GOVERNMENT OF
WESTERN AUSTRALIA

NITROGEN AND PHOSPHORUS IN TRIBUTARY INFLOWS TO THE WILSON INLET, WESTERN AUSTRALIA

[illegible]

WATER RESOURCE TECHNICAL SERIES

WATER AND RIVERS COMMISSION REPORT WRT 21
1999

WATER AND RIVERS
COMMISSION

WATER AND RIVERS COMMISSION
HYATT CENTRE
3 PLAIN STREET
EAST PERTH
WESTERN AUSTRALIA 6004
TELEPHONE (08) 9278 0300
FACSIMILE (08) 9278 0301
WEBSITE: http://www.wrc.wa.gov.au

Cover Photograph: An aerial photograph of the Hay River discharging into the Wilson Inlet

Nitrogen and Phosphorus in Tributary Inflows to the Wilson Inlet, Western Australia

by

R. B. Donohue, B. N. Jakowyna and S. W. Nelson

Water and Rivers Commission
Rivers and Estuaries Investigations

WATER AND RIVERS COMMISSION
REPORT NO WRT 21
1999

Acknowledgments

The authors would like to thank the River & Estuary Investigations Branch and the Denmark Regional Office of the Water & Rivers Commission for collecting, managing and analysing the data and for contributing valuable advice and information towards the report.

Reference Details

The recommended reference for this publication is:
Water and Rivers Commission 1999, *Nitrogen and Phosphorus in Tributary Inflows to the Wilson Inlet, Western Australia,* Water and Rivers Commission, Water Resource Technical Series No WRT 21.

ISBN 0-7309-7451-0
ISSN 1327-8436

Printed on recycled stock
November, 1999

Contents

Figures

Tables

Summary

With the establishment of the Wilson Inlet Management Authority in 1994 (WIMA) a catchment sampling program was instigated by the Agriculture Department of WA with assistance from NLP funding and using existing Water Authority gauging stations. In 1997, the National Eutrophication Management Program (NEMP) selected the Wilson Inlet and its catchment to focus specifically on the management of algal blooms and other eutrophication related problems and to demonstrate the link between catchment and estuarine water quality.

The Water and Rivers Commission took over the program in 1997 and added four new sites to the network, including flow gauging structures, to capture waters from previously ungauged portions of the catchment. Sampling from 1997 to the present has supported both the NEMP program and WIMA information needs.

Since the aim of the 1994 –1997 program was to was to derive nutrient loads being delivered from the catchment to the estuary opportunistic sampling targeting storm events was used to generate the desired information. From 1997 the information objectives changed to detecting changes in ambient nutrient concentration in tributaries and estimating nutrient loads generated from regular, fixed-interval sampling. All data collected between 1994 and 1998 were analysed to determine the best use of the data in determining status of the catchments with respect to nutrients and loading to the estuary. This analysis provides the basis for determining future sampling requirements.

Existing data have been used to:

- Compare among sites (streams)
- Compare among seasons
- Show relationships between concentration and flow
- Establish classification of streams based on nutrient concentrations
- Derive estimates of nutrient loading to the estuary

Comparisons of the nutrient concentrations in the sampled streams revealed that four tributaries are high in nutrients contributors to the eutrophication-related problems in Wilson Inlet. These were Cuppup Creek, Little River, Sleeman River and Sunny Glen Creek indicating the need to focus management action in those catchments. Extensive land clearing, seen in Cuppup Creek, Sunny Glen Creek and Sleeman River catchments, leads to elevated nutrient levels in surface runoff. Losses of animal waste, plant material and applied fertiliser from farm stock is also known to significantly contribute to excessive nutrient concentrations in some streams.

Tributary hydrology was found to be a significant factor in determining nutrient concentration. Storm events delivered the bulk of nutrients to the tributaries from a combination of surface runoff, soil water and erosion processes. However, groundwater was observed to strongly influence nutrient concentration in the periods between storm events, especially in those catchments that have been extensively cleared or where groundwater levels are high (eg: Cuppup Creek).

Seasonal patterns in nutrients were observed for many tributaries, especially those situated lower in the catchment where groundwater is thought to be an influencing factor. Peak delivery of nutrients to Wilson Inlet occurred during late winter to early spring coinciding with peak rainfall and catchment flushing.

Inorganic supplies of nutrients, derived mainly from leaching and runoff, provide algal species with a readily available source of nutrients in the estuary. Most inorganic nitrogen appears to be rapidly removed from the catchment following initial catchment flushing (ie. June), while peak inorganic phosphorus concentrations coincided with peak rainfall and (possibly) peak erosion events in the tributaries (ie. August / September).

The biologically *less* useful organic forms of nitrogen and phosphorus, derived from plant and animal waste, is the dominant nutrient fraction delivered to the estuary. Organic nutrients delivered to the estuary are likely to have long residence times through sediment storage, but eventually contribute to the bio-available nutrient supply through biochemical reactions. This enables opportunistic aquatic plant species to have a year-round store of bio-available nutrients in the estuary and, given that the nutrient supply is not exhausted, would limit their growth to other factors such as light availability, temperature, turbulence, etc.

Measuring nutrient loads delivered to estuaries has been the traditional approach for investigating catchment changes, rather than measuring catchment condition as expressed by tributary water quality. Estimates in nutrient loading are biased due to an inadequate sampling of storm events and errors in rating curve techniques used in calculation of loads. For this reason, trends in nutrient concentration should be used as a statistical measure of long-term change in water quality. Nutrient loading to the estuary has been estimated using a statistical approach developed by the Rivers and Estuaries Investigations Section of the Water and Rivers Commission.

To meet the continuing need for reliable estimates of loading to the estuary, data from autosamplers situated on the Denmark and Sleeman rivers will be used to sample at various stages of the storm hydrograph. Nutrient loads with a known precision and accuracy will be derived from these data.

Preliminary analysis for trends (changes in time) in the nitrogen and phosphorus concentration data series revealed *emerging* increasing trends in the Sleeman River from 1994-97. However, verification of this trend was not possible due to an inadequate sample size. When five years of nutrient data becomes available for each site the detection of statistically significant temporal trends in ambient nutrient concentration will become an achievable option. To meet these information requirements in the Wilson Inlet catchment nutrient monitoring program a fortnightly fixed interval sampling regime is recommended for both permanent and ephemeral tributaries. An important feature of the monitoring program is that information objectives will be closely linked to the error probabilities associated with detecting change in a nutrient concentration data series. This will give managers a better perspective of long-term temporal changes in nutrient losses from the catchment, and will allow classification of stream status and provide the ability to measure against targets.

1. Introduction

1.1 Background

The Waterways Commission began monitoring nutrient concentrations in the tributary inflows to Wilson Inlet in 1991 (Figure 1). In 1994, the Wilson Inlet Management Authority (WIMA) was established and the monitoring program was upgraded as part of a National Landcare Program project aimed at measuring the contribution of nutrients and sediment to Wilson Inlet from non-point sources. The water quality monitoring program was set up to identify surface drainage containing high levels of nutrients and sediment, and to provide estimates of annual loading of the estuary with nutrients over time. Estimates of annual phosphorus and sediment load have been reported for the period 1994 to 1996 (Tipping 1997). In 1997, the Waters and Rivers Commission became the agency responsible for the catchment monitoring program.

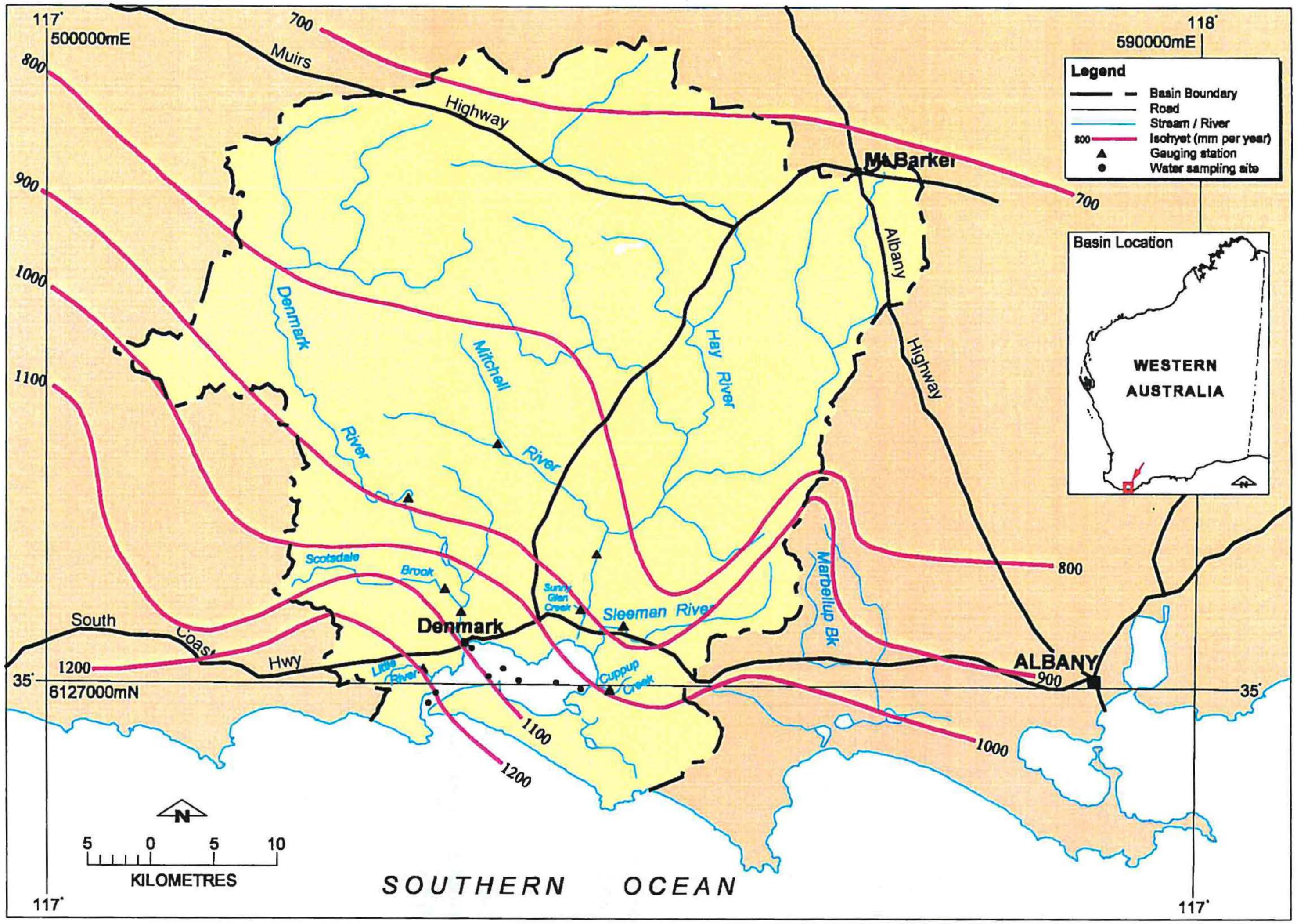
In 1997, the catchment of the Wilson Inlet was selected as one of only four 'focus' catchments in Australia for the National Eutrophication Management Program (NEMP). The NEMP is concerned primarily with the management of algal blooms (especially blue-greens) although the program also has an interest in the investigation and management of other eutrophication related problems. The Wilson Inlet was selected in part because it could illustrate linkages between water quality in the catchment with trophic condition in the estuarine environment.

The NEMP committee has identified six priority areas for research that address the bio-availability of nutrients, nutrient sources and sinks, and phytoplankton population dynamics. Two of the six research priorities are most relevant to the work reported in this report, these are: '*Evaluation of effectiveness of actions to manage nutrients*' and '*Effects of episodic events on waterbody ecology*'. The two information goals can not necessarily be met by the current nutrient monitoring program.

1.2 Purpose of this report

Since existing data has been collected over a range of sampling frequencies and sites, the primary purpose of this report is to examine how best, in a statistical sense, the data can be utilised. The secondary aim of the report is to develop a sampling program that meets current and anticipated information requirements for the Wilson Inlet catchment.

Section 2 of this report presents an analysis of nutrient concentrations in the monitored waterways with an emphasis made on the examination of variation in the nutrient concentration series due to flow effects and seasonal patterns. Section 2 also contains estimates of nutrient load in the monitored waterways. In Section 3, a review of the current monitoring program was performed and improvements subsequently recommended. An analysis of the trend results was carried out to assess the sensitivity of the current monitoring program towards detecting trends in nutrient concentration. The information objectives of the program were defined, followed by a description of the procedures used in selecting the appropriate sampling frequency to meet these goals. Section 3 subsequently recommends an improved sampling strategy for measuring mass nutrient loads in rivers.


117°
500000mE
118°
590000mE
Legend
Basin Boundary
Road
Stream / River
800 Isohyet (mm per year)
▲ Gauging station
● Water sampling site
Basin Location
WESTERN AUSTRALIA
N
700
800
900
1000
1100
1200
Muirs Highway
Mt Barker
Albany Highway
Denmark River
Mitchell River
Hay River
Scotsdale Brook
Sunny Glen Creek
Sleeman River
Marbellup Bk
South Coast Hwy
Denmark
Little River
Cuppup Creek
ALBANY
35°
6127000mN
N
5 0 5 10
KILOMETRES
SOUTHERN OCEAN
117°

2. Variation in nutrient concentration (1991-1997)

2.1 The Wilson Inlet monitoring program

The monitoring program in the Wilson Inlet drainage basin was based on grab samples collected broadly in weekly intervals, combined with opportunistic sampling collected during high flows. Before 1994, the actual sampling frequency varied widely in *ad hoc* intervals of time in response to rainfall events. To improve the reliability of the loading estimates, stage-height samplers were added to the monitoring network for the 1995-1996 flow years.

In the period 1991 to 1997, Cuppup, Denmark (Mount Lindsay), Hay and Sleeman rivers were sampled, while the Mitchell River was sampled between 1994-1996. During 1997 sampling at other sites in the Wilson catchment commenced including Denmark (Agricultural College) River, Little River, Scotsdale Brook and Sunny Glen Creek. Samples were analysed for oxidised nitrogen (NO_2 and NO_3), ammonium, total nitrogen (TN), filterable reactive phosphorus and total phosphorus (TP).

Recognising the importance of loading estimates with a known precision to process related work in Wilson Inlet, programmable autosamplers were installed on the Denmark and Sleeman Rivers. These data will be reported when the data become available.

This section reports the results of an analysis of the nutrient data collected in the Wilson catchment since 1991. The aims of the analysis were to review the current catchment nutrient monitoring program in terms of its capacity to efficiently provide management with desired information.

2.1.1 Adequacy of part program

The data collected by sampling programs in Wilson Inlet are shown in Figures 2 and 3. The figures show when samples were collected in the past and which nutrient parameters were sampled. It is apparent that there are many gaps in the data series. In optimally designed fixed-interval sampling regimes, samples should be collected over the entire duration of a tributary's flow period to ensure a representative historic record. Missing data in the series pose a serious threat to both the accuracy and precision of many data analysis techniques. Measuring the relative amount of missing data can illustrate the effectiveness of the fixed-interval sampling regime that is currently in place.

Table 1 shows the per centage of flow weeks actually sampled in each year at each monitored site. Trend detection objectives require a single observation per period at regular intervals (one sample per week for example). Much of the earlier collected data (between 1991-94) appears to have been erratically collected in response to storm events and is suited only for obtaining loading information objectives. Sampling in this manner can result in a large portion of a stream's flow period not being sampled and results in a loss of potential independent samples. The opportunistic sampling strategy is generally recognised as unsuitable for the detection of trends in ambient nutrient concentrations.

