Analysis of Flow and Preliminary Estimates of Phosphorus Loads in the Namoi Basin, NSW, Australia

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The Namoi Basin in north eastern New South Wales, Australia is a major contributor of flow and associated phosphorus to the Barwon-Darling River. Phosphorus (P) is a limiting nutrient in the production of toxic blue-green algae, and P loads are of concern to local stakeholders. In this preliminary analysis, we show the potential importance of flow variability in the historical record at various stations in the Namoi Basin stream network. Analysis of monthly flows indicates that extremes over a period of two or three decades could transport a significant portion of the load. Furthermore, we demonstrate how existing data yield very different load estimates, depending on whether we assume that (a) the data are representative of relatively constant concentrations, or (b) concentration is linearly related to daily flow. In either case, loads from tributaries that traverse the Liverpool Plains agricultural region occur during the extreme flow months. At the downstream end, Pian Creek diverts up to 1/3 of the monthly flow from the Namoi River and exports a significant portion of the load to the Barwon-Darling only during high-flow events.

INTRODUCTION

Blooms of blue-green algae (cyanobacteria) in the Darling River have motivated studies of nutrient transport in the Namoi Basin. Other factors, such as low flow, reducing conditions, and high temperature, are commonly associated with algal blooms. Stakeholders and agencies are interested in improving land management to reduce the supply of P to streams, and hence, reduce the potential incidence and severity of blooms.

To assess management options, it is necessary to understand how P moves from the land and to the streams. This includes understanding spatial patterns of P movement. Donnelly (1995) and Short (1995) presented the following understanding of the sources of P and transport mechanisms:

- Most of the P exported from the land in the Murray-Darling Basin originates from native soil, rather than fertiliser.
- Most of this soil comes from banks of gullies and streams, rather than the general land surface, except in sloping upland sub-basins.
- Over much of the stream network, there are substantial in-stream stores of sediment/P, and there is considerable interaction between suspended and stored sediment. This, combined with sediment trapping in reservoirs and deposition of much upland-sourced sediment onto the flood plains, suggests that sediment delivered to streams may have long average residence times before reaching the basin outlet. The residence times are not known, but tracer data suggest that surface soils delivered to streams in the uplands of the Namoi Basin take much more than 30 years to reach the outlet at Walgett (Olley, personal communication).

Adequate data on flow and sediment/P loads constitute one requirement for resolving an appropriate view of P movement. Daly (1994) pointed out that existing data do not permit us to compute accurate P loads at the several points studied on the Namoi River due to infrequent sampling. Based on high-frequency sampling of two events, major storm events make major contributions to annual P loads. These two provisos were given for the estimates of annual loads made by applying a statistical technique of Preston *et al.* (1989).

Magnitudes and spatial patterns of P load estimated from infrequent P-sampling may be subject to large errors, unless we understand how P moves through the stream network. We demonstrate how existing data yield very different load estimates in the Namoi Basin stream network, depending on whether we assume that (a) the data are representative of relatively constant concentrations, or (b) concentration is perfectly correlated with flow. Preston *et al.* (1989) compared these methods with "true" loads and found that neither approach was consistently better than the other. The two approaches provide preliminary estimates of the possible range of loads delivered by historic flows. The significance of flow variability is emphasised, both in upland catchments and near the confluence with the Barwon-Darling River.

RELATIONSHIPS BETWEEN FLOW AND PHOSPHORUS CONCENTRATIONS

Simple relationships have been assumed between sediment or phosphorus (P) concentration and flow to compute loads at various time scales (Preston, et al., 1989). However, statistical correlations without mechanistic transport often show a great deal of scatter, and flow fails to explain most of the variance in sediment/P concentrations. This would be true even if a known relationship existed for concentration and flow. Although such a relationship has not been derived, Figure 1 illustrates the possibility of more information in the data than regression yields. In Figure 1, flow recession is rapid after events, even at this downstream station in the Namoi Basin (see Figure 2). The apparent recession time for total phosphorus (TP) concentration is much longer, and concentrations tend to remain relatively high for days to weeks after a large flow event. Complex processes of resuspension of particle-bound P during high flows and release of soluble P during low flows cannot be characterised here, and we note the uncertainty due to the low temporal resolution in the sampling. However, the data here appear to relate more to P released at low flows, presumably from bottom sediments, than to particle-bound P transported at high flows (and thus, high loads). Future modelling may resolve this issue.

