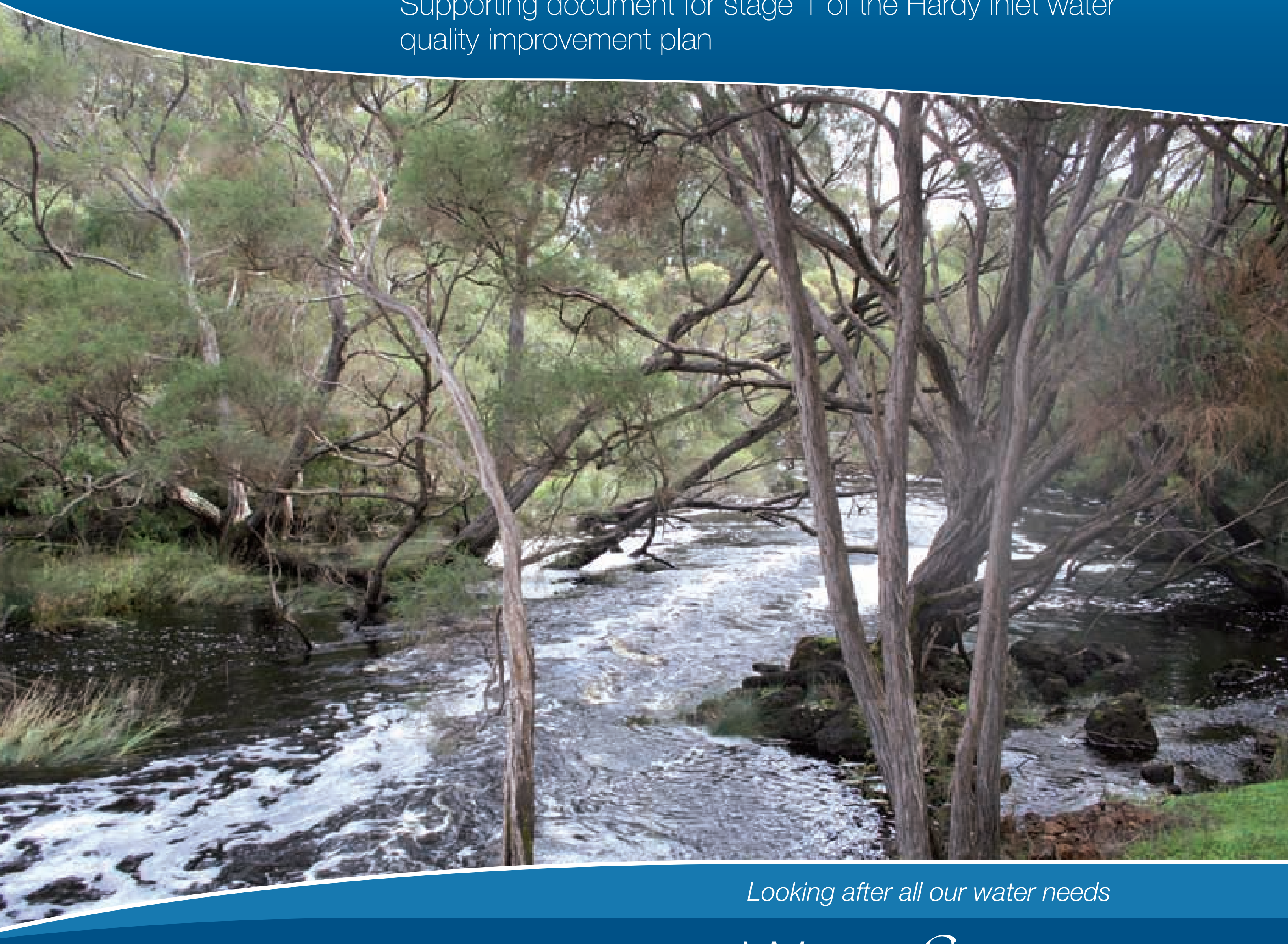
Government of **Western Australia**
Department of **Water**

Scott River catchment hydrological and nutrient modelling

Supporting document for stage 1 of the Hardy Inlet water quality improvement plan



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March 2011

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Supporting document for stage 1 of the *Hardy Inlet water quality improvement plan*

Department of Water

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Cover photograph: Lower Scott River, K Lynch (2010).

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Summary

A numerical hydrological and nutrient export model has been developed for the Scott River catchment, with the objective of quantifying the water and nutrient inflows from the Scott River to the Hardy Inlet, and to examine the nutrient sources and timing of delivery. The model was used to determine a cost/benefit analysis for a range of on-ground best management practices (BMPs) for the Scott River catchment. The model supports the *Hardy Inlet water quality improvement plan.*

The modelling package Source Catchments (eWater 2010) was used to construct the Scott River model, which was calibrated at two flow gauging stations and seven water quality sampling locations. The calibration achieved the required criteria of a Nash-Sutcliffe efficiency of >65% for each flow gauging station, and observed versus predicted median winter nutrient concentrations within 10% of one another.

The model was simulated for the period 2000 – 2009: it predicted the average annual flow to be 72 GL, and the average annual nutrient export loads to be 12 tonnes for phosphorus and 72 tonnes for nitrogen. Nutrients were predicted to be exported primarily from the central Scott subcatchments where the land use was most intense. Molloy Island was predicted to deliver an almost negligible quantity of nutrients, primarily due to the subcatchment's small size and the minor nutrient inputs. For phosphorus, the main land-use contributors were predicted to be dryland beef and irrigated dairy, followed by immature blue gum plantations (those that are less than five years old). For nitrogen, the major land-use contributors were dryland beef, irrigated dairy, dryland dairy, immature blue gums and native vegetation.

The model incorporated a suite of BMPs for the land uses within the Scott River catchment, including fertiliser management, riparian management, effluent management and soil amendment. The most effective BMP in the catchment was predicted to be fertiliser management for cattle enterprises. Not only did this scenario predict the most significant phosphorus reduction to the estuary, it was also likely to be a good investment (based on the cost/benefit ratio).

Riparian management predicted relatively small nutrient benefits at relatively high costs (and economic benefits to landholders were difficult to define). Yet riparian vegetation provides benefits other than those related to nutrients, such as habitat for wildlife, ecological corridors, waterways shading, enhanced biodiversity and bank stabilisation. The latter three benefits aid the improvement of water quality - hence riparian revegetation should not be considered a solution for nutrient reduction only.

The Iluka mineral sands mining by-product 'neutralised used acid' (NUA) is the only potentially cost-effective soil amendment product for the Scott River catchment, as it is available locally from the Capel mineral sands refinery. However, it is not commercially available and the benefits of paddock-scale implementation are still being trialled. It is recommended that small-scale plot-trials are undertaken and measured for cost/benefit and effectiveness before it is more broadly applied.

Although the Scott River model is appropriate for estimating catchment- and subcatchment-scale flows, loads and cost/benefit, it is not suitable for detailed cost-benefit analysis at the farm or paddock scale. The modelling should prompt a site-by-site investigation of the management practices at a finer scale (a farm-paddock scale or a waterways reach scale). Detailed costs/benefits and potential nutrient reductions should be re-calculated at this scale, using more appropriate locally-scaled data.

The Scott River catchment modelling has demonstrated that the most economically viable management practice, with the largest potential reduction in nutrient export, is the effective management of phosphorus fertiliser. This management practice can achieve the multi-objective purpose of reducing waterways pollution and increasing farm profitability. However, phosphorus over-fertilisation and the resulting impacts on the Swan Coastal Plain's waterways is not a new story, and has been widely documented by various state government authorities for the past two decades. Phosphorus fertiliser management is a focus of the *Fertiliser action plan* (Joint Government and Fertiliser Industry Partners 2007). It is recommended that all government departments support this plan, as well as the roll-out of fertiliser BMPs to promote sustainable, more profitable agricultural production, and to minimise environmental pollution from agricultural enterprises.

1 Introduction

The Government of Western Australia has recognised the need for a water quality improvement plan (WQIP) for the Hardy Inlet, given the on-going deterioration of its water quality and frequent algal blooms. The inlet is located in the southern capes region of south-west Western Australia, and is highly valued for its environmental significance and recreational opportunities. The WQIP has been divided into two stages for implementation: stage 1 focuses on the Scott River catchment, and stage 2 will focus on the catchments of Lower Blackwood River, Westbay Creek and Augusta townsite.

The Scott River catchment (691 km^2) is bounded to the west and north by the Blackwood catchment, to the east by the Donnelly River catchment and to the south by coastal dunes. The Scott River flows in an east–west direction to the Hardy Inlet. The Blackwood River, which has a large (21 830 km^2) and predominantly agricultural catchment, also flows to the inlet from the north. The location of the Scott and Blackwood rivers is shown in Figure 1-1.

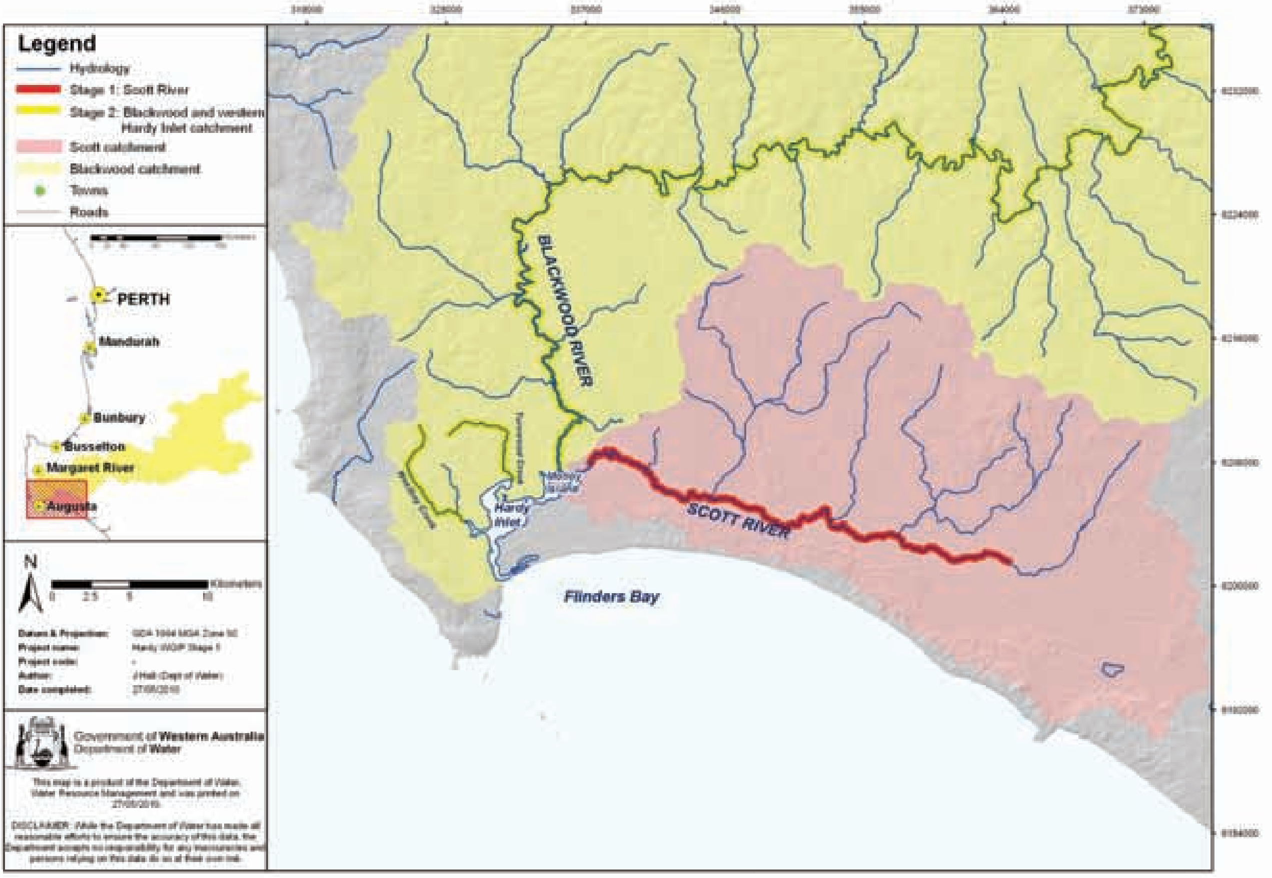


Figure 1-1: Scott River catchment and Blackwood catchment

The Scott River catchment was developed for agriculture in the 1970s and is now a highly-productive agricultural region. Regular water quality monitoring indicates the Scott River and its tributaries have high nutrient concentrations, with most sampling sites above ANZECC guideline nutrient values for lowland waterways in south-west Western Australia.

Although the high nutrient concentrations have little impact on algal growth in the river (which is light-limited due to its dark colour), this is not the case in Hardy Inlet. In January 2005 cyanobacteria blooms (*Lyngbya*) and potentially toxic dinoflagellates were reported in the inlet and have occurred every year since. In addition, high nutrient and organic loads have led to widespread deoxygenation of the estuary.

Several studies have considered the agricultural potential and environmental sensitivity of the catchment and discussed the sources and impacts of nutrient pollution (DAFWA 2001; Diamond 2002; WRC 2002).

1.1 Objective

The purpose of this study is to quantify the water and nutrient inflows from the Scott River to the Hardy Inlet, to examine the nutrient sources and timing of delivery, and to determine a cost/benefit analysis for a range of best management practices (BMPs) that are available for the Scott River catchment.

1.2 Scope

The project has the following scope:

1. Describing the catchment in detail, including climate, topography, land use, hydrology, hydrogeology and soil data.
2. Reviewing the available data (including rainfall, flow and water quality), then analysing it to determine baseflow separation, changes in flow and nutrient status, and statistical nutrient trends.
3. Constructing and calibrating a numerical model that describes the flow and nutrient export for the various land uses within the Scott River catchment, using the available data from (2). The model is required to examine the nutrient sources and timing of delivery, as well as the response to catchment land-use change.
4. Using the numerical model to run a suite of predictive scenarios to determine the change in nutrient load and concentrations for a variety of management and land-use changes. This data will be used to undertake cost/benefit analyses.

2 Catchment description

2.1 Location

The Scott River catchment is located in south-west Western Australia, east of Augusta and south of the Brockman Highway. The west side of the catchment lies in the Shire of Augusta-Margaret River and the east lies in the Shire of Nannup. The hydrological and nutrient modelling discussed in this report uses the hydrographic catchment, which has an area of approximately 69 100 ha. The local government authority boundaries, catchment boundaries, hydrology and major roads are shown in Figure 2-1.

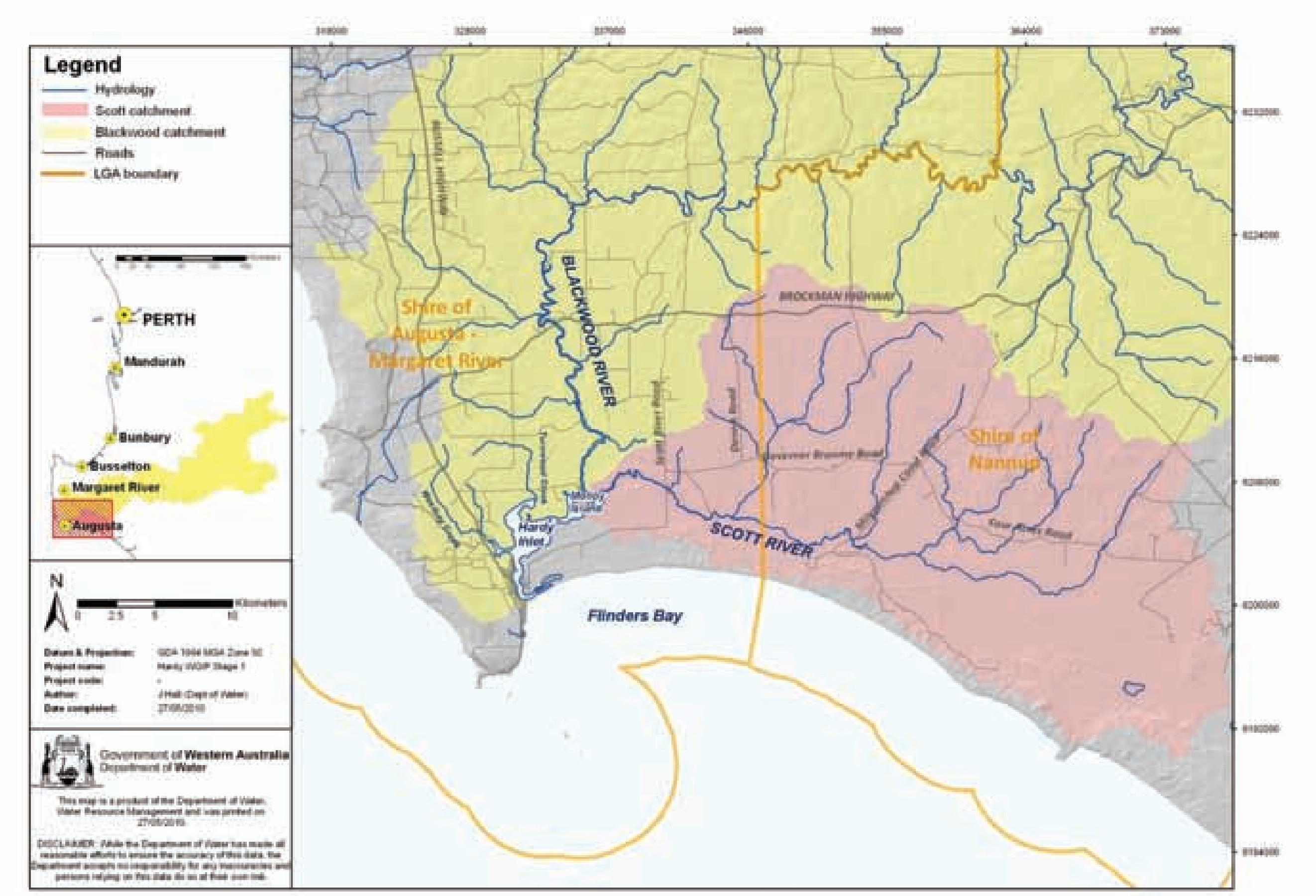


Figure 2-1: Scott River hydrologic catchment, shire boundaries and major roads

2.2 Climate and topography

The study area has a Mediterranean climate with hot dry summers and cool wet winters. The rainfall isohyets indicate long-term average annual rainfall of between 1000 and 1100 mm, which does not vary significantly throughout the catchment. Figure 2-3 shows the annual rainfall from 1970 – 2009 at the Scott River rainfall gauging station, which is located close to the catchment's centre. During this period, the average rainfall was approximately 970 mm.

The driest year was 1987, with 709 mm annual rainfall, while the wettest year was 1973, with 1286 mm annual rainfall. The average annual potential pan evaporation for the catchment is approximately 1000 mm.

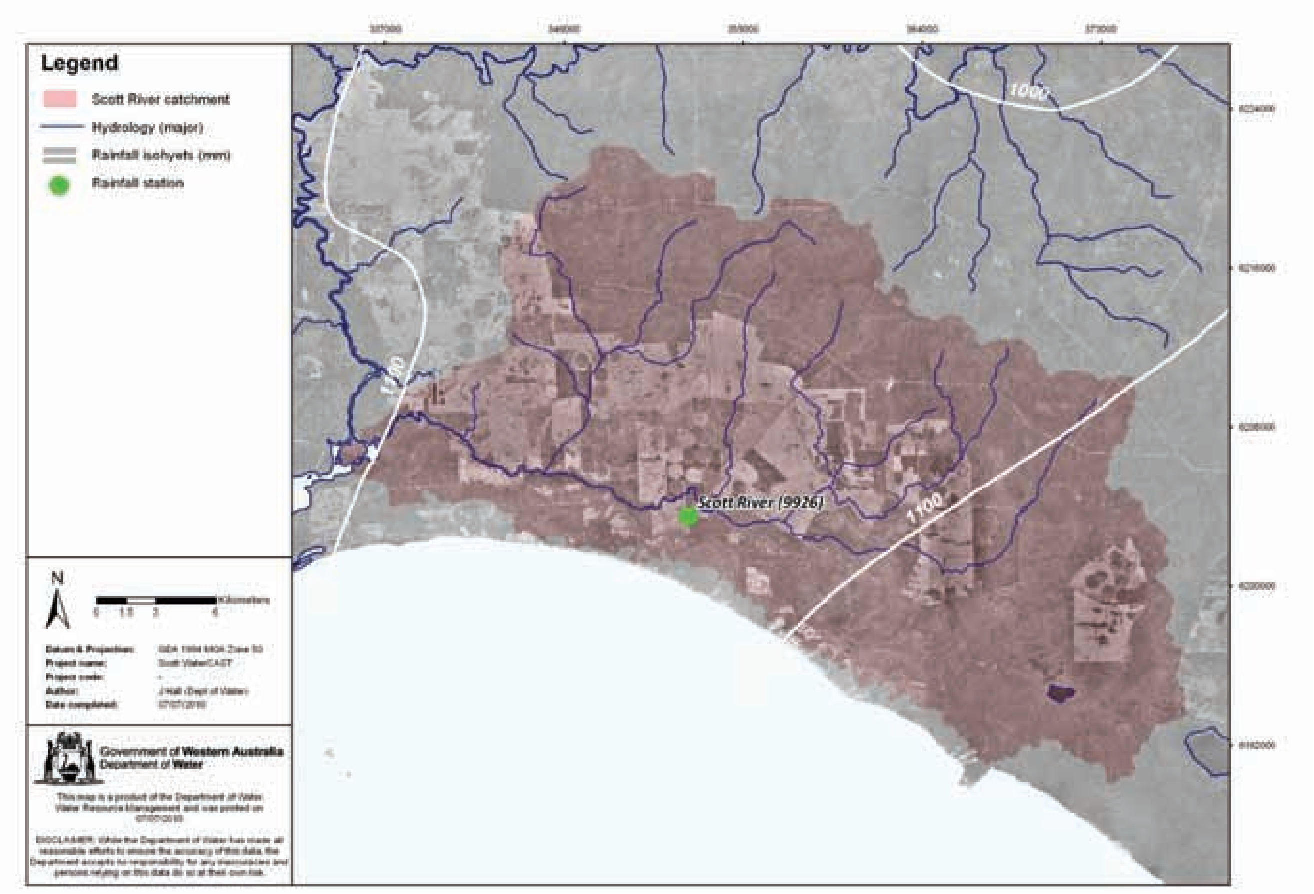


Figure 2-2: Rainfall isohyets and rainfall station for the Scott River catchment

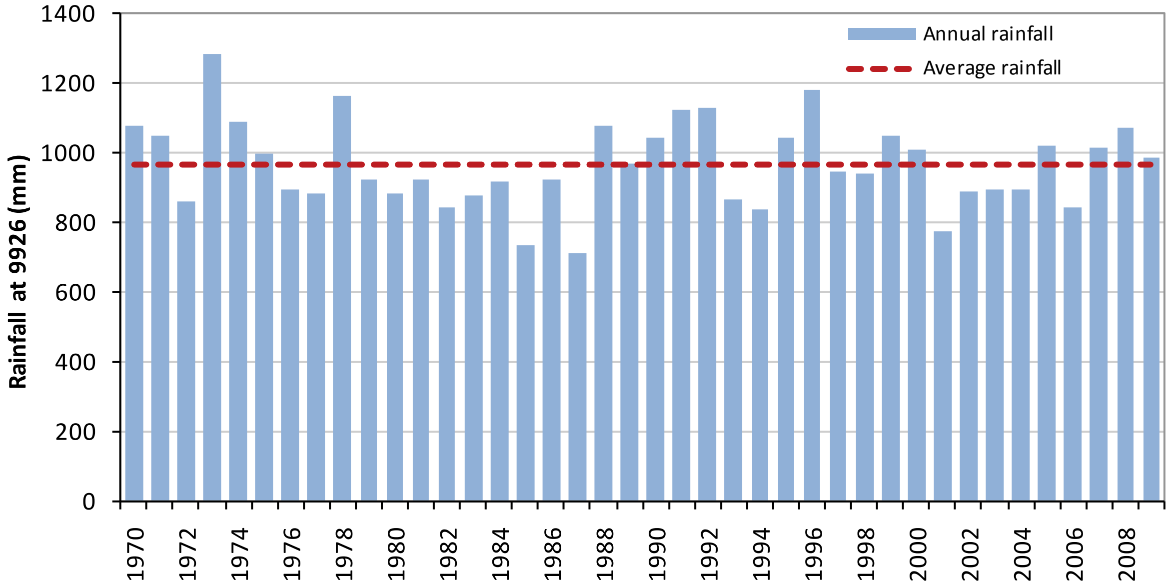


Figure 2-3: Annual rainfall at station 9926 (Scott River)

There are no significant trends in rainfall decline for the period 1970 – 2009: the average rainfall between the years 2000 and 2009 is only marginally lower than the average between 1970 and 1999 (3.4% difference). This contrasts with regions north of Perth, which have experienced significant rainfall reductions during the past 10 years (>10% difference).

Most rain falls between May and September, and average monthly rainfall ranges from 174 mm (July) to 16 mm (February). The average monthly rainfall and pan evaporation (1970 – 2009) are shown in Figure 2-4.

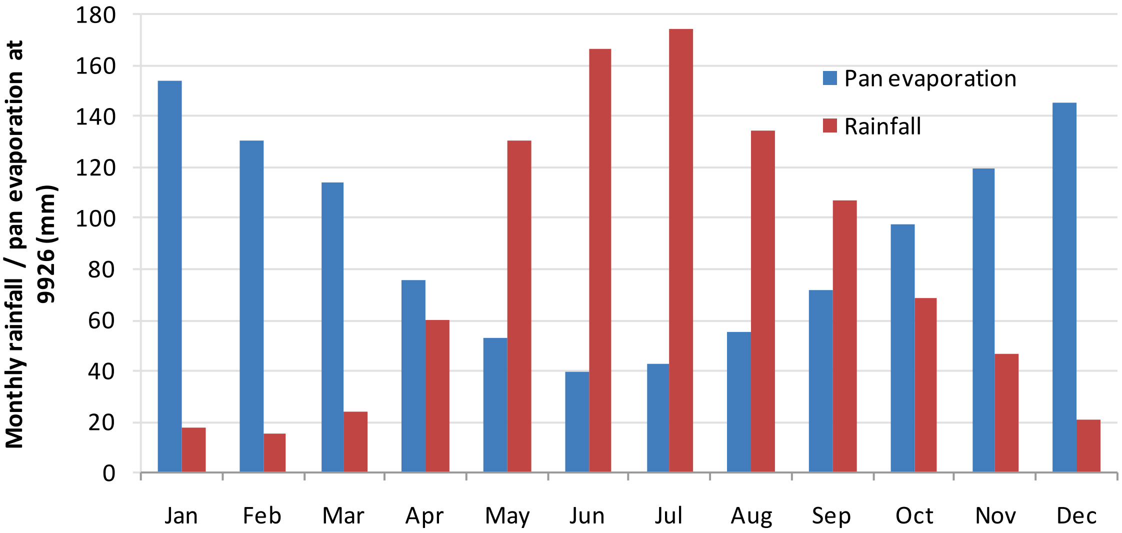


Figure 2-4: *Average monthly rainfall and pan evaporation time-series for the Scott River station (9926)*

2.3 Hydrology and hydrogeology

The Scott River catchment lies within the Perth Basin. The superficial aquifer directly overlays the Leederville, Yarragadee or Bunbury Basalt formations, and is typically between 20 and 30 m deep. The superficial aquifer is generally sandy at the surface, however it is clayey and silty in northern parts. It has discontinuous iron-organic pans developed over certain areas at about the level of the watertable: these impede the vertical movement of groundwater (Rockwater 2004).

Recharge to the Leederville and Yarragadee aquifers on the Scott Coastal Plain is thought to be from a combination of direct in situ leakage from the superficial aquifer, the Blackwood Plateau to the north, and some upward leakage from the Yarragadee Aquifer (Baddock 1995). Rockwater (2004) found that in general the shallow aquifers on the Scott Coastal Plain were not well connected with the underlying Leederville or Yarragadee aquifers. Diamond (2002) concluded that because the superficial aquifer is shallow and generally sandy on the Scott Coastal Plain, it is vulnerable to surface contamination.

Most of the catchment and the main channel of the Scott River are located on the Scott Coastal Plain. The plain is characterised by relatively flat terrain and ephemeral waterways with significant waterlogging in winter months, and the catchment is hot and dry in the summer months. The Scott River flows from east of the catchment to the west, where it discharges to the Hardy Inlet. Its flow and the flow of its tributaries are prevented from travelling from north to south (in a direct line to the ocean) by the large limestone and sand-dune ridge located at the coast, south of the Scott Coastal Plain.

2.4 Geology and soils

The Department of Agriculture and Food Western Australia (DAFWA) has adopted a hierarchy of soil-landscape mapping. Only two soil-landscape systems have been mapped for the Scott River catchment (as shown in Figure 2-5): the Donnybrook Sunkland zone and the Scott coastal zone. The Scott coastal zone constitutes approximately 60% of the area and supports most of the agricultural land uses.

Bore logs on the coastal plain indicate the occurrence of a variety of soil types, including fine white, brown and grey sands, coffee rock and clay in the top metre of the soil profile. A range of fine and course sands, as well as rock, clay, sandstone, coffee rock, shale, quartz, gravel and basalt are found at greater depths.

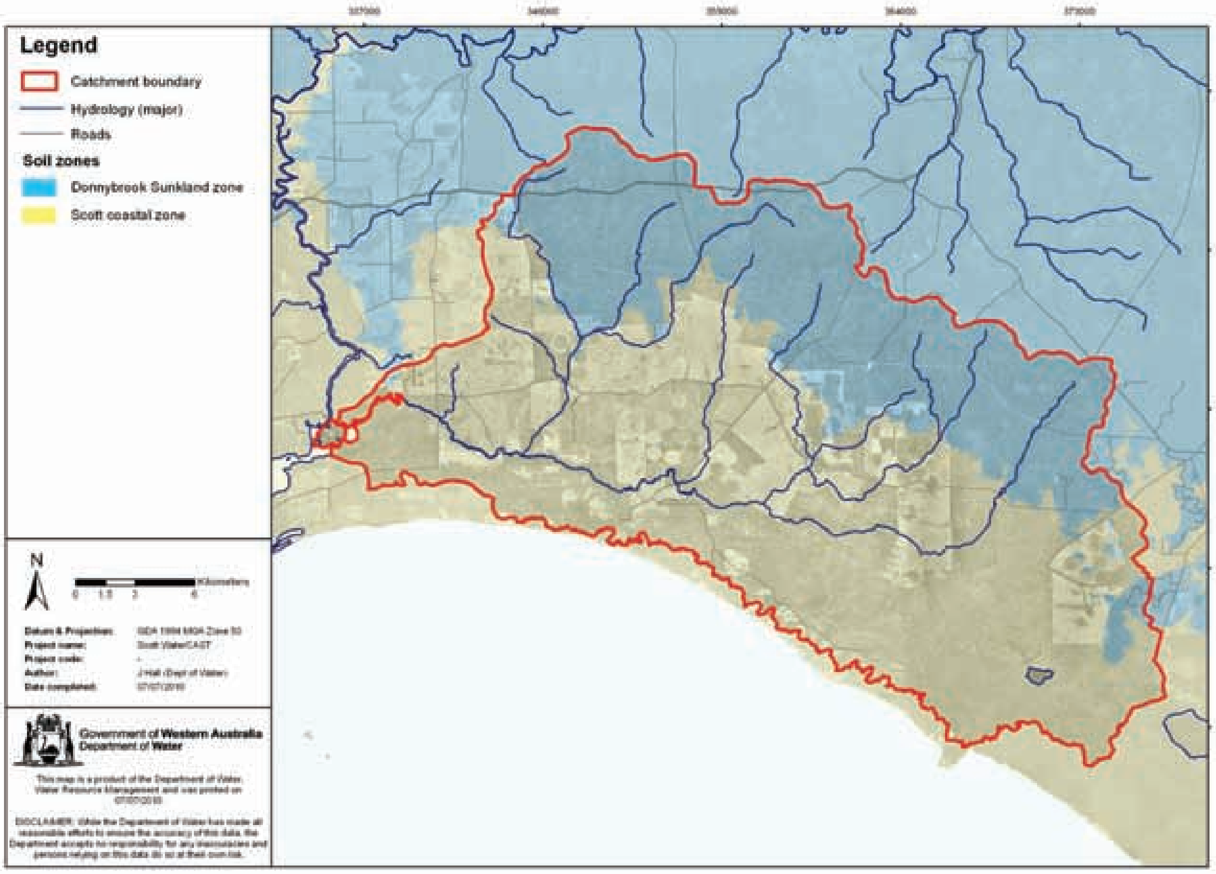


Figure 2-5: Soil zones in the Scott River catchment

Many Scott Coastal Plain soils have a low phosphorus retention index (PRI) (McPharlin et al. 1990). It should be noted that PRI is not only related to soil type, but also to subsoil characteristics, depth of the first two soil layers, and soil fertiliser history. Figure 2-6 shows the PRI for the soils within the Scott catchment.

