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Inputs from the Yarra River and Patterson River / Mordialloc Main Drain into Port Phillip Bay

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EXECUTIVE SUMMARY

The main objective of Task N1.3 and T1.2 is to estimate the loads of nutrients and toxicants entering Port Phillip Bay from the Yarra River. The task was undertaken in two stages. In the first stage, the historical water-quality measurements for the Yarra and Dandenong Valley catchments collected during the last 15 years by Melbourne Water Corporation and Environment Protection Authority have been analysed and assimilated to estimate daily loads. The second stage comprised analysis of field measurements in the Yarra Estuary (1993-1995) and aimed to relate upstream Yarra River loads to those entering Port Phillip Bay.

Among the water quality parameters which have been analysed were total suspended solids (SS), turbidity, non-filtered residue (NFR), oxidised nitrogen (NO_X), ammonium (NH_3), total kjeldahl nitrogen (TKN), total N, orthophosphate (PO_4), total phosphorus, arsenic (As) and metals: cadmium (Cd), total chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). Some of the water quality variables for the Yarra catchment have not been analysed because of a lack of measurements in the Yarra Estuary.

Patterson River and Mordialloc Main Drain have been identified as one of the major sources of nutrients and toxicants into Port Phillip Bay (NSR Environmental Consultants, 1993). A developed dynamic model has been applied to estimate daily loads from these sources entering Port Phillip Bay for the period from 1988 to 1994. The concentrations and loads for all water-quality variables have been estimated for the five sites: Dandenong Creek at Hammond Rd, Dandenong Creek at Olive Grove, Eumemmerring Creek at Worsley Rd, Mordialloc Main Drain at Wells Rd, and Patterson River at Mornington Peninsula Freeway.

The numerical prediction of water quality variables at all sites for 7-year period of measurements with fixed model parameters in general had a high accuracy, with normalised errors being on average less than 5% for the nutrients and about 10% for the metals. The low level of accuracy for ammonium, orthophosphate and total phosphorus for Mordialloc Main Drain probably related to discharge reduction and improvements in water quality of effluent from the Dandenong South Treatment Plant (DSTP) over the last seven years.

The most pronounced changes occurred in the concentration and load for ammonium and total kjeldahl nitrogen. Over the seven years, the mean annual concentration for ammonium dropped from 12 mg/L in 1988 to 2 mg/L in 1994, thus the load in Mordialloc Main Drain contracted dramatically from 1400 kg/day to 300 kg/day respectively.

By contrast the annual concentration and load of orthophosphate and total phosphorus in Mordialloc Main Drain remained approximately constant over the same period. Concentrations of PO_4 and total P in Mordialloc Main Drain (2.04 mg/L and 2.47 mg/L) were more than 20 times higher than in Dandenong Creek at Olive Grove (0.094 mg/L and 0.207 mg/L), and this indicates that the major source of these species was the DSTP, with an average concentration of orthophosphate in the effluent of about 7.5 mg/L (DVA, 1990). The concentrations and loads for the Mordialloc Main Drain for all nutrients, except oxidised nitrogen and dissolved organic N, were higher than those estimated for the Patterson River.

The concentrations of the metals are generally higher in the Mordialloc Main Drain than in the Patterson River. However, because of difference in discharges, the loads of metals in Patterson River on average exceeded significantly the loads in the Mordialloc Main Drain, especially during wet years due to intensive runoff. The inter-annual variation in metals discharges from the Paterson River are entirely determined by the changes in annual river flow.

For the numerical predictions of water-quality variables for the five different catchments within the Yarra watershed, 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 Merry Creek, and from 1980 to 1985 and from 1992 to 1995 for Gardiners Creek at Glenferrie Road.

In order to determine the long-period changes in the model parameters for different water quality variables, Yarra River observations were adopted because the data sampling strategy had 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.

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 Maribyrnong and Yarra catchments. 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.

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 nutrients concentrations was characterised by a gradual increase from 1979-82 to 1987-89, followed by slight decrease for total P and a much steeper reduction for total N. These changes caused a 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 the 80's, and were reduced to 750 tonnes/year in mid-90's.

Temporal changes in discharges, concentrations and in loads for most of the water quality variables are characterised by large sub-annual variability. In the majority of cases, the empirical distributions are strongly positively skewed, and the sampling mean values exceed mode and median values considerably. In this respect, the estimations based on the field measurements which had an inadequate sampling strategy may tend to underestimate (or overestimate) loads.

To estimate total loads of nutrients and toxicants derived from the Yarra River, the historical upstream measurements have been related to those downstream at Westgate Bridge, near the entrance to Port Phillip Bay. The six month measurement program implemented in 1995 at Westgate Bridge resulted in continuous observations of river discharges and water quality variables from five depth levels with a more intense sampling strategy during high flow events.

In general, the typical vertical distribution of nutrient and metal concentrations in the Yarra Estuary is characterised by higher levels near the surface decreasing with depth. This is indicative that the major source of various species in the estuary is related to the Yarra River flow. The most pronounced difference between the near-surface and the deeper water concentrations occurs for nitrite, nitrate, ammonium, silicate and metals (iron and lead).