The data in Figure 1 suggest that flow varies more than TP concentration at this site, and an assumption of constant concentration in the range of 0.1 to 0.2 mg/L may yield reasonable estimates of load as a first cut. Although concentrations remain high after flow has reduced, TP samples during events indicate a positive relationship between concentration and flow. We intend to show the significance of such positive correlation here, without attempting detailed quantification. Furthermore, estimates based on constant concentration should tend to underestimate the loads carried by storm events. Here, the importance of flow variability is demonstrated by assuming either constant concentration or positive correlation.

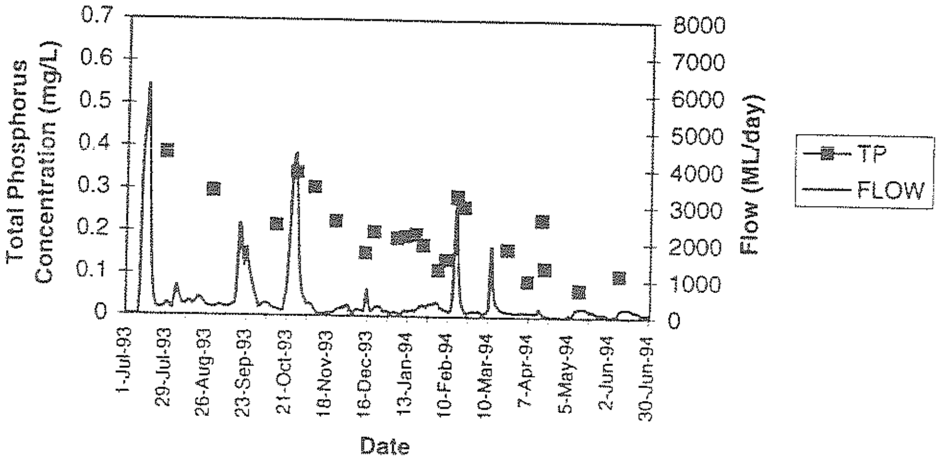

Figure 1. Time series of total phosphorus concentrations and flow in the Namoi River at Bugilbone (419021). Taken from Daly (1994, p. 24) with permission.

ANALYSIS OF MONTHLY FLOWS

Harris (1994) identified nutrient (especially phosphorus) reduction and flow control as the primary ways to control algal growth. He also notes that nutrient loadings are dominated by storm events in Australia. This suggests that much of the load entering the Barwon-Darling River from the Namoi over the last two decades could be carried during a few high-flow months in the historical record. Preliminary estimates of load based on flow records are presented below.

Water balances between stations are generally not closed. However, differences between stations along the Namoi river and upstream tributaries indicate which reaches are gaining or losing water in terms of mean flows. Figure 2 is a schematic diagram of the gauged stream network analysed for the Namoi. All reaches have other minor tributaries and/or diversions. Thus, we do not expect perfect mass balance, but gross differences can be seen.

Table 1 includes a column of monthly mean flows beginning with upstream stations. At the upstream end, differences in mean flows are <5% between Gunnedah (01) and Mollee (39), when gauged tributaries are included. Flow entering the Barwon near Walgett is approximated by the sum of flows at Goangra (26) and Pian Creek at Waminda (49). By this measure, the Namoi River loses an average of 17% of its flow (13,000 ML/mo) downstream of Mollee. More work is required to partition these losses between irrigation withdrawals, groundwater seepage, evapotranspiration, and over-bank flow. Removal of associated suspended sediment depends upon the types and proportions of losses.

Monthly flows vary seasonally and interannually. Examples of the distributions of monthly flow volumes are shown for the Namoi River at Goangra (Figure 3) and for the Mooki River at Breeza (Figure 4). At the bottom of each figure, the bar plot shows values of monthly minima, 25%, 50%, (i.e., median), and 75% quantiles that are not legible in the box plots above. Box plots emphasise high-flow months (extreme values, not "outliers") shown by horizontal lines.

