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OCCASIONAL REPORT

Water Quality Monitoring in the Gippsland Catchments - Efficient Sampling Strategies and Load Estimation Techniques

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Acknowledgements

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Executive Summary

The issue of mass load estimation is an important topic in natural resource management. Water quality monitoring in the Gippsland catchments has been undertaken by a number of agencies over many years with a view to quantifying, among other things, annual nutrient loads (principally nitrogen and phosphorous). In 2001 the Victorian DSE established an overall 40% nutrient load reduction target for the Gippsland Lakes. While much of the subsequent focus has been on identifying and implementing on-ground actions and strategies to achieve this reduction, relatively little attention has been given to the issue of *how do we actually measure improvement*? This is a critical question that needs to be answered if we are to assess the cost-effectiveness of any particular course of action or suite of actions. Furthermore, a more comprehensive analysis will require companion estimates of *uncertainty* or *precision* so as to attach levels of confidence that certain targets have been met.

This report brings together a number of key research outcomes that will: (i) provide clear (and consistent) advice on the development of water quality monitoring programs; and (ii) provide methods and tools for the provision of accurate (annual) load estimates with stated levels of uncertainty in those estimates.

For the major tributaries of the Gippsland Lakes it is recommended that:

Recommendation

- Nutrient loads be partitioned into **two components** – one associated with 'peak' flow events and the other associated with 'non peak' flows (the remainder).
- The monitoring and estimation strategy associated with **non peak** flows is to use 12-monthly composite samples and a transfer-function modelling approach as described in this and companion reports.
- The monitoring strategy for **peak** events is to obtain accurate **empirical** load estimates. Sampling on these occasions will be triggered by the exceedence of a pre-determined flow threshold (eg. the 99th. percentile).
- The annual load estimate is obtained as the **sum** of the two separate estimates.
- It is expected that on average a total of **15-20 water quality samples** per year per site will be required.

If adopted, this recommendation will, for the first time achieve a level of consistency and accuracy hitherto not realised with any previous water quality monitoring program in the Gippsland Lakes Catchment. *A key feature of the proposed strategy is that it is extremely cost-effective – it requires little or no additional monitoring effort yet has the potential to achieve a 10-fold reduction in the relative error of estimated annual loads.*

1. Introduction

Elevated nutrient loads in water bodies increases the risk of algal blooms which in turn negatively impacts light climate, disrupt photosynthesis, reduces dissolved oxygen and compromises other water quality parameters. In their natural or undisturbed state, most Australian rivers and estuaries were oligotrophic. Now after many decades of constant land-based discharges of nutrient rich wastewater and run-off their status is now mesotrophic or eutrophic. As noted in Fox (2005b), the accurate estimation of sediment and nutrient loads is an issue that is attracting considerable attention among researchers and NRM agencies in Australia and overseas. To a large extent, this has been driven by the imposition of either compliance-driven or 'aspirational' load reduction targets. For example, a 40% reduction in sediment load in rivers in Far North Queensland was deemed necessary to prevent further water quality degradation and impacts on the Great Barrier Reef (Steven et al. 2005). In Gippsland, the Victorian EPA similarly adopted a 40% nutrient (phosphorous) reduction target for the Gippsland Lakes between 2000 and 2005 (EPA Victoria 2001). Despite the widespread use of load-based targets, load-based licensing, and load reduction agreements, there is almost no accounting of the *uncertainty* in the estimates underpinning these instruments. Some would argue that this introduces an unnecessary level of complexity into an assessment process which is more to do with changing behaviours and practice than it is about accurate quantification of loads. The counter view adopted in this report is that in the absence of such an assessment, the setting of any numerical target is rendered meaningless. Indeed, it has been shown (Fox 2005b) that nutrient loads are typically *underestimated* by between 20 to 40% using conventional load sampling and estimation protocols. Thus, one could demonstrate an apparent 40% load reduction by doing nothing more than comparing a current (biased) load estimate with an unbiased baseline load.

Admittedly, the statistical issues associated with load sampling and estimation techniques are numerous and a present difficulty is the lack of clear advice to practitioners on *how* to collect and analyse data. The situation is further compounded by the plethora of computational formulae available for computing a load, although the computer software tool GUMLEAF (Tan et al. 2005) was developed in an attempt to streamline the selection process.

This occasional report distils a number of approaches and ideas for load sampling and estimation that have been investigated by researchers at the Australian Centre for Environmetrics over the past few years (Fox 2004a, 2004b, 2005a, 2005b, Etchells et al 2005). Work in this area commenced with an analysis of Southern Rural Water's drain monitoring program in the Macalister Irrigation District (Fox 2003) and has been broadened to include rivers and streams in the Gippsland catchment. A number of fundamental insights into the statistical properties of flow and concentration data that emerged from these early analyses have subsequently been found to apply to diverse catchments such as the Daintree-Mossman in far North Queensland (Steven et al 2005) and the Saginaw River, Michigan (Fox 2004)[1] which increases the confidence in their widespread applicability and utility.

In offering general advice to practitioners and natural resource managers on strategies for load estimation, we have recognised the fact that most monitoring programs are severely constrained by resource limitations. Daily monitoring of water quality parameters such as TN and TP is either a luxury that few agencies can afford or alternatively is done for a limited time as part of a research program. The data used in this report is an example of the latter and has been made available by the Victorian EPA who collected it as part of Gippsland Lakes Task Force Projects EG-0405-04.019 and EG-0506-04.016. A more comprehensive discussion of these research projects and preliminary results can be found in Davies and Martinez (2006). What is unique about these data is their high frequency sampling (daily) of TN and TP in the major rivers draining into the Gippsland Lakes (Tambo, Nicholson, Mitchell, Avon, Thomson, Latrobe). Using daily data from the Tambo River, we have been able to evaluate the effectiveness of sampling and estimation procedures that were shown to perform extremely well for the MID irrigation drains (Fox 2007). Being less regulated, rivers and streams tend to exhibit 'flashier' behaviour and tend to follow the rule of thumb that 80% of the load is delivered in 20% of the time – in fact the present analysis shows that over an almost two year period, the Tambo river delivered nearly 50% of the total N and P loads over just 12 days. This type of phenomenon is not evident to the same extent in drains and we have therefore found it necessary to estimate separately the 'peak' and 'no-peak' loads. For these strata, two separate load estimates are produced using different methods. Peak loads are to be estimated by intensive sampling for the duration of high-flow events, while the 'non peak' load is estimated using a composite sampling strategy coupled with a statistical model for *daily* concentration data. The method is described in detail in Fox (2007), although a brief outline is given in this report.

[1] This river was chosen as it had been previously used by Preston et al. (1989).

2. Statistical Issues associated with Load Estimation

Load estimation is not a new problem and a cursory examination of the relevant literature shows that many papers have been written on the statistical aspects of load estimation and sampling (Cooper and Watts 2002, Preston et al. 1989, Richards 1998, Cohn et al 1989, Thomas 1985, Degens and Donohue 2002, Moosmann et al 2005, Chu and Sanders 2003 and others). The purpose of this section is to briefly outline some of the underlying issues that have motivated the present research rather than providing a comprehensive review of all facets of load estimation. Our over-riding and persistent concern is the lack of statistical rigour in both the *design* of monitoring programs and *analysis* of load-related data. Sampling frequency of flow and concentration data is highly variable both within and between catchment monitoring programs. It is our experience in the Gippsland region and elsewhere that at best, water quality data is routinely collected on a *monthly* basis (weekly data is sometimes obtained, but this sampling frequency is generally not sustained in the long-term). However, often-times water quality data is collected on an ad hoc basis and in sporadic 'campaigns' of varying temporal intensities. This has important consequences for the *quality* of load estimates derived from those data and (in the absence of a statement of precision) renders comparisons of estimates at different times and places problematic. In this context the common practice of comparing a current load with a 'baseline' load is a futile and potentially misleading exercise – as evidenced by the application of a 40% load reduction target to load estimates that are in error by typically 30-40%. This situation is further complicated when loads estimated from catchment models which have unquantified levels of uncertainty are used. As noted by Davies and Marinez (2006) the errors in modelled baseline loads used for setting the 40% nutrient load reduction target for the Gippsland Lakes were thought to be between 20-100%.