The per cent of missing data per year for most monitored sites ranged between 16 to 100 per cent (Table 1). The per centage of missing data between 1991-94 was large primarily due to the presence of opportunistic sampling. Missing data in 1995-97 was lower and can be attributed to fixed interval sampling. However, compliance with the fixed interval sampling regime was still far from ideal. Although samples were collected in weekly fixed intervals, sampling commenced late in the flow year resulting in periods of missing data. Many monitored streams are permanent and, for the purpose of meeting trend information objectives, require that samples be taken throughout their entire flow period.

A graphical representation of when samples were collected in relation to the hydrographs of the monitored tributaries of Wilson Inlet is shown in Figure 4. Between the monitoring period of 1991-94, many samples were collected during storm events (peak flows) and very few samples were taken during smaller flows and base flows. Opportunistic sampling was replaced in 1994 to more regular fixed sampling intervals. Most samples collected after 1994 were sampled during low to medium flow periods which is usually the case for fixed-interval sampling. As shown for most sites in 1995 (Figure 4), the entire hydrograph was intensively sampled using a fixed interval sampling regime and resulted in a comparatively low per centage of missing data for that flow year (Table 1).

Table 1. The per centage of missing data assuming compliance with fixed interval sampling over the duration of flow years for monitored sites in the Wilson Inlet (1991-97).

Site	Year	Sampling Interval Used	Total Flow Weeks in Year	Number of Samples Taken per Year	Per centage of Missing Data
CUPPUP	1991	Weekly	31	8	74%
	1992	Weekly	30	23	23%
	1993		34	0	100%
	1994	Weekly	33	8	76%
	1995	Weekly	34	26	24%
	1996	Weekly	28	14	50%
	1997	Weekly	28	20	29%
Denmark(ML)	1991	Weekly	52	9	83%
	1992	Weekly	52	16	69%
	1993		52	0	100%
	1994	Weekly	52	11	79%
	1995	Weekly	52	36	31%
	1996	Weekly	52	26	50%
	1997	Fortnightly	52	10	62%
HAY	1991	Weekly	52	9	83%
	1992	Weekly	48	17	65%
	1993	Weekly	52	9	83%
	1994	Weekly	52	12	77%
	1995	Weekly	52	36	31%
	1996	Weekly	52	24	54%
	1997	Weekly	52	20	62%
Mitchell	1994	Weekly	33	12	64%
	1995	Weekly	37	31	16%
	1996	Weekly	41	24	41%
SLEEMAN	1991	Weekly	52	9	83%
	1992	Weekly	52	15	71%
	1993	Weekly	52	10	81%
	1994	Weekly	52	12	77%
	1995	Weekly	52	36	31%
	1996	Weekly	52	26	50%
	1997	Weekly	52	20	62%

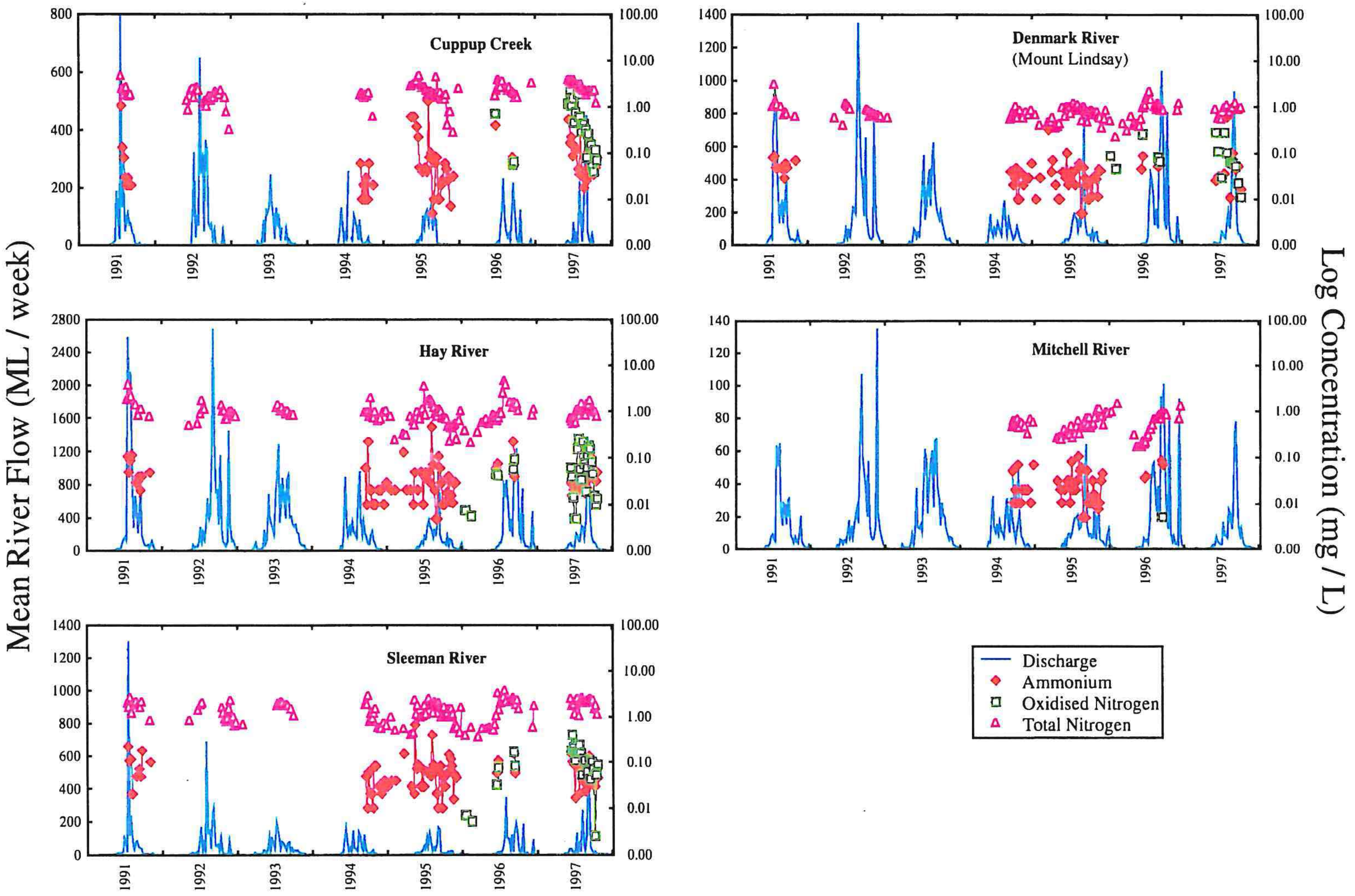


Figure 2. Time series analysis of nitrogen species concentration and stream discharge for the major streams in the Wilson catchment from 1991 - 1997.

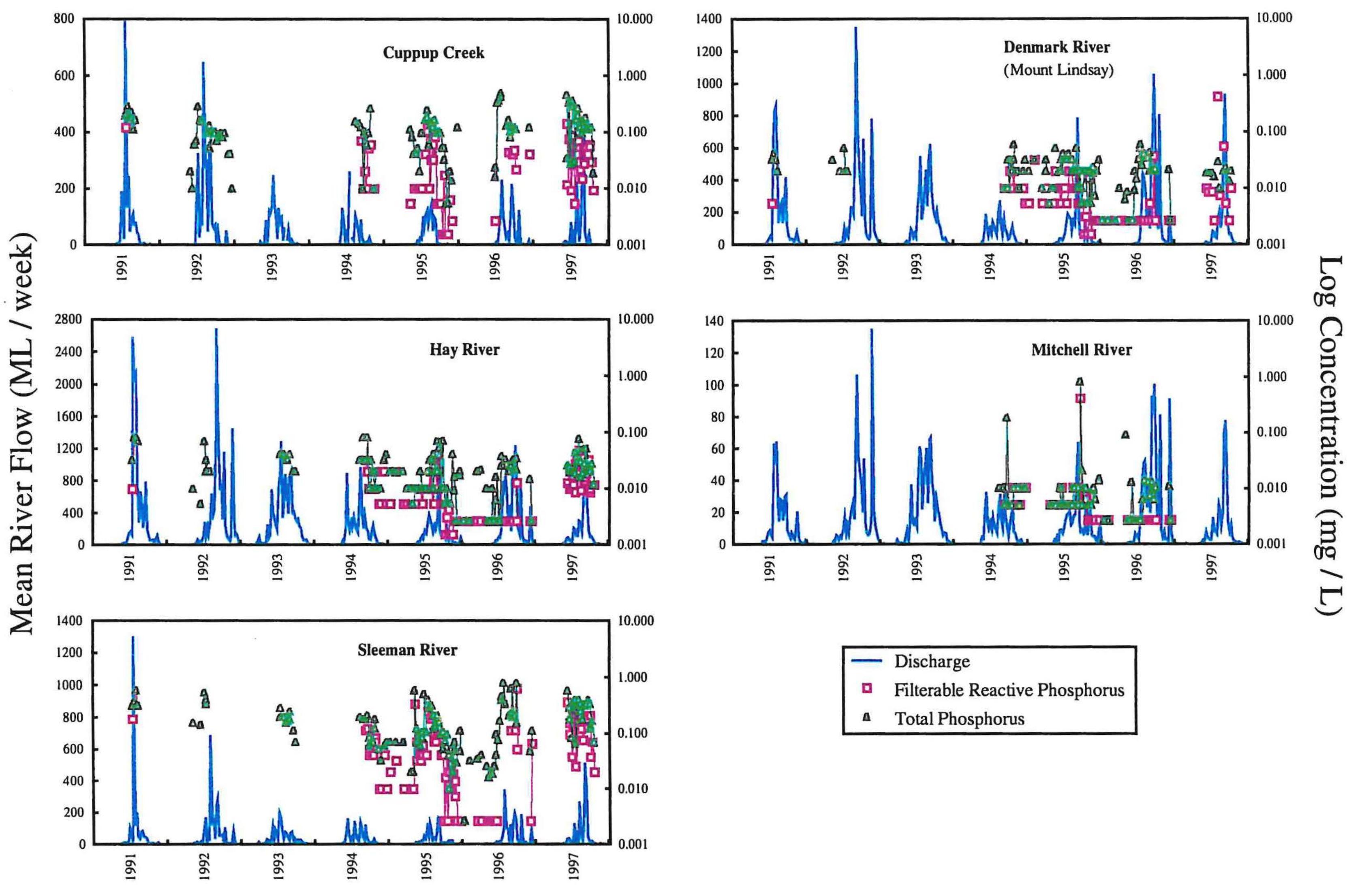


Figure 3. Time series analysis of phosphorus species concentration and stream discharge for the major streams in the Wilson catchment from 1991 - 1997.

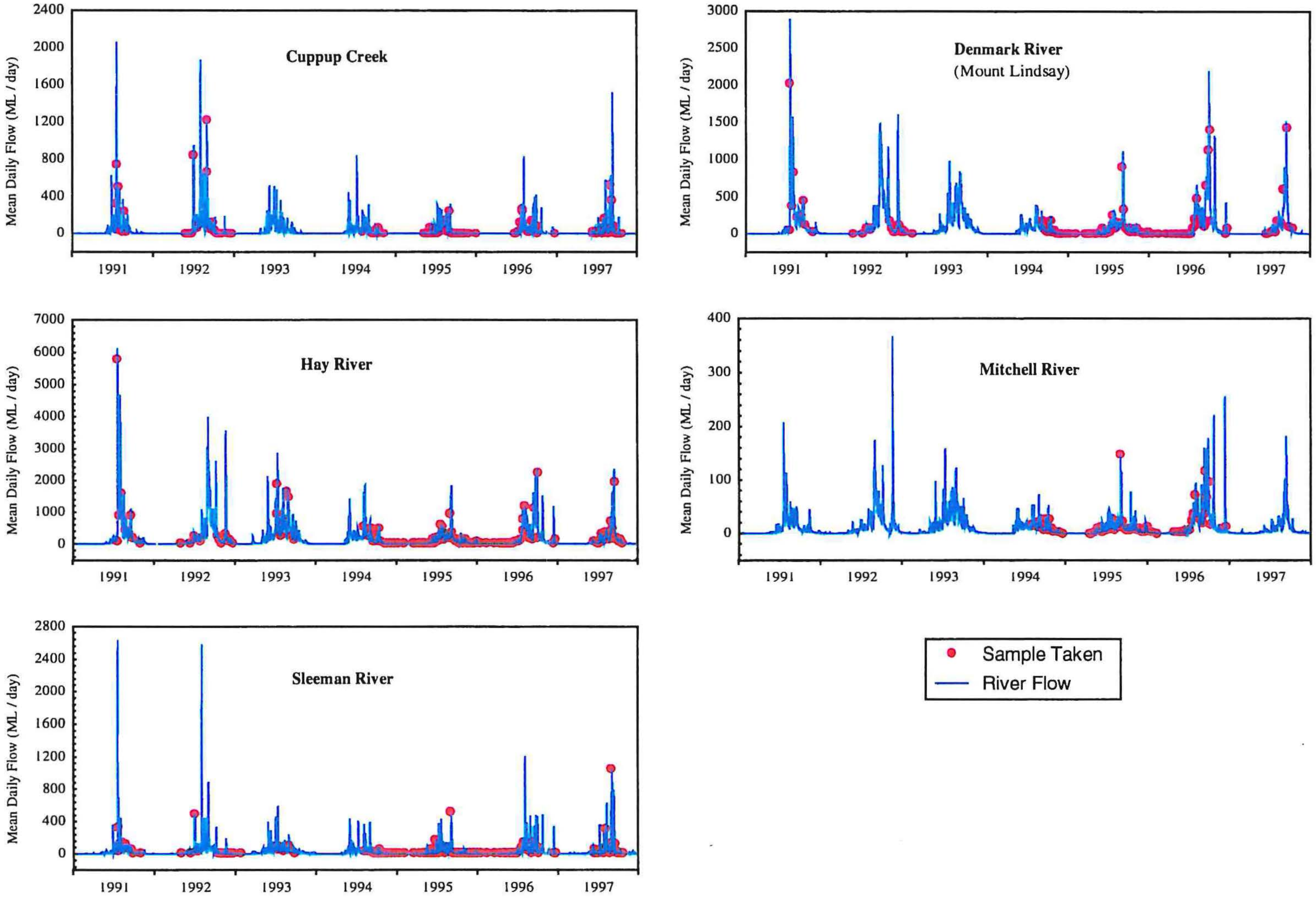


Figure 4. Time series analysis of when samples were taken in relation to each stream's hydrograph for monitored sites in the Wilson catchment for 1991-97.

2.2 Nutrients in the monitored waterways (1991 to 1997)

Existing data for the Wilson Inlet Catchment were sufficient to show:

- Comparisons among sites (streams)
- Seasonal changes in nutrient concentration
- Relationships between concentration and flow
- Establish classification of streams based on nutrient concentrations

Description of changes with time was not possible since only four years of data were available at the correct frequency (five years of data are required). Loading calculations were also made using simulation software developed by the River and Estuary Investigations Section of Water and Rivers Commission.

2.2.1 Comparisons between monitored waterways

Monitoring for nutrients in the catchment of the Wilson Inlet has indicated that Cuppup Creek, Little River, Sleeman River and Sunny Glen Creek appear to be enriched with nutrients to some extent. The highest concentrations of nitrogen were found in Sunny Glen Creek and Cuppup Creek (Figure 5). Both these waterways had median concentrations of 2.0 mg/L. The Sleeman River and Little River also had slightly elevated nitrogen concentrations with median concentrations between 1.0 and 1.5 mg/L. The highest concentrations of phosphorus were found in Sunny Glen Creek, which had a median phosphorus concentration of 0.21 mg/L. Cuppup Creek and the Little and Sleeman rivers each had median concentration of 0.12 mg/L (Figure 6). The other five monitored waterways had low concentrations of nitrogen (<1.0 mg/L) and phosphorus (<0.1 mg/L).