By contrast, orthophosphate is distributed uniformly through the water column. Moreover, the higher concentration of orthophosphate in the Yarra Estuary compared with upstream concentrations, indicates that another major influx of orthophosphate in the estuary is determined by the deeper salt wedge water source. Under low flow conditions the influx of nutrients from the Yarra River is small, and orthophosphate in fact may increase with depth. Elevation in the river flow mainly resulted in a reduction in concentration in the surface layer. However, the surface layer orthophosphate influx during high flow events is still 5 times above the low flow load.

Higher concentrations in the Yarra Estuary compared with those in the Yarra River, were also found for ammonium. This can be the case, when significant loading of ammonium occurs within the CBD of Melbourne.

In order to relate the nutrients and SS loads entering the Port Phillip Bay to those estimated upstream, the measurements of water-quality variables recorded over six months at Westgate Bridge in 1995 were adopted to estimate daily loads in the estuary using the developed model. In general, the normalised error R for predicted chemical loads does not exceed 20-25%. However an error of almost 50% for orthophosphate and ammonium indicates that in the Yarra Estuary there are additional sources of these species, which are not due to direct influx from the Yarra River.

The predicted daily loads at Westgate Bridge for 1995 were related to upstream loads estimated for the same period. In general the correlation between combined upstream loads and loads in Yarra Estuary is high, resulting in r^2 adjustment of about 85-95%. However, as expected, the relationships obtained for orthophosphate, and partially, for ammonium, are very “noisy”.

The relationship for nutrients is close to logarithmic and in the intermediate range of high flow events, loads in the Yarra Estuary exceed the combined upstream loads, indicating that there is an additional influx of nutrients generated downstream of Chandler Hwy. By contrast, the relationship obtained for total suspended solids is exponential, testifying to processes of flocculation and precipitation of colloidal material in the estuary being of major importance.

The available data shows that comparing the average annual discharges from the Yarra River with estimates for other surface inputs (Patterson River/Mordialloc Main Drain and Western Treatment Plant (Murray, 1995)), the Yarra River is one of the major sources of nutrients (except ammonium) and metals in Port Phillip Bay. By contrast to the WTP, discharges from the Yarra River are characterised by very intense sub-annual variability resulting in high extreme daily loads. The estimated maximum discharge of total suspended solids, for example, peaked at almost 27,000 tonnes/day during a notable storm event in June 1989 when the combined Yarra River flow reached 412 m^3/s. This estimate exceeds the mean daily load by more than 100 times. Thus in terms of impulse impact on the Port Phillip Bay environment, the Yarra River inputs can be treated as prevailing factors.

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1. INTRODUCTION

1.1. Background

The main objective of Task N1.3 and T1.2 was to estimate the loads of nutrients and toxicants entering Port Phillip Bay from the Yarra River. The study was undertaken by the Victorian Institute of Marine Sciences (VIMS), now part of the Marine and Freshwater Resources Institute (MAFRI), in collaboration with the Melbourne Water Corporation (MWC) Environmental Management and Technology Division and the Victorian Fisheries Research Institute (VFRI) now part of the Marine and Freshwater Resources Institute (MAFRI), for the Port Phillip Bay Environmental Study (PPBES).

The Yarra River has been identified as a major source of nutrients and toxicants to Port Phillip Bay. More importantly, in contrast to the Western Treatment Plant (WTP) at Werribee, which discharges such materials in a continuous mode at moderate levels (Murray, 1995), the inputs from the Yarra River are characterised by very intense storm induced variability resulting in high peak loads. Another significant source of nutrients and toxicants to Port Phillip Bay is the Patterson River/Mordialloc Main Drain system.

The essential goal of this task was the estimation of nutrients and toxicants loads in the Yarra River and Patterson River/Mordialloc Main Drain system on a daily basis, providing boundary conditions for ecological modelling of Port Phillip Bay. Assimilating all the most recent, up to date, measurements of water quality parameters in the Yarra River, Patterson River and Mordialloc Main Drain also enabled the calculation of robust estimates of mean annual loads, extreme loads and their standard deviations.

The further issue addressed by this study is the effect of an estuary, the transition zone from fresh to salt water, on water quality parameters, involving a complex of chemical transitions and hydrophysical processes. These processes have been treated here mainly statistically to determine empirical relationships. However, the detailed field measurements are fundamentally useful in their own right, and provide a basis for further investigations.

1.2. Structure of the report

In this report, the field program and data reduction is described in Chapter 2. Chapter 3 presents the model developed for the estimation of loads and concentrations of nutrients and toxicants on a daily basis, and provides an explanation of hysteresis in the concentration and water discharge relationship at different time scales. The loads and concentrations of nutrients and toxicants from the Patterson River/Mordialloc Main Drain system for the period from 1988 to 1994 are described in Chapter 4. The estimation of upstream loads in the Yarra River catchment, estuarine processes and loads entering Port Phillip Bay are presented in Chapter 5. A summary and comparison between estimated loads from the Yarra River catchment, the Patterson River/ Mordialloc Main Drain system and Western Treatment Plant are given in Chapter 6.

2. FIELD PROGRAM AND DATA REDUCTION

The present study was undertaken in two stages. In the first stage, the historical water-quality measurements for the Yarra and Dandenong Valley catchments 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 second stage comprised an analysis of field measurements in the Yarra Estuary (1993-1995) which aimed to relate upstream Yarra River loads to those entering Port Phillip Bay.

