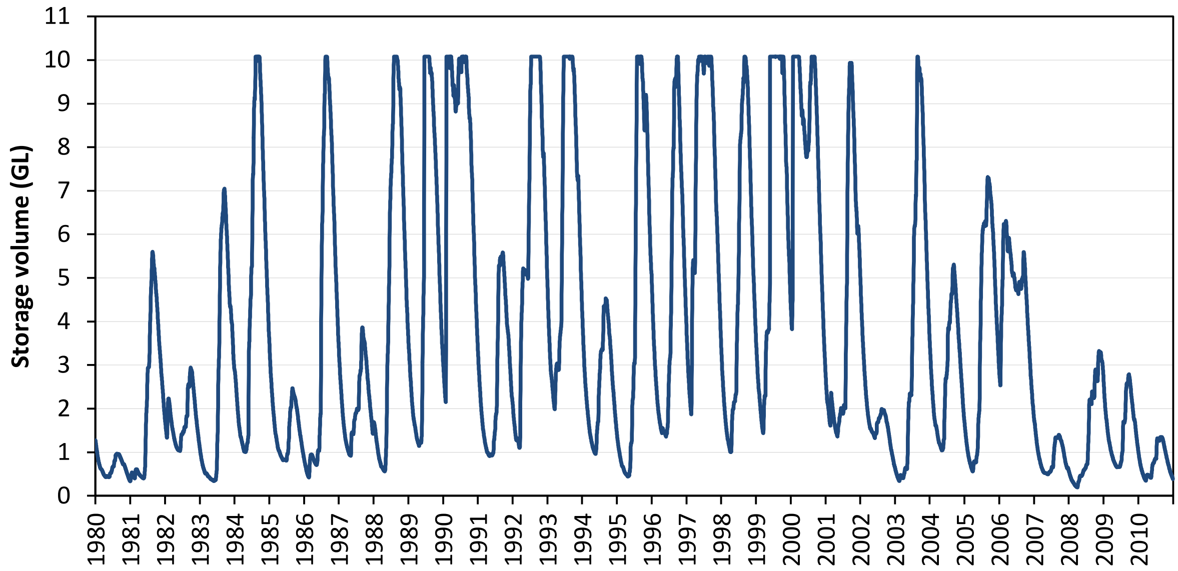


Figure 4.4: Modelled volume of the Yenyening Lakes storage node

4.2.2 Constituent-generation model

The constituent-generation model specifies the nitrogen and phosphorus concentrations in runoff from *functional units*. In the Avon modelling, two constituent generation models were considered:

- Event-mean/dry-weather concentrations (EMC/DWC)
- Power functions.

The EMC/DWC model uses fixed nutrient concentrations for flow generated on rainfall days (EMC) and days with no rain (DWC; Kelley & O'Brien 2012) for each *functional unit*. The Power function model creates a nutrient concentration-flow relationship of the form:

$$runoff\ concentration = ax^b + c$$

where *x* is flow, *a* represents the slope of the curve on a semi-log axis, *b* represents curvature and *c* is the y-intercept (Kelley & O'Brien 2012).

The concentration-flow relationship at the basin outlet, Walyunga (616011) is shown in Figure 4.5. As TN and TP concentrations increase strongly with increasing flow, a power relationship is more suitable than fixed concentrations for days of rain (EMC) and no rain (DWC) to replicate this behaviour. As similar concentration-flow relationships were observed at all other sites, power functions were chosen as the constituent generation model.

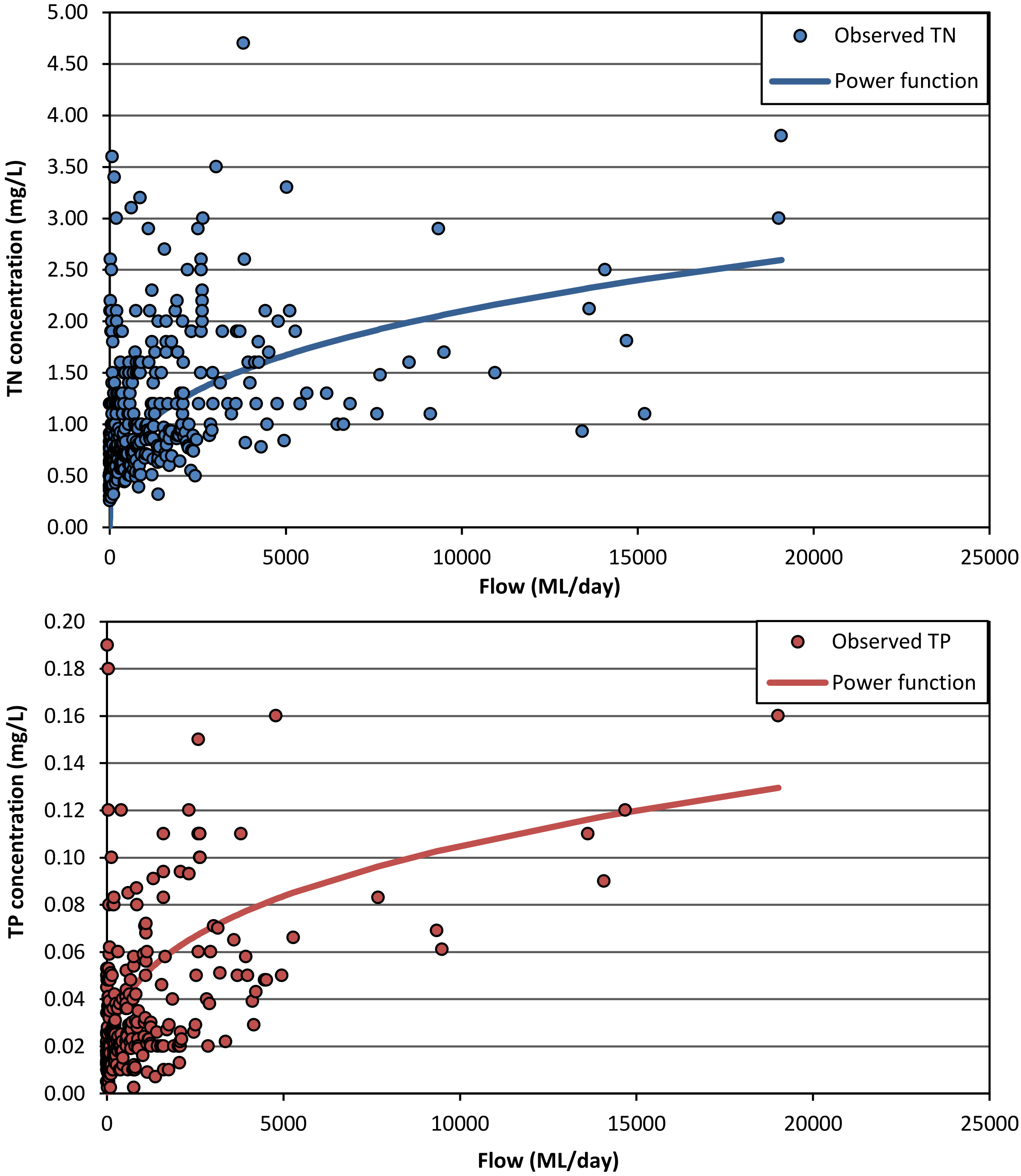


Figure 4.5: TN (top) and TP (bottom) concentration-flow relationships and power functions for Walyunga (616011)

4.3 Modelling and reporting catchments

The river network used in the model was described in Section 2.4. Modelling subcatchments (Figure 4.6) were defined based on their position within the catchment, potential catchment storages and the locations of nutrient and flow calibration sites.

The 61 modelling subcatchments were aggregated into 12 reporting catchments (Table 4.2; Figure 4.6). The reporting catchments represent the catchments associated with the major rivers and tributaries of the Avon Basin and are used for reporting the model results; that is, nitrogen and phosphorus loads. Eleven of the reporting catchments flow to the catchment outlet (616011). The twelfth, the Helena, is a forested catchment upstream of Mundaring Reservoir. Although this catchment flows to Mundaring Reservoir and not to the defined catchment outlet, it was included in the model because Mundaring Reservoir overflows go via the Helena River to the Swan Estuary.

Table 4.2: Avon Basin reporting catchments

Reporting catchment	Cleared Area		Non-cleared area		Total area
	(km^2)	%	(km^2)	%	(km^2)
Avon Basin	67 349	57	51 792	43	119 141
Lower Avon	1 333	61	847	39	2 180
Wooroloo	276	51	261	49	537
Brockman	725	48	794	52	1 519
Mortlock North	6 239	90	662	10	6 901
Mortlock East	8 886	90	1 003	10	9 889
Middle Avon	2 426	85	438	15	2 864
Dale	1 227	61	799	39	2 026
Upper Avon	2 845	89	334	11	3 180
Salt	2 981	91	289	9	3 270
Lockhart	20 963	74	7 427	26	28 391
Yilgarn	19 449	33	38 937	67	58 386
Helena	51	3	1 428	97	1 479
All modelling areas	**134 749**	**56**	**105 012**	**44**	**239 761**

4.4 Model input datasets

4.4.1 Rainfall and evapotranspiration

Rainfall and evapotranspiration data are required for each modelling subcatchment. Daily rainfall and FAO56 reference potential evapotranspiration data were obtained for modelling subcatchment centroids (Figure 4.6) from the SILO data archive (http://www.longpaddock.qld.gov.au/silo/). SILO data are spatially interpolated daily climate series, which have been generated for the whole of Australia (Jeffrey et al. 2001). FAO56 reference potential evapotranspiration data were used in place of pan evaporation data as it accounts for both physically-based water losses (e.g. solar radiation, wind) and losses by vegetation transpiration (Allen et al. 1998).

SILO climate data were compared with data from nearby meteorological stations (Muirden 2000). On two occasions (Jan 2000 and Jan 2006), SILO rainfall data (i.e. calculated rainfall) differed significantly from that observed at adjacent meteorological stations. In January 2000, SILO rainfall was low compared with observed data (Muirden 2000) and thus rainfall values (derived from SILO data) were adjusted in the Middle Avon, Dale, Upper Avon, Salt and Lockhart catchments. In 2006, SILO rainfall was greater than observed rainfall for a January event in a number of modelling catchments in the Lockhart catchment. In both cases, SILO data were compared with the nearest meteorological sites and adjusted to observed values for these periods.

4.4.2 Land use

Land-use mapping and point sources of nutrient pollution were discussed in Section 2.5. The land-use data needed as model input are Leaf Area Index (LAI) and percentage impervious area for the LASCAM hydrological model, and nutrient inputs, outputs and surpluses, which are used to derive the power-functions parameters, for the nutrient models (discussed in Section 4.5.2).

The spatial inputs to Source (land use and modelling subcatchments) were input as 100 m^2 grids.

Leaf area index (LAI) and imperviousness

LAI is the ratio of leaf area to ground area. In the Avon Basin modelling, LAI was estimated by attributing land-uses with an LAI value. LAI estimates were taken from Kelsey et al. (2011). It was found that some of the agricultural LAI values were too high for the drier inland areas, but were adequate for the higher-rainfall areas around the Darling Scarp. To resolve this, the LAIs in the eastern modelling subcatchments were modified to be consistent with the modelling of Ali et al. (2010). The resulting LAI values for the inland and escarpment areas are shown in Table 4.3.

The escarpment area included the Brockman, Wooroloo, and the Lower Avon catchments. All other catchments used 'Inland' LAI values. The LAI values ranged from 0 for bare ground to 1.9 for native forests and tree plantations in the high-rainfall area. Native forest and tree plantations in the low-rainfall area were assumed to have an LAI of 0.75. LAI values were specified for each modelling subcatchment by calculating an area-weighted average of the LAIs attributed to the subcatchment's land uses (Figure 4.7).

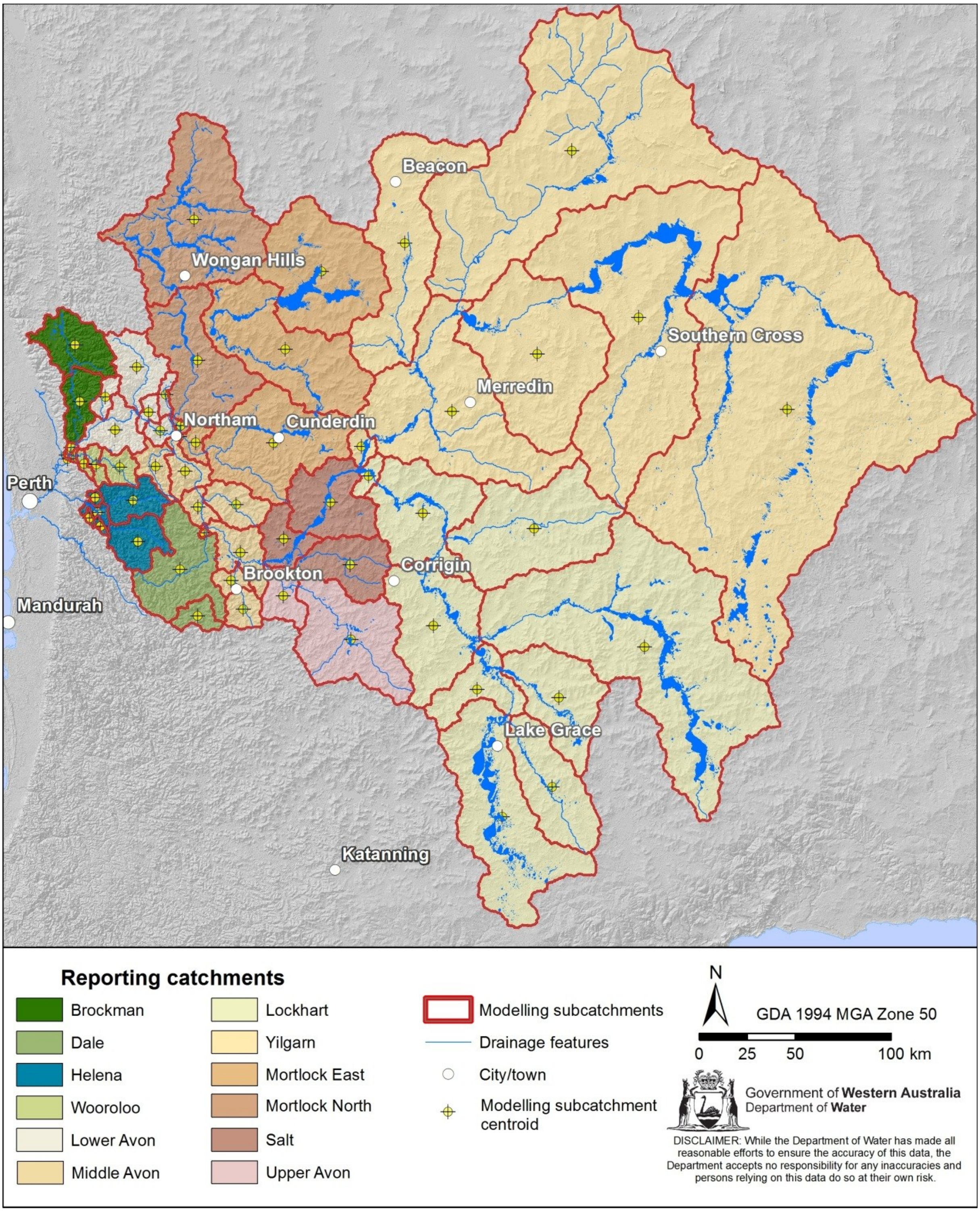


Figure 4.6: Modelling and reporting catchments

Table 4.3: Leaf Area Index (LAI) values for land-use type

Land-use category	LAI: Scarp	LAI: Inland	Land-use category	LAI: Scarp	LAI: Inland
Animal keeping – non-farming	0.50	0.33	Quarry/extraction	0.00	0.00
Annual horticulture	1.20	0.50	Recreation – grass	1.00	1.00
Aquaculture	0.00	0.00	Recreation – turf	1.20	1.20
Caravan park	0.50	0.50	Recreation / conservation – trees / shrubs	1.90	0.75
Cattle for beef	0.50	0.33	Residential – aged person	0.50	0.50
Cattle for dairy	0.50	0.33	Residential – multiple dwelling	0.10	0.10
Commercial / service – centre	0.00	0.00	Residential – single / duplex dwelling	0.50	0.50
Commercial / service – residential	0.20	0.20	Residential – temporary accommodation	0.10	0.10
Community facility – education	0.80	0.80	Rural residential / bush block	1.20	0.75
Community facility – non-education	0.50	0.50	Sewerage – non-treatment plant	1.00	1.00
Cropping	1.00	0.33	Sewerage – treatment plant	0.50	0.50
Feedlot	0.50	0.50	Sheep	0.50	0.50
Field verification required	0.00	0.00	Storage / distribution	0.00	0.00
Garden centre / nursery	1.50	1.50	Transport access – airport	0.90	0.75
Hay and silage	0.50	0.50	Transport access – railway	0.80	0.75
Horses	0.50	0.50	Transport access – roads and paths	1.80	0.75
Intensive animal farming	0.00	0.00	Tree plantation – hardwood	1.90	0.75
Inundated / saline cleared	0.32	0.32	Tree plantation – rehabilitation	1.00	0.75
Inundated / saline vegetated	0.32	0.32	Tree plantation – softwood	1.90	0.75
Landfill	0.00	0.00	Turf farm	1.20	1.20
Lifestyle block	1.20	0.50	Un-mapped	0.00	0.00
Livestock grazing - rangelands	1.00	0.50	Unused – cleared – bare soil	0.00	0.00
Manufacturing / processing	0.00	0.00	Unused – cleared – grass	0.50	0.33
Mixed grazing	0.50	0.33	Unused – uncleared – trees / shrubs	1.00	0.75
Office – with parkland	0.00	0.00	Utility	0.00	0.00
Office – without parkland	0.50	0.50	Viticulture	1.20	1.20
Perennial horticulture – trees	1.90	0.75	Water body	0.00	0.00
Piggery	0.50	0.33	Water storage and treatment	0.00	0.00
Poultry	0.00	0.00	Yacht facilities	0.00	0.00

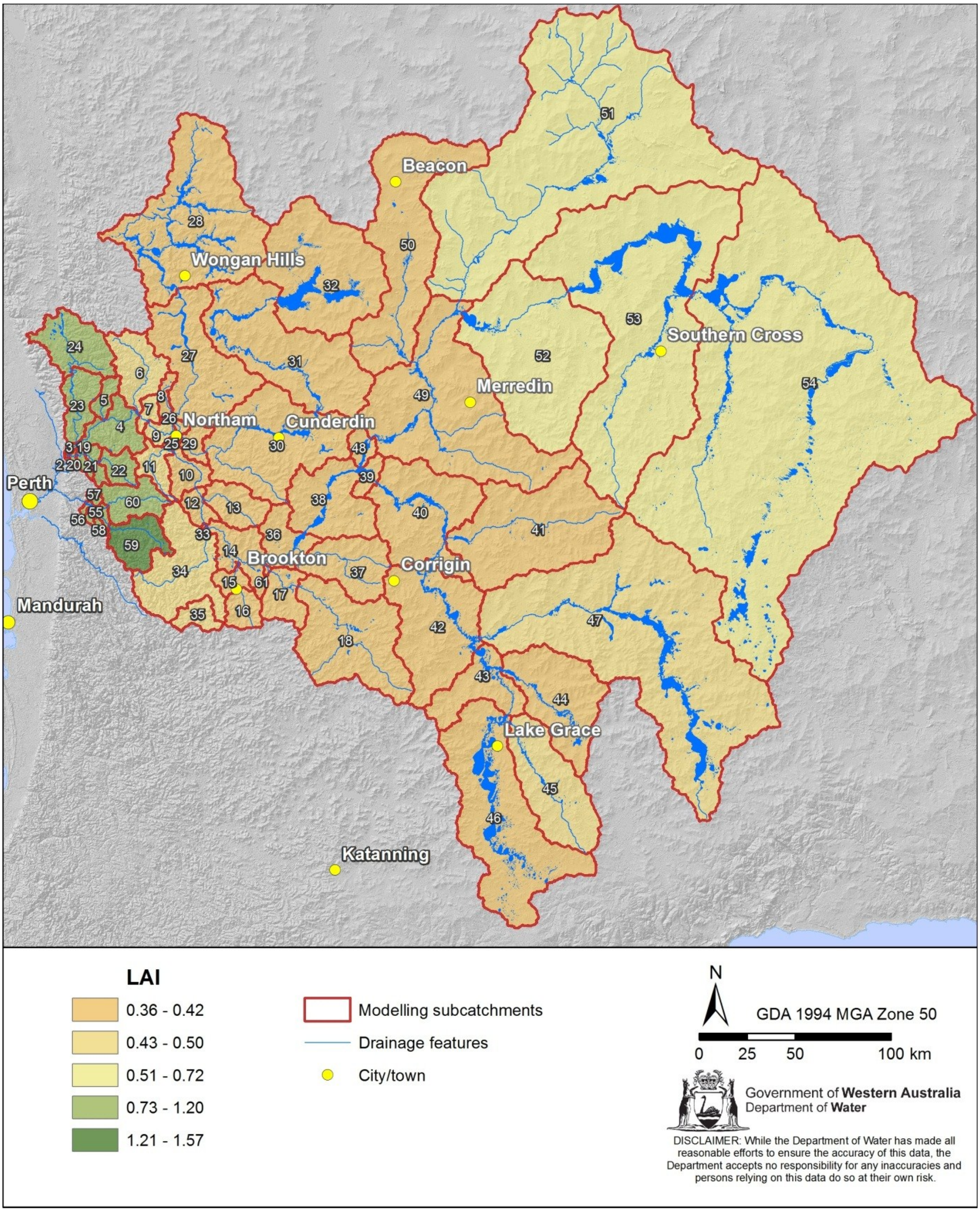


Figure 4.7: Modelling subcatchment LAI

4.4.3 Nutrient inputs and surpluses

Land-use nutrient budgets, that is, land-use nutrient inputs, outputs and surpluses, were used to calculate initial nutrient runoff parameters, which were then used in the derivation of the power functions used to describe concentration-flow relationships for each land use. The derivation of the power functions is described in Section 4.5.2.

Nutrient inputs are the masses of nutrients applied to a given land use and include fertilisation, fodder, animals and nitrogen fixation. These nutrients can then be used by plants and animals. Nutrient outputs comprise the masses of nutrients removed as produce (e.g. grain, sheep) or as waste (e.g. lawn clippings). The surplus nutrients are the nutrient inputs minus the nutrient outputs. Surplus nutrients can be bound within the soil, stored in vegetation and animals or leached/mobilised to waterways, lakes and wetlands.

The Western Australian Department of Agriculture and Food (DAFWA) has done extensive farm-gate nutrient surveys in the south-west of Western Australia (Ovens et al. 2008; Weaver et al. 2008). An analysis of nutrient surplus data for approximately 400 rural properties (mainly grazing properties) from DAFWA's database showed that the nutrient surpluses were generally 75% of the nutrient inputs (Hall 2011a). The nutrient surpluses of urban land use are not known but are likely to be large as urban land uses do not remove nutrients in produce. All land uses were assumed to have nutrient surpluses that were 75% of their nutrient inputs except for industry & transport, mixed grazing and wheat & sheep. Industry & transport were assumed to have a nutrient surplus of 100% of inputs (Table 4.4). Mixed grazing and wheat & sheep occupy the greatest area of all land uses, excluding native vegetation. Nutrient surpluses of mixed grazing and wheat & sheep were investigated further.

Table 4.4: Land-use nutrient inputs and surplus

Land-use category	Nitrogen input (kg/ha/yr)	Phosphorus input (kg/ha/yr)	Nitrogen surplus (kg/ha/yr)	Phosphorus surplus (kg/ha/yr)	Reference
Native vegetation	4.0	0.4	3	0.3	Kelsey & Hennig unpublished
Wheat & sheep	60.7	7.7	36	4.0	Planfarm 2011, 2012
Animal keeping	70.1	13.2	53	9.9	Kelsey et al. 2011
Horticulture	142.6	126.9	107	95.2	Kelsey et al. 2011
Orchard	27.2	12.3	20	9.2	Kelsey et al. 2011
Industry & transport	4.0	1.6	4	1.6	Hall 2011a
Lifestyle block	49.2	3.4	37	2.6	Kelsey et al. 2011
Mixed grazing	79.6	7.8	61	5.0	Planfarm 2011, 2012
Plantation	12.6	8.2	9	6.2	Kelsey et al. 2011
Recreation	73.4	2.6	55	2.0	JDA 2001
Residential	74.2	18.0	56	13.5	Kelsey et al. 2011
Water	-	-	-	-	Kelsey et al. 2011

Wheat & sheep and mixed grazing nutrient input and output data were taken from:

- Data provided by the DAFWA (Ovens et al. 2008; Weaver et al. 2008)
- Department of Water farm nutrient budget surveys

- Regional farm nutrient budgets derived from the *Planfarm Bankwest Benchmarks* reports (2011; 2012).

From 400 farmer surveys, DAFWA derived five-year average farm nutrient budgets for 1999–2004. Although most of the farmers surveyed had grazing properties in high-rainfall areas, 23 wheat & sheep farms, 7 sheep farms and 60 mixed-grazing farms (Ovens et al. 2008) were included. The Department of Water surveyed eight Wheatbelt farmers in 2013 using the same methodology as DAFWA. A copy of the Department of Water survey is included in Appendix C. Farm nutrient budgets obtained in DoW's survey represented five-year average nutrient budgets for 2008–12.

Farm statistics from the *Planfarm Bankwest Benchmarks* reports (2011; 2012) were also used to devise farm budgets. *Planfarm* reports most farm data on 22 regions across the south-west of Western Australia, seven of which overlap the Avon catchment. However, due to the small amount of data, they report specialised cropping and specialised sheep farm data for all regions lumped together.

Planfarm average crop area, crop yield, nitrogen and phosphorus fertiliser application, pasture area with assumed nitrogen fixation rates and livestock sales were used to devise nutrient budgets. Estimated crop nutrient content and sheep weights used in the calculations are shown in Table 4.5. Nitrogen fixation was assumed to be equivalent to 25 kg/t of total dry matter from lupins (Peoples et al. 1999), which gave an average annual nitrogen fixation rate of 69–110 kg/ha/yr.

Wheat & sheep nutrient rates were taken as the average of the seven regions in the Avon Basin and mixed grazing was taken as the average of specialist sheep rates over all 22 *Planfarm* regions.

Table 4.5: Crop nitrogen and phosphorus content and sheep weights used to calculate nutrient budgets from Planfarm regional statistics

Farm product	Nitrogen (%)	Phosphorus (%)	Weight (kg)
Sheep	2.5	0.60	45
Lambs	2.5	0.60	40
Wheat	2.0	0.36	
Barley	1.7	0.40	
Canola	3.1	0.51	
Lupins crops	5.0	0.30	
Lupins feed	4.8	0.20	

Table 4.6 shows the farm nutrient budget data from all three studies with bold text indicating median or average values from each study for wheat & sheep and mixed grazing. The wheat & sheep nitrogen surplus rates were 27–40 kg/ha/yr, with rates from the DAFWA study being higher than those from *Planfarm*, yet nitrogen-use efficiencies were roughly comparable (38–42%). Phosphorus surplus rates for wheat & sheep were 2.6–5.5 kg/ha/yr with DAFWA rates again being the highest.

For mixed grazing, DAFWA nitrogen surplus was 80 kg/ha/yr and *Planfarm* 61 kg/ha/yr and the DAFWA phosphorus surplus was 8.0 kg/ha/yr and *Planfarm* 5.0 kg/ha/yr. The differences were mainly due to DAFWA estimating lower nitrogen outputs and higher phosphorus inputs. These differences may be due to the different time periods surveyed and the fact that the DAFWA data may have included a greater proportion of cattle farms than the *Planfarm* data.

Rates from the *Planfarm* study were used for both wheat & sheep and mixed grazing in this study, as the data are more recent and better represent these land uses within the Avon Basin than the DAFWA data (Table 4.6). The nitrogen and phosphorus surpluses from the surveys undertaken by the Department of Water fall within the data range reported by *Planfarm*.

Table 4.6:Farm nutrient budgets for wheat & sheep and mixed grazing farms

	Nitrogen (kg/ha/yr)				Phosphorus (kg/ha/yr)			
Region	**Input**	**Output**	**Surplus**	**N-use efficiency**	**Input**	**Output**	**Surplus**	**P-use efficiency**
DOW (average values)								
High rainfall region	46	16	31	34%	5.5	2.3	3.2	42%
Medium rainfall region	56	20	36	36%	7.2	3.0	4.2	41%
Low rainfall region	43	17	26	40%	5.4	2.5	3.0	45%
Organic farming	19	13	6	70%	0.1	2.0	-1.9	1479%
Average wheat & sheep	**43**	**16**	**27**	**38%**	**5.0**	**2.4**	**2.6**	**48%**
DAFWA (median values)								
Sheep & cropping	**68**	**28**	**40**	42%	**13**	**8**	**5.5**	58%
Mixed grazing	**87**	**7**	**80**	8%	**10**	**2**	**8.0**	18%
Cropping	**77**	**57**	**20**	74%	**13**	**8**	**5.4**	58%
Planfarm (average values)								
High rainfall region 3	84	25	58	30%	9.2	4.5	4.7	49%
Medium rainfall region 2	78	37	41	48%	9.8	5.4	4.5	54%
Medium rainfall region 3	53	26	27	49%	7.2	3.7	3.4	52%
Medium rainfall region 4	64	24	40	38%	7.8	3.4	4.3	44%
Low rainfall region 2	50	23	27	46%	6.1	3.3	2.8	54%
Low rainfall region 3	42	20	22	48%	6.2	2.9	3.3	46%
Low rainfall region 4	55	20	35	36%	7.6	2.8	4.7	37%
Specialist Sheep	80	18	61	23%	7.8	2.8	5.0	36%
Specialist Cropping	70	40	30	58%	10.4	5.5	4.9	53%
Average wheat & sheep	**61**	**25**	**36**	**41%**	**7.7**	**3.7**	**4.0**	**48%**
Average mixed grazing	**80**	**18**	**61**	**23%**	**7.8**	**2.8**	**5.0**	**36%**

4.5 Model calibration

The calibration of the LASCAM hydrological model was largely done using an automated calibration module. The calibration module uses the shuffled-complex evolution algorithm with the Nash-Sutcliffe daily-log-bias as the objective function (Viney et al. 2009; Duan et al. 1992; Duan et al. 1994). The nutrient model component was calibrated manually.

A goal of modelling is often to predict the outcomes of future scenarios. A method for measuring the predictive performance of a model is to calibrate on a portion of the available data, then compare modelled data with observed data for a validation period not included in the calibration period. However, model validation cannot always be performed. Limited and/or highly variable observed data are two factors that may prevent validation. Omitting a validation period and calibrating over the whole period will likely improve the parameter selection, but this is at the expense of being able to measure the model's predictive power.

If the following criteria were achieved the flow and nutrient calibration statistics were considered acceptable:

- A daily Nash-Sutcliffe efficiency (NSE) > 0.6 for the flow calibration
- Total flow over the calibration period within 10% of observed total flows
- Modelled TN and TP concentrations within 10% of observed concentrations.

Model performance was also assessed by comparing modelled and observed hydrographs and modelled loads against LOESS loads. In dry catchments (Lockhart, Yilgarn, Mortlock East and Mortlock North) the focus was on calibrating to large summer events, whereas in wetter catchments it was important to represent the entire hydrograph.

4.5.1 Hydrological calibration

Eight parameter sets were obtained through calibration to 16 flow gauging stations over different periods between 1980 to 2010 (Table 4.7). Flow calibration sites are shown in Figure 4.8. Primary calibration sites (priority 1) were given a higher weighting in the calibration process than priority 2 sites. Validation was performed on only seven sites as flow records were either too short or the entire period with flow gauging was required to achieve acceptable calibration results on the other sites.

Calibration results at the basin outlet (616011) were good, with a daily NSE of 0.86 and a total water balance bias of 2% (Table 4.8). Modelled and observed daily flows are shown in Figure 4.9 and cumulative flow is shown in Figure 4.10. Modelled summer and winter flows were within 5% and 2% of observed flows respectively (Table 4.8). Daily maximum flows were underpredicted, yet the 75th and 90th percentile flows were overpredicted by 8 and 15% respectively. Validation results were acceptable with a daily NSE of 0.84 and a total water balance bias of 27% (Table 4.9).

The calibration results for 615020 (Mortlock East) had daily NSE of 0.38 and a total water balance within 3% of the observed. Although daily flows were not accurately predicted, total flows were, and the parameter set accepted (Table 4.8).

The Yilgarn parameter set overpredicted total flows by 27% and had an annual NSE of 0.65. However, Yilgarn flows were approximately 2% of the total flow of the entire Avon Basin and the Yilgarn catchment discharges to the Yenyening Lakes which have an annual dead storage capacity of approximately 10 GL and rarely overflow. As such, these model inaccuracies were considered to be of low importance.

Table 4.7: Parameter sets for reporting catchments, and validation and calibration periods

Parameter set	Reporting catchment	AWRC ref	Calibration priority	Calibration period	Validation period
1. Avon River	Lower Avon	616011	1	01/01/1980–01/03/2001	02/03/2001–31/12/2010
	Lower Avon	615026	2	18/10/1996–31/12/2010	-
	Lower Avon	615030	2	05/06/1997–15/10/2001	-
	Middle Avon	615062	2	01/01/1980–31/12/2010	-
	Upper Avon	615063	2	01/01/1980–31/12/2010	-
2. Wooroloo	Wooroloo	616001	1	30/05/1986–19/12/1998	20/12/1998–31/12/2010
	Wooroloo	616005	2	30/05/1980–05/02/1995	05/06/1995–11/06/1999
3. Brockman	Brockman	616019	1	06/07/1985–01/03/2001	02/03/2001–31/12/2010
	Brockman	616006	2	06/07/1986–01/03/2001	02/03/2001–31/12/2010
4. Mortlock	Mortlock North	615013	-	-	01/01/1980–31/12/2010
	Mortlock East	615020	1	01/01/1980–31/12/2010	-
5. Dale	Dale	615027	1	30/05/1995–31/12/2006	01/01/2007–31/12/2010
	Dale	615222	2	01/01/1980–21/05/1999	-
6. Lockhart	Lockhart	615012	1	01/01/1980–31/12/2010	-
	Salt		-	No flow data	
7. Yilgarn	Yilgarn	615015	1	01/01/1980–31/12/2010	-
8. Helena	Helena	616002	1	01/01/1980–01/03/2001	02/03/2001–31/12/2010
	Helena	616216	2	01/01/1980–01/03/2001	02/03/2001–31/12/2010

The total water balance bias of flow stations 616019 (Brockman) and 615027 (Dale) was –12%. The underprediction of total flow at 616019 was considered acceptable given that the daily NSE was 0.92. The daily NSE for 615027 was 0.74, which improved at an annual time step to an NSE of 0.89.

The daily NSE at flow station 615030 (Lower Avon River) was 0.19; and this site had a modelled water balance within 5% of the observed. Although the site predicted daily flows poorly, total flows were well represented. This site had a short modelling period and as such was given a low calibration weighting.

The water balance bias of flow sites within the Helena catchment (616216 and 616002) was 18% and –11% respectively. Summer flows were not adequately represented at either site. Site 616216 overpredicted the 90th percentile flows by 60%. Modelled flow at site 616002 was zero for 75% of the time, which was not reflected in observed flows.

All other flow sites achieved daily NSE values that were greater than 0.6 and had a total modelled water balance within 10% of the observed. The model calibration parameters, including routing parameters, are included in Appendix D.

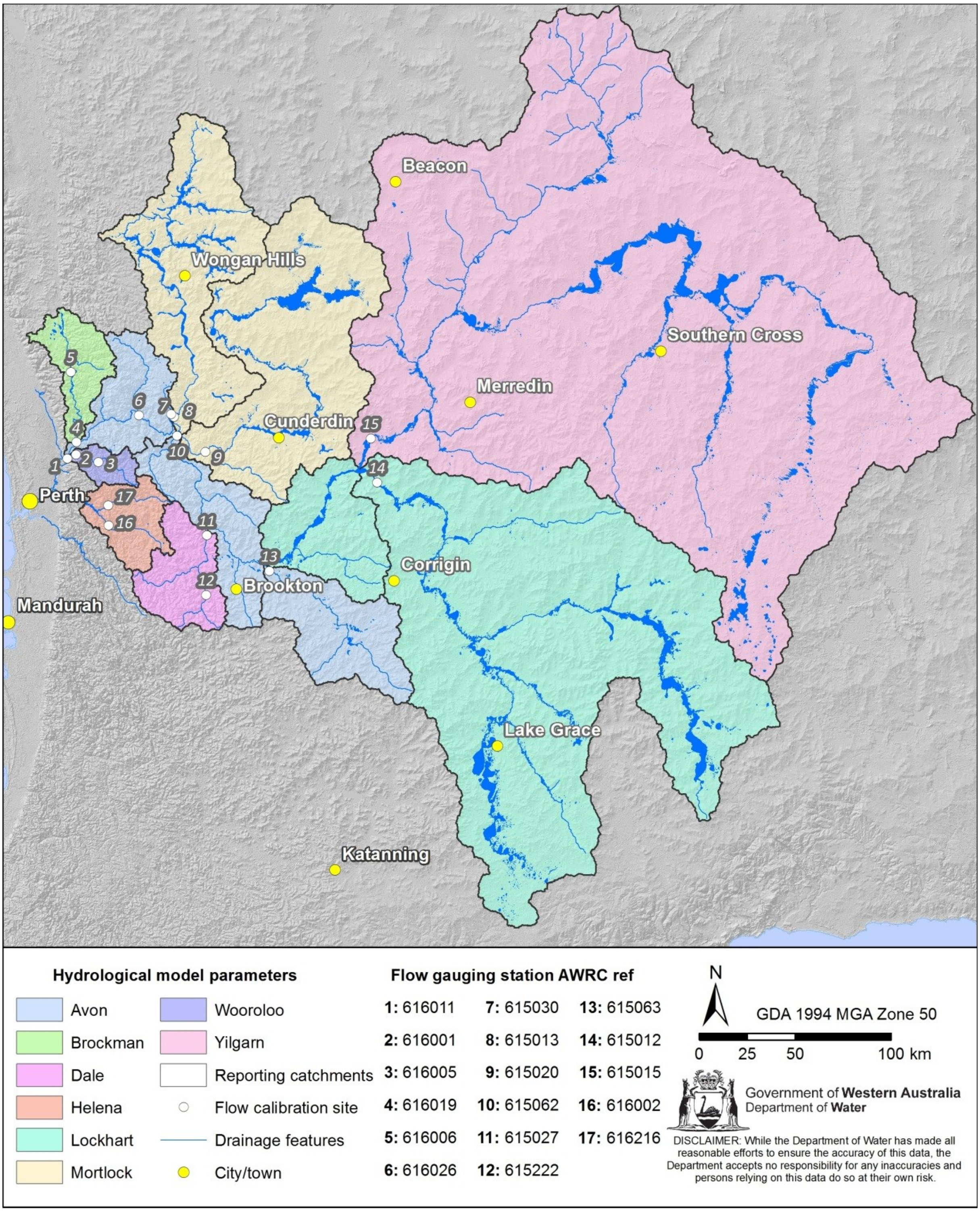


Figure 4.8: Flow gauging sites used for calibration and reporting catchments with shared LASCAM parameters

Table 4.8: Hydrological calibration results

Parameter set	ARWC ref	Observed/ modelled	NSE daily	NSE monthly	NSE annual	Bias (%)	Total runoff (GL)	Summer runoff (GL)	Winter runoff (GL)	75th percentile flow (ML/day)	90th percentile flow (ML/day)	Max flow (ML/day)
1. Avon River	616011	Observed	-	-	-	-	7 732	618	7 113	1 057	2 880	51 221
		Modelled	0.86	0.94	0.91	2	7 923	647	7 275	1 138	3 299	21 513
	615026	Observed	-	-	-	-	1 717	460	1 257	225	816	25 394
		Modelled	0.87	0.94	0.96	10	1 894	447	1 447	279	1 185	23 397
	615030	Observed	-	-	-	-	9	2	8	5	15	348
		Modelled	0.19	0.72	0.57	5	10	1	8	2	17	295
	615062	Observed	-	-	-	-	1 276	307	969	181	645	14 519
		Modelled	0.82	0.90	0.91	10	1 401	308	1 093	150	811	16 651
	615063	Observed	-	-	-	-	26	3	24	12	47	634
		Modelled	0.56	0.83	0.65	-3	25	2	24	7	45	742
2. Wooroloo	616001	Observed	-	-	-	-	606	29	577	164	386	2 676
		Modelled	0.88	0.97	0.95	3	624	25	600	193	449	1 546
	616005	Observed	-	-	-	-	322	28	293	76	174	1 284
		Modelled	0.88	0.94	0.87	-7	298	15	283	68	181	1 024
3. Brockman	616019	Observed	-	-	-	-	770	23	746	144	413	2 562
		Modelled	0.92	0.96	0.92	-12	674	18	656	127	379	2 193
	616006	Observed	-	-	-	-	383	15	367	87	232	2 161
		Modelled	0.90	0.95	0.91	8	412	11	401	87	232	2 161
5. Mortlock	615020	Observed	-	-	-	-	544	88	455	16	96	9 393
		Modelled	0.38	0.68	0.53	3	558	108	450	28	132	8 498
5. Dale	615027	Observed	-	-	-	-	440	520	27	71	242	5 750
		Modelled	0.74	0.89	0.89	-12	389	369	20	28	314	2 797
	615222	Observed	-	-	-	-	100	8	92	10	41	1 803
		Modelled	0.64	0.82	0.84	-4	96	4	92	4	55	871
6. Lockhart	615012	Observed	-	-	-	-	253	134	120	0	24	7 195
		Modelled	0.79	0.83	0.85	7	270	159	111	13	43	6 596
7. Yilgarn	615015	Observed	-	-	-	-	170	81	88	0	6	5 484
		Modelled	-0.11	0.51	0.65	27	215	62	153	1	33	4 524
8. Helena	616002	Observed	-	-	-	-	91	1	90	2	20	1 239
		Modelled	0.64	0.83	0.88	-11	80	0	80	0	24	565
	616216	Observed	-	-	-	-	136	3	159	7	31	1 069
		Modelled	0.64	0.80	0.79	18	160	0	193	3	50	908