Guidelines recommended by ANZECC (1992), suggest that 0.75 mg/L of nitrogen and 0.1 mg/L of phosphorus are acceptable concentration limits in streams. However, the ANZECC guideline of 0.75 mg/L limit for nitrogen results in a very high rate of exceedance (Water and Rivers Commission, Unpublished data). Modification to the nitrogen concentration upper limit to at least 1.0 mg/L should be considered given that streams in the south-west of Western Australia seem naturally high in nitrogen. Using the 1.0 mg/L acceptable limit for nitrogen, four of the nine monitored streams in the Wilson catchment exceeded this concentration more than fifty per cent of the time.

Four of the nine monitored sites in the Wilson catchment also exceeded the phosphorus acceptable limit (>0.1 mg/L) more than fifty per cent of the time. Interestingly enough, the same four streams exceeded both the nitrogen and phosphorus acceptable limits - Little River, Cuppup Creek, Sleeman River and Sunny Glen Creek. Both Cuppup Creek and Sleeman River drain into the estuary from the east, while Sunny Glen Creek drains into the lower Hay River and the Little River drains into the western side of the estuary. An assessment of the build-up and residence time of nutrients in the eastern estuary will help determine whether these nutrient enriched streams are influencing seagrass and phytoplankton growth. The nutrient concentrations within these four streams are of concern and an investigation of the various types of land uses, potential nutrient pollution (diffuse and point source), and the effectiveness of past management practices within each sub-catchment is needed to explain the nutrient enrichment of these streams.

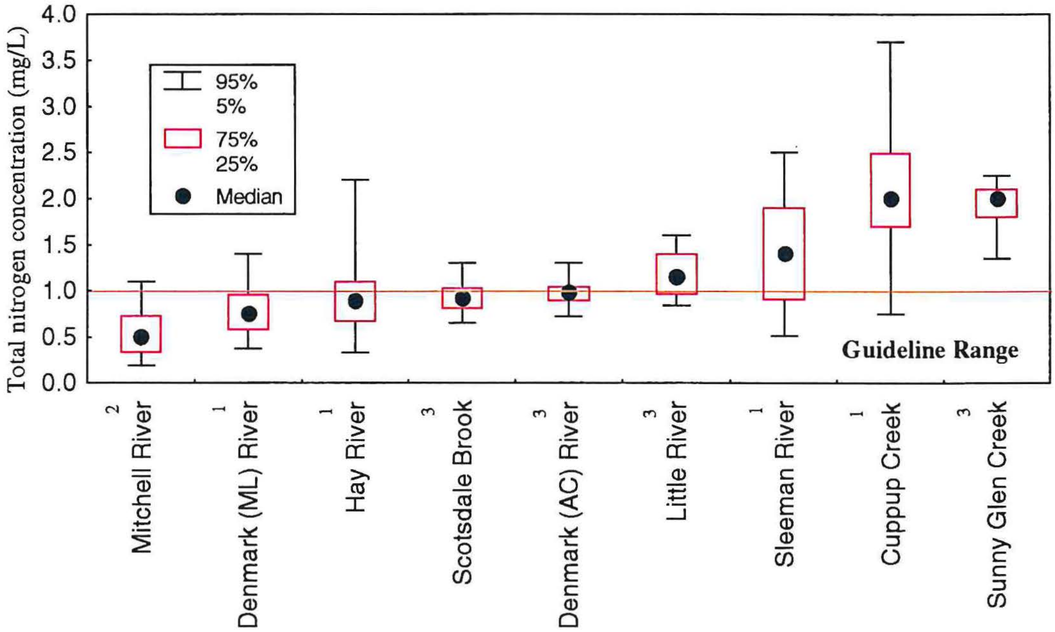


Figure 5. Total Nitrogen (TN) concentrations ranked for sites in the Wilson catchment during 1991-97.

Medians for TN with per centile ranges are shown for the monitoring period at each stream. The guideline limit, derived from the ANZECC (1992) guidelines of 1.0 mg/L for total nitrogen, was applied incorporating the occurrence of naturally high TN concentrations in Western Australia.

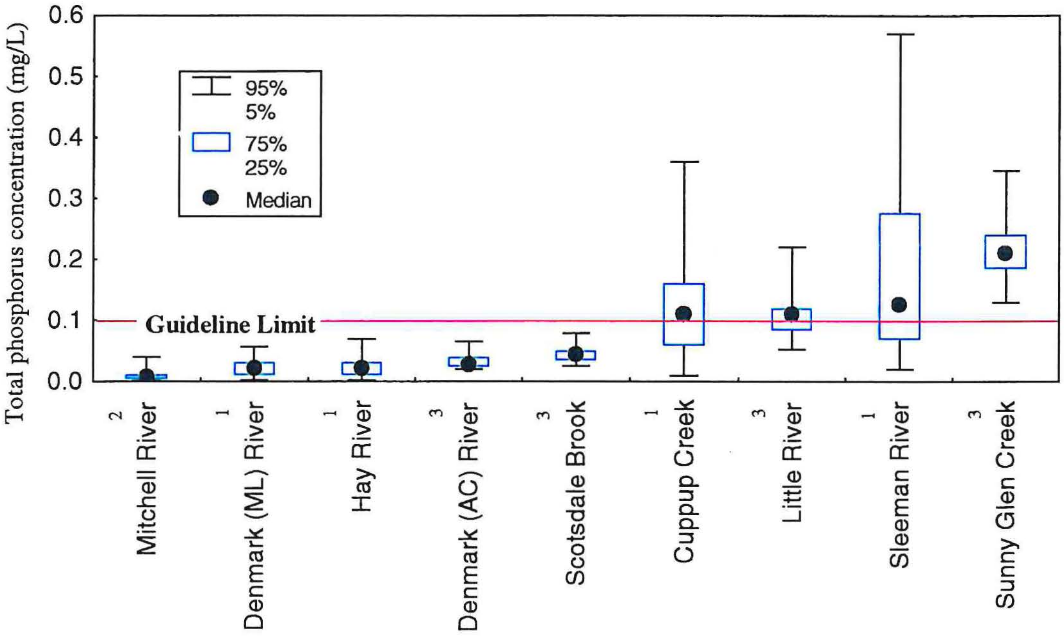


Figure 6. Total Phosphorus (TP) concentrations ranked for sites in the Wilson catchment during 1991-97.

Medians for TP with per centile ranges are shown for the monitoring period at each stream. The guideline limit, derived from the ANZECC (1992) guidelines of 0.1 mg/L for total phosphorus, was applied incorporating the occurrence of naturally high TP concentrations in Western Australia.

2.2.2 Discharge / concentration relationship

The concentrations of nutrients in flowing waters usually vary with stream discharge. Discharge, and its effect on nutrient concentration, were examined with respect to the timing of delivery of the nutrients from the catchment to the stream using a flow response model. Samples collected during various stages were categorised into rising limb (periods of increasing discharge), falling limb (periods of decreasing discharge), and inter-events that are collected between storm events and 'baseline' discharges. For most streams the relationship between nutrient concentration and flow is positive, where an increase in discharge results in an increase in nutrient concentrations (Johnson and East 1982). Negative correlations have also been observed between discharge and nutrients and some studies have identified streams in which concentration and discharge may vary independently (Richards and Holloway 1989).

Nutrient concentrations often vary in a characteristic cyclic loop (hysteresis) during storm flows, whereby the concentration at a particular discharge on the rising limb differs from the concentration at the same discharge on the falling limb. The shape of the hysteresis loop (concave / convex), its direction (clockwise or anti-clockwise) and trend (positive / negative) is controlled by the relative concentration and timing of delivery of nutrients in storm event surface water (runoff), pre-event soil water, shallow sub-surface flow and groundwater (Evans and Davis 1998, Sklash and Farvolden 1979). The shape and direction of the hysteresis loop may alter as human activity changes the hydrology of the catchment and the quality of the various sources of water to a stream (Evans and Davis 1998).

Flow effects in rivers, such as hysteresis loops, occur over short time intervals (usually measured in hours to at most days). Thus, weekly sampling will not adequately describe the relationship because the interval between sampling is longer that the period over which the variation occurs. But, by chance, weekly sampling occasions will sometimes coincide with storm flows (the frequency of the coincidence being dependent on the response time of the stream to rain events). Therefore the flow-response characteristics of nutrients will account for some of the observed temporal variation in the resulting time-series, influencing both seasonal patterns and trend components.

Generally the data series from monitoring in the catchment of the Wilson Inlet show that variation in the concentration of nutrients is due in part to variation in discharge, although the relationship varies for each of the nutrients. Figure 7 shows the relationship between discharge and the concentration of total nitrogen (TN), oxidised nitrogen species (NO_X), ammonia (NH_3), total phosphorus (TP) and filterable reactive phosphorus (FRP) for the monitored streams (1991-97). The nutrient fractions (NO_X, NH_3 and FRP) responded to flow effects in a similar manner to their corresponding total nutrient components (TN and TP).

A correlation analysis indicated that the Denmark, Hay and Sleeman Rivers are considered to be positively flow responsive for nitrogen species. Given that nutrient concentrations are generally greater for rising and falling limb samples than inter-event samples, this suggests that storm events from the catchment probably deliver the bulk of the nutrients to the estuary. Variation in nitrogen concentration for Cuppup Creek and Mitchell River was independent of variation in discharge. The scatter evident in the nitrogen flow response for Mitchell River suggests a random nutrient input to the stream. In Cuppup Creek concentrations of all nitrogen species decreased with an increase in stream discharge. The negative flow response suggests that groundwater concentrations of nitrogen are relatively high compared to surface event water (Yu 1998, Evans and Davis 1998), or that the sample site may be contaminated by a local point source.

A correlation analysis also revealed that Cuppup Creek, and the Hay and Sleeman rivers were positively flow responsive with respect to phosphorus species, again emphasising the importance of episodic events in nutrient flux to the estuary. Both Denmark River and Mitchell River are non-flow responsive for phosphorus. In many cases the flow responses for FRP and TP appeared to be very similar, suggesting that a large component of TP in the tributaries is inorganic FRP (Figure 7).

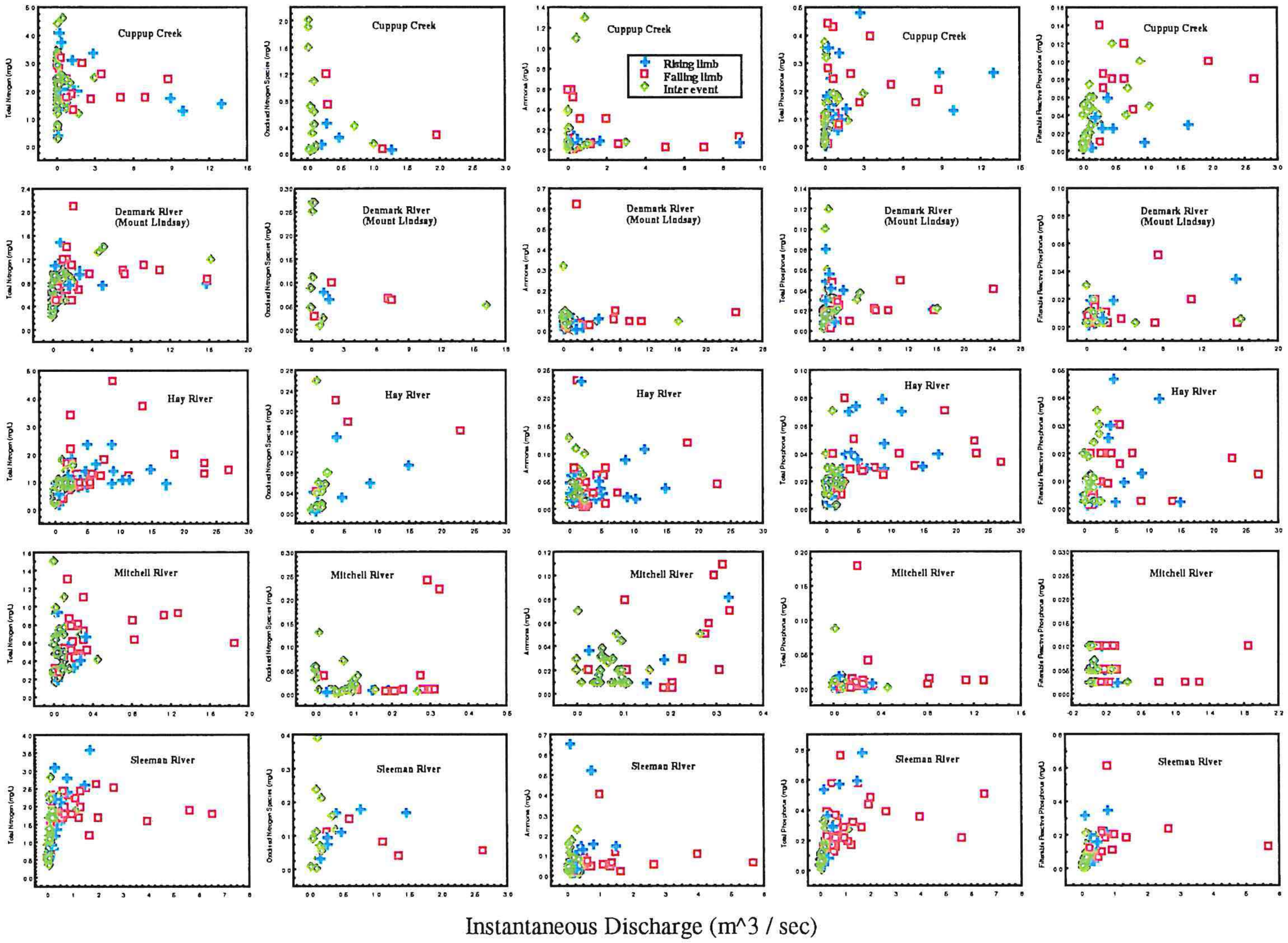


Figure 7. Instantaneous discharge versus concentration for various nutrient species in the Wilson catchment for 1991-97.

2.2.3 Seasonal patterns

Seasonality is any predictable change in a data series that occurs within a twelve month period and is characterised by a transition from low nutrient concentrations during summer to higher concentrations during winter. Seasonal cycles in nutrient concentration are known to be common in rivers, rather than the exception. They are important ecologically because they mean that nutrient delivery to the Inlet is predictable and life cycles of some plant groups can be attuned with a reliable source of nutrients. Seasonal cycles in data series also influence methods used to detect trends in water quality. Figures 8 and 9 show both nitrogen and phosphorus, and their respective inorganic and organic fractions, plotted as a function of month. The lines are a least squares fit of the data which improves the visual examination for seasonal patterns in nutrient concentration.

The nitrogen series at all of the monitored streams showed some evidence of seasonality (Figure 8). Nitrogen concentrations generally remained low for much of summer and autumn, but gradually increased through winter to peak in July to August. Peak nitrogen concentrations usually coincided with periods of maximum rainfall (as shown in Figure 2), and subsequent increased catchment flushing and stream flow. Peak inorganic nitrogen concentrations were recorded slightly earlier in the flow year (June), perhaps coinciding with initial catchment flushing of fertiliser from the soils. This suggests that NO_X and NH_3 species are readily available in soil water and become highly soluble and mobile in saturated soil conditions. Therefore, most of the inorganic nitrogen loss from Wilson catchment would be attributable to leaching processes within excessively fertilised agricultural soils (Heathwaite et. al., 1996). The organic fraction of nitrogen was the major component delivered to the streams and generally peaked later in the flow year (September) and may be attributed to the delayed transport of biologically fixed nitrogen, such as plant material and animal waste.

Most of the monitored streams also showed evidence of seasonality in phosphorus although the signal was not as pronounced as in the nitrogen series. Evidence of seasonality was less apparent in the Denmark River compared to the other sites and the Mitchell River produced an atypical seasonal pattern; similar to that observed in its nitrogen seasonal pattern (Figures 8 and 9). Like nitrogen, phosphorus concentrations generally increased from April or May to peak around August corresponding with peak rainfall (as shown in Figure 3). Both inorganic and organic phosphorus fractions were observed to peak in August / September. The inorganic component of phosphorus was generally much lower in concentration than the organic component throughout the year, implying that soil particulates, plant debris and animal waste were the major contributors towards nutrient inputs (Figure 9). Organic sources of phosphorus appear to be entering the streams year round, while a majority of the bio-available inorganic phosphorus appears to enter the streams as rainfall and catchment flushing increases.