2.1. Historical data

The water quality data analysed here for the Yarra catchment (Table 2.1) were collected from the sampling stations at Chandler Hwy (Yarra River), Keilor (Maribyrnong River), Glenferrie Road (Gardiners Creek), Mt Alexander Road (Moonee Ponds Creek) and Roseneath Street (Merri Creek). The sampling sites for the Dandenong Valley utilised in this study are presented in Table 2.2. The sites have been sampled for chemical analysis at unequal time intervals as a part of the EPA Water Quality Monitoring Program in Victoria and for several assessment projects and research studies since 1979 (EPA, 1981; EPA, 1993, MWC, 1993).

More than 1000 water samples for nutrients and about 700 samples for toxicants were collected by the EPA and MWC 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. The data set for the Dandenong Valley for the period 1988-1994 comprises, on average, about 200 samples for nutrients and more than 100 water samples for most of the metals.

Among the water quality parameters which have been sampled and analysed in this study were total suspended solids (SS), turbidity, non-filtered residue (NFR), oxidised nitrogen (NO_X), ammonium (NH_3), total kjeldahl nitrogen (TKN), total N, orthophosphate (PO_4), total phosphorus, arsenic (As) and metals: cadmium (Cd), total chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). Some of the water quality variables for the Yarra catchment have not been analysed because of a lack of measurements in the Yarra Estuary. The daily flow data analysed here were collected at either the same station or at the closest representative station (Tables 2.1, 2.2).

Table 2.1: Yarra catchment sampling stations analysed in the study.

Stream	Water-quality station	Waterway gauging station
Yarra River	Chandler Hwy 4940 (EPA)	Chandler Hwy
Maribyrnong River	Keilor 3030 (EPA)	Brimbank Park
Gardiners Creek	Glenferrie Road MD05 (MWC)	Great Valley Rd, Gardiner
Merri Creek	Roseneath Street LY06 (MWC)	St Georges Rd, Fitzroy
Moonee Ponds Creek	Mt Alexander Road LY07 (MWC)	Mt Alexander Rd, Flemington

Table 2.2: Dandenong Valley catchment sampling stations analysed in the study.

Stream	Water-quality station	Waterway gauging station
Dandenong Creek	Stud Rd 5654 (EPA)	Hammond Rd
	Olive Grove 5678 (EPA), AM49 (MWC)	Hammond Rd; Mile Creek at Cheltenham Rd
	Pillars Crossing AM51 (MWC)	Greens Rd
Mordialloc Main Drain	Wells Rd 5254 (EPA), AM09 (MWC)	Pillars Crossing
Eumemmerring Creek	Worsley Rd, AM07 (MWC)	Abbots Rd
Patterson River	NWSC Rowing Course 5681 (EPA), AM08 (MWC)	estimated

2.2. Measurements in the Yarra Estuary

Prior to the present study (1995) in the Yarra Estuary at Westgate Bridge (Fig. 2.1), two detailed pilot studies were conducted in 1993 at the same sample site. This provided a broad description of water quality, hydrology and circulation in the Yarra Estuary under a wide range of hydrological conditions (Black *et al*., 1993 a, 1993 b).

The 1995 field program was designed to measure currents at Westgate Bridge continuously over a six month period. Weekly measurements of water quality parameters were recorded at the same site throughout this period. Currents were recorded with a single bottom-mounted Acoustic Doppler Current Profiler (ADCP) and were sampled with a 10 Hz maximum pinging rate and 1 min averaging interval with 0.5 m depth cell size through the whole water column. The ADCP was located 30 m from the Channel Marker # 36 towards the mid-channel and the velocity measurements in the surface layer were obtained using a S4 current meter deployed nearby (Fig. 2.1).

The water quality measurements included total suspended solids, oxidised nitrogen, ammonium, total kjeldahl nitrogen, orthophosphate, total phosphorus, total organic carbon (TOC) and silicate (SiO_4). The water samples were taken from five levels relative to the surface: 0.1 m, 1.5 m, 3.5 m, 8 m, and 12 m. To measure the estuarine response to intensive runoff in the catchment, water quality variables during a single storm event were sampled daily during the one week with 3-hourly sampling at the peak flow. During this exercise the standard parameters were sampled together with lead, iron and total hydrocarbons (TPH).

The vertical profiles of temperature, salinity and dissolved oxygen were measured at three stations across the river and at two stations 700m upstream and 1 km downstream of Westgate Bridge. The measurements were obtained using a fast-response CTD Profiler (Fine Scale Profiler, Centre for Water Research, University of Western Australia) with a vertical resolution of 0.001 m. The temperature and salinity profiles were measured during water quality sampling, and a total of 40 transects were collected during the field program.

To determine continuous variation in temperature and salinity, and estimate the intensity of mixing processes in the estuary, a chain of temperature/conductivity sensors were deployed at the site to record the parameters through the water column (0.75 m, 1 m, 1.5 m, 2 m, 3 m, 4.5 m and 7 m below the water surface).

Wind records and additional meteorological measurements were obtained from the Bureau of Meteorology (MET) for the permanent stations at Laverton, Melbourne and Paisley. The Port of Melbourne Authority collected sea level data at Breakwater Pier, Williamstown and Harbour Control, Victoria Dock.