Compounding the ad hoc nature of many sampling programs is the plethora of computational approaches for estimating a total mass load. When applied to relatively sparse concentration data, these different computational approaches can yield wildly different load estimates. A critical missing element in the discussion of load estimation procedures to date is the coupling of *sample design* and *statistical estimation* procedure. While considerable flexibility exists in the choice of these monitoring components, they are neither totally independent nor arbitrary considerations. The difficulty it seems is that there is no universally 'optimal' approach for mass load sampling and estimation – different circumstances will dictate different approaches. The problem is further compounded by the paucity of general recommendations that enunciate the linkages between circumstances and approaches, thus leaving the practitioner with a bewildering array of sampling strategies and estimation techniques.

In this report we show how parameter estimation for a second-order transfer function model of daily concentration demands a composite sampling approach for data collection and analysis. In this way, the sampling design and the load estimation procedure are coupled thus avoiding the ambiguity of multiple load estimates when different estimating equations are applied to the same data.

3. A coupled monitoring and estimation approach for load estimation

The key inputs for any mass load estimation are *concentration* (C_t) and *flow/discharge* (Q_t) at time *t*. The instantaneous *flux rate* (F_t) is the product of concentration and discharge (equation 1).

$$F_t = C_t \cdot Q_t \tag{1}$$

The total load or mass transported in the interval [0,T] is obtained by integrating the instantaneous flux rate:

$$Load = \int_0^T C_t \cdot Q_t \, dt \tag{2}$$

In practice, equation (2) is approximated by the summation

$$L = K \sum_{i=1}^{N} C_i \cdot Q_i \tag{3}$$

where C_i and Q_i are measurements of concentration and flow respectively and *K* is a constant.

As mentioned in previous sections, an important consideration in load estimation is the frequency with which water quality determinations are made or equivalently, the sampling period $\delta T = T/N$. Typically *T* is 365 days and *N*=12. Ideally, we would like *N*=365, but this is prohibitively expensive.

The data paucity and estimation issues have been addressed in Fox (2007) using a second-order transfer function model (equation 4) whose parameters are estimated from *monthly* water quality data.

$$C_i = \frac{\alpha_0 + \alpha_1 Q_i}{\left(1 + B\beta_1 + B^2 \beta_2\right)} + \varepsilon_i \tag{4}$$

In equation (4) C_i and Q_i denote the natural logarithms of concentration and flow respectively; the αs and βs are model parameters; *B* is the backward shift operator; and ε_i is a zero-mean random error or 'shock' component with variance σ_ε^2.

Having fitted the model and estimated other key parameters such as the variance of the random error component, simulated daily time-series for the water quality parameter of interest can be constructed. The simulated concentrations are then matched with actual flows and a straightforward application of equation (3) provides an estimate of load for the period of interest. A critical modification to the (assumed) monthly monitoring for water quality is required. Instead of taking a single sample once a month for analysis, the procedure requires that an *average* concentration be obtained from a *composite* monthly sample. For example, if flows are recorded on a daily basis, then a daily water sample must be obtained and stored. At the end of the month, equal volumes from each of the 30, say, water samples are combined. A single water quality determination is then performed on this composite sample. The rationale for the composite sampling is that it provides an estimate of the average daily concentration for that month. This is a critical requirement for the correct application of the modelling and estimation methodology outlined in Fox (2007). Failure to adhere to this sampling strategy will invalidate the resulting load estimates obtained from the transfer function modelling approach.

4. Application to Tambo River

Daily water quality data for the Tambo River between 23/09/2004 and 24/05/2006 (609 days) was provided by the Marine Science Unit, EPA Victoria. Details of site locations, sampling protocols etc. can be found in Davies and Martinez (2006).

4.1 Preliminary data analysis

Figure 1 shows the daily flow for the measurement period. The trend line in Figure 1 shows an overall decline in flow during the data collection period. Nitrogen concentrations also fell on average by 73% during the same time (Figure 2 and Table 2) while phosphorous concentrations fluctuated around an average of 0.047 mg/L (Figure 3 and Table 1).

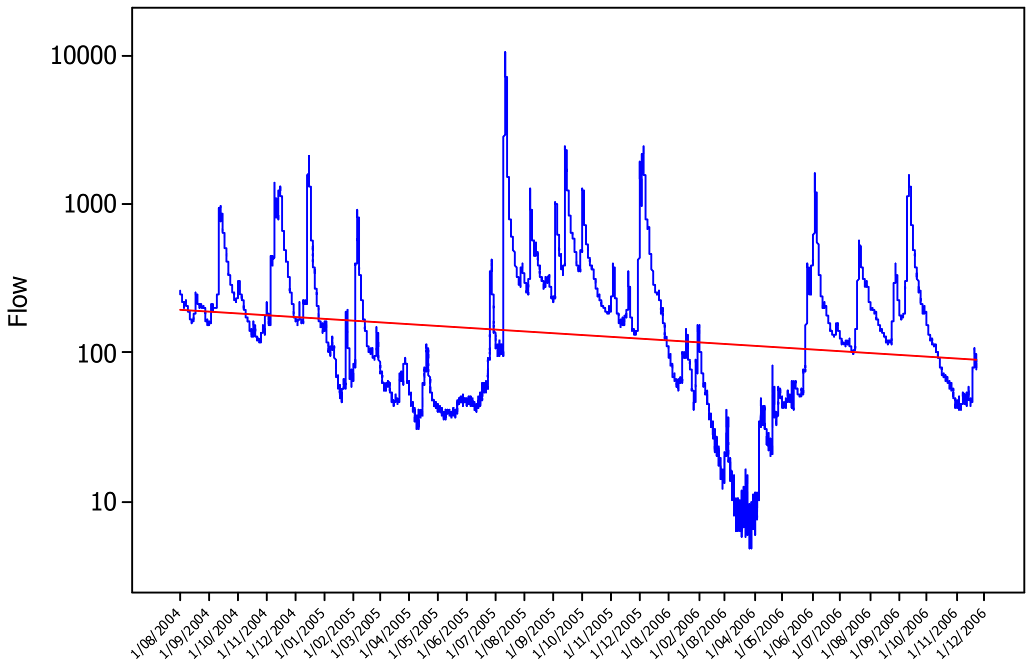

Figure 1. Times series of daily flow (ML) in the Tambo River Aug 2004 to Dec 2006. Red line is linear trend line. NB. Logarithmic scale used for vertical axis.