Seasonal variation in the nutrient data series from the Mitchell River was very different than for the other monitored streams (Figures 8 and 9). Unlike many of the monitored streams, the Mitchell River is still in relatively pristine condition with most of its catchment still forested. Nutrient concentrations at the site were higher in the drier months between October and December (generally, there was no flow from January to April). The atypical seasonal pattern may be due, in part, to the mobilisation of nutrients from areas that have undergone back burning in spring and summer. This would result in the transport of excess organic material (plant material) from the forest to the river between September and December, as is observed with the Mitchell River seasonal patterns.

Nutrient concentrations in the Wilson Inlet streams were generally higher during the winter months because nutrients were mobilised with increased flushing of leachates from soil water. To examine this effect, the data in Figures 10 and 11 are classified according to when the samples were collected on the hydrograph. With the exception of Cuppup Creek, most streams had higher nutrient concentrations in winter and were associated with storm flows (ie, rising and falling limb samples). The separation of samples into flow strata also shows that seasonal variation occurs strongly in samples collected during base flows (ie, inter-event periods). In most cases, the storm samples (rising and falling limb samples) actually represent noise about the seasonal signal produced by the base-flow samples. This is most evident in the seasonal plot of Sleeman River, which runs through a waterlogged catchment (Figures 10 and 11). For this reason, base flows are thought to be the primary influence of seasonal variation in streams nutrient concentration, the extent of which is largely determined by the proximity to groundwater. By definition, base flows are inflows from groundwater, so that the observed seasonal patterns would only occur if water tables rise and nutrient concentrations in groundwater increase. Various studies have shown that nutrient concentrations in agricultural soils become progressively higher near the surface (Schofield *et al* 1985), so the simple displacement of soil water (vadose zone) by rising water tables in winter could produce such a pattern (Gillham 1984, Sklash and Farvolden 1979).

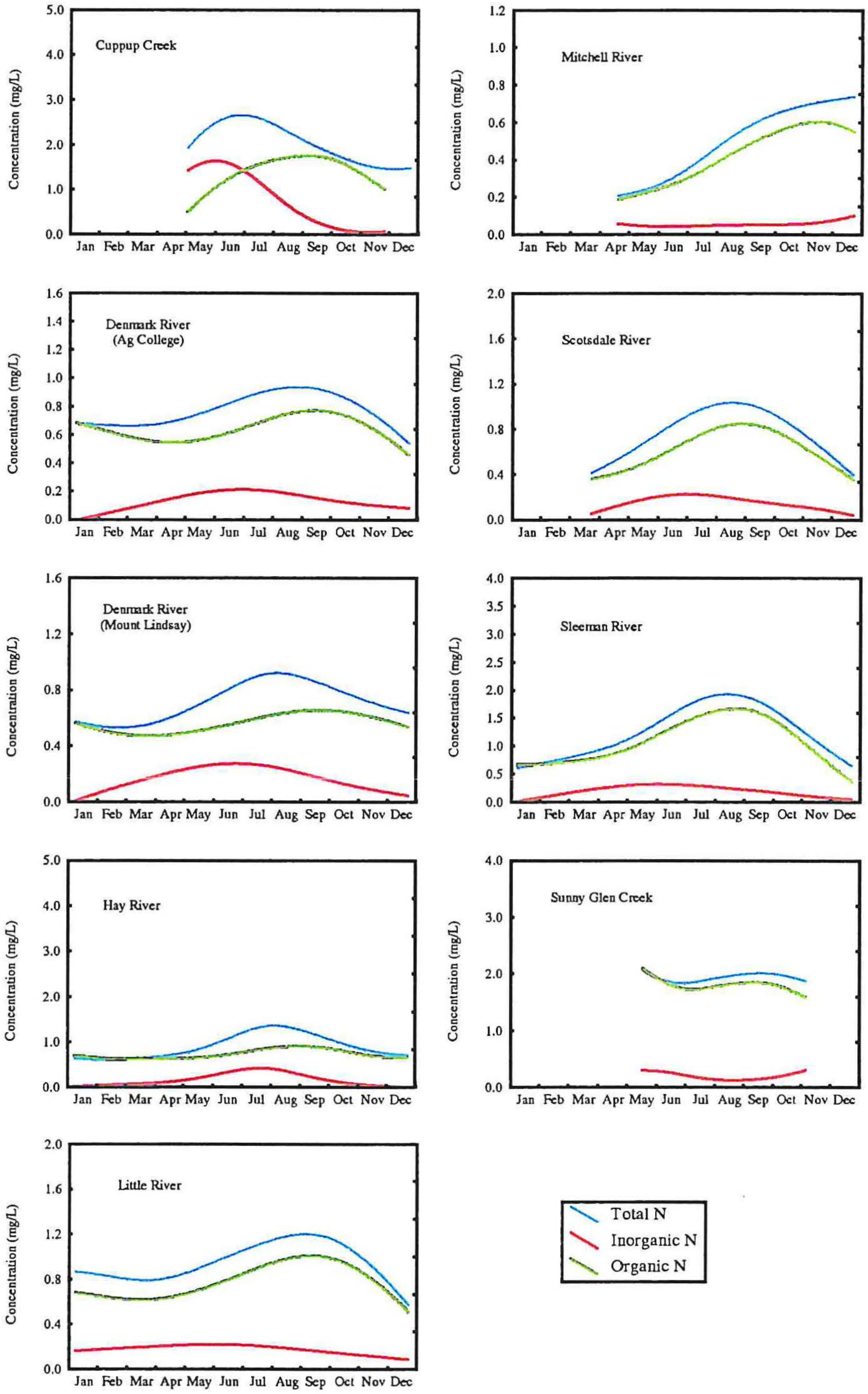


Figure 8. Seasonality patterns for total nitrogen (TN) and its fractions.

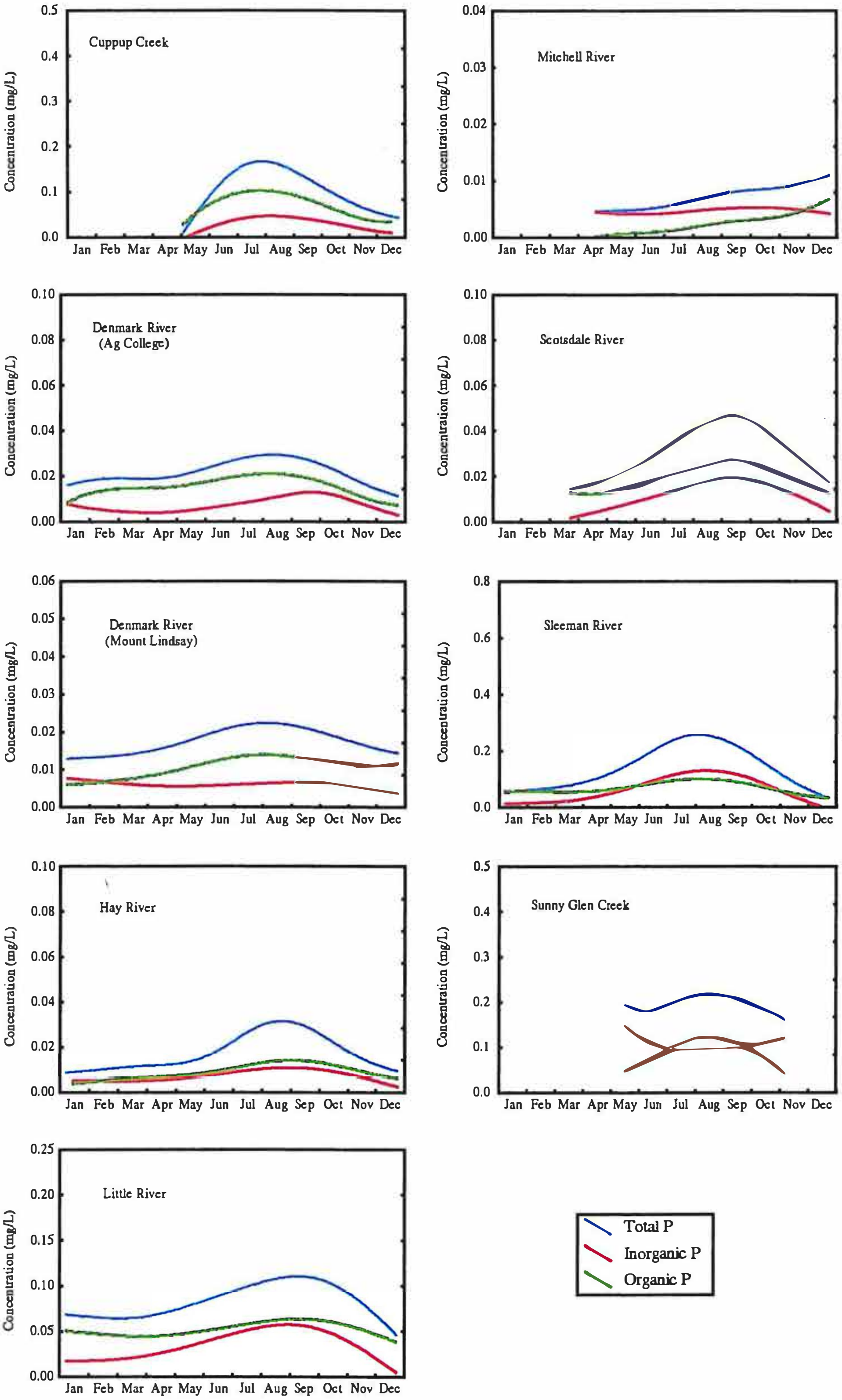


Figure 9. Seasonality pattern for total phosphorus (TP) and its fractions[1].

---

[1] In the context of this report Organic P includes all particulate material.

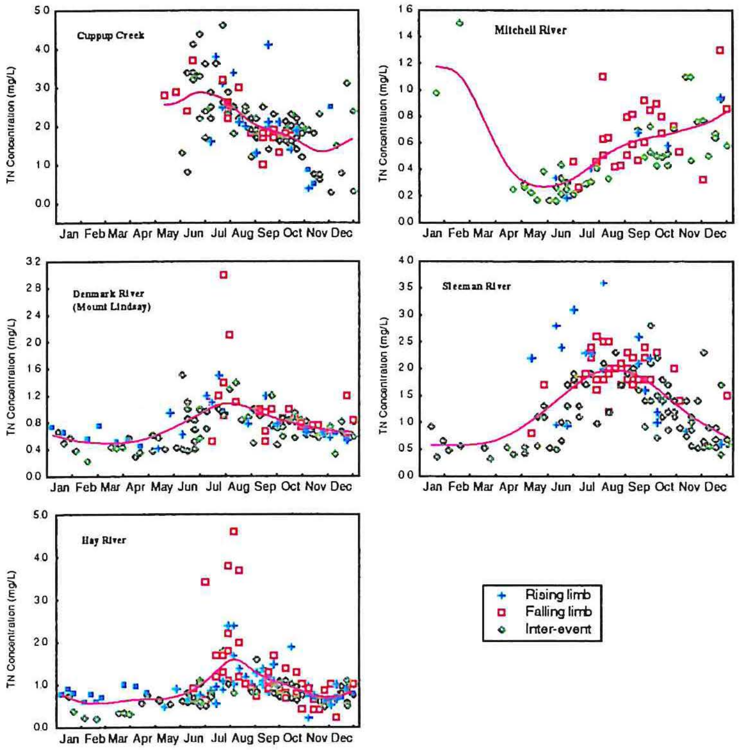


Figure 10. Seasonal variation in nitrogen concentrations of major streams in the Wilson catchment, with sub-classifications for stages of the flow response for 1991-1997. The line of best fit (least squares) approximates the seasonal pattern.

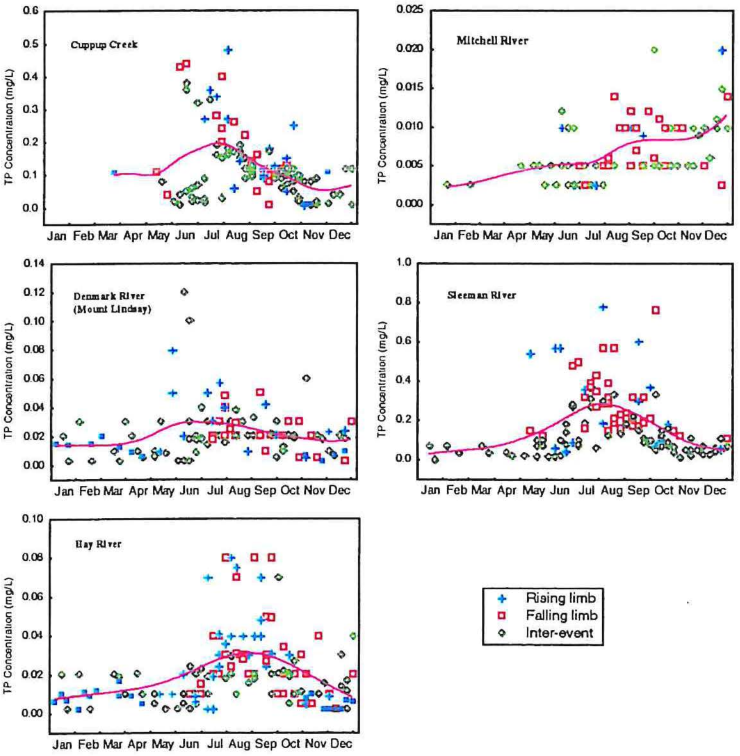


Figure 11. Seasonal variation in phosphorus concentrations of major streams in the Wilson catchment, with sub-classifications for stages of the flow response for 1991-1997.

2.2.4 Trends in nutrient concentration

Figures 10 and 11 show the time series of TN and TP concentration in the period 1991-97. The data series from 1991 to 1994 was too infrequent and the sampling frequency too erratic to be of real use for trend analysis. The data from 1994 to 1997 were collected more consistently. The plots show that there was a general rise in TN concentration for samples collected between 1994 and 1997 in all monitored waterways, except in samples collected from the Hay River (Figure 12). The concentration of TP in samples from Cuppup Creek and Sleeman River also increased marginally between 1994 and 1997. The concentration of TP in samples from the Denmark, Hay, and Mitchell rivers show no evidence of change between 1994 and 1997 (Figure 13).

Apparent changes in nutrient concentration in the sample data may, or may not, reflect trends that were occurring in the rivers themselves. The four year period between 1994 and 1997 was too short for definitive conclusions to be made regarding the temporal behaviour of nutrients in the monitoring waterways. The erratic sampling frequencies in the four year monitoring period increase uncertainty about the observed changes in the data series and inferences regarding nutrients in the waterways of the catchment. Also, it is considered that *at least* five years of consistently collected data are required to analyse time-series for trend (Ward *et al* 1990).

All data, no matter how poorly collected, contains some useful information. Section 3.1 describes how the nutrient data series, especially from 1994 to 1997, were used to improve the future design of the monitoring network for detecting trends in concentration over time.