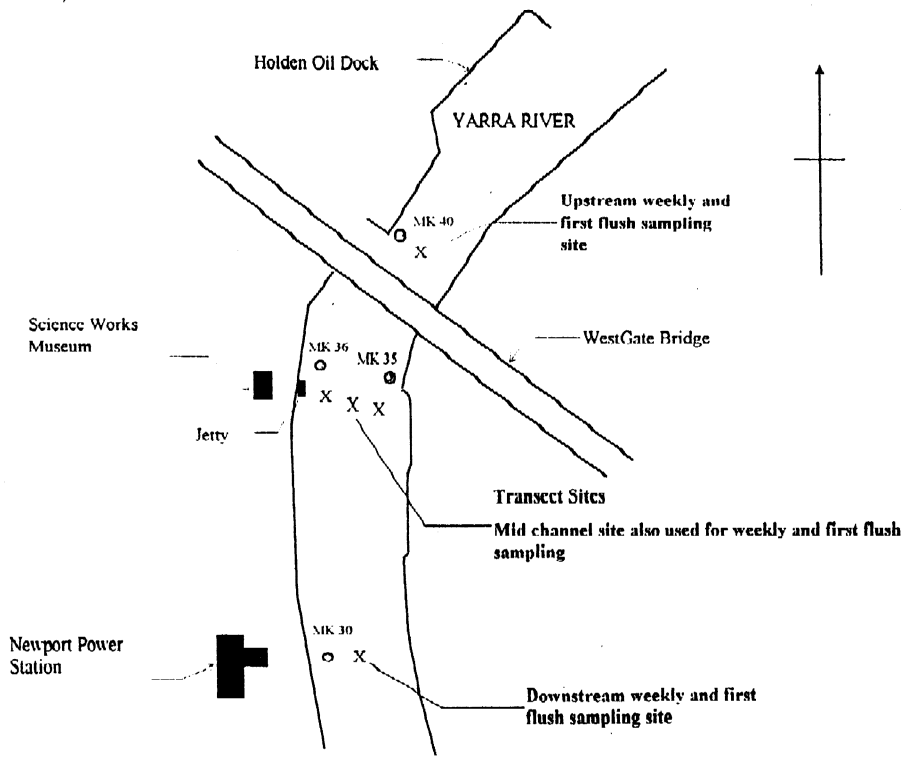

Figure 2.1 Location of sampling sites for the Yarra River Inputs Task.
Channel markers (MK) are indicated. X = sampling sites O = channel markers

3. ESTIMATION OF WATER QUALITY VARIABLES: THE THEORETICAL APPROACH

3.1. Introduction

The problem of predicting chemical loadings in a river system has remained a key issue in the determination of the impact of human activity on aquatic ecosystems and coastal marine environments. The major problems relate to the complexity of the processes within the watershed. These are determined by a physical-chemical balance between the atmospheric inputs, and/or direct anthropogenic impact, biogeochemical processes within the catchment, climatic factors and mechanisms of runoff generation.

Several approaches have been adopted in modelling the hydrochemistry. For example, some hydrochemical models represent the stream as a mixture of soil water from two ideally mixed reservoirs (soil and groundwater areas) each of which is assumed to obey simple chemical equations (Christophersen *et al.*, 1982; Cosby *et al.*, 1985; Nikolaides *et al.*, 1989; Gherini *et al.*, 1985; Bergstrøm *et al.*, 1985). The key problems and perspectives within this approach are mainly related to the transition from the models which deal with average or lumped systems toward synthesised hydrochemical models which are able to incorporate the internal structure and state variables of the catchment (Christophersen *et al.*, 1993).

A strong relationship between streamwater chemistry and discharge alone, at different spatial and temporal scales, has been identified for rivers (Whitfield, Schreier, 1981; Whitfield, Whitley, 1986; Whitfield *et al.*, 1993) and streams (Reynolds *et al.*, 1992; Stottlemyer, Troendle, 1992; Peters, 1994; Piñol *et al.*, 1992). The relationship has stimulated attempts to develop a model which can reproduce temporal variations in species concentration in rivers and streams (e.g. Sloan *et al.*, 1994). This approach can be characterised as being mainly hydrologically based.

Lack of success and criticism of the empirical approach based on regression techniques has arisen because the relationship between discharge and water chemistry is essentially nonlinear, time-dependent and varies from site to site. At different time and space scales this relationship exhibits hysteresis (Whitfield, Schreier, 1981; Whitfield, Whitley, 1986; Stottlemyer, Troendle, 1992; Piñol *et al.*, 1992) with different properties. The reason for hysteresis is unknown and usually explained by a complicity of biogeochemical processes within the catchment and other water-related factors. An attempt to classify and explain hysteresis in the relationship between sediment concentration and water discharge for a flood event has been undertaken by Williams (1989). However, there is no clear explanation of why the hysteresis exists at other temporal and spatial scales from seasonal to inter-annual.

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 made in 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 (Fig. 3.1). 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.

