Long-term Modelling of Water Quality Variables in the Yarra River

S. Sokolov

Division of Marine Research , CSIRO, GPO Box 1538, Hobart, Tas 7001, Australia

Abstract The Yarra River has been identified as one of the major sources of nutrients and toxicants in Port Phillip Bay, Australia. The historical water-quality measurements for the Yarra catchment collected during last 15 years have been analysed and assimilated to estimate daily loads. A simple dynamic model relating the temporal change of the total mass of chemicals in a catchment to the chemical loading in the river provides high accuracy predictions of absolute and time-integrated chemical loads. Three types of catchment have been examined for long-term modeling: a local urban streamwater catchment, a transition urban-agricultural catchment and a large catchment with varied land use (urban, agricultural and protected forested areas). While the catchment size, land use and background concentrations of chemicals spanned a wide range, the predictive model was found to be satisfactory after optimisation of the model parameters for each catchment. The developed model is able to effectively reproduce observed hysteresis in the relationship between chemical concentration in stream water and river discharge for all considered time scales: from inter-annual to synoptic variations. The lowest temporal scale resolved by the model is limited to a single hydrological event. The main limitations in application of the model relate to the adequacy of the sampling program which measures river discharge and water-quality variables.

1. INTRODUCTION

The Yarra River has been identified as one of the major sources of nutrients and toxicants in Port Phillip Bay, Australia. The essential task of this study was the estimation of nutrients and toxicants loads in the Yarra River on the daily basis, providing boundary conditions for ecological modelling of Port Phillip Bay.

The historical water-quality measurements for the Yarra catchment collected during the last 15 years by the Melbourne Water Corporation (MWC) and Environment Protection Authority (EPA), have been analysed and assimilated to produce estimates of daily loads. The data were collected from upstream stations and comprised more than 1000 water samples for nutrients and about 700 samples for toxicants for the station at Chandler Hwy. However, even for the most detailed data set there were few measurements during the years 1982-83 and 1987-1989. A developed dynamic model has been applied to estimate daily loads using historical data (Sokolov & Black 1996, Sokolov 1996).

2. ESTIMATION OF WATER QUALITY VARIABLES

In general, the time evolution of water-quality variables in stream water can be represented as a composition of two processes: (i) input of chemicals washed from the catchment during storms, and (ii) dilution by stream water of chemical loads coming from sources such as groundwater and/or point-source anthropogenic local emissions of wastes. The storm wash-off rate depends on the intensity of the surface runoff and on the mass of transportable chemical available within the catchment. Thus, the concentrations over a sequence of several hydrological events can often be described in terms of the "first flush", where maximum concentrations occur early in the first storm after prolonged periods without precipitation when available mass in the catchment is highest.

Field measurements obtained for the Yarra River catchment suggest that, after long periods under low river discharge conditions, any moderate storm event resulting in minor increase in the river discharge can provide a substantial peak in concentration. The subsequent storm events, even those which exceed the first event, produce a sequence of peaks in concentration which damp out with time. The amplitudes of the following peaks in concentration are determined by the duration of storm events, time separation between events and total amount of available chemical remaining in the catchment area (Sokolov and Black, 1996). Some water-quality variables, such as arsenic and total phosphorus, were found to exhibit a negative correlation with river discharge. In these cases, dilution of the chemical load by the river discharge was dominant. Ultimately, concentrations and loads depend on the relative importance of the wash-off and dilution.

2.1 Model equation

The time evolution of the total mass $M(t)$ of a chemical element in a catchment is defined by the first-order differential equation (Sokolov and Black, 1996):

$$\frac{dM}{dt} + \tilde{\beta}M = Aw; \qquad (1)$$

where $Aw = Q^{+}$ is the chemical input (natural and/or anthropogenic) into the catchment; A is the area of the catchment; w is the chemical flux per unit area entering the catchment; $\tilde{\beta}M = Q^{-}$ is the chemical input into the river system; and t is time.

The $\tilde{\beta}$ -function can be expressed in the following form

$$\tilde{\beta} = \alpha\left[\frac{F(t)-F_{*}}{F_{max}-F_{*}}\right]^{\gamma}; \quad \text{for} \quad F(t) > F_{*};$$

$$(2)$$

$$\tilde{\beta} = 0; \qquad \text{for} \quad F(t) \leq F_{*};$$

where $F(t)$ is a river discharge; F_{*} is a transitional flow; $[F(t)-F_{*}]/[F_{max}-F_{*}]$ is a normalised effective surface runoff; γ is a measure of non-linearity between chemical loading into the river system and intensity of the surface runoff; and α is a parameter.