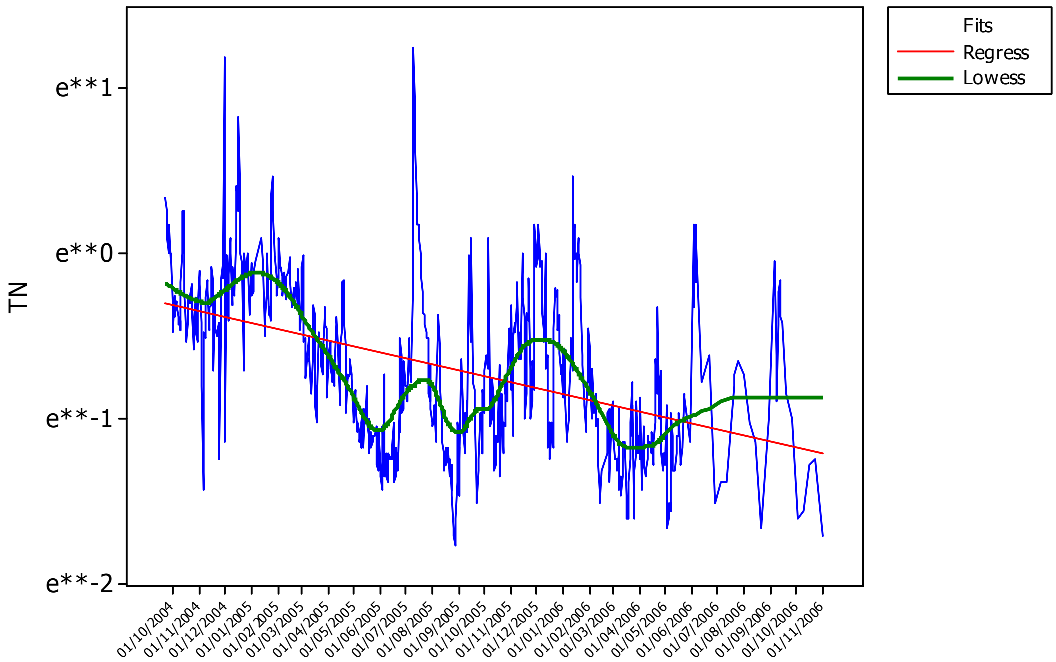

Figure 2. Daily total nitrogen (TN) concentration (mg/L) (blue line), linear trend (red line), and smoothed series (green line) for Tambo River September 2004 to November 2006. NB: Natural log scale used for concentration.

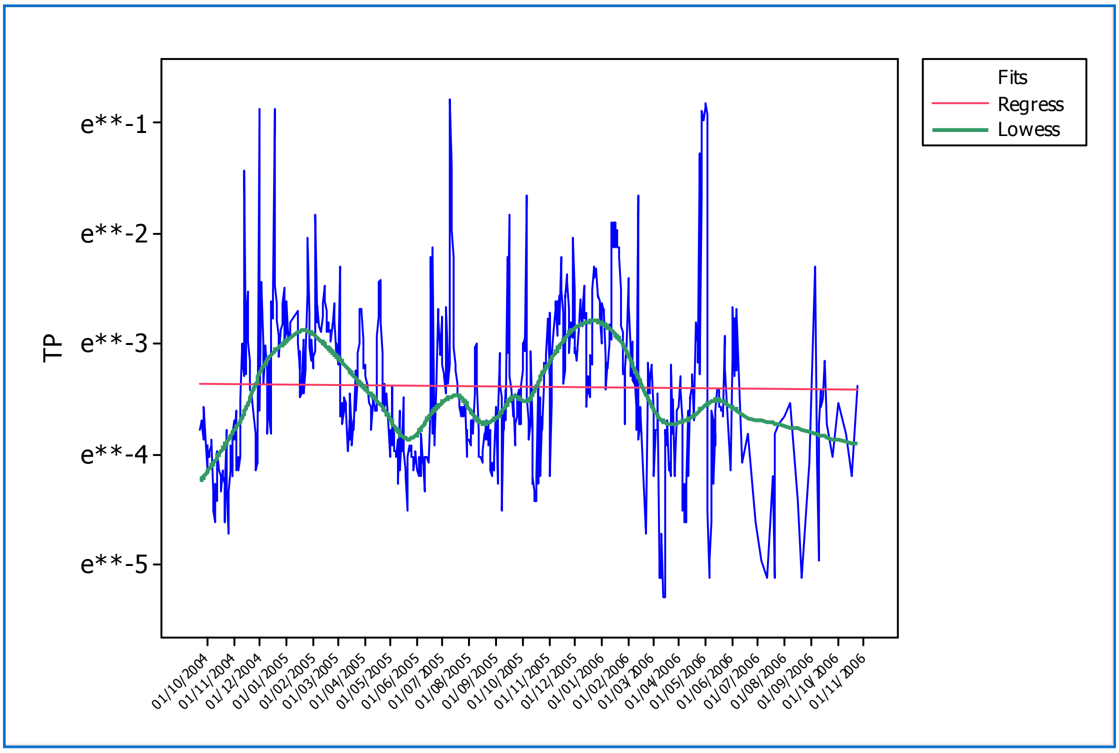

Figure 3. Daily total phosphorous (TP) concentration (mg/L) (blue line), linear trend (red line), and smoothed series (green line) for Tambo River September 2004 to November 2006. NB: Natural log scale used for concentration.

Table 1. Mean daily phosphorous concentration (mg/L) in Tambo River by month and year.

Mean TP	January	February	March	April	May	June	July	August	September	October	November	December	average
2004									0.022	0.016	0.052	0.070	0.044
2005	0.057	0.064	0.038	0.037	0.020	0.034	0.063	0.023	0.038	0.037	0.064	0.061	0.044
2006	0.076	0.045	0.020	0.069	0.074								0.057
average	**0.068**	**0.056**	**0.029**	**0.053**	**0.043**	**0.034**	**0.063**	**0.023**	**0.034**	**0.026**	**0.058**	**0.065**	**0.047**

Table 2. Mean daily nitrogen concentration (mg/L) in Tambo River by month and year.

Mean TN	January	February	March	April	May	June	July	August	September	October	November	December	average
2004									1.089	0.747	0.770	0.965	0.849
2005	0.929	0.833	0.583	0.541	0.345	0.336	0.927	0.334	0.431	0.435	0.626	0.664	0.574
2006	0.657	0.378	0.299	0.351	0.302								0.404
average	**0.776**	**0.633**	**0.439**	**0.446**	**0.326**	**0.336**	**0.927**	**0.334**	**0.570**	**0.591**	**0.698**	**0.817**	**0.581**

Table 3. Total Tambo River discharge (Ml) by month and year.

Total discharge	January	February	March	April	May	June	July	August	September	October	November	December	Total
2004									2032	5277	16500	11833	35641
2005	2146	5766	1871	1542	1307	2716	34418	12426	20340	11360	7398	18003	119292
2006	2454	1064	384	913	1282								6097
Total	**4600**	**6830**	**2255**	**2455**	**2589**	**2716**	**34418**	**12426**	**22372**	**16637**	**23898**	**29836**	**161030**

Figures 4-6 and the correlation coefficients in Table 4 show that (on a logarithmic scale) the flow and concentration data are moderately (positively) correlated. This is a common observation for Australian catchments.

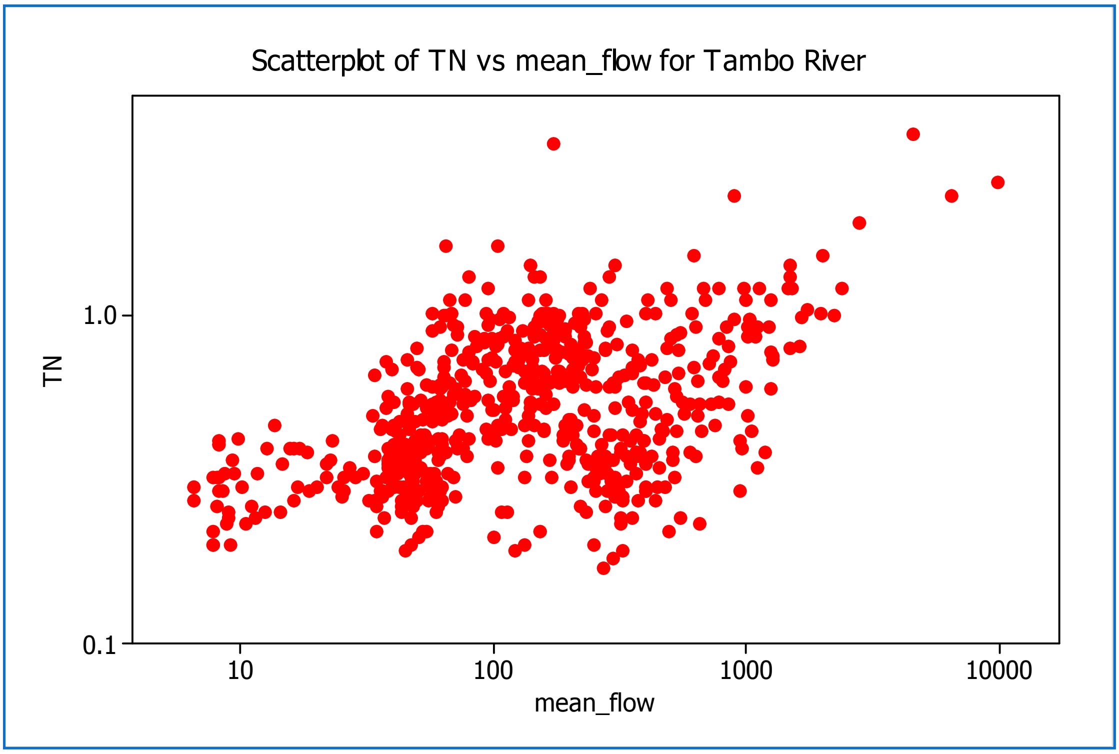

Figure 4. Scatterplot for daily log-transformed flow (ML) and log-transformed TN concentration (mg/L).