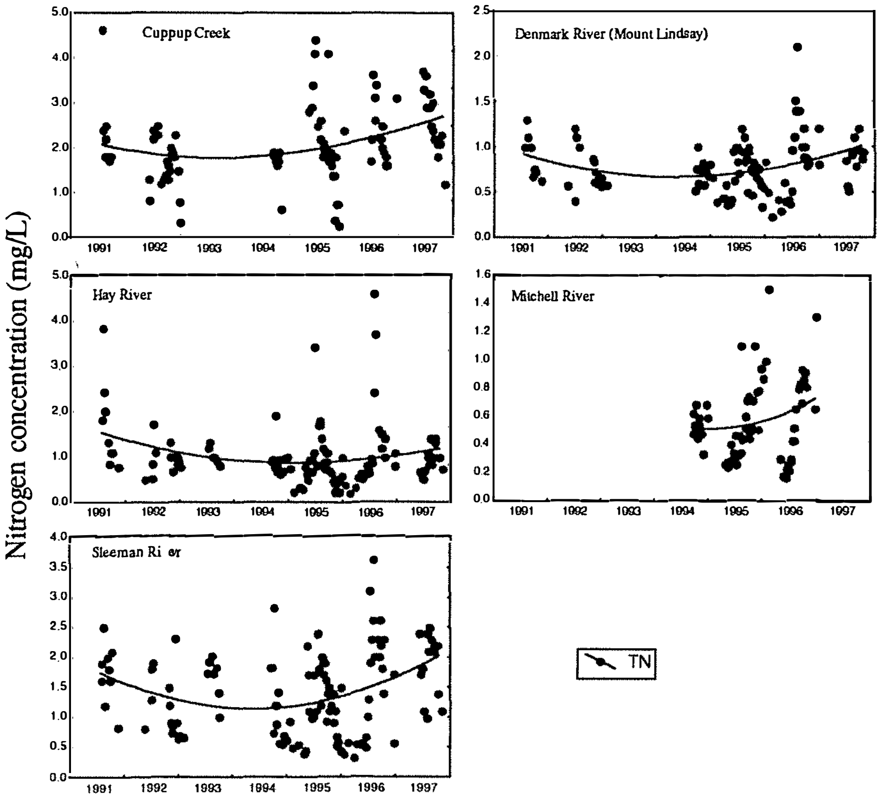


Figure 12. Observed Total Nitrogen (TN) concentrations over the period 1991-97 for major streams in the Wilson catchment. The line is a 'least squares' fit of the data.

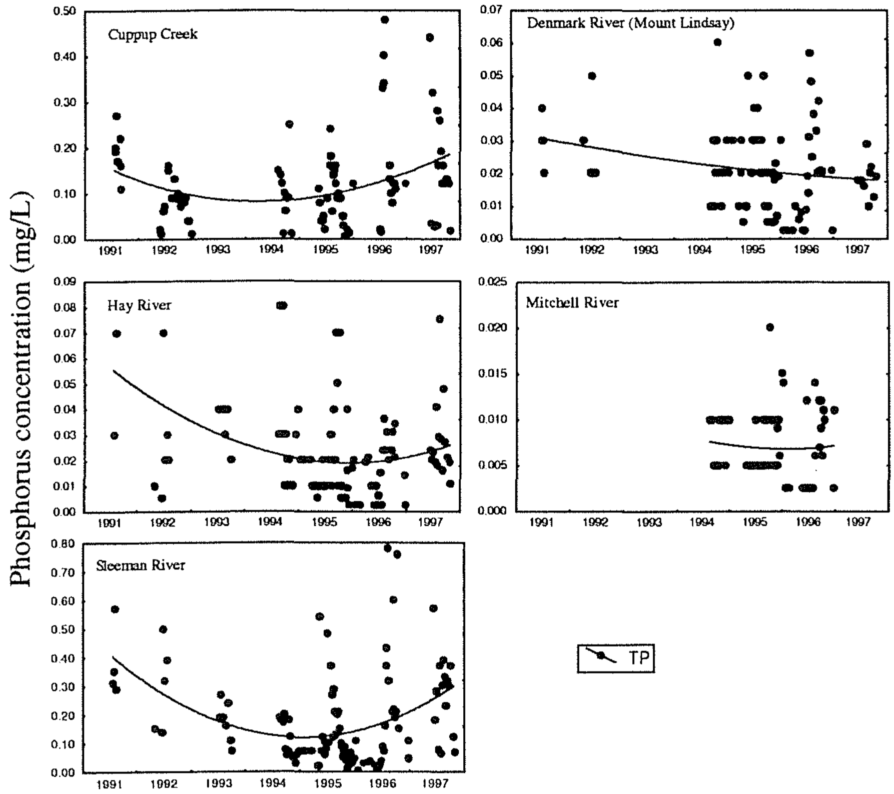


Figure 13. Observed Total Phosphorus (TP) concentrations over the period 1991-97 for major streams in the Wilson catchment. The line is a 'least squares' fit of the data.

2.3 Nutrient loading to the estuary

Estimates of nutrient loads in the tributary inflows to the Wilson Inlet are necessary to establish overall nutrient budgets, a requirement of the NEMP program. Understanding the timing and frequency of delivery of these loads is important to describe the response of flora and fauna to storm events.

2.3.1 Load estimation method

The estimates of nutrient load reported in this section were made using the fixed-interval data described in Section 2.1. Nutrient loads published by Tipping (1997) were calculated using the same data in addition to stage height sample data from 1994-96.

Load estimates are basically the product of instantaneous flow and concentration. Discharge in the monitored streams was measured continuously at flow gauging stations located at the point of sample collection. Nutrient concentrations between sample observations were estimated using a rating curve approach that expresses nutrient concentration as a continuous function of stream discharge between 1994 and 1997. The functional relationship was modelled as a look-up table based on predictions from a LOWESS smooth of the concentration-discharge pairs. Instantaneous measurements or concentration estimates were then multiplied by discharge measurements and summed over all periods to obtain estimates of annual loads. The annual loading estimates were partitioned into loads delivered during storm events and loads in base flows.

Rating curve techniques (used mainly for estimation of sediment loads) have been shown to be biased (Thomas and Lewis 1995). The accuracy of the rating technique depends on the sampling regime and the fit of the model. A majority of samples collected in Wilson Inlet catchment sites were collected during low to medium flows, resulting in a rating curve that did not adequately describe the entire flow - concentration relationship (especially for high flows). However, given the incomplete annual coverage of sampling effort at most sites the rating curve method was the only consistent approach to provide estimates of nutrient load for the entire period of flow. The estimates of loads are likely to be biased and probably underestimate the real loads by different amounts depending on the tributary and the flow year.

2.3.2 Loads in the monitored waterways

Table 2 contains the results of the calculations described above. Given the likely levels of error in the estimates it is difficult to draw too many conclusions. It is clear however, that loads of nutrients for most Wilson Inlet sites in 1996 were higher than in the other years, corresponding with a higher annual rainfall in the Wilson Inet catchment. It was also apparent that loads delivered from storm flows were larger than contributions from base flows, suggesting that most nutrient loading to the estuary is dependent on discharge from the catchment.

The Flow Weighted Concentrations (FWC's) are calculated as the ratio of nutrient load to volume discharged and are used to remove the effect of flow on nutrient loads. From Table 2 it is apparent that nutrient loads in all streams varied with discharge rather than a change in water quality, as annual FWC's varied little between years.

Table 2. Loading estimates (tonnes) for the major tributary inflows to Wilson Inlet.

Volumes are given in millions of cubic metres. FWC (Flow Weighted Concentration) gives an indication of the annual nutrient concentration taking stream flow into account (equivalent to mg/L) and also allows a comparison between years for each site to see if actual changes in nutrient concentration were recorded.

Site	Nutrient	Event	1994			1995			1996			1997		
			Load	Volume	FWC	Load	Volume	FWC	Load	Volume	FWC	Load	Volume	FWC
CUPPUP CREEK	TN	Storm event	17.34	7.690	2.255	14.85	6.529	2.274	18.38	8.175	2.248	19.46	9.189	2.118
	TN	Inter - event	1.990	0.849	2.344	2.300	0.953	2.413	2.570	1.101	2.334	1.820	0.748	2.433
	TN	*Total*	*19.33*	*8.539*	*2.264*	*17.15*	*7.482*	*2.292*	*20.95*	*9.276*	*2.259*	*21.28*	*9.937*	*2.141*
	TP	Storm event	1.720	7.690	0.224	1.450	6.529	0.222	1.990	8.175	0.243	2.030	9.189	0.221
	TP	Inter - event	0.130	0.849	0.153	0.160	0.953	0.168	0.180	1.101	0.163	0.110	0.748	0.147
	TP	*Total*	*1.850*	*8.539*	*0.217*	*1.610*	*7.482*	*0.215*	*2.170*	*9.276*	*0.234*	*2.140*	*9.937*	*0.215*
DENMARK RIVER **(Mount Lindsay)**	TN	Storm event	6.710	6.462	1.038	12.36	12.37	0.999	39.01	37.69	1.035	15.50	15.30	1.013
	TN	Inter - event	9.920	10.56	0.939	8.320	9.031	0.921	6.400	6.805	0.940	8.260	8.599	0.961
	TN	*Total*	*16.63*	*17.02*	*0.977*	*20.68*	*21.40*	*0.966*	*45.41*	*44.49*	*1.021*	*23.76*	*23.90*	*0.994*
	TP	Storm event	0.230	6.462	0.036	0.340	12.37	0.027	0.950	37.69	0.025	0.490	15.30	0.032
	TP	Inter - event	0.190	10.56	0.018	0.190	9.031	0.021	0.170	6.805	0.025	0.100	8.599	0.012
	TP	*Total*	*0.420*	*17.02*	*0.025*	*0.530*	*21.40*	*0.025*	*1.120*	*44.49*	*0.025*	*0.590*	*23.90*	*0.025*
HAY RIVER	TN	Storm event	51.05	33.26	1.535	42.57	33.22	1.282	104.7	59.37	1.764	49.74	33.28	1.494
	TN	Inter - event	16.19	15.30	1.058	3.790	4.292	0.883	14.54	12.32	1.180	4.300	4.602	0.934
	TN	*Total*	*67.24*	*48.56*	*1.385*	*46.36*	*37.51*	*1.236*	*119.2*	*71.69*	*1.663*	*54.04*	*37.89*	*1.426*
	TP	Storm event	1.160	33.26	0.035	1.000	33.22	0.030	2.220	59.37	0.037	1.080	33.28	0.032
	TP	Inter - event	0.390	15.30	0.025	0.080	4.292	0.019	0.350	12.32	0.028	0.100	4.603	0.022
	TP	*Total*	*1.550*	*48.56*	*0.032*	*1.080*	*37.51*	*0.029*	*2.570*	*71.69*	*0.036*	*1.180*	*37.89*	*0.031*
SLEEMAN RIVER	TN	Storm event	15.69	7.150	2.194	14.44	6.754	2.138	23.62	10.94	2.159	23.67	11.27	2.100
	TN	Inter - event	3.280	2.100	1.562	2.990	1.990	1.503	3.510	2.185	1.606	3.060	2.022	1.513
	TN	*Total*	*18.97*	*9.25*	*2.051*	*17.43*	*8.744*	*1.993*	*27.13*	*13.13*	*2.067*	*26.73*	*13.29*	*2.011*
	TP	Storm event	2.350	7.150	0.329	2.140	6.754	0.317	3.430	10.941	0.313	3.300	11.27	0.293
	TP	Inter - event	0.370	2.101	0.176	0.350	1.990	0.176	0.440	2.185	0.201	0.360	2.022	0.178
	TP	*Total*	*2.720*	*9.251*	*0.294*	*2.490*	*8.744*	*0.285*	*3.870*	*13.13*	*0.295*	*3.660*	*13.29*	*0.275*

3. Monitoring program design

NEMP research priorities to be addressed by the proposed monitoring program are '*Evaluation of effectiveness of actions to manage nutrients*' and researching the '*Effects of episodic events on waterbody ecology*'. Routine fixed-interval monitoring programs and the detection of trends in a data time-series can evaluate the effectiveness of water quality management most efficiently. Until concentration predictive capacity improves, the provision of river load estimates is not a viable option for routine monitoring over relatively long periods (Ellis 1987).

An interpretation of this information objective was made from the perspective of catchment management. Improvements in land management practices at the local scale (ie, at the scale of the "paddock"), indicates which practices are effective and economically viable management options. Evaluating the effectiveness of these activities can only be achieved by research at the scale of the "paddock". However, localised success stories do not measure the wider implementation of best management practices. Sustainable management practices must be widely employed throughout the catchment if improvements in water quality are to be realised at the point of discharge to the receiving estuary.

There is good evidence that the level of nutrients in Wilson Inlet's inflows rise with increasing discharge (Figure 7). Therefore it is probable that the bulk of the total load of nutrients delivered to the Inlet every year is delivered during storm events. The importance of the episodic pattern of loading to the ecology of the Inlet, especially its influence on primary productivity, is not presently known. Researchers therefore require reliable estimates of nutrient loads in the major tributary inflows to the Inlet.

The monitoring program design problem is approached here with two very different information goals that cannot necessarily be met with a single network. In the remaining sections we describe two monitoring programs. The first program is designed for the detection of long-term trends in nutrient concentration, and the second program that is run concurrently will supply reliable estimates of mass nutrient load to researchers looking at the impact of episodic events on the ecology of the Inlet.

3.1 Detecting trends in nutrient concentration

3.1.1 NEMP research priority 'Evaluating the effectiveness of actions to manage nutrients'

The approach taken here is to use trends in nutrient concentration data to evaluate management effectiveness. Generally, trends in nutrient concentration have proven to be sensitive and widely accepted measures of system degradation (Sanders *et al* 1987). There have been numerous reports linking increasing trends in the nutrient data series with eutrophication problems in the systems of interest (Heathwaite *et al*, 1996; Robson and Neal, 1996; Lettenmaier *et al*, 1991). In the same way, decreasing trends in nutrient concentration are viewed as measures of improvement in nutrient levels in the waterways. With good program design such improvements can then be attributed to management initiatives such as education programs, buffer strips, wetland filters and fertiliser use reduction campaigns.

For most environmental management organisations, continuously measuring nutrient concentration in rivers is not a practical option, so they must rely on infrequently collected sample data to make inferences regarding the temporal behaviour of the sampled population. This makes detecting trends in concentration a statistical problem (Ward *et al* 1990). Information objectives will be defined as a function of the smallest magnitude of trend that can be detected given the variability in the data. The existing data set collected since 1994 in the catchment of the Wilson Inlet will be used to estimate expected variation that will be encountered in the proposed monitoring program.

In meeting the information goal we intend to design the monitoring program as efficiently as possible. This effectively means that a minimum number of samples will be collected to meet the defined information goals. The recommended sampling regime and the appropriate data analysis procedures are described in Section 3.1.3.

3.1.2 Program design

Site selection

The sites to be used are those that were sampled since 1994. These are the sample sites on the Cuppup Creek, Hay River, Denmark River, Mitchell River and Sleeman River.

These sites should be retained for a couple of reasons. Firstly, there are existing nutrient data series from these sites with reasonable data beginning from 1994 (plus some previous data of lower quality). Secondly, a majority of sites are located low in the catchment and therefore changes in nutrient levels can be linked directly to the estuarine environment more so than if they were higher in the catchment.

Variables

The information objective of this program is to detect trends in nutrient levels entering the Wilson Inlet. This dictates that the major total fractions of nutrients are measured. Effective management may also change the species of nutrients entering as well as decrease total amounts; for example, from dissolved fertiliser derived nitrogen to higher proportions of organic fractions. It is therefore important to know the species of nutrients entering the system.

Variables to be monitored include total nitrogen (TN), ammonium (NH_3), nitrate (NO_X), total phosphorus (TP) and filterable reactive phosphorus (FRP).

Statistical procedures

Trends in nutrient concentration in the inflows to the Wilson Inlet will be verified using the *Mann-Kendall* or *Seasonal Kendall* tests for trend (Esterby 1996). These non-parametric statistical procedures have been widely used to test data series for significant trends. They test for deviations from zero slope of the linear regression of time-ordered data. The power of the tests is not affected by missing data in the series, by trace and tied values, or deviations from a normal distribution. They are therefore ideally suited to water quality applications (Gilbert 1987, Helshel and Hersch 1992, Hipel and McLeod 1992).

The Mann-Kendall test uses ranks of the data values. It is computed as (Gilbert 1987):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \qquad (1)$$

where: S is the number of positive differences between time ordered ranks minus the number of negative values.