The time evolution of chemical concentration $C(t)$ in the river is defined by

$$C = \left[\tilde{\beta}M + \upsilon\right]/F; \qquad (3)$$

where υ is the flux from constant sources, directly entering the river system (natural and/or anthropogenic).

2.2 Numerical solution

The initial value problem (1)-(3) was solved numerically using the Euler method with a variable time step to treat the irregular intervals in the measured flow data. The unknown model parameters

$$\tilde{\beta}, w, \upsilon, M(t=0)$$

were obtained using an optimisation technique which leads to a minimisation problem for the functional $\Re$ defined as

$$\Re\left[\tilde{\beta}, w, \upsilon, M(0)\right] = \left\{Q^{-} - \hat{Q}^{-}\right\}^{2} \qquad (4)$$

where $\hat{Q}^{-}(t)$ are measured chemical loads in the river basin

$$\hat{Q}^{-}(t) = \hat{F}(t)\hat{C}(t). \qquad (5)$$

The iterative process was limited by an accuracy $\varepsilon < 1\%$ for each parameter $\tilde{\beta}, w, \upsilon$ and $M(0)$.

2.3 Error estimates

Error estimations for the comparisons of model predictions and measurements were represented by a normalised error R

$$R = \frac{\langle Er \rangle}{\sigma_{\hat{Q}^{-}}};$$

where $\langle Er \rangle$ is a time-averaged absolute error

$$\langle Er \rangle = \frac{1}{\tau}\int\left|Q^{-} - \hat{Q}^{-}\right|dt;$$

$\sigma_{\hat{Q}^{-}}$ is a standard deviation of the measured loads, and τ is the duration of the analysed period; and a normalised error of the integrated load $\sum Er$ was defined as

$$\sum Er = \frac{\left|\int Q^{-}dt - \int \hat{Q}^{-}dt\right|}{\int \hat{Q}^{-}dt}.$$

3. INPUTS TO PORT PHILLIP BAY FROM THE YARRA RIVER

Three types of catchment within the Yarra River watershed have been examined for long-period modelling of water quality parameters. These are the large Yarra River catchment composed of urban, agricultural and protected forested areas, the agricultural upper Maribyrnong River and Merri Creek catchments and the totally urban catchments of Gardiners Creek and Moonee Ponds Creek.

3.1 Study area

The Yarra is the major river running through the City of Melbourne, draining a middle part of Victoria into Port Phillip Bay. The total area of the Yarra catchment is approximately 4,000 km² (Sinclair *et al.*, 1989). The Maribyrnong River is a principal tributary of the Yarra River and runs 130 km southward to join the Yarra about 4 km from Port Phillip Bay. The catchment area of the Maribyrnong River is 1433 km². Another principal tributary of the Yarra River which drains the inner south-eastern suburbs of Melbourne is Gardiners Creek (115 km²), while Merri Creek (397 km²) and Moonee Ponds Creek (145 km²) drain the northern suburbs.

3.1.1 Rver flows

The median daily flow of the Yarra River is almost 8.5 m³/s. The flow at Chandler Hwy accounts for approximately 70% of the total flow at the river mouth, although the percentage varies each year from 65 to 82%. The remaining 30% comes from a large urban catchment. The average monthly flow at Chandler Hwy, estimated for 1979-1995, varies from 5 m³/s (February) to 31 m³/s (September). The annual flows for the same period are in the range 4.7 to 28.5 m³/s, with a mean annual flow of 15.97 m³/s.

The median daily flow of the Maribyrnong River at Keilor is about 11 times less than the corresponding value for the Yarra River at Chandler Hwy. However, the daily flow of the Maribyrnong River which will be exceeded on 2 days per 1,000 (on average) is only about 1.4 times less than for the Yarra River (120 m^3/s compared with 168 m^3/s). This indicates the extreme "peakedness" of the hydrograph for the Maribyrnong River (Mills *et al.*, 1978). The median daily flows of Moonee Ponds Creek and Gardiners Creek are 0.63 and 0.29 m^3/s respectively. The median flow of Merri Creek is the smallest and accounts for only 0.2 m^3/s.

3.1.2 Land use

The Yarra River catchment consists of three distinct regions: the lower part of the catchment is urban; the upper part (ca. 1,800 km^2) is largely forested, with much of the area closed to protect the quality of the water supply to Metropolitan Melbourne and is used for recreation and forestry; and about 12.5% of the catchment (ca. 450 km^2) is used extensively for agriculture (mainly for crops and sown pasture with livestock numbers of about 90,000) (ABS, 1992).