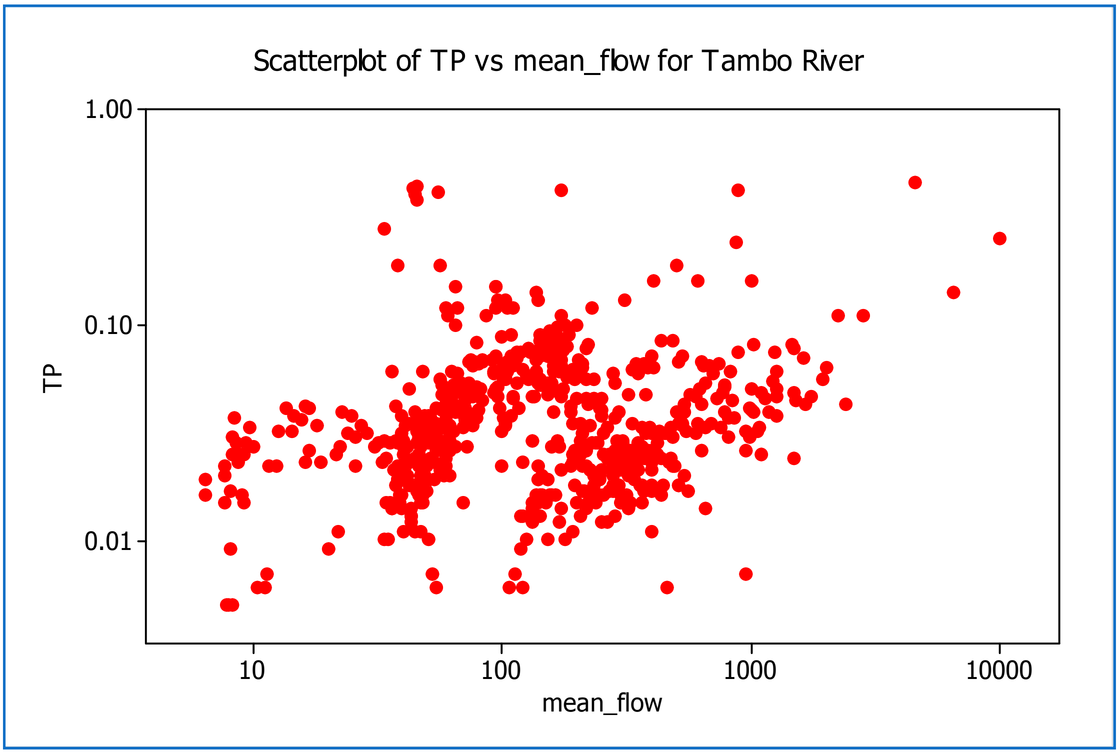

Figure 5. Scatterplot for daily log-transformed flow (ML) and log-transformed TP concentration (mg/L).

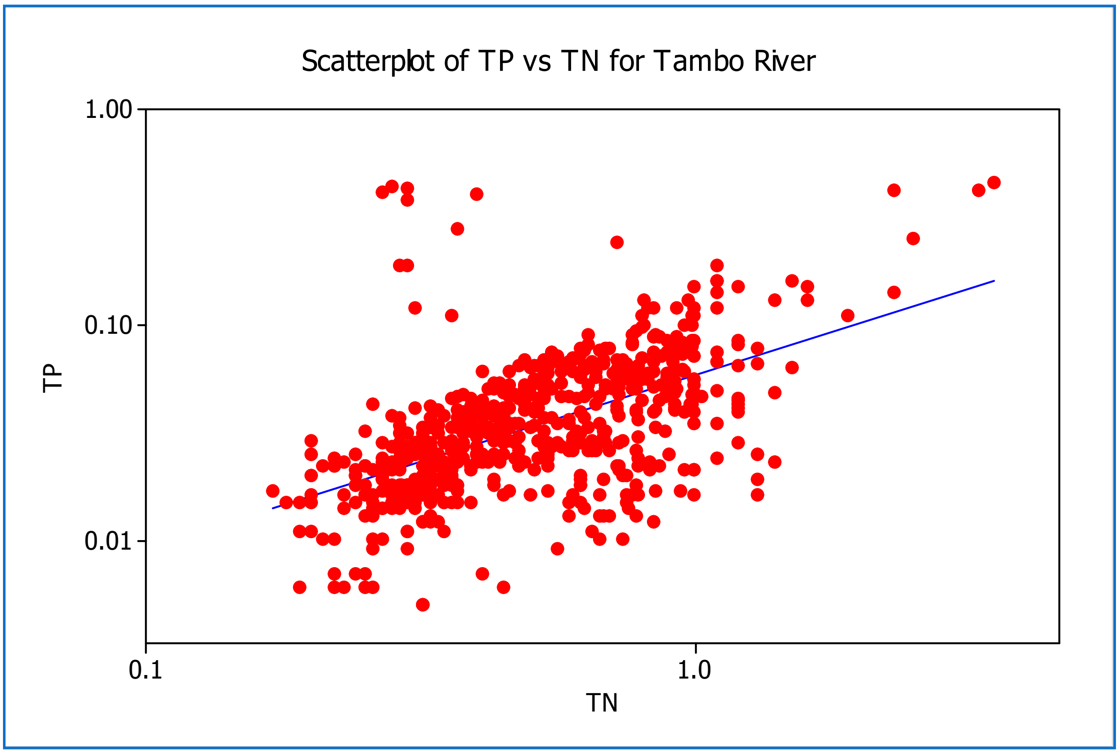

Figure 6. Scatterplot for daily log-transformed TP (mg/L) and log-transformed TN concentration (mg/L).

Table 4. Correlation coefficients between log-concentrations and log-flow.

	ln(Flow)	ln(TN)
ln(TN)	0.462	
ln(TP)	0.246	0.560

A time-series plot of the daily nitrogen and phosphorous loads is shown in Figure 7 and monthly breakdowns are provided in Tables 5 and 6.