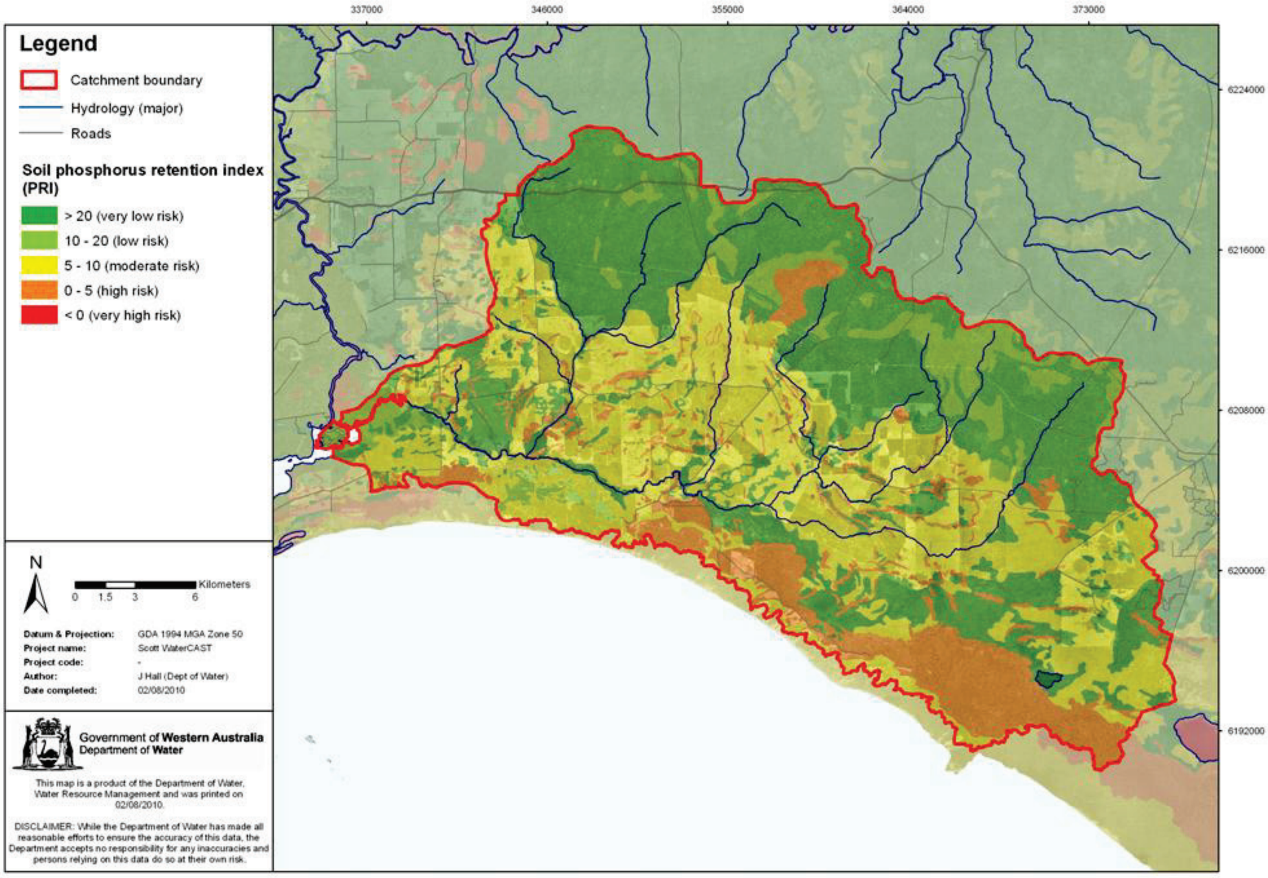


Figure 2-6: *Soil phosphorus retention index for the Scott River catchment*

In general, Western Australian soils with a PRI of less than or equal to 5 have a potentially high risk of phosphorus loss to waterways; soils with PRIs of between 5 and 15 have a potentially moderate risk; and soils with PRI >15 have a low risk of phosphorus loss. PRI should be used in conjunction with available phosphorus and other factors to determine the actual loss risk.

Acid sulfate soils

Soils with the potential to generate acidity in groundwater have been identified on the Scott Coastal Plain. In some areas of the catchment, observed acidity is associated with organic acids in humic-rich wetlands (Sommer & Horwitz 2009), and in other areas, acidity is associated with acid sulfate soils (ASS). Much of the Scott catchment is a potential acid sulfate soil (PASS) risk area due to the presence of pyrite in the soil profile. The coastal strip south of the Scott River is less problematic, given the presence of the aeolian dune systems which contain carbonate minerals that can act as a natural soil pH buffer.

A recent study of soil health in the Scott River catchment indicates that topsoil acidity is a major problem (Anderson 2007). Low pH limits the capability of plants to use nutrients, thus more nutrients may be leached to waterways. Soil pH can be increased with liming, and it is critical that agricultural regions have a soil pH adequate for plant uptake of all relevant nutrient species.

A number of detailed ASS investigations have been undertaken in the Scott River catchment. In 2003 and 2005, the former Department of Environment conducted ASS surveys whereby 49 holes (typically less than 6 m deep) were sampled, of which 12 intersected actual acid sulfate soil (AASS) and 36 intersected PASS (Angeloni 2003; Degens & Wallace-Bell 2009). The Department of Water conducted further investigations in 2008 and 2010. Bore logs and laboratory results of the soil tests are available in the following reports: *Acid sulfate soil survey of selected wetlands on the Blackwood Plateau and Scott Coastal Plain, preliminary results* (Wallace-Bell 2011) and *Bore completion report: Scott Coastal Plain* (Chan 2011).

It is expected that a report detailing ASS processes and outlining potential actions for their management in the Scott River catchment will be available from the Department of Water in early 2012.

2.5 Land use

Most of the Scott River catchment is remnant natural vegetation (67%), including national parks, nature reserves, state forest and foreshore reserves. The remainder is primarily agricultural land uses, mostly beef grazing, dairy farming and blue gum plantations.

The native vegetation covers most of the scarp and eastern margins of the catchment. Potato farming was established on sandy plains in the mid 1990s (because of the availability of water), however this became uneconomical in the late 1990s and these properties gradually converted to irrigated dairy farms (which now occupy 4% of the catchment).

During the past two decades tree farming has become profitable and many properties now have a portion or all of their area devoted to tree plantations. The catchment now has approximately the same amount of area used for blue gum plantations as for beef and dairy grazing. The nutrient inputs of these industries are very different: potatoes require large amounts of phosphorus fertilisation; dairy farming has high nitrogen inputs from fertilisation and/or fixation; and tree farms require fertilisation only during their establishment phase (first five years of growth), however they have the potential to release nutrients via soil disturbance when they are harvested.

The current land uses in the catchment were established in association with DAFWA and ground-truthed by Scott catchment farmers (Figure 2-7). The relative proportion of each land use is shown in Table 2-1 and in Figure 2-8. Horticulture and residential land uses currently occupy less than 1% of the catchment area.

***Table 2-1**: Land-use categories and areas for the Scott River catchment*

Land use	**Area**	
	km^2	%
Native vegetation	462.3	66.9%
Beef (dryland)	73.2	10.6%
Blue gums (mature)	58.9	8.5%
Blue gums (immature)	39.7	5.7%
Cleared land	16.7	2.4%
Dairy (dryland)	13.9	2.0%
Dairy (irrigated)	13.3	1.9%
Road	8.6	1.2%
Beef (irrigated)	2.0	0.3%
Horticulture (irrigated)	0.6	0.1%
Horticulture (non-irrigated)	0.6	0.1%
Residential	0.6	0.1%
Lucerne	0.3	0.0%
Total	**690.7**	100.0%

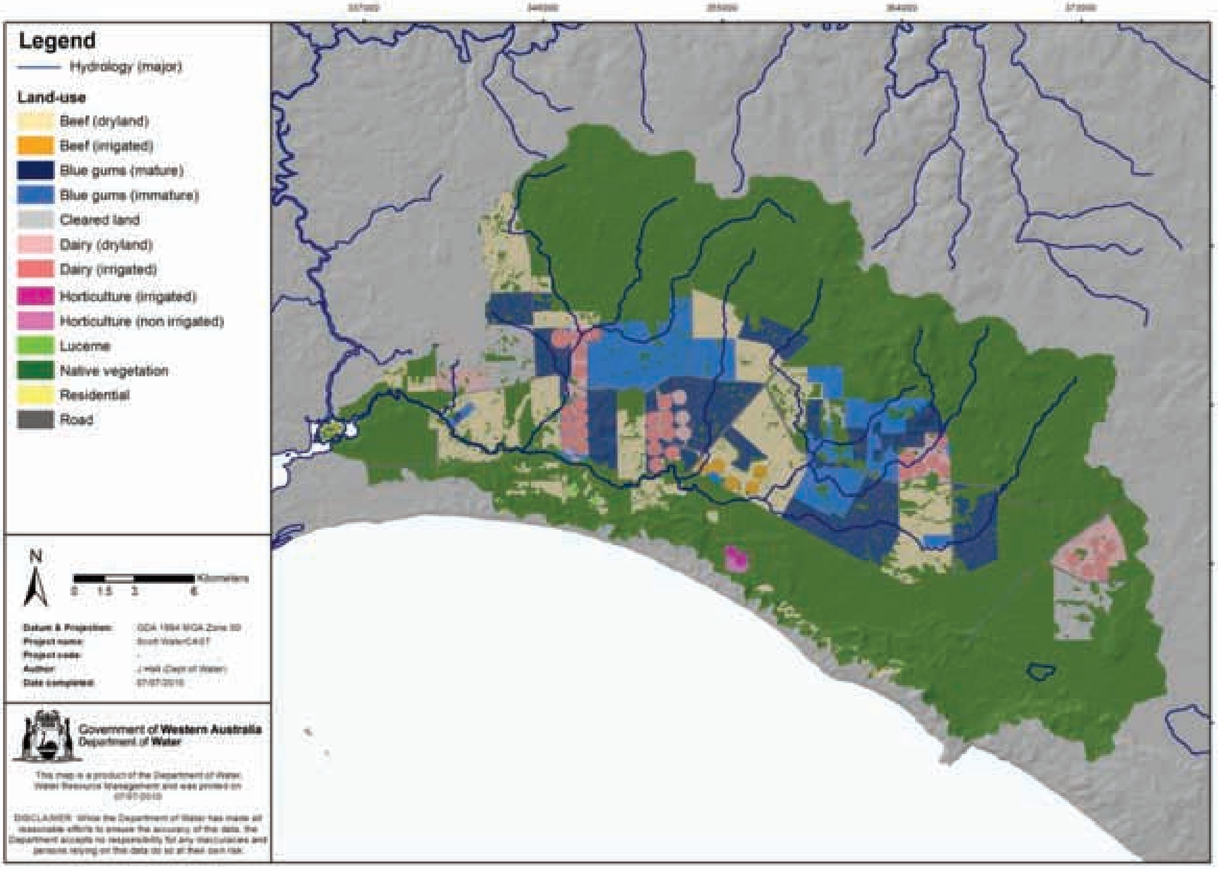


***Figure 2-7**: Land use for the Scott River catchment*

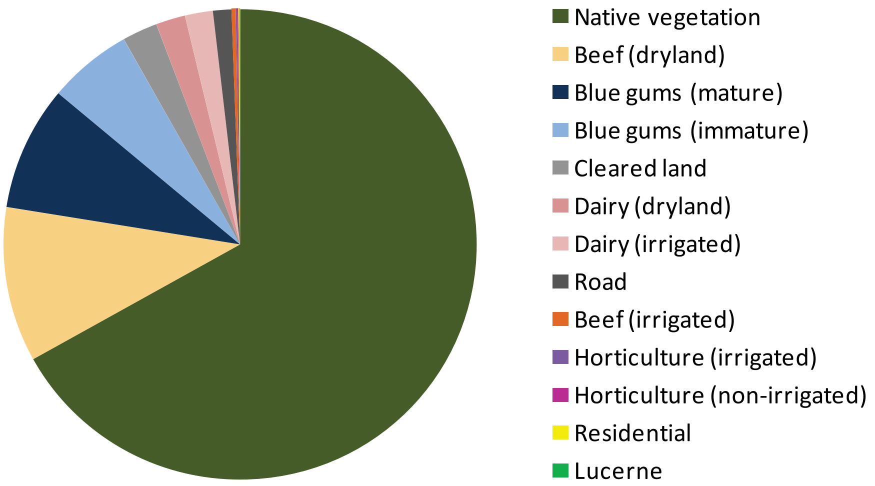


***Figure 2-8**: Land-use areas in the Scott River catchment*

3 Data analysis

3.1 Flow data collection and analysis

Flow data is collected at two sites in the Scott River catchment, both in the river’s main channel. The first is at Brennan’s Ford (AWRC reference 609002) approximately 9 km upstream of the river’s mouth – the most practical downstream location to measure flow without tidal or backwater effects. The Brennan’s Ford gauging station captures drainage from an area of 643 km^2, approximately 93% of the Scott catchment.

The second flow gauging station is at Milyeannup Bridge (AWRC reference 609026), approximately 12 km upstream of the Brennan’s Ford gauging station. Milyeannup Bridge gauging station drains the eastern Scott catchment, an area of approximately 400 km^2. The locations of the flow gauging stations are shown in Figure 3-1.

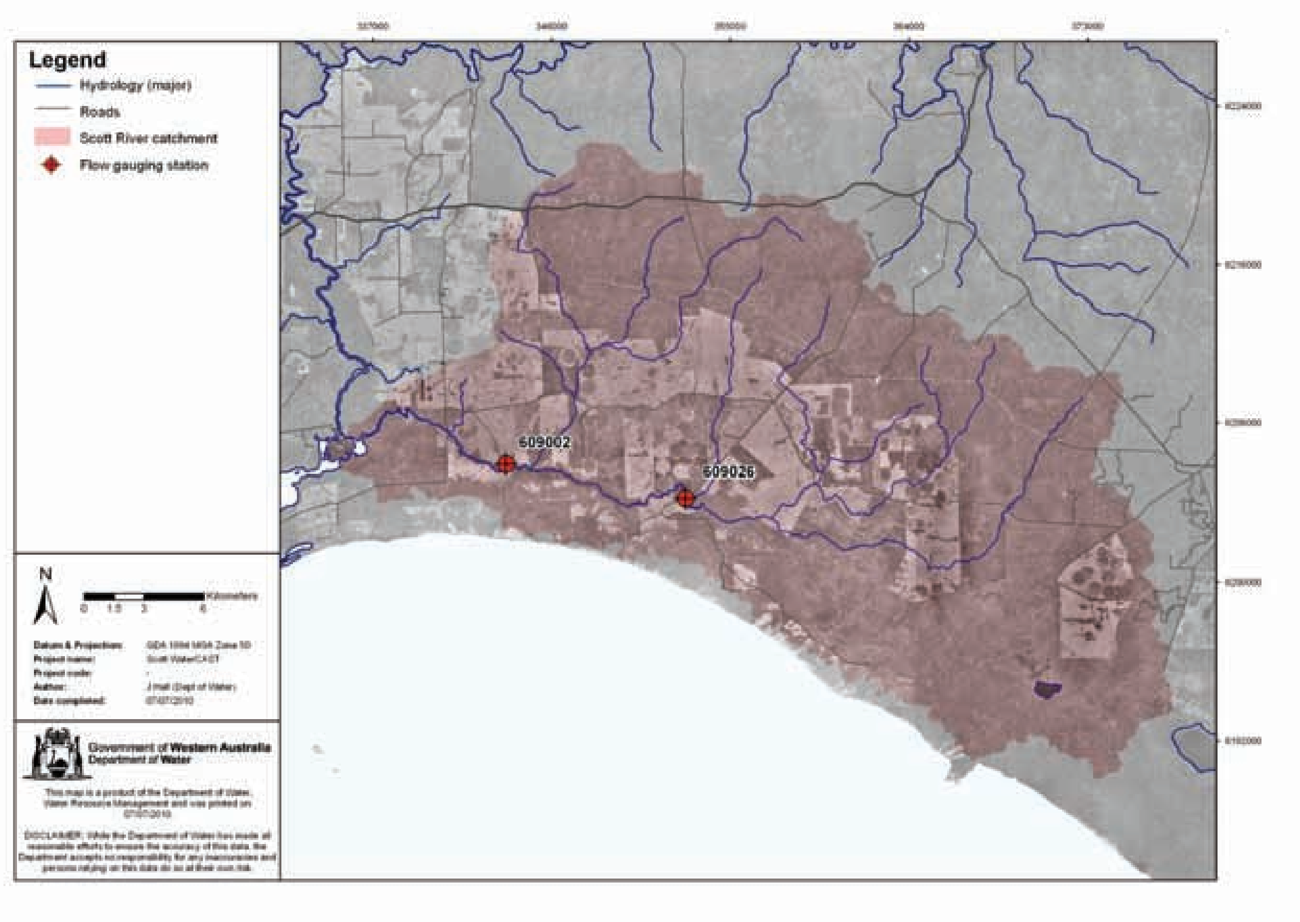


Figure 3-1: *Flow gauging station locations*

Flow at Brennan's Ford (609002) has been collected since 1969. The annual flow at this gauging station is shown in Figure 3-2. The average annual flow for the entire period is 94.7 GL. However, flow in the past decade (2000 – 2009) has greatly reduced, and is 35% lower than the average for 1970 – 2000. The decreasing trend in flow comes despite only marginal decreases in rainfall. Several possible reasons for decreased flows in the Scott River have been postulated below, and include:

- increased evapotranspiration and decreased runoff associated with blue gum plantations. Blue gum plantations have the ability to draw large amounts of water from the unsaturated zone, thereby reducing groundwater recharge, and lowering groundwater tables. This reduces the quantity of saturated excess runoff and baseflow discharge from these regions. The timing of the reduced flows in the Scott River correspond with the establishment of blue gum plantations in the catchment, and it is likely that these are a contributing factor.

- decreased runoff associated with the drawdown of the superficial aquifer as a result of abstraction from the deeper Yarragadee Aquifer. The release of large abstraction licenses in the Yarragadee Aquifer corresponds to the decrease in flows in the Scott River catchment. However, most of the Scott River catchment has a significant confining layer between the Superficial and Yarragadee formations (the Warnbro group), and it is unlikely that drawdown from the Yarragadee Aquifer will affect the groundwater levels in the superficial aquifer where the confining layer exists. However, there some (relatively minor) regions in the catchment where the confining layer is either thin or does not exist (in the far east and west of the catchment). In these regions, abstraction from the Yarragadee has the potential to affect superficial groundwater levels and surface water flows.

- the timing and intensity of the rainfall, or increasing temperatures which result in increased evapotranspiration. These factors have not been studied in detail in this catchment, and have the potential to change the annual runoff quantity.

The exact cause of the reduction in flow would need to be confirmed by analysis of bore logs, rainfall patterns, temperature patterns, evapotranspiration and abstraction regimes, and would need to be supported by groundwater modelling and monitoring.

Determining the cause of reduced streamflow in the Scott River was not the primary objective of this project; however it is recommended that this be investigated in detail in the future.

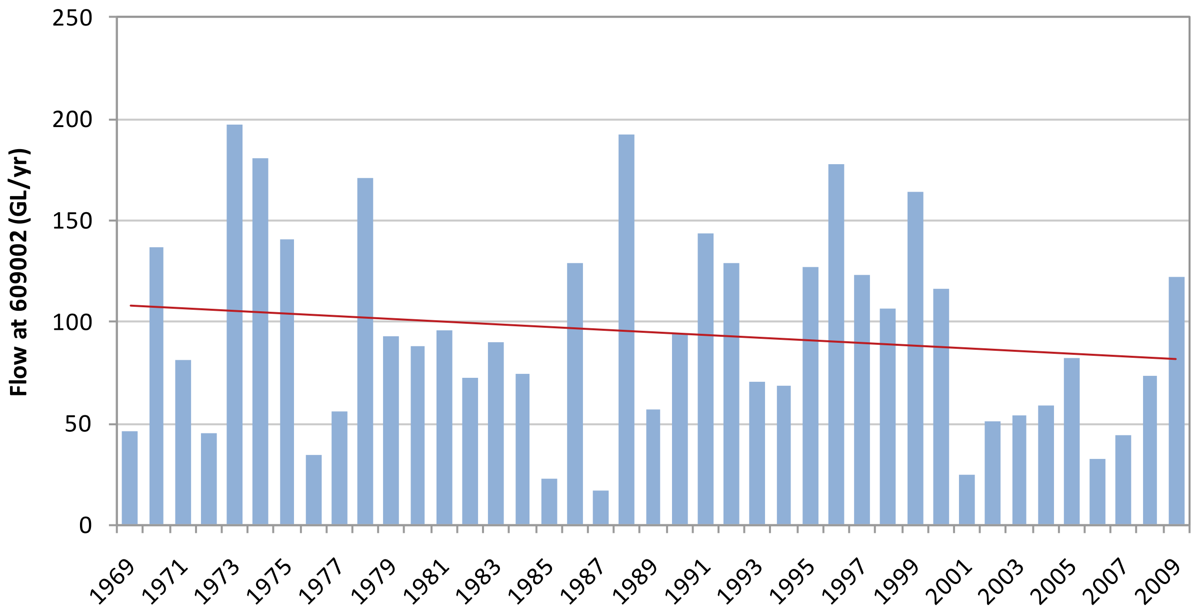


Figure 3-2: *Annual flow at Brennan's Ford (609002) for the years 1969 - 2009*

A baseflow separation (Eckhart 2005) reveals that approximately 50% of the flow at Brennan's Ford (609002) is baseflow (groundwater flow that has expressed itself in waterways), with the remainder being 'high-flow' (this is likely to be generated by surface runoff from the heavy soils of the north or from recharge rejection when the catchment's low-lying areas are waterlogged). The baseflow and surface flow components of the hydrograph are shown in Figure 3-3. Flows at Brennan's Ford gauging station are ephemeral: flows generally start in May/June and stop in November/December.

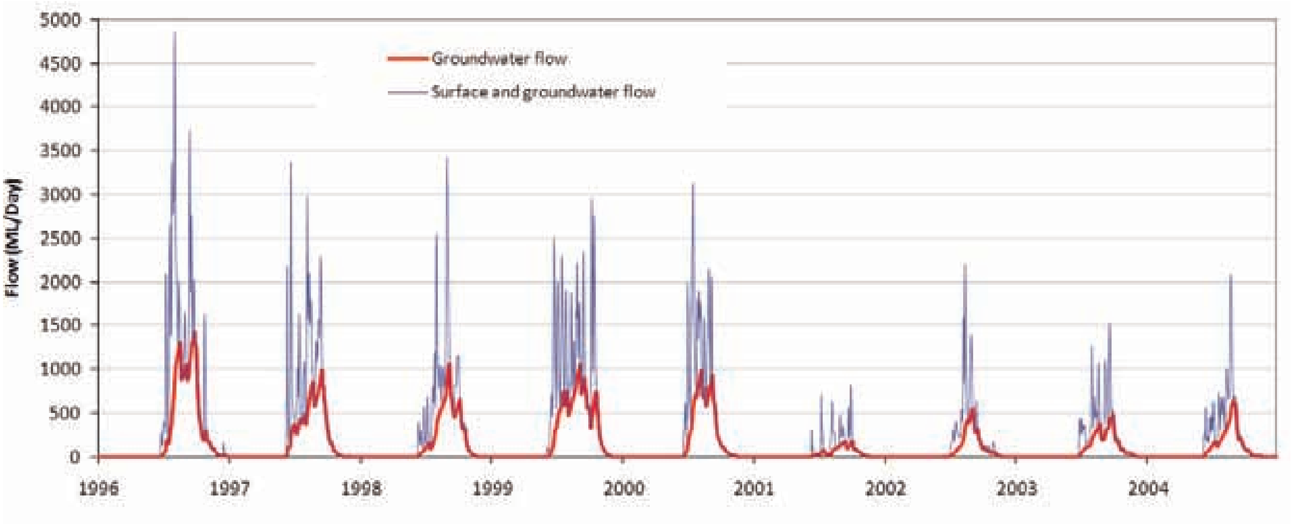


Figure 3-3: *Baseflow separation at 609002: baseflow accounts for 50% of the total flow*

The coefficient of runoff is the ratio of runoff to rainfall. On the Swan Coastal Plain in an average year, pasture and cleared land generally has a coefficient of runoff of 10 – 20%, whereas deep rooted vegetation (native vegetation or plantation) has a coefficient of runoff of 5 – 15% (urban can have a coefficient of runoff of above 30%). Irrigated land has a much higher coefficient of runoff, because it does not require the initial 1 – 200 mm of rainfall to saturate the soil before runoff occurs. Figure 3-4 shows the coefficient of runoff at Brennan's Ford, which clearly displays a step change during the past decade.

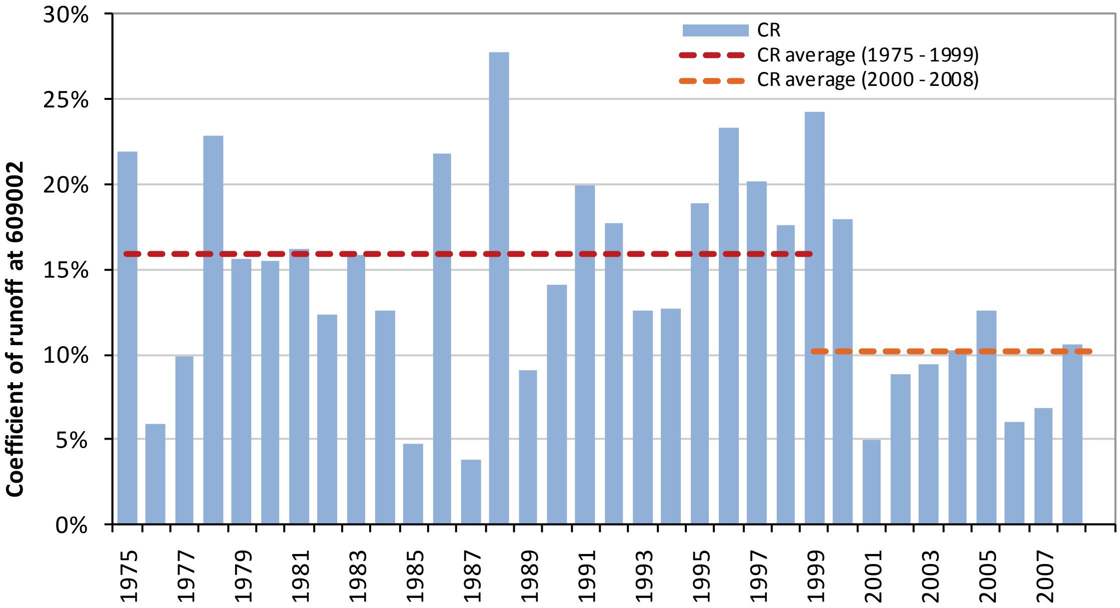


Figure 3-4: *Coefficient of runoff (runoff/rainfall) for the years 1975 - 2008 at Brennan's Ford (609002), showing the average from 1975 - 1999 and from 2000 - 2008*

Flow data at Milyeannup Bridge (609026) was collected between the years 1996 – 1998. The flow at this gauging station averaged 69 GL/yr and was consistent with the Brennan's Ford gauging station in that it had a coefficient of runoff of 20% and a baseflow component of 50%. The baseflow separation for the Milyeannup Bridge gauging station for the years 1996 – 1998 is shown in Figure 3-5.

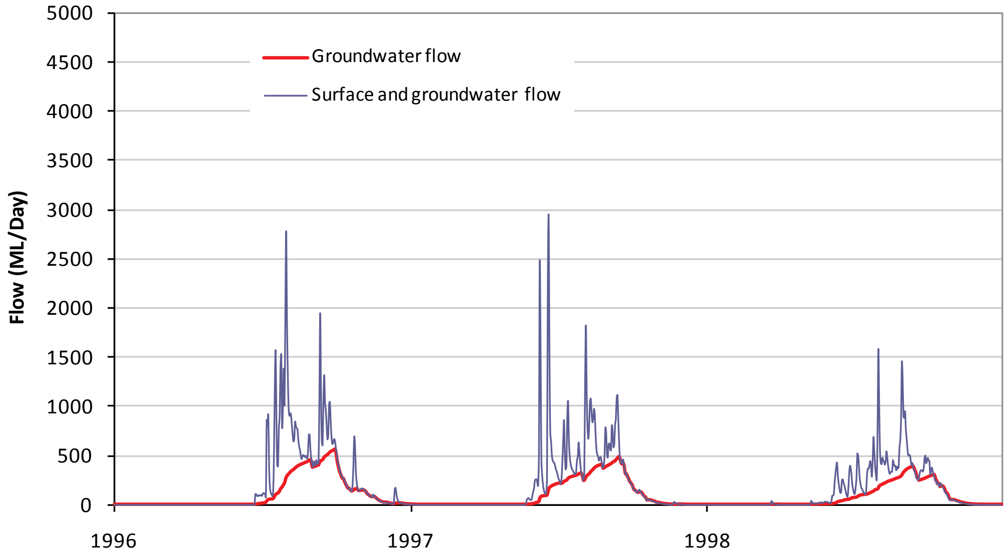


***Figure 3-5**: Baseflow separation at 609026: baseflow accounts for 50% of the total flow*

It is possible the reduction in flow during the past 10 years may have had negative ecological impacts on the Scott River. However, a study of the river's ecological flow requirements (EWRs) has not been undertaken. The river clearly demonstrates healthy natural habitat and biodiversity. However the significantly declining streamflows are a threat to its ecological values. Based on the combination of high environmental values and high potential threats to the river's ecology, we recommend an EWR study be undertaken for the Scott River.

3.2 Nutrient data collection and analysis

Since 2000 the Department of Water has conducted regular water quality sampling (surface water) at seven sites in the Scott River catchment. Data from these sites, as well as Brennan's Bridge on the Scott River (AWRC reference 6091051), have been used in this project. Nutrient samples are collected fortnightly when the waterways are flowing (generally between May and November), and are analysed for total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), filterable reactive phosphorus (FRP), nitrate/nitrite (NO_x), ammonia/ammonium (NH_3/NH_4), dissolved organic nitrogen (DON), temperature, conductivity and dissolved oxygen. The nutrient sampling sites are shown in Figure 3-6.

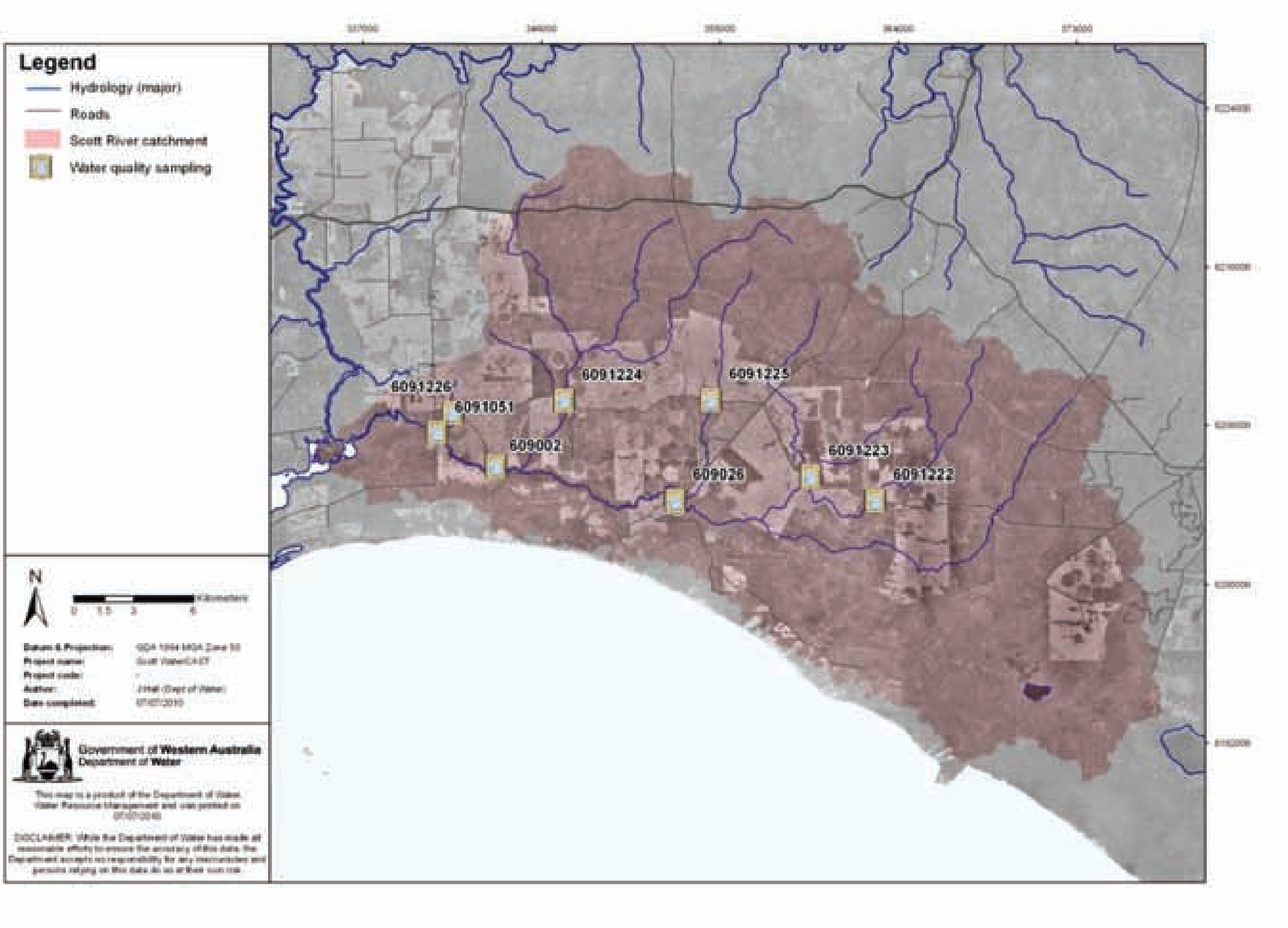


Figure 3-6: *Water quality sampling locations*

Nutrient status

The TN and TP concentrations are described in terms of the nutrient classifications shown in Table 3-1, which are from the Statewide River Water Quality Assessment webpage on the Department of Water's website <www.water.wa.gov.au/idelve/srwqa/>.

Table 3-1: *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

Depending on trends, chance sampling and sources of natural variation, the nutrient concentrations sampled from a monitored site will change. The nutrient status for a waterway is initially assigned using the median nutrient concentration for the first year of sampling. Subsequent status periods are assessed using the median and 90% confidence interval. If the median or all or part of the confidence interval remains in the earlier classification band then there is no change in status. Status only changes once both the median and entire 90% confidence interval move to a different classification band.