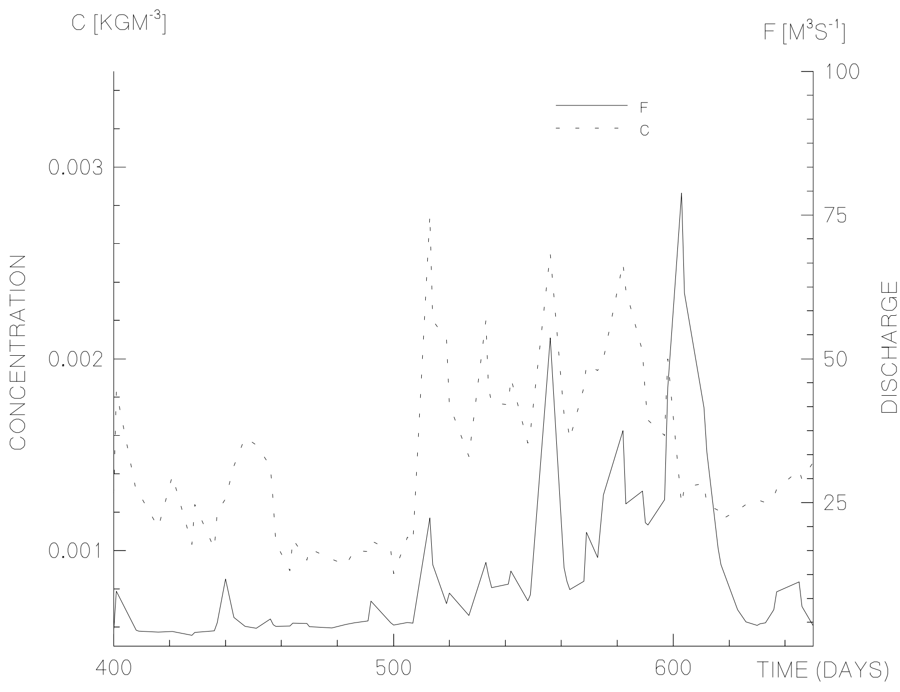

Figure 3.1. Time evolution of the river discharge (F) and total nitrogen concentration (C) at Chandler Hwy in 1981.

The relationship between chemical concentration and river discharge is essentially non-linear and time-dependent. This relationship exhibits hysteresis, i.e. forms a loop if plotted in the time sequence of occurrence. The shape and direction of the loop vary with water-quality variables and from year to year. Seasonal hysteresis in the relationship between water-quality variables and river discharge was noted in the Yarra River data and similar relationships have been obtained for the Yukon River basin, Canada (Whitfield and Whitley, 1986) and for the Fraser River basin, British Columbia (Whitfield and Schreier, 1981). Even at local streamwater catchment scales with maximum discharge up to 15 $L \cdot s^{-1}$ (Piñol *et al.*, 1992), the first storm event in autumn after the summer drought was the most outstanding annual hydrochemical event. Similar results were obtained for forested Piedmont catchment in Georgia, USA. Higher concentrations of H^+ and SO_4^{2-} in runoff than in rainfall were attributed to the wash-off of dry deposition of acidic sulfur compounds that accumulated in the catchment during the dry periods preceding the storm events (Peters, 1994).

For the forested Mediterranean catchments (Piñol *et al.*, 1992), SO_4^{2-} and Cl^- concentration time series typically reveal hysteresis, with a negative relationship to discharge and a clockwise direction of rotation. Similar clockwise hysteresis having a negative relationship between streamwater discharge (maximum value of discharge of up to 100 $L \cdot s^{-1}$) and the concentration of ions in stream water (calcium, magnesium, sodium, potassium, sulfate) was obtained for alpine and sub-alpine catchments in Colorado (Stottlemyer and Troendle, 1992).

Summarising the prior analyses, we can conclude that, in general, the time evolution of water-quality variables in a stream could be treated as a composition of the two processes: the storm wash-off of chemicals deposited in a catchment area, and the dilution by the stream water of the chemicals coming from a sources such as groundwater and/or anthropogenic local emissions of wastes. In many cases (Whitfield *et al.*, 1993; Peters, 1994), the lack of a relationship between stream chemistry and rain chemistry suggests that soil water and groundwater control the stream chemistry.

3.2. The model description

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):

$$\frac{dM}{dt} + \tilde{\beta} M = Aw; \qquad (3.1)$$

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

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

$$\tilde{\beta} = 0; \qquad\qquad \text{for} \qquad F(t) \le F_*; \tag{3.2}$$

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 transitional flow F_*, characterising the outcome of a storm event on the chemical concentrations, comprises (i) base flow and (ii) artificial emissions (if they form a significant input), plus an allowance for catchment run-off which is not strong enough to start washing-off the chemicals deposited in the catchment. For a large storm event, when $F(t) > F_*$, the relationship between water chemistry and flow discharge is positive, i.e. larger discharge results in higher concentrations (Fig. 3.2). Below these conditions when $F(t) < F_*$, the relationship is characterised by dilution of chemical loads by river discharge, and concentration decreases as the discharge rises. The parameter F_* is the transitional discharge between these two regimes.