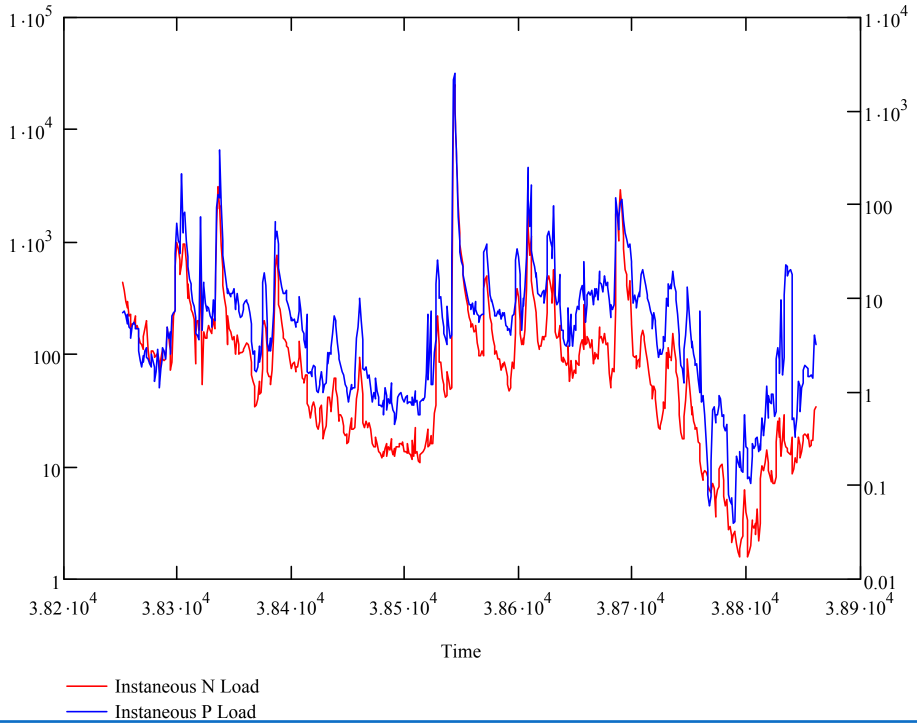

Figure 7. Daily TN and TP loads (kgs). Note: logarithmic scale used for load.

Table 5. Monthly total nitrogen loads (tonnes) for Tambo River

TN Load	Month												
Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
2004									2.25	3.92	12.10	14.18	32.45
2005	2.85	5.01	1.13	0.90	0.45	1.08	70.67	4.58	10.64	5.15	5.29	15.50	123.25
2006	1.70	0.50	0.12	0.35	0.39								3.06
Total	**4.55**	**5.51**	**1.25**	**1.25**	**0.84**	**1.08**	**70.67**	**4.58**	**12.88**	**9.07**	**17.39**	**29.69**	**158.76**

Table 6. Monthly total phosphorous loads (tonnes) for Tambo River

TP Load	Month												
Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
2004									0.046	0.085	0.894	1.108	2.133
2005	0.193	0.400	0.076	0.068	0.025	0.120	6.215	0.320	0.991	0.476	0.482	0.998	10.363
2006	0.202	0.057	0.008	0.104	0.086								0.457
Total	**0.395**	**0.456**	**0.084**	**0.172**	**0.111**	**0.120**	**6.215**	**0.320**	**1.037**	**0.561**	**1.376**	**2.106**	**12.953**

4.2 Transfer function modelling for phosphorus load estimation

We next illustrate the transfer function modelling approach using the phosphorus data as an example (similar results are obtained for the nitrogen analysis and hence are therefore not given here).

A critical assumption of the transfer function methodology (Fox 2007) is that (daily) nutrient concentration data follow a log-normal distribution. This assumption has been well-supported by empirical results from a number of other studies and the Tambo River data provides no evidence to refute this probability model. Histograms (Figure 8) and empirical *cdf* plots (Figure 9) demonstrate the applicability of the log-normal distribution for daily TN and TP concentration data.

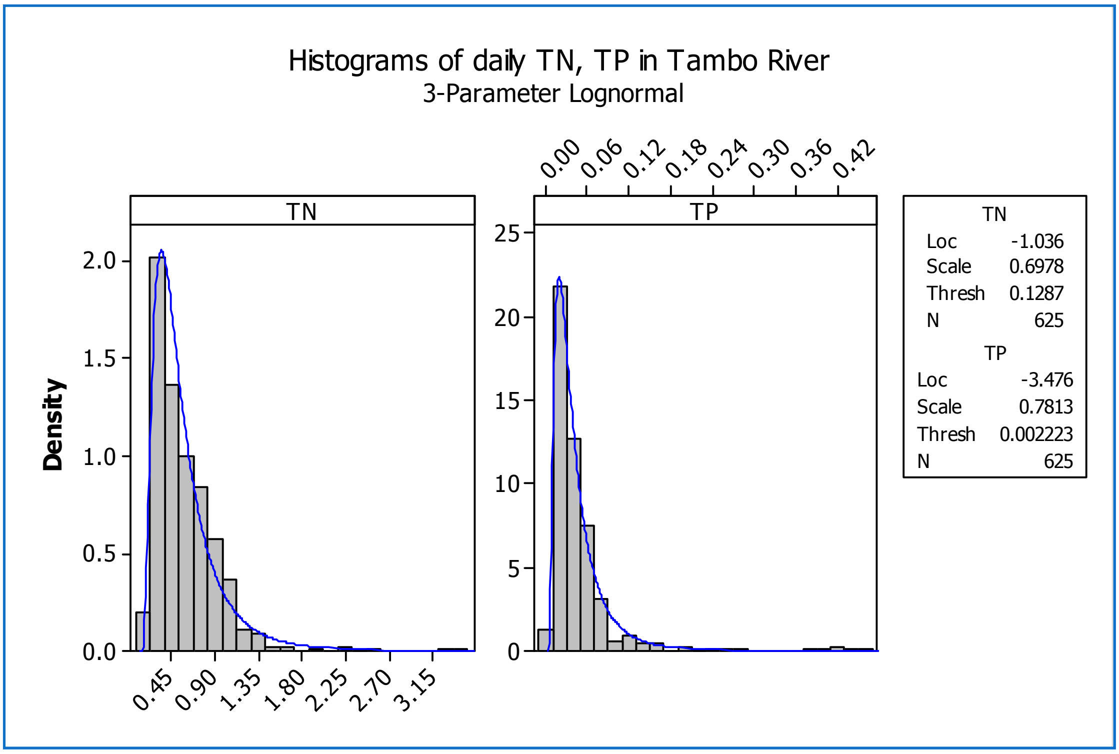

Figure 8. Histograms and theoretical log-normal probability distributions for daily TN and TP concentrations in the Tambo River.

The histogram of log-transformed daily flows (Figure 10) reveals a characteristic bi-modal distribution. Procedures for decomposing these flow distributions into mixtures of 2 or 3-component log-normal probability densities are described in Fox (2004). For the data in Figure 10, the parameters are given in table 7.

Table 7. Parameters of 2-component log-normal distributions for daily flow (lambda is mixing parameter).

μ_1	σ_1	μ_2	σ_2	λ
2.213	0.2998	4.888	1.153	0.0287

Percentiles for the daily flow distribution can be estimated using either the data in table 7 or a plot of the empirical *cdf* (Figure 11). From Figure 11 we see that the 90th., 95th., and 99th. flow percentiles are respectively 629 ML, 994 ML, and 2347 ML. We suggest that, as a starting point, the 95th. percentile (994 ML) be adopted as the threshold to differentiate 'peak' and 'non-peak' events.