As an example of how this is determined, data from the Mayfield Main Drain (in the Peel-Harvey catchment) is shown in Figure 3-7. The status was originally classified as high (the median was between 1.2 and 2.0 mg/L). By 1992 – 1994 the median had decreased and fell within the moderate classification band (0.75 – 1.2 mg/L), yet part of the 90% confidence interval was still in the high classification band and hence the status remained high. In 1994 – 1996 both the median and 90% confidence interval fell below the high classification and hence the status changed to moderate. During 1996 – 1998 the median once again dropped to a lower classification band (<0.75 mg/L), however it wasn't until 1998 – 2000 that the actual classification status changed to low.

The nutrient status for a waterway is assigned by using the median of nutrient concentration for a three-year period. The three-year period is used to diminish the influence of natural variation between years. For the sampling sites in the Scott River catchment the most recent period of analysis (2007, 2008 and 2009) was used to determine current nutrient status, based on the technique outlined above.

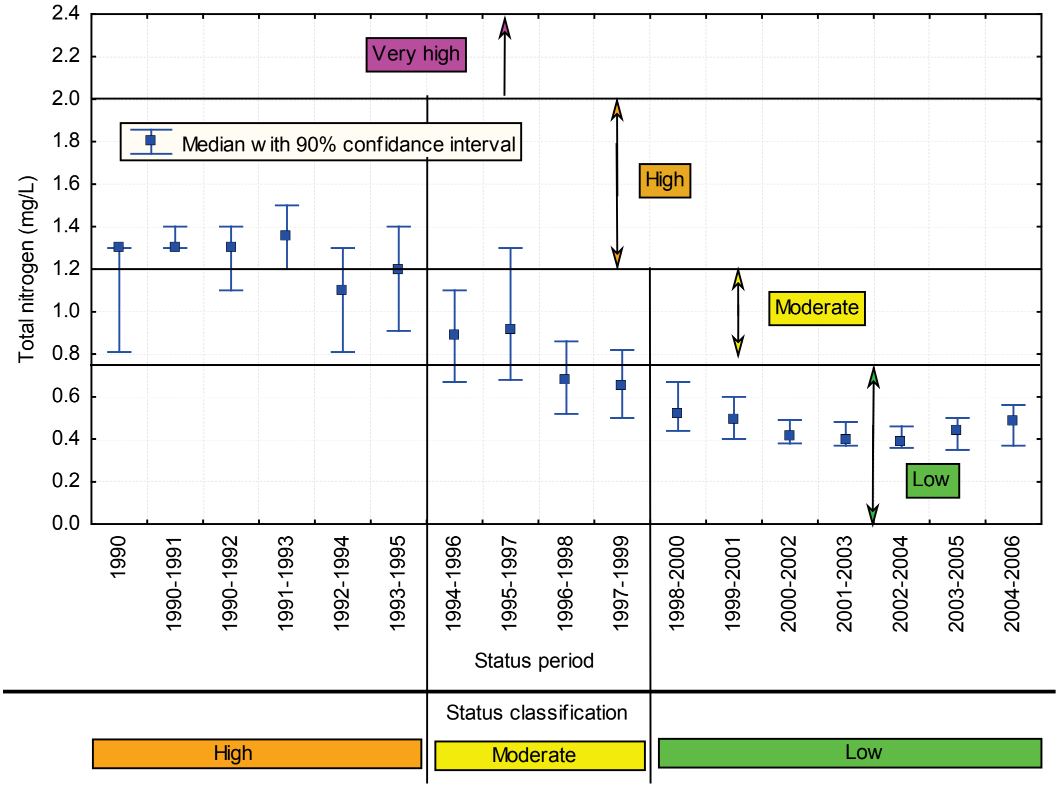


Figure 3-7: *Total nitrogen status classification for Mayfield Main Drain (AWRC 613031)*

The nutrient status results for the most recent three years of sampling at each of the Scott River catchment's nutrient sampling locations are shown in Table 3-2. According to classes taken from the Statewide River Water Quality Assessment webpage, nitrogen status is moderate to low in three of the eight sampling sites, and high to very high in the other five. Phosphorus was more of an issue, with high to very high nutrient status in seven out of the eight sampling locations. The most degraded sampling locations were at S-Bend (6091222), Milyeannup Bridge (609026) and Woodhouse (6091226). Interestingly, the locations at the lowest point in the Scott River (Brennan's Bridge and Brennan's Ford) have slightly lower status than those in the upper Scott River and in most of the tributaries. This could be due to the assimilation of nutrients in the heavily vegetated Scott River, or to dilution of the concentration in the waterways (although the latter is unlikely given the intensifying land uses downstream of Milyeannup Bridge).

***Table 3-2:** Nutrient status summary for the latest three years of data for sampling locations in the Scott River catchment*

Site name	AWRC reference	Site context	Median TN (2007 - 2009) mg/L	TN status	Median TP (2007 - 2009) mg/L	TP status
Brennan's Bridge	6091051	Bottom of the Scott River	1.00*	🟢	0.12*	🟡
Brennan's Ford	609002	Lower Scott River	1.00	🟢	0.15	🟡
Milyeannup Bridge	609026	Middle Scott River	1.40	🟡	0.18	🟡
Woodhouse	6091226	Scott River tributary	1.75	🟡	0.14	🟡
Coonack Downs	6091224	Scott River tributary	1.20	🟢	0.04	🟢
Governor Broome	6091225	Scott River tributary	1.60	🟡	0.15	🟡
Electric Fence - 4 Acres	6091223	Scott River tributary	1.40	🟡	0.15	🟡
S-Bend	6091222	Scott River tributary	2.20	🔴	0.68	🔴

* median concentration for this site was for 2004 - 2006, as samples ceased being collected at this location in 2006

Nutrient run-down

There is a lag time between when nutrients are applied to the land and their being expressed in waterways. This is due to retention of nutrients in soils, groundwater and vegetation stores. Applied nutrients (from fertilisers, animal waste, fixation, septic leachate etc.) may also be assimilated into the soil profile or, in the case of nitrogen, lost to the atmosphere.

Thus the nutrients measured in the catchment's waterways are associated with the land uses of the previous five to 10 years, so a land use from 2005 is still likely to be contributing nutrients to the waterways in 2009. Nutrient run-down makes it very difficult to attribute waterway nutrient loads to a particular land use for a particular year. However, it is likely that fertiliser applied in the catchment in 1990 is not being expressed post-2000, so the latest three years of nutrient data should roughly represent the past decade's land use.

When relating nutrient load or concentration measurements from a surface waterbody to the associated land use in the catchment, nutrient run-down and hence the previous year's land-uses in the catchment must be considered.

Statistical trends for nutrient concentrations

Nutrient concentrations in waterways vary due to:

- changes in flow
- seasonal variations
- trends related to land use or climate changes
- land management practices
- relative timing of fertiliser application, rainfall and data collection
- streambank erosion following floods or fires in the catchment
- any other disturbance or activity in the catchment that changes stream flow or amount and type of material that is washed into the waterway.

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

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

The results of the statistical trends analysis are shown in Table 3-3. 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 ($n^\#$). Thus, if $p < 0.05$ and $n^* > n^\#$, then there is a significant statistical trend. If $p < 0.05$ and $n^* < n^\#$, then there is likely to be a trend emerge if more samples are collected, however the trend is not significant. In this case the trend is labelled an 'emerging' increasing or decreasing trend. If $p > 0.05$ there is no significant trend.

No statistically significant trends were observed for the period 2000 – 2009. There were emerging increasing trends at 6091223, 6091225, 6091226 and 609002 for TP and at 609002 and 6091223 for TN. During the past decade, land use upstream of 6091223 and 6091225 has changed from beef grazing to blue gum plantations. Soil disturbance from blue gum plantations is likely to release phosphorus in the Swan Coastal Plain's sandy soils. There were emerging decreasing trends in TP at 6091224. This is likely to be related to the blue gums upstream being predominantly established and no longer requiring fertiliser (fertiliser is required in the first five years of growth only).

Table 3-3: Trend results for concentrations in waterways for the period 2000 - 2009

Site	Parameter	Period	Series	Test	Trend	p	n	n^*	$n^\#$	Trend results
6091051	TP	2000-2009	Obs.	MK	0.01	0.41	57	27	217	No trend
6091051	TP	2000-2009	Obs.	SK	0.01	0.36	57	55	158	No trend
6091051	TN	2000-2009	Obs.	MK	-0.05	0.24	57	55	246	No trend
6091051	TN	2000-2009	Obs.	SK	0.00	0.93	57	55	-	No trend
609026	TP	2000-2009	Obs.	MK	-0.01	0.19	129	37	2946	No trend
609026	TP	2000-2009	Obs.	SK	0.00	0.47	129	68	10678	No trend
609026	TN	2000-2009	Obs.	MK	0.00	0.69	129	29	-	No trend
609026	TN	2000-2009	Obs.	SK	0.01	0.44	129	45	11119	No trend
609002	TP	2000-2009	Obs.	MK	0.00	0.13	100	66	1550	No trend
609002	TP	2000-2009	Obs.	SK	0.00	0.04	100	98	1543	Emerging increasing
609002	TN	2000-2009	Obs.	MK	0.01	0.27	100	64	5220	No trend
609002	TN	2000-2009	Obs.	SK	0.02	0.06	100	98	2023	No trend
609002	TP	2000-2009	FAC	MK	0.01	0.04	100	59	729	Emerging increasing
609002	TP	2000-2009	FAC	SK	0.00	0.01	100	89	1244	Emerging increasing
609002	TN	2000-2009	FAC	MK	0.02	0.13	100	63	3207	No trend
609002	TN	2000-2009	FAC	SK	0.03	<0.01	100	98	1110	Emerging increasing
6091226	TP	2000-2009	Obs.	MK	0.01	<0.01	97	31	516	Emerging increasing
6091226	TP	2000-2009	Obs.	SK	0.01	<0.01	97	30	726	Emerging increasing
6091226	TN	2000-2009	Obs.	MK	-0.02	0.42	96	55	9129	No trend
6091226	TN	2000-2009	Obs.	SK	0.00	0.91	96	93	-	No trend
6091225	TP	2000-2009	Obs.	MK	0.01	0.07	77	15	806	No trend
6091225	TP	2000-2009	Obs.	SK	0.01	0.03	77	15	474	Emerging increasing
6091225	TN	2000-2009	Obs.	MK	0.02	0.51	77	21	6209	No trend
6091225	TN	2000-2009	Obs.	SK	0.02	0.22	77	38	2244	No trend
6091224	TP	2000-2009	Obs.	MK	0.00	0.04	106	36	1536	Emerging decreasing
6091224	TP	2000-2009	Obs.	SK	0.00	0.01	106	42	884	Emerging decreasing
6091224	TP	2000-2009	Obs.	MK	0.00	0.04	106	36	1506	Emerging decreasing
6091224	TN	2000-2009	Obs.	SK	0.00	0.85	106	11	-	No trend
6091223	TP	2000-2009	Obs.	MK	0.00	0.70	120	46	31430	No trend
6091223	TP	2000-2009	Obs.	SK	0.00	0.14	120	79	1930	No trend
6091223	TN	2000-2009	Obs.	MK	0.01	0.16	120	71	1160	No trend
6091223	TN	2000-2009	Obs.	SK	0.03	0.01	120	84	183	Emerging increasing
6091222	TP	2000-2009	Obs.	MK	0.03	<0.01	124	53	428	Emerging increasing
6091222	TP	2000-2009	Obs.	SK	0.03	<0.01	124	118	392	Emerging increasing
6091222	TN	2000-2009	Obs.	MK	0.00	0.68	124	37	-	No trend
6091222	TN	2000-2009	Obs.	SK	0.00	0.65	124	75	-	No trend

Obs. = Observed data points
FAC = Flow adjusted concentrations
MK = Mann Kendell test for trend
SK = Seasonal Kendell test for trend
n = number of samples
n^* = number of independent samples
$n^\#$ = number of independent samples required to detect a significant trend

3.3 Fertiliser application

DAFWA has undertaken surveys and collected fertiliser application data in the catchment. According to the surveys, most irrigated dairies in the catchment use the CSBP product Grazeburst^{TM}, using 12 – 15 applications per year at 160 kg/ha/application. Grazeburst^{TM} consists of 25.3% N and 3.9% P. This equates to an application rate of 450 kg N/ha/yr and 76.5 kg P/ha/yr. It should be noted that a high nitrogen rate is required for irrigated dairy pasture if viable production is to occur; however, the phosphorus rate of 76.5 kg P/ha/yr is likely to be much higher than the pasture requirements.

Dryland dairies generally use the CSBP product Hayburst^{TM} (18% N and 2.5% P) or Springburst^{TM} (13.7% N and 2.6% P) at much lower rates than irrigated dairies (approx 200 – 300 kg/ha/yr). Irrigated beef pasture also uses Grazeburst^{TM} but at 8 – 9 applications per year and at 120 kg/ha/application. A variety of fertiliser types are used for dryland beef, including Springburst^{TM}, Hayburst^{TM}, urea and other NPK mixes, which are spread at a range of application rates depending on the property.

Irrigated horticulture uses the CSBP product Potato E+^{TM} (7.0% N and 12.5% P) at a very high application rate of 2000 kg/ha pre-plant, and an extra 300 kg/ha weekly during the growing phase.

For blue gum plantations, fertilisers are applied at planting (usually in winter or spring) typically using the CSBP product Agras^{TM} (16.1% N and 9.1 % P) at 200 kg/ha. Fertilisation is then repeated once or twice over the next five years. This follow-up fertilisation is usually 200 – 300 kg/ha of Agras^{TM}.

In addition to the fertiliser application rates, significant nitrogen is added to the catchment via nitrogen fixation from pasture legume species such as clover (this also occurs with native plants, particularly acacia species). In addition, nutrients are applied via animal waste or when feed is imported on-site to supplement pasture feed for livestock. Nitrogen fixation by irrigated pasture land uses is assumed to be between 100 and 200 kg/ha/yr (Peoples et al. 1995) – a value of 150 kg/ha has been estimated for these land uses (DAFWA calculated irrigated fixation of between 88 and 152 kg/ha/yr at the Vasse Research Station in the Geographe catchment). Non-irrigated pasture was likely to have lower rates of fixation, and based on Peoples' 'rule' of 42 kg N/ha for each tonne of clover grown, the dryland pasture fixation rates were estimated to be 75 kg N/ha/yr. When the results of the surveys have been analysed and nutrients from other inputs accounted for, the result is nutrient input rates for each of the enterprises on the Scott Coastal Plain. The fertiliser application rates are shown for each land-use type in both kg/ha and the total load (based on the area of that particular land use) in Table 3-4.

Table 3-4: Average fertiliser input rates and total loads for land uses in the Scott catchment

Land use	Fertiliser rate		Fixation	Total input rate		Area	Total input load	
	TP	TN	TN	TP	TN		TP	TN
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	km^2	t/yr	t/yr
Dryland beef	19.8	39.9	75.0	19.8	114.9	73.2	144.9	841.1
Dryland dairy	21.5	91.5	75.0	21.5	166.5	12.6	27.1	209.8
Blue gums (immature)	19.0	43.8	75.0	19.0	118.8	39.7	75.4	471.4
Irrigated beef	31.0	108.4	150.0	31.0	258.4	2.0	6.2	51.7
Irrigated dairy	76.5	454.5	150.0	76.5	604.5	14.6	111.7	882.6
Irrigated horticulture	1092.0	474.0	150.0	1092.0	624.0	0.4	39.3	22.5
Seasonal horticulture	0.0	84.0	0.0	0.0	84.0	0.6	0.0	5.1
Native vegetation	0.5	0.0	21.3	0.5	21.3	462.3	20.8	984.7

Clearly, irrigated dairy has the largest total nitrogen input – it is more than three times that of the second-largest contributor, dryland beef. Other major nitrogen contributions are from dryland dairy and blue gum plantations; whereas irrigated horticulture, irrigated beef, residential and seasonal horticulture nitrogen input loads are less significant.

Phosphorus inputs are mostly contributed by dryland beef, closely followed by irrigated dairy. Theoretically, these two enterprises require similar phosphorus input rates, however dryland beef occupies five times as much land area. Other significant contributors for phosphorus inputs include immature blue gums, and to a lesser extent, irrigated horticulture and dryland dairy. Irrigated beef, seasonal horticulture and residential enterprises contribute a very small portion of phosphorus fertiliser inputs.

It should be noted that the input rates do not include fodder (feed imported on-site for stock). While this is generally a minor nutrient input, it may be significant for some land uses (e.g. dairy, which usually uses imported feed for cows to consume while milking). For more detailed farm-scale studies we recommend that fodder inputs be included in nutrient budgeting calculations.

Point sources

Point sources of nutrient pollution were investigated for the Scott River catchment, and consisted of six dairy sheds and a feedlot. The location of the point sources is shown in Figure 3-8. The export loads for the dairy sheds were calculated by multiplying the effluent volume by concentrations of 230 mg/L for TN and by 40 mg/L for TP (DoE 2002). Sites that discharged directly to surface drainage or to small infiltration ponds on sandy soils with no fertigation were assumed to be contributing 100% of their nutrients to the environment. For partially sealed pond systems with fertigation, it was assumed that 30% of the load would be reduced due to re-use, and for multiple pond systems 60% reduction was assumed. These values were taken from the Vasse-Wonnerup report to the National Pollutant Inventory (DoE 2004). The feedlot assumed export rates of 8.66 kg N/cow/yr and 2.24 kg P/cow/yr (DoE 2004; Fahrner 2002). This rate is comparable to a rate of 3.88 kg P/cow/yr reported by The

Royal Netherlands Institute for Sea Research. For the combined point sources, a total of 6.4 tonnes/yr of nitrogen and 1.34 tonnes/yr of phosphorus is estimated as the catchment input.

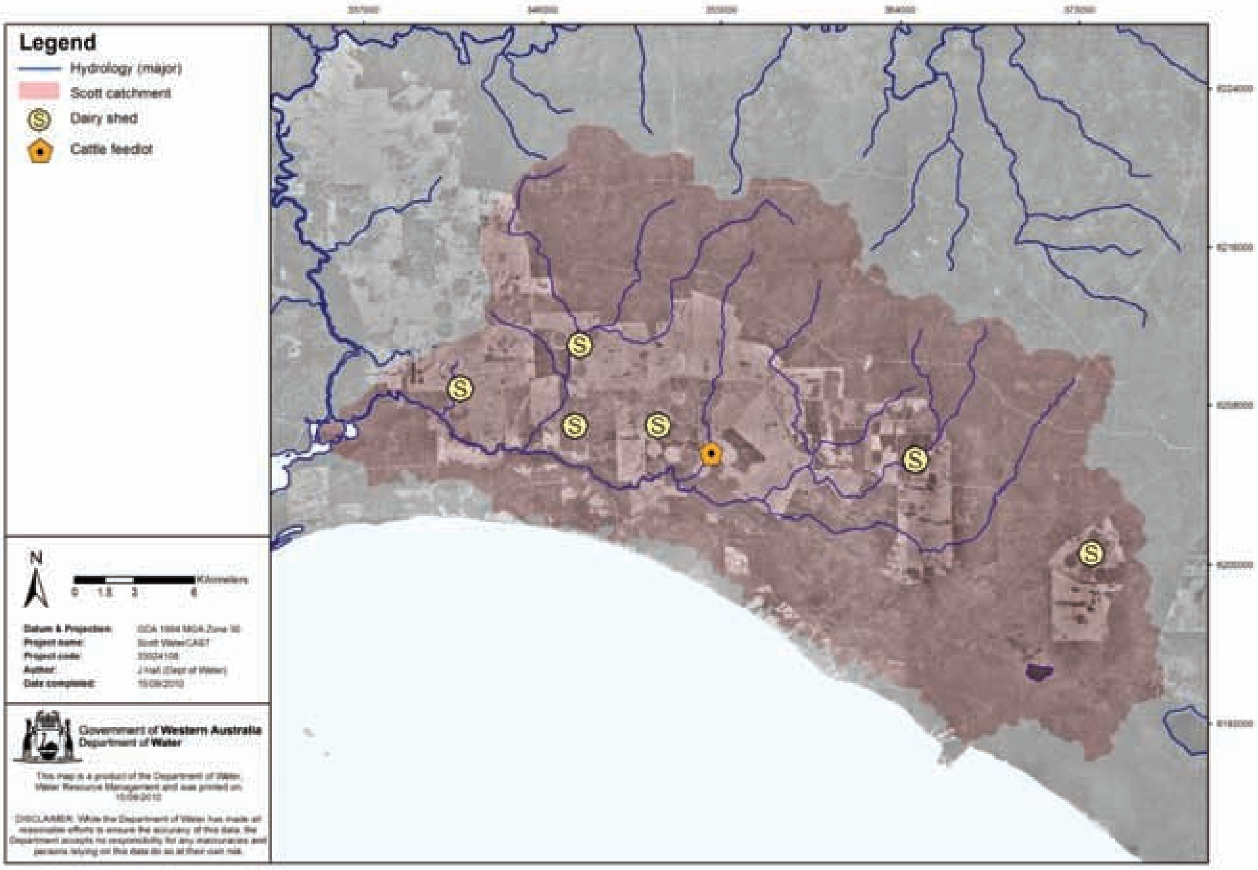


Figure 3-8: Point source locations in the Scott River catchment

Septic tanks

Total input from the Molloy Island septic tanks was determined by multiplying the number of established residences by the average septic rate of 1.1 kg/person/yr for phosphorus and 5.5 kg/person/yr for nitrogen (Wheeler & Barrow 1984). Because most of the houses are not usually occupied, an average of one person per house was estimated for the overall residency rate. This equated to an average annual TP input of 0.22 tonnes and an average annual TN input of 1.1 tonnes.

4 Conceptual model

The Scott River receives runoff primarily from rainfall, but also from irrigation returns. On the sandy coastal plain most of the rain will infiltrate to the soil, where it will either evaporate or percolate to the shallow watertable. Over the course of the year the shallow watertable will intersect the drain and riverbed levels and discharge to the waterways in late autumn/early winter. Associated soluble nutrients will be transported with this hydrological flux.

When the shallow watertable is at the ground surface (usually around mid-winter) the rainfall will flow directly over the saturated ground surface, and will transport both particulate and soluble nutrients (saturated excess flow). Large rainfall events in the heavy soils to the north of the catchment will not have the opportunity to percolate into the groundwater, and will run off directly to the downstream waterways (infiltration-excess flow). This may happen on the sandy plain in extreme rainfall events, but is much less common. Nutrients delivered to the waterways (particulate and soluble) can either precipitate or adsorb to the channel sediments, be taken up by vegetation in the river channel or be transported along with the river flow. Only a small proportion of the nutrient applied annually is exported to the Hardy Inlet. A conceptual diagram of the hydrological and nutrient processes in the Scott River catchment is shown in Figure 4-1.

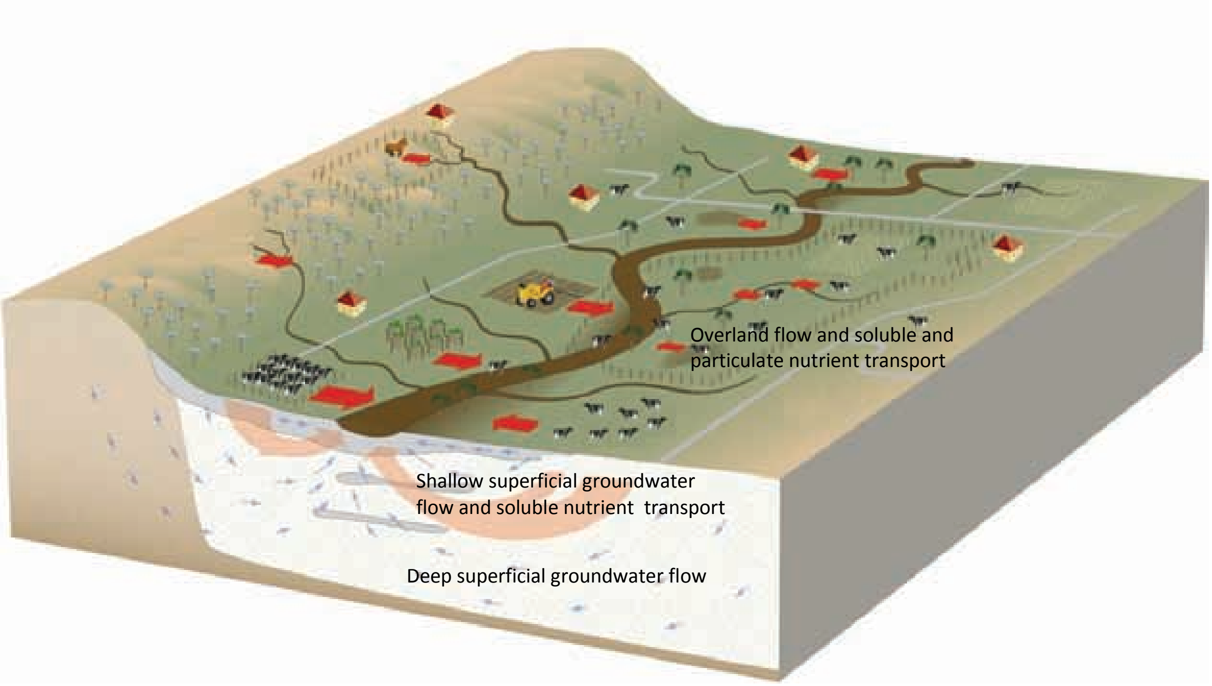


Figure 4-1: *Conceptual diagram for water and nutrient movement in the Scott River catchment*

An average annual conceptual water and nutrient balance was developed for the Scott River catchment, based on the data collected (discussed in the previous sections). The purpose of presenting conceptual fluxes is to determine their order-of-magnitude effects on the catchment and compare them. The absolute figures are not required to be precise, and 'back of envelope' style calculations are generally used to determine the conceptual flux quantities.

Data from the Scott River rainfall gauging station (9926), between the years 2000 – 2009, was used to determine the rainfall quantity over the catchment area of 691 km^2. Irrigation volume was determined using the Department of Water allocation values for abstraction bores in the catchment. The average annual river flow of 66 GL/yr was determined from data from the Brennan's Ford gauging station (609002), which drains an area of 643.4 km^2. This was scaled linearly to estimate the flows for the entire catchment. Baseflow and surface flow components were estimated using the baseflow separation results (see Section 3.1). The losses were equal to the inputs (rainfall and irrigation) minus the outputs (flow). The quantity of recharge and deep percolation versus evapotranspiration were not required for the conceptual model.

Phosphorus and nitrogen fertiliser inputs were calculated by multiplying the fertiliser rates for each of the land uses by their areas. Nitrogen included fixation as an input, and fixation was set to 150 kg/ha for irrigated pasture, 75 kg/ha for non-irrigated pasture, and 21 kg/ha for native vegetation. Native vegetation fixation rates were taken from Lawrie (1981) and pasture rates from Peoples et al. (1995). The nutrient exports were determined by taking the average concentrations at the location nearest to the outlet of the Scott River and multiplying by the flow.

The results of the conceptual flux calculations are shown in Table 4-1. Nutrient export was estimated to be approximately 2.5% of the nutrient input for phosphorus and 1.9% of the input for nitrogen. However the estimated percentage of nitrogen exported is highly dependent on the estimated nitrogen fixation amount, and thus could be greater than 1.9%.

Table 4-1: *Average annual conceptual fluxes for water and nutrients in the Scott River catchment (2000 – 2009)*

Flux	Quantity	Unit	Quantity	Unit	%
Conceptual hydrological fluxes					
Rainfall	943	mm	651	GL	98%
Irrigation	16	mm	11	GL	2%
Total river flow	147	mm	71	GL	-15%
Surface flow component	74	mm	36	GL	-8%
Baseflow component	74	mm	36	GL	-8%
Losses (EVT/percolation)	811	mm	591	GL	-85%
Conceptual phosphorus fluxes					
Fertiliser input	6.4	kg/ha	430	t	99.7%
Dairy shed / feedlot input	-	-	1.3	t	0.3%
Septic tank input	-	-	0.2	t	0.05%
Nutrient export	0.2	kg/ha	11	t	-2.5%
Losses (soil, plants, animals etc)	6.2	kg/ha	421	t	-97.5%
Conceptual nitrogen fluxes					
Fertiliser input	19.1	kg/ha	1295	t	35.3%
Dairy shed / feedlot input	-	-	6.4	t	0.2%
Septic tank input	-	-	1.1	t	0.03%
Fixation input	37.0	kg/ha	2363	t	64.5%
Nutrient export	1.0	kg/ha	71	t	-1.9%
Losses (soil, plants, animals etc)	55.0	kg/ha	3595	t	-98.1%

5 Model construction

5.1 Selection of software

Modelling software (or code) was selected according to the following considerations:

- **Project deliverables:** this includes the base model and model scenario outputs. The software must be appropriate to deliver the desired outputs to clients and stakeholders.
- **The conceptual model:** the modelling software capabilities must align with the conceptual model. The model must be able to produce rainfall-runoff and constituent generation processes that are outlined in the conceptual model. Scale (both temporal and spatial), topography and climate must be considered (e.g. in an alpine catchment where snow-melt is a major hydrological process, modelling code that does not describe snow-melt does not satisfy the conceptual model).
- **Complexity:** the modelling code should have a complexity that aligns with model deliverables. Selection of code should satisfy the simplicity principle; that is, the code should be simplified as much as possible, but retain enough complexity to adequately represent the physical system and its behaviour.
- **Cost:** some commercial software packages are very expensive (tens of thousands of dollars per licence), and the cost of the numerical code should align with project budgets.

A review of software able to model nutrient and hydrologic processes on a catchment scale was undertaken, and five potential software packages were identified. These were then scored from 1 – 5 (1 being worst and 5 being best) based on the above criteria. A list of appropriate software and the scoring is shown in Table 5-1.

Table 5-1: *Scores for relevant hydrologic and constituent modelling software*

Modelling code	**Reference**	**Criteria**				
		Deliverables	**Conceptual**	**Complexity**	**Cost**	**Total**
Mike SHE	*DHI 2005*	4	5	2	1	**12**
CMSS	*Kelsey 2010*	3	4	2	5	**14**
Source Catchments	*eWater CRC 2010*	4	4	5	4	**17**
SQUARE	*Hall et al 2010*	3	5	3	5	**16**
SSPND	*Ecotones and Associates 2008*	4	3	4	5	**16**

Mike SHE (DHI 2005) is a physically-based integrated groundwater and surface water model, and has capabilities to deliver all appropriate outputs. It had issues with run-times and over-complexity compared with the project's requirements and is very expensive, and thus scored poorly. CMSS lacked the complexity required for the project, given it does not model the desired hydrological processes.

The model SQUARE was possibly over-complex for the modelling project requirements, and does not easily implement management practices and cost/benefit analysis. Conversely, the SSPND model has a cost-benefit module but does not model rainfall-runoff processes. The modelling package Source Catchments was selected as the most appropriate software for the project, which satisfied all of the above criteria. The SQUARE model was used on the Scott River catchment in 2007 (DoW 2007) to accurately quantify catchment flows and nutrient load delivery to the Hardy Inlet, yet it is not the preferred model for simulating various combinations of management practices and determining the subsequent nutrient effects and associated cost/benefits, which was the scope of the current project.

Source Catchments

Source Catchments is a software package developed by eWater, and is designed for hydrologic and constituent modelling at the whole-of-catchment scale. Source Catchments provides a flexible structure that allows users to select a level of model complexity appropriate to the problem at hand and within constraints imposed by available data and knowledge.

Several versions of Source Catchments have been produced since its original implementation as the E2 Modelling Framework in 2005 (starting with E2 version 1.1.0) which included a basic set of model selection, analysis and scenario tools. Version 1.0.0 beta (released in October 2008) was released under the name ‘WaterCAST’ and extended the original E2 Modelling Framework with new models and scientific functionality.

Source Catchments is a node-link style system for modelling water and constituent transport within the major channels in a catchment. Subcatchment boundaries can be determined based on stream topography and land forms calculated from a Digital Elevation Model (DEM). Subcatchments are connected via links and nodes that represent river and stream reaches and confluences, terminating at a catchment outlet. After generation and filtration, the constituents pass to a node before being routed and possibly processed along links.

In Source Catchments, subcatchments are divided into areas with a common hydrologic response or behaviour – ‘functional units’ (FUs) – based on various combinations of land use/cover (e.g. forest, crop, urban), management, position in landscape (flat, hill-slope, ridge) and/or hazard (however defined).

An FU refers to an area of particular hydrologic response and is not the same as a land use. Different land uses may have the same hydrologic response; similar land uses could have different hydrologic responses. When creating a Source Catchments model, FUs reflect the different hydrologic responses in the area of interest.

Three basic ‘processes’ are defined to operate in an FU:

- runoff generation
- constituent (contaminant) generation
- filtering.

This enables the availability of a ‘menu’ of different algorithms for each process in each subcatchment, delivering the resulting flows and loads to the subcatchment node.

Rainfall-runoff component models are applied to each FU in each subcatchment, and the user can apply different parameter sets to each FU. Similarly, different constituent generation and filter models can be used in different FUs or different subcatchments. Source Catchments supports a split of flow and loads into notional surface and subsurface (quick and slow) portions from each FU.

A node is a point below which subcatchment loads enter the system, where water and materials may enter or leave, or where there is a confluence. Nodes provide a position in the catchment network where water management information, such as extractions and demands, can be placed. Nodes can also be used as points where model flows and loads can be set to pre-defined values, allowing representation of, for example, an upstream area that is not being explicitly modelled. A range of node models is available to support these requirements. Flows and loads from subcatchments enter as virtual lateral fluxes below the relevant subcatchment node. Thus, in uppermost subcatchments without explicit incoming nodal fluxes, node flows will be null.

Links act to store water and to route or process water and constituents passing from node to node. They also allow for interaction with the floodplain for reaches/links with large floodplain areas. Within a subcatchment, some level of interaction with ‘floodplains’ is represented by the filtering components – in the case of links we are dealing with floodplains of major rivers. Due to the conceptual similarity between links and storages (e.g. spatial extent, routing inflow to outflow, evaporation, water quality processing), storages are viewed as short links, rather than nodes. Along links there are ‘blocks’ providing basic in-stream processing functions where a choice of algorithm is possible.