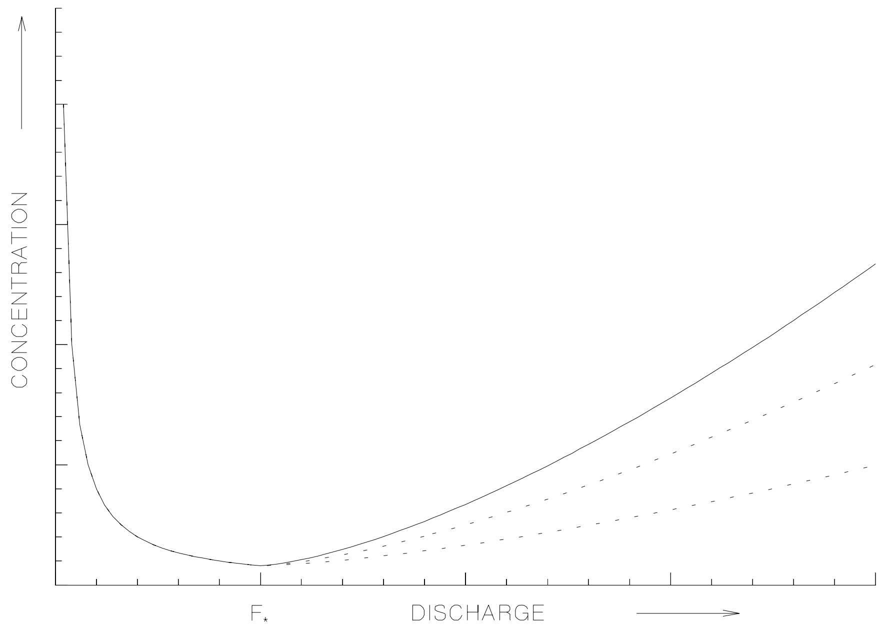

Figure 3.2. Chemical concentration in the river C(t) versus river discharge F(t); the dashed lines show cases of decreasing available mass M(t) in the catchment.

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

$$C = \left[\tilde{\beta} M + \upsilon\right] / F; \qquad (3.3)$$

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

To obtain a non-dimensional form of equations (3.1)-(3.3) we introduce the following intrinsic scales: F_0 - flow scale; C_0 - concentration scale; $L_0 = A^{1/2}$ - catchment length scale; $\ell_0 = S^{1/2}$ - river flow length scale, where S is a river cross-sectional area. Using these, we can determine a river time scale τ_0 which is an estimate of the typical period for water to be replaced in the river $\tau_0 = L_0 \ell_0^2 F_0^{-1}$; a catchment time scale T_0 which characterises the replacement period of the total available mass of chemical element in the catchment $T_0 = L_0^2 \ell_0 F_0^{-1}$; a mass scale $\mathbb{M}_0$ of chemical loading into the river $\mathbb{M}_0 = F_0 C_0 \tau_0$; and a mass scale M_0 of chemical element in the catchment $M_0 = F_0 C_0 T_0$.

Thus, scaling of variables in equations (3.1) - (3.3) yields

$$\frac{dM^*}{dt^*} + \tilde{\beta} M^* = \tilde{w}; \qquad (3.4)$$

$$C^* = \left[\tilde{\beta} M^* + \upsilon^*\right] / F^*; \qquad (3.5)$$

where

$$\tilde{w} = w L_0^2 C_0^{-1} F_0^{-1}.$$

Typical values of F_0, L_0 and ℓ_0 for the Yarra River at the Chandler Hwy are 14.5 m³/s (mean flow), $5.6 \cdot 10^4$ m and 6 m respectively. The time scale of the typical water replacement period in the river τ_0 is about 1.6 days. The replacement period of the total mass of chemical element in the catchment T_0 is approximately 40 years. For total nitrogen with a mean concentration in the river of $C_0 = 1.5 \cdot 10^{-3}$ kg/m³, the scale of chemical loading into the river $\mathbb{M}_0$ is about 3000 kg, and the mass scale of total nitrogen in the catchment is of order $M_0 \sim 2.8 \cdot 10^7$ kg.

For comparison, the calculated scales for Gardiners Creek at Glenferrie are

$F_0 = 0.77$ m³/s;	$L_0 = 1.07 \cdot 10^4$ m;	$\ell_0 = 2$ m;
$C_0 = 2.28 \cdot 10^{-3}$ kg/m³;	$T_0 = 9.3$ years;	$\tau_0 = 15$ hr;
$\mathbb{M}_0 = 94$ kg;	$M_0 = 0.5 \cdot 10^6$ kg.	

Numerical solution

The initial value problem (3.4)-(3.5) 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

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

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

$$\Re\left[\tilde{\beta}, \tilde{w}, \upsilon, M^{*}(0)\right] = \left\{Q^{-} - \hat{Q}^{-}\right\}^{2} \qquad (3.6)$$

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

$$\hat{Q}^{-}(t) = \hat{F}(t)\hat{C}(t). \qquad (3.7)$$

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

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

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

3.3. Hysteresis formation

The model has been tested using historical water-quality data collected by MWC from a station at Chandler Hwy. The main theoretical result obtained in these numerical exercises is that the developed model is able to effectively reproduce observed hysteresis in the relationship between chemical concentration in stream water and river discharge, simultaneously for all considered time scales.

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).

To illustrate these statements, consider three examples. To remove high-frequency (synoptic) oscillation in the relationship between concentration of chemicals in the river and the river discharge, the seasonal variation of river discharge $F(t)$ is obtained as a time-averaged long-period trend. The low frequency response is determined by the sequence of storm events (Fig. 3.3).