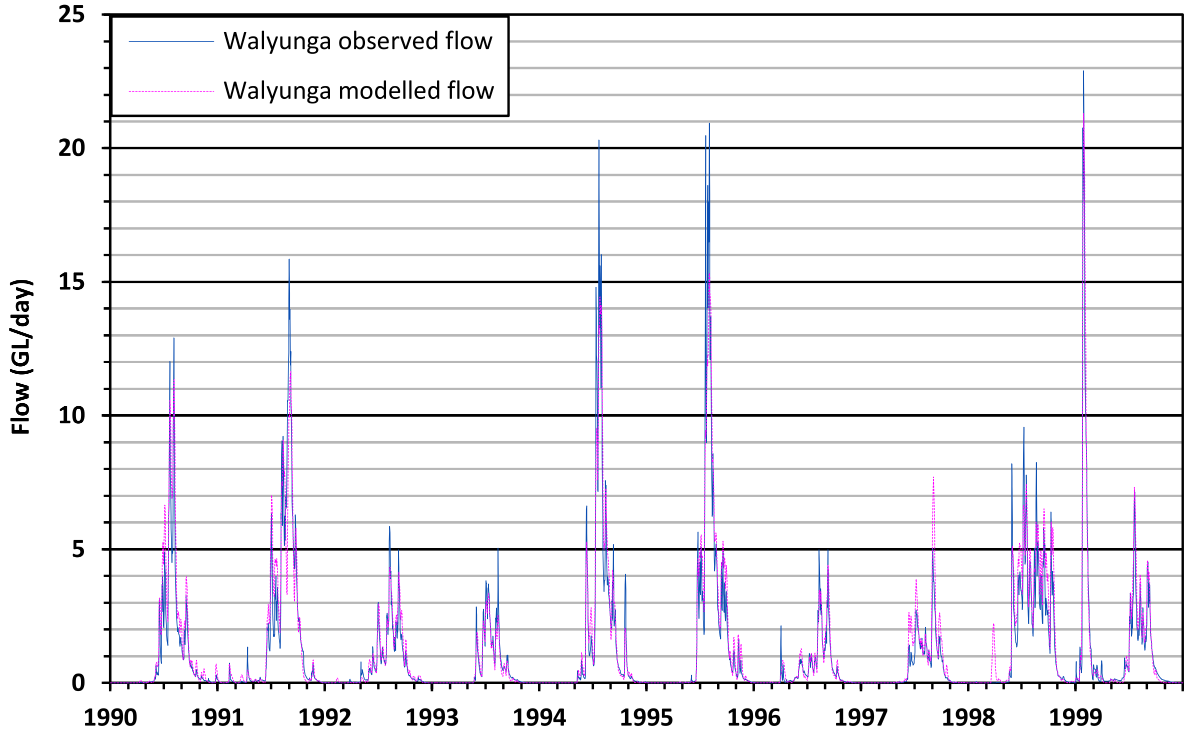


Figure 4.9: Modelled and observed daily flow at Walyunga (616011)

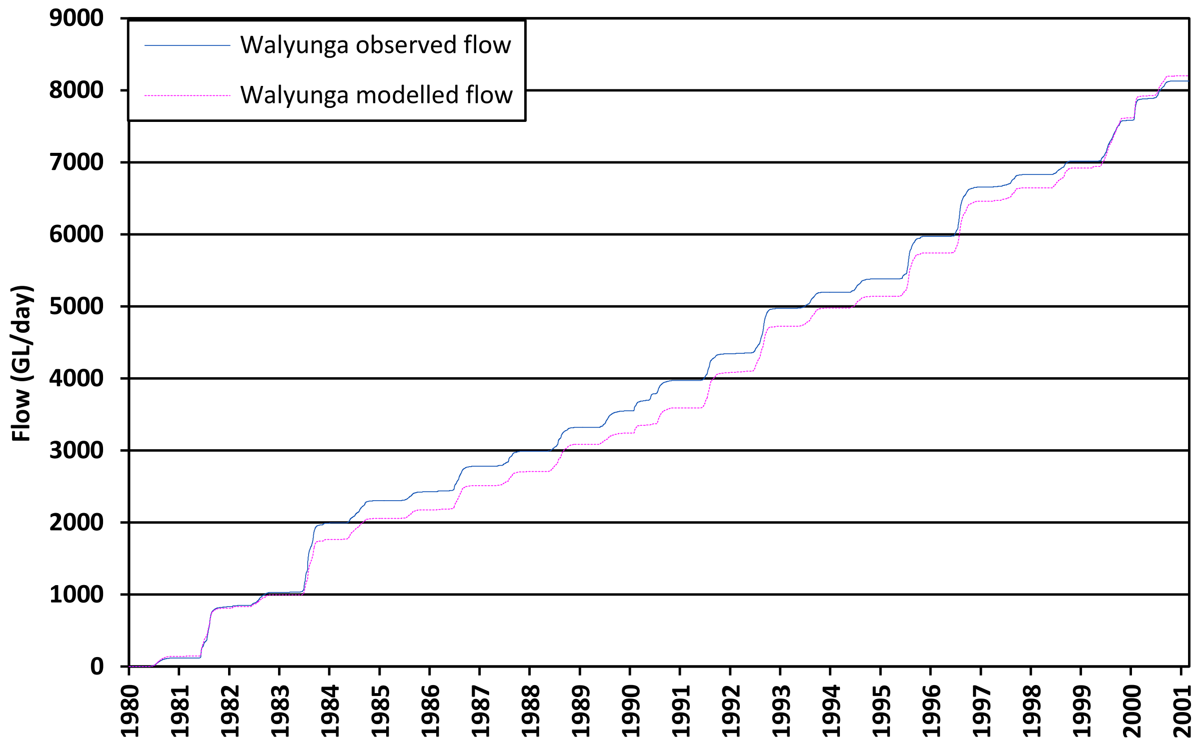


Figure 4.10: Modelled and observed cumulative flow at Walyunga (616011)

Table 4.9: Hydrological validation results

Parameter set	ARWC ref		NSE daily	NSE monthly	NSE annual	Bias (%)	Total runoff (GL)	Summer runoff (GL)	Winter runoff (GL)	75th percentile flow (ML/day)	90th percentile flow (ML/day)	Max flow (ML/day)
1. Avon River	616011	Observed	-	-	-	-	1 534	100	1 435	334	1 343	12 480
		Modelled	0.84	0.87	0.63	27	1 950	121	1 830	441	1 803	9 243
2. Wooroloo	616001	Observed	-	-	-	-	349	11	338	102	275	2 365
		Modelled	0.88	0.97	0.93	8	375	13	362	126	343	1 426
	616005	Observed	-	-	-	-	87	7	79	48	164	1 384
		Modelled	0.93	0.85	0.86	9	95	22	72	70	210	885
3. Brockman	616019	Observed	-	-	-	-	220	7	213	74	234	1 346
		Modelled	0.69	0.92	0.90	-16	185	7	178	56	205	890
	616006	Observed	-	-	-	-	117	5	112	36	97	690
		Modelled	0.91	0.95	0.89	-10	106	63	101	36	102	483
4. Mortlock	615013	Observed	-	-	-	-	548	45	139	29	125	5 221
		Modelled	0.40	0.70	0.74	-2	536	53	167	32	135	4 828
5. Dale	615027	Observed	-	-	-	-	107	3	104	45	170	3 969
		Modelled	0.72	0.85	0.58	4	111	0	110	7	220	2 817
8. Helena	616002	Observed	-	-	-	-	17	0	17	0	12	299
		Modelled	0.55	0.74	0.80	-10	16	0	16	0	13	293
	616216	Observed	-	-	-	-	25	1	25	4	21	370
		Modelled	0.49	0.63	0.37	33	80	0	33	4	21	370

4.5.2 Nutrient calibration

Ideally, nutrient runoff concentrations measured at the paddock-scale for different land uses would be used to validate modelled concentrations. However, such data are not available within the Avon Basin. Thus paddock land-use nutrient concentrations were derived from nutrient surplus data and flow yield, and then adjusted to match in-stream concentrations with a leaching rate. As such, losses between the paddock and the stream, and in-stream nutrient removal or generation are encapsulated in the land-use nutrient runoff concentrations.

Land-use runoff concentrations

Nitrogen and phosphorus land-use nutrient concentrations for the Wooroloo (616001), Brockman (616019) and Mortlock East (615020) reporting catchments were estimated. The surplus load for the catchment, that is the sum of the surplus loads for each land use, was used to calculate a flow-weighted concentration (total surplus load/catchment flow). A leaching rate was then deduced by comparing this flow-weighted concentration with the observed median concentration of the stream. This leaching rate was then applied to the land-use flow-weighted nutrient concentrations (land-use nutrient surplus/flow attributed to the land use) to derive the land-use runoff concentrations. Point sources were included using the assumed leaching rates discussed in Section 2.6. An example of the land-use runoff concentration calculation process for nitrogen at Wooroloo (616001) is shown in Table 4.10. The nitrogen and phosphorus land-use runoff concentrations for Wooroloo (616001), Brockman (616019) and Mortlock East (615020) are given in Table 4.11.

Table 4.10: Example of nitrogen land-use runoff concentration calculations for Wooroloo reporting catchment (616001)

Land-use	Area	Average flow 2007–09	Surplus	Surplus load	Leaching rate	Leached load	Land-use runoff concentration
	(ha)	(ML/yr)	(kg/ha/yr)	(kg/yr)	%	(kg/yr)	(mg/L)
Native vegetation	25 971	18 290	3.0	77 912	1.2	935	0.05
Wheat & sheep	816	575	35.7	29 124	1.2	349	0.61
Animal keeping	1 591	1 120	52.6	83 628	1.2	1 004	0.90
Horticulture	10	7	107.0	1 086	1.2	13	1.82
Orchard	251	177	20.4	5 114	1.2	61	0.35
Industry & transport	1 592	1 121	4.0	6 369	1.2	76	0.07
Lifestyle block	2 003	1 410	36.9	73 893	1.2	887	0.63
Mixed grazing	20 788	14 640	61.4	1 275 643	1.2	15 308	1.05
Plantation	185	131	9.5	1 753	1.2	21	0.16
Recreation	94	66	55.1	5 182	1.2	62	0.94
Residential	166	117	55.7	9 228	1.2	111	0.95
Point Sources	97	69	-	9 883	3.3	325	4.73
Water	127	89	-	-	-	-	-
Total	**53 690**	**37 812**		**1 578 816**	**1.2**	**19 152**	**0.51†**

† Observed three-year winter median concentration (2007–09) = 0.52

Table 4.11: Land-use nutrient runoff concentrations

Land use	Wooroloo		Brockman		Mortlock East	
	TN (mg/L)	TP (mg/L)	TN (mg/L)	TP (mg/L)	TN (mg/L)	TP (mg/L)
Native vegetation	0.05	0.000	0.10	0.002	0.16	0.007
Wheat & sheep	0.61	0.006	1.16	0.033	1.94	0.098
Animal keeping	0.90	0.014	1.69	0.072	2.85	0.215
Horticulture	1.82	0.135	3.45	0.694	5.79	2.062
Orchard	0.35	0.013	0.66	0.067	1.11	0.200
Industry & transport	0.07	0.002	0.13	0.012	0.22	0.035
Lifestyle block	0.63	0.004	1.19	0.019	2.00	0.055
Mixed grazing	1.10	0.009	2.09	0.046	1.94	0.098
Plantation	0.16	0.009	0.30	0.045	0.51	0.133
Recreation	0.94	0.003	1.77	0.014	2.98	0.042
Residential	0.95	0.019	1.79	0.099	3.01	0.293
Total	**0.53**	**0.005**	**0.95**	**0.026**	**1.77**	**0.099**

Power function parameters

A power function was used to depict the stream concentration-flow relationship:

$$y = a.x^b + c$$

where y is the concentration

x is the flow, and

a, b and c, are the parameters that describe the shape of the function,

A power function was created for 616001 (Wooroloo Brook), 616019 (Brockman River) and 615020 (Mortlock East). The parameters a, b and c, were derived by comparing

1) observed and modelled concentrations

   and

2) annual LOESS-loads with loads calculated from daily flow data and concentrations taken from the concentration-flow power relationship.

This concentration-flow relationship represents contributions from all land uses. The concentration-flow relationship for Wooroloo Brook is shown in Figure 4.11 as a dotted black line.

The base parameter set (a, b and c) for each site was then adjusted using the land-use nutrient runoff concentrations, discussed above, to create power functions for each land use (with parameters a_{lu}, b and c_{lu}). Parameter b was constant for all land uses (i.e. power function curves have similar shape for each land use); parameter a_{lu} was a function of the land-use nutrient runoff concentration and modelled winter median concentration from 2007 to 2009 as shown below:

$$a_{lu} = \frac{a \times land{-}use\ nutrient\ runoff\ concentration}{modelled\ winter\ median\ concentration\ 2007{-}09}.$$

Parameter c_{lu} was set an order of magnitude less than a_{lu} or at a predetermined minimum. This produced concentration-flow relationships that differ by the same ratio as the land-use nutrient runoff concentrations for each land use, at all river flow volumes (Figure 4.11).

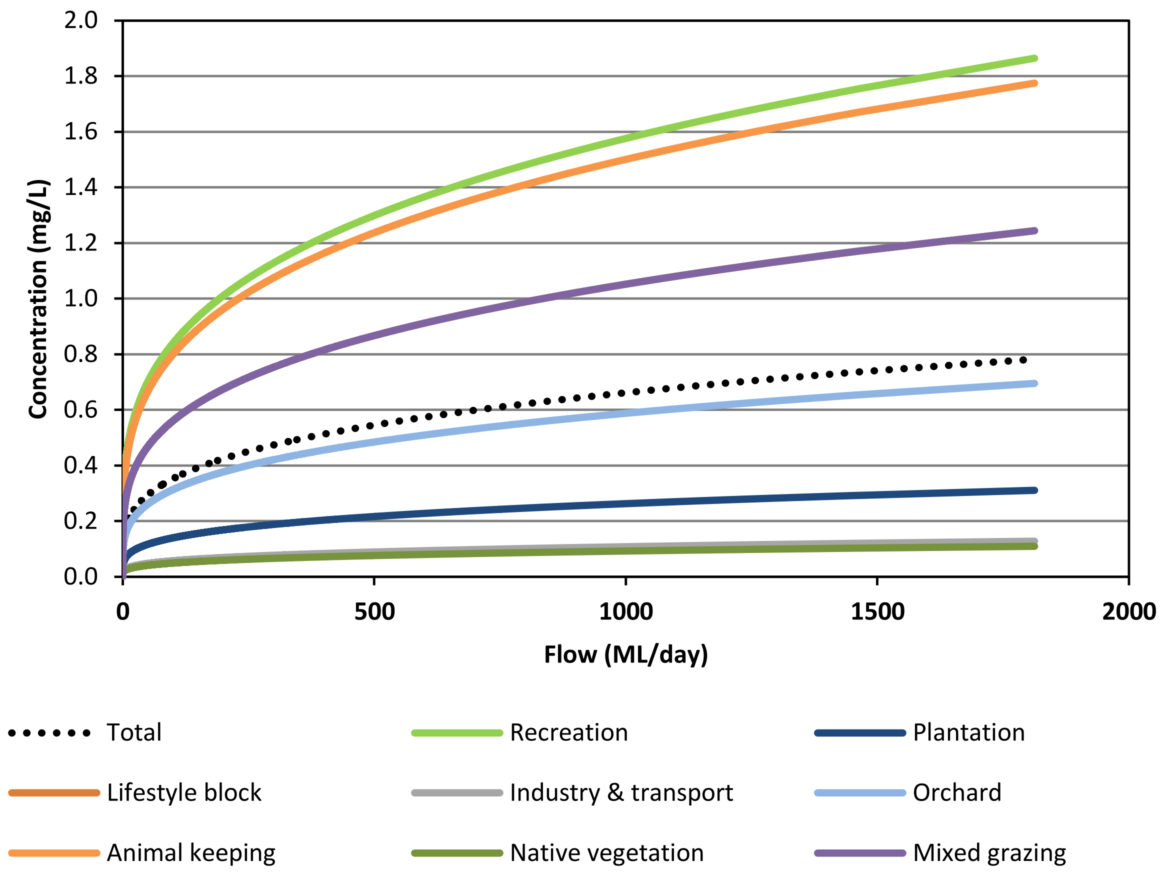


Figure 4.11: Land-use nitrogen concentrations from the Wooroloo Brook reporting catchment

Power function refinement and final parameter sets

Model concentrations should be within 10% of the observed three-year median concentrations and modelled nutrient loads should reflect LOESS loads at the calibration sites.

The power functions derived for Wooroloo (616001), Brockman (616019) and Mortlock East (615020) were then used for other reporting catchments. The parameters for each reporting catchment were refined to meet three-year median concentrations (generally 2007–09) at the reporting catchment outlets (listed in Table 4.13) with the effects of upstream catchments included and upstream catchment parameters adjusted if necessary. This was straightforward at four sites for both nitrogen and phosphorus (Wooroloo, Brockman, Mortlock East and Mortlock North). However, adjustments were required to the parameter sets to achieve adequate calibrations at the seven other sites. This process, described below, led to four additional parameter sets for nitrogen and phosphorus (Table 4.12):

- **Dale reporting catchment:** To achieve a reasonable calibration nutrient concentrations from mixed grazing were set higher in the Dale catchment than in other catchments. A catchment visit showed that there was a considerable area of 'cattle for beef' farming amongst mixed grazing land use.

- **Lower and Middle Avon catchments**. The Lower and Middle Avon catchments had areas of high rainfall, which led to excessive modelled nutrient concentrations. A new land-use parameter set was created that produced lower concentrations at high flows.
- **Upper Avon and Yilgarn catchments:** The Upper Avon and Yilgarn have areas of low PRI soils. Observed TP concentrations were higher than adjacent catchments, but were not as high as in the Mortlock catchments. Parameters for wheat & sheep were adjusted so that the modelled concentrations matched the three-year observed TP nutrient concentrations.
- **Lockhart and Salt catchments**: TN and TP parameters were adjusted to reflect nutrient concentrations measured during the 2000 summer flood. TN concentrations of 4.4 mg/L and TP concentrations of 0.2 mg/L were observed on 24 January 2000 at Kwolyn Hill (615012). Although this puts great weight on data from a single large flow event, it was unavoidable due to the scarcity of data.

Table 4.12: Nutrient model parameter sets

Nutrient	Parameter set	Reporting catchment
Nitrogen	Wooroloo	Wooroloo
	Brockman	Brockman
	Dale	Dale
	Avon	Lower Avon Middle Avon
	Upper Avon	Upper Avon
	Mortlock East	Mortlock East Mortlock North Yilgarn Helena
	Lockhart	Lockhart Salt
Phosphorus	Wooroloo	Wooroloo
	Mortlock East	Mortlock East Mortlock North
	Avon	Lower Avon Middle Avon
	Upper Avon	Upper Avon Yilgarn
	Brockman	Brockman Helena
	Dale	Dale
	Lockhart	Lockhart Salt

This exacting calibration process produced modelled concentrations similar to the observed concentrations and modelled nutrient loads comparable to LOESS-calculated nutrient loads. Modelled TN and TP concentrations were within 7% and 6% of observed concentrations at the basin outlet (Table 4.13). Modelled TN concentrations were within 10% of observed concentrations for all sites except for 615015 (Yilgarn reporting catchment). Three sites had modelled TP concentrations that were more than 10% different from the observed concentrations. Modelled TP concentrations at 615026 (Lower Avon reporting catchment, Toodyay) were 22% higher than observed concentrations. Modelled upstream TP concentrations (615062, 615013 and 615020) were all within 11% of observed concentrations. The elevated modelled TP concentration at 615026 compared with the observed median concentration may be due to phosphorus removal in this river reach which is not accounted for in the model.

The model parameters, standardisation factors and initial nutrient runoff concentrations are given in Appendix E.

Table 4.13: Modelled and observed nutrient concentrations

			Nitrogen			Phosphorus		
Reporting catchment	**AWRC ref**	**Period**	**Observed three-year winter median**	**Modelled**		**Observed three-year winter median**	**Modelled**	
			(mg/L)	**(mg/L)**	%	**(mg/L)**	**(mg/L)**	%
Basin outlet	616011	2007–09	0.89	0.96	7%	0.022	0.023	6%
Wooroloo	616001	2007–09	0.52	0.49	-5%	0.007	0.006	-8%
Brockman	616019	2006–08	0.91	0.88	-3%	0.024	0.023	-2%
Lower Avon	615026	2007–09	1.30	1.40	7%	0.032	0.039	22%
Mortlock North	615013	2007–09	1.70	1.75	3%	0.086	0.082	-4%
Mortlock East	615020	2007–09	1.70	1.59	-7%	0.093	0.082	-11%
Middle Avon	615062	2007–09	1.20	1.11	-7%	0.025	0.026	5%
Dale	615027	2007–09	0.95	0.95	0%	0.032	0.031	-3%
Upper Avon	615063	2007–09	1.70	1.68	-1%	0.044	0.046	4%
Lockhart	615012	2007–09	2.00	2.15	7%	0.023	0.026	16%
Yilgarn	615015	2007–09	1.30	1.46	12%	0.032	0.031	-3%

4.6 Model limitations, intended uses and assumptions

Generally, as well as with this model, key assumptions and methodologies restrict the application of model results. The following lists the intended uses of this model, key assumptions and limitations:

Model outputs can be used to do the following:

- Calculate flows at a daily, monthly and yearly time step at the outlets of the 61 modelling subcatchments.
- Calculate nitrogen and phosphorus loads at a monthly and yearly time step at the outlets of the 61 modelling subcatchments.
- Estimate the impacts of climate variability on catchment flows and nutrient loads.
- Estimate the effects of land use and management on flows and nutrient loads.

Assumptions:

- The Avon Basin land-use mapping used in the model is assumed to be representative of the period 2005–10.
- Rainfall at the centroid of each modelling catchment is assumed to be representative of the rainfall across the modelling catchment.
- Catchment characteristics, such as soil type and topography, are assumed to be uniform within a modelling subcatchment.
- The nutrient model assumed the same flow yield for all land uses in each reporting catchment.
- The directly connected impervious area of the Avon Basin has been assumed to be zero. The directly connected impervious area was calculated and was near to zero in most locations.
- The Mundaring Reservoir has no flow and nutrient contribution downstream of the weir.

Limitations:

- Losses and gains of in-stream nutrients are encapsulated in the nutrient calibration process. The model cannot be used to examine in-stream processes. An exception to this is the decay of stored nutrients in the Yenyening Lakes, as discussed in Section 4.1.
- The only lakes (or reservoirs) explicitly modelled were the Yenyening Lakes.
- The nutrient component of the model is not physically based. As a result, the model represents the hydrology and nutrient transport processes of the calibration period.
- Deep drainage for salinity management has not been included in the model. The flow and nutrient loads from these drains have been lumped with total river flows and nutrient loads.

5 Results

5.1 Annual flows and nutrient loads

The average annual flows and nutrient loads for 2001–10 for the reporting catchments are listed in Table 5.1.The catchments upstream of Yenyening Lakes (Salt, Lockhart and Yilgarn) constitute approximately 76% of the catchment area but on average contribute less than 1% of the flow and nitrogen and phosphorus loads to the Avon River. These lakes only overflow in very wet years or during extreme events such as the year 2000 summer storm. The estimated flows and nutrient loads into Yenyening Lakes are also included in the table. The catchments that contribute most of the flow to the Avon River are the catchments to the west in the high rainfall area: the Lower Avon, Wooroloo, Middle Avon, Dale and Brockman. These catchments, together with the Upper Avon catchment, also contribute most of the nitrogen load. The pattern is slightly different for phosphorus, with the Mortlock North and Mortlock East catchments contributing nearly as much phosphorus load as the Dale catchment. The nitrogen and phosphorus reporting catchment loads are shown in Figure 5.1 and Figure 5.2 respectively.

Table 5.1: Average annual flows and nitrogen and phosphorus loads for the period 2001-10

Reporting catchment	**Flow**		**Nitrogen**		**Phosphorus**	
	GL	%	**tonnes**	%	**tonnes**	%
Helena	3.5		0.7		0.01	
Yilgarn	3.1		5.6		0.16	
Lockhart	3.4		8.7		0.15	
Salt	1.0		3.5		0.07	
Yenyening Lakes inflow	7.5		18		0.37	
Yenyening Lakes outflow	0.31	0.2	0.92	0.43	0.02	0.33
Upper Avon	10	5.3	22	10	0.60	11
Dale	27	14	41	19	1.1	20
Middle Avon	29	15	29	14	0.35	6.6
Mortlock East	9.1	4.7	18	8.4	1.0	18.7
Mortlock North	10	5.1	19	8.9	1.0	18.9
Brockman	23	12	24	11	0.62	12
Wooroloo	32	16	18	8.6	0.26	4.8
Lower Avon	54	28	40	19	0.41	7.6
Basin outlet	**195**	**100**	**213**	**100**	**5.3**	**100**

Although the period chosen for reporting average flows and nutrient loads is 2001–10, model outputs in the form of daily flows and loads are available for 1980–2010. So monthly and seasonal flows and loads, as well as changes over the period 1980–2010, may be examined. Figure 5.3 shows the modelled annual flows and nutrient loads at the basin outlet (616011) for 1980–2010.

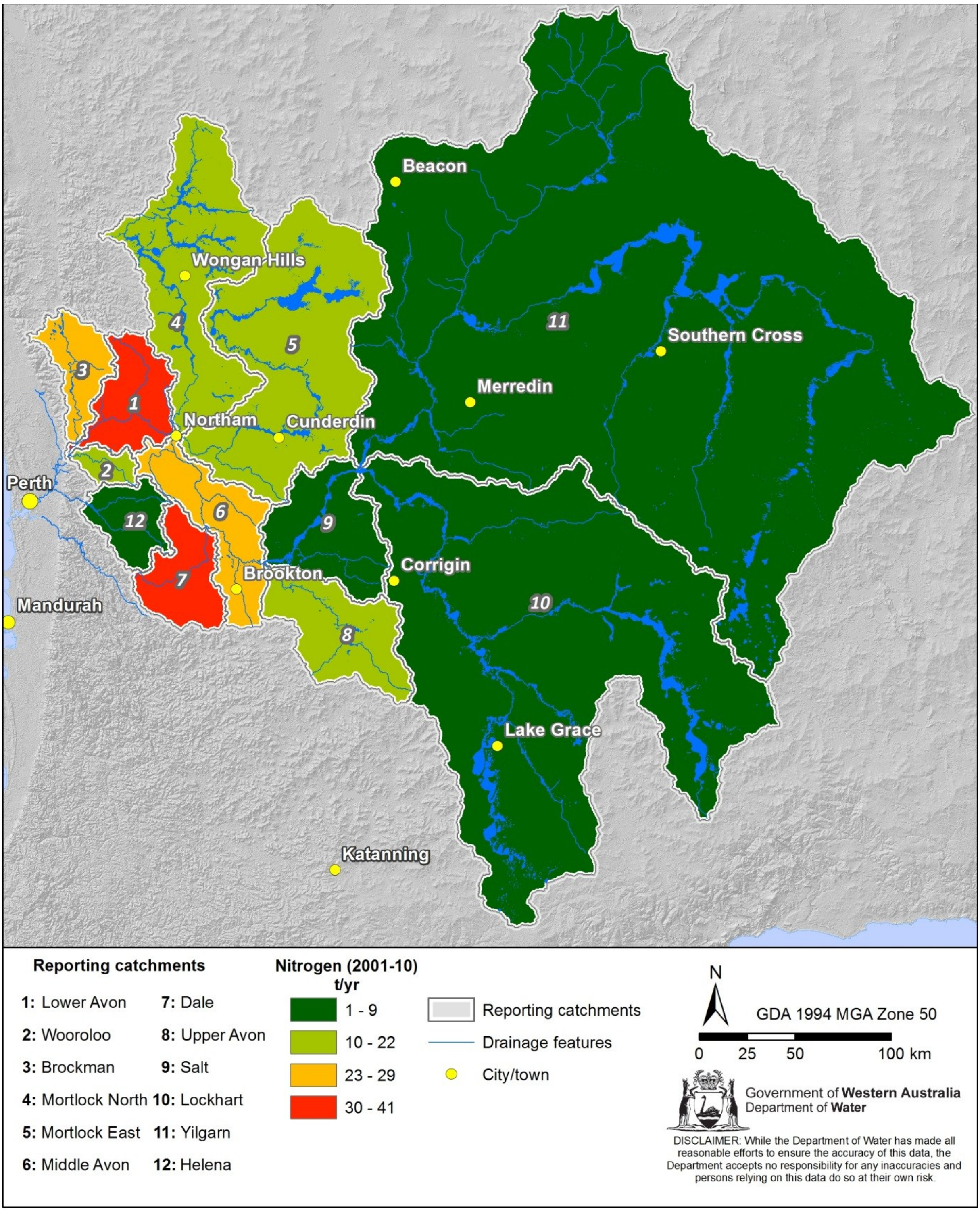


Figure 5.1: Reporting catchment average annual nitrogen load 2001–10

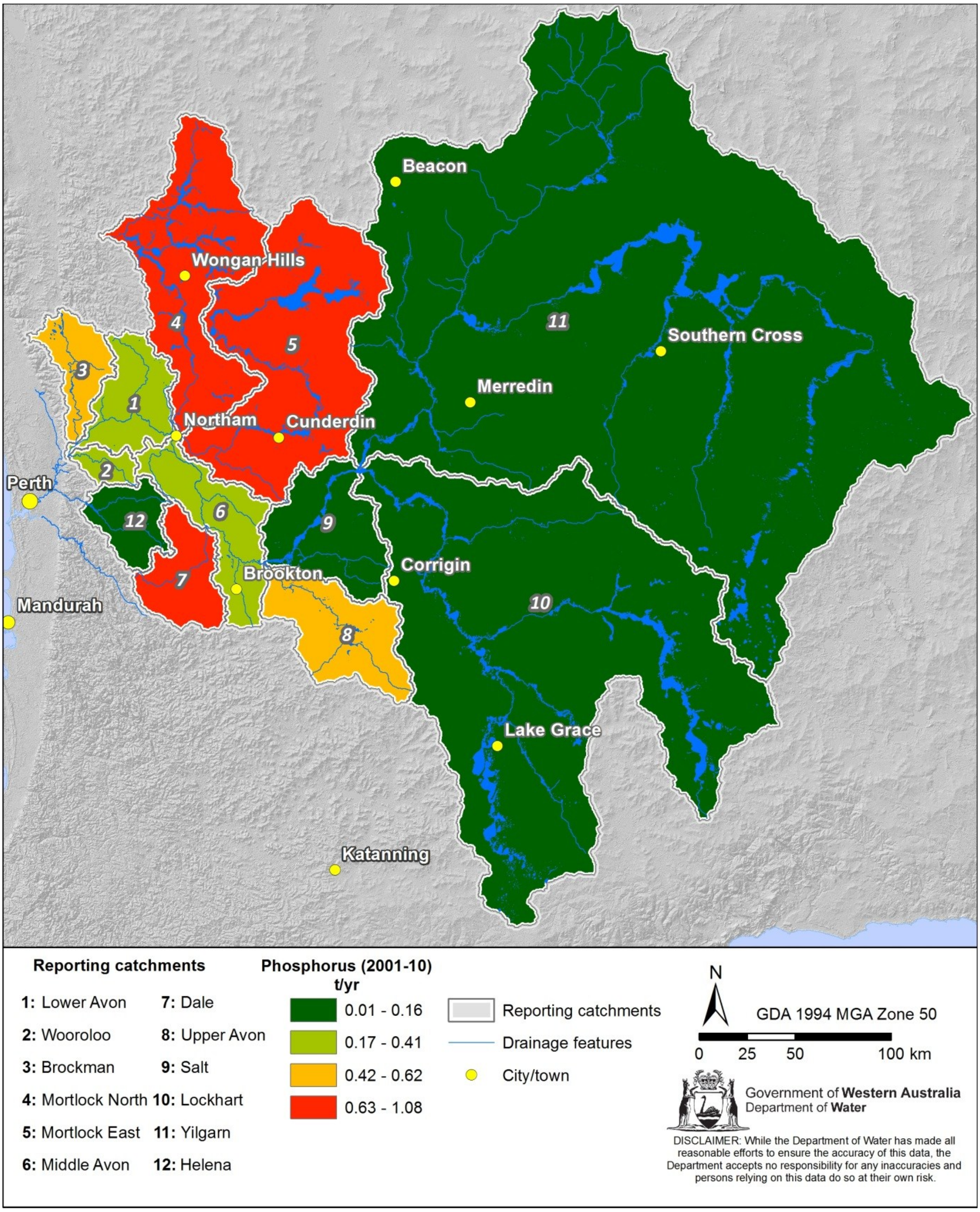


Figure 5.2: Reporting catchment average annual phosphorus load 2001–10

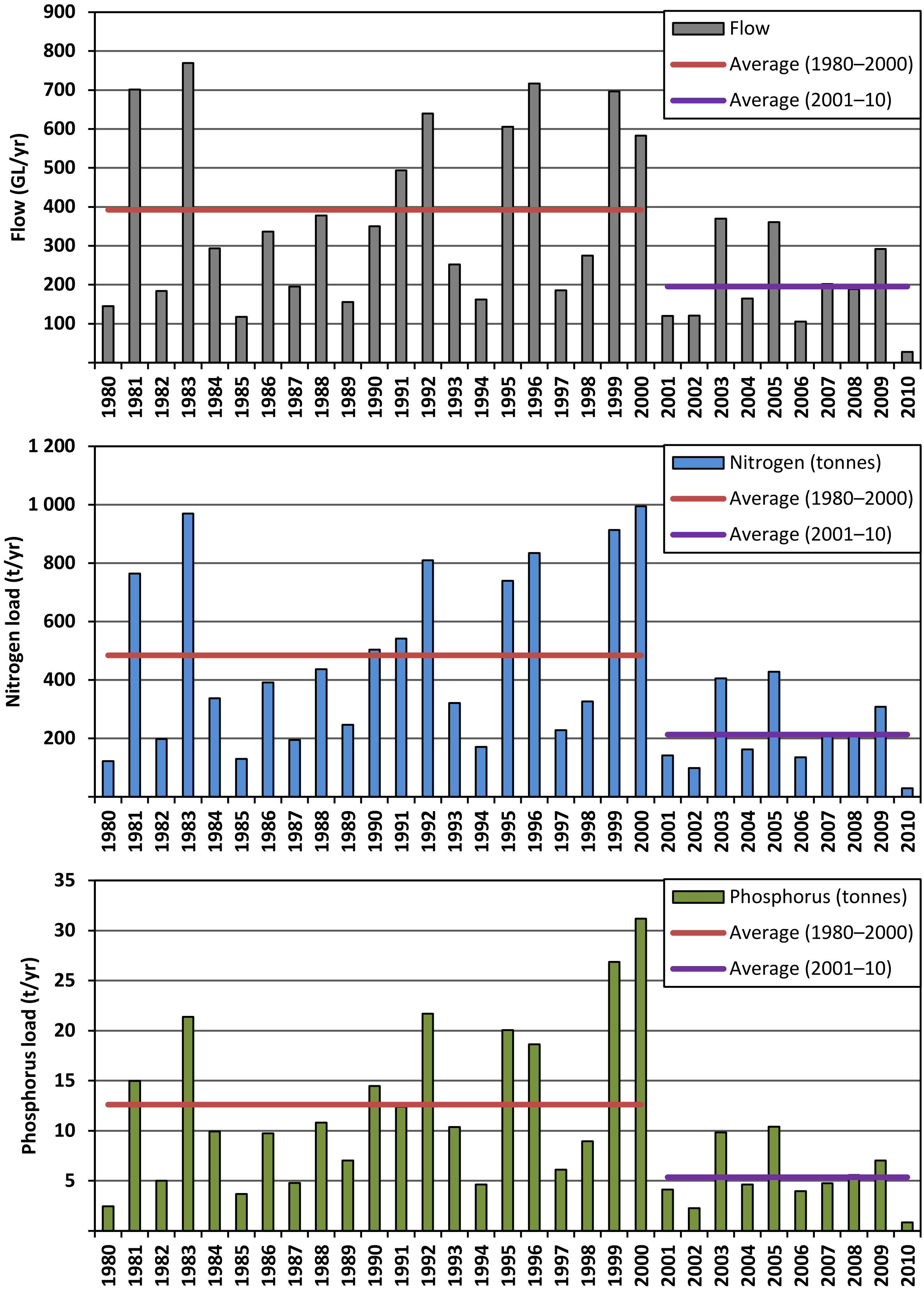


Figure 5.3: Annual flows and nitrogen and phosphorus loads at the basin outlet (616011)

The year-to-year variability of annual flows and loads is large, with the smallest flows and loads in 2010, and the largest flow in 1983 and the largest nitrogen and phosphorus loads in 2000. The 2000 load was mainly delivered to the estuary in January and February following cyclonic rainfall which produced large flows in the east of the catchment (mainly in the Lockhart and Upper Avon catchments).

There is a trend towards smaller flows and loads at the end of the 1980–2010 period compared with the beginning. The drying climate in the south-west of Western Australia, which has been observed in many locations (Frederiksen et al. 2012) and predicted by global climate models (CSIRO 2009), has caused large changes to the hydrology. For example, reduced rainfall has resulted in greatly decreased inflows to Perth water supply dams in recent years. In 1911–79 the average annual dam inflow would have been 378 GL/yr (if all the dams had been built). In 1980–99 inflows were 232 GL/yr (39% lower), and in 2001–08 inflows were 113 GL/yr (70% lower) than those estimated for 1911–79 (Water Corporation 2009). The trend in rainfall and streamflow reduction is predicted to continue into the future (CSIRO 2009).

The average annual flow at the basin outlet for 2001–10 was approximately 50% less than the average annual flow for 1980–2000. The nitrogen and phosphorus loads for 2001–2010 were approximately 56% and 58% respectively less than the loads for the earlier period 1980–2000.

5.2 Annual sediment loads

Estimations of sediment loads generally have very large errors as many factors affect stream sediment concentrations and inconsistent measurement methods make sediment data difficult to interpret. In the Avon catchment sampling, many different suspended sediment measurement methods were used. The total suspended sediment data (TSS) were collected using WIN measurement methods: PEI-003 and WL 126, and turbidity data were collected using measurement methods: PEI-005 and WL130 (Table 5.2).

Table 5.2: Analysis methods for TSS and turbidity data (www.wir.water.wa.gov.au)

Variable	Analysis method code	Description
TSS	PEI-003	Total suspended solids in water by dried filter at 103–105 deg C, and/or loss on ignition/volatile suspended solids dried filter at 550 deg C. Determined by gravimetric analysis.
	WL 126	Total suspended solids by filter residue drying at 105 deg C, and/or loss on ignition dried at 550 deg C. Determined by gravimetric analysis.
Turbidity	PEI-005	Turbidity in water by nephelometer/photoelectric detection of light scattered 90 degrees from path determined by a turbidity meter.
	WL130	Turbidity in water determined by a nephelometer (turbidity meter) and photoelectric detector.

The Source modelling did not include suspended sediment loads; however, TSS loads at Walyunga Swan River (616011) were calculated using a LOESS technique (Cleveland 1979; Helshel & Hirsch 1992) for the period with data, 1996–2010. The estimated annual TSS loads are listed in Table 5.3 and plotted in Figure 5.4. Suspended sediment concentrations are strongly correlated to flow, with large flows having large suspended sediment concentrations and loads. In the year 2000 TSS loads were very large with most of the sediment mobilised by the large flows following the January cyclonic rainfall. The reduced river flows of the 2001–10 period had proportionally greater decreases in annual TSS load than the decrease in annual flow. The average annual TSS load of approximately 6500 t for the period 2001–10 was 85% less than the average annual TSS load (42 300 t) for the period 1996–2000. Between the 1996–2000 and 2001–10 periods the percentage decreases in flow, nitrogen and phosphorus loads were 60%, 68% and 71% respectively.

Table 5.3: Estimated annual flow and TSS loads, and observed average annual concentrations at Swan River, Walyunga 616011

Year	Flow (GL)	TSS load (tonnes)	Average TSS concentration (mg/L)
1996	682	83 383	20
1997	174	5 841	9.0
1998	188	6 035	8.1
1999	564	43 258	92
2000	548	72 874	105
2001	86	1 952	17
2002	81	1 261	16
2003	267	12 634	-
2004	111	2 399	-
2005	292	13 805	38
2006	107	3 184	7.4
2007	140	4 292	7.0
2008	182	11 682	7.3
2009	246	13 500	7.0
2010	24	259	5.8
Average (1996–2000)	431	42 278	
Average (2001–10)	154	6 497	
Average (1996–2010)	246	18 424	

Note: no observed TSS data in 2003 and 2004

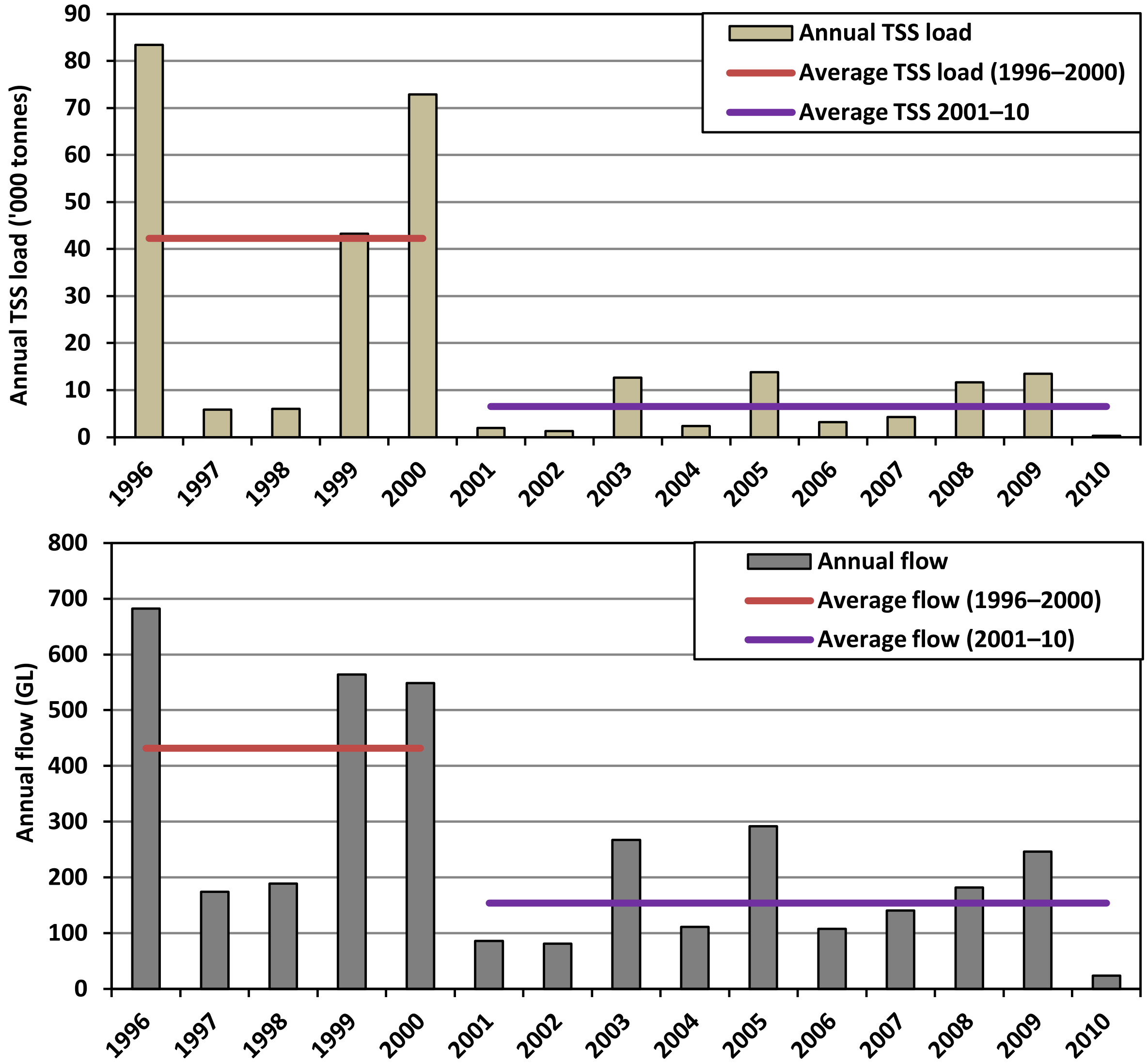


Figure 5.4: Annual flows and TSS loads at Swan River, Walyunga 616011 for the period 1996–2012

5.3 Flow and nutrient loads per unit area

The flow and nutrient loads per cleared unit area are given in Table 5.4 and shown spatially in Figure 5.5 and Figure 5.6. Flows and nutrient exports were most intensive in the west of the basin. The four most intensive catchments for flow, nitrogen and phosphorus were the: Wooroloo, Dale, Brockman and Lower Avon catchments where flows were 22–115 mm/yr, nitrogen loads 30–66 kg/km^2/yr and phosphorus loads 0.31–0.93 kg/km^2/yr.