Model limitations

Limitations to Source Catchments are as follows:

- Source Catchments adopts a particular conceptual structure for integrated catchment models. This structure may not be the most appropriate for all types of problems (such as explicit groundwater modelling).
- The predictive power of Source Catchments depends on the available component models, and the appropriate use of those models in the problem domain, or with the available data.
- Source Catchments is not suitable for detailed water quality modelling (e.g. the interactions between nutrient subspecies), hydraulic modelling or ecological modelling.
- Source Catchments assumes a static land-use map, and results are steady-state (i.e. it does not account for changing land use during calibration).

5.2 Model input datasets

Spatial data

Source Catchments requires that the model be divided into a series of subcatchments. The results of flow and constituent generation can then be reported at the outlet of each subcatchment, and compared with observed data for calibration. The Scott River catchment was divided into 14 separate subcatchments (Figure 5-1). The base of each of these subcatchments was either at the confluence of a major tributary, or at a flow or nutrient sampling location.

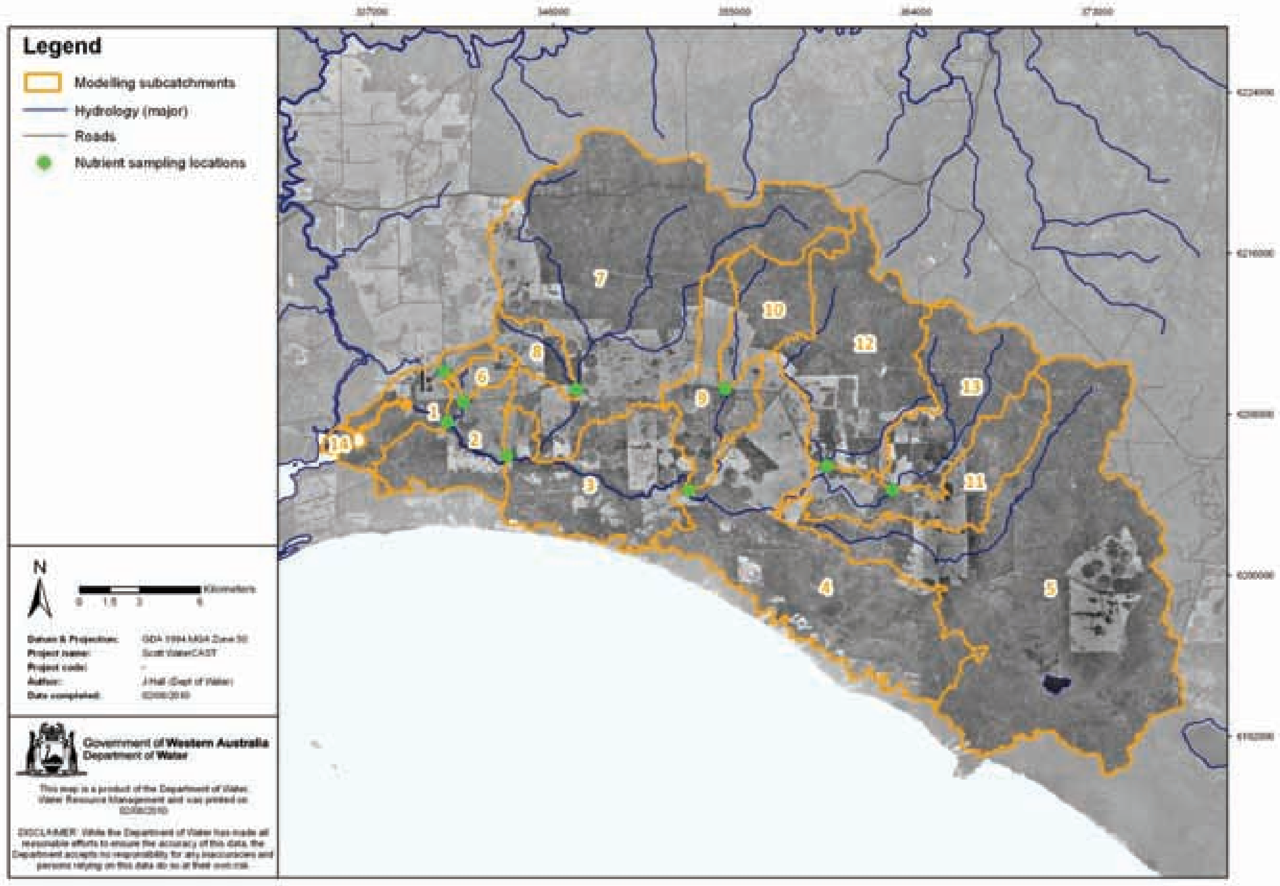


Figure 5-1: Subcatchment delineation for the Scott catchment Source Catchments model

The other spatial dataset required for the Source Catchments model was the land-use dataset which was used to determine the functional units (FUs) within the model.

The land-use categories from Figure 2-6 were adopted for the model. The spatial datasets were re-sampled to a 20 m by 20 m grid, which was used to determine the FUs and their associated subcatchments.

Time-series data

Rainfall and evapotranspiration did not vary significantly throughout the catchment. Therefore the model used a single gauging station for the rainfall and evapotranspiration data over the entire model domain. The rainfall was taken from the Scott River rainfall station (9926) and averaged 966 mm/yr between the years 1970 and 2009. The average annual pan evaporation was 1100 mm. Daily rainfall and evaporation data was used in the model (the data is summarised in Section 2.2).

5.3 Rainfall-runoff model selection

A series of rainfall-runoff models (SYMHYD, AWBM and LASCAM) were trialled for the Scott River catchment and the best calibration for the simplest model was achieved using the Australian Water Balance Model (AWBM). AWBM (Boughton 1996) is a catchment water balance model that relates runoff to rainfall with daily or hourly data, and calculates losses from rainfall for flood hydrograph modelling. The implementation of AWBM for the Scott River project is modelled at a daily time-step.

The model contains five stores: three surface stores to simulate partial areas of runoff, a baseflow store, and a surface runoff routing store. There are eight associated parameters (a list and description of these are shown in Table 5-2).

Table 5-2: *AWBM model parameters, defaults and limits*

Parameter	Description	Units	Default	Minimum	Maximum
A_1	Partial area of surface store 1	-	0.13	0.00	1.00
A_2	Partial area of surface store 2	-	0.43	0.00	1.00
BFI	Base flow index	-	0.35	0.00	1.00
C_1	Capacity of surface store 1	mm	7	0	200
C_2	Capacity of surface store 2	mm	70	0	500
C_3	Capacity of surface store 3	mm	150	0	800
K_{base}	Baseflow recession	day^{-1}	0.95	0.00	1.00
K_{Surf}	Surface flow recession	day^{-1}	0.35	0.00	1.00

The water balance of each surface store is calculated independently of the others. The model calculates the moisture balance of each partial area at each time-step. Rainfall is then added to each of the three surface moisture stores and evapotranspiration is subtracted from each store. The water balance equation is:

$$\text{store}_n = \text{store}_n + \text{rain} - \text{evap} \quad (n = 1 \text{ to } 3)$$

If the value of moisture in the store becomes negative, it is reset to zero, as the evapotranspiration demand is superior to the available moisture. If the value of moisture in the store exceeds the capacity of the store, the moisture in excess of the capacity becomes runoff and the store is reset to the capacity.

The three parameters A_1, A_2 and A_3 representing the proportions of the areas of the catchment are constrained; thus only A_1 and A_2 can be set. When A_1 and/or A_2 are changed, A_3 will be adjusted to respect the constraint (the sum of A_1, A_2 and A_3 must always be equal to 1).

When runoff occurs from any store, part of the runoff becomes recharge of the baseflow store if there is baseflow in the streamflow. The fraction of the runoff used to recharge the baseflow store is BFI multiplied by runoff, where BFI is the baseflow index; that is, the ratio of baseflow to total flow in the streamflow. The remainder of the runoff (1.0 - BFI) multiplied by runoff, is surface runoff. The baseflow store is depleted at the rate of (1.0 - K) multiplied by BS, where BS is the current moisture in the baseflow store and K is the baseflow recession constant of the time-step.

The surface runoff can be routed through a store if required to simulate the delay of surface runoff reaching the outlet of a medium to large catchment. The surface store acts in the same way as the baseflow store, and is depleted at the rate of (1.0 - KS) multiplied by SS, where SS is the current moisture in the surface. A conceptual diagram of the AWBM is shown in Figure 5-2.

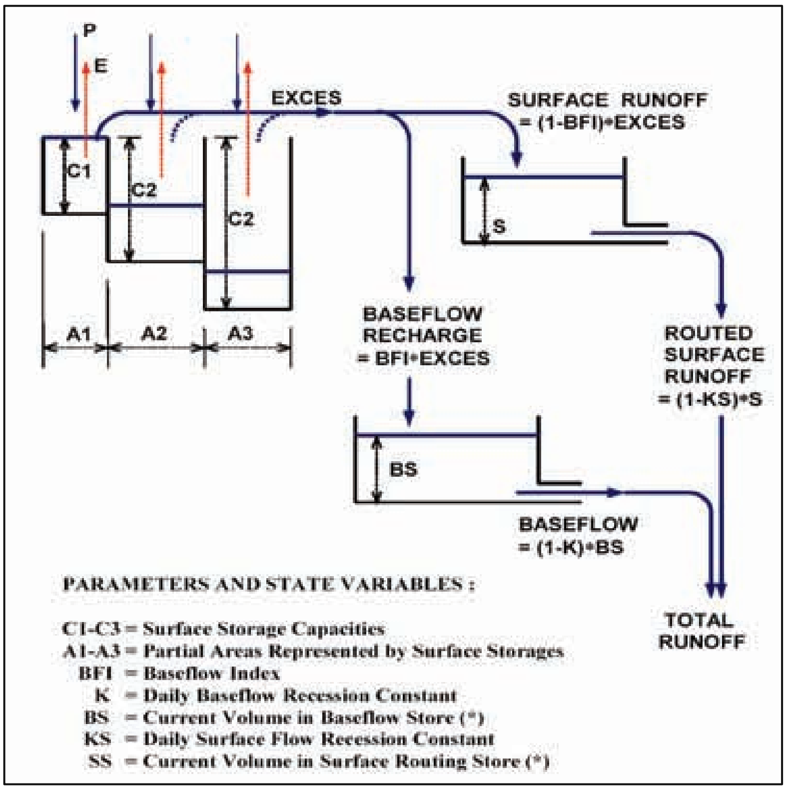


Figure 5-2: *Conceptual diagram for the AWBM model (eWater 2010)*

5.4 Selection of constituent generation model

Constituent generation models describe how constituents are generated within a functional unit (FU). This may be static or time-varying as a function of flow or other variables. Source Catchments has a selection of constituent generation models – event mean concentration (EMC)/dry weather concentration (DWC), export coefficient/export rate, and observed constituent. The constituent generation model selected for the Scott was the EMC/DWC model. The EMC/DWC model applies a fixed constituent concentration to an FU.

EMC values are applied to surface (quick) flow, and DWC values to slow (base) flow. Because the separation for input data of DWC and EMC flows were not available, the Scott model used a constant value for both DWC and EMC for each FU. This model was selected because values for edge-of-paddock concentrations are often measured and well documented, so users and managers can relate concentrations used in the model calibration to both measured concentration data for a particular type of FU, or concentration data from the literature for a particular land-use type in a particular soil type. Selection of the initial concentration values for each FU is described in the following section. These values were adjusted in calibration.

Initial runoff concentration values

Concentration runoff values for each of the FUs are parameters that are usually adjusted during calibration of the Source Catchments model – however it is imperative that concentrations are within reasonable bounds and based on sound science and literature if the model is to accurately represent the catchment. The initial concentration used in the modelling was determined by dividing the estimated export load by the estimated flow for each of the land uses. The export load was estimated to be 3% of the nutrient surplus. The values for fertiliser rates, fixation, surplus, export, and runoff concentration for each of the land uses are shown in Table 5-3.

Table 5-3: *Derivation of initial runoff concentrations for each of the land-uses*

Land use	Fertiliser rate		Fixation	Surplus*		Flow rate	Export**		Runoff mean	
	TP	TN	TN	TP	TN		TP	TN	TP	TN
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	mm/yr	kg/ha	kg/ha	mg/L	mg/L
Dryland beef	19.8	39.9	75.0	14.9	86.2	148	0.45	2.6	0.30	1.75
Dryland dairy	21.5	91.5	75.0	16.1	124.9	148	0.48	3.7	0.33	2.53
Blue gums (immature)	19.0	43.8	75.0	14.3	89.1	148	0.43	2.7	0.29	1.81
Irrigated beef	31.0	108.4	150.0	23.2	193.8	249	0.70	5.8	0.28	2.33
Irrigated dairy	76.5	454.5	150.0	57.4	453.4	249	1.72	13.6	0.69	5.46
Irrigated horticulture	1092.0	474.0	150.0	819.0	468.0	249	24.57	14.0	9.87	5.64
Residential	6.6	27.4	0.0	4.9	20.5	148	0.15	0.6	0.10	0.42
Seasonal horticulture	0.0	84.0	0.0	0.0	63.0	148	0.00	1.9	0.00	1.28
Blue gums (mature)	0.2	0.0	21.3	0.2	16.0	74	0.01	0.5	0.01	0.65
Cleared land	0.5	0.0	21.3	0.4	16.0	148	0.01	0.5	0.01	0.32
Roads	1.6	4.0	21.3	1.2	19.0	148	0.04	0.6	0.02	0.38
Lucerne	1.6	77.5	150.0	1.2	170.6	148	0.04	5.1	0.02	3.46
Native vegetation	0.5	0.0	21.3	0.3	16.0	74	0.01	0.5	0.01	0.65

* surplus is estimated as 75% of total input

** assuming an export:surplus ration of 3%

Runoff and export concentrations generally agree with values in the literature, and measured values from the Swan Coastal Plain. Stewart (2010) measured runoff values for south-west Western Australian blue gum plantations of 0.24 mg/L TP (14 samples with a standard deviation of 0.81 mg/L) and 1.81 mg/L for TN (14 samples with a standard deviation of 2.87 mg/L). The same paper has pasture measured at 0.61 mg/L TP (22 samples with a standard deviation of 0.82 mg/L) and 3.56 mg/L TN (22 samples with a standard deviation of 3.65 mg/L). Remnant vegetation had a median TN value of 0.71 mg/L (11 samples with a standard deviation of 0.15). Young (1995) reported export loads in Western Australian catchments for improved pasture of 0.5 – 1.9 kg/ha/year for TP and 2.4 – 3.5 kg/ha/year for TN. The same paper reported market garden exports (in south-eastern Australia) of 2.7 – 14.3 kg/ha/yr for TP and 20 – 34.5 kg/ha/yr for TN.

DAFWA has collected a large number of TP and TN samples from edge-of-paddock runoff for dryland beef, irrigated dairy, and dryland dairy land uses. This was undertaken at the Vasse Research Station in south-west Western Australia as part of the Greener Pastures project. Between 230 and 570 nutrient samples were collected for analysis from each of the land uses between the years 2003 – 2009. TN rates for dryland beef had a median of 2.7 mg/L, while irrigated dairy had a median concentration of 6.7 mg/L and dryland dairy of between 6 and 10 mg/L depending on the fertilisation rate. TP rates for dryland beef had a median of 0.6 mg/L, with irrigated dairy having a median runoff rate of 0.45 mg/L and dryland dairy 0.7 to 1.10 mg/L depending on nitrogen fertilisation rates. These values were relatively consistent with the initial values used for the Scott River model.

6 Model calibration

Calibration is the process by which the independent variables (parameters and fluxes) of a model are adjusted, within realistic limits, to produce the best match between simulated and measured data (surface flow monitoring and nutrient concentration sampling). Calibration aims to solve a problem inversely by adjusting the unknowns (model parameters) until the solution matches the knowns (flows and concentrations).

The Scott River Source Catchments model is a medium-complexity model, and calibration to measured data before use (for prediction simulations) is a fundamental requirement. The calibration performance is presented in qualitative and quantitative terms in comparison with target criteria. The calibration criteria described below have been used to assess the calibration result:

- **Water balance:** the total measured and modelled flow volume should be within 5% and ideally within 1% of one another over the calibration period.
- **Qualitative measures:**
  - modelled versus measured hydrographs for daily, monthly and annual flow data
  - scattergram of measured versus modelled flows for daily, monthly and annual flow data
  - plot of modelled versus measured median winter concentration values for TN and TP
  - scattergram of measured versus modelled median winter concentration values for TN and TP.
- **Quantitative measures:**
  - Nash-Sutcliffe efficiency of above 65% for daily and monthly flow data
  - the modelled versus observed median TP and TN values will be within 10% of one another at all sampling locations

6.1 Hydrological calibration

The calibration period was from 1 January 2000 – 31 December 2009. Modelled and measured flows were compared over the selected calibration time-period. Selected model parameters were adjusted both manually and automatically to minimise the difference between the modelled and measured data.

The Australian Water Balance Model (AWBM) was selected as the hydrological driver for the flow for all functional units (FUs) within the Scott Source Catchments model. Auto-calibration modules are not available in the current version of Source Catchments, so AWBM needed to be coded externally (in Microsoft Excel^{TM} in this case), so automatic calibration optimisation techniques could be applied. The following processes were used to calibrate the model:

1. Land uses were divided into the various areas of three different hydrological categories – cleared, uncleared and irrigated. Uncleared land-use categories included native vegetation and established blue gums; irrigated land-use categories included irrigated dairy, irrigated beef and irrigated horticulture; the remaining categories were assigned as cleared.
2. A different set of AWBM parameters was set for each of the land areas of the three different categories – with careful deliberation to keep the coefficient of runoff for the cleared land between 10 and 20%, for the uncleared land between 5 and 15%, and for the irrigated land >20%.
3. The Nash-Sutcliffe efficiency (the objective function) was maximised using the Microsoft Excel^{TM} add-in Solver^{TM}.
4. The parameters were adjusted so that the modelled and observed flows were within 1%.

Model calibration results were assessed at the two flow gauging stations. Both gauging stations achieved acceptable criteria for calibration and validation. The catchment areas for uncleared, cleared and irrigated flows, as well as the Nash-Sutcliffe efficiency (NSE) are shown in Table 6-1. The calibration satisfied the criteria for both flow volumes and the NSE at both flow gauging stations.

***Table 6-1:** Calibration summary for the two flow gauging stations*

Parameter	Units	609002	609026
Catchment area	km^2	643	399
Uncleared area	km^2	493	290
Cleared area	km^2	134	102
Irrigated area	km^2	16	7
Uncleared flow	mm/yr	74	108
Cleared flow	mm/yr	148	227
Irrigated flow	mm/yr	249	339
Nash-Sutcliffe efficiency	-	77%	68%

The flow statistics for Brennan’s Ford are shown in Table 6-2. The daily observed versus modelled flows closely align, and baseflow rates appear to be consistent for the predicted data (Figure 6-1).The predicted water balance was within 1% of the observed water balance, and satisfied the flow criteria. The cumulative water balance for the observed and modelled flows at Brennan’s Ford is shown in Figure 6-2.

Table 6-2: *Observed versus predicted flow statistics for 609002, Brennan's Ford*

Flow statistics	Units	Observed	Predicted
Number of observations	-	3601	3601
Maximum	ML/day	4705	2882
Minimum	ML/day	0.05	0.07
Average flow	ML/day	183	183
Winter median flow	ML/day	199	193
Sum	GL	660	660

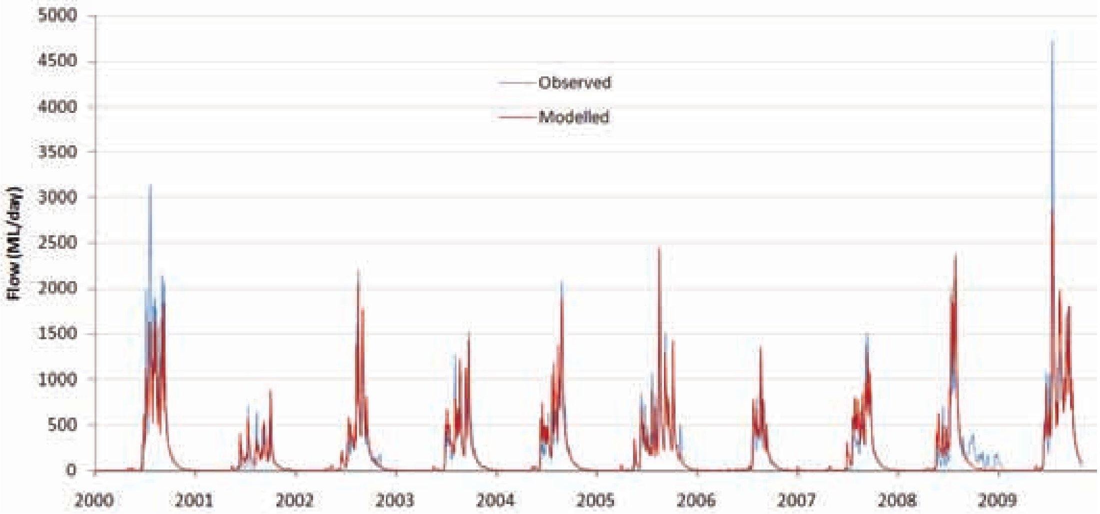


Figure 6-1: *Observed versus predicted daily flows for 609002, Brennan's Ford*

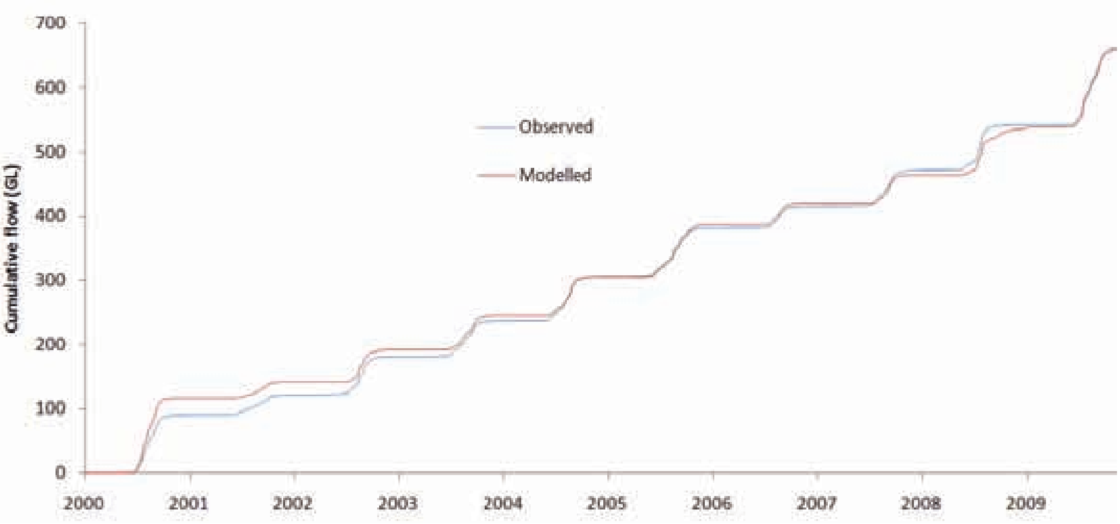


Figure 6-2: *Observed versus predicted cumulative flows for 609002, Brennan's Ford*

The resulting set of calibrated parameters for the AWBM models for uncleared, cleared and irrigated FUs in the Scott River catchment are shown in Table 6-3.

Table 6-3: *Calibrated AWBM parameters and coefficient of runoff (CR) for the Scott River Source Catchments model*

Parameter	Units	Uncleared land	Cleared land	Irrigated land
A_1	-	0.20	0.05	0.08
A_2	-	0.23	0.87	0.87
BFI	mm	0.66	0.22	0.22
C_1	mm	149	20	40
C_2	mm	405	305	190
C_3	mm	800	800	800
K_{base}	day^{-1}	0.95	0.97	0.97
K_{Surf}	day^{-1}	0.76	0.76	0.76
CR	-	0.08	0.16	0.27

6.2 Nutrient calibration

Source Catchments produces daily nutrient concentration results. However, due to the large variability in the measured data, and because only the annual results were used in the analysis, the median annual concentrations were used for calibration. The methodology for selecting the initial nutrient concentrations for each of the FUs is outlined in the conceptual model section (Section 5.4). These values were adjusted (within reasonable bounds) in the model calibration process, so that the modelled median winter (June – November) concentrations at the sampling sites were within 10% of the observed winter median (for the period 2007 – 2009).

The nutrient calibration achieved the criteria at all seven of the nutrient sampling locations. The predicted and observed winter median concentrations for each of the sampling locations are shown in Table 6-4.

Table 6-4: *Observed and predicted concentrations at each of the nutrient sampling locations for the period 2007 – 2009*

Sub	Site (AWRC ref.)	TP observed (mg/L)	TP predicted (mg/L)	Difference (%)	TN observed (mg/L)	TN predicted (mg/L)	Difference (%)
3	609002	0.15	0.15	0.7%	1.00	1.00	-0.2%
4	609026	0.18	0.16	6.3%	1.40	1.46	-4.0%
6	6091226	0.14	0.15	-5.7%	1.75	1.73	1.1%
8	6091224	0.04	0.04	3.4%	1.20	1.17	2.4%
10	6091225	0.15	0.15	-0.7%	1.60	1.59	0.4%
12	6091223	0.15	0.14	2.8%	1.40	1.38	1.4%
13	6091222	0.68	0.68	0.4%	2.20	2.15	2.2%

For TP, the observed versus modelled concentrations are shown in Figure 6-3. The maximum difference in concentration was at site 609026, where the observed TP was 0.18 mg/L and the modelled was 0.16 mg/L (a difference of 6.3%). The predicted values were not consistently above or below the observed TP values.

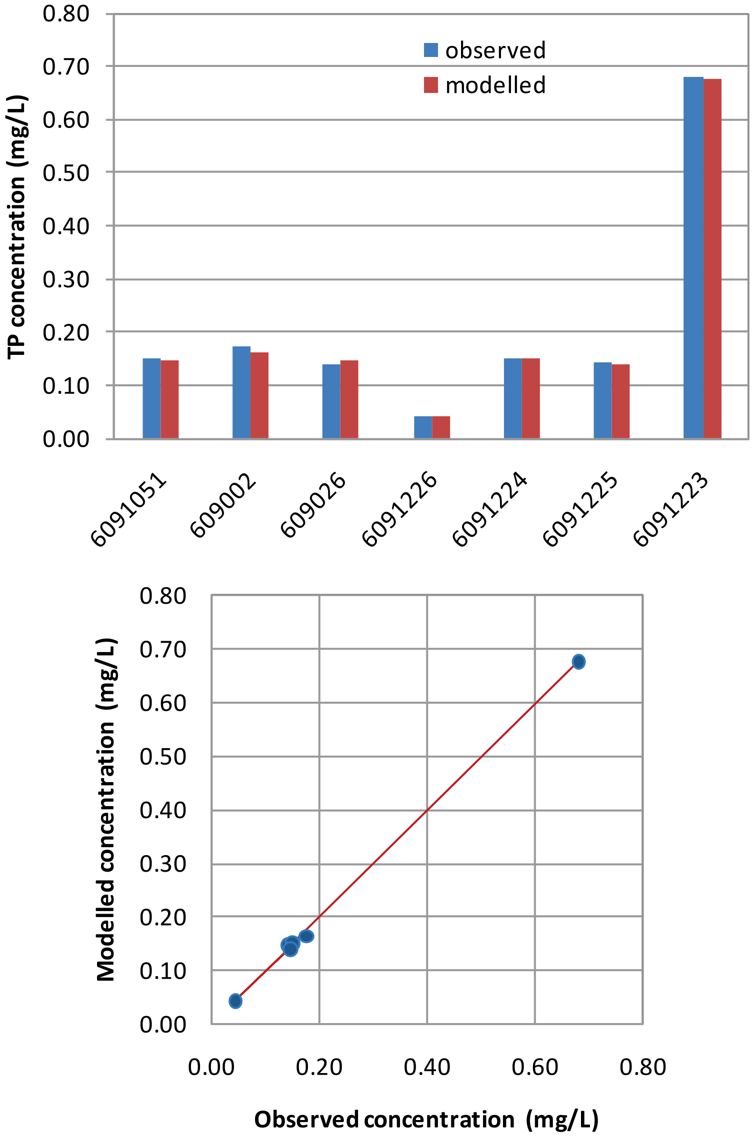
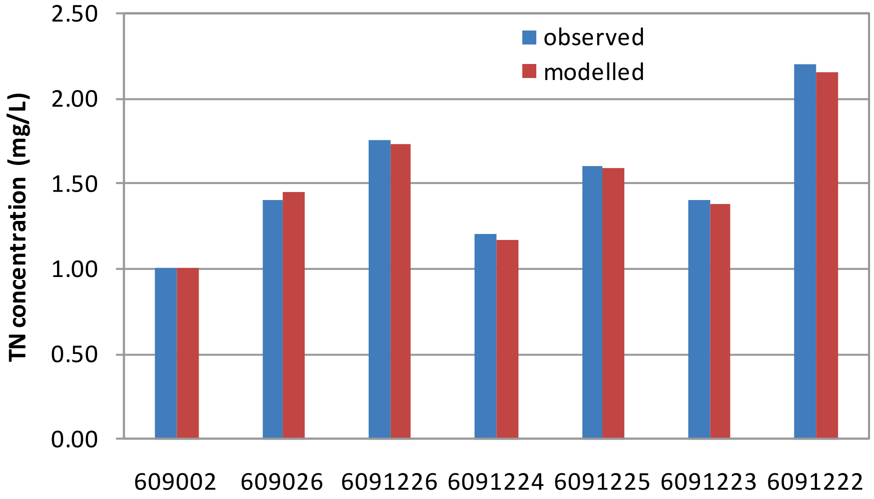


***Figure 6-3**: TP calibration results for 2007 - 2009*

For TN the maximum difference between predicted and observed values was 4.0% at site 609026. For TN, the observed versus modelled concentrations are shown in Figure 6-4. The predicted values were not consistently above or below the observed TN values.



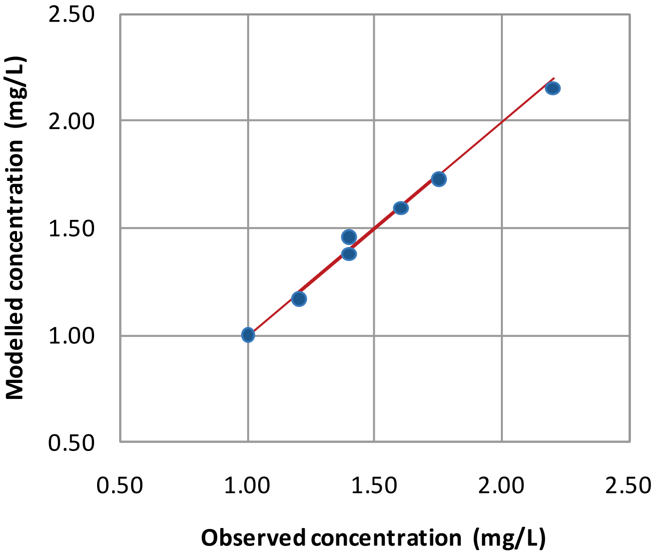


Figure 6-4: *TN calibration results for 2007 - 2009*

The nutrient calibration was considered adequate, and satisfied the calibration criteria outlined in Section 6.1. The calibrated nitrogen and phosphorus EMC/DWCs, and the estimated nutrient load as a percentage of the nutrient surplus for each land use, are shown in Table 6-5.

Nutrient assimilation in the Scott River's highly vegetated main channel was identified in the conceptual model (Section 4) and put into the numerical model. An in-stream nutrient decay model was implemented for both nitrogen and phosphorus flowing through the river's main channel (links 3 and 4 in the Source Catchments model). Calibrated half-life values for each of the decay models are shown in Table 6-6.

Table 6-5: Calibrated nutrient export concentrations for all land uses in the Scott River catchment

Land use	Runoff mean TP mg/L	 TN mg/L	Runoff : surplus TP %	 TN %
Dryland beef	0.37	4.0	3.7	6.9
Dryland dairy	0.40	3.7	3.7	4.4
Blue gums (immature)	0.38	2.9	3.9	4.8
Irrigated beef	0.29	2.3	3.1	3.0
Irrigated dairy	0.72	5.5	3.1	3.0
Irrigated horticulture	5.18	2.8	1.6	1.5
Residential	0.11	0.4	3.3	2.9
Seasonal horticulture	0.00	1.3	-	3.1
Blue gums (mature)	0.01	1.0	4.0	4.6
Cleared land	0.01	0.3	3.7	2.8
Roads	0.03	0.4	3.1	3.1
Lucerne	0.03	3.5	3.7	3.0
Native vegetation	0.01	0.7	3.0	3.0

* surplus is estimated as 75% of total input

Table 6-6: Calibrated decay model half-life values for nitrogen and phosphorus assimilation in the Scott River's main channel

Link	model type	TP half-life days	TN half-life days
Link4	Decay model	2.78	0.65
Link3	Decay model	-	4.05

Nutrient export concentrations were applied consistently throughout the catchment. However, in some subcatchments the export concentrations for land uses were altered slightly to reflect individual land-use conditions, and/or to better reflect the measured stream concentrations. For TP, runoff from immature blue gums was adjusted to 0.55 mg/L in the Governor Broome and Four Acres subcatchments, and to 0.1 mg/L in the Dennis subcatchment. This was considered acceptable, given the large variety in the timing and application of fertiliser to establishing blue gums. Also, the TP and TN export concentrations were halved for land uses that did not directly connect to waterways (to account for assimilation in the nutrients as they travel overland or through groundwater exclusively). This included the dairy in the Upper Scott subcatchment, and the horticulture enterprise in the Middle Scott subcatchment. The only nutrient concentration requiring a significant change from its initial concentration value was the dairy in Four Acres, which was increased to 4.5 mg/L runoff for TP and 8 mg/L for TN. This was required as there was a sampling point just downstream of the dairy, and the large nutrient export was necessary to meet the measured concentration. These larger concentrations can possibly be attributed to the big, deep drains of the Four Acres dairy (unique to the Scott Coastal Plain's dairies), or it may be due to pre-existing soil phosphorus concentrations. We recommend that the export of phosphorus from dairy land use in the Four Acres catchment be investigated to verify this value.