The S value and its variance var(S) are used to compute a test (Z) statistic using the following rule:

$$\begin{aligned} Z &= S\text{-}1/[\mathrm{var}(S)]^{1/2} && \text{if } S > 0 \\ &= 0 && \text{if } S = 0 \\ &= S\text{+}1/[\mathrm{var}(S)]^{1/2} && \text{if } S < 0 \end{aligned}$$

The Z value is compared to a critical value (α) using a standard normal probability table. When the Z statistic is positive and exceeds a critical value, the data series contains a statistically significant increasing trend. If the Z score is negative, and exceeds the critical level, a significant falling trend has been detected. The test is reliable except when a large number of tied groupings occur, for example when the observed data contain a large number of censured data points.

If the data series contain seasonal cycles the Seasonal-Kendall test should be used. The Seasonal Kendall test is a variant of the Mann-Kendall equation that accounts for the presence of auto-correlation in the data due to seasonal cycles. The 'S' statistic for the Seasonal Kendall test calculated separately for each season and summed to derive an overall measure for the series. The summation was used to calculate a Z statistic as described above.

To use the Seasonal-Kendall and the seasonal slope estimator (Section 3.1.2.4.) the direction of a trend must the same in each season (that is, the trend is homogenous between seasons). To test for the homogeneity of trend between seasons the van Belle & Hughes (1984) test can be used (see also Gilbert 1987 for algorithm). The van Belle & Hughes test assumes that each season contains at least ten observations, and that the data are independent. If these assumptions are not met, the critical value obtained from the chi-square distribution may be too small, and the trends may be wrongly classified as heterogenous. When the number of years in the time series are few, or there is a great deal of missing data, the van Belle & Hughes test can not be calculated. When unable to test for homogeneity of trends within seasons, the Mann-Kendall test is favoured unless the seasonal cycling in the data series is pronounced.

Estimating rate of change

To estimate the slope of the trend line, the Sen slope estimator is used. With a parametric linear regression, the slope parameter is calculated as part of the regression equation. However, the slope of the regression slope is sensitive to outliers in the data series and the slope parameter can deviate from the true slope. An alternative method to estimate the slope of a trend is the Sen estimator (Gilbert 1987). The Sen is closely related to the Mann-Kendall test and is also unaffected by outliers and missing data.

To provide an estimate of the slope of the trend in the period of interest, the slope between all possible combinations of observations is calculated:

$$Q = (x_{i'} - x_i)/(i' - i) \tag{2}$$

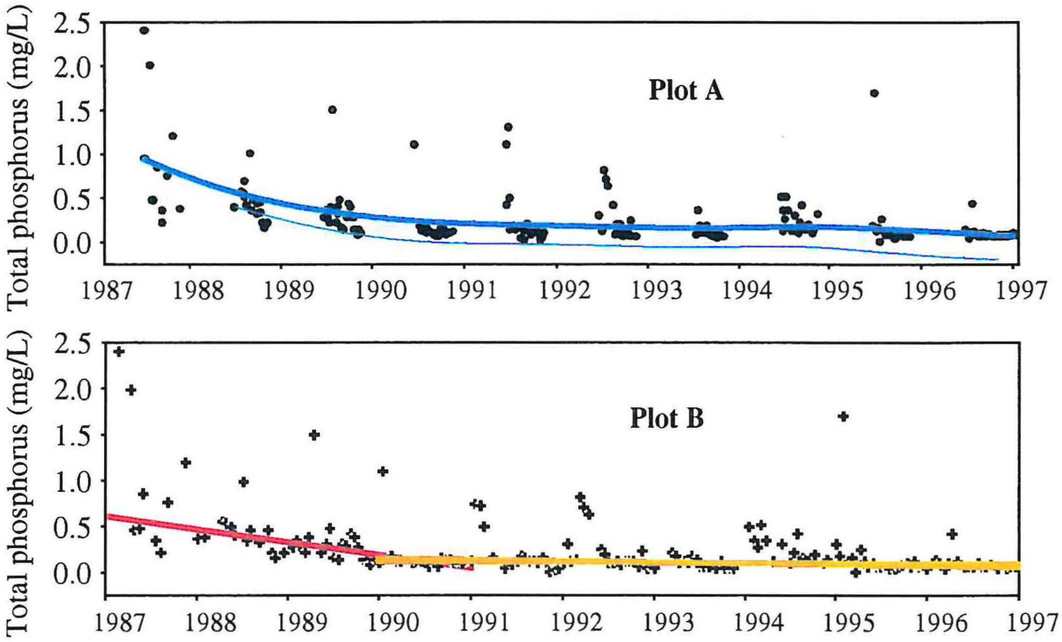
where: Q is the Sen estimator of slope (the median of the slopes)

To estimate the slope of the trend line in the presence of seasonal cycles, a modification of the Sen estimator may be used. The Seasonal-Kendall slope estimator uses the slope between all possible combinations of observations within each season. The calculated slopes across seasons were then ranked, and the median of these estimates used as the overall trend estimate in the data series.

Monotonic trends

The analysis described tests for the presence of linear, monotonic trends. Temporal trends are monotonic when nutrient concentrations either consistently increase or decrease in the time period of interest. The assumption of monotonicity should be verified by visual examination of a LOWESS (LOcally WEighted Scatterplot Smooth) over the period of interest (Helshel and Hersh 1992, Aulenbach *et al* 1996). When non-monotonicity was evident the period analysed should be changed (shortened) so that trends in the period tested become approximately monotonic.

As an example, Figure 14 shows the phosphorus time series from sampling in the Bayswater Main Drain, which flows into the Swan Estuary (Donohue *et al*, in prep.). The upper plot (Plot A) shows the observed data overlain with a LOWESS smooth to show the general trend in the series. The LOWESS helps in deciding periods over which concentrations are changing monotonically and which should be tested statistically for confirmation. The bottom plot (Plot B) shows the same series showing the results of the Mann-Kendall test for trend, the rate of change in the tested periods and the plotted Sen estimator.



1987 - 1990
Z = -6.99 p = .0000
Slope:-0.1400mg/L/yr
95% CI: Lower -0.1862
Upper -0.1086
Alpha: 0.05 Beta: 0.10
N: 62 N#: 57
Neff: 62
S.D. 0.371

1990 - 1997
Z = -3.46 p = .0003
Slope:-0.0085mg/L/yr
95% CI: Lower -0.0136
Upper -0.0040
Alpha: 0.05 Beta: 0.10
N: 130 N#: 1663
Neff: 114
S.D. 0.215

Figure 14. Time series comparison of the observed TP concentration series for Bayswater MD (1987-97), fitted with a LOWESS smooth line (Plot A) for identifying monotonic periods, and with a Sen slope estimator (Plot B) for identifying temporal trends.

Estimating sample size

The number of samples ($n^{\#}$) required to detect a linear trend (in a variable distributed normally about the trend line) can be estimated using the function:

$$n^{\#} = \frac{12(\sigma)^2\,[\,t_{\alpha/2,(n-2)} + t_{\beta,(n-2)}\,]^2}{\Delta^2} \qquad (3)$$

where: σ = the standard deviation of the time series in the absence of trend

Δ= the magnitude of change over the period of interest

t = the critical values of the t-distribution, where:

α = denotes the probability of a false detection (type 1 error)

β = denotes the risk that a trend will fail to be detected (type 2 error)

This equation is from the parametric family of statistical procedures. However it has been found to approximate sample sizes needed to detect trends using non-parametric tests such as the Mann-Kendall (Ward *et al* 1990, Lettermaier 1975).

Independence of Time-Ordered Observations

The equation to derive '$n^{\#}$' above provides an estimate of the number of *independent* samples required to detected a trend of magnitude 'Δ' given the variation around the line of trend of 'σ'. Research has shown that river quality time series collected at frequencies greater than monthly to fortnightly will tend to be serially correlated (Ward *et al* 1990). Correlated data series contain redundant samples because fewer samples would have resulted in the same net information content. As a rule, the level of serial correlation in a data series increases as the frequency of sampling increases. The maximum sampling frequency possible without encountering serial correlation can be thought of as the point of information saturation and it represents the maximum sampling frequency possible.

To select an appropriate frequency at which to sample it is useful to know the effective number of independent samples in data series known to contain serial correlation. This quantity can be estimated using a formula given by Bayly and Hammersley (1946), and used recently by Lettenmaier (1976), Lachance (1992), Close (1989), Zhou (1996):

$$n^* = [1/n + 2/n^2 \sum_{j=1}^{n-1} (n - j)\, \rho\, (jt)]^{-1} \qquad (4)$$

where: t = sampling interval

n = number of samples

ρ = coefficient of correlation.

n^* = effective number of independent observations in period

The maximum number of independent samples n_{max} which can be taken over a time period (T) is given by Lettenmaier (1976):

$$n_{max} = (T^2 / 2)((\ln r)^2 / (r^T - T \ln r - 1)) \qquad (5)$$

where: r = correlation coefficient for the Markov process.

The ratio n^*/ n_{max} may be considered a measure of the information saturation level over the period of record (LaChance, 1992). This ratio was then multiplied by the actual sample size (n) in the period of record to obtain an estimate of the number of effective *independent* samples actually collected

Correcting for Discharge / Concentration Relationships

Flow / concentration responses complicate the detection of trends in data series (Esterby 1996, Heathwaite et al 1996, Ward et al 1990, Hirsch and Slack 1984, Hirsch *et al* 1982). For this analysis, the relationship between nutrient concentration and stream discharge was modelled using a LOWESS line (Lettenmaier *et al* 1991). To account for hysteresis, flow responses were modelled separately within each of three flow strata — on the rising limb of the hydrograph, the falling limb and the inter-event period. The residuals from the LOWESS predicted concentration and the observed concentration can be considered as flow-adjusted concentrations (FAC) and the time-ordered residuals as a flow-adjusted time series (Gilbert 1987, Helsel and Hersh 1992, Harned *et al* 1981, Hipel and McLeod 1994, Lettenmaier *et al* 1991). LOWESS is well suited to water quality applications, especially when the aim is to examine residuals from deterministic processes (Esterby 1996, Robson and Neil 1996, Lettenmaier *et al* 1991).

To determine whether a stream was flow responsive, the observed data was compared to the predicted data from a LOWESS smooth. If the square of the Pearson's product moment correlation coefficient (rsq) of the regression analysis was greater than (or equal to) 0.15 the stream was considered to be flow responsive. If the rsq value of the regression analysis was less than 0.15 the stream was considered non-flow responsive. Subsequently, flow responsive streams had their observed nutrient concentrations adjusted for the effects of flow, the results of which are shown in Figures 12 and 13. The flow adjusted time series were then analysed for evidence of trend components.

3.1.3 Statistical design criteria for catchment monitoring

With sample size estimates from equation (2) and the quantity n^*/n_{max} derived from equations (3) and (4) we are in a position to define the information objectives of the proposed monitoring program.

Analysis Approach

Trends between 1994 and 1997 in the nutrient data series from each of the monitoring sites were analysed for statistical significance using the Mann-Kendall test (Equation 1). When variation in the time series was found to be influenced by discharge / concentration relationships the flow adjusted series were also analysed using the Mann-Kendall (Figures 15 and 16). The flow-adjustment process also tended to remove seasonal variation from the series (Figures 17 and 18). The series that were not flow responsive (TN from Cuppup Creek and Mitchell River, and TP from the Mitchell River and Denmark River) either displayed no indication of seasonality or insufficient observations were available to adequately describe seasonal variation. The results of the analyses for trend are provided in Table 3.

To estimate the standard deviation of nutrient concentrations in the absence of trend ('σ' in equation 2) the data series from monitoring in the Wilson Inlet (*1994 to 1997 only*) were de-trended using the Sen estimator (Equation 2). Using equation (3) with error risks $\alpha = 0.05$ and $\beta = 0.1$, the derived estimates of 'σ' were used to estimate the number of samples actually required to detect trends of the observed magnitude 'Δ'. Equations (5) and (6) were then used obtain the quantity n^{*}/n_{max}, thus estimating the number of effective *independent* samples in the data series in the period analysed for trend.

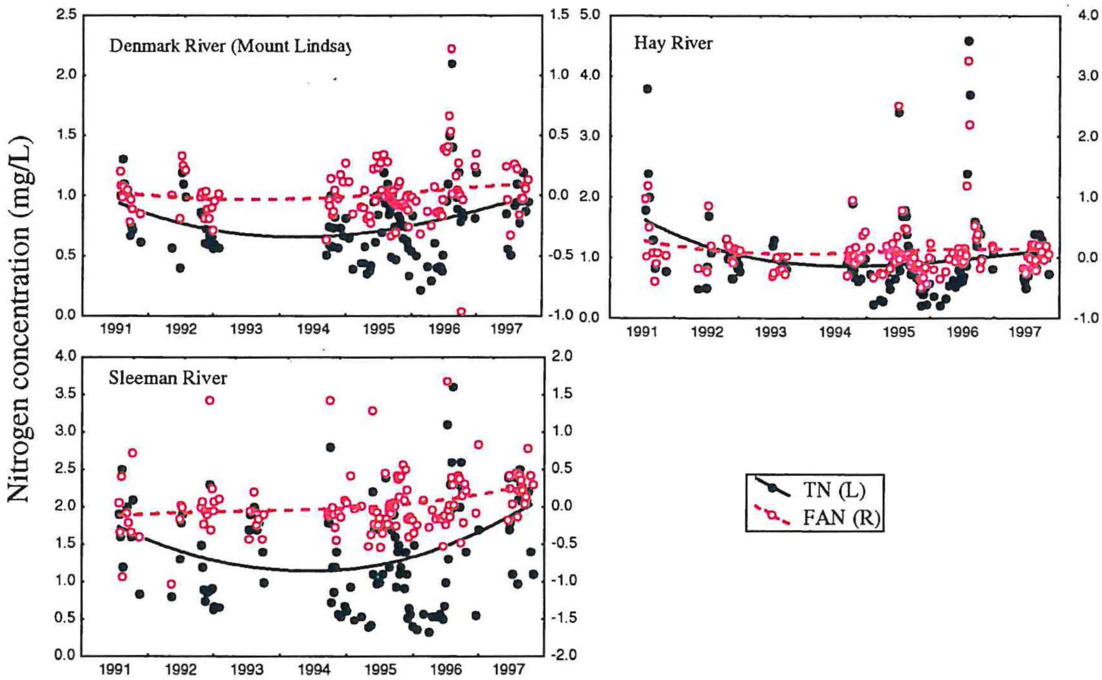


Figure 15. Total Nitrogen (TN) concentration in comparison with Flow Adjusted Nitrogen (FAN) concentration over the period 1991-97 for streams in the Wilson catchment that are responsive for nitrogen.