Seasonality associated with median flows is dominated by winter rainfall (June-Sept.). However, interannual variability is greatest during the summer months of January and February. This contrast is most marked in upstream reaches and tributaries, such as the Mooki River, where high-flow months carry significant fractions of the flow to the Namoi, despite relatively minor contributions at median flows (see Figure 4).

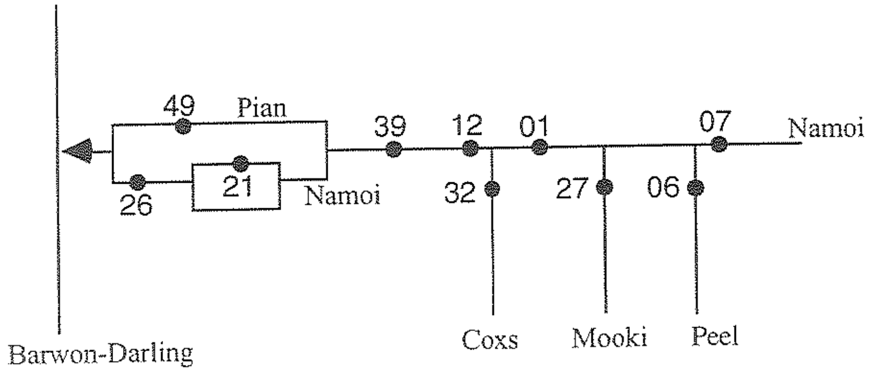

Figure 2. Schematic Diagram of the Namoi River Network and its tributaries. Numbers (XX) are the last two digits of the station numbers (4190XX).

Station	No.	Mean	50%	75%	90%	95%	100%	Max/Med
Namoi@Keepit	07	26839	12756	34701	66491	107384	213099	17.
Peel@CarrolGap	06	24211	8377	21574	66638	108795	376225	45.
Mooki@Breeza	27	10232	668	3876	22843	50439	299480	448.
Namoi@Gunnedah	01	63405	30354	52476	113316	253078	903136	30.
Coxs@Boggabri	32	7930	107	2341	20279	53956	227319	2114.
Namoi@Boggabri	12	70241	31421	58805	156137	302392	967496	31.
Namoi@Mollee	39	74491	34814	58813	164182	269630	1257792	36.
Namoi@Bugilbone	21	44003	12050	38459	129283	187002	444381	36.
Namoi@Goangra	26	53989	9903	41719	130549	243976	950559	96.
Pian@Waminda	49	7499	612	2879	9541	19623	421018	688.

Table 1. Monthly Flow Statistics (ML) for each Station (Full Number is 4190xx)

Station	No.	Mean	50%	75%	90%	95%	Max
Namoi@Keepit	07	0.448	0.845	0.517	0.510	0.445	0.395
Peel@CarrolGap	06	0.497	1.288	0.831	0.509	0.440	0.224
Mooki@Breeza	27	0.189	0.067	0.092	0.174	0.206	0.315
Namoi@Gunnedah	01	1.174	3.065	1.257	0.868	1.037	0.950
Coxs@Boggabri	32	0.146	0.010	0.056	0.155	0.221	0.239
Namoi@Boggabri	12	1.301	3.172	1.409	1.196	1.239	1.017
Namoi@Mollee	39	1.379	3.515	1.409	1.257	1.105	1.323
Pian@Waminda	49	0.138	0.061	0.069	0.073	0.080	0.442

Table 2. Ratios of Monthly Flow Statistics for each Station Relative to Goangra (26).

LOADS ASSUMING CONSTANT CONCENTRATION

Next, we explore the potential contributions of extreme flow months to the sediment and phosphorous loads. Without detailed (high temporal resolution) sediment and nutrient measurements, preliminary load estimates are based on the assumption of constant concentration. If concentration increases with flow (as illustrated in the next section), the constant concentration assumption should yield conservative estimates of the relative impact of high-flow months. The computed P loads are proportional to loads of water.