6.3 Model limitations

That the conceptual model adequately portrays the physical processes in the catchment is more important than achieving a small error between simulated and observed flows and nutrient concentrations in the calibration process. A model will not give accurate predictions beyond the calibration period or for land use and management changes unless the catchment processes have been adequately represented. The model's application should be constrained by the limitations inherent in its underlying conceptualisation.

The Scott River Source Catchments model is a catchment-scale model with a temporal resolution of one day. The model generally assumes the same nutrient export and rainfall-runoff relationships for each land-use type, whereas in reality this will vary from site-to-site based on various factors that are not captured in this model (e.g. timing of fertilisation, pre-existing land condition and soil nutrient concentrations, soil phosphorus buffering index, soil pH, groundwater level and catchment waterlogging, stocking rate, site topography etc.). The results are designed to be relative and indicative, and only to be used for catchment-scale applications. Based on the model's structural limitations, the errors discussed in the previous section and the calibration quality, the model is considered suitable for:

- Estimating the total flow and nutrient load exported from the catchment and various subcatchments within the Scott River model domain.
- Estimating the relative proportion of the flow and export load that can be attributed to the various land uses, at both the catchment and reporting subcatchment scales.
- Evaluating changes in flow and nutrient export from the catchment and reporting subcatchments as a result of land-use change, climate change, or changes in nutrient input/export rates for various land uses due to the implementation of management practices.
- First-pass cost/benefit analysis of the implementation of management practices on the catchment. The objective of the cost/benefit analysis is to determine the most appropriate management practices relative to one another. It is a tool to be used for detailed cost budgeting of on-ground management practices.

The model's structural limitations suggest the Scott River Source Catchments model is not the preferred platform for the following applications:

- **Detailed cost/benefit analysis on a farm scale:** the model should inform the user of the management practices likely to have the greatest impact at the best-possible cost/benefit ratio. The next phase should be to undertake a site-by-site investigation of the management practices at a finer scale (a farm paddock scale or a waterways reach scale). Detailed costs/benefits and potential nutrient reductions should be re-calculated at this scale, with more appropriate locally-scaled data.

- **Groundwater investigations**: the Source Catchments model is a surface water model that conceptualises groundwater as a hydrological store. It is not the appropriate model to determine the effects of groundwater-driven issues (e.g. river flow reductions as a result of abstraction or drawdown of the superficial watertable from widespread blue gum plantations). A distributed groundwater model such as MODFLOW, FEFLOW or MIKE SHE would be more appropriate for this type of investigation.
- **Acid sulfate soils (ASS) investigations**: the Scott River Source Catchments model does not have the appropriate inputs or processes to describe ASS issues and effects.

7 Model results

When the calibration was complete, the model was used to calculate the following outputs:

- current load
- predicted load
- separation of output load into land-use sources.

The catchment was divided into seven reporting subcatchments based on the major tributaries of the waterways in the Scott River catchment (Figure 7-1). The modelling results in the following section are presented for the entire modelling domain, and for each of the reporting subcatchments. Reporting subcatchments are useful to determine where in the catchment most of the nutrient load is coming from, and which land uses in these various subcatchments are contributing to the load.

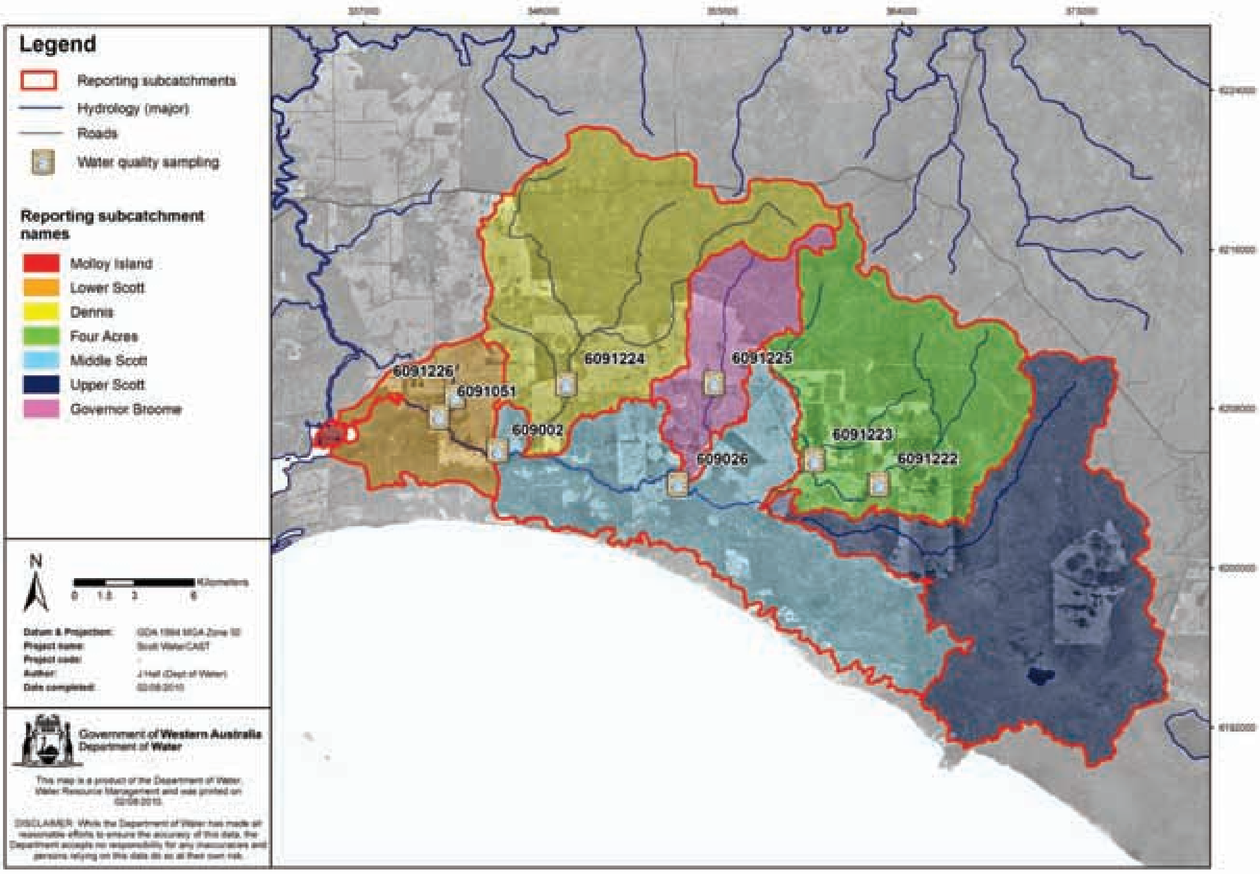


Figure 7-1: Reporting subcatchments for the Scott River catchment model

The load exported from each of the subcatchments was reported, as well as the load exported at the catchment outlet. The export load at the catchment outlet was slightly less than the sum of the subcatchment exports due to in-stream assimilation associated with flow routing in the highly vegetated reaches of the Scott River main channel.

7.1 Average annual loads

The model produces daily flow and nutrient load outputs from 2000 – 2009. Daily loads can be aggregated to produce monthly, seasonal or annual loads. The average annual load, which is reported for each of the subcatchments, is the average annual load for the period 2000 – 2009. It was important to represent the annual load as an average annual load over a number of years, because large variations in annual loads occur due to annual rainfall variability. Loads are extremely dependent on the quantity, timing and intensity of rainfall for any given year. The current flows and nitrogen and phosphorus loads are presented in Table 7-1. The median winter (June – November) concentration for the period is also shown.

It should be noted that the modelled concentrations shown are produced by the reporting subcatchment without any influence from upstream subcatchments. Modelled and observed concentrations would not correspond in second-order catchments (subcatchments with their headwaters in an upstream subcatchment), as the observed concentration values would be affected by upstream nutrient concentrations. However, in the Scott River model, this only affects the Middle Scott and Lower Scott subcatchments.

Table 7-1: *Average annual flows, nutrient loads, load per cleared area, and median winter concentrations for the period 2000 - 2009*

Summary	**Lower Scott**	**Middle Scott**	**Upper Scott**	**Dennis**	**Governor Broome**	**Four Acres**	**Molloy Island**	**Total**	**Outlet**
Flow (GL/yr)	5.2	15.4	16.5	16.0	5.2	13.3	0.2	71.7	71.7
Average annual load (2000 - 2009)									
Phosphorus load (t/yr)	0.78	3.61	1.05	2.17	1.17	4.22	0.01	13.01	11.21
Nitrogen load (t/yr)	9.6	34.5	21.3	30.8	11.6	24.9	0.1	132.9	78.1
Median winter concentration (2000 - 2009)									
TP concentration (mg/L)	0.14	0.22	0.06	0.13	0.22	0.30	0.06	-	0.15
TN concentration (mg/L)	1.81	2.11	1.23	1.80	2.19	1.74	0.51	-	1.00
Export load per cleared area									
Nitrogen load (kg/ha)	0.42	0.74	0.27	0.43	0.44	0.96	0.16	-	0.49
Phosphorus load (kg/ha)	5.2	7.0	5.5	6.1	4.3	5.7	1.2	-	3.4

The average annual flow, total nitrogen and phosphorus loads, and nitrogen and phosphorus loads per unit cleared area for each of the reporting subcatchments is shown in figures 7-2 – 7-4. Phosphorus is exported primarily from the Four Acres and Middle Scott subcatchments, with smaller but significant quantities being delivered by the Dennis, Governor Broome, Upper Scott and Lower Scott subcatchments. Molloy Island subcatchment delivers a negligible quantity of phosphorus, primarily due to its small size and the extremely small relative septic tank nutrient inputs.

For nitrogen, the largest contributing subcatchments are Middle Scott, Dennis and Four Acres; however, Upper Scott, Lower Scott and Governor Broome all deliver significant quantities of nutrients. Once again, Molloy Island delivers negligible nitrogen loads.

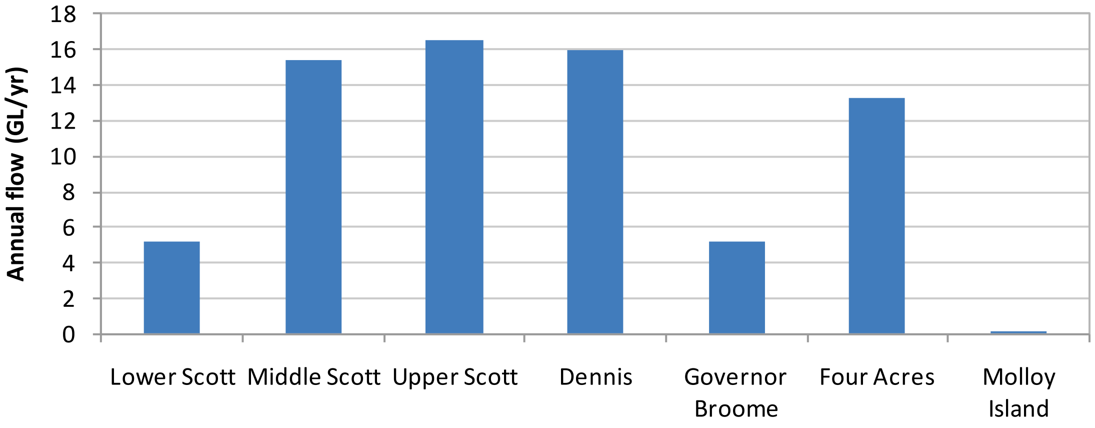


***Figure 7-2**: Average annual flows for each reporting subcatchment for the period 2000 - 2009*

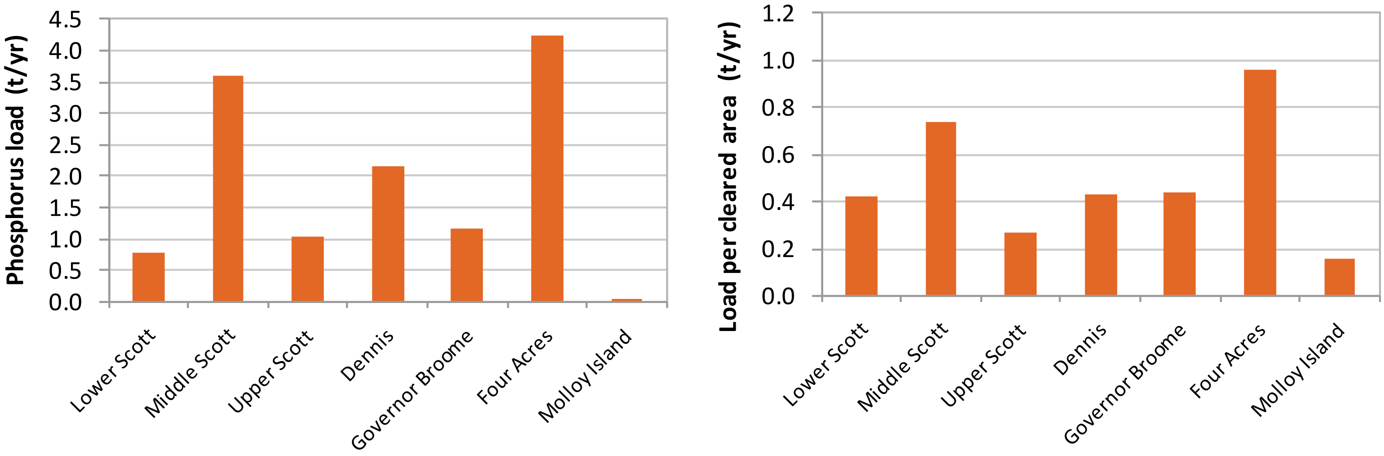


***Figure 7-3**: Average annual total phosphorus load and phosphorus load per cleared area for each reporting subcatchment for the period 2000 - 2009*

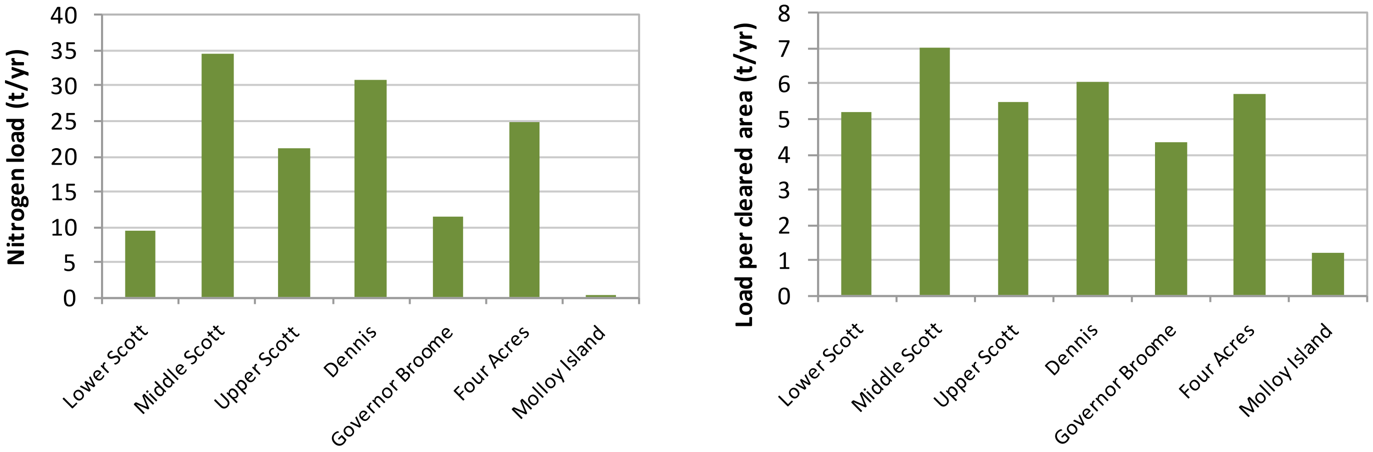


***Figure 7-4**: Average annual total nitrogen load and nitrogen load per cleared area for each reporting subcatchment for the period 2000 - 2009*

The nitrogen and phosphorus loads from each reporting subcatchment are presented spatially in Figure 7-5.

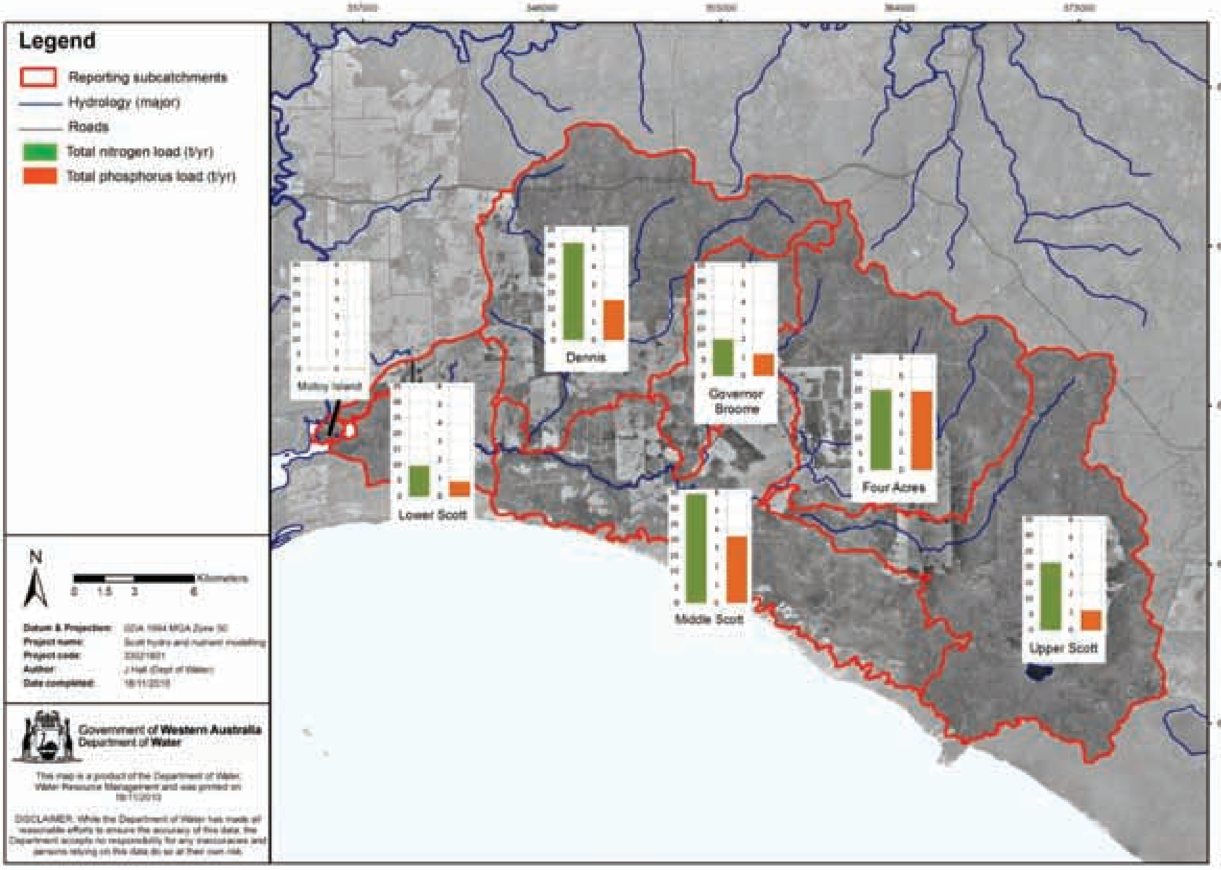


Figure 7-5: Average annual nutrient load for each reporting subcatchment for the period 2000 – 2009

7.2 Land-use source contributions

The model was used to separate the output load into its land-use sources, and estimated the amount of load coming from each land-use type. The separation was undertaken for the entire catchment and for each reporting subcatchment. This feature allows managers to target specific land uses that contribute most strongly to the total load output. The functional units were aggregated to form 11 different land-use categories to present the land-use source contribution results. The results for the land-use separation for each of the reporting subcatchments, and for the outlet of the Scott River catchment, are shown in Table 7-2 and Figure 7-6.

Table 7-2: *Land-use nutrient load contributions for reporting subcatchments and for the outlet of the Scott River catchment*

Land use	Lower Scott	Middle Scott	Upper Scott	Dennis	Governor Broome	Four Acres	Molloy Island	Total	Outlet
Average annual total phosphorus load (tonnes)									
Dryland beef	0.54	1.10	0.43	0.91	0.38	0.39	0.00	3.66	3.31
Irrigated beef	0.00	0.18	0.00	0.00	0.01	0.00	0.00	0.16	0.13
Dryland dairy	0.18	0.06	0.16	0.11	0.11	0.26	0.00	0.90	0.79
Irrigated dairy	0.00	0.95	0.20	0.81	0.17	2.11	0.00	4.35	3.74
Horticulture and lucerne	0.00	1.07	0.00	0.00	0.00	0.00	0.00	0.92	0.70
Roads and residential	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02
Blue gums (immature)	0.03	0.05	0.09	0.24	0.42	1.37	0.00	2.34	1.95
Blue gums (mature)	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.05	0.04
Dairy sheds	0.01	0.05	0.05	0.02	0.05	0.02	0.00	0.20	0.18
Feedlot	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.04	0.03
Native vegetation	0.02	0.09	0.11	0.08	0.02	0.06	0.00	0.38	0.32
Total	0.78	3.61	1.05	2.17	1.17	4.22	0.01	13.01	11.21
Average annual total nitrogen load (tonnes)									
Dryland beef	6.1	19.1	5.1	11.5	4.1	4.7	0.0	50.6	31.6
Irrigated beef	0.0	1.2	0.0	0.0	0.1	0.0	0.0	1.3	0.4
Dryland dairy	1.6	0.5	3.1	1.0	1.0	1.3	0.0	8.4	5.0
Irrigated dairy	0.0	6.3	3.3	5.9	1.3	4.9	0.0	21.8	13.8
Horticulture and lucerne	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.3
Roads and residential	0.1	0.1	0.2	0.1	0.0	0.1	0.0	0.6	0.4
Blue gums (immature)	0.2	0.3	0.7	6.5	2.7	8.1	0.0	18.8	10.9
Blue gums (mature)	0.0	0.8	1.2	0.7	0.9	1.1	0.0	4.8	2.5
Dairy sheds	0.1	0.2	0.3	0.1	0.3	0.1	0.0	1.2	0.8
Feedlot	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.1
Native vegetation	1.5	4.9	7.4	5.0	1.0	4.6	0.0	24.4	12.3
Total	9.6	34.5	21.3	30.8	11.6	24.9	0.1	132.9	78.1

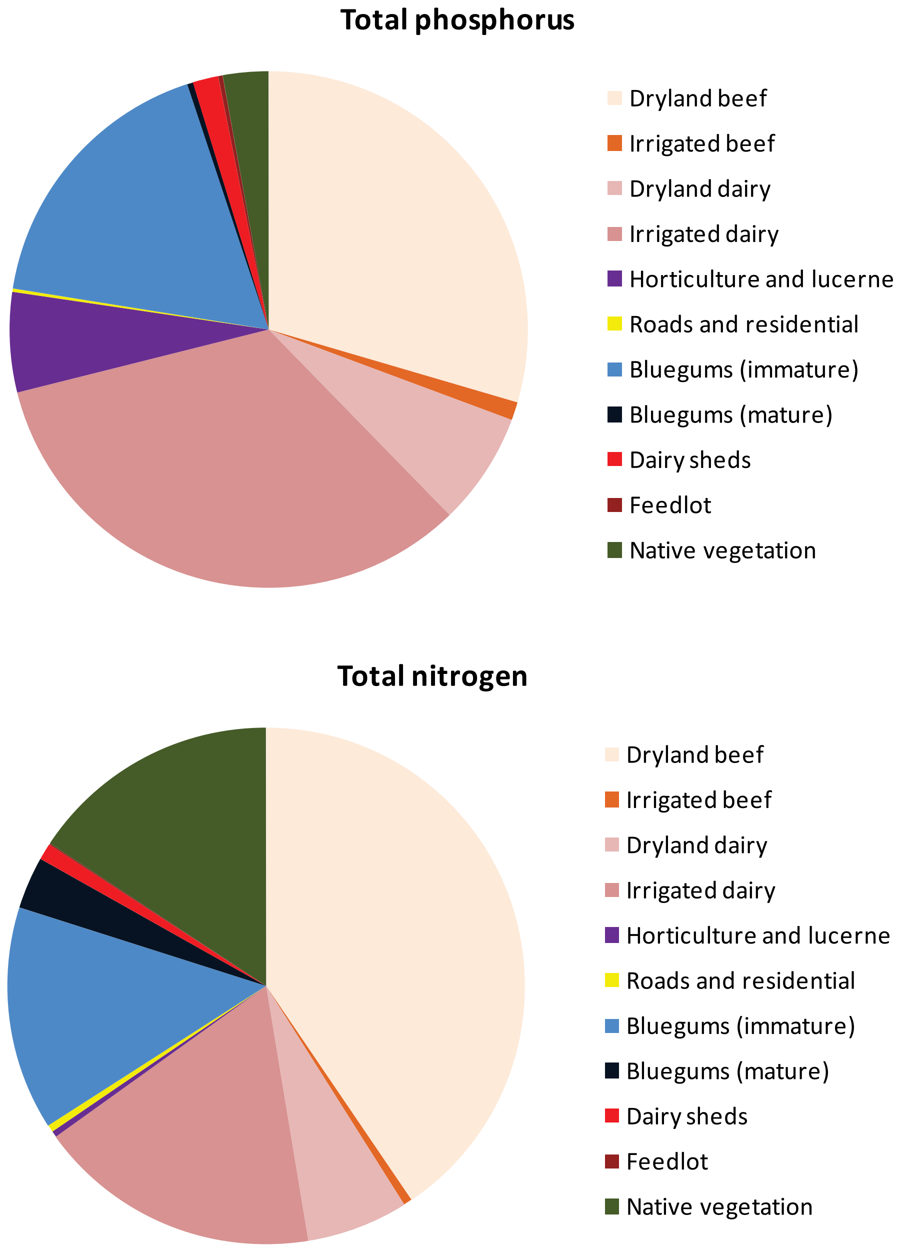


***Figure 7-6**: Land-use nutrient load contributions for reporting subcatchments and for the outlet of the Scott River catchment*

For phosphorus, the main contributors are dryland beef and irrigated dairy, followed by immature blue gums. Dryland beef occupies five times as much area in the catchment as irrigated dairy, and according to DAFWA scientists, both are likely to require similar phosphorus fertiliser inputs (D. Bennett pers. comm.; M. Staines pers. comm.). The fact that beef and dairy are producing similar nutrient-output quantities implies that irrigated dairies are likely to be over-fertilising phosphorus. For nitrogen, the major land-use contributors are dryland beef, irrigated dairy, dryland dairy, immature blue gums and native vegetation. The spatial distribution for the separation of sources for phosphorus and nitrogen are shown in figures 7-7 and 7-8.

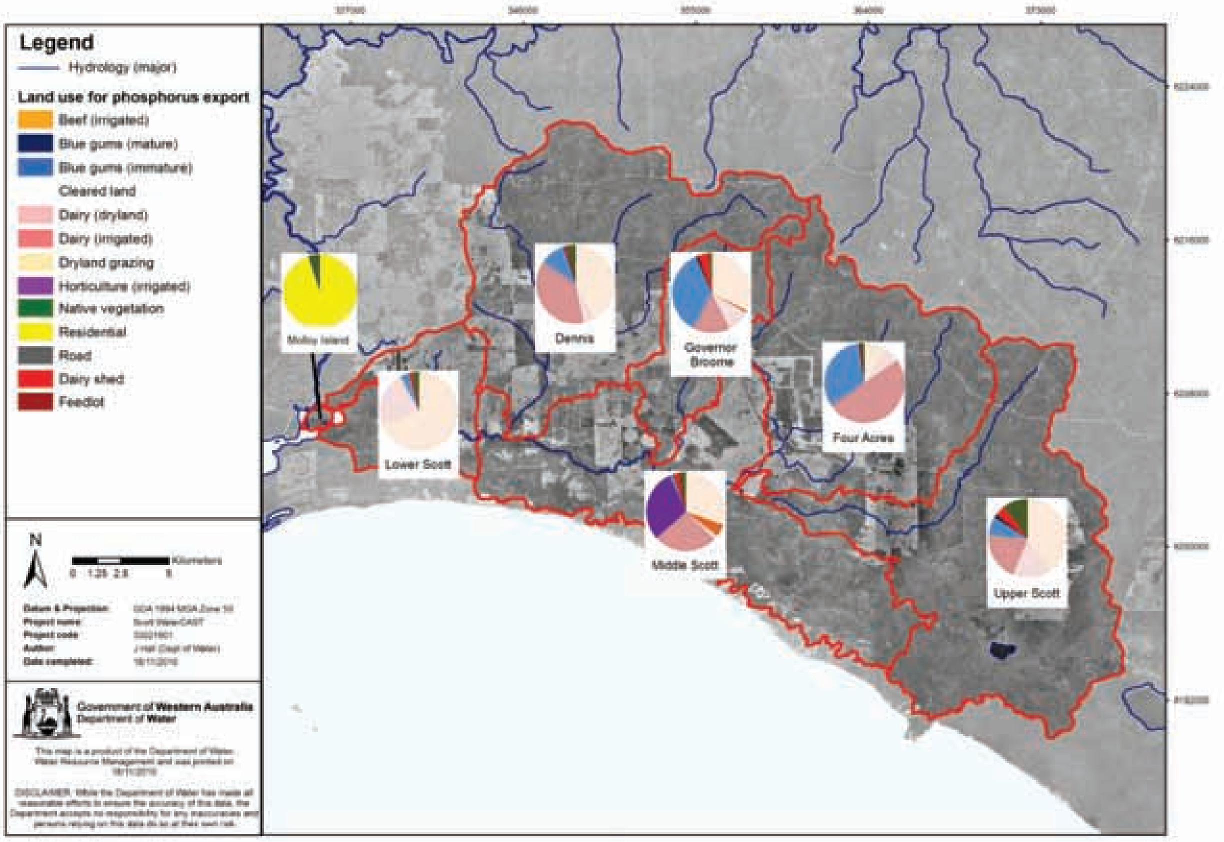


Figure 7-7: Phosphorus nutrient source land-use components for Scott River subcatchments

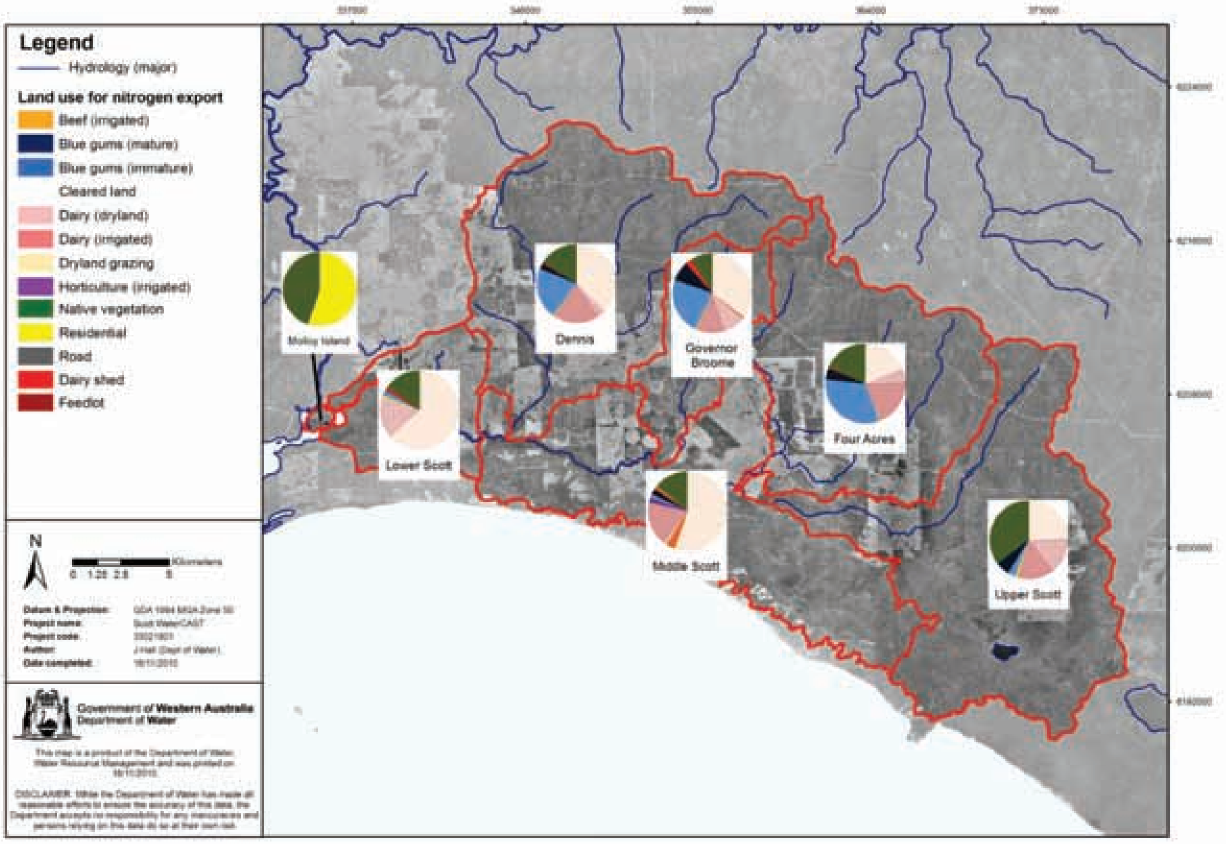


Figure 7-8: Nitrogen nutrient source land-use components for Scott River subcatchments

8 Scenarios

8.1 Best management practices

A suite of modelling scenarios incorporating best management practices (BMPs) were undertaken for various land uses within the catchment. Export loads delivered from the Scott River catchment to the Hardy Inlet were primarily from agricultural land uses, so urban BMPs were not applied to the model. The list of BMPs for managing these sources effectively is relatively limited. Four management practices were analysed, with the potential capital costs, annual costs/benefits and nutrient reductions estimated. The management practices included:

- **Fertiliser management**, involving soil and plant tissue testing of paddocks to determine the required nutrients and pH to meet pasture needs. It also involves best management in fertiliser timing and spreading, and using nutrient budgets to make fertiliser decisions.