Excluding the Middle Avon catchment, the flows per cleared area were an order of magnitude less in the Upper Avon, Mortlock North and Mortlock East catchments and two orders of magnitude less in the Salt, Lockhart and Yilgarn catchments. The same was true for nitrogen loads per cleared area, except for, the Salt catchment, which was more nitrogen-intensive than it was flow-intensive.

The pattern for phosphorus loads per cleared area was slightly different. The Upper Avon, Mortlock North and Mortlock East catchments had phosphorus loads per cleared area that were of the same order of magnitude as the four most intensive catchments. This indicates that these catchments had considerably higher phosphorus loads relative to their nitrogen loads than other catchments. The Salt, Lockhart and Yilgarn catchments had phosphorus loads per cleared area that were one to two orders of magnitude less that all other reporting catchments.

Table 5.4: Average annual flow and nitrogen and phosphorus loads per unit cleared area (2001–10)

Reporting catchment	Cleared area (km^2)	Total area (km^2)	Flow (mm/yr)	Nitrogen (kg/km^2)	Phosphorus (kg/km^2)
Helena	51	1 479	69	14	0.12
Yilgarn	19 449	58 386	0.16	0.29	0.008
Lockhart	20 963	28 391	0.16	0.42	0.007
Salt	2 981	3 270	0.33	1.2	0.023
Yenyening Lakes inflow	43 393	90 046	0.17	0.41	0.009
Yenyening Lakes outflow	43 393	90 046	0.007	0.021	0.000
Upper Avon	2 845	3 180	3.6	7.8	0.21
Dale	1 227	2 026	22	34	0.88
Middle Avon	2 426	2 864	12	12	0.14
Mortlock East	8 886	9 889	1.0	2.0	0.11
Mortlock North	6 239	6 901	1.6	3.1	0.16
Brockman	725	1 519	32	33	0.86
Wooroloo	276	537	115	66	0.93
Lower Avon	1 333	2 180	41	30	0.31
Basin outlet	**67 349**	**119 141**	**2.9**	**3.2**	**0.08**

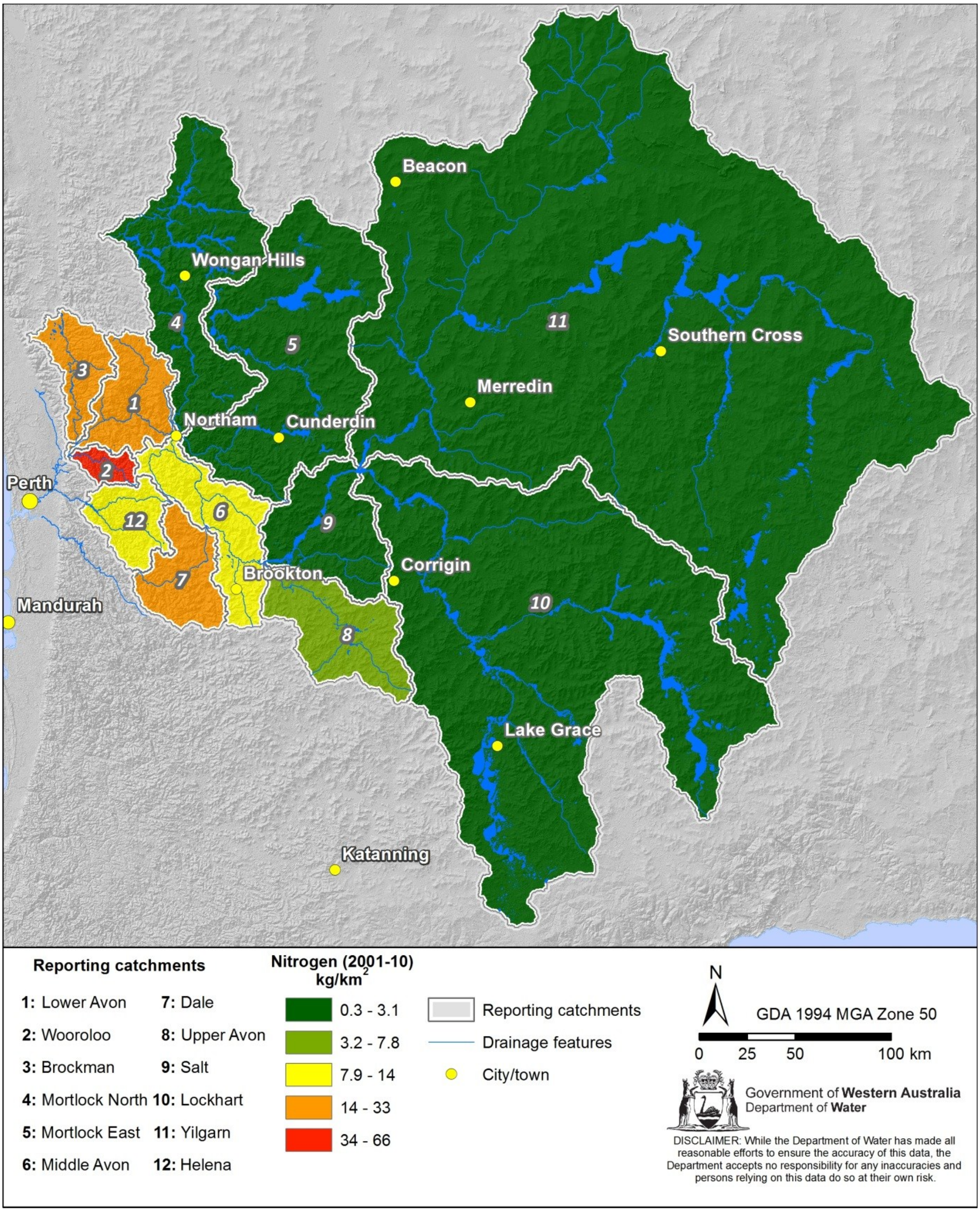


Figure 5.5: Average annual nitrogen loads per unit cleared area 2001–10

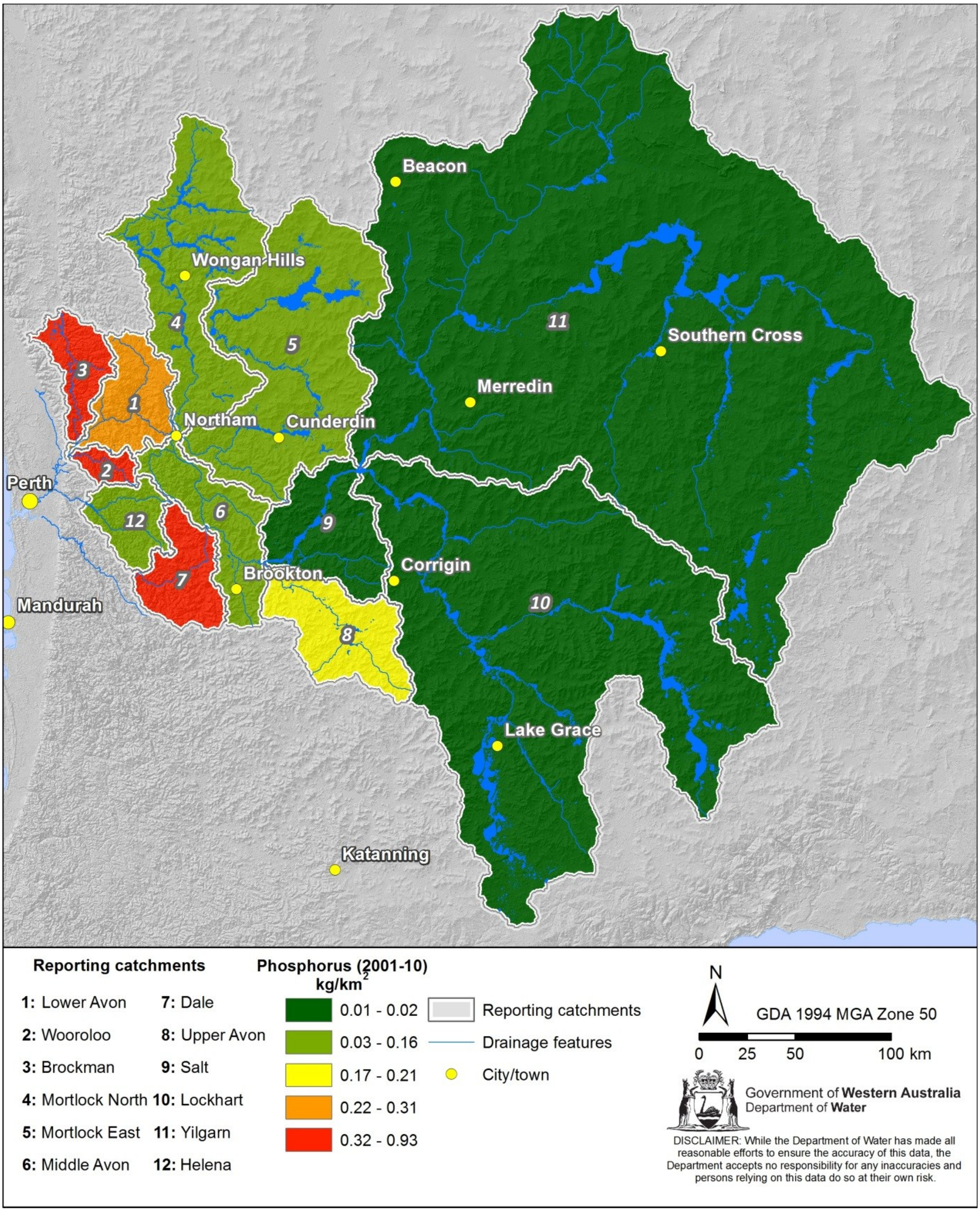


Figure 5.6: Average annual phosphorus loads per unit cleared area 2001–10

5.4 Seasonal flows and loads

The average monthly flows at the basin outlet for the periods 1980–2000 and 2001–10 are shown in Figure 5.7. The relatively large average flows in January and February for the 1980–2000 period were caused by the large cyclonic event of January 2000. A similar graph that does not include year 2000 monthly flows is shown in Figure 5.8, and the changing flow pattern is discussed below without inclusion of this exceptional summer 2000 event.

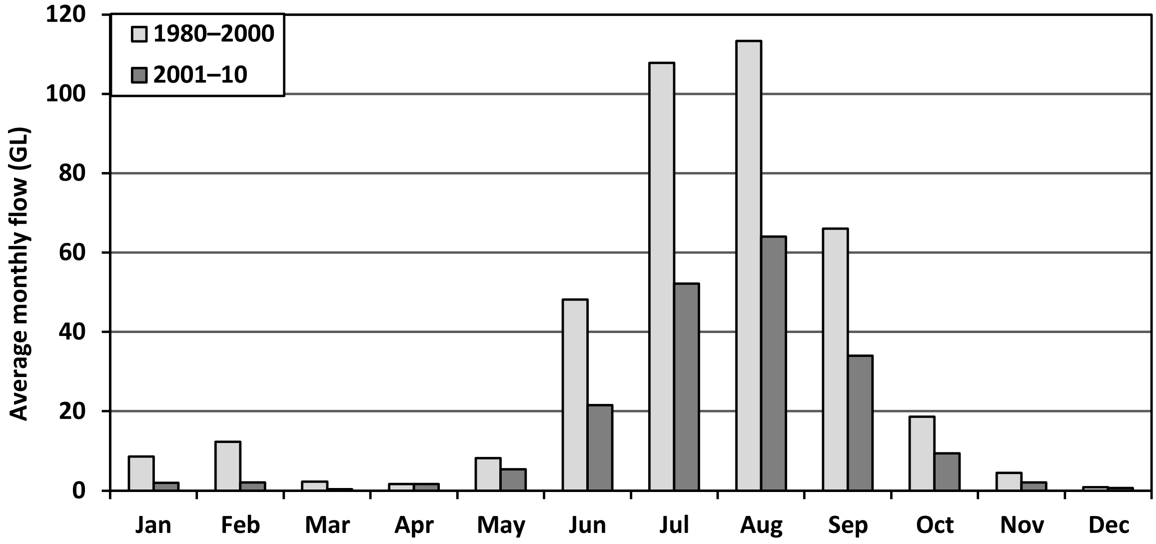


Figure 5.7: Average monthly flows at basin outlet for the periods 1980-2000 and 2001-10

Most flow in the Avon River occurs during June–September. The pattern of flow for the months May–November has not changed between the two periods, 1980–99 and 2001–10, although the flow volumes have decreased significantly. The average flows for May–November in the 2001–10 period are 0.43–0.63 of the monthly averages for the earlier period 1980–99 (Table 5.5).

The monthly summer (December–April) flows have not decreased by similar percentages; in fact, the changes to flow over the drier months are not consistent, with some months having similar (April) or higher (January) flows compared with previously. Although climate models predict more summer rainfall in the south-west of Western Australia (CSIRO 2009) this global warming impact is difficult to quantify statistically from observations of recent rainfall due to the highly variable nature of summer rainfall.

The monthly nitrogen and phosphorus loads have similar patterns to the flows (Figure 5.8). The current average monthly nitrogen and phosphorus loads (2001–10) are reduced in all months except January when compared with the 1980–99 data. The average April nitrogen load though is only slightly reduced (0.93 of 1980–99 load).

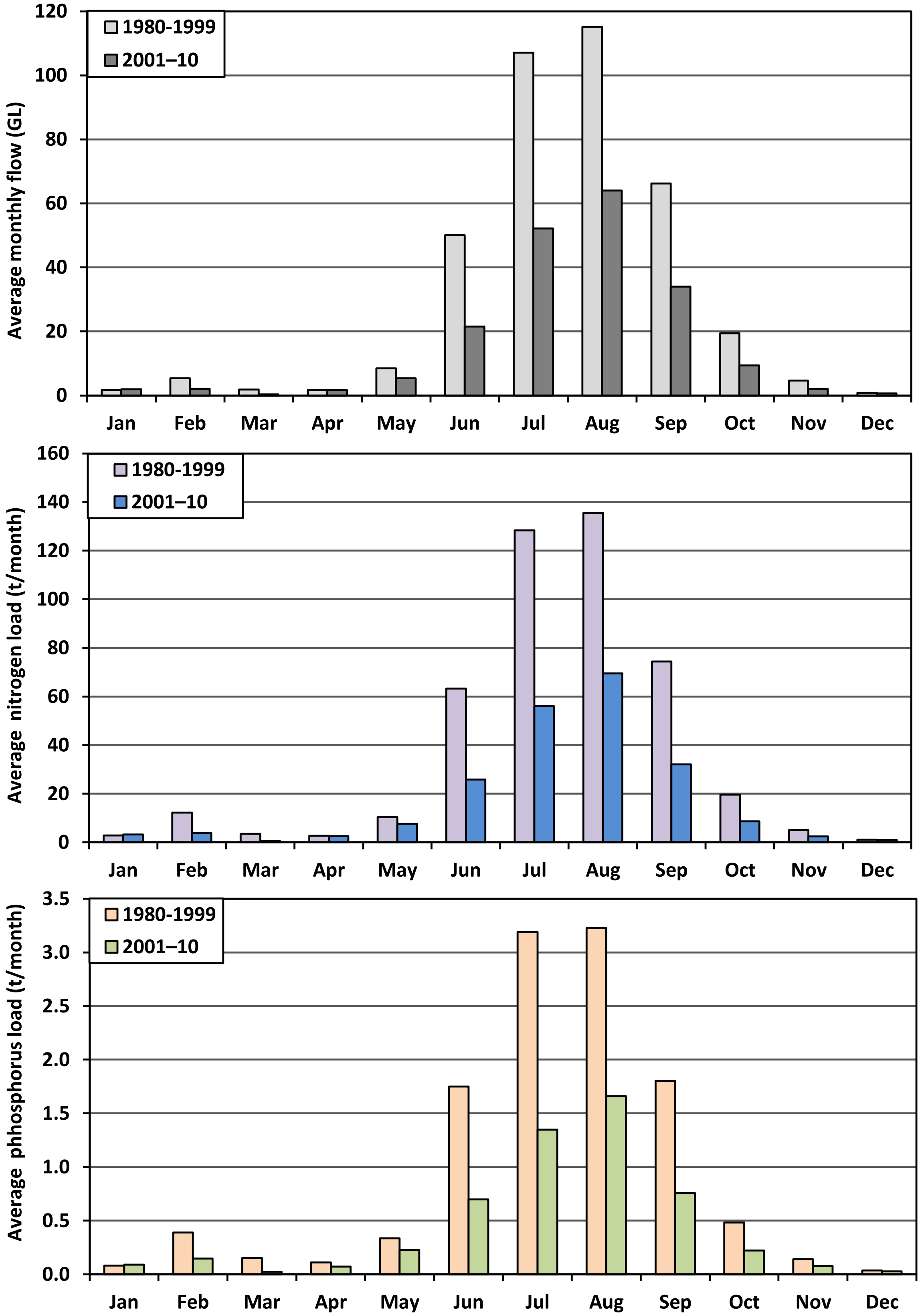


Figure 5.8: Average monthly flows, nitrogen and phosphorus loads at the basin outlet for the periods 1980-99 and 2001-10

Table 5.5: Average monthly flows and nitrogen and phosphorus loads at the basin outlet for the periods 1980–99 and 2001–10

Month	Flow			Nitrogen			Phosphorus		
	1980–99	2001–10		1980–99	2001–10		1980–99	2001–10	
	(GL)	(GL)	Fraction (1980–99)	(tonnes)	(tonnes)	Fraction (1980–99)	(tonnes)	(tonnes)	Fraction (1980–99)
Jan	1.6	1.9	1.17	2.8	3.2	1.14	0.08	0.09	1.08
Feb	5.4	2.1	0.39	12	3.9	0.32	0.39	0.15	0.38
Mar	1.8	0.3	0.17	3.5	0.63	0.18	0.15	0.02	0.16
Apr	1.7	1.7	0.99	2.7	2.6	0.93	0.11	0.07	0.64
May	8.5	5.4	0.63	10	7.6	0.73	0.33	0.23	0.68
Jun	50	21	0.43	63	26	0.41	1.7	0.70	0.40
Jul	107	52	0.49	128	56	0.44	3.2	1.3	0.42
Aug	115	64	0.56	136	69	0.51	3.2	1.7	0.51
Sep	66	34	0.51	74	32	0.43	1.8	0.76	0.42
Oct	19	9.4	0.48	20	8.6	0.44	0.48	0.22	0.46
Nov	4.7	2.0	0.43	5.1	2.4	0.48	0.14	0.08	0.56
Dec	0.9	0.6	0.70	1.1	0.93	0.84	0.04	0.03	0.76
Annual	**383**	**195**	**0.51**	**459**	**213**	**0.46**	**12**	**5.3**	**0.46**

5.5 Comparison of flows and loads from the Avon River with those from the coastal catchments

5.5.1 Flows and nutrient loads

Kelsey et al. (2010a) used the LASCAM flow and the Streamflow Quality Affecting Rivers and Estuaries (SQUARE) models to estimate the flows and nutrient loads from the 30 coastal catchments, with an area of approximately 2090 km^2, to the Swan and Canning estuaries. Total estimated average annual nitrogen and phosphorus loads from all coastal catchments for the period 1997–2006 were 250 and 26 t respectively. Kelsey et al. (2010a) also estimated Avon River loads at 616011 (the basin outlet) using a locally-estimated scatterplot smoothing (LOESS) technique (Cleveland 1979; Helshel & Hirsch 1992). Their estimated nitrogen and phosphorus loads of 575 and 20 t respectively for 1997–2006 are much greater than the loads from this study's Source modelling for the same period, which are 383 t of nitrogen and 11 t of phosphorus. A review of TN and TP concentration data from 616011 and Kelsey et al.'s (2010a) LOESS load calculations revealed that erroneous TN and TP data with high concentrations during high river flow were included in the calculations. These data came from the January 2000 flow event and were due to the autosampler's inlet being too low in the river profile as a result of the increased river depth. Consequently, the samples contained suspended sediment and organic matter from the 'bed load' and did not represent the 'average' concentrations of the river profile. The LOESS concentration-flow relationship was thus incorrect for large flows, and the sensitivity of the load calculation to the concentration values attributed to large flows led to the overestimation of the nitrogen and phosphorus loads. The data collected by the autosampler during the January 2000 high-flow event are no longer used to estimate nitrogen and phosphorus loads.

The Avon River flows into the Swan Estuary and its flows, nutrient and sediment loads primarily impact the estuary upstream of the Narrows Bridge in the areas designated Upper and Middle Swan Estuary in Figure 5.9. The average annual flows and nutrient loads for the period 1997–2006 from the Avon River (this study) and the coastal catchments (Kelsey et al. 2010a) that flow to the Upper and Middle Swan Estuary are listed in Table 5.6.

The total average annual flow to the Upper and Middle Swan Estuary for 1997–2006 was approximately 403 GL; the average annual nitrogen and phosphorus loads were 544 and 29 t respectively (Table 5.6). Of these the Avon River contributed 298 GL (74%) of the flow, 383 t (70%) of the nitrogen load and 11 t (38%) of the phosphorus load, Ellen Brook 27 GL (7%) of the flow, 71 t (13%) of the nitrogen load and 10 t (35%) of the phosphorus load, and the other 18 coastal catchments 78 GL (19%) of the flow, 89 t (16%) of the nitrogen load and 8 t (27%) of the phosphorus load. The relative average annual flow and load contributions from the Avon River, Ellen Brook and the coastal catchments to the Upper and Middle Swan Estuary are shown in Figure 5.10.

Table 5.6: Average annual flows and nutrient loads to the Swan Estuary from the Avon River and the coastal catchments for 1997–2006

Catchment	**Area** (km^2)	**Average annual flow** (ML)	**Average annual nitrogen load** (tonnes)	**Average annual phosphorus load** (tonnes)
Avon River	119 141	298 100	383	11
Bayswater	27.2	8 267	9.8	0.60
Belmont Central	3.6	900	0.7	0.06
Bennett	113.1	4 997	7.1	0.42
Blackadder	17.1	2 993	2.5	0.17
CBD	13.7	2 413	5.2	0.24
Claisebrook	16.1	3 411	4.7	0.30
Ellen	716.4	26 750	71	10
Helena	175.7	4 876	5.8	0.23
Henley	12.6	681	0.8	0.05
Jane	137.7	14 780	11	0.58
Maylands	18.7	3 726	11	0.27
Millendon	35.2	3 154	2.6	0.15
Perth Airport N	28.1	3 070	2.0	0.21
Perth Airport S	24.6	2 048	1.1	0.17
Saint Leonards	9.8	594	1.4	0.14
South Belmont	10.5	2 427	1.7	0.24
South Perth*	27.0	9 487	8.5	1.3
Susannah	54.7	6 207	4.8	0.65
Upper Swan	40.5	4 004	8.6	2.0
Subtotal (Swan coastal tributaries)	1 482	104 800	161	18
Total	**120 623**	**402 900**	**544**	**29**

*South Perth delivers approximately 2/3 of its flow and nutrient yield to the Swan Estuary and the remainder to the Canning Estuary

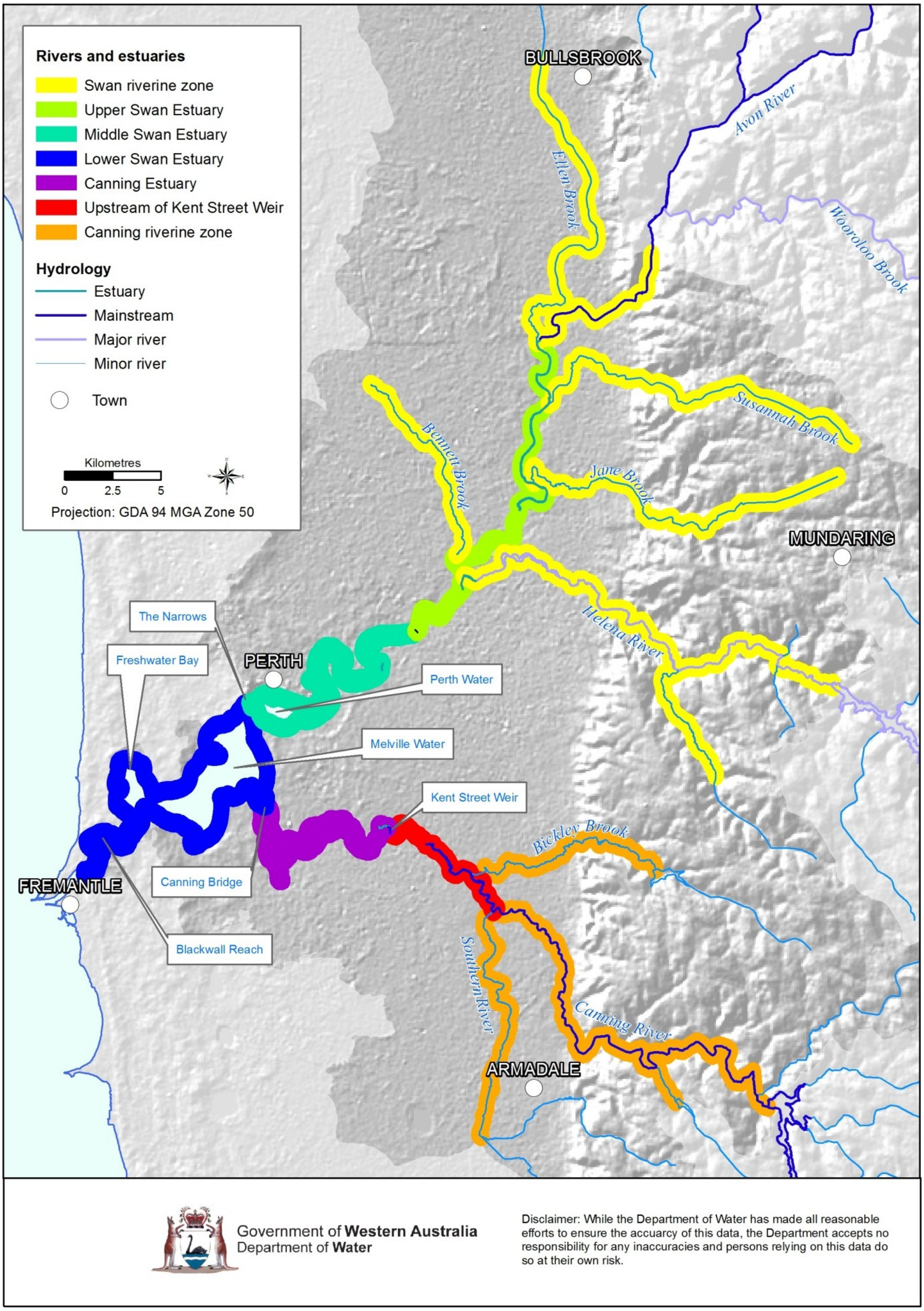


Figure 5.9: Major rivers and estuaries of the Swan-Canning system; the Narrows is the restriction between the Middle and Lower estuaries

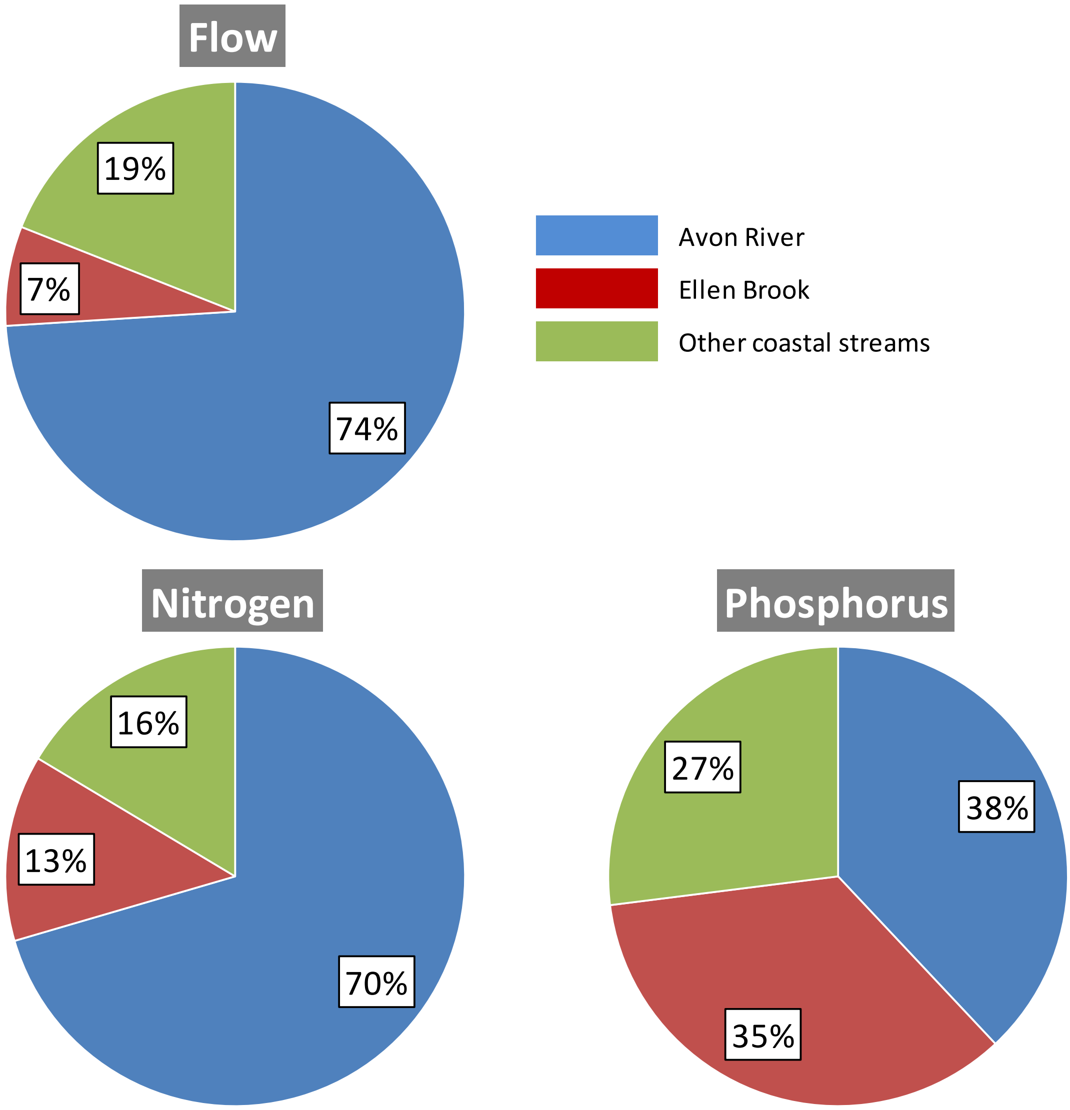


Figure 5.10: Average annual flow and nitrogen and phosphorus loads from the Avon River, Ellen Brook and the other 18 coastal catchments that flow to the Upper and Middle Swan Estuary

The timing of nutrient delivery to the estuary is also important. Kelsey et al. (2010a) examined the monthly flows and nutrient loads from the coastal catchments and the Avon River for the year 1997. This was a fairly average year in terms of total flow volumes from the coastal catchments and the Avon River, and the rainfall had a typical winter pattern. The monthly flows and loads from the Avon River, Ellen Brook and the 18 other coastal catchments that flow to the Upper and Middle Swan Estuary are shown in Figure 5.11.

Note: these graphs are different from Figures 5.8 and 5.9 in Kelsey et al. (2010a) which included flows and loads from all the coastal catchments to the Swan and Canning estuaries.

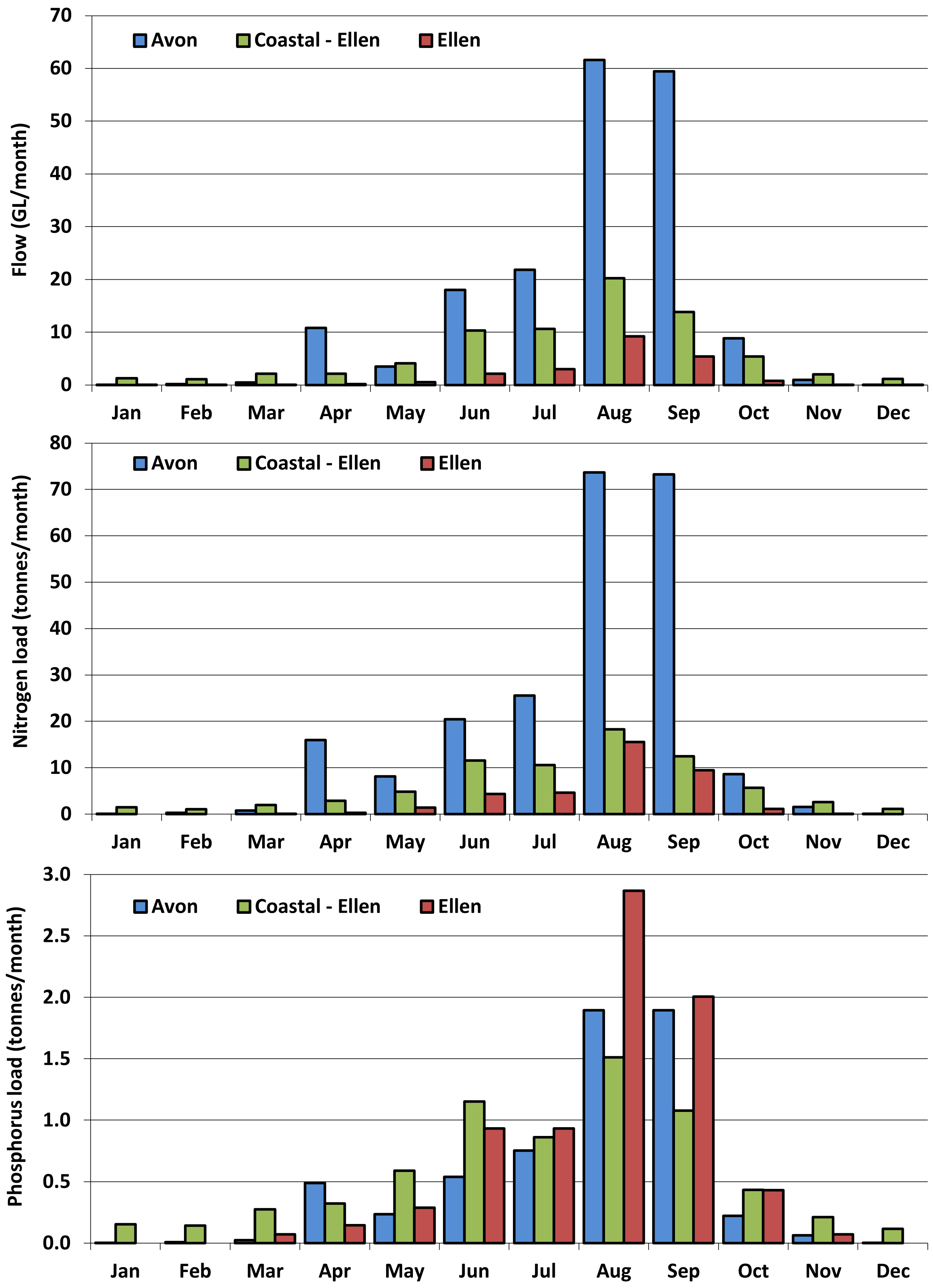


Figure 5.11: Monthly flows, nitrogen and phosphorus loads for 1997 from the Avon River, the coastal tributaries (not including Ellen Brook) and Ellen Brook that flowed to the Swan Estuary

In 1997 for most of the period April–October flows from the Avon River were greater than the combined flows from Ellen Brook and the other coastal catchments. However, in May the coastal catchment flows exceeded flows from the Avon River. The monthly nitrogen load graphs for the Avon River, Ellen Brook and the other coastal catchments have similar shapes to the flow graphs but slightly different relative magnitudes as TN concentrations in the Avon inflows are generally greater than TN concentrations of the impervious coastal catchments (coastal catchments other than Ellen Brook) and lower than Ellen Brook concentrations.

The pattern for phosphorus loads from the three contributing areas is very different. During the main flow period June–September all areas contributed significant phosphorus loads. This is reflected in the total phosphorus loads for 1997, which were estimated to be approximately: Avon 6.1 t, Ellen Brook 7.7 t and the other coastal catchments 6.8 t.

During the summer months of 1997 (January, February, March, November and December) there was very little input to the Swan Estuary from the Avon River and Ellen Brook but the inputs, particularly phosphorus loads from the impervious, urban coastal catchments, kept ‘dribbling in’. Nutrient inputs, particularly inorganic nitrogen and phosphorus, in summer are likely to be available for algal growth due to the strong light conditions and high temperatures. It is, thus important to minimise nutrient inputs from the urban catchments surrounding the estuary.

5.5.2 Sediment loads

The previous flow and nutrient modelling by Kelsey et al. (2010a) and the Source modelling done in this study did not include sediments. TSS loads in the Avon River, calculated using LOESS techniques were discussed in Section 5.2. TSS loads (LOESS) have also been calculated for Ellen Brook (Table 5.7; Figure 5.12). The urbanised coastal plain tributaries generally have TSS concentrations an order of magnitude smaller than the average values for the Avon River (Table 5.8) and small flow volumes relative to Ellen Brook and the Avon River. The average annual sediment loads from the Avon River and Ellen Brook for the period 1996–2010 were 18 400 and 570 t respectively. Considering the relative flows and TSS concentrations in other tributaries, it can be concluded that the Avon River has sediment loads two orders of magnitude greater than other sediment sources.

Sediment flows into the Swan Estuary during periods of high flow. The Avon River and Ellen Brook monthly sediment loads for 1997, which was a typical year in terms of flows and loads, are plotted in Figure 5.13 superimposed on the flows from the three contributing areas to the Swan Estuary: Avon River, Ellen Brook and the other coastal catchments. The sediment loads from Ellen Brook are much smaller than Avon River sediment loads and Ellen Brook has no flow for several months of the year.

Table 5.7: Annual flows and TSS loads at Ellen Brook Railway Parade 616189

Year	Annual flow (GL)	Annual TSS load (tonnes)
1996	48	1 657
1997	17	666
1998	22	641
1999	37	1 138
2000	28	822
2001	13	185
2002	16	315
2003	28	689
2004	12	235
2005	31	907
2006	7.5	236
2007	14	296
2008	13	277
2009	19	461
2010	2.3	31
Average (1996–2000)	30	985
Average (2001–10)	16	363
Average (1996–2010)	21	570

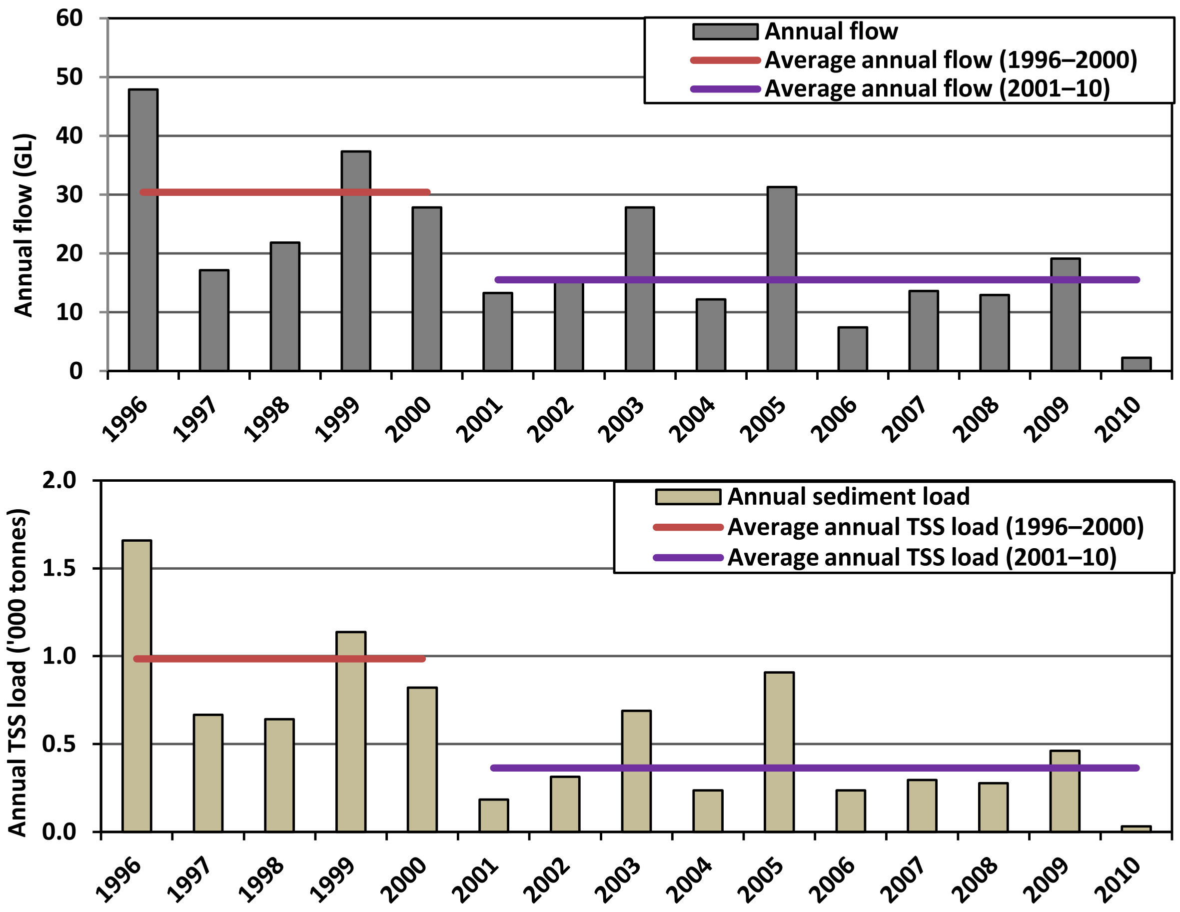


Figure 5.12: Annual flows and TSS loads at Ellen Brook, Railway Parade 616189

Table 5.8: Average TSS concentrations at sampling sites on the coastal plain and at Swan River Walyunga and Ellen Brook Railway Parade

Site	AWRC context	AWRC name	No. readings	Average TSS (mg/L)
616011	Swan River	Walyunga	391	36.8
616189	Ellen Brook	Railway Parade	1851	38.6
616040	Susannah Brook	Gilmours Farm	2	1.5
616082	Bayswater Main Drain	Slade Street	686	29.7
616084	Bennett Brook Main Drain	Benara Road	126	16.1
616086	Helena River	Whiteman Road	423	9.1
616087	Sth Belmont Main Drain	Abernethy Road	558	7.6
616088	Jane Brook	Gt Nthn Hwy - Road Bridge	333	5.1
616099	Susannah Brook	River Road	228	8.2
6161692	Henley Brook Catchment	Hbbrock	112	6.1
616178	Jane Brook	National Park	49	5.1
6162317	Perth Airport South	Second Av Access	144	2.1
6162318	Perth Airport North	Great Eastern Hwy Bypass	151	12.7
6162925	Blackadder Creek	Francis Street	446	8.9
6163143	Bennett Brook	Benara Rd (200M D-S of Swan 1)	521	5.3
Average of all sites (excluding Walyunga and Railway Parade)				9.0

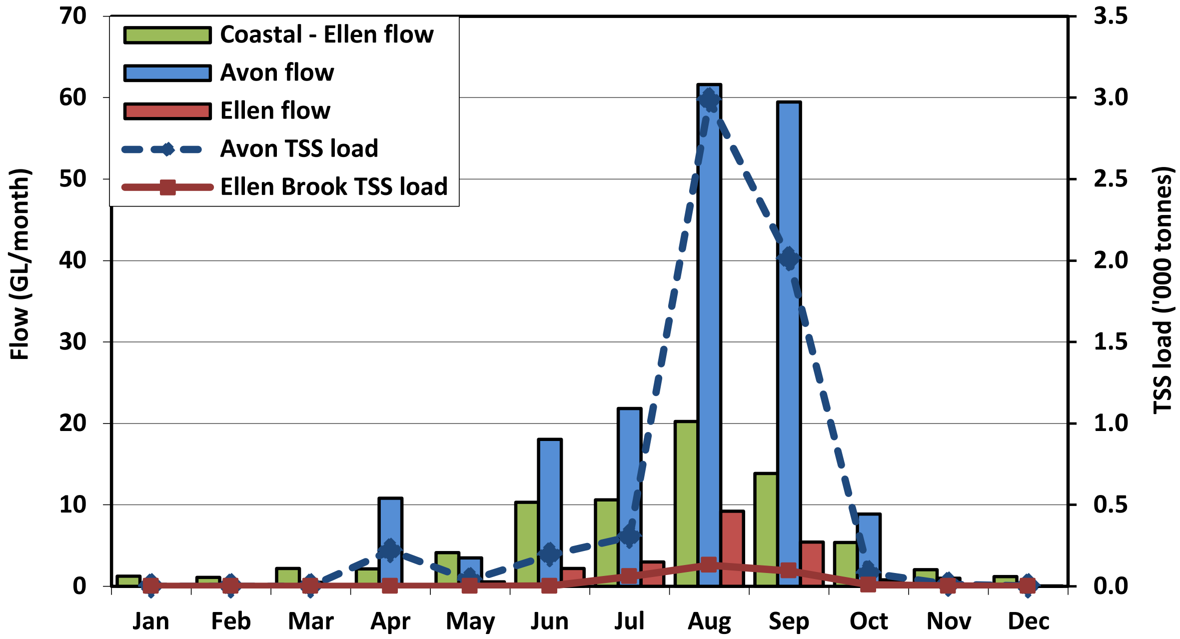


Figure 5.13: Avon River and Ellen Brook TSS loads and flows to the Swan Estuary

5.6 Fate of flow, nutrient and sediment loads

Understanding estuary dynamics

The Swan Estuary is a classic estuary with most of its freshwater input (the Avon River) entering the estuary far from the ocean outlet (Figure 5.9). The flow travels the length of the estuary to reach the ocean outfall at Fremantle harbour. The estuary is deepest in the lower portions (particularly Blackwall Reach) but 3.5 km from the harbour mouth has a shallow sill

3–5 m deep which slows water exchange with the ocean. Upstream of Perth the depth is generally 2–3 m with some 5–6 m deep pools. The Lower Estuary has a surface area of about 32 km^2 and average depth of 4.9 m, while the Upper and Middle estuary has an area of approximately 8 km^2 and average depth of 3.7 m. Tides penetrate 50 km upstream and the average tidal variation is 0.5 m.