In addition to mean values, Table 1 shows flow quantiles (50, 75, 90, 95, 100%) for all months in the calendar years 1973-93. Skewness in the distributions of monthly flows leads to median values that are generally much lower than arithmetic mean values. Ratios of maxima to median values for each station are in the right-hand column. These ratios point to interannual variability and the significance of extreme events to the load. Over the period of the record analysed (21 years), ratios greater than 252 indicate stations where the load in one high-flow month exceeded the load that would be carried by the median flow over the entire 21-year period. The notable stations are Cox's Creek at Boggabri (32), Pian Creek at Waminda (49) and Mooki River at Breeza (27). Cox's and Mooki are important because they traverse the agricultural (and thus politically sensitive) Liverpool Plains. Pian Creek is significant because it is near the outlet of the Namoi Basin and diverts a significant portion of flow from the Namoi River during high flows.

In addition to the relative contributions of extremes at each site, we also explore the contributions of each station relative to the Namoi River at Goangra (26). Table 2 contains those ratios at mean values and various quantiles. For each station, the largest value indicates which statistic is most significant relative to that same statistic at Goangra. Median flows are most significant for the Peel River, and the Namoi River at Keepit (07), Gunnedah (01), Boggabri (12), and Mollee (39). As expected, median flows at Goangra are determined by median flows upstream in the Namoi. Mean values and quantiles exceeding 90% are most significant for Cox's Creek and Mooki River. Relatively high ratios of the means (0.15 for Cox and 0.19 for Mooki) are caused by the high flows with maximum values of 0.24 for Cox's Creek and 0.32 for the Mooki River. Thus, loads exiting the Liverpool Plains during high-flow months constitute a large portion of the loads in the Namoi at Goangra.

Pian Creek, in turn, diverts almost a third of the flow from the Namoi River that might otherwise flow past Goangra during the highest flow month. That is, Pian Creek transports almost half the load of that in the Namoi River at Goangra at its maximum, if we assume equal concentrations at both stations. Ephemeral flows in Pian Creek may cause higher concentrations of sediment to be transported during events than at Goangra. Although the statistics for Pian Creek are particularly skewed by one high-flow month in 1974, even higher flows would have been observed in 1971.

We estimate total phosphorus (TP) loads from approximate values of median concentrations reported in Daly (1994). Although concentrations vary in both space and time, a constant value of 0.1 mg/L is used. Mean annual loads are computed from mean monthly values of flow in Table 1:

$$\text{Load [kg/yr]} = \text{Conc [mg/L]} \cdot \text{Flow [ML/mo]} \cdot 12 \text{ [mo/yr]}$$

Thus, mean annual TP loads are computed to be 9000 kg/yr through Pian Creek at Waminda and 65,000 kg/yr through the Namoi at Goangra. Similarly, peak monthly loads would have been 42,000 kg at Waminda and 93,000 kg at Goangra in January 1974 alone.

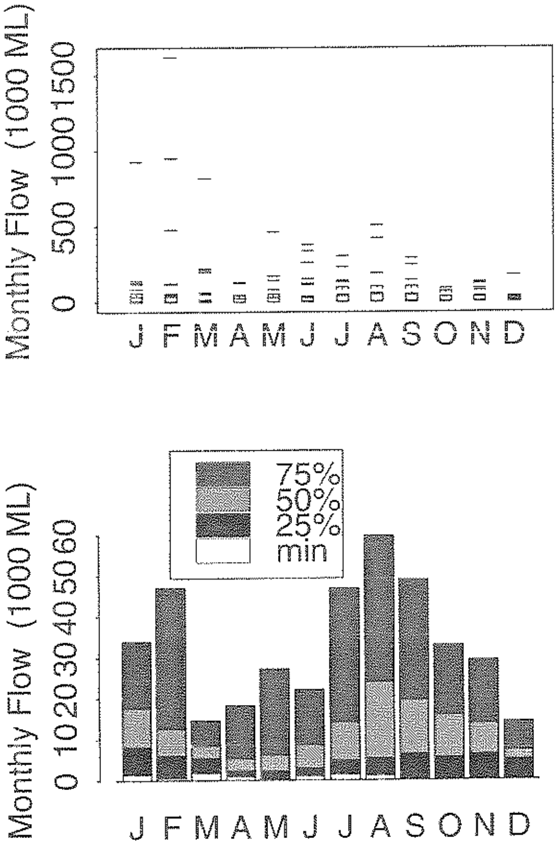

Figure 3. Box plots of monthly flows (1965-93) on the Namoi River at Goangra (26).