- **Riparian management**, involving riparian re-vegetation, rehabilitation, stream fencing, construction of stock and vehicle crossings, and the provision of off-stream watering points for stock. Riparian management in the Scott catchment was restricted to high-order streams (third or above) to minimise the disturbance to agricultural land. The riparian zones are shown in Figure 8-1, and the values for length of reaches within subcatchments with and without riparian vegetation are shown in Table 8-1.

- **Effluent management**, involving the containment and storage of effluent for application to pasture from a lined effluent-settlement pond.

- **Soil amendment**, involving the application of phosphorus-fixing materials to sandy soils to improve their phosphorus-retention capacity and thereby reduce phosphorus leaching.

Table 8-2 summarises the BMPs and the land-uses they can be applied to, the associated nutrient reductions and the costs/benefits. More detailed explanations of the derivation, limitations and benefits for each of the BMPs is provided in the *Scott water quality improvement plan* (DoW 2010), as well as DAFWA's *BMP costs and definitions for the Vasse-Geographe and Ellen Brook catchments* (Ecotones and Associates 2008).

***Table 8-1**: Riparian length, un-vegetated riparian length within blue gum plantations, and un-vegetated riparian length within grazing paddocks in the Scott River catchment*

Subcatchment	Riparian length (km)	Un-vegetated length - grazing (km)	Un-vegetated length - bluegums (km)
Lower Scott	10.3	3.6	0.0
Middle Scott	20.7	1.7	0.0
Upper Scott	14.4	4.0	10.4
Dennis	22.5	6.3	11.6
Governor Broome	8.1	2.0	6.1
Four Acres	27.6	15.6	8.7
Total	103.6	33.3	36.8

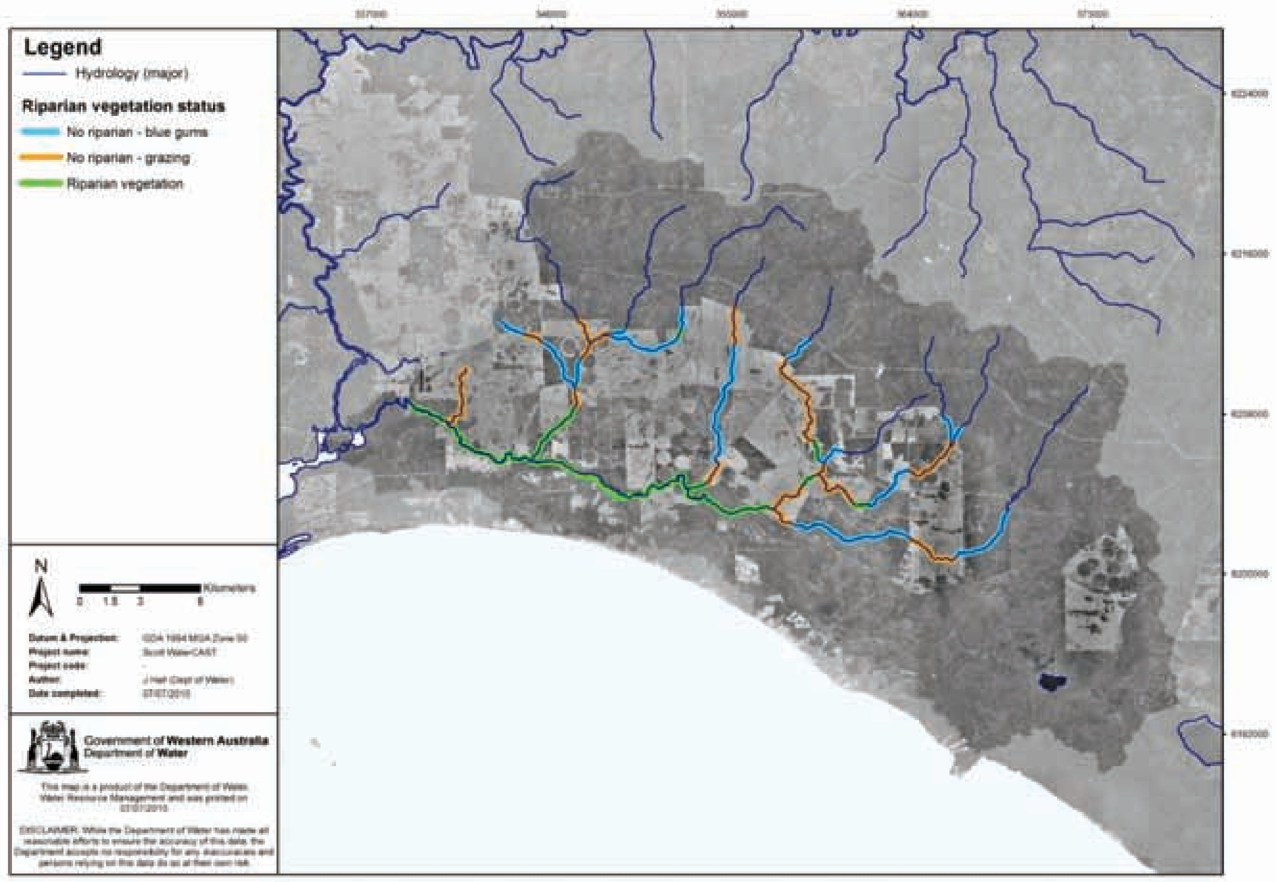


***Figure 8-1**: Riparian vegetation and unlined waterways in pasture and plantation enterprises in the Scott River catchment*

Table 8-2: *Estimated BMP costs/benefits and removal of nitrogen and phosphorus for the Scott River catchment – costs are negative and benefits (returns) are positive*

BMP name	Land use impacted	Units	Estimated phosphorus reduction (%)	Estimated nitrogen reduction (%)	Estimated capital cost (per unit)	Estimated annual cost/benefit (per unit)
Best practice effluent management	Dairy sheds	shed	60%	60%	-$180,000	$10,000
Fertiliser program - beef	Beef	ha	8%	5%	-$11	$23
Fertiliser program - dairy	Dairy	ha	60%	5%	-$11	$146
Perennials	Beef	ha	5%	40%	-$330	$39
Riparian management - grazing	all	km	5%	15%	-$27,965	$0
Riparian management - blue gums	all	km	5%	15%	-$17,965	$0
Soil amendment	all	km	50%	5%	-$220	$38

A combination of the above list of BMPs was selected at varying uptake rates, and implemented in the Scott River catchment model. The scenarios included:

- **Scenario 1: Fertiliser management**: this involved implementation of the fertiliser program at 100% uptake by all dairy and beef pasture. This was selected as the initial scenario, because it is most easily implemented, achieves relatively good reductions (especially for irrigated dairy), and has the highest rate of estimated benefit compared with capital costs. Although blue gum plantations are not selected in this scenario, we recommend further studies for determining an efficient use of blue gum fertiliser.
- **Scenario 2: Fertiliser and effluent management**: this involved the same level of fertiliser management as for scenario 1, with all dairies being upgraded to include best-management effluent systems.
- **Scenario 3: Fertiliser, effluent and riparian management**: this involved fertiliser and effluent management equivalent to scenario 2, but with targeted riparian management at various locations throughout the catchment. The locations were selected based on the achievement of some viable improvements in biological function (i.e. joining gaps in existing riparian areas close to the main river channel). The targeted subcatchments and modelled amount of riparian restoration in each of the subcatchments is shown in Table 8-3. Note that these areas would need to be confirmed by an on-ground survey.
- **Scenario 4: Fertiliser, effluent, riparian management and soil amendment**: this scenario involved the same level of fertiliser, effluent and riparian management as scenario 3, but also included the application of soil amendment to targeted blue gum and horticulture enterprises. A 50% uptake was assumed for blue gum plantations, and a 100% uptake for horticulture (as there was only one horticulture enterprise in the catchment).

Table 8-3: *Uptake of riparian vegetation for un-vegetated waterways in pasture and blue gum plantations from scenario 3*

Reporting subcatchment	Riparian restoration uptake	
	Pasture	Blue gums
Lower Scott	100%	0%
Middle Scott	100%	0%
Upper Scott	0%	50%
Dennis	20%	10%
Governor Broome	0%	0%
Four Acres	30%	0%
Molloy Island	0%	0%

Each of the scenarios were run with the capital costs, annual costs/benefits and nutrient reductions estimated from Table 8-2. A broad-brush catchment-scale approach such as this will not be entirely accurate, because costs and nutrient reductions will vary on a site-by-site basis. For fertiliser management, for example, savings and nutrient reductions will depend on a suite of variables including soil phosphorus content, the phosphorus buffering index of the soil, the farming enterprise's intensity, the pH of the soil, and the rate of application of nutrients. These will vary on a paddock-by-paddock basis. The level of detail required to determine accurate cost savings and nutrient reductions for the entire catchment on a site-by-site basis is outside the scope of this modelling project. The modelling results in this project aim to provide first-pass, order-of-magnitude indications of costs and savings. Recommendations derived from the modelling results should prompt further investigation into the recommended BMPs on a farm scale, rather than an immediate catchment-wide response.

Table 8-4: *Estimated BMP costs/benefits and removal of nitrogen and phosphorus for the Scott River catchment (costs are negative and benefits are positive)*

Scenario	Description	Total capital cost	Annual cost or benefit	Phosphorus load removed	Nitrogen load removed	Phosphorus proportion of annual load	Nitrogen proportion of annual load	Phosphorus annual benefit	Nitrogen annual benefit
				t/yr	t/yr	%	%	$/kg	$/kg
1	Fertiliser management strategy for all beef and dairy pasture in the Scott River catchment	-$112,530	$573,065	3.31	3.5	29.5%	1.2%	173.0	163.7
2	Scenario 1 plus management of all dairy effluent systems to include ponds and fertigation	-$1,012,530	$623,065	3.42	4.2	30.5%	1.2%	182.2	149.7
3	Scenario 2 plus targeted riparian management in various subcatchments*	-$1,442,303	$623,065	3.49	7.3	31.1%	1.3%	178.5	85.4
4	Scenario 3 plus targeted soil amendment to horticulture and blue gum plantations	-$1,912,403	$703,055	4.57	7.8	40.7%	1.6%	153.9	90.3

Discussion of results

Clearly the most effective BMP in the catchment is fertiliser management for cattle enterprises. Not only does this scenario predict the most significant phosphorus saving, the cost/benefit ratio indicates that undertaking fertiliser management is likely to be a good investment.

Effluent management is predicted to reduce phosphorus exports to the estuary by 0.11 tonnes/yr. Although this is a relatively small quantity, the discharge has an extremely high concentration and is likely to have effects on local higher-order waterways. In addition, coliforms and other faecal contaminants are exported with dairy effluent, which can pose a threat to the environment and human health. Large capital costs and the requirement for ongoing maintenance to ensure proper operation of effluent systems has been a barrier to the installation and effectiveness of these systems in the past.

Riparian management predicts only marginal reductions at a relatively high cost, and with no economic benefit to landholders. Riparian management is most effective for reducing phosphorus in particulate form, because the vegetation's primary mechanism for phosphorus reduction is the trapping of sediment. Most of the phosphorus in the Scott River catchment is in soluble form, thereby reducing the potential for nutrient removal by vegetation. Apart from the (relatively small) nutrient benefits, riparian vegetation also provides habitat for wildlife, promotes biodiversity, encourages bank stabilisation, and provides ecological corridors. All of these factors contribute to improving the health of waterways and enhancing water quality. The decision to promote riparian vegetation should not be made in reference to the cost/benefit of nutrient reductions alone.

Soil amendments using industrial by-products, such as Iluka's NUA, have been used successfully to reduce nutrient outputs and increase productivity in turf farms (Wendling & Douglas 2010). NUA is the only potentially cost-effective product for the Scott River catchment, as it is available locally from the Capel refinery. All other products (including Alcoa's Alkaloam^{TM}) are not viable because transportation costs are prohibitive. However NUA is not commercially available and the risks and benefits of paddock-scale implementation have not been intensively trialled and reported. It is proposed in the scenarios that NUA is used exclusively on blue gum plantations. Application to blue gum plantations is likely to be much more cost-effective than for pasture, given the NUA can be applied when the trees are ripped up and then tilled into the soil with the harvesting and replanting process. For pasture, additional costs to till the amendment into the soil (and thereby make it more effective) are often cost prohibitive. Because there is so little data on the effectiveness and potential risks associated with using NUA on blue gum plantations, it is recommended that small-scale plot-trials are undertaken and measured for cost/benefit and effectiveness, before this method is more broadly applied. It should be noted that NUA's potential risks are very well quantified from turf-farm field studies, but there is an information gap in relation to the potential risks of exposure to livestock on NUA treated soil.

8.2 Land-use change scenarios

The Scott River model was used to assess the effects of a potential future land-use change. A new irrigated dairy is proposed in the Lower Scott catchment and – assuming rainfall runoff and nutrient export rates are the same as the calibrated irrigated dairies from the current model – the model was run with the new land use in place.

The proposed dairy is to be located in the Lower Scott subcatchment, and covers an area of 560 ha (292 ha irrigated) (Figure 8-2). It should be noted that the nutrient input rates for the new dairy were assumed to be consistent with the catchment's other dairies, which are likely to be significantly over-fertilising. If the dairy used fertiliser BMPs, the resultant increases in phosphorus load were not likely to be as large. Nitrogen load was predicted to increase by 2.5 tonnes/yr (3.2%), with the concentration increasing from 1.00 mg/L to 1.04 mg/L. Phosphorus load was predicted to increase by 0.47 tonnes/yr when compared with the base case (4.1%), with the concentration increasing by 4.7%.

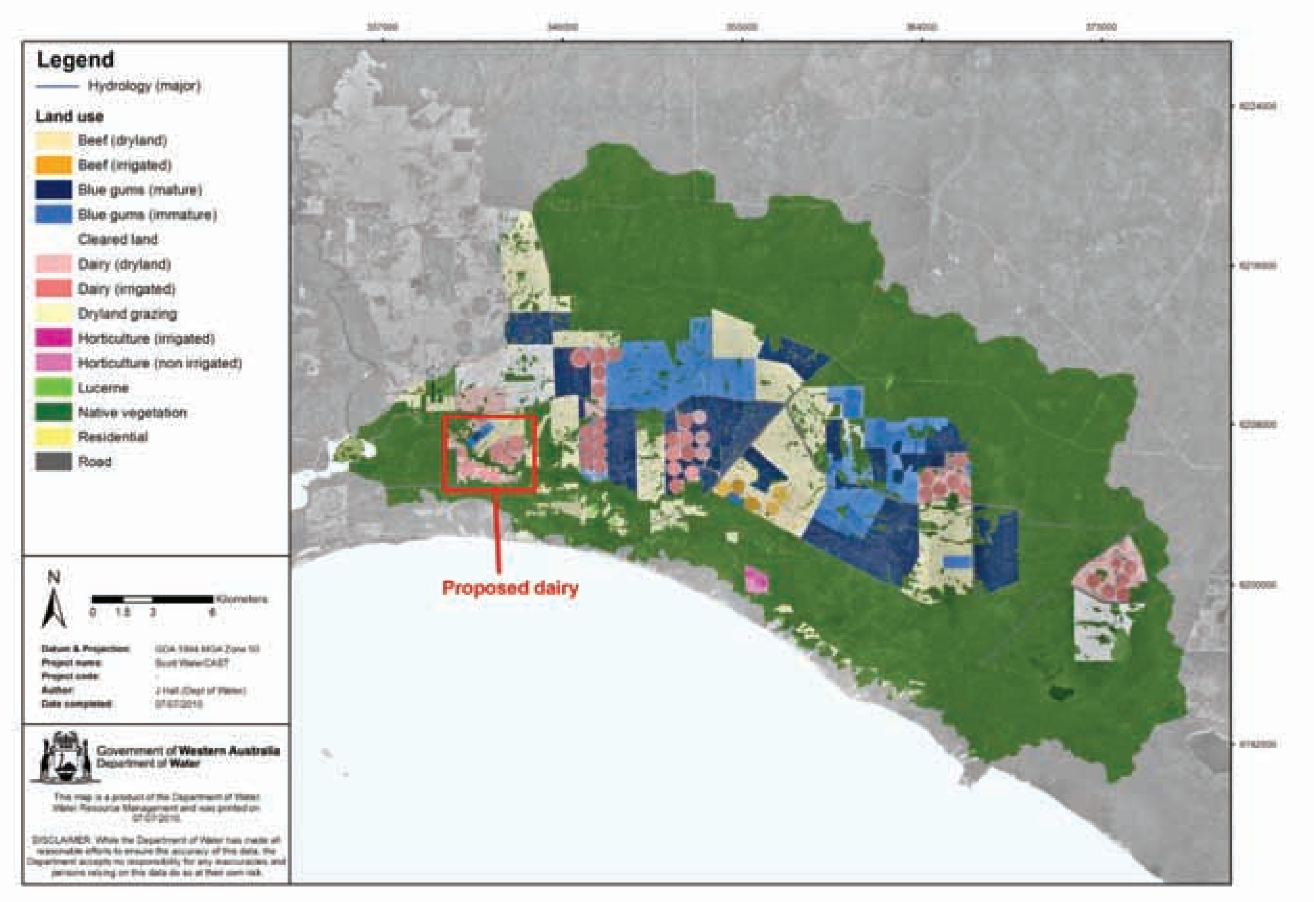


Figure 8-2: Potential future land use in the Scott River catchment displaying the proposed dairy in the lower Scott catchment

The results of the model when the proposed dairy was included (for the rainfall period 2000 – 2009), taken at the outlet of the Scott River, are shown in Table 8-5. Flow is predicted to increase by 0.4 GL/yr (0.5%) as a result of the extra water being used on the dairy for irrigation purposes (even if the irrigation water does not directly drain from the pasture, the soil moisture in irrigated paddocks is mostly recharged at the start of winter, so a small amount of rainfall is required to cause runoff in these paddocks).

***Table 8-5:** Predicted changes in nutrient load, concentration and flow as a result of the proposed dairy in the Lower Scott River*

Nutrient & flow status	Base case	Proposed dairy scenario	Increase (%)
Phosphorus load (t/yr)	11.21	11.68	4.1%
TP concentration (t/yr)	0.15	0.15	4.7%
Nitrogen load (t/yr)	78.1	80.6	3.2%
TN concentration (mg/L)	1.00	1.04	3.9%
Flow (GL/yr)	71.7	72.1	0.5%

9 Conclusions and recommendations

In recent years the Hardy Inlet has been subject to on-going water quality deterioration and frequent algal blooms. In response, the Government of Western Australia instigated the development of a water quality improvement plan. The plan has been divided into two stages for implementation: stage 1 focuses on the Scott River catchment, and stage 2 will focus on the Lower Blackwood catchment and Augusta townsite.

The purpose of this study was to quantify the water and nutrient inflows from the Scott River to the Hardy Inlet, to examine the nutrient sources and timing of delivery, and to determine a cost/benefit analysis for a range of on-ground best management practices (BMPs) that are available for the Scott River catchment.

The catchment receives annual rainfall of between 1000 and 1100 mm/yr, while its average annual potential pan evaporation is approximately 1000 mm/yr. Most of the catchment is remnant natural vegetation (67%), with the remainder being agricultural land uses – primarily beef grazing, dairying and blue gum plantations.

A conceptual model of the inputs and exports for the catchment showed that most of the nutrient input was in diffuse form (fertiliser inputs and nitrogen fixation), and only a small proportion was from point sources (dairy sheds and feedlots). The conceptual model formed the basis for developing a numerical hydrological and nutrient export model. The numerical model was constructed using the software package Source Catchments. Source Catchments is a node-link style system for modelling water and constituent transport within the major channels in a catchment. The Scott River Source Catchments model used the Australian Water Balance Model (AWBM) as the hydrological driver, and the event mean concentration/ dry weather concentration (EMC/DWC) constituent driver. The land use was divided into three hydrological categories (irrigated land, cleared land and vegetated land), and 14 land-use categories for nutrient generation.

The model was calibrated at two flow sites and seven water quality sampling locations. The model achieved the calibration criteria of a daily Nash-Sutcliffe efficiency of greater than 65% at each flow gauging station, and modelled and observed winter median concentrations within 10% of one another at each nutrient sampling location. The model was considered suitable for estimating catchment-scale flow and nutrient export, as well as evaluating the change in nutrient and flow export resulting from land-use changes or the implementation of on-ground BMPs. Because of the uncertainty associated with the model, and the highly complex nature of nutrient export processes, the model was not considered suitable for detailed cost/benefit analysis on a farm or paddock scale. The results are designed to be relative and indicative, and only to be used for catchment-scale applications. Model results should prompt site-by-site investigations of the management practices, and detailed costs/benefits would need to be re-calculated at this scale.

The model predicted delivery of an average of 72 GL flow, 11.2 tonnes of phosphorus and 78.1 tonnes of nitrogen annually (for the years 2000 – 2009). Most of the flow and nutrient export was delivered from the Middle Scott, Four Acres and Dennis subcatchments. Negligible loads were predicted to be exported from Molloy Island.

For phosphorus, the main land-use contributors were predicted to be dryland beef, irrigated dairy and blue gum plantations. Dryland beef occupies five times as much area in the catchment as irrigated dairy, yet contributes similar phosphorus exports – thus it is likely that irrigated dairies are over-fertilising phosphorus. For nitrogen, the major land-use contributors were dryland beef, irrigated dairy, dryland dairy, immature blue gums and native vegetation.

A suite of BMPs were incorporated for the land uses within the Scott River catchment. Export loads delivered from the Scott River catchment to the Hardy Inlet were primarily from agricultural land uses, so urban BMPs were not applied to the model. The management practices included fertiliser management, riparian management, effluent management and soil amendment. The most effective BMP in the catchment was predicted to be fertiliser management for cattle enterprises. Not only did this scenario predict the most significant phosphorus reduction to the estuary, but the cost/benefit ratio indicated that undertaking fertiliser management was likely to be a good investment.

Riparian management predicted relatively small nutrient benefits at relatively high costs (and there were no economic benefits to the landholders). However, apart from the nutrient benefits, riparian vegetation also provides habitat for wildlife, promotes biodiversity, shades waterways, stabilises stream banks, and provides ecological corridors. Riparian revegetation should not be considered as a solution for nutrient reduction only.

The Iluka mineral sands mining by-product ‘neutralised used acid’ (NUA) is the only potentially cost-effective soil amendment product for the Scott River catchment, as it is available locally from the Capel mineral sands refinery. However, it is not commercially available and the benefits of paddock-scale implementation are still being trialled. It is recommended that small-scale plot-trials are undertaken and measured for cost/benefit and effectiveness before it is more broadly applied.

9.1 Future work

Analysis of flow in the Scott River has indicated large flow reductions during the past two decades despite a relatively consistent rainfall series. It is possible these reductions in flow may have had negative impacts on the river’s ecology. However, a study of the river’s ecological water requirements (EWRs) has not been undertaken. The river clearly demonstrates high levels of natural habitat and biodiversity, but has significantly declining streamflows. We recommend an EWR study be undertaken for the Scott River.

There is a lack of accurate data both for nutrient reductions and the costs/benefits associated with BMPs in different settings. To improve the precision of decision-support systems, a more accurate capture of this data is necessary. We recommend further research on the suite of agricultural BMPs so they can be adequately measured and monitored for nutrient reductions and for economic costs/benefits. This includes products such as NUA and low-water-soluble phosphorus fertilisers, as well as riparian vegetation, perennial pastures, and the effect of fertiliser BMPs (based on soil and tissue test recommendations).

The Scott River catchment modelling has demonstrated that the most economically viable management practice, with the largest potential reduction in nutrient export, is the effective management of phosphorus fertiliser. This management practice can achieve the multi-objective purpose of reducing waterways pollution and increasing farm profitability. However, phosphorus over-fertilisation and the resulting impacts on the Swan Coastal Plain's waterways is not a new story, and has been widely documented by various state government authorities for the past two decades. Phosphorus fertiliser management is a focus of the *Fertiliser action plan* (Joint Government and Fertiliser Industry Partners 2007). It is recommended that all government departments support this plan, as well as the roll-out of fertiliser BMPs to promote sustainable, more profitable agricultural production, and to minimise environmental pollution from agricultural enterprises.

Appendix A: Nutrient sampling summaries

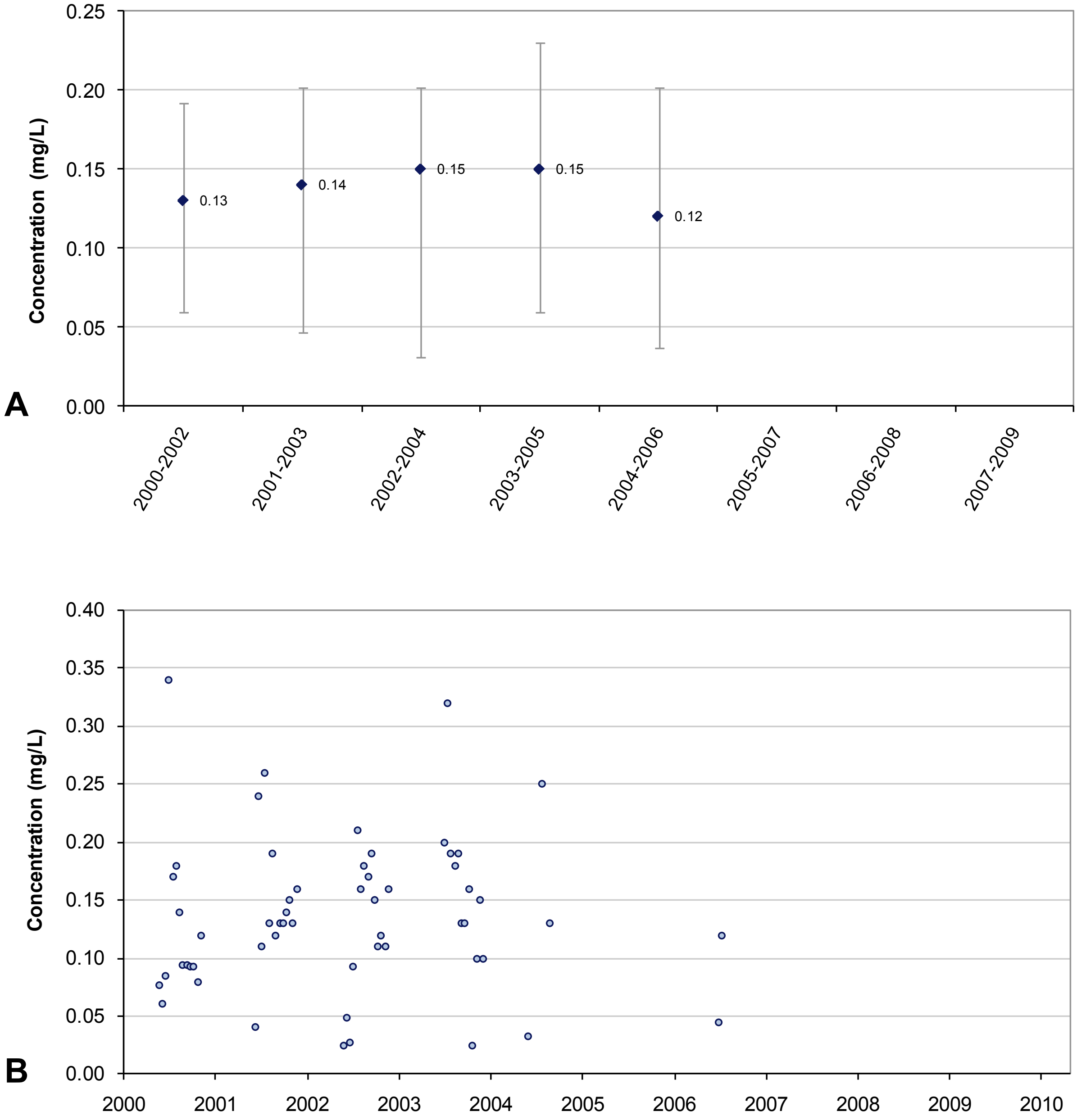


Figure A-1: *Total phosphorus for sampling location 6091051 (Brennan's Bridge) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

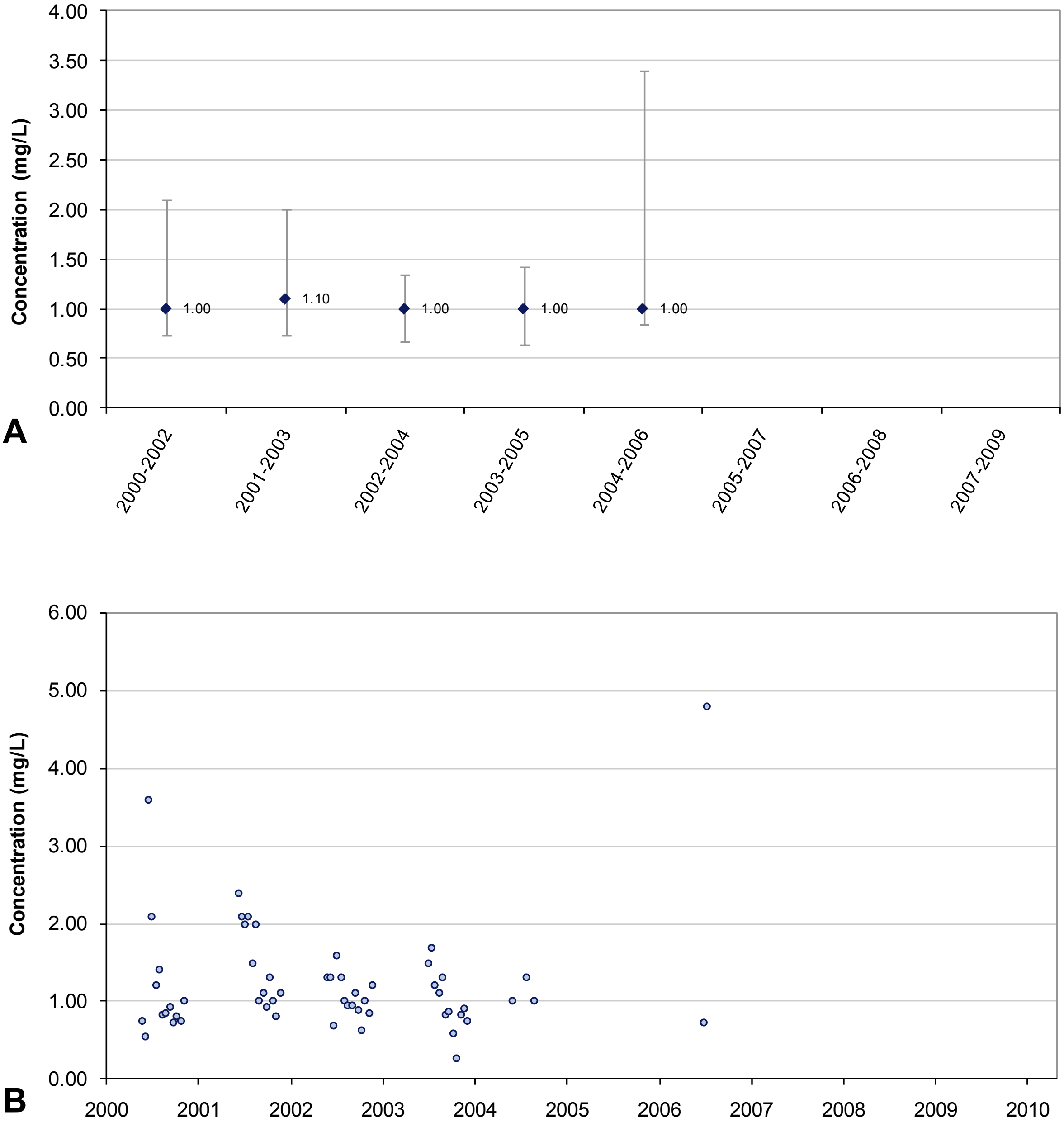


***Figure A-2**: Total nitrogen for sampling location 6091051 (Brennan's Bridge) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