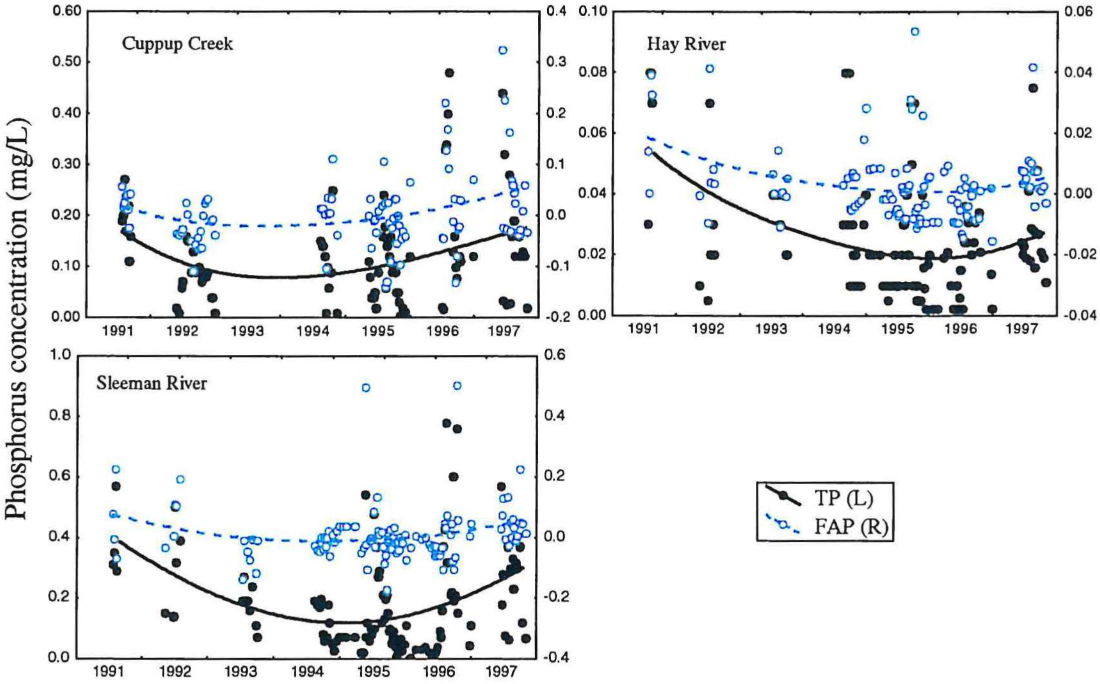


Figure 16. Total Phosphorus (TP) concentration in comparison with Flow Adjusted Phosphorus (FAP) concentration over the period 1991-97 for streams in the Wilson catchment that are responsive for phosphorus.

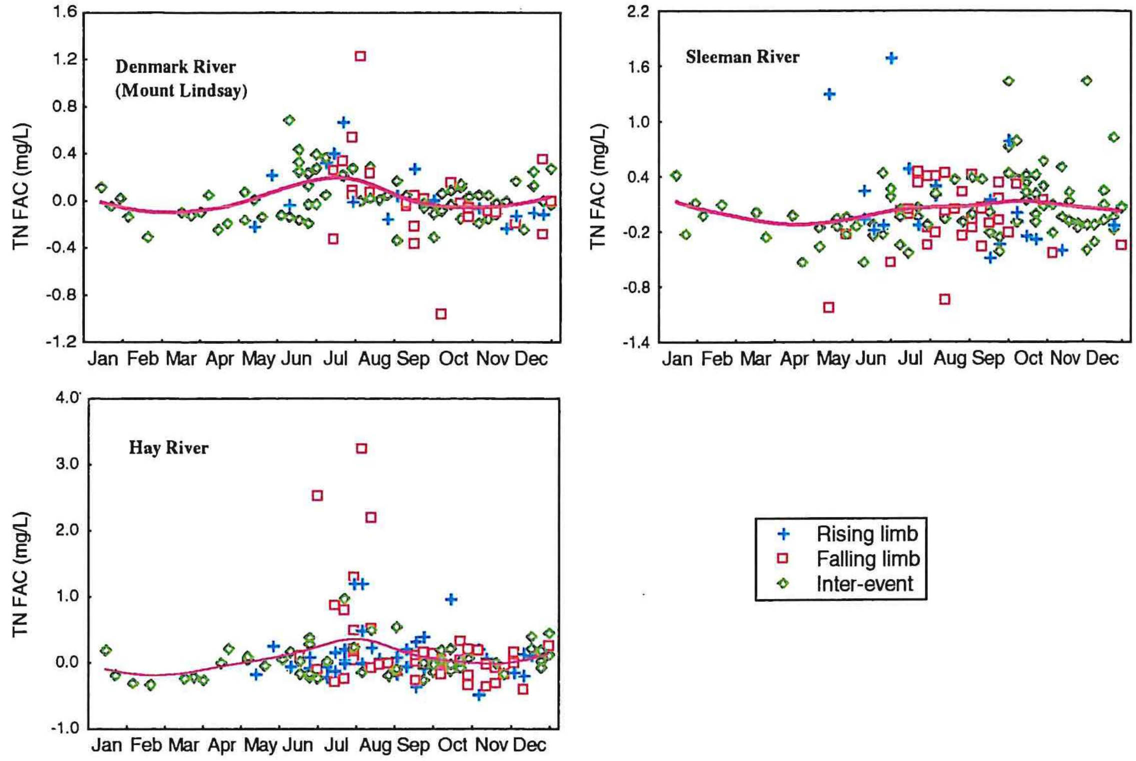


Figure 17. Seasonal variation in flow adjusted nitrogen concentrations for flow responsive streams in the Wilson catchment, with sub-classifications representing various stages of the flow response.

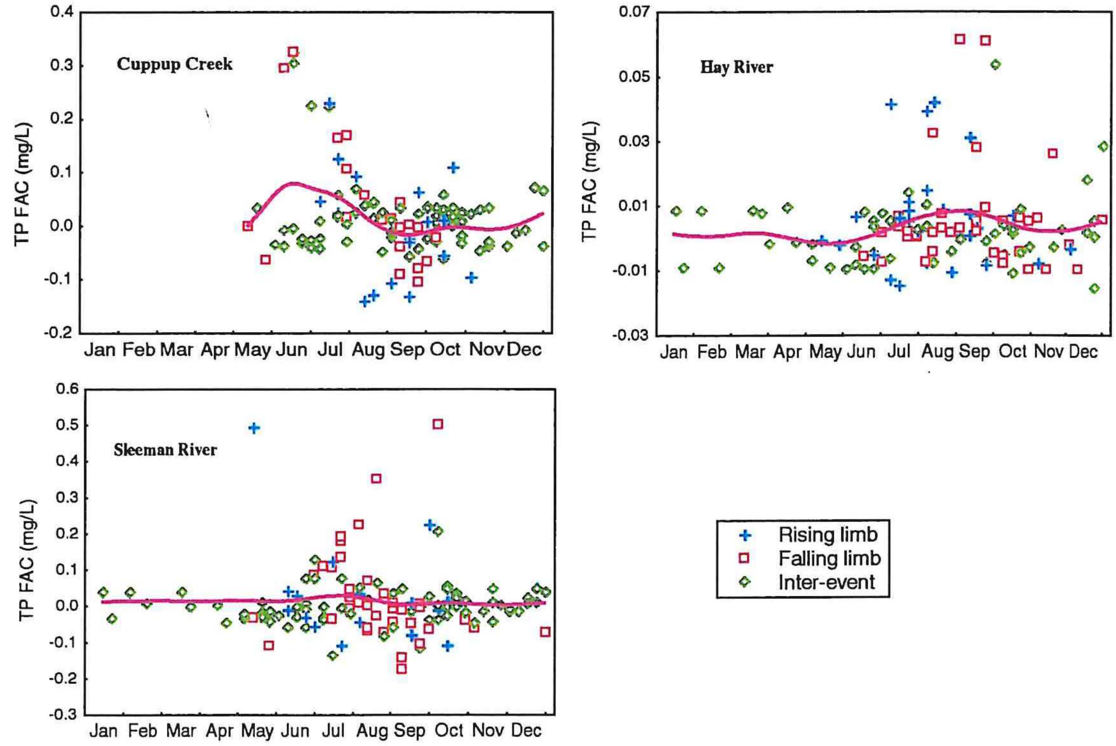


Figure 18. Seasonal variation in flow adjusted phosphorus concentrations for flow responsive streams in the Wilson catchment, with sub-classifications representing various stages of the flow response.

Table 3. Results from statistical analysis of the TN and TP, and their flow-adjusted equivalents, for data series from the monitored streams in the Wilson catchment.

Obs = observed data; FAC = Flow adjusted concentrations; n = number of samples in period; n = effective number of independent samples in series; n# = sample size needed to detect trend ($\alpha = 0.05$ and $\beta = 0.1$).*

Monitored Waterway	Period	Nutrient	Series	Slope (mg/L/yr)	Z	p-value	n	n*	n#	Conclusion
Cuppup Creek	1994-97	TN	obs	0.079	1.04	0.15	59	48	653	no trend
Denmark (Mount Lindsay) River	1994-97	TN	obs	0.044	1.01	0.56	53	53	398	no trend
Denmark (Mount Lindsay) River	1994-97	TN	FAC	0.009	0.36	0.36	53	50	>1000	no trend
Hay River	1994-97	TN	obs	0	-0.04	0.49	63	63		no trend
Hay River	1994-97	TN	FAC	-0.01	-0.25	0.40	63	63	>1000	no trend
Mitchell River	1994-96	TN	obs	0.092	1.22	0.11	45	31	79	no trend
Sleeman River	1994-97	TN	obs	0.129	**1.62**	**0.05**	65	46	179	emerging increasing trend
Sleeman River	1994-97	TN	FAC	0.121	**2.92**	**<0.01**	65	65	75	emerging increasing trend
Cuppup Creek	1994-97	TP	obs	-0.002	-0.47	0.32	61	48	>1000	no trend
Cuppup Creek	1994-97	TP	FAC	-0.002	-0.24	0.40	61	48	>1000	no trend
Denmark (Mount Lindsay) River	1994-97	TP	obs	-0.002	-1.37	0.09	53	53	>1000	no trend
Hay River	1994-97	TP	obs	0	0.42	0.34	65	65		no trend
Hay River	1994-97	TP	FAC	0.001	0.89	0.19	65	65	>1000	no trend
Mitchell River	1994-96	TP	obs	0	-0.60	0.27	47	47		no trend
Sleeman River	1994-97	TP	obs	0.029	**1.67**	**0.05**	67	67	260	emerging increasing trend
Sleeman River	1994-97	TP	FAC	0.017	**2.42**	**0.01**	65	67	263	emerging increasing trend

Table 4. Size of trends that will be detected at each of the sites in the monitoring network proposed for the catchment of the Wilson Inlet.

The numbers relate to trends that will be detected in a five year period with at least 74 samples using a Mann-Kendall test with $\alpha = 0.05$ *and* $\beta = 0.1$*. See Equation (3) for explanation of symbols. Table 5 presents sampling frequencies that need to be employed at each of the sites.*

Monitored Waterway	Period	Nutrient	Series	Observed trend (mg/L/yr)	Observed Δ (mg/L)	Observed σ (mg/L)	Δ/σ (mg/L)	Detectable Δ[2] (1.32*σ)	Detectable Trend (mg/L/yr)
Cuppup Creek	1994-97	TN	obs	0.079	0.316	0.71	0.44	0.94	0.19
Denmark (Mount Lindsay) River	1994-97	TN	obs	0.044	0.176	0.31	0.56	0.41	0.08
Denmark (Mount Lindsay) River	1994-97	TN	FAC	0.009	0.036	0.32	0.11	0.42	0.08
Hay River	1994-97	TN	obs	0.000	0.00	0.74		0.98	0.20
Hay River	1994-97	TN	FAC	-0.01	0.04	0.63	0.06	0.83	0.17
Mitchell River	1994-96	TN	obs	0.092	0.276	0.22	1.28	0.29	0.06
Sleeman River	1994-97	TN	obs	0.129	0.516	0.61	0.84	0.81	0.16
Sleeman River	1994-97	TN	FAC	0.121	0.484	0.37	1.32	0.49	0.10
Cuppup Creek	1994-97	TP	obs	-0.002	0.008	0.11	0.07	0.15	0.03
Cuppup Creek	1994-97	TP	FAC	-0.002	0.008	0.10	0.08	0.13	0.03
Denmark (Mount Lindsay) River	1994-97	TP	obs	-0.002	0.008	0.02	0.40	0.03	0.01
Hay River	1994-97	TP	obs	0.000	0.00	0.02		0.03	0.01
Hay River	1994-97	TP	FAC	0.001	0.004	0.02	0.25	0.02	0.01
Mitchell River	1994-96	TP	obs	0.000	0.000	0.12		0.16	0.03
Sleeman River	1994-97	TP	obs	0.029	0.116	0.17	0.69	0.22	0.04
Sleeman River	1994-97	TP	FAC	0.017	0.068	0.10	0.70	0.13	0.03

---

[2] Detectable Δ is the change required before a trend is likely to be detected. ‘1.32’ is the critical ratio of Δ/σ likely to produce a trend.

3.1.4 Results and recommended program design

The results of the trend analyses are shown in Table 3.

With regard to monitoring program design, the data in Table 4 allow some general observations to be made regarding the sensitivity of the current monitoring program. The *a posteriori* analyses showed that more independent samples were in fact needed to detect these trends with nominal error risks set at $\alpha = 0.05$ and $\beta = 0.1$ (Table 3). For example, the trends in the data series from the Sleeman River were found initially to be statistically significant using Mann-Kendall test. However, on the basis of the *a posteriori* analyses, it was shown that the number of samples were too low and consequently there was insufficient evidence to conclude that slope of the trend line was significantly different from zero. The small sample sizes were due in part to the short period analysed (only four years), but primarily were caused by the erratic nature of the sampling operation and the resulting large number of missing data.

The data in Table 4 suggest that weekly sampling is right on the point of information saturation for the monitored streams, or marginally beyond it in the case of Cuppup Creek and for TN in the Mitchell and Sleeman rivers. Again the erratic sampling interval from the nominal "weekly" sampling interval probably means the levels of correlation were probably underestimated. The increasing trend in the flow-adjusted TN series was the closest to being detected with the nominated error risks (in fact, with the current sample size the actual probability of a Type 1 error associated with accepting the presence of the trend in the Sleeman was only 0.08). As equation (3) implies, it is not the absolute magnitude ('Δ' in equation 3) of the change that determines the number of samples needed to detect a trend, it is the size of the change relative to the deviation of the data about the trend line.

The trend in TN concentration in the Sleeman River was 1.32 times the standard deviation in the series (Table 4). In the period of interest there were 65 samples collected, but to detect a trend equal to 1.32 times the deviation around the trend line requires at least 74 samples with error risks set at $\alpha = 0.05$ and $\beta = 0.1$. It may not have been possible to collect this number of samples in the four year period because the sampling frequency would need to be too high and the resulting data series too correlated. With sampling frequencies that are at or near information saturation (fortnightly to monthly intervals), five years of monitoring or longer are normally needed to detect trends (Smith and McBride 1990). Intuitively it makes no real sense to analyse for trends over periods of anything less than five years in any case.

Based on these results, and similar work carried on data series from the Swan-Canning monitoring network, it was decided that the information objective for the monitoring program should be:

to detect, in a five year minimum period, a trend in nutrient concentration at least 1.32 times the standard deviation of the de-trended time series ($\alpha = 0.05$ and $\beta = 0.1$).

Table 4 shows the magnitude of trend that is needed before a trend is detected in each of the monitored streams. To detect a trend of this magnitude requires that *at least* 74 samples be collected in the five year period. There are two constraints in selecting the sampling interval to achieve this minimum number of samples. They must be collected in intervals equal to fortnightly or greater to avoid serial correlation in the data series. They must also be collected more frequently than once a month because at this frequency only 60 samples would be available after five years for the permanent streams, and between 30 and 50 samples would be available for the ephemeral streams (ie, Mitchell River and Cuppup Creek).

Considering operational realities, this only leaves the option of sampling at intervals of either two or three weeks. Sampling intervals of both two and three weeks in the permanent streams would produce 130 and 87 samples respectively over a five year period which are both capable of meeting the described information objectives (Table 5). However, sampling every three weeks in the ephemeral tributaries would result in an insufficient number of samples over the five year period (Table 5). Fortnightly sampling in the Mitchell River would generate a sufficient number of samples over any five year period, although fortnightly sampling in Cuppup Creek is only just adequate and will probably result in less than the required 74 samples on some occasions after five years of sampling (Table 5). There is little option given the constraints described, so it may be necessary to analyse for trends in Cuppup Creek over at least six years (or to accept a less demanding error probability in five year intervals of $\alpha = \beta = 0.1$). To meet the stated information objective it is recommended that the monitored tributaries of Wilson Inlet be sampled every two weeks while flowing. Although fortnightly sampling appears excessive for the permanent streams it also allows an adequate buffer of samples for the ephemeral streams, which may be necessary given exceptionally dry years or periods of missing data.