The bulk of the Maribyrnong River and Merri Creek catchments beyond Melbourne is agricultural grazing land (~25% of the total area with almost 120,000 livestock). Around Melbourne, urban and industrial development is intensive. However, most of the heavy industries have little impact on water quality in the river because their process effluents are discharged to the sewer (EPA, 1981). The average population density for the urban part of the Maribyrnong River catchment is in the range 100 to 1000 persons/km^2. The Gardiners Creek and Moonee Ponds Creek catchments are entirely urban with a population density of 2,000-3,000 persons/km^2.

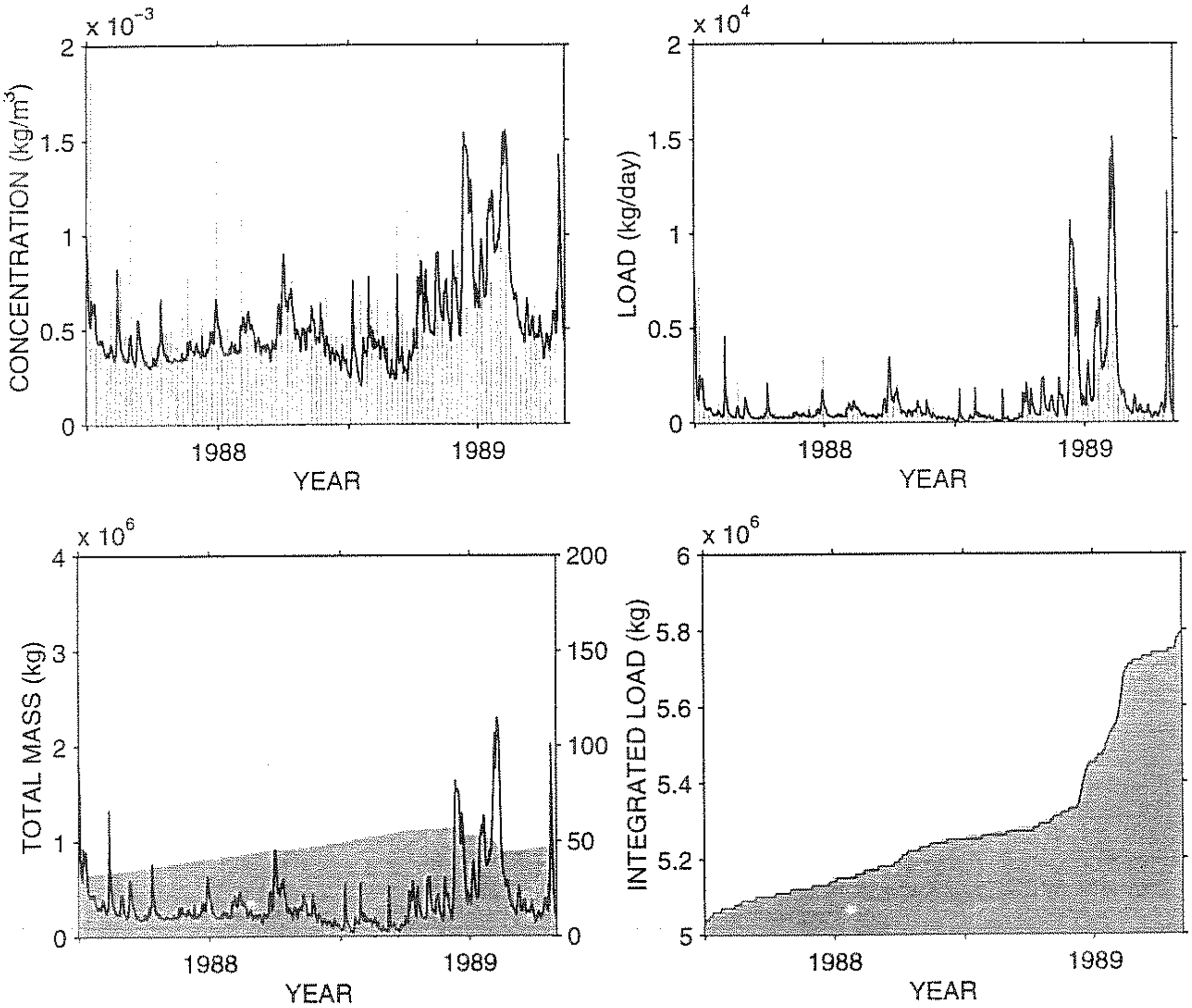

Figure 1: Two-year segment of time evolution of modelled parameters for TKN in the Yarra River during the period 1988-1995.