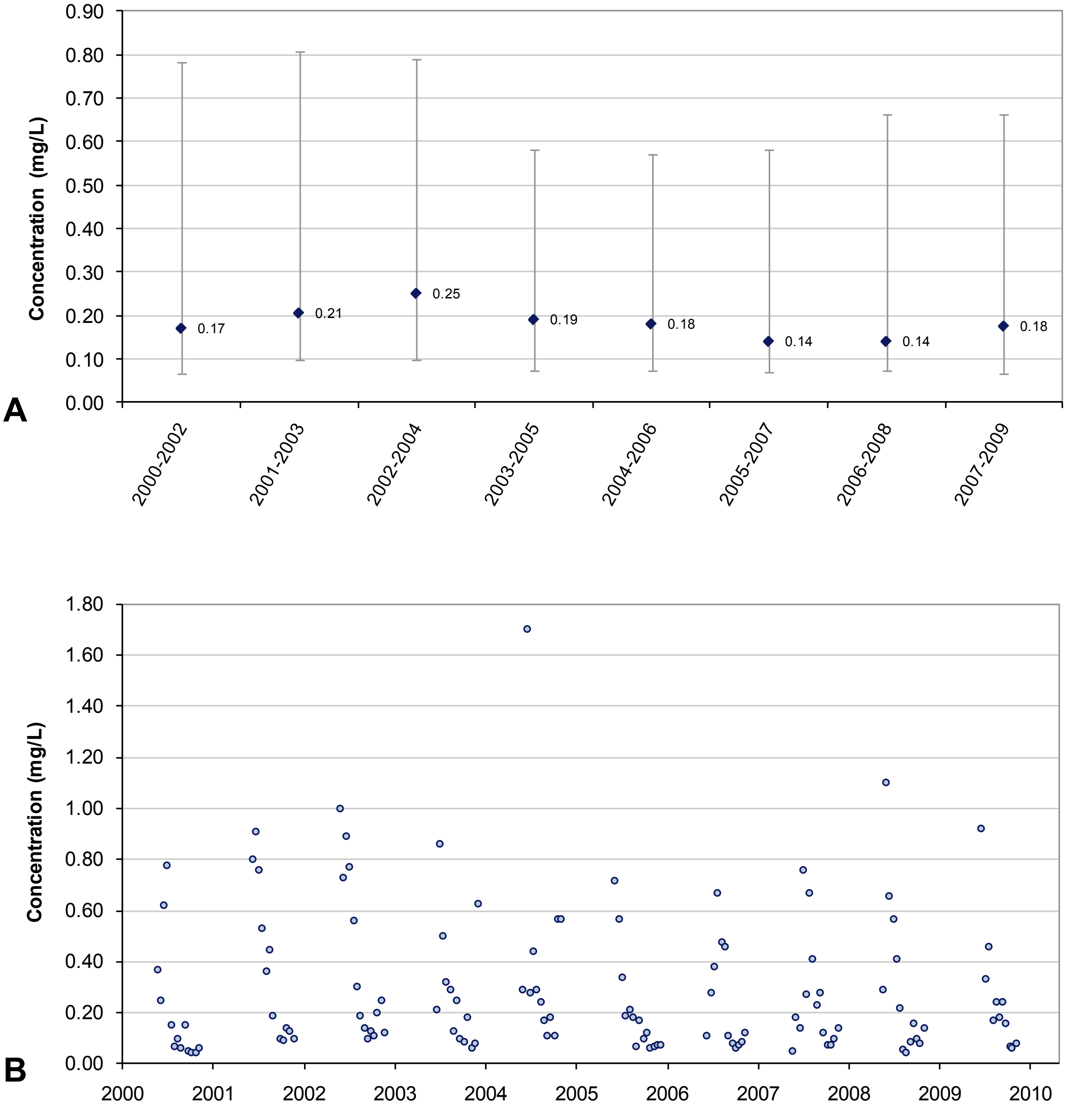


***Figure A-3**: Total phosphorus for sampling location 609026 (Milyeannup Bridge) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

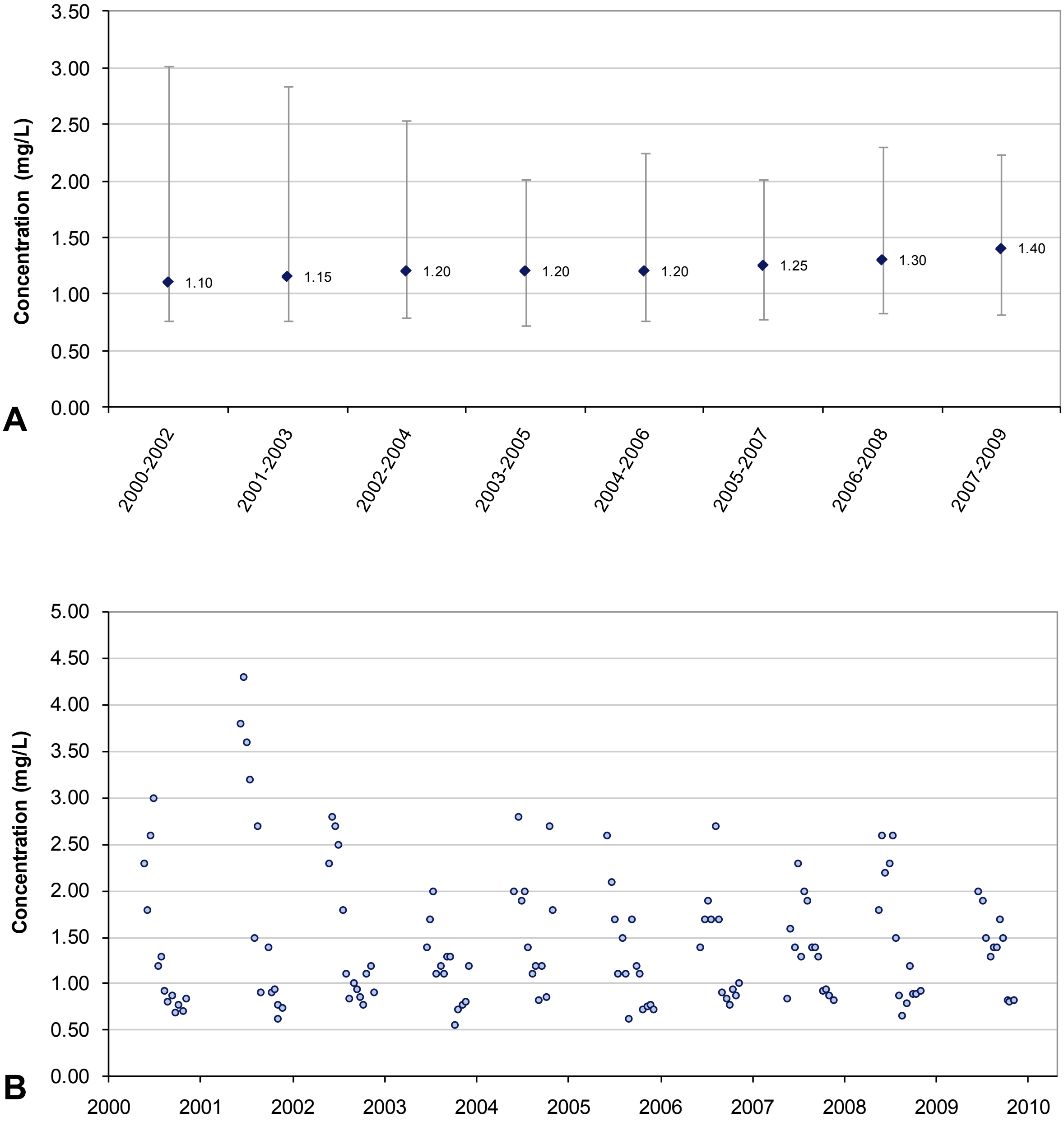


Figure A-4: *Total nitrogen for sampling location 609026 (Milyeannup Bridge) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

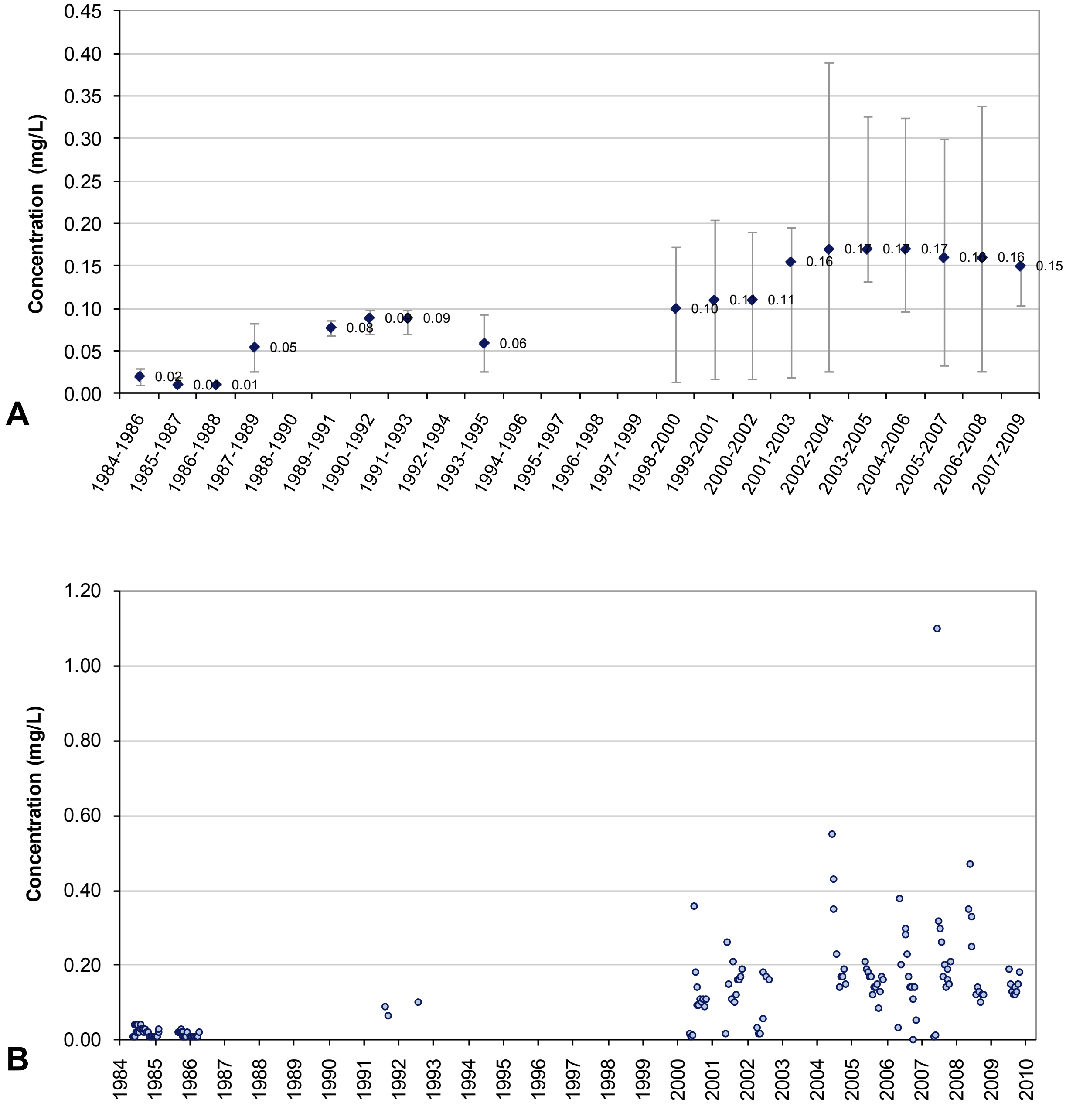


***Figure A-5**: Total phosphorus for sampling location 609002 (Brennan's Ford) displaying changing median, 90th and 10th percentiles for three-year periods from 1984 – 2010 (a) and all data points used for the analysis (b).*

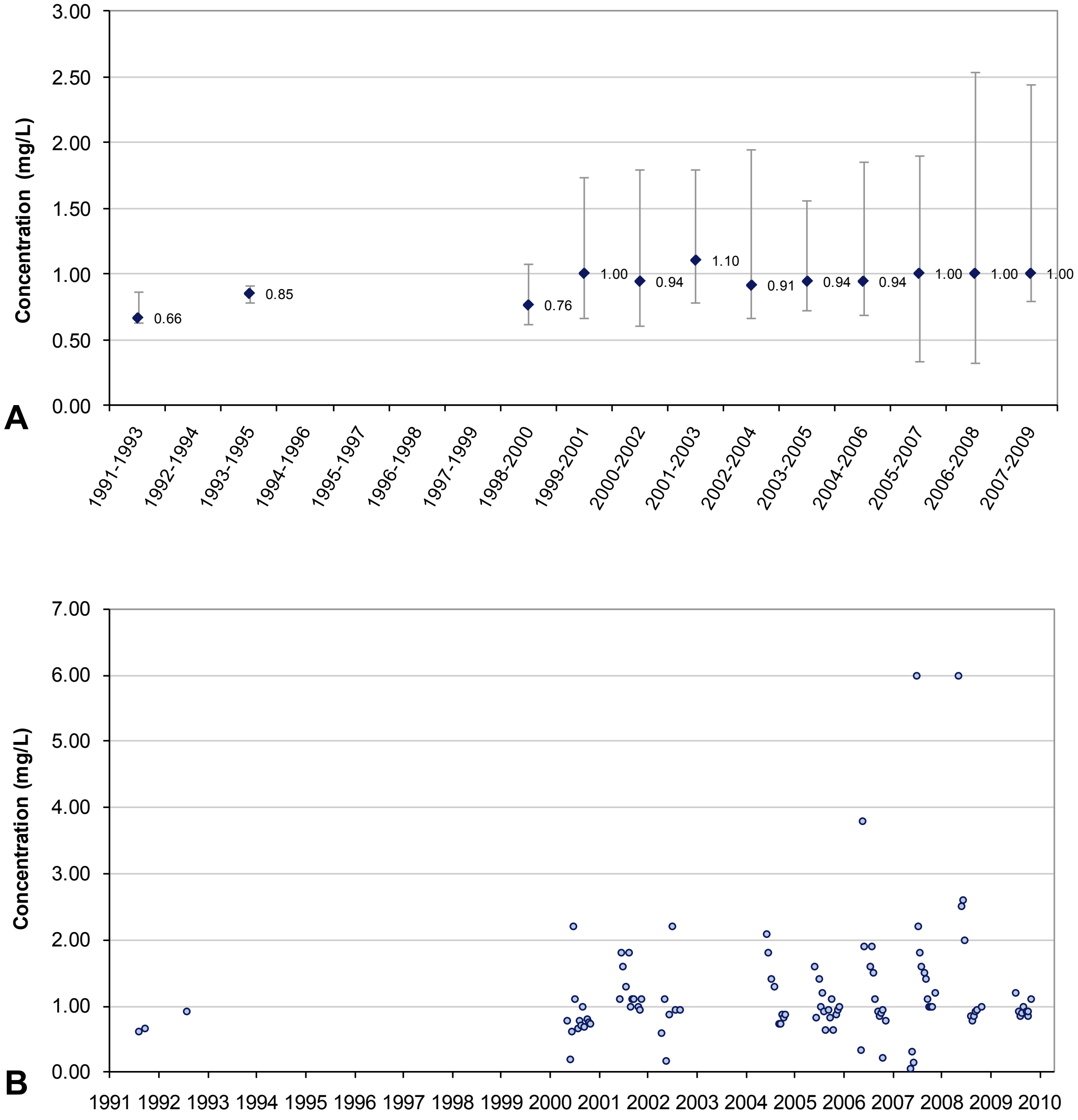


***Figure A-6**: Total nitrogen for sampling location 609002 (Brennan's Ford) displaying changing median, 90th and 10th percentiles for three-year periods from 1991 – 2010 (a) and all data points used for the analysis (b).*

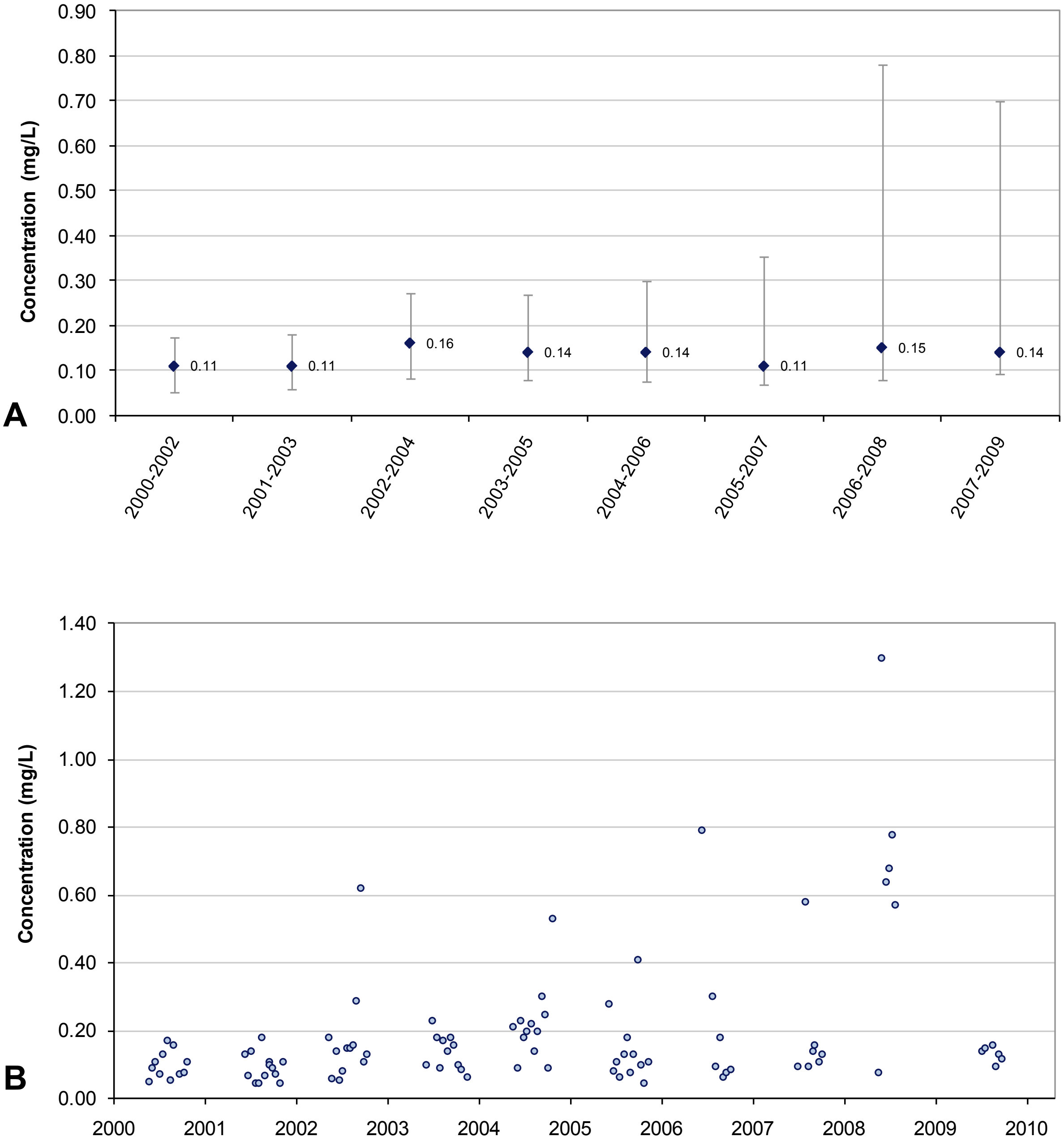
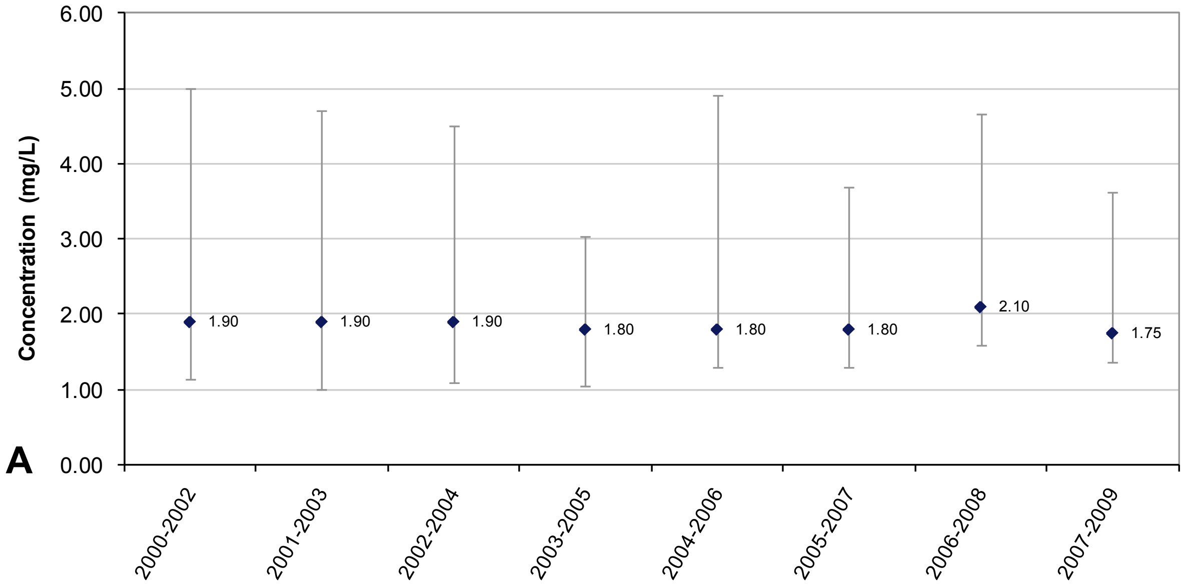


***Figure A-7**: Total phosphorus for sampling location 6091226 (Woodhouse) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*



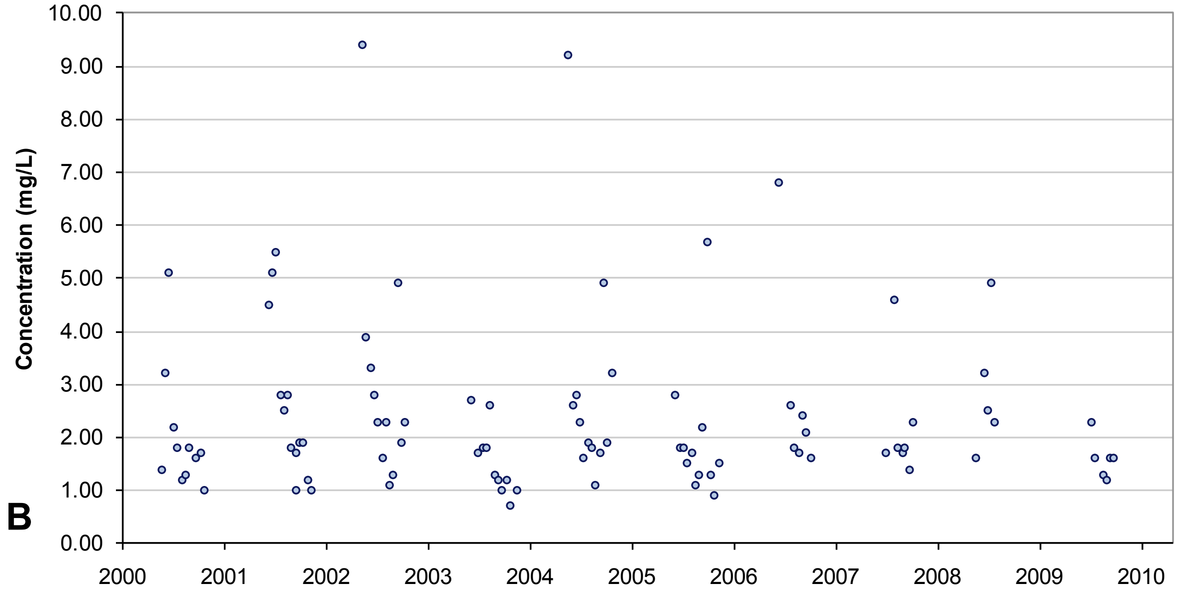


Figure A-8*: Total nitrogen for sampling location 6091226 (Woodhouse) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

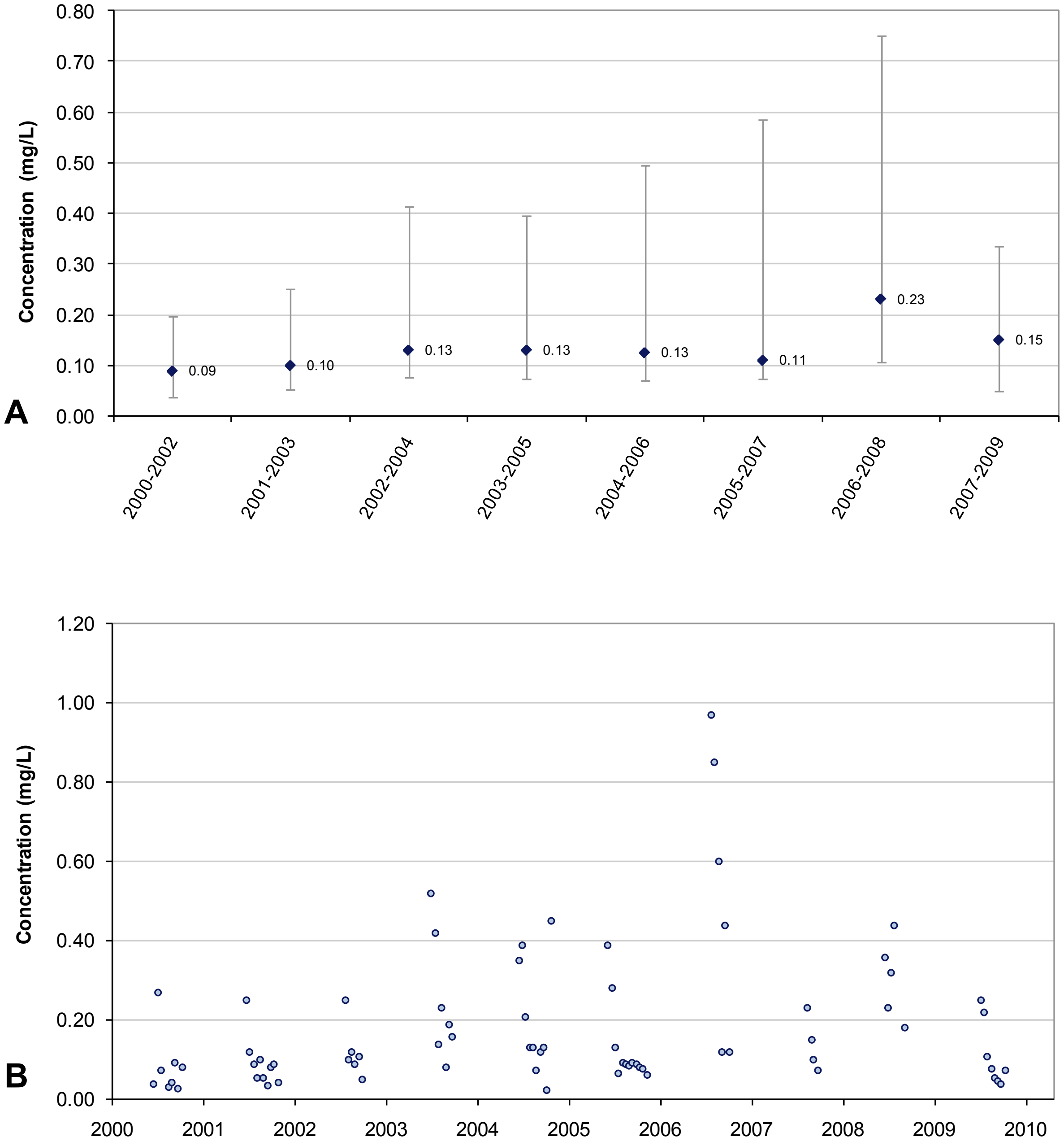


Figure A-9: *Total phosphorus for sampling location 6091225 (Governor Broome Road) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 - 2010 (a) and all data points used for the analysis (b).*

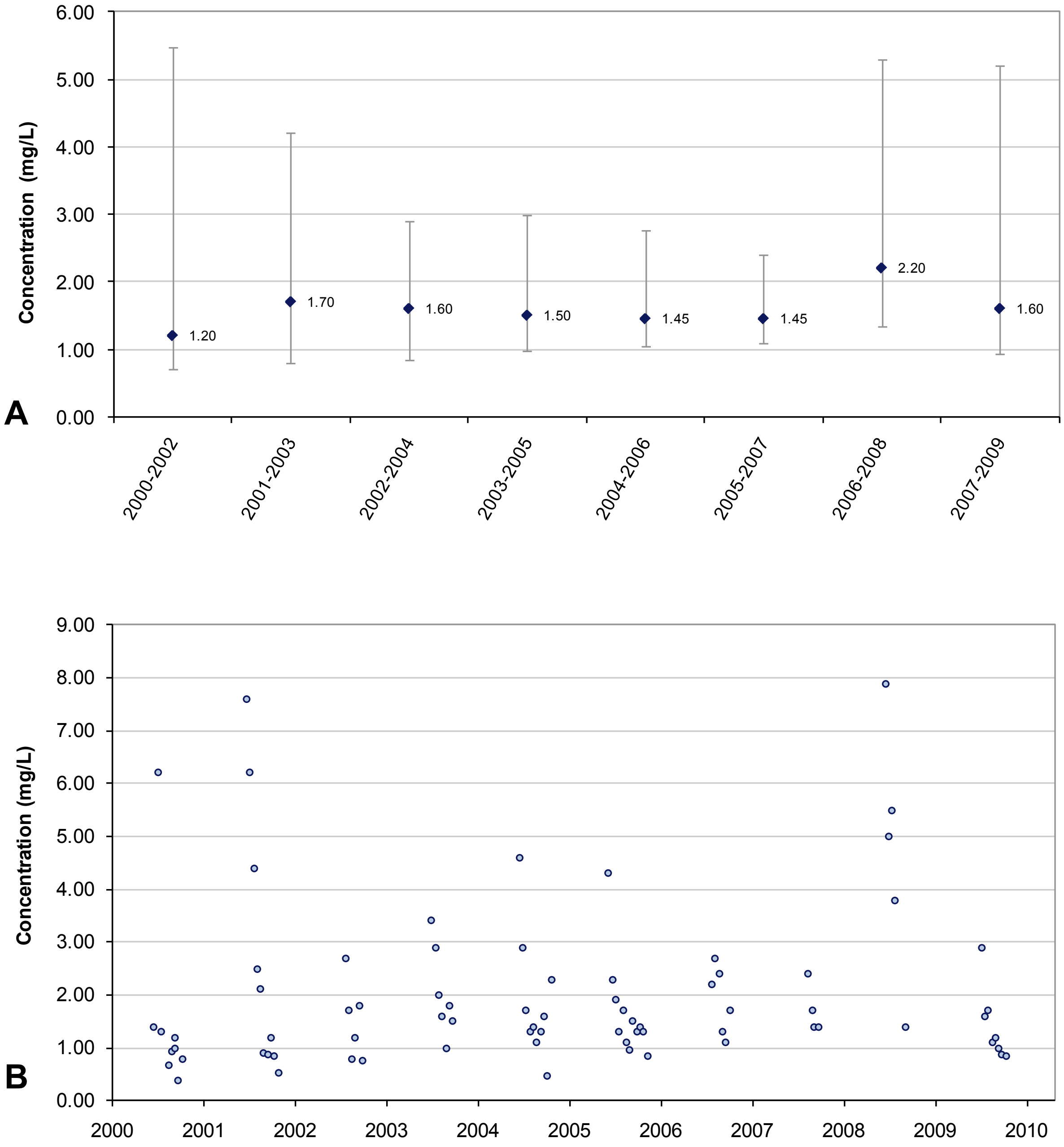


Figure A-10: *Total nitrogen for sampling location 6091225 (Governor Broome Road) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 - 2010 (a) and all data points used for the analysis (b).*

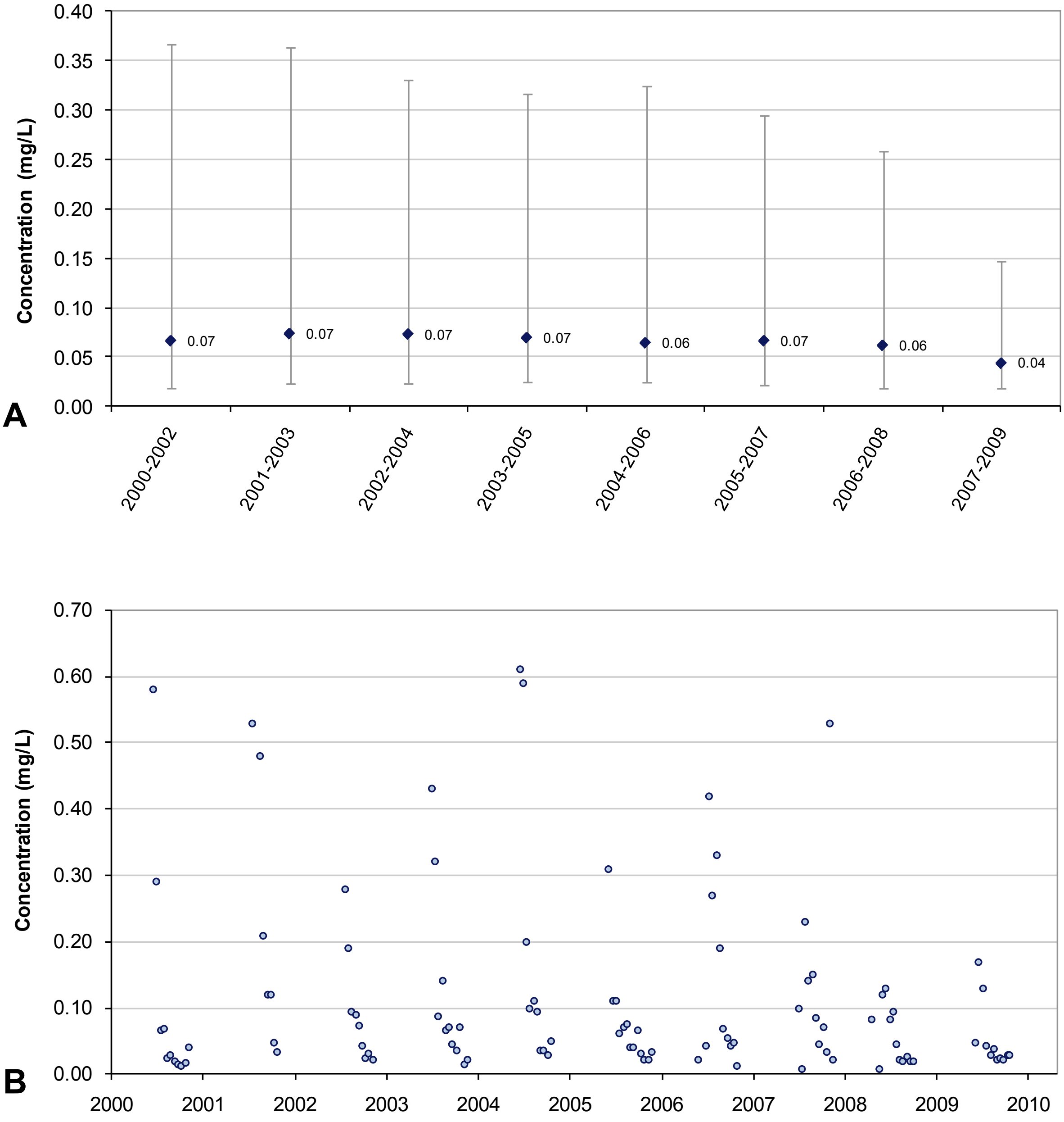


Figure A-11: *Total phosphorus for sampling location 6091224 (Coonack Downs) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