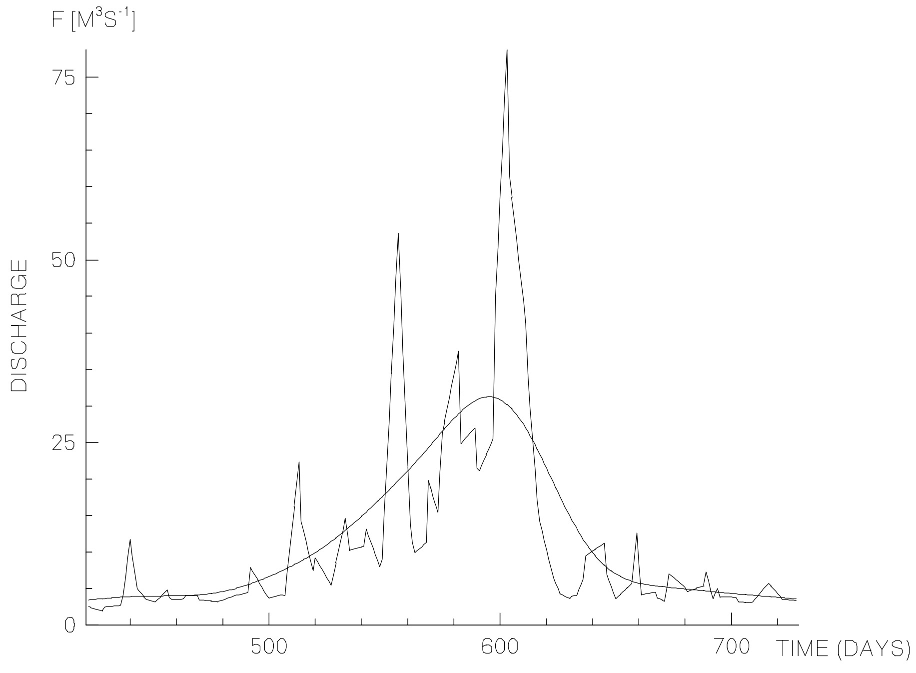

Figure 3.3. Seasonal variation in the river discharge with low frequency response.

When storm wash-off is the predominant process in the chemical loading in the river

$$\lambda = \frac{Q^-}{\upsilon} > 1$$

As shown in Figures 3.4 and 3.5, the relationship is positive (the concentration is increasing with rising river discharge). The model parameters chosen for this illustration were taken from the actual estimates obtained for total nitrogen (Figs. 3.4, 3.5) and arsenic (Fig. 3.6).

In the first two cases (Table 3.1), the rise in river discharge (Figs 3.4 c, 3.5 c) is accompanied by increasing chemical concentration (Figs. 3.4 a, 3.5 a) and loading in the river (Figs. 3.4 b, 3.5 b). The relationship between concentration and river discharge (Figs. 3.4 d, 3.5 d) is positive and reveals hysteresis. The direction of hysteresis is determined by the ratio of chemical loading into the catchment area to chemical loading in the river basin,

$$\theta = \frac{Aw}{Q^-}.$$

Table 3.1: Model parameters for limiting regimes of chemical loading formation.

Case #	Model parameters				
	α^*	γ	υ $\frac{kg}{day}$	w $\frac{kg}{m^2 s}$ x 10^6	M(0) kg
1	0.25	1.45	0	2.30 x 10^{-6}	0.87 x 10^6
2	0.25 x 10^{-2}	1.45	0	8.70 x 10^{-6}	0.87 x 10^6
3	0.08	1.00	2	10^{-24}	584

If the ratio $\theta < 1$ (Table 3.1; Case 1), the direction of hysteresis is clockwise due to the reduction of the total mass $M(t)$ of chemical element in the catchment area (Fig. 3.4). If the ratio $\theta > 1$ (Table 3.1; Case 2), the direction of hysteresis is counter-clockwise because of accumulation of chemical element in the catchment (Fig. 3.5).

In the case when dilution predominates, $\lambda < 1$ (Table 3.1 Case 3), the relationship between chemical concentration in the river and river discharge is negative (Fig. 3.6). Increasing river discharge leads to decreasing concentration (Fig. 3.6 a). As for the cases considered above (Cases 1 and 2), the direction of hysteresis will be determined by the ratio θ.

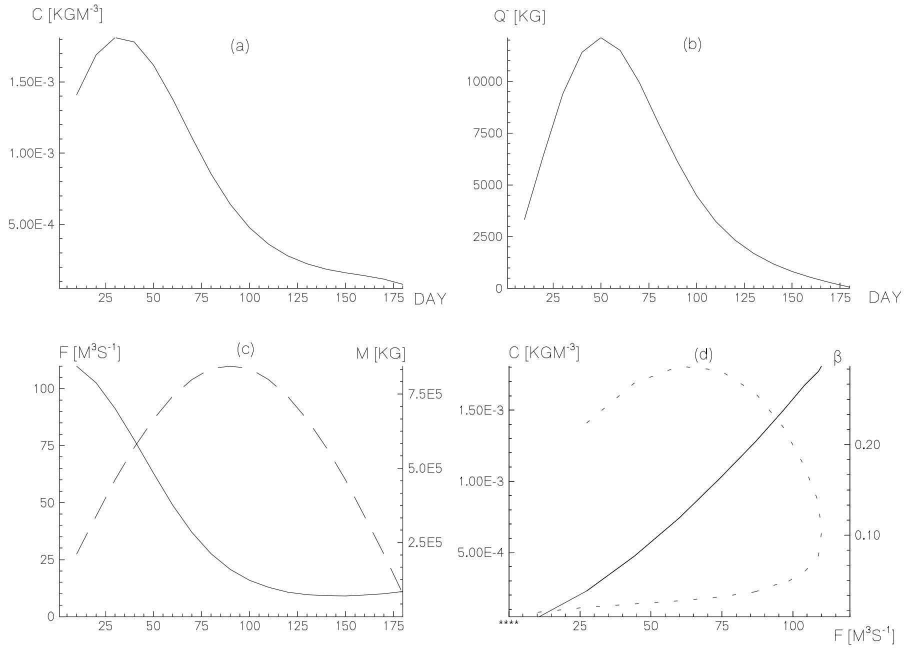

Figure 3.4: Time evolution of modelled parameters in the river: Case #1 (Table 3.1). (a) concentrations (C); (b) loads in the river ($Q^{-}(t)$); (c) river discharge (F; dashed line) and total mass of chemical element in the catchment area (M); (d) concentration vs. river discharge (dashed line) and $\tilde{\beta}$-function (solid line).