(a) observed (grey bars) and predicted (solid line) concentrations; (b) observed (grey bars) and predicted (solid line) loads in the river; (c) river discharge (solid line) and total mass of chemical element in the catchment (grey bars); (d) observed (grey bars) and predicted (solid line) time integrated loads in the river.

3.2 Estimation of loads: 1979-1995

For the numerical predictions of water-quality variables for the five different catchments, flow and chemical concentration data were available from 1979 to 1995 for the Yarra River at Chandler Hwy, from 1980 to 1995 for the Maribyrnong River at Keilor, from 1993 to 1995 for Moonee Ponds Creek and Merri Creek, and from 1980 to 1985 and from 1992 to 1995 for Gardiners Creek at Glenferrie Road.

In order to determine long-period changes in the model parameters for different water quality variables, Yarra River observations were adopted because the data sampling strategy has resulted in the most detailed dataset. The model parameters and statistical characteristics of chemical concentrations and loads were then estimated for two periods: from 1979 to 1987 and from 1988 to 1995.

An example of the numerical simulations for TKN in the Yarra River using equations (1)-(3) is presented in Fig. 1, and the estimation of the model parameters and error analyses for some cases are summarised in Tables 1 and 2.

The contrast in the background concentrations for the three different types of catchment (all within the Yarra River watershed) is very pronounced. For the most urbanised Gardiners Creek catchment, the average concentration of metals (*Pb*, *Cu* and *Zn*) is one to two orders of magnitude greater than for the Maribyrnong and Yarra catchments (Table 1). Consequently, the rate of chemical loading of these metals into the catchment for Gardiners Creek is the greatest. For example, the chemical loading of *Zn* into Gardiners Creek catchment is approximately 40 times higher than for the Yarra River and more than 100 times higher than for the Maribyrnong River. Thus, despite the fact that the average Yarra River discharge is 20 times greater than Gardiners Creek, the average daily loads of *Zn* for both rivers are comparable.

The average concentrations of nutrients and their rates of loading are similar for the three different types of catchment, even though the sources of chemical elements must vary (Table 2). For example, the predominant input of nutrients is related to urbanisation in Gardiners Creek and Moonee Ponds Creek, whereas, for the Maribyrnong River, the chemical loads are mainly determined by agricultural activities. Concentrations of nutrients in discharges from Moonee Ponds Creek, Merri Creek and Gardiners Creek are generally in excess of those, obtained in the Yarra River and Maribyrnong River.

Despite the fact that the annual averaged concentrations of *Zn*, *Pb* and *Cu* in the Yarra River were significantly reduced during the last 15 years, due to a long-term increase in the river flow from about 8 m^3/s in 1979-82 to up to 25 m^3/s in 1992-93, the chemical loads of these metals in the river were practically constant (lead) or slightly raised (copper and zinc). In contrast, the time evolution of nutrient concentrations was characterised by a gradual increase from 1979-82 to 1987-89, followed by a slight decrease for total P and a much steeper reduction for total N. These changes cause the constant elevation in total P loads during the last 15 years. Total N loads increased from about 500 tonnes/year to 1500 tonnes/year in 80's, and were reduced to 750 tonnes/year in the mid-90's.

Table 1: Estimated mean concentrations and loads, and model parameters (1979-87). The three numbers in each cell relate to Yarra River (top), Maribyrnong River (middle), and Gardiners Creek (bottom).

Variable	**Statistical characteristics**		**Model parameters**		**Accuracy**
	$\langle C \rangle$ mg/L	$\langle Q^- \rangle$ kg/day	γ	w $kg m^{-2} s^{-1} \times 10^{12}$	R
Pb	0.021 0.002 0.050	15.6 1.3 5.7	1.40 1.25 1.30	0.045 0.012 1.071	0.47 0.16 0.30
Cu	0.0048 0.0027 0.0189	4.4 1.8 1.2	1.15 1.25 1.00	0.012 0.030 0.126	0.33 0.09 0.04
Zn	0.052 0.010 0.189	41.7 5.4 20.2	1.50 1.25 1.15	0.171 0.052 6.999	0.41 0.15 0.07

Table 2: Estimated mean concentrations and loads, and model parameters (1988-95). The three numbers in each cell relate to Yarra River (top), Maribyrnong River, and Merri Creek (bottom).