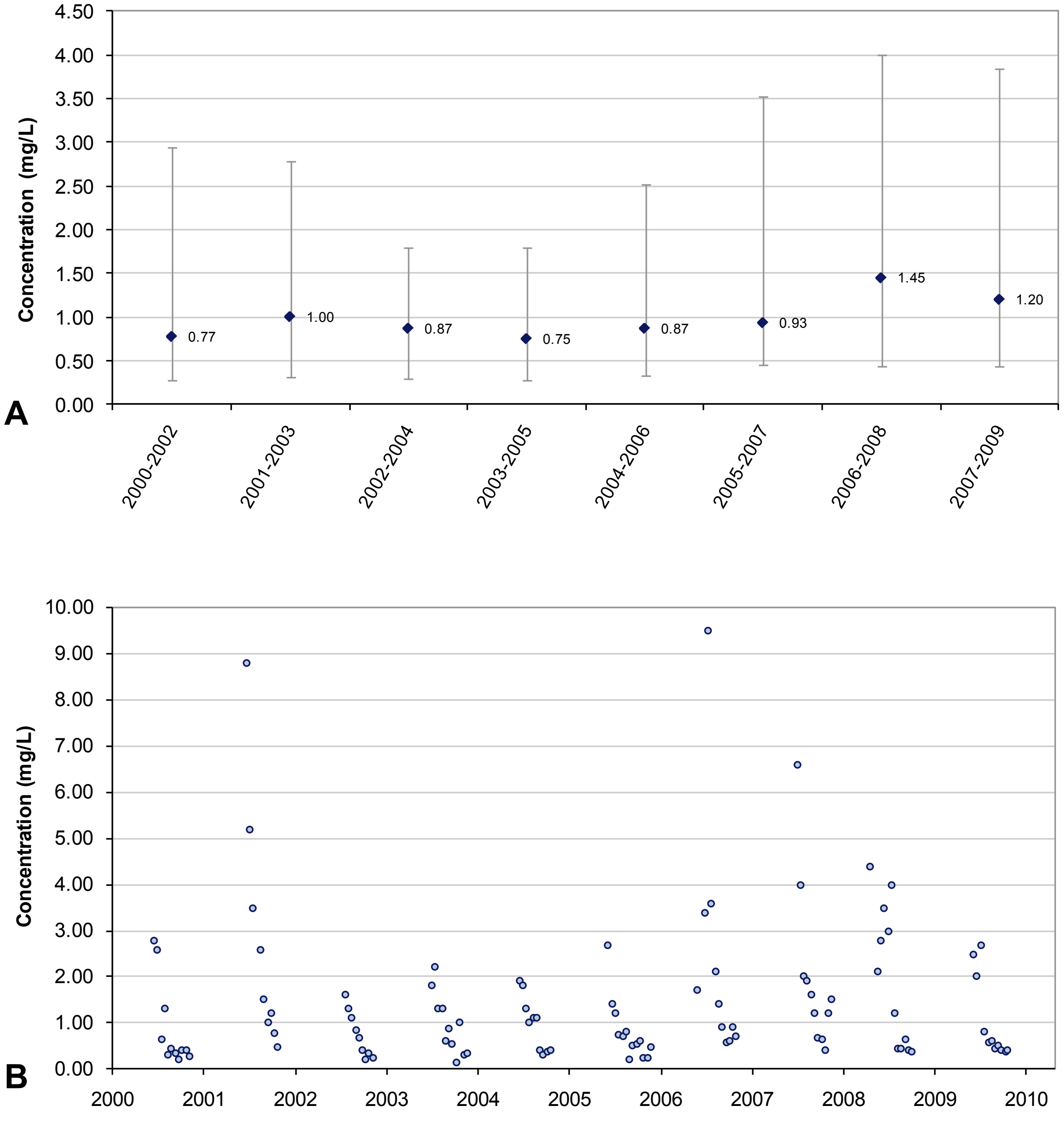


Figure A-12: *Total nitrogen for sampling location 6091224 (Coonack Downs) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

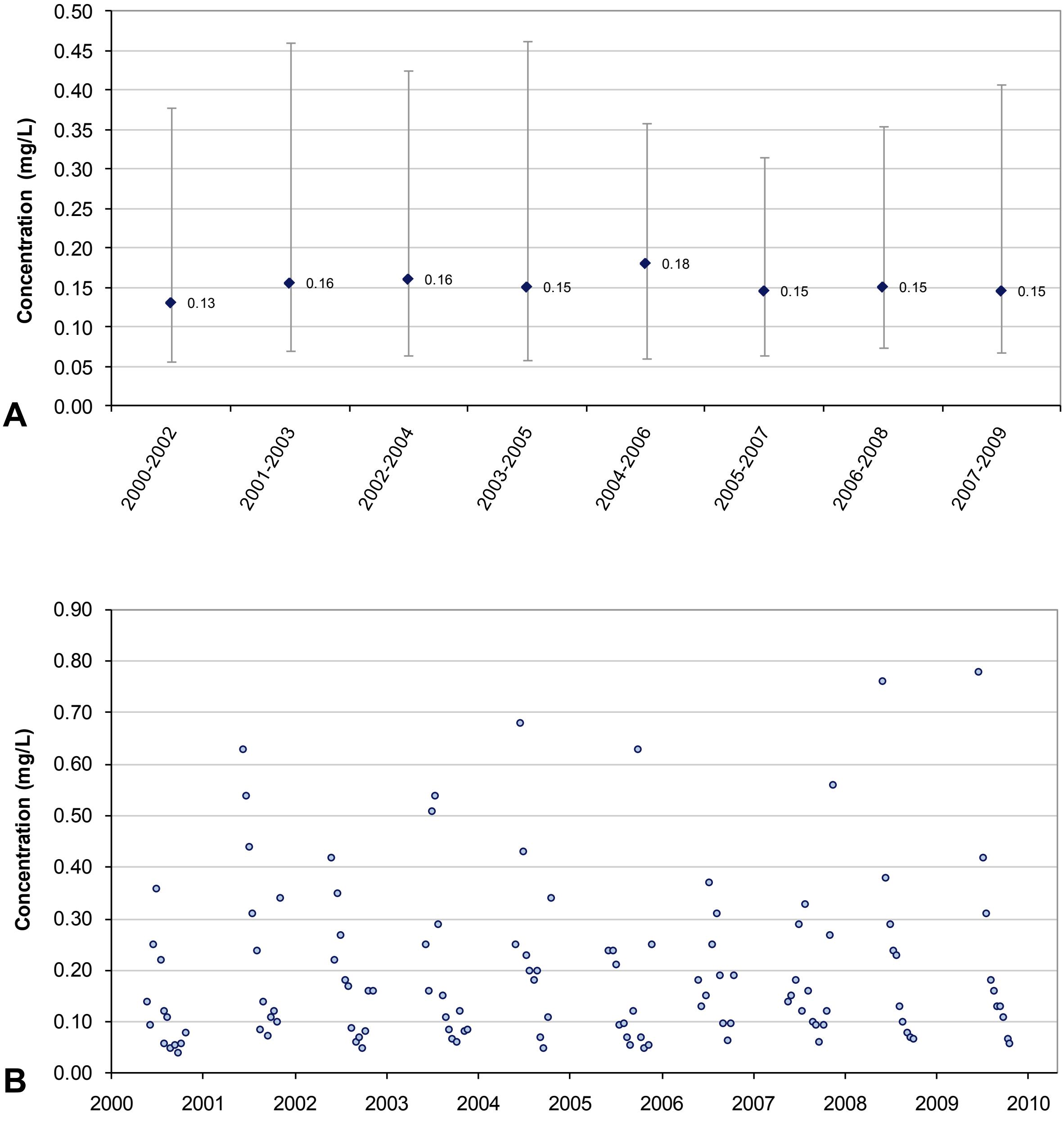


Figure A-13: *Total phosphorus for sampling location 6091223 (Electric Fence – 4 Acres) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 - 2010 (a) and all data points used for the analysis (b).*

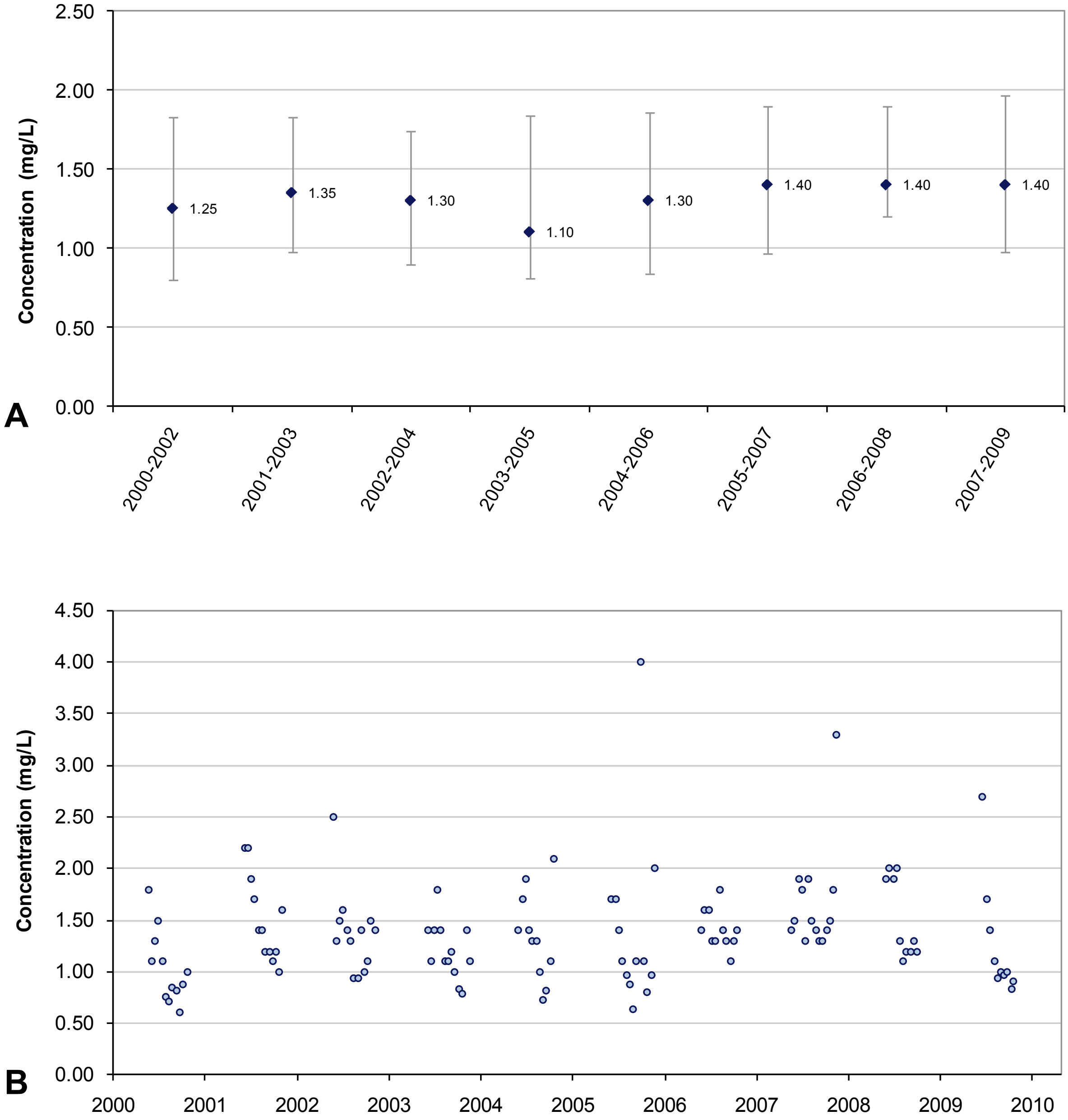


__Figure A-14:__ Total nitrogen for sampling location 6091223 (Electric Fence – 4 Acres) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 - 2010 (a) and all data points used for the analysis (b).

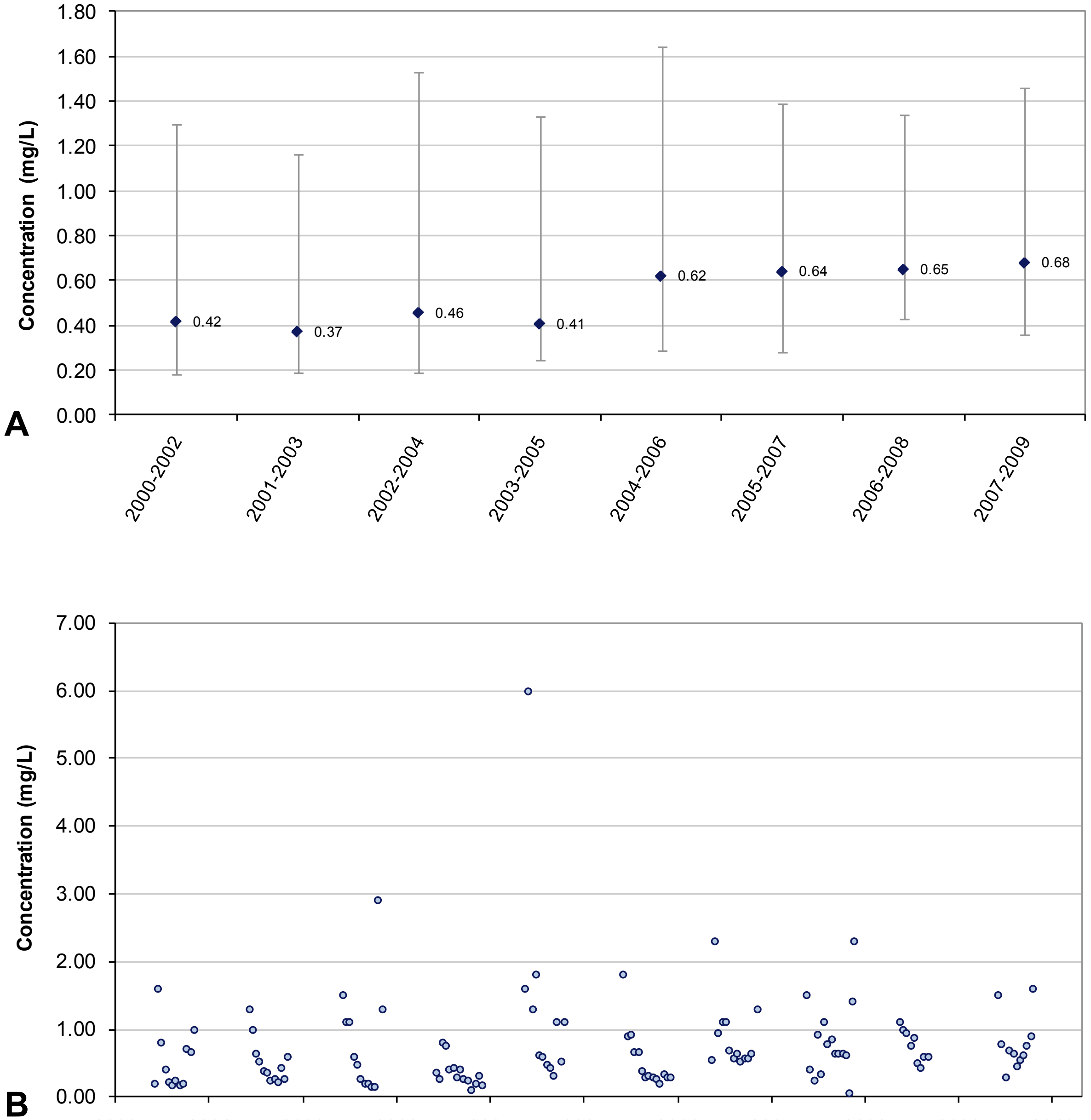
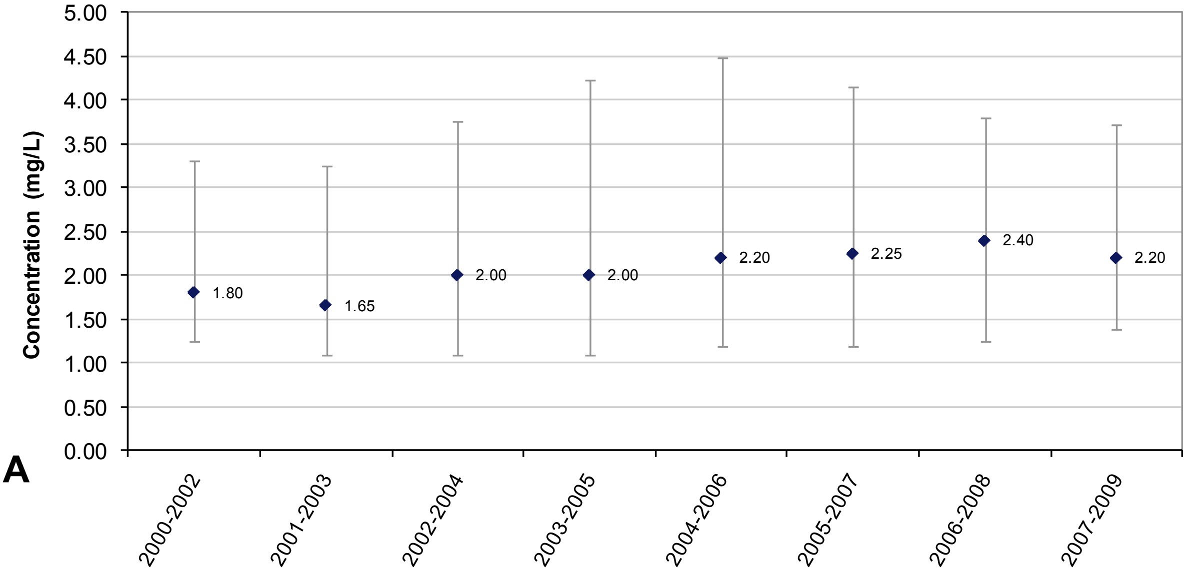


Figure A-15: *Total phosphorus for sampling location 6091222 (S-Bend) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*



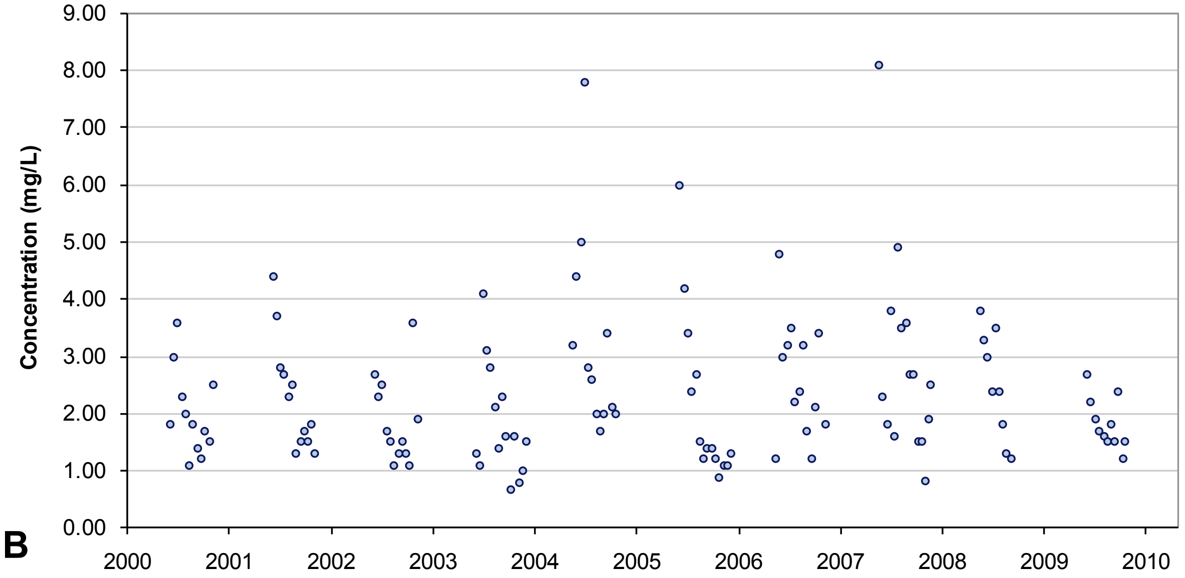


Figure A-16: *Total phosphorus for sampling location 6091222 (S-Bend) displaying changing median, 90th and 10th percentiles for three-year periods from 2000 – 2010 (a) and all data points used for the analysis (b).*

Appendix B: statistical trend methodology

Testing for statistically significant changes

The Mann-Kendall test is used to determine the statistical significance of the trends in water quality over time (Gilbert 1987). It is a non-parametric test and is only used when the data series exhibits independence (i.e. no correlation in the data series) (Figure B-1). The Mann-Kendall test works by calculating a statistic 'S' and testing the significance of this statistic. Each data pair is compared and assigned a plus or a minus depending on whether the later data point is higher than the earlier data point. 'S' is the overall number of pluses or minuses (where one plus cancels out one minus) for the whole dataset (Nelson 2004). The Z-statistic, from which the 'p-value' is derived, is calculated as follows:

$$Z = \frac{S-1}{[Var(S)]^{1/2}} \qquad \text{if S > 0}$$

$$Z = 0 \qquad \text{if S = 0}$$

$$Z = \frac{S+1}{[Var(S)]^{1/2}} \qquad \text{if S < 0}$$

Where *Var(S)* is the variance of the dataset used to derive 'S'. An increasing trend will have a large positive Z-statistic, while the Z statistic for a decreasing trend will be negative and have a large absolute value.

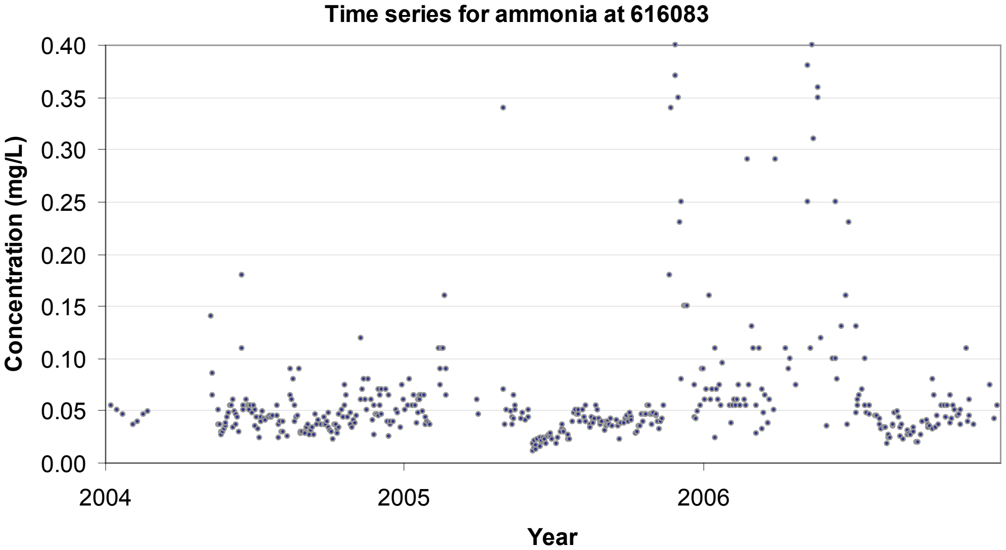


Figure B-1: Example of a time-series with little evidence of a seasonal pattern in total phosphorus concentration, hence the Mann-Kendall test for trend is used.

Seasonal cycles in nutrient concentration are common in waterways and can be introduced by natural cycles in rainfall, runoff, tributary hydrology and seasonal variation in groundwater. When seasonal cycles are evident in a data series (Figure B-2) the Seasonal-Kendall test is used to test for trend. The Seasonal-Kendall test is a variant of the Mann-Kendall test that accounts for the presence of seasonal cycles in the data series (Gilbert 1987). The 'S' statistic is calculated slightly differently in the Seasonal-Kendall test. Rather than comparing all data pairs, only data points falling in the same 'season' are compared. For example, if a weekly season is used, data points from the first weeks of the year are only compared with data points from the first week of all other years.

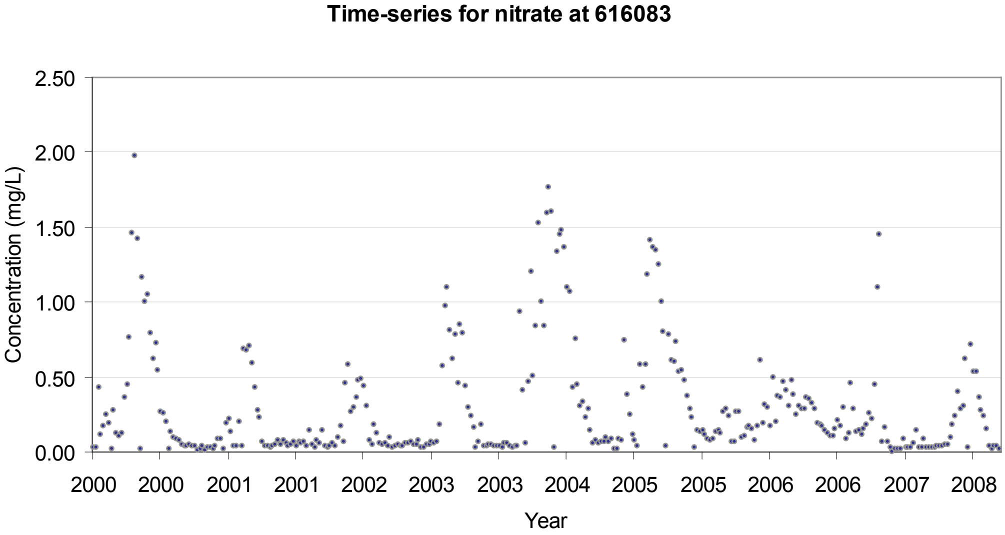


Figure B-2: *An example of a pronounced seasonal pattern in total phosphorus concentration.*

Nutrient concentrations in waterways can also be affected by changes in flow. The relationship between nutrient concentration and flow is modelled using a locally weighted scatterplot smoothing (LOWESS) fit between the concentration and flow (Helsel & Hirsch 1992). The difference of 'residuals' between the observed and LOWESS modelled concentration are termed flow-adjusted concentrations (FAC), as shown in Figure 5-9 (Hipel & McLeod 1994). Trend analyses may then be performed on the flow-adjusted concentrations. The flow-adjustment process often helps to remove seasonal variation (as shown by comparing figures B-2 and B-3b), although some evidence of seasonal variation often remains in the flow-adjusted data series.

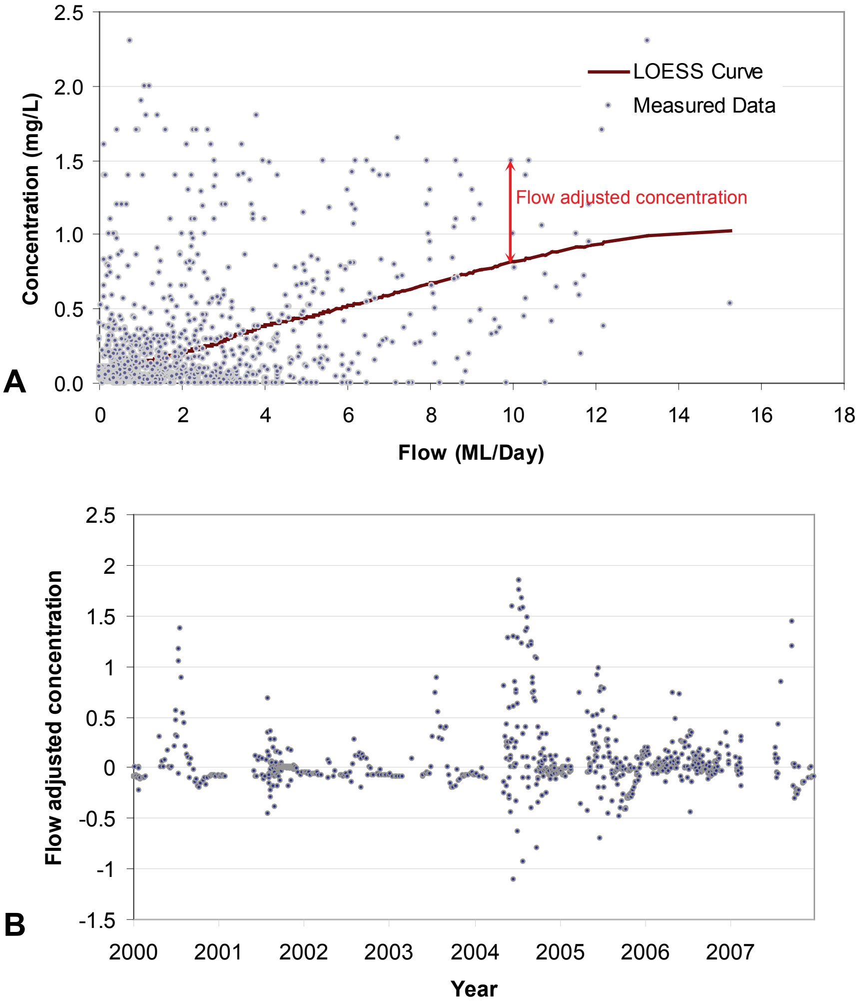


Figure B-3: *The flow response plot shows whether a relationship exists between discharge and nutrient concentration (A). The flow-adjusted concentrations (or residuals) are the difference between observed and modelled (LOWESS) concentrations (B).*

Estimating the rate of change

The Sen slope estimator is used to estimate the slope of the trend line (Gilbert 1987). The Sen estimate is calculated in a similar manner to the test statistic ‘S’ from the Mann-Kendall test. Rather than comparing each data pair from an increase or decrease over time, a slope is calculated using each data pair. The Sen slope estimator is taken as the median slope of all slopes calculated using all data pairs. In the presence of seasonal cycles the Seasonal-Kendall slope estimator is used. This is similar to the seasonal test ‘S’ in the Season-Kendall test, in that slopes are only calculated for data pairs from the same season. The Sen slope estimator is the median of all these slopes. Figure B-4 shows an example of a slope estimated for a seasonal nutrient data series.

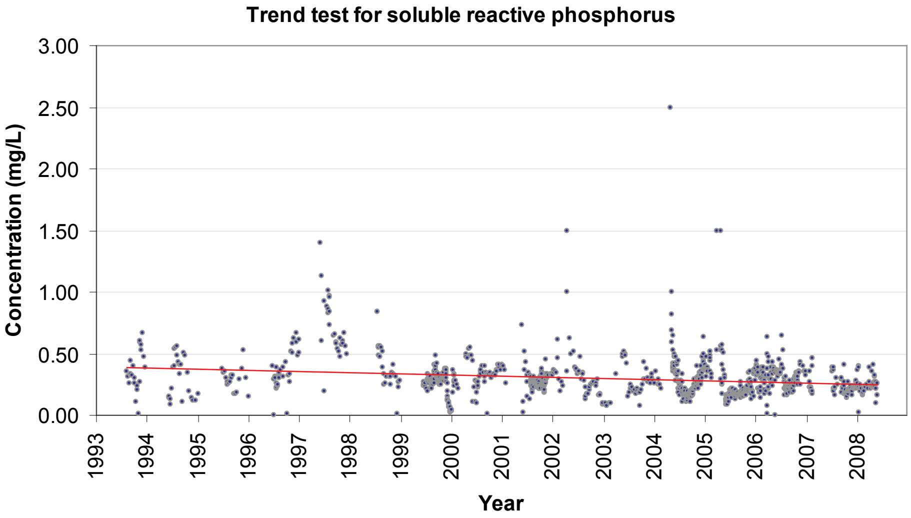


Figure B-4: *An example of how the Seasonal Sen slope estimator represents the slope of the trend line in a seasonal nutrient data series.*

Detecting the trend

A trend in the nutrient data series is significant only when two criteria are met. Firstly, the Mann-Kendall or Seasonal-Kendall test for trend and the data series must be statistically significant (i.e. $p<0.05$). Secondly, the number of independent measurements collected (n^*) has to be approximately equal to or exceed the 'estimated' number of independent measurements ($n^\#$) required to detect a trend.

The effective information content in the data series; that is, the effective number of independent values, is estimated for each of the data series analysed for trend using the formula provided by Bayly and Hammersley (1946) (op. cit. Lettenmaier 1976; Lachance 1992; Close 1989; Zhou 1996).

$$n^* = \left[\frac{1}{n} + \frac{2}{n^2} \sum_{j=1}^{n-1} (n-j)\rho(jt) \right]^{-1}$$

Where:

n^* = effective number of independent observations

n = number of measurements

j = lag number

t = sampling interval

ρ = coefficient of correlation

Where seasonal cycles are found, the nutrient data series are de-trended and de-seasonalised (using seasonal medians) before calculating the number of independent measurements (n^*). The estimated number of measurements needed to detect a linear trend (in a variable distributed normally about the trend line) is performed using the functions (Lettenmaier 1976; Ward et al. 1990):

$$n^{\#} = 12\sigma^{2} \frac{\left[t_{\alpha/2,(n-2)} + t_{\beta,(n-2)}\right]^{2}}{\Delta^{2}}$$

Where:

$n^{\#}$ = estimated number of measurements needed to detect a trend

σ = the standard deviation of the de-trended series

Δ = the magnitude of the trend

t = the critical values of the t-distribution where $\alpha = 0.05$ and $\beta = 0.1$

This function relies on probabilities predicted by the t-distribution and is therefore from the parametric family of statistical procedures. Data requirements for parametric and the equivalent non-parametric tests are similar, so the equation will approximate the sample size needed for non-parametric tests of significance (Ward et al. 1990).

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