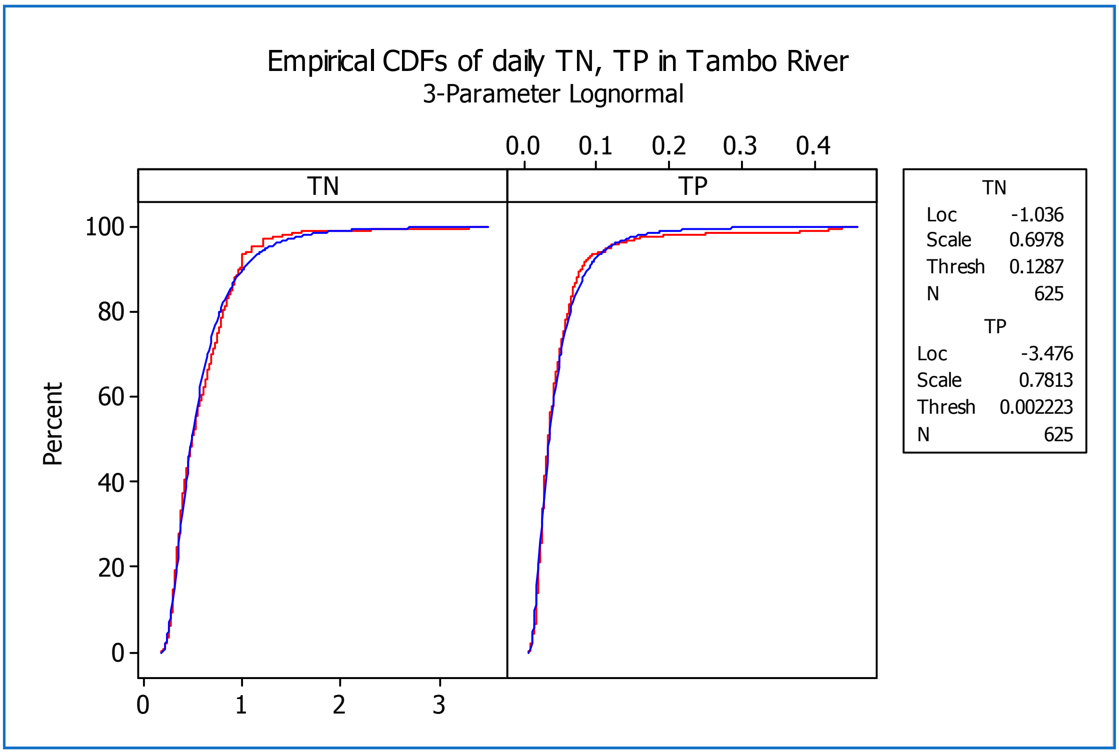

Figure 9. Emprical *cdf* (red lines) and theoretical lognormal *cdf* (blue lines) for daily TN and TP concentration data.

An examination of the daily TP flux on an untransformed scale (Figure 12) clearly shows a very large, but short-lived peak in July 2005. It is evident that a large proportion of the total load is delivered during this short time. This is more clearly illustrated by a plot of the cumulative load distribution versus time (Figure 13) which shows that 68.184 tonnes (43%) of the total TN load (158.758 tonnes) and 6.0685 tonnes (47%) of the total TP load (12.908 tonnes) was delivered between 10-Jul-2005 and 21-Jul-2005. Although the transfer function model has a flow-dependency it cannot model these short, transient peaks very well. An alternative approach is to separate out the peak and non-peak calculations. We use a transfer function modelling approach to estimate the non-peak load component and add to it the load from event-based sampling.

The composite sampling strategy and transfer function modelling approach described in Fox (2007) provides a single estimate of the *average* monthly nutrient concentration. Because the transfer model of equation 4 uses logarithmic flows and logarithmic concentrations[2] we will require

[2] Logarithmic scales are used since this provides for a better-fitting model.

estimates of the *average log*-concentration. Subtly, this is not the same as the logarithm of the average concentrations. A method for reconciling these two quantities is also given in Fox (2007).

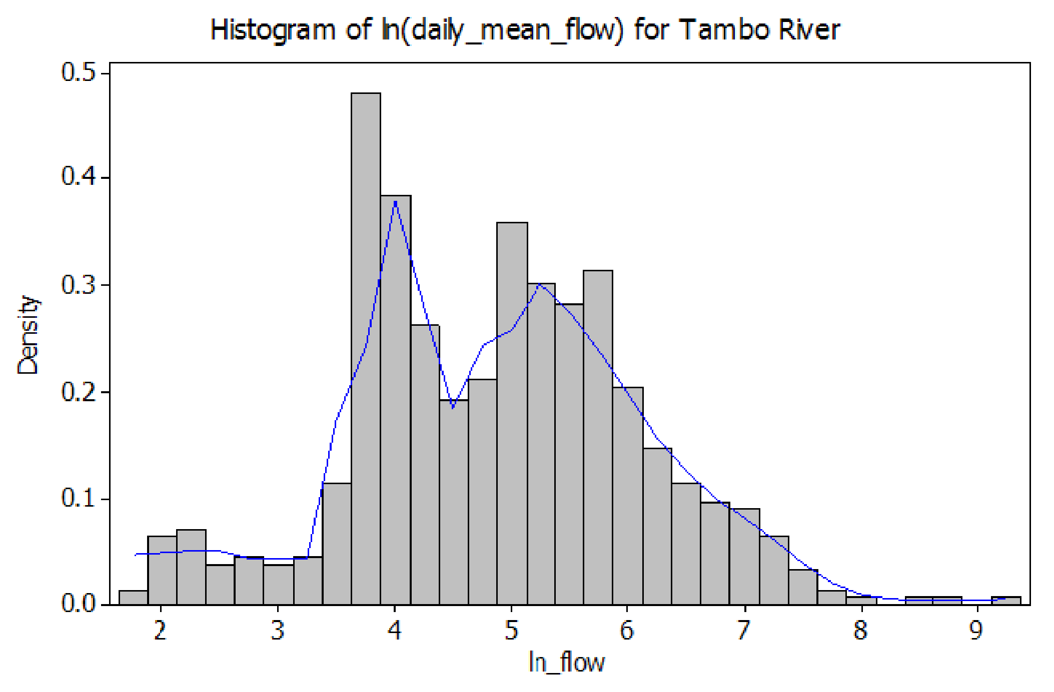

Figure 10. Histogram of log-transformed daily flows in the Tambo River with smoothed overlay.

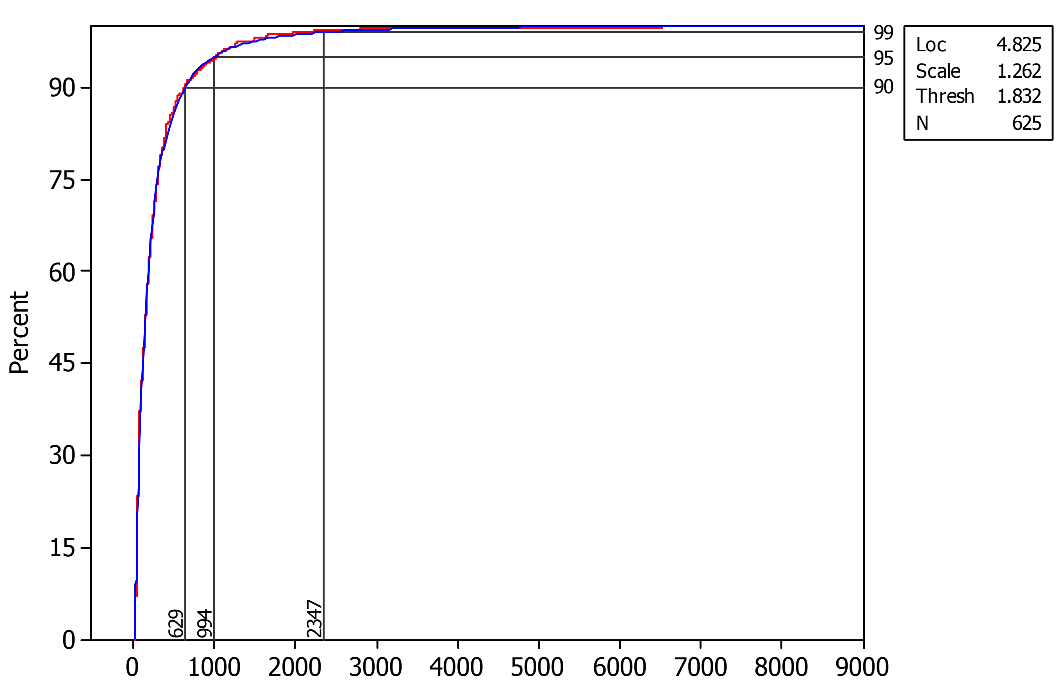

Figure 11. Emprical *cdf* (red line) and log-normal *cdf* (blue line) for Tambo River daily flow data.