Variable	**Statistical characteristics**		**Model parameters**	**Accuracy**
	$\langle C \rangle$ mg / L	$\langle Q^- \rangle$ kg / day	γ	R
NH_3	0.044 0.078 0.140	90 25 8	1.25 1.00 0.80	0.22 0.13 0.12
TKN	0.77 0.99 1.24	2,020 486 182	1.55 1.15 1.15	0.19 0.02 0.03
NTOT	1.32 1.67 1.75	3,120 630 250	1.45 1.05 1.15	0.14 0.02 0.01
PO_4	0.044 0.031 0.075	59.1 8.0 9.4	0.85 0.90 1.10	0.74 0.32 0.04
PTOT	0.136 0.083 0.162	270 60 26	1.35 1.30 1.20	0.44 0.04 0.01
Cu	0.0038	7.6	1.20	0.33
Pb	0.0074 0.0032	14.7 1.0	1.20 1.40	0.52 0.19
Zn	0.0356	59	2.15	0.47
TURB	52 61 27	125 200 42 500 9 600	1.40 1.30 1.55	0.26 0.12 0.04

4. DISCUSSION

4.1 Hysteresis formation

Sokolov and Black [1996] showed that hysteresis occurs because the chemical loads in the river are controlled by the total mass of chemical element in the catchment area. The balance between the chemical loads entering the river $Q^-(t)$ and those entering the catchment area w determines the direction of rotation of the hysteresis (clockwise or counter-clockwise). The predominance of one of the main processes in the formation of chemical loads in the river (the storm wash-off of chemicals deposited in the catchment area or the dilution by stream water) will govern the sign (slope) of the relationship (positive or negative).

Many examples of hysteresis exhibiting similar patterns can be found in the results of field studies from different catchments with various magnitudes of the river discharge (Stottlemyer, Troendle, 1992; Piñol *et al.*, 1992; Peters, 1994; Whitfield, Schreier, 1981; Whitfield, Whitley, 1986; Whitfield *et al.*, 1993).

The results are equally relevant to the long-period (inter-annual) variation of chemical concentration and river discharge.

4.2 Long-period trends

For the determination of long-period changes in the model parameters, the main period of measurements was grouped into 4-year overlapping segments. Long-period changes in the watershed hydrochemical response are determined by natural trends in biogeochemical and geomorphological processes within the local catchment, supplemented by alterations in the relative land uses. The developed model can be used for estimation of such useful parameters as the rate of chemical loading w and the amount of total mass $M(t)$ of chemical elements in the catchment. The approach should be further tested against particular catchments, knowing the alterations to land uses, for a range of hydrochemical and geomorphological conditions under different hydrological regimes.

4.3 Accuracy

The two main factors determining the accuracy of the predictions are the sampling strategy and accuracy of measurements. Calculations provided for two periods with the most intensive sampling strategy for the Yarra River at Chandler Hwy (Sokolov and Black, 1996) demonstrated the high accuracy of the prediction of absolute and time-integrated chemical loads in the river (3-10% and less than 2% respectively) and suggested that this approach is appropriate and properly represents the main integral processes in the watershed.

The numerical prediction of water quality variables in the Yarra River for 9 and 8-year periods (Tables 1, 2) with fixed model parameters had accuracy with normalised errors of about 20% for the nutrients (except orthophosphate) and 40-50% for the metals. The 4-year overlapping segmentation, performed to account for long-period changes in the watershed hydrochemical response, produced a significant improvement in the predictions with errors of 7-10% for the nutrients and 20-35% for the metals. The accuracy for catchments with uniform land use (Maribyrnong River, Gardiners Creek and Merri Creek) was even higher. It must be stressed that a normalised error of the integrated load $\sum \mathrm{Er}$ was always less than 1-2%.

The lowest temporal scale resolved by the model is limited to a single hydrological event, where the concentration-discharge relationship is determined by the internal structure of the watershed, precipitation intensity and areal distribution, floodwater volumes and sediment transport rates (Williams, 1989). The time evolution within a hydrological event is described by the model as a linear temporal response, without consideration of temporal lags between internal catchment characteristics.

The main limitations in the application of the model relate to the adequacy of the sampling program which measures river discharge and water-quality variables. The automated stream water sampling strategy developed by Peters (1994) is an example of an appropriate methodology. Both long and short-term changes in physical and chemical stream characteristics were recorded, with intensive sampling during rainstorms.

For catchments where most of the suspended particulate matter is transported during high flow events, sampling around peak flow is imperative, otherwise loads will be significantly underestimated (Hart *et al.*, 1988; MWC, 1992). High concentrations are equally possible during rainstorm events after prolonged periods without precipitation and under low discharge conditions as well, because of low dilution.

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