Freshwater flowing through the estuary to the ocean pushes against seawater. The freshwater flows on the top of the seawater in a layer that gradually thins as it moves seaward while the denser seawater moves landward along the bottom of the estuary forming a wedge-shaped layer. Thus this interface between the freshwater flowing out and the seawater moving inland is referred to as the 'salt-wedge'. The location of the salt-wedge is affected by changing ocean levels caused by tides, changes in atmospheric pressure and other phenomena, such as low-frequency continental-shelf waves (Pattiaratchi & Eliot 2005), and the volume of freshwater inflow. The velocity difference between the salt and freshwater flows creates shear forces, which gradually mix the seawater into the freshwater.

Relationship between flow and salt-wedge location

Under high-flow conditions the force of the freshwater flows pushes the salt-wedge towards the estuary mouth, while under low-flow conditions the salt-wedge can encroach up the estuary. Figure 5.14 shows the position of the salt-wedge in January 2000 following large flows in the Avon River. At the Narrows the salinity was about 5 parts per thousand (ppt) for most of the water depth, similar to the salinity of the inflows (4 ppt). In these large Avon River flows, freshwater flows to the Lower estuary and the ocean. The strong salinity gradient of the salt-wedge inhibits oxygen mixing and all of the Lower Estuary can have low dissolved oxygen concentrations at the estuary bed, as evident in January 2000 (Figure 5.15). In contrast, January 2001 had typical summer flow and the Avon River ceased flowing completely on 7 January. The salinity profile (Figure 5.15) shows that the salinity at the Narrows was close to seawater salinity of about 35 ppt. Under these conditions the salt-wedge is in the Upper estuary and low oxygen concentration at depth is apparent in that location. Under these conditions there is negligible freshwater flow to the Lower estuary.

The locations of the salt-wedge in July 2003 and July 2004 are shown in Figure 5.15 and Figure 5.16 respectively. The Avon River had considerably more flow in July 2003 (87 GL) than in July 2004 (25 GL; Figure 5.17). Examination of the weekly salinity profiles for these months shows that the salt-wedge was much further downstream in July 2003 than July 2004 and much more freshwater was reaching the Lower estuary.

The impact of Avon River freshwater inflow on the location of the salt-wedge was examined by Kurup et al. (1998). They deduced that "the correlation between the longitudinal location of the salt-wedge and the inflow volume ($r^2 = 0.86$) suggests that freshwater inflow is the most important mechanism affecting the salt-wedge position in the Swan River estuary". The position of the salt-wedge had a relationship to inflow, of $L = 23.71\ \mathrm{Q}^{-0.544}$, where L (km) is the distance upstream from the Narrows and Q is averaged daily Avon River inflow (m^3/day) for the previous 7 days.

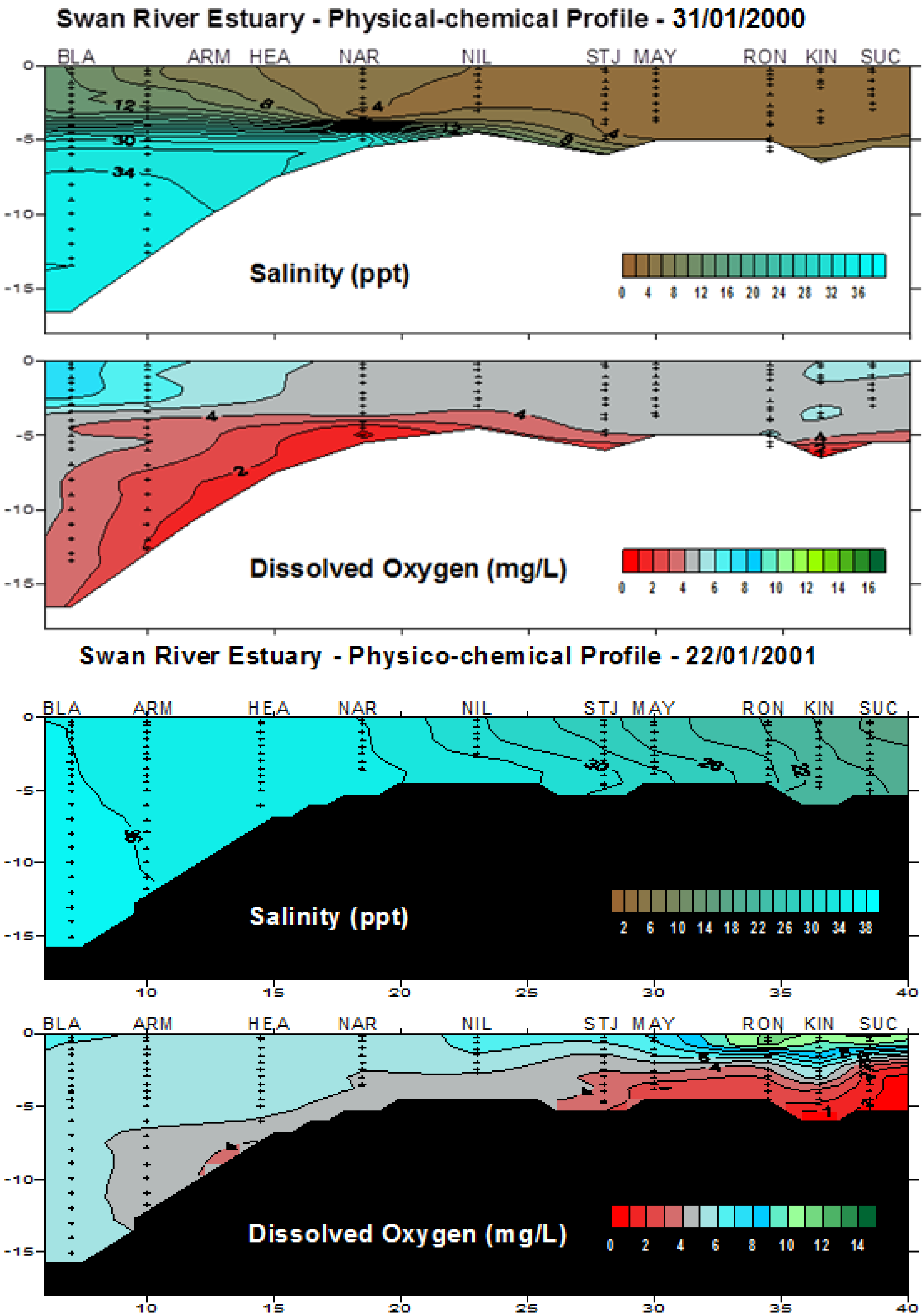


Figure 5.14: Swan Estuary salinity and dissolved oxygen profiles for 31 Jan 2000 and 22 Jan 2001 (SRT 2014)

Fate of nutrient inflows

The impact of nutrients in the inflows from the Avon River on the estuary will depend on the proportion of the flow and nutrient load that remains in the estuary and where in the estuary the nutrients are deposited (in the case of particulate matter) or utilised for plant or animal growth.

To understand and quantify the fate of the flow and nutrient loads from the Avon River a model of estuary hydrodynamics and geochemical processes is required. However, the location of the salt-wedge indicates the area of the estuary being affected by the inflows. The portion of the freshwater and associated nutrients retained in the Upper and Middle estuaries increases with the distance of the salt-wedge upstream from the Narrows, that is, it increases with decreasing Avon River flow. Thus, it could be postulated that the portion of nutrients retained in the Upper and Middle estuaries has a power or exponential relationship, with a negative exponent, to the Avon River inflow volume (similar to Kurup et al.'s relationship for salt-wedge position).

A de facto for the 'average' position of the salt-wedge is the average salinity at the Narrows. Figure 5.18 shows the annual average daily Narrows salinity plotted in decreasing order of annual flow. In high-flow years the average salinity is about 26 ppt whereas in low-flow years, such as 2010, the salinity is similar to that of seawater most of the time (average salinity is 33 ppt compared with seawater salinity of 35 ppt). This indicates that in low-flow years none, or very little, of the Avon freshwater inflow reaches the Lower Estuary.

Although the average annual flows and nitrogen and phosphorus loads from the Avon River have decreased greatly in the reporting period 2001–10 (by 50%, 56% and 58% respectively) compared with the 1980–2000 period, the proportion of the flow and nutrient load that is retained in the Upper and Middle estuaries will have increased greatly. A simple estuary model similar to the previous work of Kalnejais et al. (2006) could be considered to estimate fate of the inflows and nutrient loads under different flow conditions.

Fate of sediment and particulate matter

The inflows from the Avon River have visibly high sediment loads (brown colour). Ellen Brook flows into the Avon River inflows at the extreme tidal extent of the estuary with tannin-stained water that contains a large fraction of soluble phosphorus (~60% on average). The Avon River water provides a ready supply of suspended sediment for the Ellen Brook soluble phosphorus to bind to. Clearly, in the recent low-flow years, suspended sediment, sediment-bound nutrients and particulate matter in Avon River inflows will have deposited and been retained in the Upper and Middle estuaries, as discussed above. The Avon River suspended sediment load will also have provided a mechanism for retention of Ellen Brook phosphorus inflow in this part of the estuary.

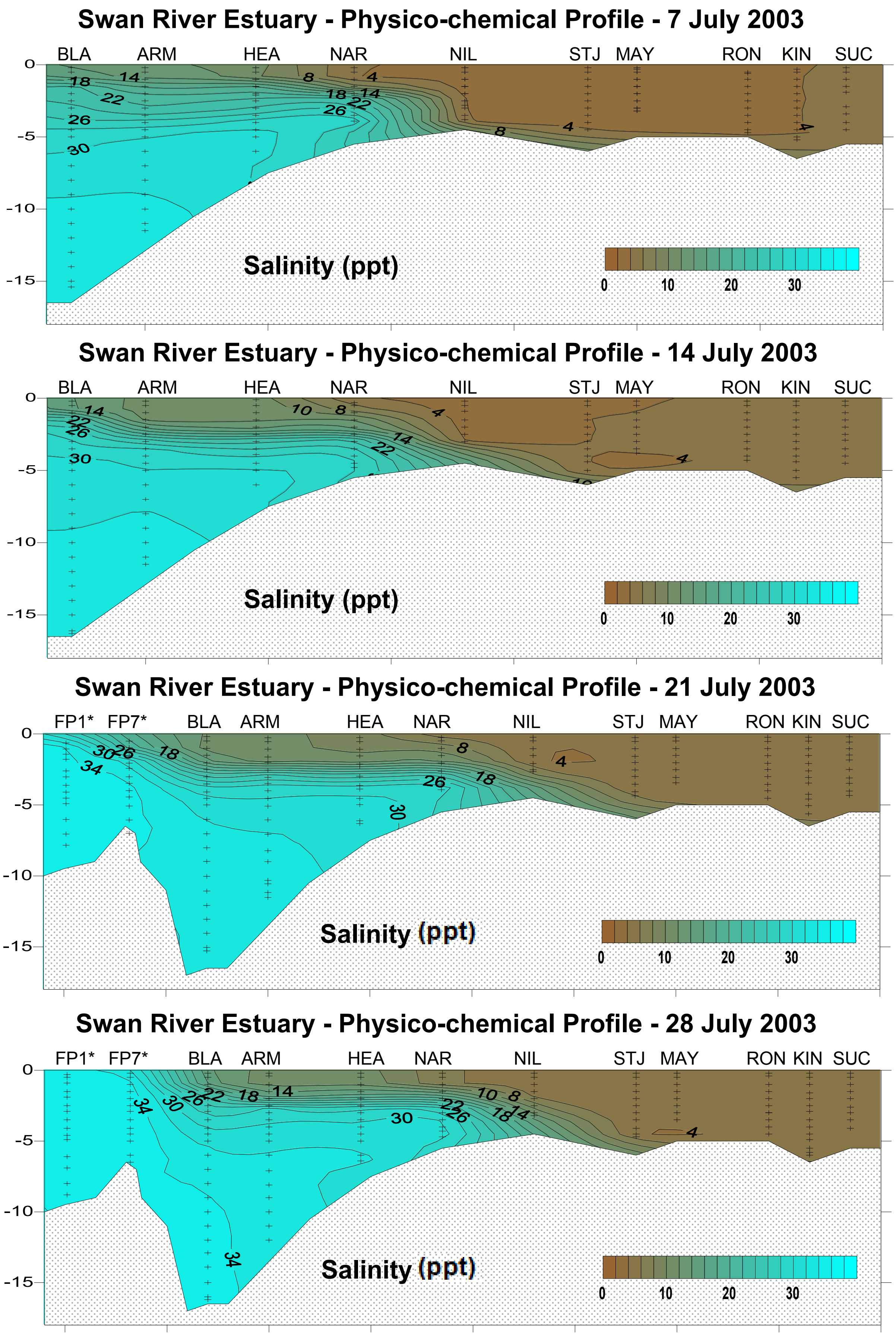


Figure 5.15: Swan Estuary salinity profiles for July 2003 (SRT 2014)

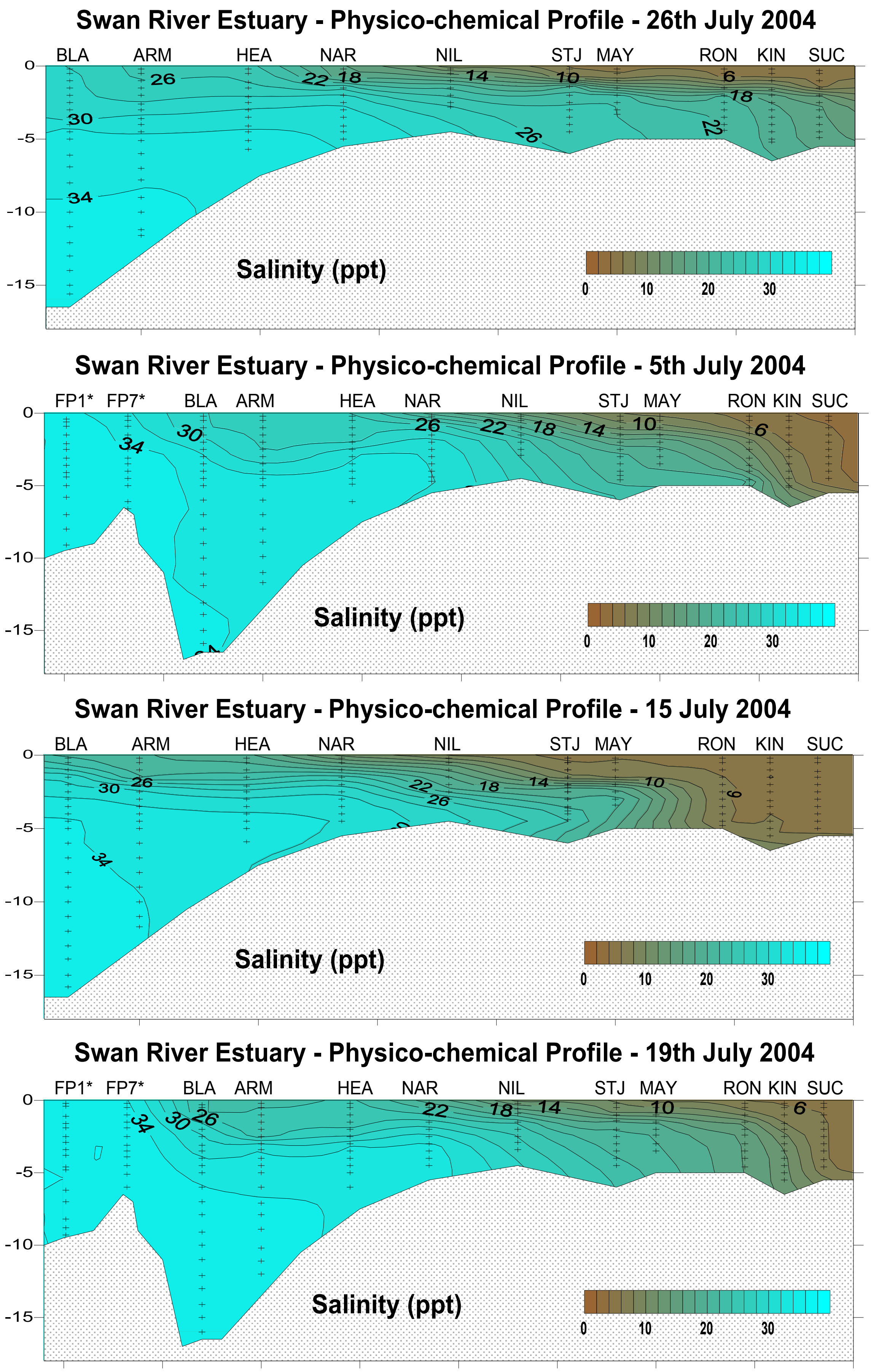


Figure 5.16: Swan Estuary salinity profiles for July 2004(SRT 2014)

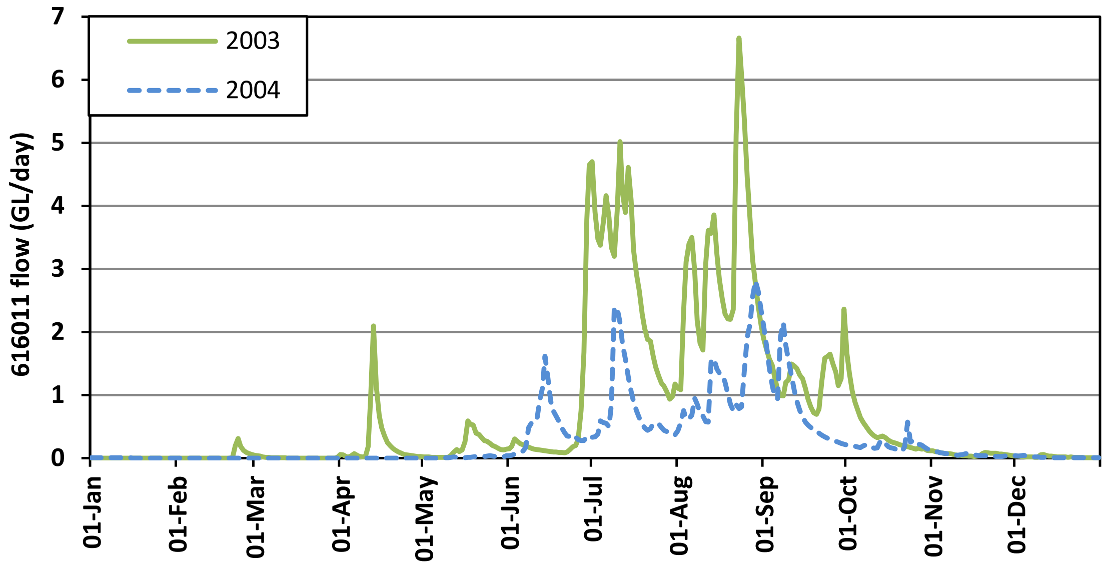


Figure 5.17: Daily flows for 2003 and 2004 at Swan River Walyunga 616011

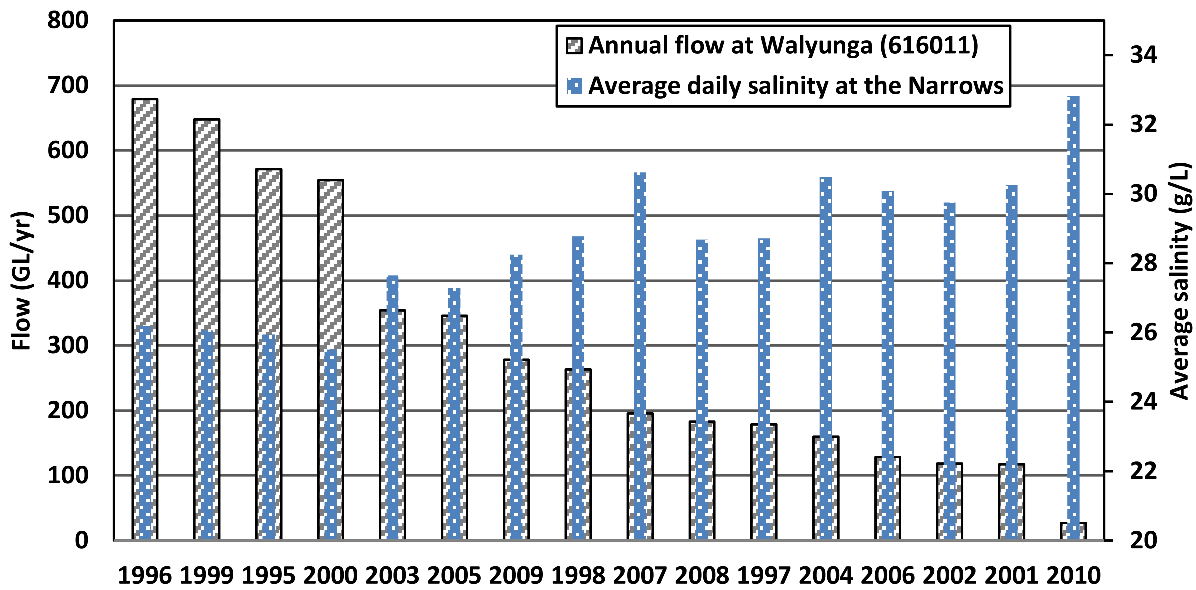


Figure 5.18: Annual flow at Walyunga (616011) and average daily salinity at the Narrows

5.7 Sources of nitrogen and phosphorus by land use

The areas and average annual nitrogen and phosphorus loads by land use are presented in Table 5.9 and plotted in Figure 5.19. This information is also given in Appendix F for each reporting catchment. The nutrient loads reported here represent the loads reaching all waterways in the Avon Basin and do not account for losses of nutrients at the Yenyening Lakes.

Wheat & sheep land use was the major source of nutrients, generating 60% of the nitrogen and 69% of phosphorus loads of the Avon Basin. This is not unexpected as 54% of the Avon Basin is occupied by this land use. Mixed grazing was the next largest contributor, generating 29% of nitrogen loads and 21% of phosphorus loads. Mixed grazing occupies only 1.1% of the total basin area, indicating that it is an intensive source of nutrients. Mixed grazing is also exclusively located in the wettest areas of the basin.

Point sources of nutrients (WWTPs, septic tanks and intensive animal use) generated 4.6% of the nitrogen load and 6.1% of the phosphorus load of the whole basin. Of this, over half the nitrogen and two-thirds of the phosphorus load came from WWTPs with most of the remaining load from intensive animal uses (piggeries, abattoirs, feedlots and stockyards).

Nutrient loads from point sources contributed a large percentage of loads in some reporting catchments. In the Lower Avon catchment the nitrogen and phosphorus loads from the Northam WWTP were 13% and 14% of the total reporting catchment load respectively. Intensive animal use in the Brockman catchment made up 6.3% of the nitrogen load and 10% of the phosphorus load of the catchment.

Native vegetation contributed 3.1% of the nitrogen load and 1.1% of the phosphorus load of the whole basin. This was due to its large area (42% of the basin) and the fact that a considerable area of native vegetation is located in the wettest areas of the catchment.

The contributions of nutrient loads by land use varied in catchments from west to east across the basin. For instance, in the Wooroloo Brook catchment, 76% of the nitrogen load and 72% of the phosphorus load came from mixed grazing, with the remaining load made up by animal keeping and lifestyle blocks, while in the Lockhart catchment, nutrients came almost exclusively from wheat & sheep and point sources (Figure 5.20).

Table 5.9: Average annual nitrogen and phosphorus loads from land uses of the Avon Basin

Land use	**Area**		**Nitrogen**		**Phosphorus**	
	(km^2)	**(%)**	**(t/yr)**	**(%)**	**(t/yr)**	**(%)**
Native vegetation	50 099	42	7.2	3.1	0.06	1.1
Wheat & sheep	64 619	54	139	60	3.9	69
Animal keeping	47	0.04	2.2	1.0	0.06	1.1
Horticulture	3	0.003	0.22	0.09	0.04	0.74
Orchard	13	0.01	0.24	0.10	0.02	0.33
Industry & transport	1 238	1.0	0.19	0.08	0.01	0.23
Lifestyle blocks	90	0.08	3.1	1.4	0.03	0.51
Mixed grazing	1 261	1.1	67	29	1.2	21
Plantation	28	0.02	0.12	0.05	0.02	0.31
Recreation	16	0.01	0.18	0.08	0.001	0.02
Residential	22	0.02	0.27	0.12	0.01	0.16
WWTPs	-	-	6.0	2.6	0.23	4.0
Septic tank (towns)	-	-	0.22	0.09	0.001	0.01
Intensive animal use	-	-	4.5	2.0	0.12	2.1
Water	1 693	1.4	-	-	-	-
Total	**119 141**		**231**		**5.7**	

Note: the total nitrogen and phosphorus loads differ from the basin outlet due to attenuation at the Yenyening Lakes

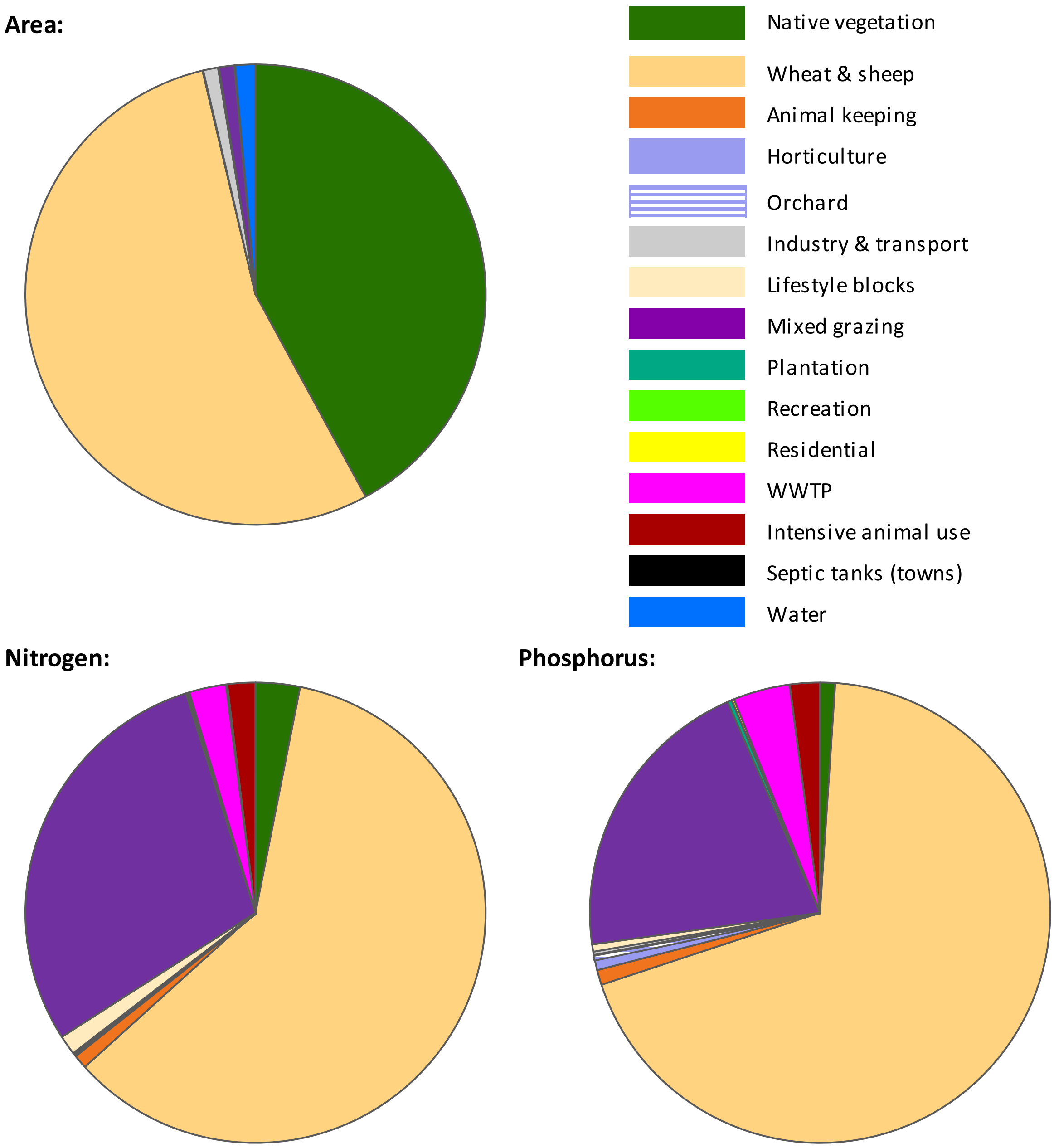


Figure 5.19: Land-use areas and average annual nitrogen and phosphorus loads for the Avon Basin

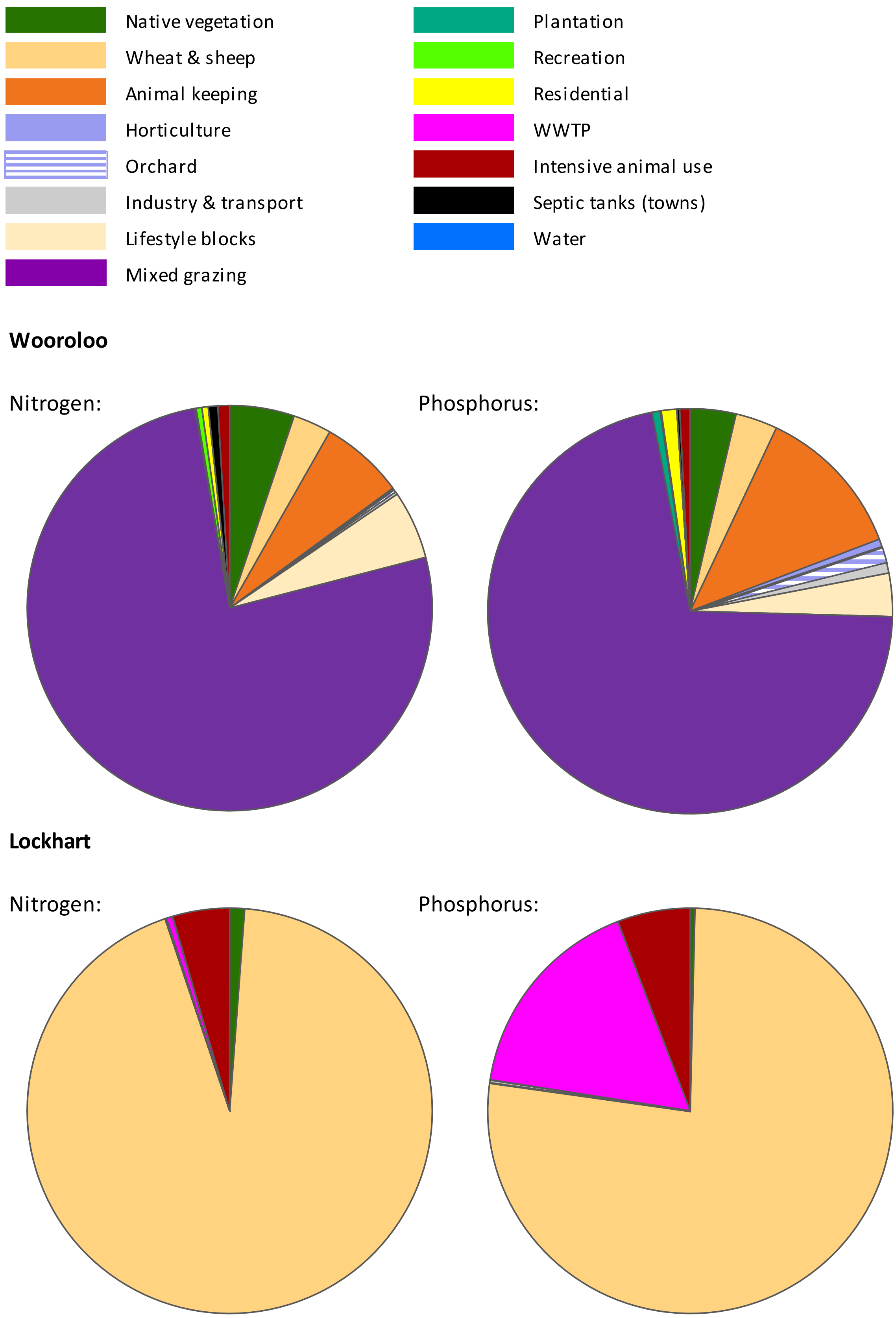


Figure 5.20: Land-use nitrogen and phosphorus loads from the Wooroloo and Lockhart catchments

6 Scenarios

Several scenarios were modelled to examine the effects of land-use change, point source management, changes to farm practice, riparian zone rehabilitation and climate change on flow and nitrogen and phosphorus loads (Table 6.1). The implementation details and results are discussed in the following sections with all scenario results for each reporting catchment given in Appendix F.

Table 6.1: Scenarios modelled

Scenario		Description
1. **Farm practice**		
	Soil acidity management	Farmers treat soil acidity by applying lime. This improves crop nutrient uptake and thus reduces the quantity of nutrients that can be leached. Proportion of farm area treated: - no action - 5% - 20% - 50% - 100%
	Farm nutrient management	Farmers treat soil acidity, manage soil nutrient stores and apply fertilisers to meet crop demand. This decreases the quantity of nutrients applied to the landscape, increases crop nutrient uptake and thus reduces the quantity of nutrients that can be leached. Proportion of farm area treated: - 5% - 20% - 50%
2. **Riparian zone rehabilitation**		Riparian zone rehabilitation within the Lower Avon, Middle Avon, Wooroloo, Brockman and Dale catchments at a rate of: - 10 km/year - 20 km/year - 40 km/year A scenario that rehabilitated all riparian zones in the Avon Basin was also included.
3. **Point sources**		
	Town sewage management	WWTPs that discharge treated wastewater into rivers and towns with septic tanks were modelled as wastewater re-use (recreation irrigation) and detention systems.
	Point source discharge removal	All point sources are assumed to cease to discharge to the environment
4. **Urban expansion**		Projected urban developments undertaken by 2031, from the: - Avon Arc Sub-Regional Strategy (2001) - Northam Regional Centre Growth Plan (2013)
5. **Revegetation**		All modelling subcatchments had their percentage of native vegetation increased by: - 5% - 10% - up to 30% Modelling subcatchments that had more than 30% native vegetation were not affected
5. **Climate change**		
	Dry	A1 emissions scenario and the Geophysical Fluid Dynamics Laboratory Coupled Climate Model 2.0.
	Wet	B2 emissions scenario and the Model for Interdisciplinary Research on Climate High Resolution.

6.1 Farm practice

6.1.1 Soil acidity management

Subsurface soil acidity is a major constraint to agricultural productivity. Soil pH values less than 4.8 generate toxic levels of soluble aluminium in most soil types of the Wheatbelt (Gazey & Davies 2009). Aluminium toxicity deforms root nodules and reduces plant root mass, which decreases the ability of plants to access soil moisture and nutrients (Gazey & Davies 2009). Farm nutrient-use efficiency (NUE) in the Wheatbelt is currently on average less than 50% (see Section 4.4) with high soil acidity likely to be a major contributing factor.

Andrew & Gazey (2010) studied soil acidity in the Avon Basin (not including Brockman, Wooroloo and Helena catchments or the Great Western Woodlands). They estimated that 78% of their study area had surface soils (0–10 cm) that were moderately-to-highly acidic (pH of 4.3–5.5). In addition, Andrew & Gazey's data showed that 80% of mid soils (10–20 cm) were also moderately-to-highly acidic. This high mid-soil acidity inhibits root penetration.

Causes of soil acidification include plant removal, the excessive use of ammonium-based fertilisers and animal waste though some soils are naturally acidic (Moore 2001). The treatment of soil acidity has traditionally been to add to the topsoil alkaline lime sands which can be incorporated into the soil profile (e.g. by spading and mouldboard ploughing). Lime application can protect against soil acidification over a number of years. Other treatment methods include in-furrow applications of alkaline products (usually liquids).

Plants have differing tolerances to soil acidity. For instance, lupins are very tolerant yet barley is very sensitive (Gazey & Davies 2009). DAFWA has conducted a number of trials testing the effect of liming on wheat, canola and barley crop yields. Local liming trials conducted near Kellerberrin have shown considerable improvements in yields of wheat (6–34%) and barley (57–217%; Gazey & Andrew 2013). However, generalised results from multiple studies (Gazey & Davies 2009) show more modest improvements to wheat (8–13%), barley (7–47%) and canola (12–15%) yields from lime application.

Scenario modelling implementation

Lime application was chosen as the notional method for treating soil acidity in this scenario, as there is a large body of evidence to support its use (summarised in Gazey and Davies 2009). A liming regime of an initial top-dress of 2.5 tonnes/ha to recover soil pH, with follow-up lime applications of 1 tonnes/ha every three years was assumed, which was based on the recommendations of Gazey & Davies (2009).

The effect of improved farm NUEs (by treating soil acidity) on reduced nitrogen and phosphorus leaching was modelled at four levels of adoption (5, 20, 50 and 100%) and compared with the base case (the 2001–10 nitrogen and phosphorus loads). The scenarios assumed the same hydrology and land use as in 2001–10. Adoption rates were assumed to be the same in each modelling subcatchment and were taken as a percentage of productive farm area. A further scenario that modelled the impact of no action – that is the likely impact of moderately acidic soils (pH > 4.9) acidifying, was also included.

A whole-of-farm yield response to liming (assuming all the productive area of the farm was treated) was calculated using crop area and yield statistics from the 2010–12 *Planfarm Bankwest Benchmarks* reports (Planfarm 2011; Planfarm 2012) and liming trial data for wheat, lupins, canola and barley (Gazey & Davies 2009). Table 6.2 shows the whole-of-farm crop yield response to liming, which improves total farm yields by 17% on average.

Figure 6.1 shows a map of farm soil acidity for modelling subcatchments. Because the land characteristics and model inputs (Section 4.4) are 'lumped' at the modelling subcatchment scale, the map shows the 'area-weighted average' of soil pH for each subcatchment and does not show the variability of pH across the landscape. Thus, all farm land in the Avon Basin is considered to be moderately or highly acidic; that is, to have subsurface pH of 4.9–5.6 or 4.3–4.9 respectively (Andrew & Gazey 2010).

Table 6.2: Calculated farm productivity benefits from liming all productive farm areas

	Base case			Liming	
Crop type	Area[1] (ha)	Proportion of farm[1] (%)	Yield[1] (t/ha)	Yield[3] (t/ha)	Yield improvement[2] (%)
Wheat	2183	65%	1.6	1.8	12%
Lupins	329	10%	0.8	0.8	0%
Barley	440	13%	1.8	2.7	47%
Canola	427	13%	0.7	0.8	12%
Total	3379	100%	-	-	**17%**

1. Statistics taken from the *Planfarm Bankwest Benchmarks reports* (2011 & 2012)
2. Yield improvement from soil acidity treatment taken from Gazey & Davies (2009)
3. Calculated yield after lime application using the yield improvement data from Gazey & Davies (2009)

In the scenario modelling, soil acidity treatment was assumed to be applied to a portion (5, 20, 50 or 100%) of the productive area of wheat & sheep, and mixed grazing farms in each subcatchment, and to produce 17% yield improvement in the areas treated in both moderately and highly acidic soils. Farmers were assumed to apply nutrients at the same rates as the base case (Section 4.4) but have lower surplus nutrients (due to improved productivity) and thus reduced nutrient leaching from the farm. The reduction in nutrient leaching was assumed to be linearly related to the reduction in surplus nutrients.

For the no-action scenario, highly-acidic areas were assumed to have similar productivity to the base case, while moderately acidic areas were assumed to become more acidic and have decreased crop yields. Yield losses of between 3–9% are expected to occur from acidification (Gazey pers. comm.). Thus, the no-action scenario assumed farm productivity loss of 5% due to acidification in areas with moderately acidic soils.