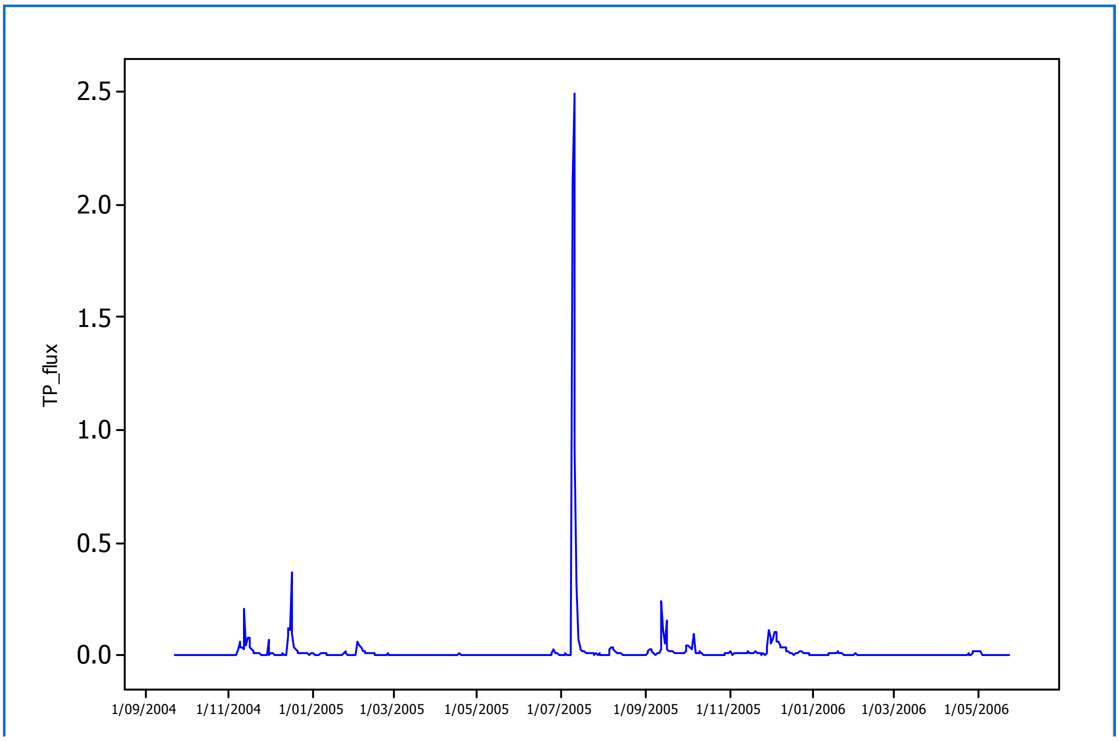

Figure 12. Daily TP flux (tonnes).

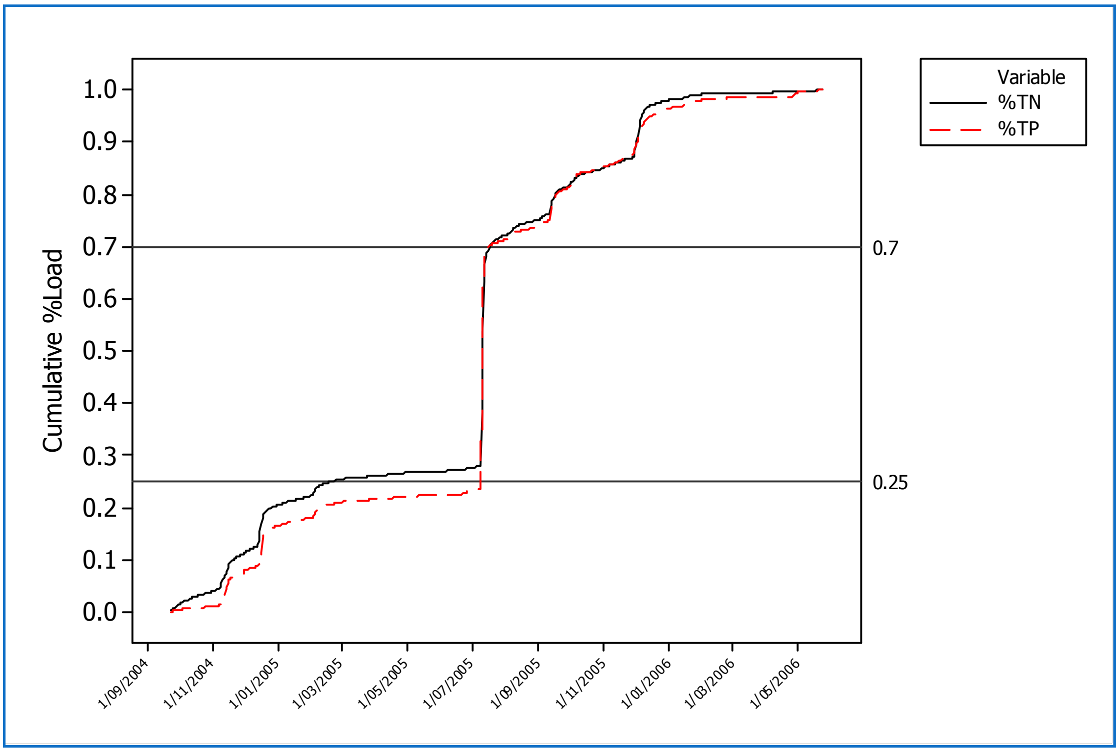

Figure 13. Cumulative proportion for TN and TP load as a function of time.

Figure 14 shows the *actual* monthly averages of the *log-transformed* daily TP concentration data, together with the individual daily log-TP series.

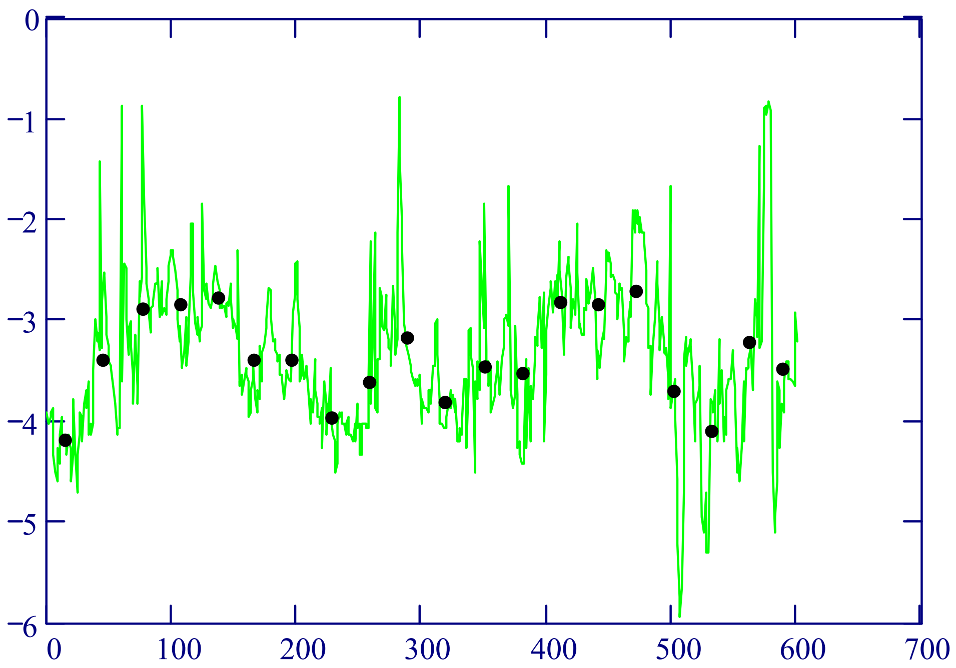

Figure 14. Time series of actual daily log-transformed TP values (green line) and the monthly averages (solid black dots).