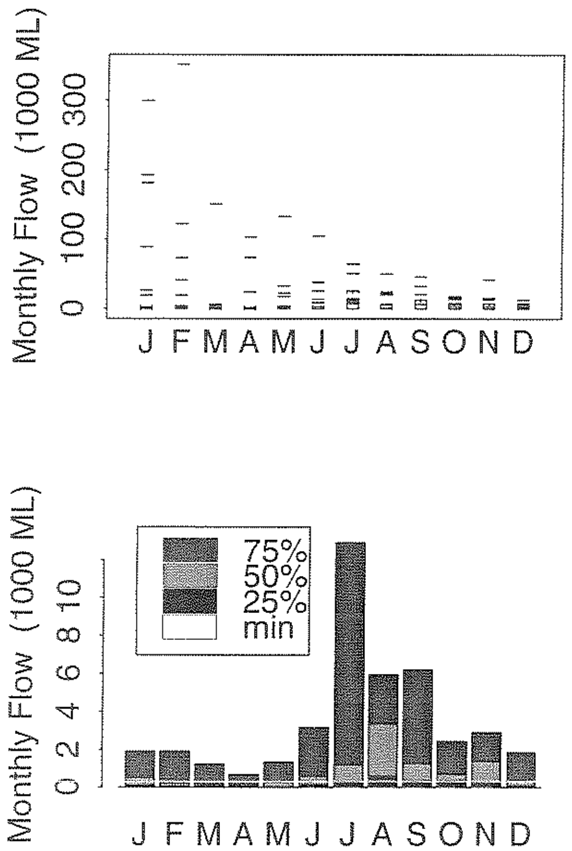

Figure 4. Box plots of monthly flows (1965-93) on the Mooki River at Breeza (27).

LOADS FROM LINEAR CONCENTRATION VERSUS FLOW RELATIONSHIP

During high flows, suspended sediment concentrations can increase due to re-suspension of bed material, stream bank collapse, and sheet and rill erosion. Particle-bound P show corresponding concentration increases. Linear relationships between P concentration and flow are used in the following estimates of loads at Goangra (26). These load numbers are computed using daily flows for comparison with loads estimated assuming constant concentration (or zero correlation between concentration and flow).

Two linear relationships are used based on peak and mean or median concentrations from Daly (1994). In the first case,

$$c\ [\text{mg/L}] = 0.0819 + 1.07 \times 10^{-5} \cdot q\ [\text{ML/day}]$$

which is a straight line with c = 0.1 mg/L (kg/ML) at the mean flow of q = 1694 ML/day, and c = 1.0 mg/L at the maximum flow of q = 86 097 ML/day. For the period 1973-1993, the average annual load is approximately 161 000 kg/yr, which is 2.5 times greater than the load computed at constant concentration of 0.1 mg/L. Using the same linear relationship, the load for January 1974 is 634 000 kg, which is 6.8 times the peak monthly load at constant c. By this linear method, the peak monthly load is 3.9 times the annual average load computed by the same method.

In the second case, a similar linear relation passes through c = 0.1 mg/L at the median flow of 242 ML/day, yielding a slope of 1.05×10^{-5} and offset of 0.0975 mg/L. The computed loads are very similar to the first case, in spite of the mean flow being several times the median flow value. Here, the average annual load is 169 000 kg/yr, and the load for January 1974 is 639 000 kg, which is 3.8 times the average annual load. Using a constant concentration of 0.1 mg/L, the January 1974 load was only 1.5 times the average annual load.