Table 5. Number of samples available for analysis after a running five year period using simulated two and three week sampling intervals for both ephemeral (eg. Mitchell River and Cuppup Creek) and permanent rivers.

At least 74 samples are necessary per five year period to meet the information objectives. N/A = flow record was not available.

		EPHEMERAL				PERMANENT	
		Mitchell River		Cuppup Creek			
PERIOD OF FLOW USED	Years Used	*Sampling every 2 weeks*	*Sampling every 3 weeks*	*Sampling every 2 weeks*	*Sampling every 3 weeks*	*Sampling every 2 weeks*	*Sampling every 3 weeks*
1986-90	5	92	61	N/A	N/A	130	87
1987-91	5	94	63	N/A	N/A	130	87
1988-92	5	94	63	N/A	N/A	130	87
1989-93	5	97	65	N/A	N/A	130	87
1990-94	5	87	58	80	53	130	87
1991-95	5	84	56	75	50	130	87
1992-96	5	87	58	70	47	130	87
1993-97	5	92	61	68	45	130	87

3.2 Estimating river loads

3.2.1 NEMP research priority: 'Effects of episodic events on waterbody ecology'

The estimation of mass loads in rivers presents many technical and operational difficulties. The load estimation problem relates primarily to the flow-response characteristics of nutrients in rivers. Sampling texts generally offer minimal or no guidance on sampling for measuring mass loads or actually recommend against using standard statistical procedures to determine sampling requirements.

The concentration of nutrients in flowing waters usually varies with stream discharge. In most streams, the relationship is positive whereby as discharge increases nutrient concentrations also increase (Johnson and East 1982). The combination of an increase in discharge with an increase in nutrient concentration can generate very large loads during storm events. Negative correlations have been observed between discharge and nutrient concentration and some studies have identified streams in which concentration and discharge may vary independently.

It is not practically possible to provide unbiased estimates of load but with judicious sampling it is possible to keep the levels of bias between stations and between years within predicted bounds. A variety of load estimation systems have been developed that prescribe sampling protocols that forecast bias and precision in the resulting load. They are all based on knowledge of variations in the nutrient population structure over the storm hydrograph making sample decisions that reflect changes that occur in chemical conditions. The loading estimates can then be made based on a model between discharge and concentration. These rating techniques are biased mainly due to inadequate sampling (and nutrient concentration is related to factors other than stream discharge). The rating technique can be unbiased if the sampling frequency is high or the sampling effort is focused on storm events (Littlewood 1992). Such sampling strategies rely on data loggers to make real-time decisions about when to operate automatic pump samplers.

The concentration of nutrients in the main tributary inflows to the Wilson Inlet will be characterised using automatic sampling equipment. Programmable data loggers will adjust sampling regimes to real-time flow conditions. The program has several user-defined parameters to tailor sampling to the hydrograph at the proposed site (shown in Table 6). Figure 19 shows the typical pattern of sampling that will result from the parameter settings shown in Table 6.

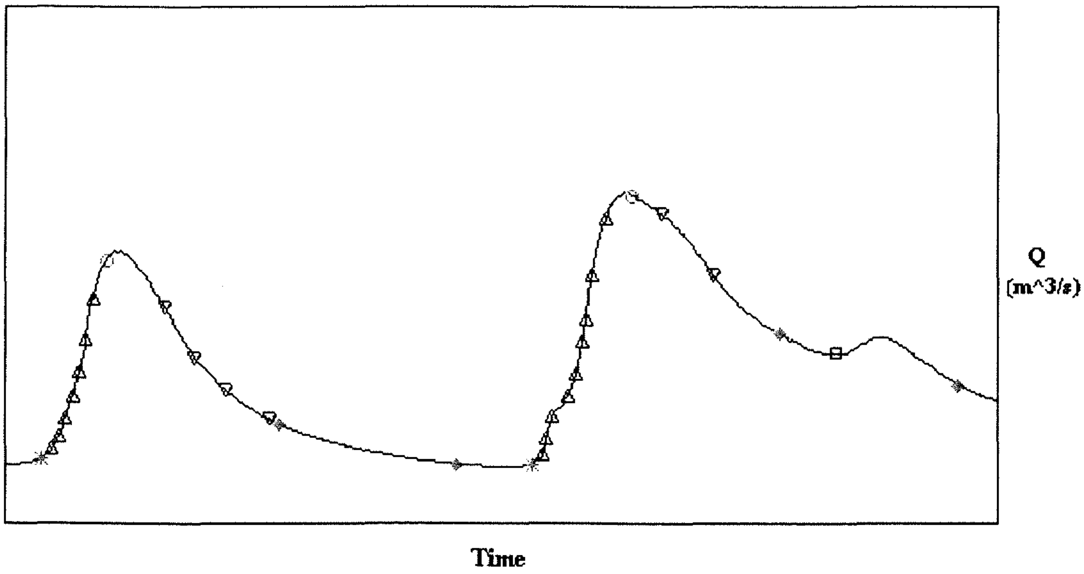


Figure 19. Typical hydrograph with samples taken in accordance with various stages set by the parameters in Table 6.

Table 6. Parameters for Campbell logger sampling program.

Symbols from Figure 19 are included which correspond to a particular parameter setting and the per centage of samples expected to be collected from the regime.

Station Location		Sleeman River		Denmark River	
Station Name		Sleeman Rd Bridge		Agricultural College	
AWRC Station Number		S603007		S603076	
SWRIS Catalogue Page		p 25		p 25	
Symbol	Parameter:	Value	%n	Value	%n
*	15 minute storm trigger	0.005	14	0.35	10
+	24 hour storm trigger	0.06		2	
Δ	Rising limb stage change	0.15	23	0.3	12
∇	Falling limb stage change	-0.25	10	-0.5	4
	% cut off	0.2		0.25	
◊	Inter event period (days)	2	40	4	33
o	Maximum	180	11	50	27
	Minimum	180	2	100	13
	Noise filter	0.005		0.15	

4. Discussion

The nutrient data series from the catchment of the Wilson Inlet since 1991 have yielded clues on how and when nutrients are mobilised and delivered to the estuary. Nutrient levels in samples from Cuppup Creek, Hay River and the Sleeman River clearly respond to increasing discharge. The combination of increasing concentration and discharge would probably result in very large loading of Wilson Inlet with nutrients in relatively short periods. The bar across the mouth of the Inlet is open in mid-winter when the episodic loadings occur, during which a large proportion of the nutrients would be carried out of the estuary to the ocean. Some of the nutrients carried in storm flows may be retained and added to the internal nutrient store of the estuary.

Monitoring has shown that nutrient concentrations in the surface waters of the Wilson catchment vary seasonally, probably in a predictable pattern (the data series were too short to describe quantitatively seasonal variation). Unfortunately, sampling in the permanent rivers was less frequent in the spring and summer months when small (possibly nutrient rich) inflows may have influenced productivity disproportionably to the small total loading in this period (especially when the bar is closed in January / February). For some rivers, the more predictable seasonal increases in nutrient concentration were seen in samples collected during the period between storm flows. Similar patterns of seasonal variation have been noted elsewhere (Donohue et. al. in prep.) and show that concentrations in the rivers are higher when base flows are high. The exact mechanism of the correlation is not known but base flows are comprised of groundwater, which suggests that the concentration of nutrients in streams will vary with seasonal changes in groundwater depth.

The predicability of the supply of nutrients to the Inlet is very important because different plant groups will evolve to take advantage of different sources. Large amounts of nutrients would be supplied to the Inlet in storm flows but exploiting these supplies presents some difficulties. Much of the storm-derived nutrients occur in winter when light availability and water temperatures are low and not conducive for nutrient uptake and growth. So most of this supply cannot be used immediately by plants and is either lost to the ocean or bound to sediments to be released when chemical conditions are favourable. Temperatures and light availability in spring do favour growth but the nutrient enrichment with spring storms is episodic, delivering large amounts of nutrients in very short periods of time. Plants with the right physiological adaptations can take advantage of the riches: they need to be opportunistic and be able to grow and reproduce very rapidly. Thus in a relatively healthy system we may see phytoplankton activity in spring, such as observing a "bloom" immediately after a spring storm event.

Much of the seasonal pattern of nutrient delivery to the Inlet was seen in samples collected during base-flows. A larger proportion of the nutrient flux in base flows would be retained in the Inlet, especially in very low flows in spring and summer. These base-flow nutrient inputs to the Inlet are very predictable in the southwest of Western Australia. It may be that nutrient increases in base flows have a large impact on productivity in estuaries. More predictable seasonal sources may be exploited by long-lived plant groups with pronounced seasonal patterns of growth, reproduction and senescence, such as macro and epiphytic algae. These supplies are chronic, very seasonal and predictable and they are generally in a form that can be used by plants. Enriched ground waters supplying nutrients to stream channels in base flows may therefore have severe ecological repercussions in receiving waters. Nutrient enriched agricultural soils on low-lying areas probably represent the greatest risk.

The net retention of nutrients delivered episodically and their role in controlling the primary productivity of the Inlet is currently being researched as part of the NEMP program. The monitoring program using pump samplers (described in the previous section) will measure variation in nutrient concentrations in the inflows to the Inlet over very short time-scales. Currently, automatic pump samplers are located on the Denmark and Sleeman rivers with another being considered for the Hay River. The data will allow plant ecologists studying the Inlet to relate primary productivity in various plant groups in the Inlet with the timing and magnitude of nutrient fluxes.

Apart from the emerging increasing trend in the concentration of nitrogen and phosphorus in the Sleeman River, there was no indication that the nutrient levels in most of the catchment's streams were changing in the period of monitoring. However, there were indications that nutrient levels in Cuppup Creek, Sleeman River, Little River, and Sunny Glen Creek were elevated. This means that there is room for improvement in these catchments.

Section 3.1.3 described the monitoring program designed to detect changes (if they occur) and closely examined the monitoring program's sensitivity to change. One of the important aspects of the analysis is that the information objects are closely linked to the error probabilities. For example, the same magnitude of trend (1.32 times the standard deviation) would be detected with only 60 samples and a sampling frequency of one sample per month if we were to accept statistical error risks of $\alpha=\beta=0.1$.

5. References

ANZECC: Australian Water Quality Guidelines 1992, Australian and New Zealand Environment and Conservation Council.

Aulenbach, B. T., Hooper, R. P. & Bricker, O. P. 1996, Trends in the chemistry of precipitation and surface water in a national network of small watersheds, *Hydro. Proc.* **10** (2): 151-181.

Bayley, G. V. & Hamersley 1946, The effective number of independent observations in an auto-correlated time series, *Supplement to the Journal of the Royal Statistical Society,* **8**:184-197.

Close, M. E. 1989, Effect of serial correlation on groundwater water quality sampling frequency, *Water Resour. Bull.,* **25**: 507-515.

Donohue, Wittenoom, Nelson and Bowyer in prep, Temporal trends in phosphorus in tributary inflows to the Swan-Canning Estuary, *Water and Rivers Commission Report,* Perth, Western Australia.

Ellis, J. C. 1989, *Handbook on the Design and Interpretation of Monitoring Programmes,* Water Research Centre Publication, Medmenham.

Esterby, S. R. 1996, Review of methods for the detection and estimation of trends with emphasis on water quality applications, *Hydrolo. Proc,.* 10 (2): 127-149.

Evans, C. & Davis, T. D. 1998, Causes of concentration / discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry, *Water Resour. Research, Vol 34 (1): 129-137.*

Gilbert, R. O. 1987, *Statistical Methods for Environmental Pollution Monitoring,* Van Nostrand Reinhold, New York, 250pp.

Gillham, R. 1984, The capillary fringe and its affect on water table response, *J. Hydrology,* **67**:307-324.

Hamed, D. A., Daniel, C. C. III, & Crawford, J. J. 1981, Methods of discharge compensation as an aid to the evaluation of water quality trends, *Water Resour. Research,* **17**: 1389-1400.

Heathwaite, A. L. & Johnes, P. J. 1996, Contribution of nitrogen species and phosphorus fractions to stream water quality in agricultural catchments, *Hydro. Proc.,* **10**:971-983.

Helshel, D. R. & Hirsch, R. M. 1992, *Statistical Methods in Water Resources,* Elsevier, Amsterdam, 522 pp.

Hipel, K. W. & McLeod, A. I. 1994, *Time Series Modelling of Environmental and Water Resources Systems,* Elsevier, Amsterdam.

Hirsch, R. M., Slack, J. R., & Smith, R. A. 1982, Nonparametric tests for trend in water quality, *Water Resour. Res.,* **18**: 107-121.

Hirsch, R. M. & Slack, J. R. 1984, A non-parametric trend test for seasonal data with serial dependence, *Water Resources Res,.* **20**: 803-813.

Johnson, F. A. & East, J. W. 1982, Cyclic relationships between river discharge and chemical concentration during flood events, *J. Hydrology,* **57**: 93-106.

Lachance, M. 1992, Monitoring Lakes in Quebec, Case study in: *Design of Water Quality Monitoring Systems,* R. Ward, J. Loftis & G. McBride, Van Nostrand Reinhold, New York.

Lettenmaier, D. P. 1975, Design of monitoring systems for ambient stream quality monitoring, Technical Report 39, Charles W. Harris Laboratory, University of Washington, Seattle, Washington.

Lettenmaier, D. P. 1976, Detection of trends in water quality from records with independent observations, *Water Resour. Res.,* **12** **(5)**: 1037-1046.

Lettenmaier, D. P., Hooper, E. R., Wagoner, C., & Faris, K. 1991, Trends in Stream Quality in the Continental United States, 1978-1987, *Water Resour. Res.,* **27** **(3)**: 327-339.

Littlewood, I. G. 1992, Estimating contaminant loads in rivers: a review, *Institute of Hydrolog,.* National Environment Research Council, Report No. 117.

Richards, R. P. & Holloway, J. 1987, Monte Carlo Studies of Sampling Strategies for Estimating Tributary Loads, *Water Resour. Res.,* **23 (10)**: 1939-1948.

Robson, A. J., & Neal, C. 1996, Water quality trends at an upland site in Wales, *Hydro. Proc.,* **10 (2)**: 183-203.

Sanders, T. G., War, R. C., Loftis, J. C., Steele, Adrian, D. D., & Yevjevich, V. 1987, *Design of Networks for Monitoring Water Quality (2nd ed.),* Water Resources Publications, Littleton, Colorado.

Sklash, M. G. & Farvolden, R. N. 1979, The role of groundwater in storm runoff, *J. Hydrology.* **43**: 45-65.

Schofield, N. J., Bettenay, E., McAlpine, K. W., Height, M. I., Hurle, D. H., Richie, G. S. P., & Birch, P. B. 1985, Water and phosphorus transport mechanisms in permeable grey sands at Talbot's site near Harvey, Western Australia, *Department of Conservation and Environment, Bulletin 209.*

Smith & McBride, G. B. In: *Design of Water Quality Monitoring Systems,* R. Ward, J. Loftis. & G. McBride 1990, Van Nostrand Reinhold, New York.

Thomas, R. B. & Lewis, J. 1995, An evaluation of flow stratified sampling for estimating suspended sediment loads, *J. Hydrology.* **170**: 27-45.

Tipping, P. 1997, Wilson Inlet Catchment Monitoring 1994-1996, *Agriculture WA,* National Landcare Program, Project Number 93 / 5616.

van Belle, G., & Hughes, J. P. 1984, Nonparametric tests for trend in water quality, *Water Resour. Res.,* **20**: 127-136.

Ward, R., Loftis, J. & McBride, G. 1990, *Design of Water Quality Monitoring Systems,* Van Nostrand Reinhold, New York.

Yu, Xianwen 1998, *A preliminary investigation of nutrient loads discharged from groundwater into Wilson Inlet, Denmark,* Water and Rivers Commission, Hydrogeology Report No. 102.

Zhou, Y. 1996, Sampling frequency for monitoring the actual state of groundwater systems, *J. Hydrology,* **180**: 301-318.

Notes