The farm productivity change (change in nutrient output) was altered according to the scenario and the surplus nutrients calculated by subtracting the nutrient output from the input for wheat & sheep and mixed grazing farms (Table 6.3). The whole-of-farm nitrogen surplus following soil acidity management decreased by 12% and 5% for wheat & sheep and mixed

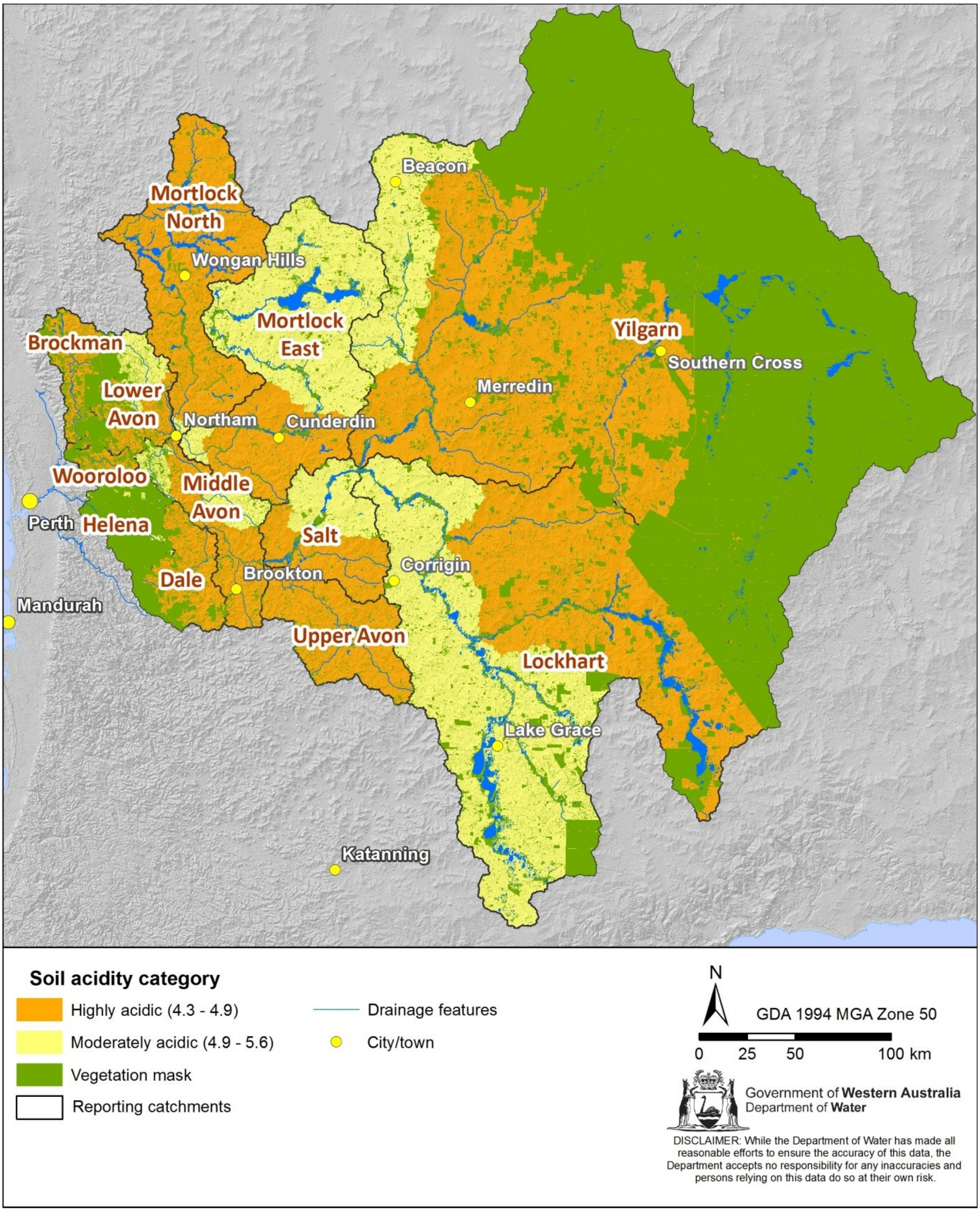


Figure 6.1: Subsurface soil acidity (depth 10–20 cm) by modelling subcatchments

grazing respectively, and phosphorus surplus decreased by 16% and 9% respectively. If soils were allowed to acidify (no action), the whole of farm nitrogen surplus would increase by 4% and 1% for wheat & sheep and mixed grazing respectively, and surplus phosphorus would increase by 5% and 3% respectively.

Table 6.3: Farm-gate nutrient budgets for wheat & sheep and mixed grazing for the base case, whole-of-farm soils acidity treatment (17% productivity increase) and no action in moderately-acidic areas (5% productivity decrease)

Scenario	Nitrogen				Phosphorus			
	Input (kg/ha/yr)	Output (kg/ha/yr)	Surplus (kg/ha/yr)	NUE (%)	Input (kg/ha/yr)	Output (kg/ha/yr)	Surplus (kg/ha/yr)	NUE (%)
Wheat & sheep								
Base case	60.7	25.0	35.7	41	7.7	3.7	4.0	48
Soil acidity management	60.7	29.3	31.4	48	7.7	4.3	3.3	56
% difference			-12	17			-16	17
Soil acidification	60.7	23.8	36.9	39	7.7	3.5	4.2	46
% difference			4	-5			5	-5
Mixed grazing								
Base case	79.6	18.2	61.4	23	7.8	2.8	5.0	36
Soil acidity management	79.6	21.3	58.3	27	7.8	3.2	4.5	42
% difference			-5	17			-9	17
Soil acidification	79.6	17.3	62.3	22	7.8	2.6	5.1	34
% difference			1	-5			3	-5

Note: Percentage difference compared to base case

Results

The average annual nitrogen and phosphorus loads following different adoption rates (5%, 20%, 50%, 100%) of acidity treatment are shown in Table 6.4, Table 6.5 and Figure 6.2. Reductions in nutrient loads at the basin outlet were less than 3% with an adoption rate below 20%. A 50% adoption rate reduced nitrogen and phosphorus loads at the basin outlet by 4.2% and 6.4% respectively. The 100% adoption scenario reduced nitrogen loads by 18 t/year (8.4%) and phosphorus loads by 0.7 t/year of (13%) at the basin outlet.

For the 100% adoption scenario, decreases in reporting catchment nutrient loads were generally 7–12% for nitrogen and 11–16% for phosphorus. The Wooroloo and Brockman catchments had smaller load reductions: nitrogen 4–5% and phosphorus 7–8%. This was due to the large area of mixed grazing within these catchments, which has a lower reduction of nutrient surplus following liming compared with wheat & sheep farming (Table 6.3).

The soil acidification scenario (no action) resulted in a 0.4% and 0.6% increase in nitrogen and phosphorus loads at the catchment outlet, as only a relatively small area of the catchment was affected by this scenario (yellow area in Figure 6.1). The catchments that were impacted the most were the Lockhart and Mortlock East catchments which had 1.7–2.4% more nitrogen and phosphorus as a result of soil acidification. These catchments had large areas of moderately acidic soils. Nutrient loads increased by approximately 1% in the Middle Avon and Salt catchments. The Yenyening Lakes outflow had a 1.3% increase in nutrient loads due to the acidification of the Salt and Lockhart reporting catchments.

Increases in loads from the remaining catchments were negligible as a majority of their soils are already highly acidic.

Table 6.4: Average annual reporting catchment nitrogen loads for the farm soil acidity scenarios. The percentage difference is the change in load with respect to the base case

Reporting catchment	Base case (t/yr)	No action (t/yr)	Diff (%)	5% (t/yr)	Diff (%)	20% (t/yr)	Diff (%)	50% (t/yr)	Diff (%)	100% (t/yr)	Diff (%)
Yilgarn	5.6	5.7	0.17	5.6	-0.58	5.5	-2.3	5.3	-5.8	5.0	-12
Lockhart	8.7	8.9	2.2	8.7	-0.56	8.5	-2.2	8.2	-5.6	7.8	-11
Salt	3.5	3.6	1.01	3.5	-0.59	3.5	-2.4	3.3	-5.9	3.1	-12
Yenyening Lakes inflow	18	18	1.3	18	-0.57	18	-2.3	17	-5.7	16	-11
Yenyening Lakes outflow	0.92	0.93	1.3	0.91	-0.57	0.90	-2.3	0.87	-5.7	0.81	-11
Upper Avon	22	22	-	22	-0.56	22	-2.3	21	-5.6	20	-11
Dale	41	41	-	41	-0.42	41	-1.7	40	-4.2	38	-8.3
Middle Avon	29	30	1.05	29	-0.46	29	-1.8	28	-4.6	27	-9.2
Mortlock East	18	18	1.7	18	-0.56	17	-2.2	17	-5.6	16	-11
Mortlock North	19	19	0.08	19	-0.58	19	-2.3	18	-5.8	17	-12
Brockman	24	24	-	24	-0.25	24	-1.00	24	-2.5	23	-5.0
Wooroloo	18	18	-	18	-0.21	18	-0.84	18	-2.1	18	-4.2
Lower Avon	40	40	0.78	40	-0.38	39	-1.5	39	-3.8	37	-7.6
Basin outlet	**213**	**214**	**0.45**	**212**	**-0.42**	**210**	**-1.7**	**204**	**-4.2**	**195**	**-8.4**

Table 6.5: Average annual phosphorus loads from the soil acidity management scenarios. The percentage difference is the change in load with respect to the base case

Reporting catchment	Base case (t/yr)	No action (t/yr)	Diff (%)	5% (t/yr)	Diff (%)	20% (t/yr)	Diff (%)	50% (t/yr)	Diff (%)	100% (t/yr)	Diff (%)
Yilgarn	0.16	0.16	0.18	0.16	-0.66	0.15	-2.6	0.15	-6.6	0.14	-13
Lockhart	0.15	0.15	2.4	0.15	-0.61	0.15	-2.4	0.14	-6.1	0.13	-12
Salt	0.07	0.07	1.16	0.07	-0.79	0.07	-3.1	0.06	-7.9	0.06	-16
Yenyening Lakes inflow	0.37	0.38	1.3	0.37	-0.66	0.36	-2.6	0.35	-6.6	0.32	-13
Yenyening Lakes outflow	0.02	0.02	1.3	0.02	-0.66	0.02	-2.6	0.02	-6.6	0.02	-13
Upper Avon	0.60	1.08	-	0.59	-0.75	0.58	-3.0	0.55	-7.5	0.51	-15
Dale	1.1	1.1	-	1.1	-0.64	1.1	-2.6	1.0	-6.4	0.9	-13
Middle Avon	0.35	0.35	1.35	0.35	-0.56	0.34	-2.3	0.33	-5.6	0.31	-11
Mortlock East	1.0	1.0	2.2	1.0	-0.71	1.0	-2.8	0.9	-7.1	0.9	-14
Mortlock North	1.0	1.0	0.11	1.0	-0.78	1.0	-3.1	0.9	-7.8	0.9	-16
Brockman	0.6	0.6	-	0.6	-0.39	0.6	-1.56	0.6	-3.9	0.6	-7.8
Wooroloo	0.26	0.26	-	0.25	-0.36	0.25	-1.46	0.25	-3.6	0.24	-7.3
Lower Avon	0.41	0.41	1.09	0.41	-0.54	0.40	-2.2	0.39	-5.4	0.36	-11
Basin outlet	**5.3**	**5.4**	**0.60**	**5.3**	**-0.64**	**5.2**	**-2.6**	**5.0**	**-6.4**	**4.7**	**-13**

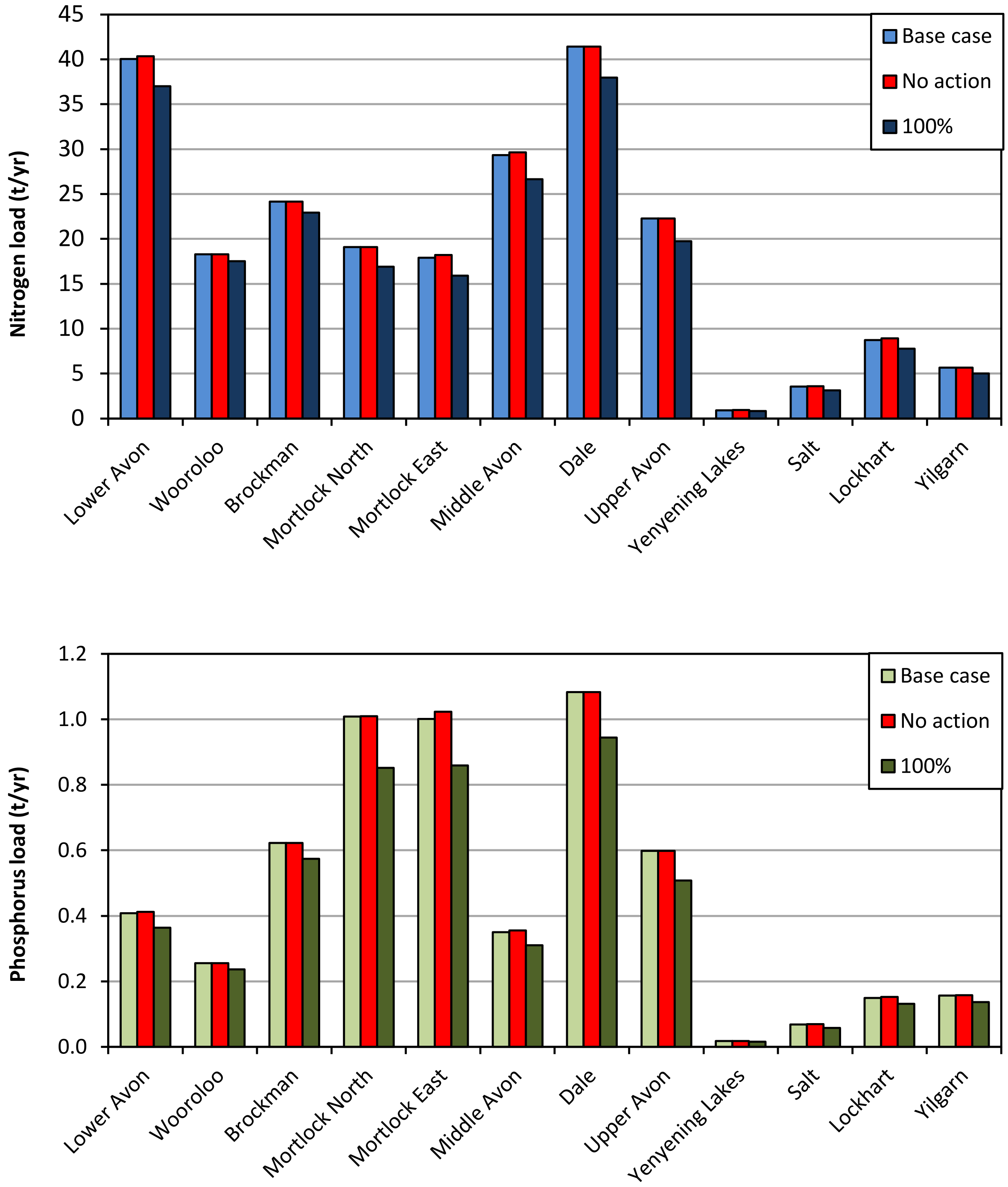


Figure 6.2: Annual average reporting catchment nitrogen (top) and phosphorus (bottom) loads for the base case, no soil acidity treatment and soil acidity treatment of 100% of farms

6.1.2 Farm nutrient management

The major cause of nutrient pollution in the Avon Basin is the inefficient use of farm nutrients. Farm nutrient-use inefficiencies are caused by:

- Drought
- Livestock (animal farming is inherently less nutrient efficient than cropping)
- Excessive nutrient applications relative to seasonal fertilisation requirement
- Soil acidity
- Poor timing of nutrient application and the loss of nutrients during intense weather events
- Poor soil structure
- Low soil biological activity.

Farm nutrient-use efficiency is highly dependent on seasonal rainfall. The examination of the *Planfarm* data revealed that nitrogen-use efficiencies varied from 36% in 2010, a drought year, to 56% in 2011, an average-to-above-average year for the Avon Wheatbelt (Planfarm 2011; 2012). Given the recent dry climate of 2001–10 and the prediction of an even dryer future climate, farm systems will need to better adapt to less and more variable growing-season rainfall. The conservative use of fertilisers and facilitating deeper plant roots will improve both farm nutrient-use efficiency and profitability during periods of drought.

Livestock also heavily affects farm nutrient-use efficiency, as only a small portion of nutrients are accumulated within livestock relative to the nutrient inputs to pastures (Ovens et al. 2008). Table 6.6 shows the nutrient inputs and outputs for an average wheat & sheep and mixed grazing farm. For wheat & sheep, pasture nitrogen and phosphorus inputs were 49% and 28% of total farm inputs respectively, yet pasture nitrogen and phosphorus outputs (wool and animals in Table 6.6) were less than 4% and 3% of total farm outputs. Thus the nutrient-use efficiency of farms with livestock will be inherently lower than those with small livestock numbers.

Soil testing measures soil physical and chemical properties, including soil nitrogen and phosphorus content. Regular soil tests allow farmers to tailor their fertilisation regime to allow for soil nutrient stores and crop requirements. Soil stores of both nitrogen and phosphorus are dynamic and can be built and utilised under particular conditions. Currently, 30–50% of Western Australian farmers test their soils (GRDC 2012) but it has been shown that soil phosphorus content still greatly exceeds crop needs (Weaver & Wong 2011). Additionally, soil nitrogen stores were thought to be underutilised due to the highly acidic soils which inhibit soil biological activity (Gupta et al. 2011) and occur across most of the Avon Basin (Andrew & Gazey 2010).

Table 6.6: Average annual nutrient inputs and outputs of an average wheat & sheep and mixed grazing farm (Planfarm 2011; Planfarm 2012)

	Wheat & sheep				Mixed grazing			
	Nitrogen		Phosphorus		Nitrogen		Phosphorus	
	(t/yr)	%	(t/yr)	%	(t/yr)	%	(t/yr)	%
Inputs								
Fertiliser (pasture)	-	-	9	28	-	-	10	50
Fertiliser (crop)	102	42	22	72	52	28	10	50
Fixation (pasture)	120	49	-	-	119	64	-	-
Fixation lupins (crop)	22	9	-	-	14	8	-	-
Feed (pasture)	0.1	0	0.01	0	1.4	1	0.1	0
Pasture subtotal	120	49	9	28	120	65	10	50
Crop subtotal	125	51	22	72	66	35	10	50
Total farm inputs	**244**	**100**	**31**	**100**	**186**	**100**	**19**	**100**
Outputs								
Wheat	63	61	9	63	22	52	3	48
Barley	17	16	2	16	8	19	1	16
Canola	10	10	2	15	7	16	1	20
Lupins	9	9	0.5	4	0.0	0	0.0	0
Wool (pasture)	2	2	0.0	0	3	7	0.0	0
Animals (pasture)	2	2	0.4	3	3	7	0.7	10
Pasture subtotal	4	4	0.4	3	6	14	0.7	10
Crop subtotal	98	96	14	97	37	86	6	84
Total farm outputs	**102**	**100**	**15**	**100**	**43**	**100**	**7**	**100**

Soil nitrogen stores are built through fertilisation, animal waste, crop residue (which contains carbon and nitrogen and is mineralised by soil microbes) and nitrogen fixation. Both nitrogen fixation and the nitrogen mineralisation of crop residues are dependent on healthy soil biology. However, soil biological activity is inhibited by soil acidity and moisture availability (Gupta et al. 2011). By neutralising acidic soils, retaining stubble, and adopting no-till farming practices, it has been demonstrated that soils can generate between 10–38 kg/ha/year of nitrogen for 2–10 years through soil biological processes, such as nitrogen mineralisation (Gupta et al. 2006). In the Western Australian Wheatbelt these practices were observed to liberate 10–15 kg/ha/year of nitrogen (Gupta et al. 2006).

Stores of phosphorus can be built progressively over years of fertiliser use. However, soil phosphorus is dynamic and moves from soluble (i.e. plant-available) to insoluble forms (Moody 2007). The relationship between crop yield and soil phosphorus (measured with the Colwell P test) is used to calculate the concentration of plant-available soil phosphorus required to sustain crop production (termed critical P). The critical P soil content is taken as the soil phosphorus content required to achieve a crop yield 90% of maximum crop yield[1]. The critical P was further refined for the soil phosphorus buffering capacities (phosphorus

[1] Maximum crop yield assumes no nutrient or water limitations

adsorbed per unit change in solution concentration) of local soils (Moody 2007; Anderson et al. 2013). For soils with a phosphorus content above critical P, phosphorus fertiliser application would produce a minimal increase in crop productivity. Thus, fertilisation is only recommended when the soil phosphorus content is/will be below the critical P value.

It was found that 87% of 106 000 soil samples in the south-west of Western Australia had phosphorus concentration in excess of critical P values (Weaver & Wong 2011). Clearly there is the potential for phosphorus stores to be utilised in these areas. The CSIRO is currently studying the relationship between soil phosphorus content and crop productivity. They have examined soils with phosphorus content above critical P to work out how many crops can be grown before the soil phosphorus content falls below critical P. Given the high soil phosphorus content of many areas of the Wheatbelt, it has been estimated that crops could be grown for two years with no inputs of phosphorus from fertilisers or losses to crop yield (Weaver *pers. comm.;* Wong *pers. comm.*).

Efficient farm nutrient-use has been successfully demonstrated by Stuart McAlpine (pers. comm.; Wong pers. comm.) whose property is near Buntine, Western Australia. Remediating soil acidity, soil testing and using excess soil nutrients, and encouraging soil biological processes (through addition of humates and other biological agents) have been employed on the McAlpine farm for more than five years. Wheat was sown on a paddock with twice the critical P values with 0.8 kg/ha phosphorus fertiliser, 1 kg/ha of nitrogen fertiliser and 282 mm of growing season rainfall. Wheat yields averaged 2.5 t/ha with a grain protein of 10.8%, yet fertiliser inputs were less than 10% of traditional farming.

Scenario modelling implementation

Although there is scope to utilise excessive nitrogen and phosphorus soil stores for two or more years in some locations, as discussed above, this was not included in this scenario, as this behaviour could not continue indefinitely. Instead, farmers were assumed to remediate soil acidity, have maximum nutrient-use efficiencies for 9 years, and be affected by drought in one year of every 10. That is, the following assumptions were made:

1. Farmers treat soil acidity over the entire farm and, as a result, farm outputs increase by 17% (Table 6.3).
2. The maximum nutrient-use efficiencies of wheat & sheep farms were taken as 60% for nitrogen and 80% for phosphorus (Weaver pers. comm.). The nutrient-use efficiencies for mixed grazing were estimated to be 30% for nitrogen and 60% for phosphorus. Assuming nutrient outputs are the same as in the soil acidity management scenario (that is, 17% greater than the base case), then for wheat & sheep and mixed grazing farms, nutrient inputs would be (Table 6.7):
    - Wheat & sheep farms: 49 kg/ha/year nitrogen and 5.4 kg/ha/year phosphorus
    - Mixed grazing farms: 71 kg/ha/year nitrogen and 5.4 kg/ha/year phosphorus.

   Farms were assumed to achieve these rates for nine years of the 10-year cycle by monitoring soil nutrient stores and applying to seasonal crop demand.
3. Farms were assumed to be adversely affected by drought in one year of every ten years. Nutrient outputs were assumed to be a third of the average in this year. This was done to

give a representation of the effect of drought on farm nutrient-use efficiency in the scenario modelling.

The resulting 10-year average farm nutrient budgets for wheat & sheep and mixed grazing are given in Table 6.7. The 10-year average NUEs are:

- Wheat & sheep farms: nitrogen: 56% and phosphorus 75%.
- Mixed grazing farms: nitrogen: 28% and phosphorus 56%.

This behaviour was modelled with 5, 20, 50 and 100% adoption rates, assuming the same hydrology and land use as in 2001–10. Adoption rates were assumed to be the same in each modelling subcatchment.

Table 6.7: Wheat & sheep and mixed grazing farm nutrient budgets for the farm management scenarios. The rates in this table assume that nutrients applied and removed are relative to the whole farm area.

	Nitrogen				Phosphorus			
Scenario	**Input (kg/ha/yr)**	**Output (kg/ha/yr)**	**Surplus (kg/ha/yr)**	**NUE (%)**	**Input (kg/ha/yr)**	**Output (kg/ha/yr)**	**Surplus (kg/ha/yr)**	**NUE (%)**
Wheat & sheep								
Base case	60.7	25.0	35.7	41	7.7	3.7	4.0	48
Soil acidity management								
Liming	60.7	29.3	31.4	48	7.7	4.3	3.3	56
% difference			-12	17			-16	17
No action	60.7	23.8	36.9	39	7.7	3.5	4.2	46
% difference			4	-5			5	-5
Farm nutrient management								
Efficient nutrient use	48.8	29.3	19.5	60	5.4	4.3	1.1	80
Drought year	48.8	9.8	39.0	20	5.4	1.4	4.0	27
10-year average	48.8	27.3	21.5	56	5.4	4.0	1.4	75
% difference			-40	36			-65	55
Mixed Grazing								
Base case	79.6	18.2	61.4	23	7.8	2.8	5.0	36
Soil acidity management								
Liming	79.6	21.3	58.3	27	7.8	3.2	4.5	42
% difference			-5	17			-9	17
No action	79.6	17.3	62.3	22	7.8	2.6	5.1	34
% difference			1	-5			3	-5
Farm nutrient management								
Efficient nutrient use	70.9	21.3	49.7	30	5.4	3.2	2.2	60
Drought year	70.9	7.1	63.8	10	5.4	1.1	4.3	20
10-year average	70.9	19.9	51.1	28	5.4	3.0	2.4	56
% difference			-17	22			-52	57

Results

The average annual nitrogen and phosphorus loads following farm nutrient management at different rates of adoption are shown in Table 6.8, Table 6.9 and Figure 6.3. Nitrogen loads at the basin outlet decreased by 1.4, 5.6, 14 and 28% for the 5, 20, 50 and 100% adoption scenarios respectively, and phosphorus loads decreased by 2.8, 11, 28 and 56% respectively.

Nitrogen percentage load reductions were greatest in the Yilgarn, Lockhart, Salt, Upper Avon, Mortlock East and Mortlock North reporting catchments. For example, these catchments had nitrogen load reductions of approximately 19% for the 50% adoption scenario. These reporting catchments have large areas of wheat & sheep farming which have greater relative improvements in NUE than mixed grazing in this scenario. The Brockman and Wooroloo reporting catchments had the largest proportion of mixed grazing farming, and had the lowest nitrogen reductions in percentage terms (8% and 7% respectively for the 50% adoption scenario).

Phosphorus load reductions for the 50% adoption scenario were 24–32% in catchments without mixed grazing. The phosphorus percentage reductions varied more between these catchments than the nitrogen percentage reductions, due to the differences in soil types. The Salt and Mortlock North catchments had the largest phosphorus percentage load reductions (32%). This was because phosphorus loads from wheat & sheep made up 98% of the total load in these catchments whereas the Mortlock East had a lower percentage phosphorus reduction because phosphorus from wheat & sheep was 90% of the total catchment load. The lowest percentage phosphorus reductions for the 50% adoption scenario (20%) were for the Wooroloo and Brockman reporting catchments.

Table 6.8: Average annual nitrogen loads for the modelling catchments for the farm nutrient management scenarios

Reporting catchment	**Base case (t/yr)**	**5% (t/yr)**	**Diff (%)**	**20% (t/yr)**	**Diff (%)**	**50% (t/yr)**	**Diff (%)**	**100% (t/yr)**	**Diff (%)**
Yilgarn	5.6	5.5	-1.9	5.2	-7.7	4.6	-19	3.5	-39
Lockhart	8.7	8.6	-1.9	8.1	-7.5	7.1	-19	5.5	-37
Salt	3.5	3.5	-2.0	3.3	-7.9	2.8	-20	2.1	-39
Yenyening Lakes inflow	18	18	-1.9	17	-7.6	14	-19	11	-38
Yenyening Lakes outflow	0.92	0.90	-1.9	0.85	-7.6	0.74	-19	0.57	-38
Upper Avon	22	22	-1.9	21	-7.5	18	-19	14	-38
Dale	41	41	-1.4	39	-5.6	36	-14	30	-28
Middle Avon	29	29	-1.5	28	-6.2	25	-15	20	-31
Mortlock East	18	18	-1.9	17	-7.5	15	-19	11	-37
Mortlock North	19	19	-1.9	18	-7.7	15	-19	12	-39
Brockman	24	24	-0.8	23	-3.3	22	-8.4	20	-17
Wooroloo	18	18	-0.7	18	-2.8	17	-7.0	16	-14
Lower Avon	40	40	-1.3	38	-5.1	35	-13	30	-25
Basin outlet	**213**	**210**	**-1.4**	**201**	**-5.6**	**183**	**-14**	**153**	**-28**

Table 6.9: Average annual phosphorus loads for the modelling catchments for the farm nutrient management scenarios

Reporting catchment	Base case (t/yr)	5% (t/yr)	Diff (%)	20% (t/yr)	Diff (%)	50% (t/yr)	Diff (%)	100% (t/yr)	Diff (%)
Yilgarn	0.16	0.15	-2.8	0.14	-11	0.11	-27	0.07	-54
Lockhart	0.15	0.15	-2.5	0.13	-10	0.11	-25	0.07	-50
Salt	0.07	0.07	-3.2	0.06	-13	0.05	-32	0.02	-65
Yenyening Lakes inflow	0.37	0.36	-2.8	0.33	-11	0.27	-27	0.17	-55
Yenyening Lakes outflow	0.02	0.02	-2.8	0.02	-11	0.01	-27	0.01	-55
Upper Avon	0.60	0.58	-3.1	0.52	-12	0.41	-31	0.23	-62
Dale	1.1	1.1	-2.9	0.96	-12	0.76	-29	0.45	-59
Middle Avon	0.35	0.34	-2.5	0.32	-10	0.26	-25	0.18	-50
Mortlock East	1.0	1.0	-2.9	0.88	-12	0.71	-29	0.41	-59
Mortlock North	1.0	1.0	-3.2	0.88	-13	0.68	-32	0.36	-64
Brockman	0.62	0.61	-2.0	0.57	-8.0	0.50	-20	0.37	-40
Wooroloo	0.26	0.25	-2.0	0.24	-7.9	0.20	-20	0.15	-40
Lower Avon	0.41	0.40	-2.4	0.37	-10	0.31	-24	0.21	-48
Basin outlet	**5.3**	**5.2**	**-2.8**	**4.7**	**-11**	**3.9**	**-28**	**2.4**	**-56**

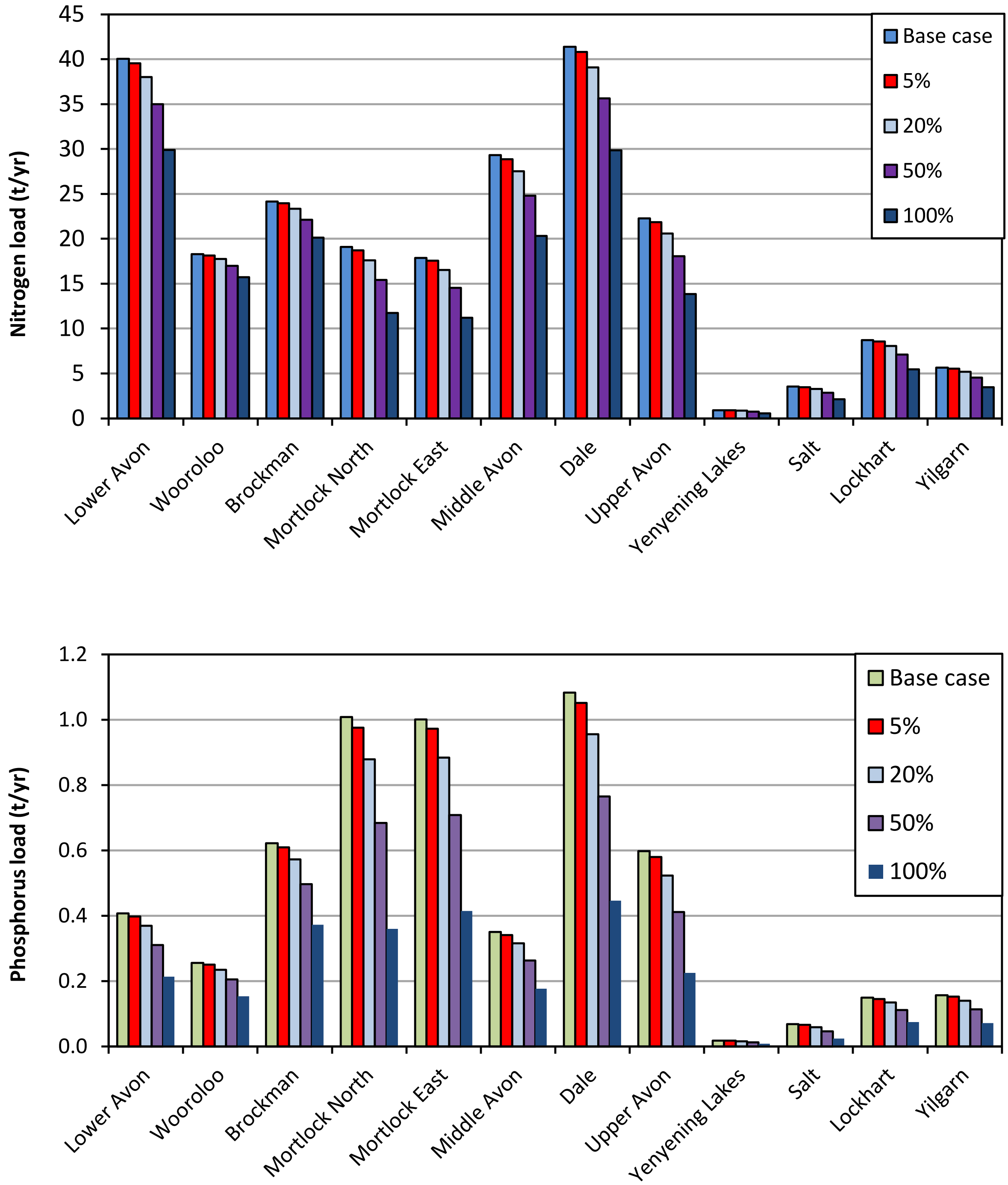


Figure 6.3: Average annual nitrogen (top) and phosphorus (bottom) reporting catchment loads for the farm nutrient management scenarios

6.2 Riparian zone rehabilitation

Healthy riparian zones have been shown to effectively remove nutrients and sediment and improve stream ecology in many locations in Australia and elsewhere (Gilliam 1994; Parkyn 2004). Vegetated riparian zones in agricultural landscapes can be considered to have four main functions:

- Reduction of bank erosion
- Interception of nutrients and sediment in surface and groundwater flows from adjacent paddocks to streams
- Restoration and/or maintenance of the stream ecosystem
- Provision of biodiversity corridors to link fragmented natural landscapes and provide refuge for terrestrial fauna.

Vegetated riparian zones reduce sediment and nutrient flows to steams by intercepting and slowing overland flows allowing sediment deposition, promoting denitrification in the soil zone and nutrient uptake by plants. Shading by riparian zone vegetation decreases water temperature (Rutherfurd et al. 2000) and reduces light availability for algal growth (Quinn et al. 1997; Roberts 2004). Near-stream vegetation provides food for native fauna and woody debris for stream habitat. The carbon inputs (leaf litter and wood) from intact riparian zones can also increase stream-bed denitrification (Parkyn 2004). Intact riparian zones of native vegetation provide wind protection.

It is difficult to define appropriate buffer widths and expected nutrient removal rates for riparian rehabilitation. There is little Western Australian and Australian literature that quantifies nutrient removal in buffer zones while there are many manuals and guidelines that promote them (Rutherfurd et al. 2000; DoW 2008). However, there are international studies which have examined and summarised published literature, such as Wenger (1999; Georgia USA), Mayer et al. (2005b; USA EPA) and Parkyn (2004; NZ). A discussion on riparian buffers and their removal efficiencies for TN, TP and TSS is given in Appendix G, with relevant published data given in Table 6.10.

Table 6.10: Reported riparian zone and grass buffer TN, TP and TSS removal rates

Study	Location	Buffer type	Width (m)	Reduction TN (%)	TP (%)	TSS (%)
Wenger 1999	Georgia, USA	Grass buffer	9.1	48–74	46–79	53–93
			16–68	78–99		
Mayer et al. 2005b	Literature review	Grass and forest buffer	3	50		
			28	75		
			112	90		
Palone & Todd 1997	Chesapeake Bay, USA	Native vegetation	10–50	68–90	27–70	65–95
Parkyn 2004	New Zealand	Native vegetation	4.6–27		53–98	
Fennessy & Cronk 1997		Forest	10		70	
McKergrow et al. 2006	Albany, Western Australia	Grass	10	50–60	50–60	50–60
		Eucalyptus globulus	10	10–40	10–40	10–40
McKergrow et al. 2003		Native vegetation	NA	23	0	93

Scenario modelling implementation

Rehabilitation widths of 15 m on low-order streams and 30 m on main rivers and large tributaries were assumed. Two levels of riparian zone rehabilitation (‘high’ and ‘low’) have been used to express the range of nutrient removal expected for differing rehabilitation practice (Table 6.11). ‘High’ riparian zone rehabilitation includes fencing, stock exclusion and dense re-vegetation. ‘Low’ rehabilitation includes fencing and less dense re-vegetation.

Table 6.11: Sediment and nutrient removal rates used for the riparian rehabilitation scenario

	Definition	TSS	TN	TP
High	fencing, stock exclusion and dense re-vegetation	90%	50%	30%
Low	fencing and less dense re-vegetation	70%	40%	15%

Stream locations and lengths were taken from the 250K Statewide linear hydrography data set (Geoscience Australia 2006) and intersected with the modelling land-use dataset. Streams in areas of ‘native vegetation’ were assumed to be vegetated and streams in areas without ‘native vegetation’ were assumed to be unvegetated. Lengths of vegetated and unvegetated streams were estimated for each reporting catchment (Table 6.12).

This scenario models four rates of adoption of riparian rehabilitation:

- 10 km/yr
- 20 km/yr
- 40 km/yr
- Rehabilitation of all riparian zones in the Avon Basin.

Table 6.12: Length of vegetated and unvegetated streams by reporting catchment

Reporting catchment	Total stream length (km)	Vegetated stream length (km)	(%)	Unvegetated stream length (km)	(%)
Lower Avon	968	495	51	473	49
Middle Avon	1538	391	25	1147	75
Upper Avon	1511	317	21	1194	79
Wooroloo	204	95	47	109	53
Brockman	575	258	45	317	55
Mortlock North	2397	487	20	1911	80
Mortlock East	3405	413	12	2992	88
Dale	911	417	46	494	54
Salt	1704	183	11	1521	89
Lockhart	9695	2367	24	7328	76
Yilgarn	6263	2305	37	3958	63
Helena	543	509	94	35	6
Total Avon	**29170**	**7727**	**26**	**21443**	**74**

To achieve the greatest possible reductions in nutrient loads from riparian zone rehabilitation, (for the 10, 20 and 40 km/yr scenarios) rehabilitation was undertaken only in the catchments with the greatest loads per cleared area: Wooroloo, Dale, Brockman, Lower Avon and Middle Avon. Revegetation was distributed evenly within these catchments over a period of 20 years. If a catchment's riparian zone was completely revegetated, the rehabilitation effort moved to another catchment.

Past rehabilitation programs within the Avon Basin had rehabilitation rates of 4.5–45.7 km/yr, depending on funding. Between 2002 and 2011, an average of 20 km/yr of stream was thought to have been rehabilitated (approximately 200 km total; Kelly pers. comm.). Given past practice, the 10 km/yr scenario represents a low rate of rehabilitation, 20 km/yr represents current rates, and 40 km/yr would represent a high rate of riparian zone rehabilitation which would require sustained funding.

It would be unreasonable to assume that a riparian zone could achieve the specified removal rates in the same year that it is rehabilitated. So riparian zone rehabilitation is only considered effective two years after its establishment. Therefore, the load reductions at year 20 will represent 18 years of effective riparian rehabilitation.

The 'entire basin' scenario assumes that all streams are rehabilitated in an unspecified timeframe. Given that there is an estimated 21 500 km of unvegetated stream within the basin, the rehabilitation of all streams within the Avon Basin, at a rate of 40 km/yr, would take 538 years. Clearly, the modelled rehabilitation rates are much lower than required. A rehabilitation rate of 300–400 km/yr would restore all streams within approximately 60 years.

Results

Average annual reporting catchment nitrogen and phosphorus loads are shown in Table 6.13, Table 6.14 and Figure 6.4. Loads at the basin outlet were reduced by 1.9–9.4% (4–20 t/yr) for nitrogen and 0.3–3.6% (< 0.1–0.2 t/yr) for phosphorus for the 10, 20 and 40 km/yr scenarios. The differences between 'low' and 'high' implementation were < 1.1% for 10 km/yr and 20 km/yr rehabilitation and 2% for the 40 km/yr scenario.

At the reporting-catchment scale, the percentage reduction of nutrient loads was greatest in the Wooroloo with a 34% reduction in nitrogen load and an 18% reduction in phosphorus loads for the 40 km/yr 'high' rehabilitation scenario. The Wooroloo's riparian zone was completely revegetated in this scenario. The Dale and Brockman catchments had the next highest percentage nutrient load reductions, with 13–15% less nitrogen and 6.8–7.8% less phosphorus respectively for the 40 km/yr 'high' rehabilitation scenario.

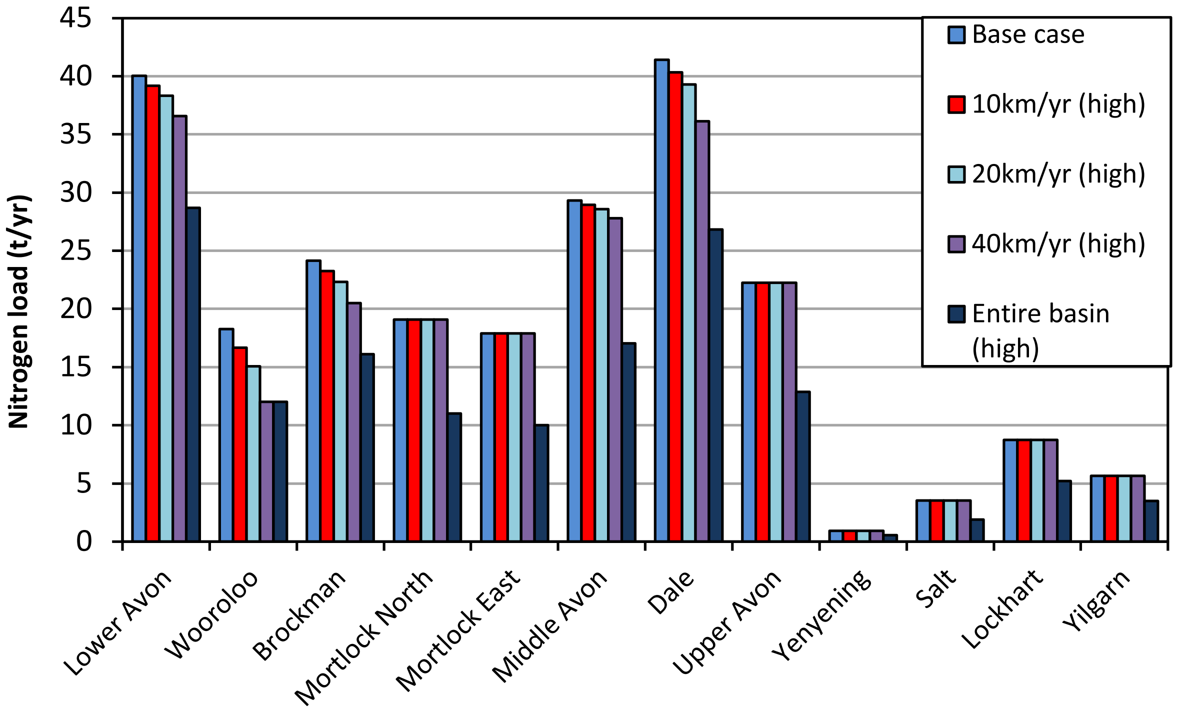
The 'high' rehabilitation of the entire basin scenario resulted in load reductions of 37% (78 t/yr) of nitrogen and 21% (1.1 t/yr) of phosphorus at the catchment outlet. There were also large local load reductions, with nitrogen loads reduced by 28–46% and phosphorus loads reduced by 15–27% in reporting catchments.