The two cases of linear relationships yield similar loads because the maximum concentration is the same for both cases. Similar loads are a result of most of the load being carried by extreme events in the record. This is true over periods of decades or one month using the linear relationship.

These example calculations show the extent to which concentration variation may affect loads. Perfect correlation between concentration and flow, compared with no correlation, more than doubles the estimate of annual average load and increases the peak monthly load by a factor of 7. These ratios are sensitive to the maximum concentration estimate and the maximum daily flow encountered.

DISCUSSION

In this preliminary analysis, we have shown the potential importance of flow variability in the historical record at various stations in the Namoi Basin stream network. Analysis of monthly flows indicates that extremes over a period of two or three decades could transport a significant portion of the load. These events generally occur during summer months (Jan, Feb), suggesting monsoonal influence, rather than coinciding with the winter months of high median flows. These extremes show large interannual variability, and any load estimates should span at least one decade. The time scale of decades is also consistent with estimates of mean particle transport times from upland areas to the confluence with the Barwon River (Olley, personal communication).

Our load estimates provide a range of potential loads during high flow months. For lack of high-temporal-resolution concentration data at this time, the simplifying assumptions were (a) constant concentration at approximately the median value (although loads can be easily re-scaled) and (b) a linear increase in concentration with flow. The latter is presumably an upper bound for P loads, because flow and concentration peaks are not necessarily synchronous, and because dilution of the soluble P fraction is likely during high flows. Furthermore, based on flow and concentration measurements like those shown in Figure 1, we expect changes in flow and concentration to occur at different time scales, such that simple correlation fails to explain much of the variability. Improved understanding and quantification of the transport mechanisms are needed.

Comparisons of loads at Goangra using a constant concentration of 0.1 mg/L with the linear relationship method showed the importance of concentration increases coinciding with high-flow events. Perfect correlation using feasible concentration increases with flow could more than double the average annual load. In either case, much of the load is expected to be carried during high-flow events.

Sufficient flow records exist to make estimates of historical loads, despite the lack of data and transport modelling. Even without an increase in concentration with flow, high-flow months would carry much of the load over a period of several years. Ephemeral creeks and streams, in particular, carry much of their load during a few high-flow months associated with summer storms. This is true both in upland catchments of the Liverpool Plains and in the downstream flat areas containing bifurcating channels. Pian Creek carries about 1/3 of the flow exiting the Namoi Basin during peak months, even though it carries little (6%) of the monthly median flow. The relative importance of Pian Creek in terms of P load requires further study, as concentrations of resuspended sediment (and associated particle-bound P) are expected to differ between the main channel of the Namoi River and Pian Creek. Future analyses will include high-resolution turbidity sampling in the lower Namoi, as well as the Liverpool Plains region. Estimates of particle-bound P deposited downstream of Mollee during various flow regimes are also required.

Future work will aim to verify whether P loads can be explained largely by flow at the monthly time step. If so, historical records of flow provide valuable information about the export of P and sediment from the Namoi Basin over several decades. Management implications include flow control, or at least characterisation, over many years where climatic variability becomes especially important. Future analyses of loads in conjunction with tracer studies will help clarify the timing and locations of sediment/P sources and sinks in the Namoi Basin.

REFERENCES

Daly, H., Central and North Western Regions Water Quality Program: 1993/94 Report on Nutrient and General Water Quality Monitoring, Department of Water Resources TS94.088, 1994.

Donnelly, T.H. (ed), Review and scoping study of catchment phosphorus sources, CSIRO Division of Water Resources, Consultancy Report 94/26, 1995.

Harris, G.P., Nutrient loadings and algal blooms in Australian waters - a discussion paper, LWRRDC Occasional Paper No. 12/94, 99 pp., August 1994.

Preston, S.D., V.J. Bierman, and S.E. Silliman, An evaluation of methods for the estimation of tributary mass loads, *Water Resources Research*, 25(6), 1379-89, 1989.

Short, D.L., Implications for improving catchment modelling, in J. Olley (ed), Sources of phosphate and its temporal variation in the Murrumbidgee Catchment, CSIRO Division of Water Resources, Consultancy Report 95/32, 1995.