In simple terms, it is the black dots in Figure 14 that are available to us from the composite sampling methodology and which are used to estimate the parameters of equation 4. Having estimated the parameters of equation 4 it can be used in conjunction with the *actual* daily flows to provide estimates of the actual *daily concentrations* (the green line of Figure 14). Figure 15 compares the performance of equation 4 using the *true* parameter values obtained from the daily data and using parameter values estimated from the monthly data[3].

The fitted model (together with an estimate of the error variance σ_ε^2 associated with equation 4, is used to randomly simulate realisations of the daily concentration time-series. In this case, we have simulated 500 such series (Figure 16) from which 500 total load estimates are produced.

[3] Note, in practice this comparison cannot be made since we will not have *daily* concentration data. The purpose for doing so here is to illustrate the efficacy of the estimation procedure when data obtained from *monthly* composite sampling is used.

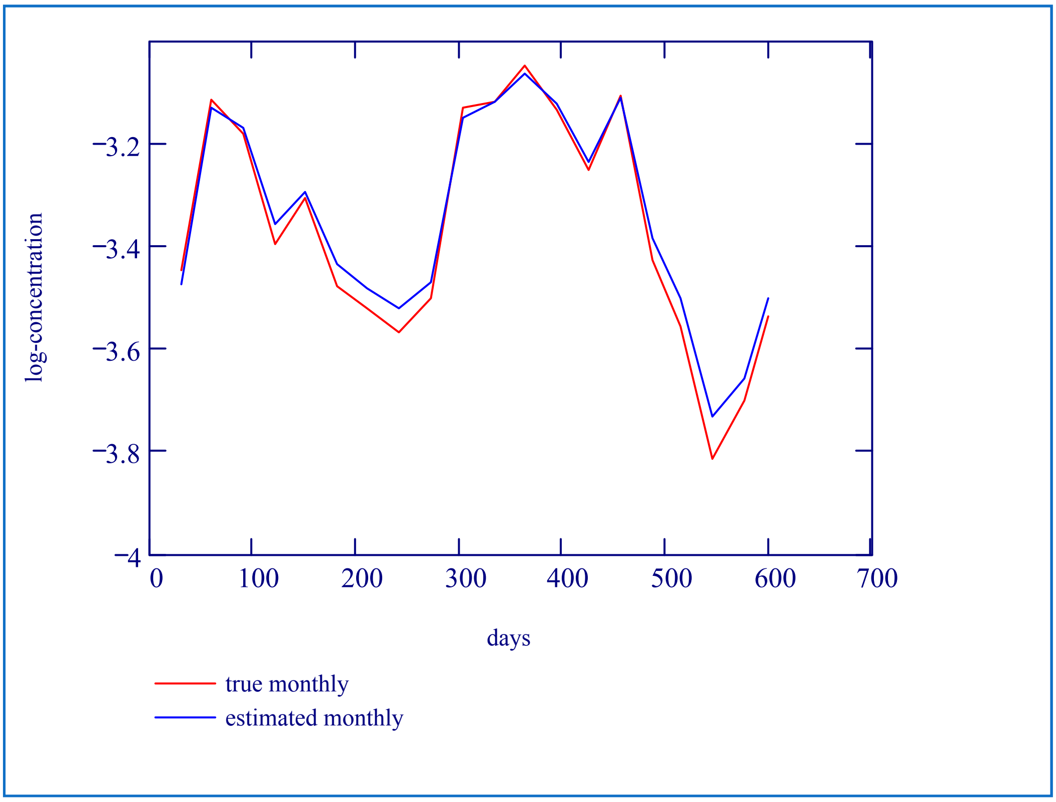

Figure 15. Modelled average monthly TP concentrations using true parameter estimates (red line) and parameters estimated from monthly data (blue line).

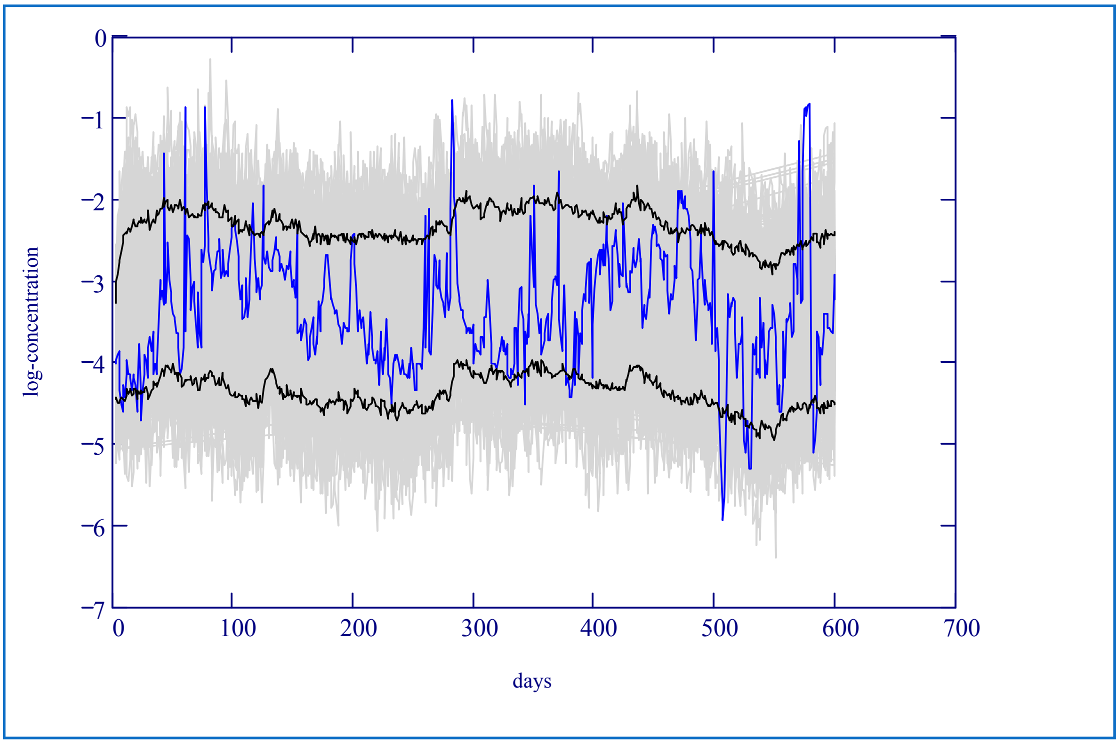

Figure 16. Comparison of simulated (grey line) and actual TP daily (blue line) concentrations. Black lines define an approximate 95% content interval.

From these 500 estimates, a mean 'non-peak' TP load of 6.673 tonnes is obtained (ie. *exclusive* of the load delivered between 10-Jul-2005 and 21-Jul-2005). The standard error is 0.0435 tonnes. Adding the measured peak load of 6.0685 tonnes gives a total load of 12.74 tonnes TP which is in close agreement with the actual 12.908 (an error of 1.3%).

5. Conclusions

In this report we have summarised the outcomes of a number of separate, but related research activities associated with the efficient sampling and estimation of nutrient loads in rivers and streams in the Gippsland catchments. This work was initially motivated by a requirement to identify appropriate sampling frequencies for load estimation in the MID drains. The techniques developed for that application have been shown to have far broader applicability. The availability of daily nutrient data for the Tambo River during an approximate 18 month period has enabled us to evaluate the performance of the composite sampling and transfer function method developed by Fox (2007). Owing to the more dynamic nature of flows in rivers and streams we suggest that total nutrient loads be separated into 'peak' and 'non-peak' components and each estimated separately. It is suggested that the peak load component be estimated using from *daily* concentration samples acquired during the peak flow event. While there is opportunity to develop thresholds for triggering this event-based sampling, one method is to use a suitably chosen percentile (eg. 95^{th}.) of the flow distribution.

We have demonstrated that the 'non-peak' load component can be reliably estimated using *monthly composite sampling* together with a transfer function modelling approach as outlined in Fox (2007). Using this method the total phosphorous load in the Tambo River between 23/09/2004 and 24/05/2006 was estimated with less than 1.5% error.

6. References

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