Table 6.13: Average annual reporting catchment nitrogen loads for the riparian zone rehabilitation scenarios

Scenario	Units	Yilgarn	Lockhart	Salt	Yenyening Lakes inflow	Yenyening Lakes outflow	Upper Avon	Dale	Middle Avon	Mortlock East	Mortlock North	Brockman	Wooroloo	Lower Avon	Basin outlet
Base case	(t/yr)	5.6	8.7	3.5	18	0.92	22	41	29	18	19	24	18	40	213
10km/yr (low)	(t/yr)	5.6	8.7	3.5	18	0.92	22	41	29	18	19	23	17	39	209
Difference	(%)	-	-	-	-	-	-	-1.9	-1.0	-	-	-5.0	-6.6	-1.6	-1.9
10km/yr (high)	(t/yr)	5.6	8.7	3.5	18	0.92	22	40	29	18	19	23	17	39	209
Difference	(%)	-	-	-	-	-	-	-2.6	-1.3	-	-	-3.8	-8.8	-2.1	-2.2
20km/yr (low)	(t/yr)	5.6	8.7	3.5	18	0.92	22	40	29	18	19	23	16	39	206
Difference	(%)	-	-	-	-	-	-	-3.9	-2.0	-	-	-5.7	-13	-3.2	-3.4
20km/yr (high)	(t/yr)	5.6	8.7	3.5	18	0.92	22	39	29	18	19	22	15	38	204
Difference	(%)	-	-	-	-	-	-	-5.1	-2.6	-	-	-7.6	-18	-4.3	-4.5
40km/yr (low)	(t/yr)	5.6	8.7	3.5	18	0.92	22	37	28	18	19	21	14	37	198
Difference	(%)	-	-	-	-	-	-	-9.6	-4.1	-	-	-11	-26	-6.5	-7.1
40km/yr (high)	(t/yr)	5.6	8.7	3.5	18	0.92	22	36	28	18	19	20	12	37	193
Difference	(%)	-	-	-	-	-	-	-13	-5.3	-	-	-15	-34	-8.6	-9.4
Entire basin (low)	(t/yr)	4.0	6.0	2.3	12	0.63	15	30	20	12	13	18	14	32	153
Difference	(%)	-29	-31	-36	-32	-32	-33	-27	-33	-35	-34	-25	-26	-21	-28
Entire basin (high)	(t/yr)	3.5	5.2	1.9	11	0.54	13	27	17	10	11	16	12	29	135
Difference	(%)	-38	-40	-46	-41	-41	-42	-35	-42	-44	-42	-33	-34	-28	-37

Table 6.14: Average annual reporting catchment phosphorus loads from the riparian zone rehabilitation scenarios

Scenario	Units	Yilgarn	Lockhart	Salt	Yenyening Lakes inflow	Yenyening Lakes outflow	Upper Avon	Dale	Middle Avon	Mortlock East	Mortlock North	Brockman	Wooroloo	Lower Avon	Basin outlet
Base case	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.1	0.35	1.0	1.0	0.62	0.26	0.41	5.3
10km/yr (low)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.1	0.35	1.0	1.0	0.62	0.25	0.41	5.3
Difference	(%)	-	-	-	-	-	-	-0.6	-0.3	-	-	-0.9	-2.2	-0.5	-0.3
10km/yr (high)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.07	0.35	1.0	1.0	0.61	0.24	0.40	5.3
Difference	(%)	-	-	-	-	-	-	-1.4	-0.6	-	-	-1.9	-4.7	-1.1	-0.8
20km/yr (low)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.07	0.35	1.0	1.0	0.61	0.24	0.40	5.3
Difference	(%)	-	-	-	-	-	-	-1.3	-0.6	-	-	-1.8	-4.4	-1.0	-0.7
20km/yr (high)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.05	0.35	1.0	1.0	0.60	0.23	0.40	5.3
Difference	(%)	-	-	-	-	-	-	-2.7	-1.3	-	-	-3.9	-9.5	-2.2	-1.7
40km/yr (low)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.05	0.35	1.0	1.0	0.60	0.23	0.40	5.3
Difference	(%)	-	-	-	-	-	-	-3.2	-1.2	-	-	-3.6	-8.5	-2.0	-1.6
40km/yr (high)	(t/yr)	0.16	0.15	0.07	0.37	0.02	0.60	1.01	0.34	1.0	1.0	0.57	0.21	0.39	5.2
Difference	(%)	-	-	-	-	-	-	-6.8	-2.5	-	-	-7.8	-18	-4.5	-3.6
Entire basin (low)	(t/yr)	0.14	0.14	0.06	0.34	0.02	0.53	0.99	0.32	0.88	0.89	0.57	0.23	0.38	4.8
Difference	(%)	-8	-9	-13	-9	-9	-12	-9	-10	-12	-12	-7.9	-8.5	-6.7	-10
Entire basin (high)	(t/yr)	0.13	0.12	0.05	0.30	0.01	0.45	0.88	0.28	0.76	0.76	0.52	0.21	0.35	4.2
Difference	(%)	-18	-18	-27	-20	-20	-24	-19	-20	-25	-25	-17	-18	-15	-21



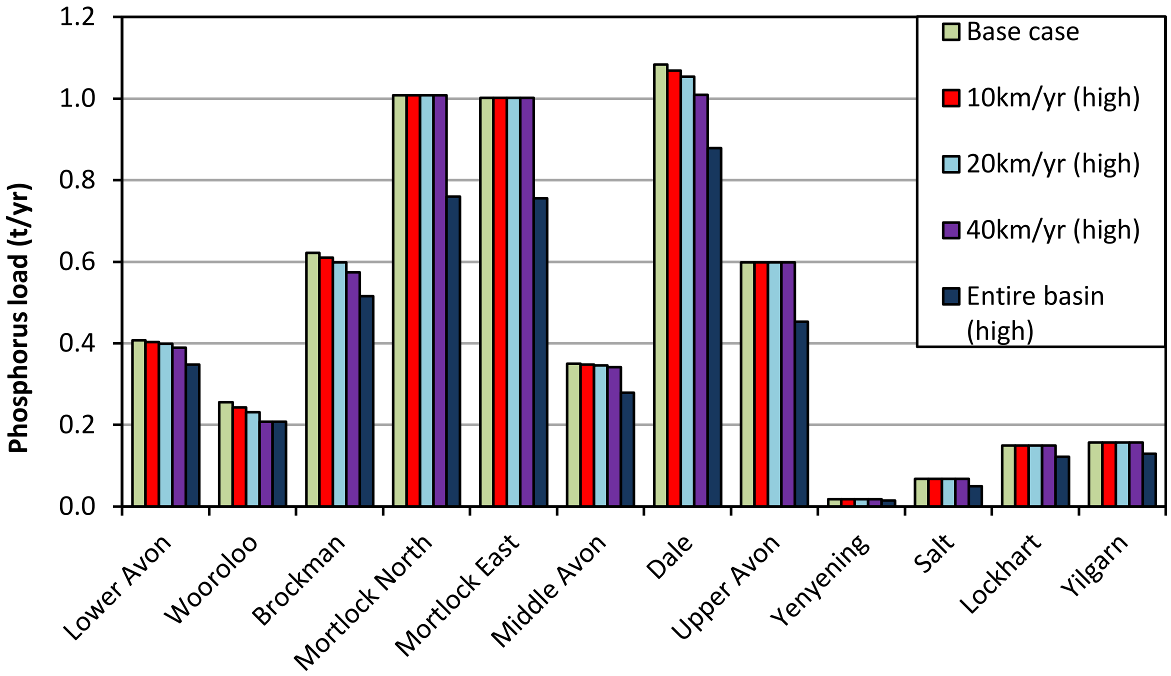


Figure 6.4: Average annual nitrogen (top) and phosphorus (bottom) loads from the riparian zone management scenario

6.3 Point sources

6.3.1 Town sewage management

Background

Wastewater disposal is particularly challenging for inland towns as there is a limited suite of methods for disposing of treated wastewater. Coastal cities and towns typically discharge treated wastewater to the ocean whereas some inland towns have historically discharged into rivers. This practice still continues in some locations as the costs to detain, reuse or treat wastewater are considered too high. However, most towns have wastewater reuse and detention systems to minimise impacts on local waterways and decrease potable water usage.

Of the 30 major towns in the Avon catchment, 27 were identified as having deep-sewerage systems. Of these, five towns discharge treated wastewater into nearby rivers, with the remaining towns detaining and/or reusing all surplus wastewater for irrigation on public open space. WWTPs that discharge directly into rivers are:

- Northam (Lower Avon catchment)
- Cunderdin (Mortlock East catchment)
- Meckering (Mortlock East catchment)
- Lake Grace (Lockhart catchment)
- Brookton (Middle Avon catchment).

The Northam WWTP is the largest within the Avon Basin and services a population of approximately 7000 people. Given its size, an additional treatment measure is implemented to reduce its effects on the environment. The Northam WWTP, the only WWTP in the Avon Basin to do so, uses alum to remove phosphorus from its wastewater prior to discharge. Approximately half of Northam's treated wastewater is used for irrigation, mostly during summer.

Three towns do not have deep-sewerage systems and rely on septic tanks and alternative treatment units to treat their wastewater:

- Bakers Hill (Middle Avon catchment)
- Bruce Rock (Lockhart catchment)
- Chidlow (Wooroloo catchment).

Scenario modelling implementation

WWTPs that discharge wastewater into waterways, and towns with septic tanks were modelled as reuse/detention systems. All WWTPs and towns with septic tanks were assumed to cease discharge by detaining and reusing wastewater for irrigating public open space. Recreational areas used for wastewater disposal were assumed to irrigate at the maximum allowable rates for wastewater irrigation: 480 kg/ha/yr nitrogen and 120 kg/ha/yr phosphorus (DoW 2006).

These rates were then converted into power function parameters (Appendix E) to model nutrient loads from recreational areas irrigated with wastewater. These areas are shown in Table 6.15.

Table 6.15: Recreational areas irrigated with wastewater in the town sewage management scenario

Reporting catchment	**Total recreation area**	**Area of recreation modelled**	
	(ha)	**(ha)**	**(%)**
Lower Avon	64	8	**13**
Wooroloo	94	4	**4**
Middle Avon	174	43	**25**
Mortlock East	182	93	**51**
Lockhart	395	170	**43**
Total	**909**	**318**	**35**

Results

The average annual nutrient loads after town sewage management are shown in Table 6.16 and Figure 6.5. Loads at the basin outlet decreased by 2.8% (6.0 t/yr) for nitrogen and 3.7% (0.20 t/yr) for phosphorus. Most of the nitrogen load reduction (5.3 t/yr) was from the Northam WWTP whereas the reductions in phosphorus loads were split between the Cunderdin and Meckering (0.08 t/yr), Northam (0.06 t/yr) and Brookton (0.05 t/yr) WWTPs.

The Lower Avon catchment had 13% and 14% less nitrogen and phosphorus respectively than the base case (Table 6.16). Nitrogen percentage load reductions were less than 2% for all other reporting catchments. The Lockhart (Lake Grace WWTP) and Middle Avon (Brookton WWTP) catchments had the largest percentage reductions in phosphorus, with 20% and 15% less load respectively. Phosphorus loads from the Mortlock East catchment were reduced by 8.1%. The Wooroloo Catchment had one town (Chidlow) that relied on septic tanks to treat its wastewater. The modelling predicted a negligible reduction in nutrient loads following septic tank removal from Chidlow.

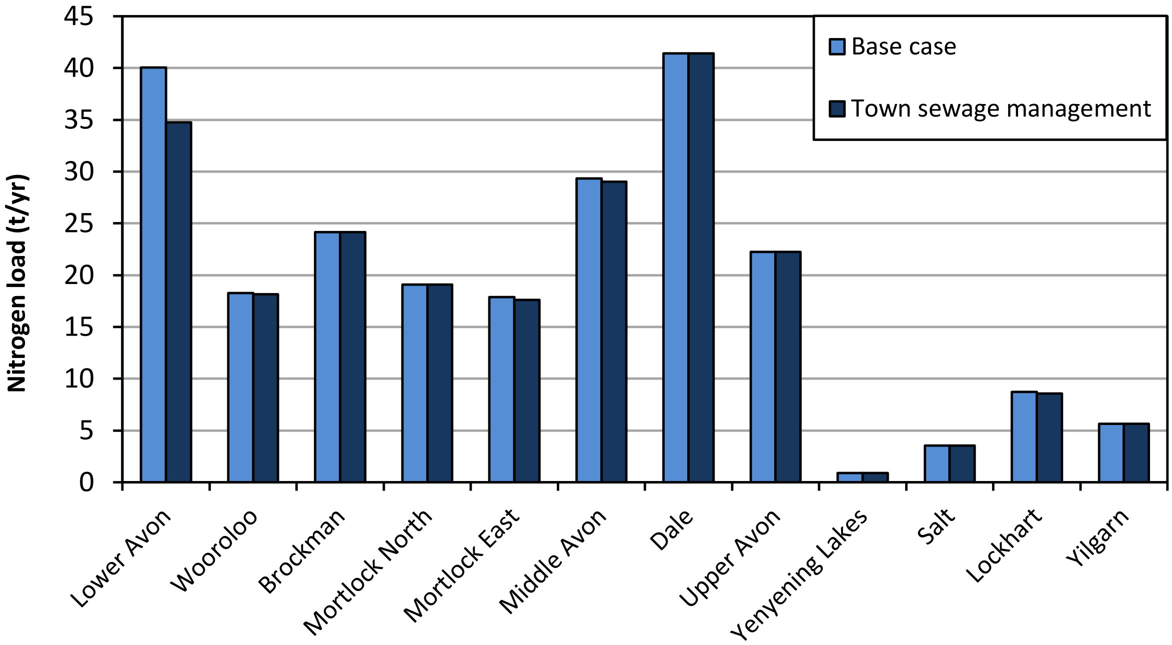
Table 6.17 shows nutrient loads from recreational areas irrigated with wastewater. An additional 0.13 t/yr of nitrogen and a negligible amount of phosphorus was generated by irrigating recreational areas with wastewater.

Table 6.16: Average annual nutrient loads from town sewage management

Reporting catchment	Nitrogen				Phosphorus			
	Base case	Town sewage management	Difference		Base case	Town sewage management	Difference	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(t/yr)	(%)
Yilgarn	5.6	5.6	0.00	0.0	0.16	0.16	0.00	0.0
Lockhart	8.7	8.6	-0.13	-1.5	0.15	0.12	-0.03	-20
Salt	3.5	3.5	-	-	0.07	0.07	-	-
Yenyening Lakes inflow	18	18	-0.13	-0.7	0.37	0.34	-0.03	-7.9
Yenyening Lakes outflow	0.92	0.91	-0.01	-0.7	0.02	0.02	0.00	-7.9
Upper Avon	22	22	-	-	0.60	0.60	-	-
Dale	41	41	-	-	1.1	1.1	-	-
Middle Avon	29	29	-0.32	-1.1	0.35	0.30	-0.05	-15
Mortlock East	18	18	-0.26	-1.5	1.0	0.9	-0.08	-8.1
Mortlock North	19	19	-	-	1.0	1.0	-	-
Brockman	24	24	-	-	0.62	0.62	-	-
Wooroloo	18	18	-0.12	-0.7	0.26	0.26	0.00	0.0
Lower Avon	40	35	-5.3	-13	0.41	0.35	-0.06	-14
Basin outlet	**213**	**207**	**-6.0**	**-2.8**	**5.3**	**5.1**	**-0.20**	**-3.7**

Table 6.17: Average annual nitrogen and phosphorus loads from recreational areas before and after town sewage management and its percentage contribution to the total load of reporting catchments and the Avon Basin

Reporting catchment	Nitrogen				Phosphorus			
	Base case		Town sewage management		Base case		Town sewage management	
	Recreation	Percentage of total load	Recreation	Percentage of total load	Recreation	Percentage of total load	Recreation	Percentage of total load
	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)	(t/yr)	(%)
Yilgarn	0.00	0.03	-	-	0.000	0.00	-	-
Lockhart	0.00	0.02	0.00	0.05	0.000	0.00	0.000	0.07
Salt	0.00	0.01	-	-	0.000	0.00	-	-
Yenyening Lakes inflow	0.00	0.02	0.01	0.07	0.000	0.00	0.000	0.08
Yenyening Lakes outflow	0.00	0.03	0.00	0.07	0.000	0.00	0.000	0.08
Upper Avon	0.01	0.05	0.01	0.05	0.000	0.01	0.000	0.01
Dale	-	-	-	-	-	-	-	-
Middle Avon	0.04	0.12	0.12	0.42	0.000	0.03	0.002	0.79
Mortlock East	0.01	0.04	0.03	0.19	0.000	0.02	0.004	0.43
Mortlock North	0.01	0.07	-	-	0.000	0.03	-	-
Brockman	0.02	0.06	-	-	0.000	0.02	-	-
Wooroloo	0.08	0.45	0.09	0.52	0.000	0.09	0.001	0.29
Lower Avon	0.01	0.03	0.02	0.05	0.000	0.01	0.000	0.04
Basin outlet	**0.18**	**0.08**	**0.31**	**0.15**	**0.001**	**0.02**	**0.008**	**0.15**



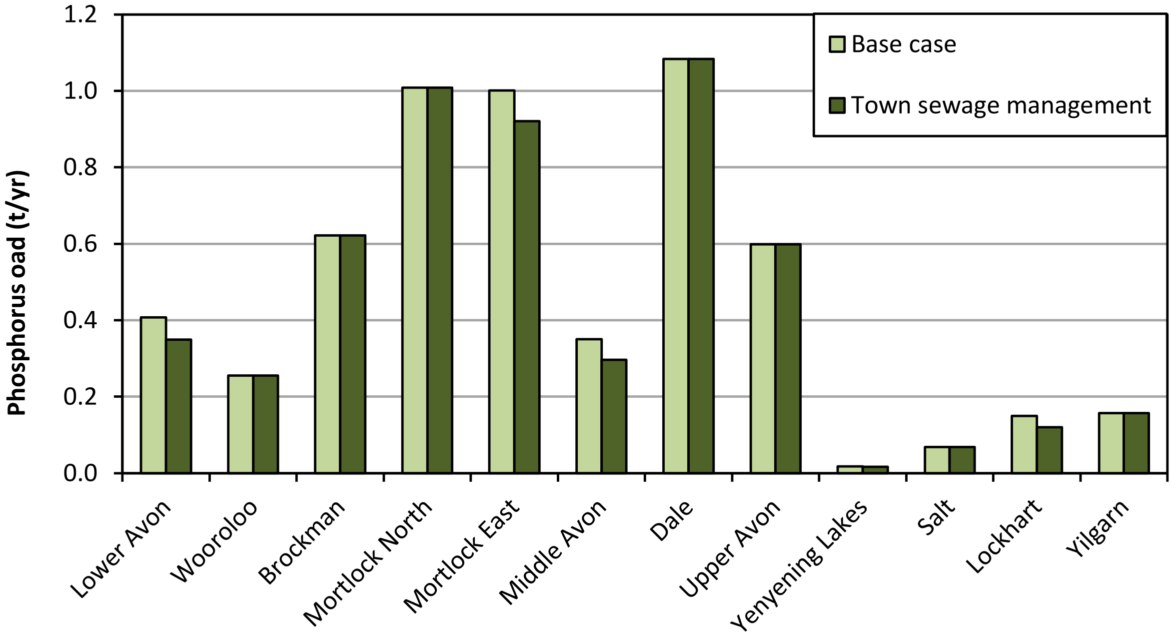


Figure 6.5: Annual average nitrogen (top) and phosphorus (bottom) loads from the base case and town sewage management scenario

6.3.2 Point source discharge removal

Forty-two point sources (abattoirs, feedlots, stockyards, piggeries, towns with septic tanks and WWTPs) have been included in the modelling as discussed in Section 2.6. These point sources together contribute 11 t of nitrogen and 0.42 t of phosphorus to waterways (Table 6.18). In this scenario all point sources were assumed to have ended discharge to land and rivers. For towns with septic tanks and WWTPs the effluent was not used to irrigate recreational areas, as in the previous scenario, but was assumed to be removed from the catchment completely.

Table 6.18: Average annual loads of nitrogen and phosphorus from point sources in the Avon Basin

Point source type	Number of point sources	Load that reaches the waterways Nitrogen (tonnes)	Phosphorus (tonnes)
Abattoir	5	0.2	0.003
Feedlot	12	2.3	0.05
Septic tanks (towns)	3	0.2	0.003
Stockyard	5	0.1	0.002
Piggery	12	1.6	0.06
Lake Grace WWTP	1	0.02	0.01
Brookton WWTP	1	0.4	0.15
Meckering WWTP	1	0.04	0.01
Cunderdin WWTP	1	0.3	0.08
Northam WWTP	1	5.6	0.06
All WWTPs	5	6.3	0.31
All point sources	**42**	**10.80**	**0.42**

Results

The average annual nutrient loads for the point source discharge removal scenario are given in Table 6.19 and Figure 6.6. Nutrient loads at the basin outlet were reduced by 4.8% (10 t/yr) and 5.8% (0.31 t/yr) for nitrogen and phosphorus respectively (these amounts are less than the total contributions from point sources due to nutrient losses in the Yenyening Lakes). The largest nitrogen load reductions were in the Lower Avon (5.4 t/yr), Brockman (1.5 t/yr) and Upper Avon (1.0 t/yr) reporting catchments although, in percentage terms, nitrogen reductions in the Lower Avon catchment were 13%, with 1.3–6.3% reductions in all other catchments.

The largest phosphorus load reductions were in the Mortlock East (0.09 t/yr), Lower Avon (0.06 t/yr), Brockman (0.06 t/yr) and Middle Avon (0.06 t/yr) catchments. However, the largest reduction in phosphorus (in percentage terms) was in the Lockhart reporting catchment, which had 22% less phosphorus load. All other reporting catchments had nutrient reductions of 0.5–15%.

Table 6.19: Annual average loads from point source discharge removal

Reporting catchment	Nitrogen				Phosphorus			
	Base case	Point source removal	Difference		Base case	Point source removal	Difference	
	(t/yr)	(t/yr)	(t/yr)	(%)	(t/yr)	(t/yr)	(t/yr)	(%)
Yilgarn	5.6	5.6	-0.07	-1.3	0.16	0.16	-0.001	-0.49
Lockhart	8.7	8.3	-0.39	-4.5	0.15	0.12	-0.03	-22
Salt	3.5	3.5	-	-	0.07	0.07	-	-
Yenyening Lakes inflow	18	17	-0.46	-2.6	0.37	0.34	-0.03	-9.0
Yenyening Lakes outflow	0.92	0.89	-0.02	-2.6	0.02	0.02	-0.002	-9.0
Upper Avon	22	21	-1.0	-4.6	0.60	0.57	-0.03	-4.4
Dale	41	41	-	-	1.1	1.1	-	-
Middle Avon	29	29	-0.51	-1.7	0.35	0.29	-0.06	-16
Mortlock East	18	17	-0.96	-5.4	1.0	0.9	-0.09	-9.3
Mortlock North	19	19	-0.42	-2.2	1.0	1.0	-0.01	-0.55
Brockman	24	23	-1.5	-6.3	0.62	0.56	-0.06	-10
Wooroloo	18	18	-0.31	-1.7	0.26	0.25	-0.003	-1.1
Lower Avon	40	35	-5.4	-13	0.41	0.35	-0.06	-15
Basin outlet	**213**	**203**	**-10**	**-4.8**	**5.3**	**5.0**	**-0.31**	**-5.8**

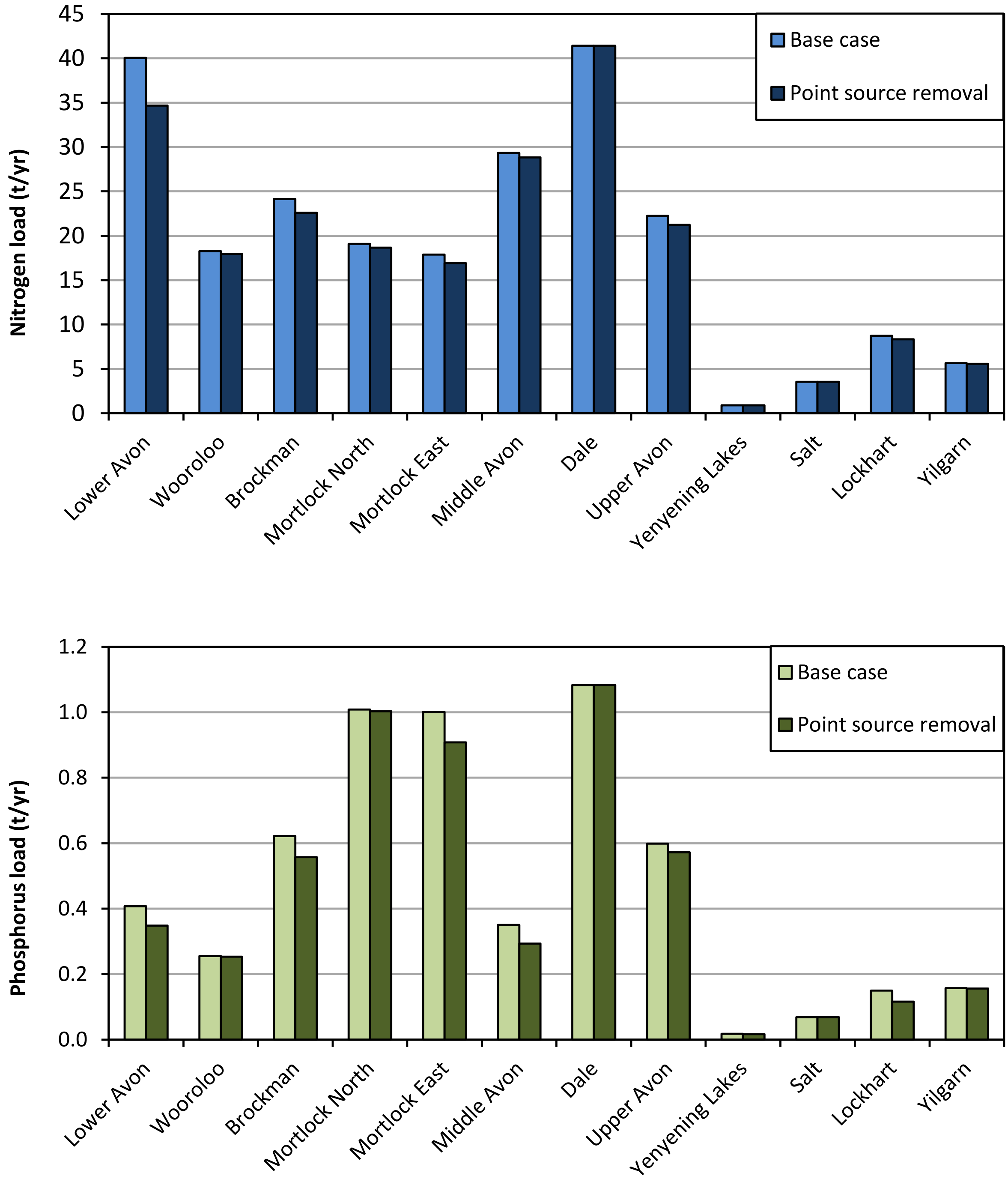


Figure 6.6: Average annual nitrogen (top) and phosphorus (bottom) loads from point source discharge removal

6.4 Urban expansion

The impacts of urban expansion were modelled using the Avon Arc Sub-Regional Strategy (WAPC 2001) and the Northam Regional Centre Growth Plan (Department of Regional Development and Lands 2013).

Avon Arc Sub-Regional Strategy

The Avon Arc Sub-Regional Strategy (referred to as the Sub-Regional Strategy) details a framework for land-use planning for 2001–26. The strategy includes the Lower Avon, Middle Avon, Wooroloo, Brockman and small areas of the Mortlock North and East reporting catchments. An annual population growth of approximately 2% was assumed. This equates to a regional growth from 26 600 people in 2001 to 43 400 people in 2026. The Sub-Regional Strategy includes land-use planning maps for the following towns:

- Northam
- Toodyay
- York
- Beverley
- Brookton
- Wundowie
- Bakers Hill
- Bindoon.

Industrial, residential, and urban areas were included in the mapping but housing densities, roads and areas of public open space areas were not specified.

Northam Regional Centre Growth Plan

The Northam Regional Centre Growth Plan (referred to as the Growth Plan) details plans to develop Northam as a major regional centre for housing, employment and the supply of services to the Wheatbelt region (Department of Regional Development and Lands 2013). The plan extends from 2010–31 and supersedes the Sub-Regional Strategy for the town of Northam.

The Growth Plan accounts for a population growth of 5.2% per year. This equates to a population growth from 7000 people in 2010 to 20 000 in 2031. Land-use planning maps are provided in the Growth Plan, which detailed the locations of new residential and industrial areas, new schools and offices. New residential housing densities were mostly R5, with areas of R15 and R30. Areas of undeveloped lots and lots with a high-redevelopment potential were also highlighted for future development.

Scenario modelling implementation

The land-use planning maps from the Growth Plan were used to represent the changes in the town of Northam, with all other towns represented by the Sub-Regional Strategy. Land-use planning categories were aggregated into four modelling categories (Table 6.20). It was assumed that all new industrial and residential areas had 10% of their land area allocated to roads. Residential areas had another 10% of land area devoted to public open space. All residential areas, schools and offices were modelled as having lots with areas greater than 730 m^2 (Kelsey et al. 2010b). The imperviousness and LAI of the aggregated land-use categories were assumed the same as the base-case modelling; that is, it was assumed that the hydrology did not change.

Table 6.20: Land-use planning categories and modelling categories

Modelling land-use category	Land-use planning category	
Industry & transport	Roads	
	Industrial	†
Lifestyle blocks	R5	
Recreation	Public open space	
Residential	R15	*†
	R30	*†
	Urban/residential	*†
	Undeveloped lots	
	Lots with high redevelopment potential	
	Schools	

*10% of land area assumed to be public open space

†10% of land area assumed to be roads

The aggregated land-use categories were then modelled using the future land-use areas shown in Table 6.21. This scenario modelled the urban development in 2031 (that is when the development outlined in the Growth Plan and the Sub-regional Strategy will be fully developed) for a 10-year period assuming the same hydrology as 2001–10.

Northam and Brookton are the only towns within the strategy area that discharge WWTP effluent directly to the Avon River. The Brookton WWTP was modelled assuming the base-case WWTP nutrient loads, with recreational areas irrigated by the extra wastewater generated due to population growth.

The Northam WWTP currently discharges 51% of its treated effluent into the Avon River, with the remaining effluent used for irrigation. It was assumed that the percentage increase in WWTP effluent volume would be the same as the percentage increase in population growth (i.e. 286% increase from 2010 to 2031). It was also assumed that the Northam WWTP would continue to discharge 51% of its treated effluent to the Avon River, with the remaining effluent used for irrigation on recreational areas. These assumptions result in the average annual nitrogen loads discharged to the Avon River increasing from 5.3 to 15.1 t/yr and phosphorus load increasing from 0.06 to 0.17 t/yr.

It was assumed that all other towns within the strategy area detained and reused the additional wastewater generated through population growth. The assumptions related to WWTP effluent irrigation are the same as those stated in Section 6.3.1.

Table 6.21: Land-use areas for the base case and urban expansion scenario for the Avon Basin

Reporting catchment	Base case (km^2)	Urban expansion (km^2)	Difference (km^2)	(%)
Native vegetation	50 099	50 099	-	-
Wheat & sheep	64 619	64 591	-28	-0.04
Animal keeping	47	47	-	-
Horticulture	3.3	3.3	-	-
Orchards	13	13	-	-
Industry & transport	1 238	1 242	3.7	0.30
Lifestyle blocks	90	92	2.7	3.1
Mixed grazing	1 261	1 260	-0.34	-0.03
Plantation	28	28	-	-
Recreation	16	18	2.4	15
Residential	22	42	19	86
Intensive animal use	9.9	9.9	-	-
Point sources	2.0	2.0	-	-
Water	1 693	1 693	-	-
Total	**119 141**	**119 141**	**-**	**-**

Results

The average annual loads caused by urban expansion are shown in Table 6.22 and Figure 6.7. Loads at the catchment outlet increased by 5.1% (11 t/yr) for nitrogen and 3.0% (0.16 t/yr) for phosphorus as a result of urban expansion. The most heavily affected areas were those downstream of the Northam Weir (Lower Avon). This was a result of the increased discharge from the Northam WWTP, which made up 90% of the additional nutrient load caused by urban expansion (Table 6.23). The Lower Avon reporting catchment also became the largest source of nitrogen within the Avon Basin. Loads upstream of the Northam Weir (Middle Avon) rose by 1.8% (0.53 t/yr) for nitrogen and 4.0% (0.014 t/yr) for phosphorus. The greater percentage increase for phosphorus compared to nitrogen was a result of the higher loads from recreational areas irrigated with wastewater.

Table 6.23 shows the average annual nutrient loads by land use. Recreational areas had the greatest changes in load, with approximately seven times more nitrogen (1.0 t/yr) and 50 times more phosphorus (0.05 t/yr). Loads from residential areas increased by 2.3 times with 0.34 t/yr more nitrogen and 0.01 t/yr more phosphorus. Wheat & sheep and mixed grazing nutrient loads decreased by 0.1–0.2% for nitrogen and 0.1% for phosphorus.

Table 6.22: Average annual nutrient loads caused by urban expansion

Reporting catchment	Nitrogen Base case (t/yr)	Nitrogen Urban expansion (t/yr)	Nitrogen Difference (t/yr)	Nitrogen Difference (%)	Phosphorus Base case (t/yr)	Phosphorus Urban expansion (t/yr)	Phosphorus Difference (t/yr)	Phosphorus Difference (%)
Yilgarn	5.6	5.6	-	-	0.16	0.16	-	-
Lockhart	8.7	8.7	-	-	0.15	0.15	-	-
Salt	3.5	3.5	-	-	0.07	0.07	-	-
Yenyening Lakes inflow	18	18	-	-	0.37	0.37	-	-
Yenyening Lakes outflow	0.92	0.92	-	-	0.02	0.02	-	-
Upper Avon	22	22	-	-	0.60	0.60	-	-
Dale	41	41	-	-	1.1	1.1	-	-
Middle Avon	29	30	0.53	1.8	0.35	0.36	0.014	4.0
Mortlock East	18	18	0.05	0.30	1.0	1.0	0.008	0.77
Mortlock North	19	19	0.10	0.52	1.0	1.0	0.013	1.3
Brockman	24	24	0.00	-0.01	0.62	0.62	0.001	0.19
Wooroloo	18	19	0.26	1.4	0.26	0.27	0.013	5.1
Lower Avon	40	50	10	25	0.41	0.52	0.11	28
Basin outlet	**213**	**224**	**11**	**5.1**	**5.3**	**5.5**	**0.16**	**3.0**

Table 6.23: Land-use nutrient loads from urban expansion

Land use category	Nitrogen Base case (t/yr)	Nitrogen Future (t/yr)	Nitrogen Difference (t/yr)	Nitrogen Difference (%)	Phosphorus Base case (t/yr)	Phosphorus Future (t/yr)	Phosphorus Difference (t/yr)	Phosphorus Difference (%)
Wheat & sheep	139	138	-0.25	-0.18	3.9	3.9	-0.004	-0.09
Industry & transport	0.19	0.19	0.004	2.2	0.01	0.01	0.000	1.7
Lifestyle blocks	3.1	3.2	0.05	1.6	0.03	0.03	0.001	2.1
Mixed grazing	67.3	67.2	-0.09	-0.13	1.2	1.2	-0.001	-0.11
Recreation	0.18	1.2	1.0	548	0.001	0.05	0.05	4765
Residential	0.27	0.62	0.34	126	0.01	0.02	0.01	101
Point sources	10.6	20.5	9.8	92	0.37	0.48	0.11	30
WWTPs	6.0	15.8	9.8	164	0.25	0.36	0.11	44
Northam WWTP	5.3	15.1	9.8	186	0.06	0.17	0.11	186
Other WWTP's	0.71	0.71	-	-	0.19	0.19	-	-
Total	**230**	**241**	**11**	**4.7**	**5.7**	**5.9**	**0.16**	**2.8**

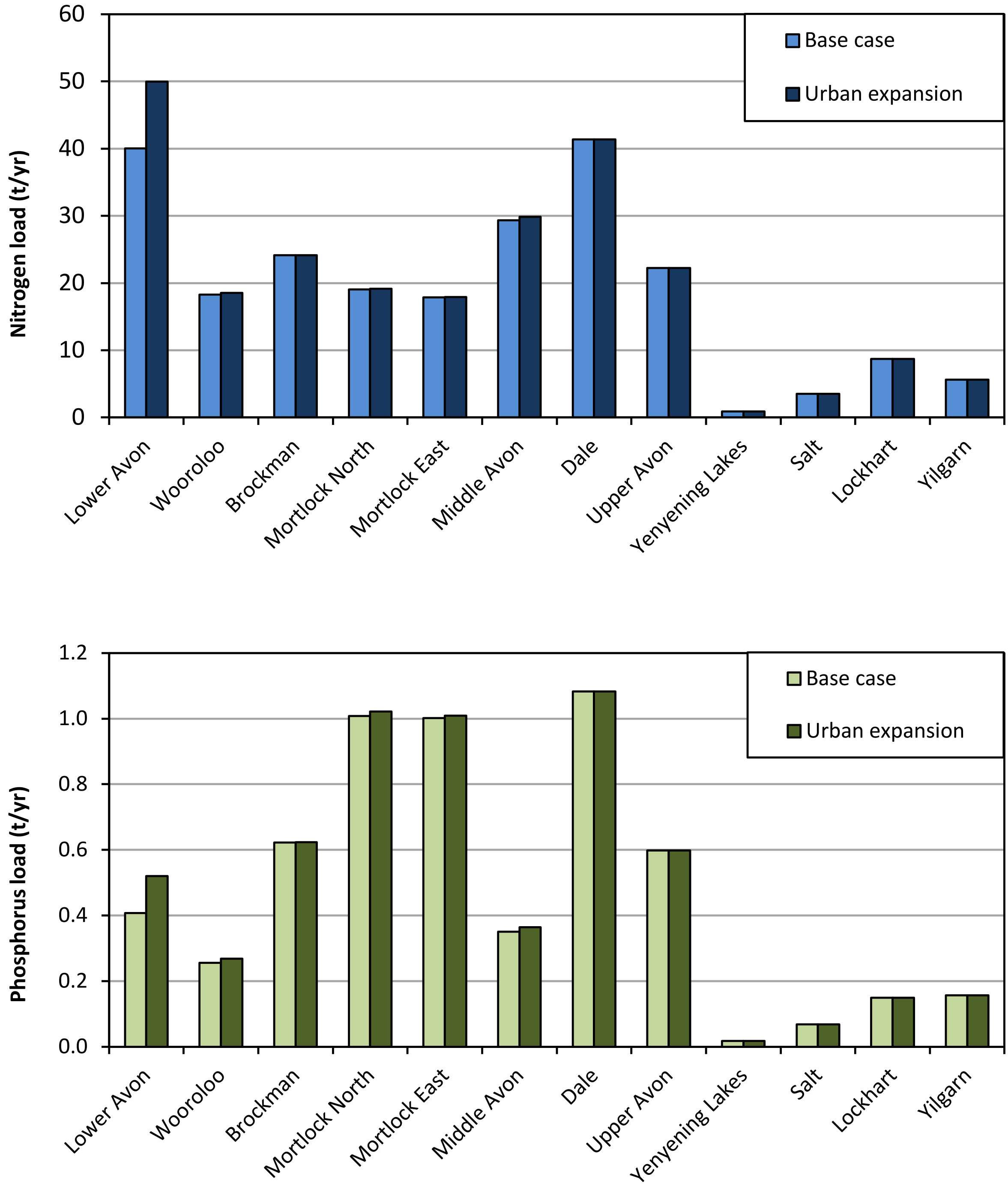


Figure 6.7: Average annual nitrogen (top) and phosphorus (bottom) loads from urban expansion

6.5 Large-scale revegetation

Landscape revegetation has the potential to reduce secondary salinisation, provide biofuel feedstock, enhance biodiversity and sequester carbon. Oil mallee plantations produce harvestable quantities of eucalyptus oil, can be used in wood-fired electricity generation (Verve 2006; Stucley et al. 2012) and can regulate groundwater levels. A revegetation project initiated by the Wheatbelt NRM resulted in approximately 1200 ha of oil mallees being planted during 2005–09 (http://www.wheatbeltnrm.org.au/projects/projects-2005-2009/salinity-management-strategic-tree-cropping/). Future revegetation is planned in the Mortlock catchments: 1628 ha of land is to be revegetated to rehabilitate riparian zones and restore biodiversity corridors.

Large-scale revegetation in the Avon Basin would depend on market-driven incentives that could compete with current profitable uses of the land. As such incentives are too difficult to predict, a generalised revegetation scenario was modelled to estimate the potential impacts on flow and nutrient loads.

Scenario modelling implementation

Modelling subcatchments with less than 30% of their area as native vegetation had their deep-rooted vegetation area increased by:

- 5%
- 10%
- Up to 30%.

For the 5 and 10% scenarios the percentage increase was less if the deep-rooted vegetation area had increased to more than 30% of the subcatchment area (i.e. the maximum subcatchment area with deep-rooted vegetation is limited to 30%). Modelling subcatchments with deep-rooted vegetation area greater than 30% were not affected by this scenario.

Only cleared, non-urban land uses were converted to deep-rooted vegetation. Modelling subcatchment Leaf Area Index (LAI) was recalculated to account for the new vegetation areas (Table 6.24). The scenario had the same climate drivers as the 2001–10 period and the revegetation growth was assumed to be complete.

Table 6.24: Areas of native vegetation and LAI for modelling subcatchments with less than 30% native vegetation for the base case and the revegetation scenarios

Catchment		Base case				+ 5% scenario			+ 10% scenario			30% scenario		
Reporting	Modelling	Total area	Native vegetation		LAI	Native vegetation		LAI	Native vegetation		LAI	Native vegetation		LAI
		(km^2)	(km^2)	(%)		(km^2)	(%)		(km^2)	(%)		(km^2)	(%)	
Lower Avon	6	846	221	26	0.45	254	30	0.46						
	7	155	31	20	0.42	39	25	0.45	46	30	0.47	47	30	0.47
	8	142	22	15	0.39	29	20	0.42	36	25	0.44	43	30	0.46
	9	182	39	22	0.43	48	27	0.45	54	30	0.47			
Middle Avon	10	421	59	14	0.40	80	19	0.42	102	24	0.44	126	30	0.47
	12	246	24	10	0.38	37	15	0.40	49	20	0.42	74	30	0.46
	13	595	62	10	0.38	91	15	0.40	121	20	0.42	179	30	0.46
	14	689	91	13	0.39	125	18	0.41	160	23	0.43	207	30	0.46
	15	201	21	11	0.38	31	16	0.40	41	21	0.42	60	30	0.46
	16	347	52	15	0.40	70	20	0.42	87	25	0.44	104	30	0.46
Upper Avon	17	557	59	11	0.38	87	16	0.40	115	21	0.42	167	30	0.46
	18	2 607	258	10	0.38	388	15	0.40	519	20	0.42	782	30	0.46
	61	15	2	14	0.39	3	19	0.42	4	24	0.44	5	30	0.46
Mortlock North	25	6	0	7	0.46	1	12	0.48	1	17	0.50	2	30	0.56
	26	58	3	6	0.37	6	11	0.39	9	16	0.41	17	30	0.47
	27	2 331	275	12	0.38	391	17	0.40	508	22	0.43	699	30	0.46
	28	4 506	311	7	0.36	536	12	0.38	762	17	0.40	1 352	30	0.46
Mortlock East	29	238	13	5	0.36	25	10	0.38	37	15	0.40	71	30	0.46
	30	2 947	224	8	0.37	372	13	0.39	519	18	0.41	884	30	0.46
	31	3 366	301	9	0.37	470	14	0.39	638	19	0.41	1 010	30	0.46
	32	3 338	328	10	0.37	495	15	0.39	662	20	0.41	1 001	30	0.45
Dale	33	22	2	10	0.38	3	15	0.40	4	20	0.42	6	30	0.46
Salt	36	622	71	11	0.38	102	16	0.40	133	21	0.42	187	30	0.45
	37	1 153	69	6	0.36	127	11	0.38	185	16	0.40	346	30	0.46
	38	1 495	128	9	0.37	202	14	0.39	277	19	0.41	448	30	0.46
Lockhart	39	203	16	8	0.37	26	13	0.39	37	18	0.41	61	30	0.46
	40	2 433	209	9	0.37	330	14	0.39	452	19	0.41	730	30	0.46
	41	3 615	452	13	0.39	633	18	0.41	814	23	0.43	1 085	30	0.46
	42	2 613	253	10	0.37	383	15	0.39	514	20	0.41	784	30	0.45
	43	1 078	119	11	0.37	173	16	0.39	227	21	0.41	324	30	0.45
	44	2 003	420	21	0.42	520	26	0.44	601	30	0.45			
	46	4 210	783	19	0.39	994	24	0.41	1 204	29	0.43	1 263	30	0.44
Yilgarn	48	222	21	9	0.38	32	14	0.40	43	19	0.42	67	30	0.47
	49	5 322	572	11	0.38	839	16	0.40	1 105	21	0.42	1 597	30	0.46
	50	3 907	545	14	0.39	740	19	0.41	935	24	0.43	1 172	30	0.46
	52	4 855	848	17	0.55	1 091	22	0.58	1 334	27	0.61	1 456	30	0.63

Results

The flow and nitrogen and phosphorus loads following the 5, 10 and 30% revegetation scenarios are shown in Table 6.25, Table 6.26 and Table 6.27 and Figure 6.8, Figure 6.9 and Figure 6.10. Average annual flows and nitrogen and phosphorus loads at the basin outlet were reduced by 3, 6 and 10% respectively for the 5% revegetation scenario. The reductions were 6, 12 and 19% respectively for the 10% revegetation scenario, and 11, 21 and 34% respectively for the 30% revegetation scenario.

Nitrogen and phosphorus percentage reductions were greater than percentage flow reductions, indicating that nutrient concentrations were reduced as a result of revegetation. Additionally, phosphorus loads at the basin outlet decreased by a greater percentage than nitrogen loads. This was due to large reductions in phosphorus loads from the Mortlock East and Mortlock North catchments, which contribute 38% of the phosphorus load at the basin outlet.

Percentage flow and nutrient load reductions were greatest in the drier catchments; that is, the Yilgarn, Lockhart, Salt, Mortlock East and Mortlock North reporting catchments. Flow and nutrient load reductions from these catchments were greater than 15, 27 and 45% for the 5, 10 and 30% revegetation scenarios respectively.

Flows from the Yenyening Lakes were reduced by 52, 61 and 79% for the 5, 10 and 30% revegetation scenarios. Nitrogen and phosphorus load reductions from the Yenyening Lakes were greater with approximately 80, 85 and 93% less nutrient load from the 5, 10 and 30% revegetation scenarios respectively.

Revegetation had less effect (in percentage terms) on reducing flows and nutrient loads in the Upper Avon, Middle Avon and Lower Avon reporting catchments with flow and nutrient reductions of 0.2–31% for all scenarios.

The Wooroloo and Brockman reporting catchments were unchanged by this scenario as they already have more than 30% native vegetation. The Dale reporting catchment had less than a 1.4% reduction in flow and nutrient loads over all scenarios because only one small modelling subcatchment had less than 30% native vegetation.

Table 6.25: Average annual flow as a result of large-scale revegetation

Reporting catchment	**Base case (GL/yr)**	**Revegetation 5% (GL/yr)**	**Diff %**	**Revegetation 10% (GL/yr)**	**Diff %**	**Revegetation 30% (GL/yr)**	**Diff %**
Yilgarn	3.1	1.9	-38	1.1	-64	0.29	-91
Lockhart	3.4	2.7	-19	2.4	-28	1.7	-49
Salt	1.0	0.82	-15	0.71	-27	0.45	-54
Yenyening Lakes inflow	7.5	5.5	-27	4.2	-43	2.5	-67
Yenyening Lakes outflow	0.31	0.15	-52	0.12	-61	0.07	-79
Upper Avon	10	10	-3.4	10	-5.7	9.0	-13
Dale	27	27	-0.2	27	-0.4	27	-0.8
Middle Avon	29	28	-2.8	28	-5.2	26	-11
Mortlock East	9.1	7.4	-18	6	-32	3.1	-66
Mortlock North	10	8.0	-20	7	-32	3.2	-67
Brockman	23	23	-	23	-	23	-
Wooroloo	32	32	-	32	-	32	-
Lower Avon	54	54	-0.6	51	-5.0	50	-7.3
Basin outlet	195	190	-2.7	184	-5.7	174	-11

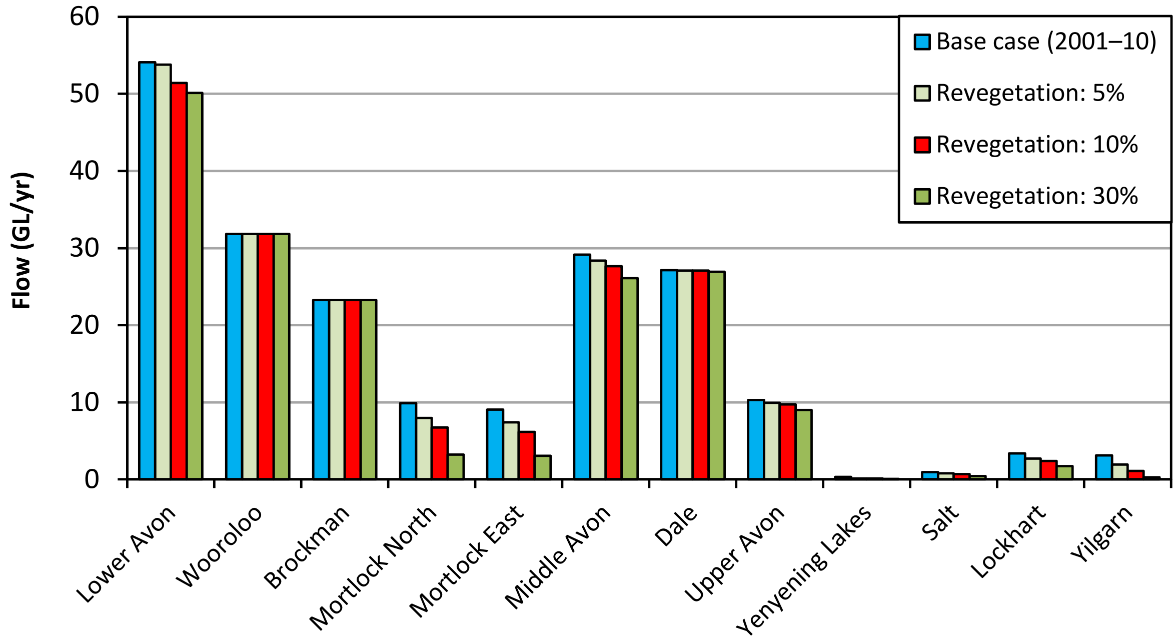


Figure 6.8: Average annual flow as a result of large-scale revegetation

Table 6.26: Average annual nitrogen loads as a result of large-scale revegetation

Reporting catchment	Base case (t/yr)	Revegetation 5% (t/yr)	Diff %	Revegetation 10% (t/yr)	Diff %	Revegetation 30%	Diff %
Yilgarn	5.6	3.3	-42	1.9	-67	0.48	-91
Lockhart	8.7	6.8	-23	5.7	-34	4.0	-55
Salt	3.5	2.8	-20	2.3	-34	1.2	-65
Yenyening Lakes inflow	18	13	-28	10	-45	5.7	-68
Yenyening Lakes outflow	0.92	0.20	-78	0.16	-83	0.08	-92
Upper Avon	22	20	-8.0	19	-15	16	-30
Dale	41	41	-0.3	41	-0.6	41	-1.3
Middle Avon	29	28	-4.2	26	-10	24	-19
Mortlock East	18	14	-22	11	-38	5.2	-71
Mortlock North	19	14	-24	12	-39	5.0	-74
Brockman	24	24	-	24	-	24	-
Wooroloo	18	18	-	18	-	18	-
Lower Avon	40	39	-2.5	36	-9.3	35	-12
Basin outlet	213	200	-6.3	188	-12	168	-21

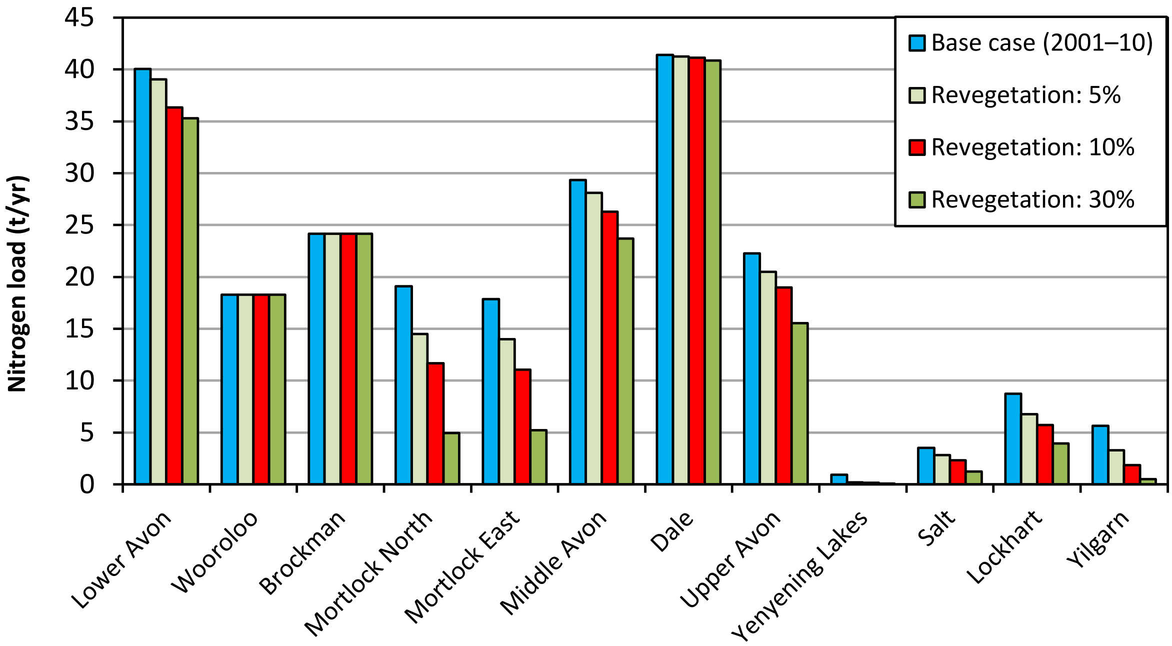


Figure 6.9: Average annual nitrogen loads as a result of large-scale revegetation

Table 6.27: Average annual phosphorus loads as a result of large-scale revegetation

Reporting catchment	Base case (t/yr)	Revegetation 5% (t/yr)	Diff %	Revegetation 10% (t/yr)	Diff %	Revegetation 30%	Diff %
Yilgarn	0.16	0.10	-36	0.06	-58	0.03	-82
Lockhart	0.15	0.12	-19	0.11	-28	0.08	-45
Salt	0.07	0.05	-20	0.04	-34	0.02	-65
Yenyening Lakes inflow	0.37	0.28	-26	0.22	-42	0.14	-62
Yenyening Lakes outflow	0.02	0.003	-83	0.002	-87	0.001	-94
Upper Avon	0.60	0.55	-8	0.51	-15	0.41	-31
Dale	1.1	1.1	0	1.1	-1	1.1	-1.4
Middle Avon	0.35	0.34	-2	0.32	-10	0.29	-18
Mortlock East	1.0	0.79	-21	0.63	-37	0.32	-68
Mortlock North	1.0	0.76	-25	0.61	-40	0.25	-76
Brockman	0.62	0.62	-	0.62	-	0.62	-
Wooroloo	0.26	0.26	-	0.26	-	0.26	-
Lower Avon	0.41	0.40	-3	0.33	-18	0.32	-21
Basin outlet	5.3	4.8	-10	4.4	-19	3.5	-34

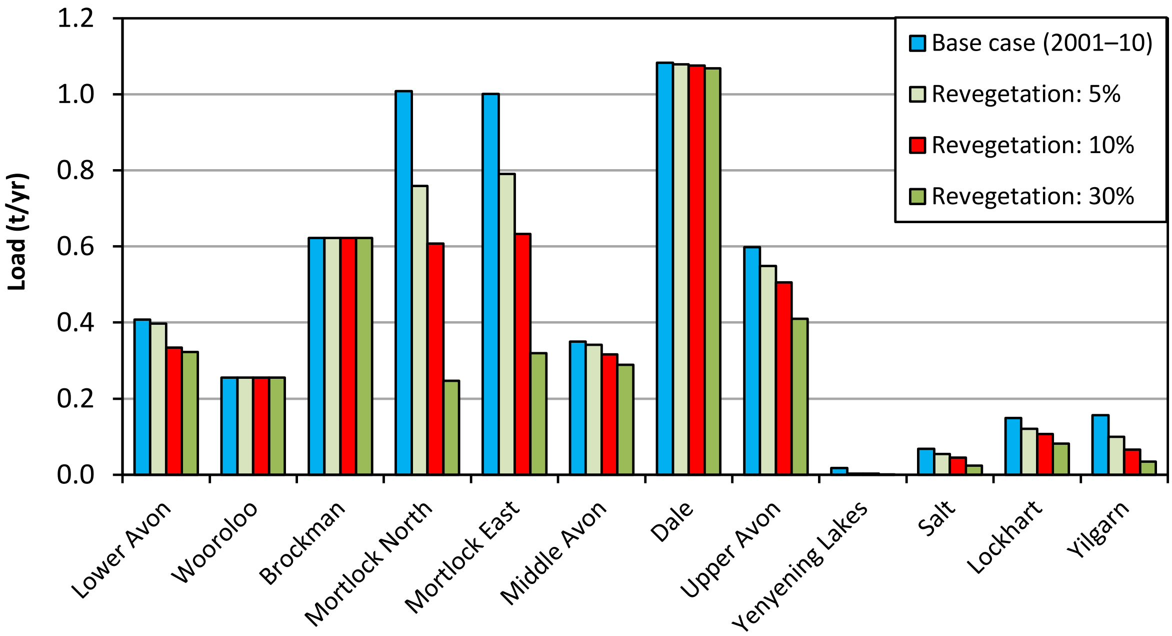


Figure 6.10: Average annual phosphorus loads as a result of large-scale revegetation

6.6 Climate change

It is recognised that the south-west of Western Australia is experiencing a change in climate (IOCI 2012) as a result of anthropogenic causes (IPCC 2007). Additionally the climate of the south-west is predicted to dry further (Charles et al. 2010).

To project the range of potential impacts of climate change, the International Panel on Climate Change (IPCC) developed four greenhouse gas emissions scenarios based on a range of potential global-scale human actions and behaviours. The emissions scenarios developed by the IPCC (2000) are:

- A1 describes a world of very rapid economic growth, global population peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.
- A2 describes a very heterogeneous world with continuously increasing global population, regionally-oriented economic growth and slow technological change.
- B1 describes a world with global population that peaks in mid-century and declines thereafter, as in A1, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity.
- B2 describes a world with emphasis on local solutions to economic, social, and environmental sustainability, with continuously increasing population (but lower than A2) and intermediate economic development.

The Department of Water (DoW in press) has developed a standard set of climate projections to use as model drivers for hydrological models of south-west catchments. Because of the uncertainty associated with climate projections, it is important that multiple emissions scenarios and global climate models (GCMs) are considered. The climate projections resulted from analysis of four emissions scenarios and 12 GCMs – a total of 48 potential future climate scenarios. The scenarios were ranked according to their projected change in annual rainfall. The 10th, 50th and 90th percentile-ranked scenarios were selected to represent the future ‘Dry’, ‘Median’ and ‘Wet’ climates.

The climate projections are scaled from observed baseline data from the World Meteorological Organisation (WMO) ‘climate normal’ period of 1961–90 to derive the future climate time-series data. As an example, the rainfall from modelling subcatchment 25, near Northam, was projected to 2100 using the 10th, 50th and 90th ranked scenarios (Figure 6.11). Several observations can be made about the historical and future projected rainfall at this location:

- From 1990 onwards the 30-year moving average of observed annual rainfall has roughly coincided with the DoW’s dry climate predictions.

- The average annual observed rainfall for the period 2001–10 of 358 mm is less than the projected average annual future ‘dry climate’ rainfall for 2001–10 of 397 mm. That is, this location appears to have experienced a very dry period.
- The very dry year experienced in 2010 is within the bounds of the projected rainfall series.
- The average future ‘dry climate’ rainfall (355 mm) for 2030 is similar to the average annual rainfall (358 mm) experienced in the 2001–10 period. However, it is important to note that this is a comparison of a 10-year average with a 30-year average, which encapsulates more rainfall variability and is less affected by outliers.
- The average of the future ‘median climate’ rainfall for the 10-year period centred on 2030 is wetter than the rainfall experienced in the 2001–10 period (386 mm compared with 358 mm).

Although the science underlying the climate projections is sound, the climate of this area seems to be drying faster than predicted by the climate models. Whether this is due to the inherent variability of climate (i.e. 2001–10 was an unusually dry decade) or a ‘real’ climate trend is impossible to decide. The reader should note that while future climate corresponding to the ‘median climate’ projections is a possibility, it is also highly likely that the future climate will be similar to the ‘dry climate’ scenario.

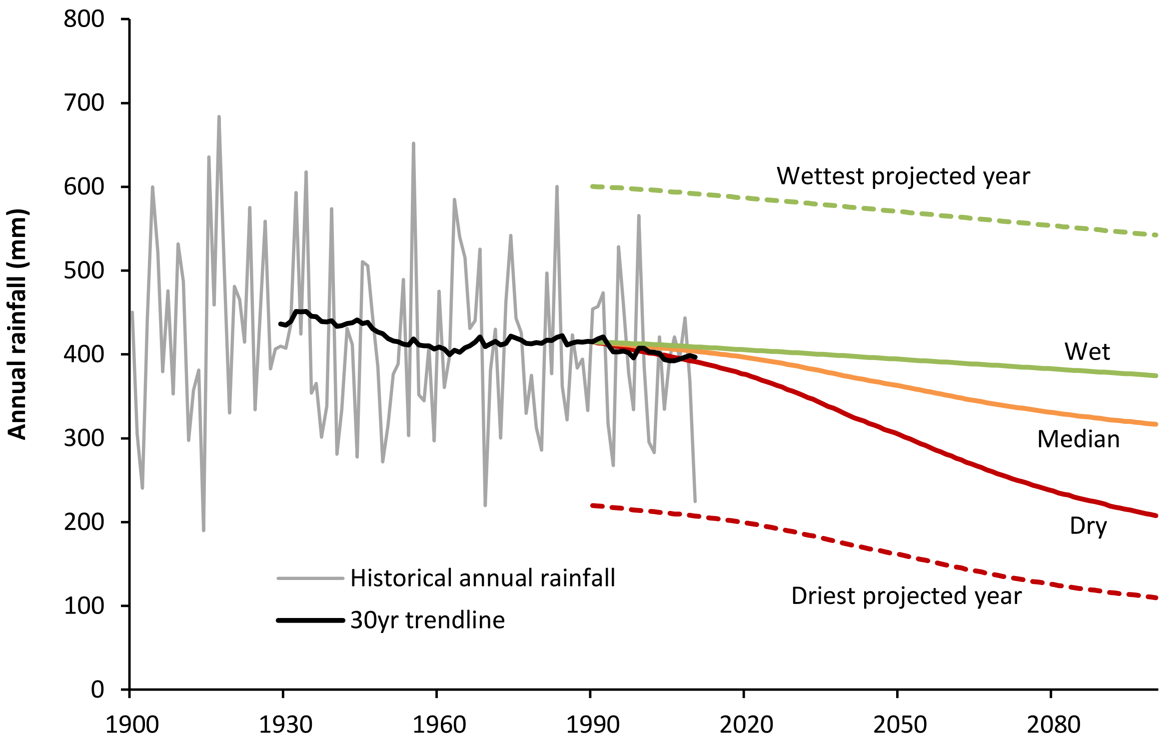


Figure 6.11: Annual SILO data drill rainfall for modelling subcatchment 25 (Northam) and projected future climate using rainfall anomalies from the Department of Water’s standard climate projection tool (DOW in press) at 542273 mE and 6472670 mN (GDA zone 50)

Scenario modelling implementation

This study used the Department of Water's future 'Dry' and 'Wet' climate projections for 2030 for climate-change scenario modelling, so that the 'full' range of possible future conditions could be examined. The 'Dry' scenario uses results from the A1 emissions scenario and the Geophysical Fluid Dynamics Laboratory Coupled Climate Model 2.0 (GFDLCM2.0). The 'Wet' scenario uses results from the B2 emissions scenario and the Model for Interdisciplinary Research on Climate High Resolution (MIROC-HI). Figure 6.12 illustrates projected rainfall anomalies for 2030 for the 'Dry' scenario. For this scenario, annual rainfall is projected to decrease by approximately 15% over most of the Avon Basin compared with the 1961–90 baseline period.

Monthly rainfall and evaporation anomalies for 2030 for the 'Dry' and 'Wet' scenarios were derived for the eastern and western regions of the Avon Basin (Table 6.28) using the DoW climate tool (DoW in press). Modelling catchments within these regions had the climate anomalies of the region applied to their climate data for the WMO 'climate normal' period of 1961–90. This derived a 30-year time-series of climate data that represents the potential future climate around the time horizon of 2030. These data were then used as input to the LASCAM/Source model and potential future flows and nitrogen and phosphorus loads estimated.

Table 6.28: Rainfall and potential evapotranspiration anomalies for the East and West regions of the Avon Basin derived from the DoW climate tool (DoW in press)

	West				East			
	Easting: 542 273		Northing: 6472 670		Easting: 715 105		Northing: 6523 559	
	Dry		Wet		Dry		Wet	
Month	**Rainfall (%)**	**PET (%)**	**Rainfall (%)**	**PET (%)**	**Rainfall (%)**	**PET (%)**	**Rainfall (%)**	**PET (%)**
Jan	-3.0	1.4	-1.9	2.0	-9.3	1.3	-1.4	2.0
Feb	-7.3	2.1	3.6	1.8	-5.6	1.7	2.5	1.6
Mar	3.2	1.2	0.6	2.6	1.7	0.9	3.8	2.1
Apr	-6.3	2.9	1.1	3.8	-2.6	2.8	3.0	3.6
May	-13.3	3.1	-7.0	4.2	-13.9	1.8	-5.7	3.9
Jun	-13.6	4.2	-4.1	4.5	-15.2	4.3	-1.3	4.2
Jul	-17.4	9.1	-0.7	6.9	-20.1	7.8	-0.9	6.3
Aug	-21.2	8.2	-4.4	4.7	-25.1	7.0	-2.9	4.3
Sep	-24.4	6.0	-2.9	4.0	-26.9	4.6	-2.4	3.4
Oct	-20.7	5.4	-1.9	3.3	-26.8	5.1	-1.2	2.9
Nov	-24.5	3.5	-4.8	2.9	-22.3	4.0	-3.1	2.8
Dec	-15.8	1.1	-6.6	2.3	-12.1	1.8	-6.0	2.2
Annual	**-14.9**	**3.1**	**-2.8**	**3.0**	**-15.1**	**3.0**	**-1.4**	**2.8**

Annual flows and nutrient loads were calculated from the modelled daily flows and loads for the 30-year future climate simulation period. For reporting purposes, the average annual flows and nutrient loads of the last 10 years of the 30-year period are compared with the flows and loads of the 2001–10 base-case period. Appendix H presents the climate-change scenario results for the predicted changes relative to the WMO 'climate normal' period.

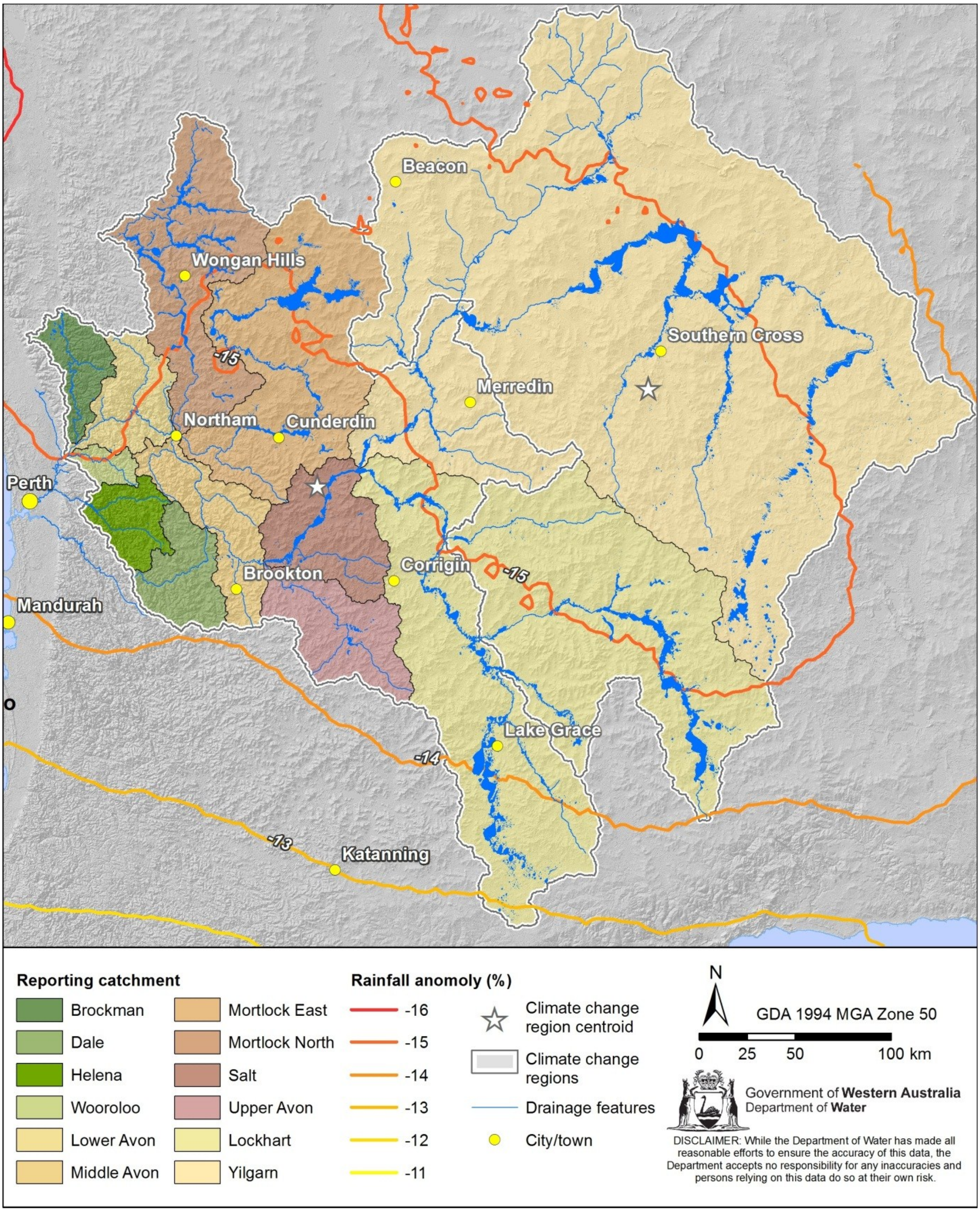


Figure 6.12: Climate-change modelling regions and centroids at which climate anomalies were determined. The rainfall anomalies for 2030 represent expected rainfall change in 2030 for the 'dry' scenario, relative to the WMO baseline period 1961–90

Results

The average annual flow and nutrient loads at the basin outlet for the base case and the dry and wet climate scenarios are listed in Table 6.29 and shown in Figure 6.13. The dry climate scenario predicts reductions in average annual flow, nitrogen load and phosphorus load of about 20%. The wet climate scenario predicts increases to average annual flows and nitrogen and phosphorus loads of 51–63%.

Table 6.29 Flows and nutrient loads at the basin outlet for the base case and the climate scenarios

Scenario	Flow		Nitrogen load		Phosphorus load	
	GL	% change	tonnes	% change	tonnes	% change
Base case	195		213		5.3	
Dry	155	-20	173	-19	4.2	-22
Wet	294	51	348	63	8.4	57

The average annual flows for the base case and the dry and wet climate scenarios for each of the reporting catchments are shown in Table 6.30 and Figure 6.14. The corresponding average annual nitrogen and phosphorus loads are in Table 6.31, Figure 6.15, Table 6.32 and Figure 6.16. At the outlets of all reporting catchments, except for the Lockhart, the average annual flow was predicted to be less for the dry climate scenario than for the base case. The climate drivers for the climate scenarios were data scaled from the period 1981–90 to represent the expected 2030 climate. The rainfall pattern for the climate scenarios is thus different temporally (distribution of rainfall during the year and year-to-year variability) and spatially to the 2001–10 rainfall pattern. This produces some unexpected results such as the increase in flow in the Lockhart catchment in the dry scenario – this may have been caused by one or two large rainfall events in the 1981–90 period, for which there were no equivalents in the 2001–10 period. This also appears to have caused larger Yenyening Lakes overflows in the future dry scenario than in the base case. This phenomenon is accentuated in the load estimations.

Interestingly, the future wet scenario predicts greater average annual flows at all reporting catchment outlets than those of the base case. As discussed above, the climate of the Avon Basin seems to be tracking at, or below, the dry climate predictions and/or 2001–10 was an unusually dry decade. At the basin outlet the future wet climate scenario predicts a 51% increase in average annual flow compared with the base case. This seems an unlikely outcome.

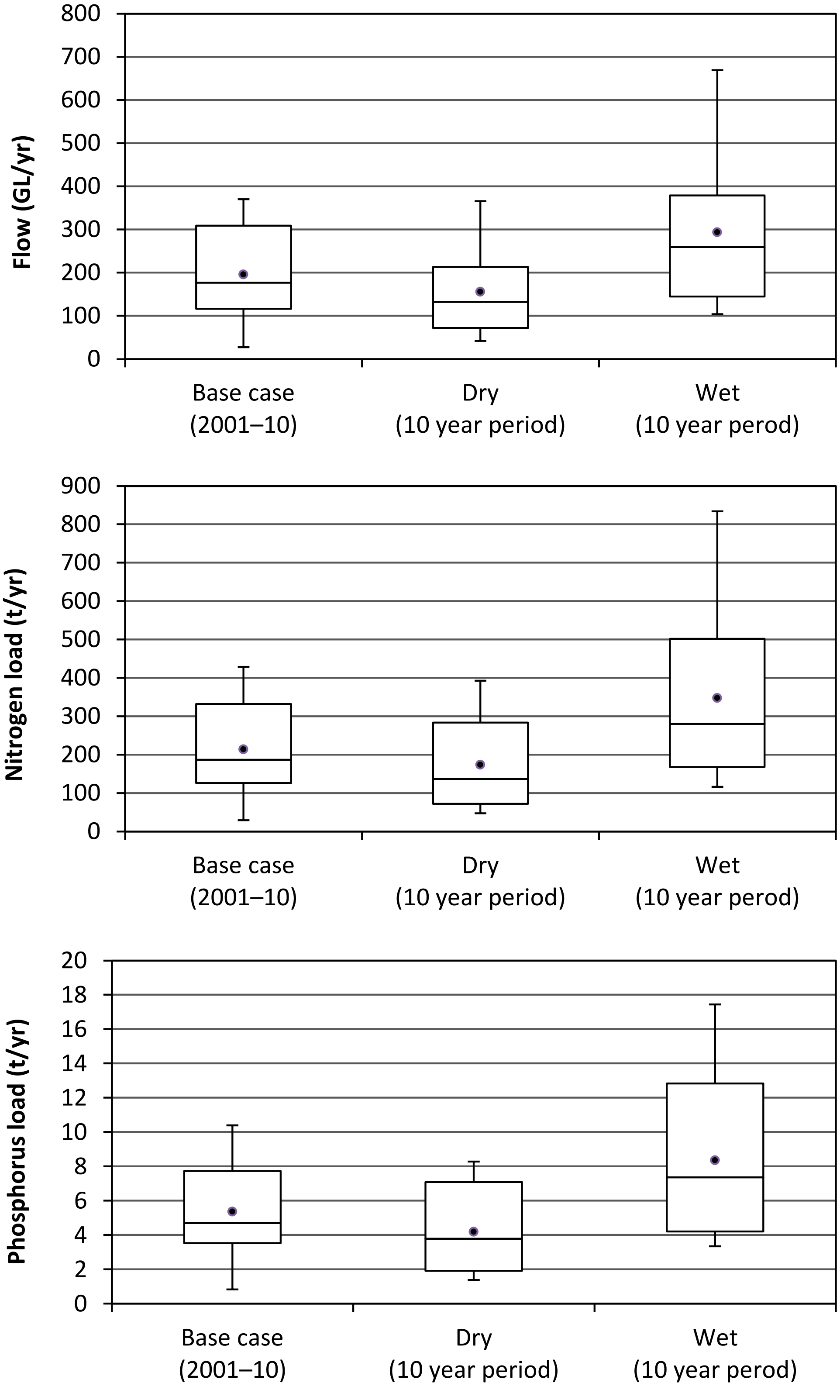


Figure 6.13: Box and whisker plots showing maximum, minimum, 25th, 50th and 75th percentiles and average annual values (dot) for flow (top), nitrogen (middle) and phosphorus (bottom) loads at the basin outlet for the base case modelling period (2001-10) and the wet and dry climate scenarios

Table 6.30: Average annual flow for the base case and the wet and dry climate scenarios

Reporting catchment	**Base case (2001–10) GL/yr**	**Dry GL/yr**	**Diff %**	**Wet GL/yr**	**Diff %**
Yilgarn	3.1	0.6	-80	3.2	0.9
Lockhart	3.4	3.4	1.5	6.0	78
Salt	1.0	0.5	-44	1.1	9.4
Yenyening Lakes inflow	7.5	4.6	-39	10	37
Yenyening Lakes outflow	0.31	0.45	44	1.8	473
Upper Avon	10	8.3	-19	15	49
Dale	27	23	-17	44	61
Middle Avon	29	28	-5.4	52	78
Mortlock East	9.1	5.9	-35	14	49
Mortlock North	10	6.6	-33	14	39
Brockman	23	14	-39	30	30
Wooroloo	32	23	-27	40	26
Lower Avon	54	46	-14	84	55
Basin outlet	**195**	**155**	-20	**294**	51

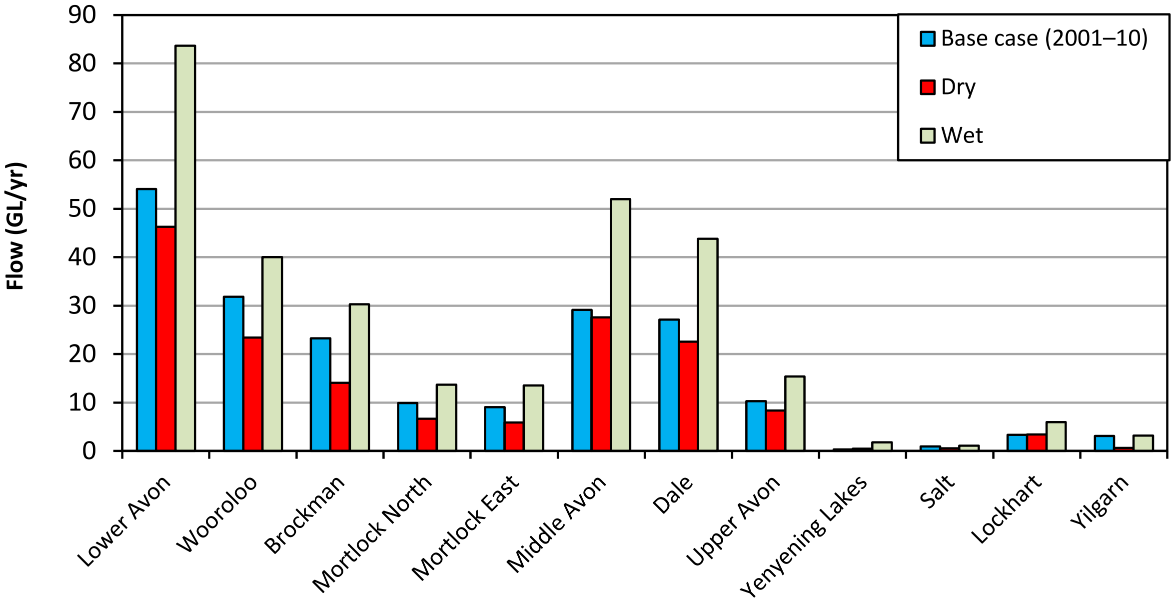


Figure 6.14: Average annual flow for the base case and wet and dry climate scenarios at reporting catchment outlets

Table 6.31: Average annual nitrogen loads for the base case and the wet and dry climate scenarios

Reporting catchment	Base case (2001–10) (t/yr)	Dry (t/yr)	Diff %	Wet (t/yr)	Diff %
Yilgarn	5.6	1.1	-80	5.8	3.0
Lockhart	8.7	11	26	19	112
Salt	3.5	1.8	-49	3.6	0.4
Yenyening Lakes inflow	18	14	-22	28	56
Yenyening Lakes outflow	0.92	4.0	334	13	1365
Upper Avon	22	19	-13	36	60
Dale	41	33	-20	70	69
Middle Avon	29	28	-3.3	54	85
Mortlock East	18	12	-33	27	53
Mortlock North	19	13	-30	27	43
Brockman	24	14	-41	33	37
Wooroloo	18	13	-29	24	32
Lower Avon	40	36	-10	63	58
Basin outlet	**213**	**173**	-19	**348**	63

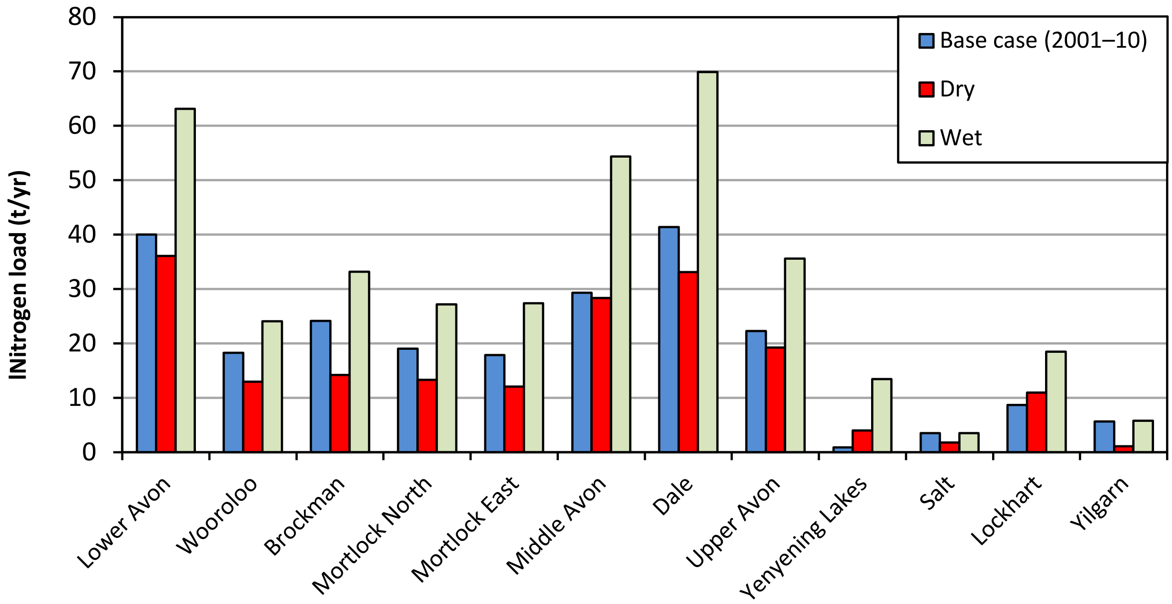


Figure 6.15: Average annual nitrogen loads for the base case and wet and dry climate scenarios at reporting catchment outlets

Table 6.32: Average annual phosphorus loads for the base case and the wet and dry climate scenarios

Reporting catchment	Base case (2001–10) (t/yr)	Dry (t/yr)	Diff %	Wet (t/yr)	Diff %
Yilgarn	0.16	0.05	-66	0.17	6.4
Lockhart	0.15	0.23	54	0.36	141
Salt	0.07	0.03	-56	0.06	-12
Yenyening Lakes inflow	0.37	0.31	-16	0.59	57
Yenyening Lakes outflow	0.02	0.09	429	0.29	1528
Upper Avon	0.60	0.51	-15	0.94	58
Dale	1.1	0.88	-19	1.8	65
Middle Avon	0.35	0.35	-0.9	0.62	76
Mortlock East	1.0	0.70	-30	1.5	53
Mortlock North	1.0	0.70	-31	1.4	44
Brockman	0.62	0.39	-37	0.82	32
Wooroloo	0.26	0.18	-28	0.33	29
Lower Avon	0.41	0.37	-9.2	0.65	59
Basin outlet	**5.3**	**4.2**	-22	**8.4**	57

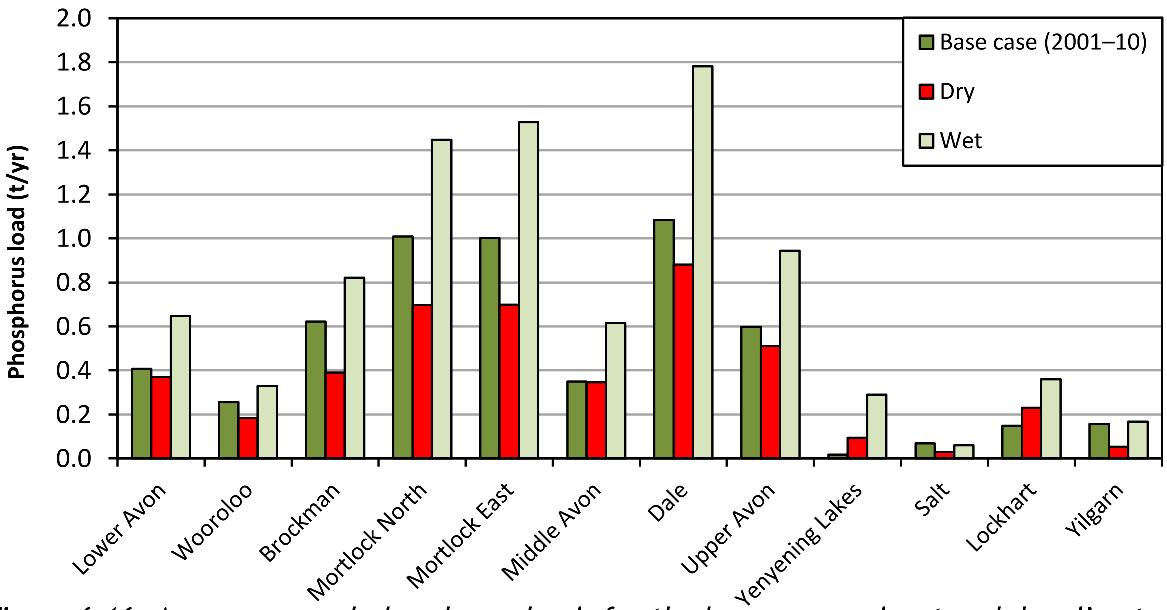


Figure 6.16: Average annual phosphorus loads for the base case and wet and dry climate scenarios at reporting catchment outlets

6.7 Cumulative impacts

Three scenarios were modelled to compare the effects of a range of land-use changes and management actions with the base case. The scenario implementation for the individual actions is the same as described in the previous sections. These scenarios were:

- **Current management practices and planned urban development:**
  - Riparian revegetation at a modest rate of 20 km/yr for 20 years
  - Urban expansion as described in the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan.
- **Moderate intervention:**
  - Riparian revegetation at rate of 40 km/yr for 20 years
  - Urban expansion as described in the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan
  - Soil acidity management (50% adoption)
  - Farm nutrient management (5% adoption)
  - Town sewage management.
- **Large intervention:**
  - Riparian revegetation at rate of 40 km/yr for 20 years
  - Urban expansion as described in the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan
  - Soil acidity management (100% adoption)
  - Farm nutrient management (50% adoption)
  - Town sewage management.

All scenarios are presented as the average annual likely change in nitrogen and phosphorus loads for a 10-year period with climate similar to 2001–10.

Results

The average annual nitrogen and phosphorus loads are given in Table 6.33, Table 6.34 and Figure 6.17.

Current management practices result in 1.1% and 1.8% respectively increases of nitrogen and phosphorus loads at the basin outlet. Most of the additional nutrients came from the Lower Avon reporting catchment with 8 t/yr more nitrogen and 0.11 t/yr more phosphorus, mainly due to increased discharge from the Northam WWTP following urban development. Phosphorus loads increased by 3.0% in the Middle Avon reporting catchment. Interestingly, increased nitrogen loads from urban expansion in the Middle Avon reporting catchment were mitigated by riparian revegetation. This occurred to a greater extent in the Wooroloo and Brockman reporting catchments, which had 14% and 6.6% reductions of nitrogen loads and 1.8% and 2.7% reduced phosphorus loads respectively. The Dale reporting catchment also had reductions of nitrogen and phosphorus loads, but had no additional loading from urban expansion. The Mortlock North and Mortlock East reporting catchments had increases of nitrogen and phosphorus loads of less than 1.3%. All other reporting catchments were unchanged.

The moderate intervention scenario reduced nitrogen and phosphorus loads at the basin outlet by 12%. Increases in nutrient loads from urban expansion in the Lower Avon reporting catchment were mostly mitigated in this scenario. All other reporting catchments had nutrient load reductions of 7–32% for nitrogen and 10–28% for phosphorus. Localised nitrogen reductions were greatest (32%) in the Wooroloo reporting catchment due to load reductions from riparian zone revegetation. Phosphorus load reductions were greatest in the Lockhart reporting catchment (28%), primarily from town sewage management and soil acidity management.

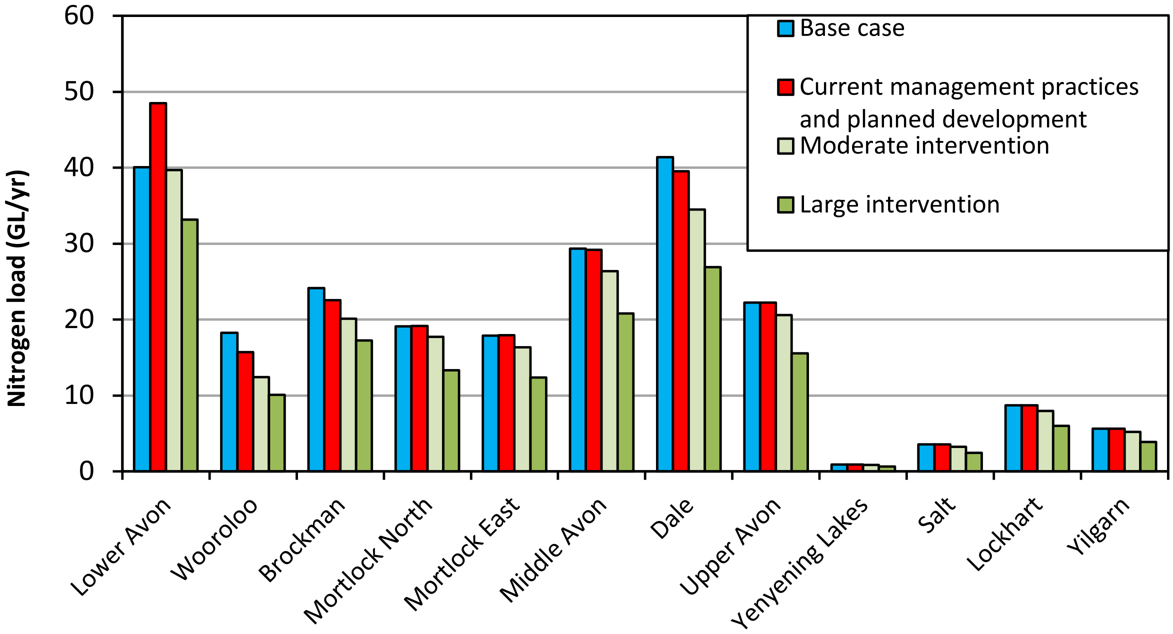
The large intervention scenario reduced nutrient loads at the basin outlet by 30% (nitrogen) and 45% (phosphorus). The large reductions in nutrient loads were a result of the widespread adoption of farm nutrient management practices. Localised nutrient reductions ranged from 17–45% for nitrogen and 26–57% for phosphorus. Nutrient loads in the Dale reporting catchment were reduced by 35% (nitrogen) and 49% (phosphorus). This is important as the Dale reporting catchment is the largest source of both nitrogen and phosphorus in the basin.

Table 6.33: Average annual reporting catchment nitrogen loads for the base case, current management practices, moderate intervention and large intervention scenarios

Reporting catchment	Base case (t/yr)	Current management (t/yr)	Diff (%)	Moderate intervention (t/yr)	Diff (%)	Large intervention (t/yr)	Diff (%)
Yilgarn	5.6	5.6	-	5.2	-7.7	3.9	-31
Lockhart	8.7	8.7	-	7.9	-9.0	6.0	-31
Salt	3.5	3.5	-	3.3	-7.9	2.4	-32
Yenyening Lakes inflow	18	18	-	16	-8.3	12	-31
Yenyening Lakes outflow	0.92	0.92	-	0.84	-8.3	0.63	-31
Upper Avon	22	22	-	21	-7.5	16	-30
Dale	41	40	-4.5	34	-17	27	-35
Middle Avon	29	29	-0.51	26	-10	21	-29
Mortlock East	18	18	0.30	16	-8.6	12	-31
Mortlock North	19	19	0.52	18	-7.2	13	-30
Brockman	24	23	-6.6	20	-17	17	-28
Wooroloo	18	16	-14	12	-32	10	-45
Lower Avon	40	48	21	40	-0.9	33	-17
Basin outlet	**213**	**216**	**1.1**	**189**	**-12**	**150**	**-30**

Table 6.34: Average annual reporting catchment phosphorus loads for the base case, current management practices, moderate intervention and large intervention scenarios

Reporting catchment	Base case (t/yr)	Current management (t/yr)	Diff (%)	Moderate intervention (t/yr)	Diff (%)	Large intervention (t/yr)	Diff (%)
Yilgarn	0.16	0.16	-	0.14	-10	0.09	-41
Lockhart	0.15	0.15	-	0.11	-28	0.06	-57
Salt	0.07	0.07	-	0.06	-11	0.04	-48
Yenyening Lakes inflow	0.37	0.37	-	0.31	-17	0.19	-49
Yenyening Lakes outflow	0.02	0.02	-	0.01	-17	0.01	-49
Upper Avon	0.60	0.60	-	0.53	-11	0.32	-46
Dale	1.1	1.1	-2.0	0.93	-14	0.55	-49
Middle Avon	0.35	0.36	3.0	0.28	-21	0.17	-50
Mortlock East	1.0	1.0	0.77	0.83	-17	0.49	-51
Mortlock North	1.0	1.0	1.3	0.91	-10	0.54	-46
Brockman	0.62	0.61	-2.7	0.55	-11	0.40	-35
Wooroloo	0.26	0.25	-1.8	0.22	-14	0.15	-40
Lower Avon	0.41	0.51	26	0.42	2.2	0.30	-26
Basin outlet	**5.3**	**5.4**	**1.8**	**4.7**	**-12**	**2.9**	**-45**



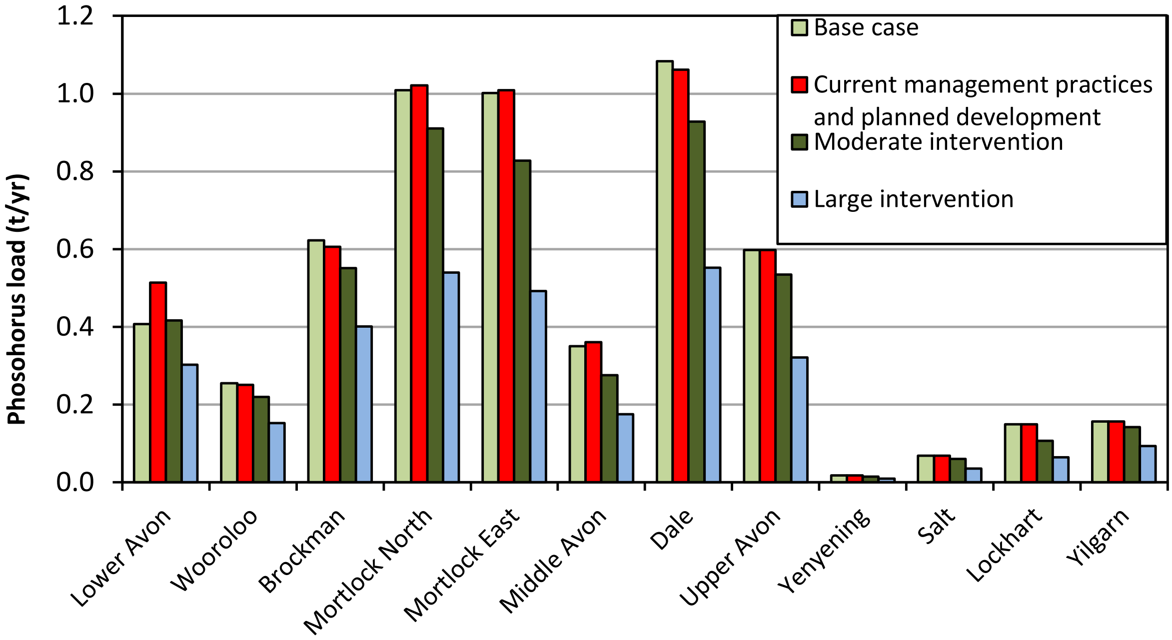


Figure 6.17: Average annual reporting catchment nitrogen (top) and phosphorus (bottom) loads for the base case, current practices, moderate intervention and large intervention scenarios

7 Discussion

7.1 Summary of modelling and discussion of results

The average annual flow and nutrient and sediment loads to the Swan Estuary from the Avon River for the period 2001–10 were:

- 195 GL flow
- 213 t of nitrogen
- 5.3 t of phosphorus
- 6500 t of sediment.

The catchments that contributed most of the flow and loads (more than 99% on average) were those in the west and they occupy 24% of the Avon Basin area:

> Lower Avon, Middle Avon, Upper Avon, Wooroloo, Brockman, Mortlock North, Mortlock East and Dale.

While the catchments to the east:

> Salt, Lockhart and Yilgarn

occupy 76% of the basin area, on average, they contribute less than 1% of the flow and nitrogen and phosphorus loads. These catchments flow to the Yenyening Lakes which only overflow in very wet years or during extreme events such as the year 2000 summer storm. In 2000, the area upstream of the Yenyening Lakes contributed 20% of the flow, 25% of nitrogen and 27% of phosphorus loads to the Swan Estuary.

To decrease loads to the Swan Estuary (on average) management of the western catchments downstream of Yenyening Lakes is the priority. However, the whole Avon Basin has highly degraded terrestrial and riverine environments (Section 2.7). Clearing of the catchment and riparian zones for agriculture and town development (82% of the western catchments and 48% of the eastern catchments are cleared) and the river-training scheme of the mid-1950s to the mid-1970s has contributed to many forms of degradation:

- Soil acidity – All cleared and farmed land has extreme potential to acidify, with most (85%) already acidic.
- Secondary salinisation – The Avon Basin is the National Action Plan for Salinity and Water Quality region with the most extensive challenge with 450 000 ha or 2279 average-sized farms affected.
- Wind and water erosion.
- Soil structure and health decline.
- Biodiversity loss – Fourteen mammal species have been lost since European settlement and many species are threatened: 343 plants, 23 mammals, 14 birds, 1 fish and 4 reptiles.

- Feral animal ingress – rabbits, foxes, pigs and fish (primarily the eastern mosquito fish)
- Sedimentation of river pools – The deep river pools between Beverley and Toodyay have filled with sediment. There has been considerable (and ongoing) effort to clear sediments from river pools.
- Eutrophication – Algal activity is a regular occurrence in the Avon River pools, catchment lakes and tributaries.

So, improved environmental management will need to be practiced throughout the whole basin to address the acidification and salinity issues of arable land, improve ecological health of terrestrial, stream and lake environments and minimise biodiversity loss. Improved local environments will enhance farm productivity, social amenity and ecosystem services.

Nutrient sources

The major source of nutrient loads to Avon Basin waterways is from broad-acre farming (wheat & sheep and mixed grazing supply approximately 90% of both nitrogen and phosphorus loads). Other land uses, such as WWTPs and intensive animal uses, although producing small loads on a basin-scale, can contribute significant local-scale loads. The average annual nutrient loads by land use for the whole catchment (Section 5; Appendix F) are:

Land use	Area		Nitrogen		Phosphorus	
	(km^2)	(%)	(tonnes)	(%)	(tonnes)	(%)
Native vegetation	50 099	42	7.2	3.1	0.06	1.1
Wheat & sheep	64 619	54	139	60	3.9	69
Mixed grazing	1 261	1.1	67	29	1.2	21
Intensive animal use	-	-	4.5	2	0.12	2.1
WWTPs	-	-	6	2.6	0.23	4
Urban	38	0.03	0.7	0.3	0.01	0.2
All other land uses	3 113	2.6	6.2	2.7	0.18	3.2
Total	119 140		230		5.7	

Native vegetation occupies 42% of the basin area and contributes 3.1% of the nitrogen load and 1.1% of the phosphorus load. Urban contributions are small compared with other sources but significant when WWTPs are included. Although mixed grazing contributes smaller nutrient loads than wheat & sheep farming, it is a much more intensive land-use (greater load per unit area).

There are some differences in nutrient sources of the various catchments (Appendix F) with the Wooroloo, Brockman, Middle Avon and Dale catchments having larger proportions of their nutrient loads from mixed grazing than the other drier catchments which are dominated by wheat & sheep farms. Catchments with contributions from WWTP outflows are the Lower Avon (Northam WWTP), Middle Avon (Brookton WWTP), Mortlock East (Cunderdin and Meckering WWTPs) and Lockhart (Lake Grace WWTP).

Scenario modelling

Clearly, to decrease nutrient pollution in the Avon Basin the loads from wheat & sheep and mixed grazing farms need to be reduced. Examination of nutrient-use efficiency (NUE) of wheat & sheep and mixed grazing properties revealed that, although these Wheatbelt farms are more nutrient efficient than grazing properties in southern WA, there is scope to improve their NUEs, which are affected by acidic soils and drought. Wheat & sheep and mixed grazing are currently on average less than 50% nutrient efficient, meaning that more than half of farm nutrients applied in fertiliser and feed or fixed from the atmosphere are not used by plants or animals but are available for leaching from farms to waterways.

Two scenarios were formulated to improve NUEs by:

1) Addressing soil acidity (acidity management)
2) Addressing soil acidity and applying fertiliser to crop requirements (nutrient management).

These scenarios were modelled with different adoption rates. Average farm-gate NUEs for the base case, the acidity management and the nutrient management scenarios are listed below:

Scenario	Nitrogen NUE	Phosphorus NUE
Base case:		
Wheat & sheep	41%	48%
Mixed grazing	23%	36%
Acidity management:		
Wheat & sheep	48%	56%
Mixed grazing	27%	42%
Nutrient management:		
Wheat & sheep	56%	75%
Mixed grazing	28%	56%

The treatment of subsoil acidity is a farm practice well known to Wheatbelt farmers. However, as the costs of liming or other treatments to raise soil pH can be far greater than the cost of excess nutrients lost through poor plant uptake in the short-term, widespread adoption is not guaranteed.

Treatment of subsoil acidity is a component of the nutrient management scenario. This scenario describes a farming system where soil health and deeper-rooted crops are encouraged; farmers do not apply fertiliser when soil nutrient values are higher than the 'critical' values required for crop growth. This enables fertilisers that have built up in the soil profile over time to be utilised. This approach requires a greater level of management than perhaps previously pursued but results in improved crop yields, particularly in dry years, and in improved farm profitability.

Although not explicitly included in the modelling, farm management to improve soil health may also include the addition of humates and other biological agents to encourage soil biological processes once soil acidity has been ameliorated.

The acidity management scenario, with 100% uptake, decreased nitrogen and phosphorus loads at the catchment outlet by 8% and 13% respectively. The nutrient management scenario, with 50% uptake, which also assumed that farmers treated their soil acidity, decreased nitrogen and phosphorus loads at the catchment outlet by 14% and 28% respectively. Loads at the basin outlet for varying levels of uptake of the nutrient management scenario are listed below:

Scenario	**Average annual load at basin outlet (tonnes)**	
	Nitrogen	**Phosphorus**
Base case	213	5.3
Nutrient Management scenario adoption rate:		
5%	210 (-1.4%)	5.2 (-2.8%)
20%	201 (-5.6%)	4.7 (-11%)
50%	183 (-14%)	3.9 (-28%)
100%	153 (-28%)	2.4 (-56%)

Riparian zones

There has been considerable effort by the Wheatbelt NRM, catchment groups, the Water and Rivers Commission (now Department of Water) and other agencies to rehabilitate the Avon River and its tributaries by fencing, revegetating riparian zones and removing sediment from river pools (Section 6.1).

Healthy riparian zones have demonstrated effectiveness in reducing stream nutrient and sediment loads and improving stream ecology (Appendix G; Gilliam 1994; Parkyn 2004). Vegetated riparian zones in agricultural landscapes can be considered to have four main functions:

- Reduction of bank erosion
- Interception and uptake of nutrient and sediments in surface and groundwater flows from paddock to stream
- Restoration and/or maintenance of stream ecosystems (provides food, habitat, shading, wind protection and woody debris)
- Provision of biodiversity corridors to link fragmented natural landscapes and provide refuge for terrestrial fauna.

In the Avon catchment, the role of riparian revegetation in reducing sediment loads in streams, by both reducing bank erosion and preventing soils eroded from paddocks from entering streams, is particularly important because of the ongoing problem of sedimentation of river pools. Revegetation of riparian zones with deep-rooted vegetation also lowers groundwater levels, thus reducing potential for salinisation and waterlogging. Shading by riparian zone vegetation decreases water temperature (Rutherfurd et al. 2000) and reduces light availability for algal growth (Quinn et al. 1997; Roberts 2004). Because of the abundant supply of woody material vegetated riparian zones can promote denitrification in both the areas adjacent to the stream and in the stream itself.

Approximately 75% of Avon Basin streams have unvegetated riparian zones. Past riparian revegetation schemes have revegetated an average of 20 km/yr of stream (Kelly, pers. comm.). Modelling estimated that, if this rate of riparian zone revegetation continued for the next 20 years, the nitrogen and phosphorus loads would be reduced by up to 4.5% and 1.7% respectively at the catchment outlet. The nutrient loads at the catchment outlet for other rates of (high) riparian zone rehabilitation are listed below:

Scenario	**Average annual load at basin outlet (tonnes)**	
	Nitrogen	**Phosphorus**
Base case	213	5.3
Riparian zone rehabilitation:		
10 km/year	209 (-2.2%)	5.3 (-0.8%)
20 km/year	204 (-4.5%)	5.3 (-1.7%)
40 km/year	193 (-9.4%)	5.2 (-3.6%)
All streams	135 (-37%)	4.2 (-21%)

Reducing sediment and nutrient loads in the Avon and its tributaries would help rehabilitate river pools and improve ecology in the pools and elsewhere. The highest rate and quality of riparian zone rehabilitation that can be achieved has the highest nutrient load reductions. However, cleared riparian areas are, when not affected by salinity or waterlogging, often the more profitable areas on farms. So, some land owners may be reluctant to allow these more profitable areas of land to be removed from productive use.

Point source management

There are 42 nutrient points sources (12 feedlots, 12 piggeries, 5 abattoirs, 5 stockyards, 3 towns with onsite sewage disposal and 5 WWTPs) included in the modelling. The estimated annual nutrient exports to waterways from all sites are 11 t of nitrogen and 0.42 t of phosphorus. Removal of all the point sources decreased nitrogen load by 10 t (4.8%) and phosphorus load by 0.31 t (5.8%) at the basin outlet.

A further scenario was run; it considered the impact of reusing all effluent that is currently discharged to waterways from the five WWTPs or to the soil profile by onsite sewage disposal in the three towns. This scenario assumed:

1) Discharges from WWTPs to streams ceased (affecting Northam (Lower Avon catchment), Brookton (Middle Avon), Cunderdin and Meckering (Mortlock East catchment) and Lake Grace (Lockhart catchment) WWTPs).
2) Towns with onsite sewage disposal (Bakers Hill, Bruce Rock and Chidlow) stopped discharging sewage to the soil profile.

3) Both the WWTP effluent and onsite sewage disposal effluent were assumed to be treated and irrigated to public open space.

Loads at the basin outlet decreased by 6.0 t/yr for nitrogen (2.8%) and 0.20 t/yr (3.7%) for phosphorus. Most of the nitrogen load reduction (5.3 t/yr) was a result of the changes to the Northam WWTP. The greatest decrease in phosphorus load was from changes to the Meckering and Cunderdin WWTPs (0.08 t/yr), which, unlike Northam WWTP, are not alum dosed.

Urban expansion

Although WWTPs contribute small nitrogen and phosphorus loads when compared with loads at the basin outlet (2.6% of nitrogen and 4.0% of phosphorus), localised impacts of WWTPs are evident with significant contributions from WWTPs in some reporting catchments (Lower Avon: 13% of nitrogen, 14% of phosphorus loads; Mortlock East: 2% of nitrogen 9% of phosphorus loads; Middle Avon: 1% of nitrogen 16% of phosphorus loads; Lockhart: 0.5% of nitrogen, 16% of phosphorus loads). Almost all WWTP discharge occurs during winter, due to detention and wastewater reuse in summer. Projected impacts of climate change indicate reduced river flow volumes in the future. Therefore, stream concentrations downstream of WWTP discharge points would be greater and dispersion less. Nutrients and other pollutants in WWTP discharge will have bigger impacts on local riverine environments, particularly river pools, in the future, if the climate continues to dry.

The urban expansion (Avon Arc Sub-Regional Strategy and Northam Regional Centre Growth Plan) increased nitrogen and phosphorus loads at the basin outlet by 11 t (5%) and 0.16 t (3%) respectively. Most of the increased load (9.8 t of nitrogen and 0.11 t of phosphorus) was due to the expansion of the Northam WWTP to cater for the higher population. This modelling highlights the problems of sewage disposal in inland areas and the need for new methods of wastewater disposal if population is to rise and nutrient loads are to be minimised.

Large-scale revegetation

The following increases in percentage of deep-rooted vegetation in each modelling subcatchment were modelled:

- 5% increase
- 10% increase
- to 30% of modelling subcatchment.

If modelling subcatchments had more than 30% deep-rooted vegetation they were not affected by this scenario. Revegetation changed flows as well as nutrient loads. The flows and loads at the basin outlet are listed below:

Scenario	**Average annual flow and loads at basin outlet**		
	Flow (GL)	**Nitrogen tonnes**	**Phosphorus tonnes**
Base case	195	213	5.3
Revegetation change:			
5% increase	190 (-2.7%)	200 (-6.3%)	4.8 (-10%)
10% increase	184 (-5.7%)	188 (-12%)	4.4 (-19%)
up to 30%	174 (-11%)	168 (-21%)	3.5 (-34%)

Planting large areas of deep-rooted vegetation would only occur if it supported a profitable industry. Strategic plantings of small areas of deep-rooted vegetation may be beneficial for reducing salinisation, rehabilitating riparian zones or to provide habitat for endangered species.

Comparison of potential management regimes

Three scenarios were modelled to estimate the impacts of several management and land-use changes occurring together. All scenarios include the expected urban expansion, and the first also includes the current level of riparian zone management, the second a moderate amount of intervention and the third a large amount:

1) **Current practices:** urban expansion of the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan and riparian rehabilitation at the modest rate of 20 km/yr. The recent past management actions to ameliorate catchment or riverine condition will have been implicitly accounted for in the base-case modelling.

2) **Moderate intervention:** urban expansion of the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan, town sewage management, riparian rehabilitation at the rate of 40 km/yr, 50% adoption of soil acidity management and 5% adoption of farm nutrient management.

3) **Large intervention:** urban expansion of the Avon Arc Sub-Regional Strategy and the Northam Regional Centre Growth Plan, town sewage management, riparian rehabilitation at the rate of 40 km/yr, 100% adoption of soil acidity management and 50% adoption of farm nutrient management.

The estimated nitrogen and phosphorus loads at the basin outlet are:

Scenario	**Average annual load at basin outlet (tonnes)**	
	Nitrogen	**Phosphorus**
Base case	213	5.3
Current practice	216 (+1.1%)	5.4 (+1.8%)
Moderate intervention	189 (-12%)	4.7 (-12%)
Large intervention	150 (-30%)	2.9 (-45%)

This modelling indicates that urban expansion in the Avon Basin could increase nitrogen and phosphorus loads to the Swan Estuary, unless improved sewage effluent disposal is achieved. Moderate intervention is estimated to significantly decrease loads at the basin outlet, even with the urban expansion. The large intervention scenario demonstrates that there is scope to greatly decrease nitrogen and phosphorus loads at the basin outlet.

7.2 Recommendations

The Avon Basin has a long history of productive agricultural industry. Despite the current environmental problems of acidity and salinity and the challenge of declining winter rainfall, the basin produces one-fifth to one-quarter of Australia's wheat. Improving farm practices in the Western Australian Wheatbelt are required for farming to be more sustainable, that is for farms to be more profitable and do not adversely affect adjacent environments. To achieve this, NUEs need to be increased to minimise nutrient leaching, riparian zones need to be restored to provide a buffer between farmed land and the natural environment and salinity controlled by re-planting where possible, so that deep drainage, which delivers acidic, salty water to downstream environments is minimised. Several actions are required to achieve these benefits:

- Different options for ameliorating soil acidity need to be studied and cost-effective options made available.
- The economics of farm management that ameliorates soil acidity and applies nutrients to meet crop demand (thus improving crop production and reducing nutrient leaching off-farm) need to be examined and demonstrated to farmers, so that farmers are confident that their profitability will not be decreased if they pursue these actions.
- The reductions in nutrient leaching off-farm due to increased farm-gate NUEs needs to be studied at the paddock scale.
- Farm management that minimises wind and water erosion needs to be encouraged to minimise soil losses.
- Other farming systems, such as perennial pastures, which provide environmental benefits without decreasing farm profitability, need to be investigated and promoted in appropriate locations.
- Deep-rooted perennial crops which can contribute to salinity mitigation and other environmental improvements, including carbon sequestration, need to be investigated to establish whether they can be profitable and sustainable. Establishment of demonstration sites would likely assist these investigations.
- Soil amendments, which improve water holding, nutrient retention and uptake need to be investigated and promoted if appropriate.
- Discharge from WWTPs to waterways need to be phased out in favour of alternative treatment solutions, which retain and reuse discharge as an alternative water supply option.

Based on this study, the following actions could be expected to improve the drought resilience of farming systems in the Avon Basin:

- Measures that improve soil biology and rooting depths, and thus plant vigour, need to be investigated and regimes established that make farms more drought tolerant.
- Improved weather forecasting needs to be researched. Farmers require better short- and medium-term weather forecasts so that they can better manage timing of planting, fertilising and harvesting.

Continuing and expanding the valuable catchment and riverine rehabilitation of the last few decades would have the following benefits based on the results of this study:

- Catchment rehabilitation to reverse rising groundwater and thus restrict the area of salinised land, waterlogging and water erosion.
- Riparian rehabilitation through fencing to exclude stock and revegetation with the requirement for ongoing maintenance of restored riparian zones will be included in rehabilitation plans. Strategic rehabilitation will create biodiversity corridors and provide habitat for terrestrial and riverine fauna with emphasis on all medium- and high-order streams in the Avon Basin.
- Biodiversity preservation through measures to protect endangered species; feral animal eradication; establishment and preservation of habitat for endangered species; and an absence of further clearing.

Fostering of partnerships and communication between farm management groups (e.g. Liebe Group, Kondinin Group), catchment groups (e.g. Wheatbelt NRM, Toodyay Friends of the River), government departments (e.g. DAFWA, Department of Water, Department of Environment Regulation, Department of Parks and Wildlife, SRT), local governments and other agencies (e.g. Soils for Life) will support improved farm management and the communication of results and benefits. To make a significant improvement to the condition of the Avon Basin's terrestrial and water environments large amounts of funding, effort and support will be necessary. The societal benefits would however be huge – sustainable and profitable farming systems, healthy waterways that can be used for boating and swimming, and town pools that provide enhanced amenity and a focus for recreation.

8 Conclusions

- Historical clearing (from 1830) and river training (mid-1950s to the mid-1970s) in the Avon Basin have left a badly degraded catchment and river system, with severe problems of salinisation, waterlogging, wind and water erosion, soil acidity, soil structure and health decline, biodiversity loss, and waterway sedimentation and eutrophication.
- Current nutrient and sediment loads are causing environmental damage to the Avon Basin's waterways and the Swan Estuary. Macroalgal and potentially toxic microalgal blooms are common in tributaries, lakes and river pools. The Northam Town Pool suffers from algal blooms (often toxic) most summers. In February 2013, a potentially toxic cyanobacterial bloom established itself in the 34 km stretch of the Avon River from Northam to Toodyay and persisted for approximately five weeks. An extreme summer rainfall event in 2000 led to a toxic *Microcystis aeruginosa* bloom in the Swan Estuary that prohibited recreational activities for two weeks. The flows and algae that supported the bloom came from the 'greater' Avon catchment (mainly the Lockhart catchment).
- There has been considerable effort to restore waterways and many local improvements have been achieved. However, approximately 75% of the catchment's streams still have little or no riparian zone vegetation. As healthy riparian zones can greatly reduce sediment and nutrient loads in streams, mitigate waterlogging and salinity, and provide habitat and biodiversity corridors in fragmented landscapes, extensive riparian zone rehabilitation would need to be undertaken to significantly reduce sediment and nutrient loads.
- The average annual flow and loads to the Swan Estuary from the Avon River for the period 2001–10 were: 195 GL flow, 213 t of nitrogen, 5.3 t of phosphorus, 6500 t of sediment. More than 99% of nitrogen and phosphorus loads (on average) came from the western areas of the basin (Lower Avon, Middle Avon, Upper Avon, Wooroloo, Brockman, Mortlock North, Mortlock East and Dale catchments). To reduce loads to the Swan Estuary these are the priority areas where management changes would need occur.
- Approximately 90% of the stream nitrogen and phosphorus (and sediment) loads originate from broad-acre farming (wheat & sheep and mixed grazing). Stream nutrient loads will not change significantly without large changes in farm practices. To reduce the amounts of farm nutrients available for leaching, farm nutrient use efficiencies (NUEs) must be improved.

  Urban nutrient loads (including WWTPs) are currently 6.6 t (2.9%) and 0.24 t (4.2%) of the nitrogen and phosphorus loads respectively. Although these are small percentages of the total nutrient loads for the basin, WWTPs have local detrimental impacts.

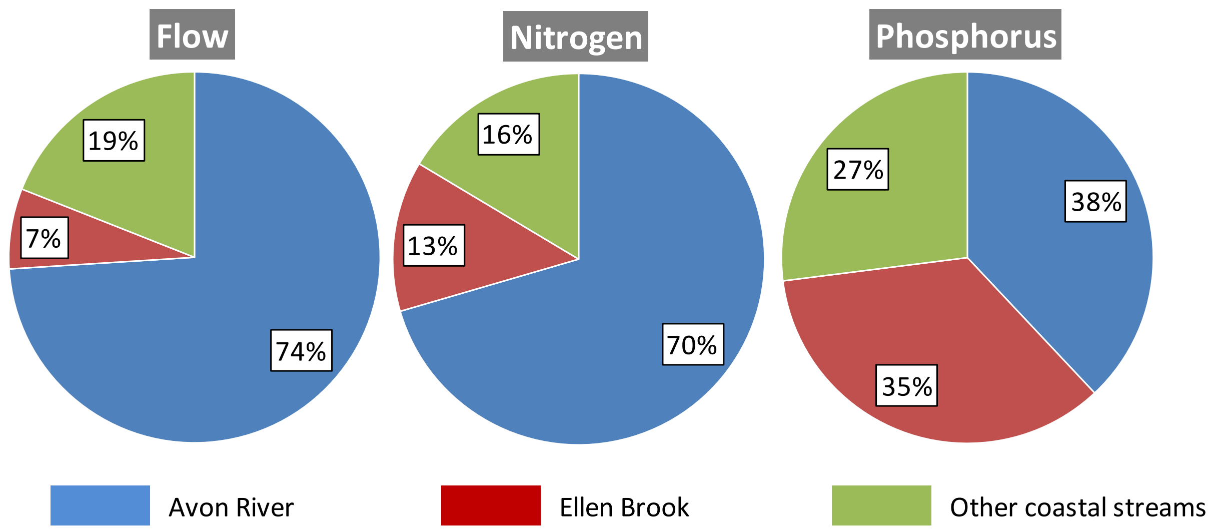
  Other sources of nutrient loads are from intensive animal uses: 4.5 t (2.0%) nitrogen and 0.12 t (2.1%) phosphorus; native vegetation: 7.2 t (3.1%) nitrogen and 0.06 t (1.1%) phosphorus; and all other land-uses: 6.2 t (2.7%) nitrogen and 0.18 t (3.2%) phosphorus.
- Most flows in the Avon River occur during May–November with generally only small flows during December–April. Although the recent drying climate has reduced flows

significantly during the 'winter' period, 'summer' flows have not changed appreciably. There may be a perception that summer rainfall in the basin is increasing but, because of the great variability in climate and in summer rainfall especially, this cannot be statistically verified. Since 1950, there have been summer flow events in 1955 (215 GL), 1971 (25 GL), 1982 (25 GL), 1990 (80 GL), 2000 (215 GL) and 2006 (55 GL). (Note: the volume given is the total flow for the duration of the event. Estimated volumes are very approximate due to selection of event duration).

- Relative to other south-west WA catchments, which lie wholly or partially on coastal plains, the Avon Basin has a larger ratio of nitrogen to phosphorus load. This is due to the large pasture areas in the basin used for grazing and the (mostly) high PRI soils. The drier areas of the Avon catchment would also have lower denitrification rates than other wetter catchments. (Avon Basin, N load/P load = 40; compare with Swan Coastal 9.7, Peel-Harvey 6.3, Leschenault 11, Geographe Bay 7.7 and Scott 6.9).
- Previous modelling of the Swan-Canning coastal plain catchments reported flows, nitrogen and phosphorus loads for 1997–2006. The flow, nitrogen and phosphorus loads to the Swan Estuary from the Avon River, Ellen Brook and the other coastal catchments that flow to the Swan Estuary (Bayswater, Belmont Central, Bennett, Blackadder, CBD, Claisebrook, Helena, Henley, Jane, Maylands, Millendon, Perth Airport North and South, Saint Leonards, South Belmont, South Perth, Susannah, Upper Swan) for 1997–2006 were:

Catchment	Area (km^2)	Flow (GL)	Nitrogen load (tonnes)	Phosphorus load (tonnes)
Avon River	119 140	298	383	11
Ellen Brook	716	27	71	10
Other coastal	766	78	90	8
Total	120 620	403	544	29

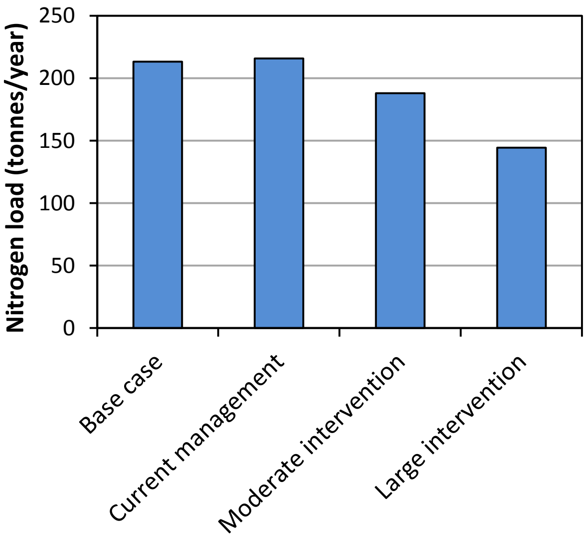
The relative flows and nutrient loads from the Avon River, Ellen Brook and the other coastal plain catchments that drain to the Swan Estuary are:

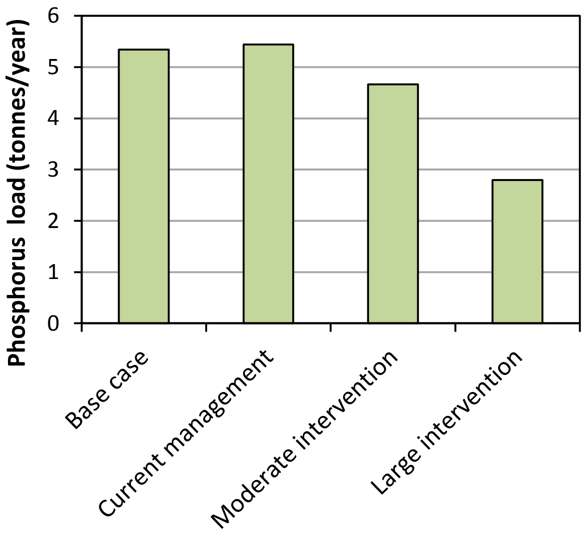


- Decreases in flows and nutrient loads due to the recent dry climate have not improved the ecological health of waterways and the estuary. Decreased flows can lead to greater nutrient concentrations. Nutrient, sediment and organic loads have greater impacts on the Upper Swan estuary in low-flow years as they are not flushed to the Lower estuary, and the salt wedge remains in the Upper estuary for most of the year. In the area of the salt wedge, there is strong salinity stratification, which inhibits mixing of the water column and bottom water can become anoxic as oxygen consumed by aquatic fauna is not replaced. Sediment nutrients are more soluble in low-oxygen water and thus become available to fuel algal growth under these conditions. The future climate is predicted to be as dry or drier than the recent climate, which will further stress the system's ecological health.
- The proposed urban development in the Avon Arc Sub-Regional Strategy (WAPC 2001; regional growth from 26 757 people in 2001 to 43 366 people in 2026) and the Northam Regional Centre Growth Plan (2013; Northam population growth from 7000 people in 2010 to 20 000 in 2031) is estimated to increase nitrogen and phosphorus loads at the basin outlet by 11 t (5%) and 0.16 t (3%) respectively. Most of the estimated increased loads (9.8 t of nitrogen and 0.11 t of phosphorus) are due to the expansion of the Northam WWTP to cater for the increased population. This highlights the problems of sewage disposal in inland areas and the need for new methods of wastewater disposal if the population increases and nutrient loads are to be minimised.
- NUEs of wheat & sheep and mixed grazing land-use are on-average less than 50%, which means that more than 50% of the nutrient in fertiliser applied or nitrogen fixed from the atmosphere has the potential to leach to waterways. NUE is reduced by acidic soils inhibiting plant uptake of nutrients, and drought. Most arable land in the catchment is highly acidic (pH 4.3–4.9) and the remainder is moderately acidic (pH 4.9–5.6). Management that reduces soil acidity and applies nutrients that closely match crop demand has the potential to increase NUEs and to greatly reduce nutrient loads in local waterways and at the catchment outlet. These measures would also improve soil biology, increase rooting depths and make farms more drought resistant.
- Three scenarios of combined land-use and management changes demonstrated potential changes to nutrient loads. All scenarios included the projected urban expansion. The current practices scenario includes the current level of riparian rehabilitation (20 km/yr), the moderate intervention scenario includes a higher rate of riparian rehabilitation (40 km/yr), 50% adoption of soil acidity management, 5% adoption of farm nutrient management (closely matches fertiliser application to crop requirement) and town sewage management (removes discharges from WWTPs and onsite sewage disposal systems in towns), and the large intervention scenario includes riparian rehabilitation (40 km/yr), 100% adoption of soil acidity management, 50% adoption of farm nutrient management and town sewage management.

Nitrogen and phosphorus loads for the three levels of intervention are:

Scenario	Average annual load at basin outlet (tonnes)	
	Nitrogen	**Phosphorus**
Base case	213	5.3
Current practice	216 (+1.1%)	5.4 (+1.8%)
Moderate intervention	189 (-12%)	4.7 (-12%)
Large intervention	150 (-30%)	2.9 (-45%)





With the projected urban expansion and similar level of catchment management to the current, nitrogen and phosphorus loads are expected to increase at the basin outlet (assuming similar climate). Moderate intervention is estimated to significantly decrease loads at the basin outlet, even with the urban expansion (by 12% for nitrogen and phosphorus). The large intervention scenario demonstrates that there is scope to greatly decrease nitrogen and phosphorus loads at the basin outlet (30% for nitrogen and 45% for phosphorus) with appropriate resources and support.

- Observed rainfall in the Avon Basin for the 2001–10 period was less than the average annual rainfall predicted by the dry climate scenario for this period. That is, current climate seems to be tracking on or below the dry climate scenario. Whether this is due to inherent climate variability (i.e. 2001–10 was an unusually dry decade) or a 'real' climate trend not encapsulated in current emissions scenarios and global climate models is impossible to determine.

  Modelling of projected 'dry' and 'wet' climate for 2030 estimated the following potential changes to average annual flows and loads:

Scenario	Flow		Nitrogen load		Phosphorus load	
	GL	% change	tonnes	% change	tonnes	% change
Base case (2001–10)	195		213		5.3	
Dry	155	-20	173	-19	4.2	-22
Wet	294	51	348	63	8.4	57

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