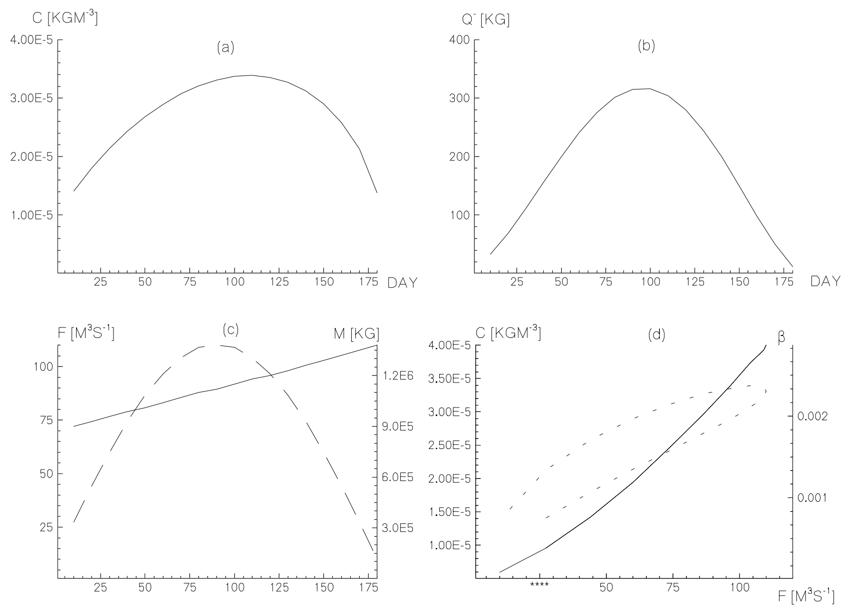

Figure 3.5. Time evolution of modelled parameters in the river: Case #2 (Table 3.1). (a) concentrations (C); (b) loads in the river ($Q^{-}(t)$); (c) river discharge (F; dashed line) and total mass of chemical element in the catchment area (M); (d) concentration vs. river discharge (dashed line) and $\tilde{\beta}$-function (solid line).

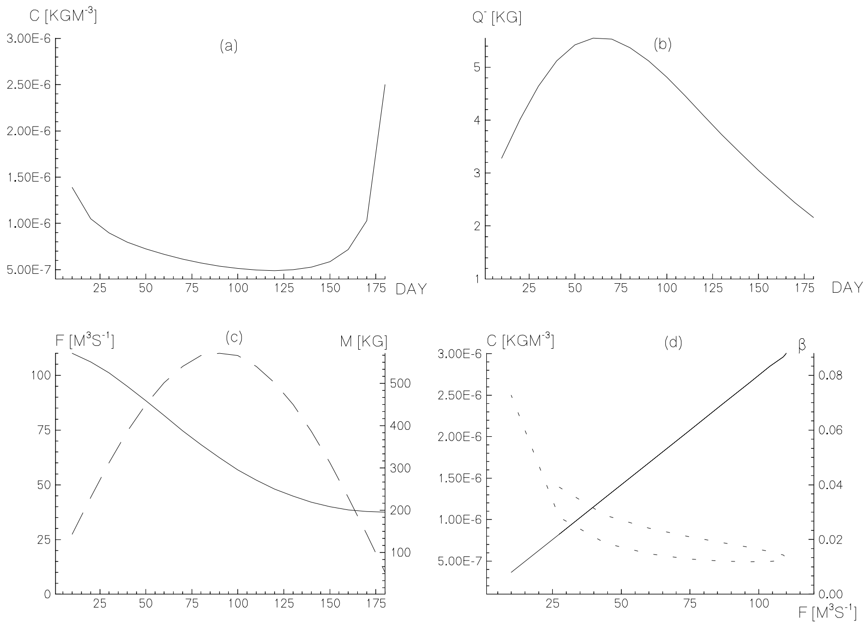

Figure 3.6. Time evolution of modelled parameters in the river: Case #3 (Table 3.1). (a) concentrations (C); (b) loads in the river ($Q^{-}(t)$); (c) river discharge (F; dashed line) and total mass of chemical element in the catchment area (M); (d) concentration vs. river discharge (dashed line) and $\tilde{\beta}$-function (solid line).

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. After a sequence of dry-wet years, the annual river discharge magnitudes and concentrations will exhibit hysteresis determined by the ratios λ and θ.

The relationship between concentration of total nitrogen and water flow in the Yarra River at Chandler Hwy, after isolating the inter-annual, seasonal and residual components in the measurements from 1984 to 1993, are presented in Fig. 3.7. The relationship for the inter-annual and seasonal component reveals hysteresis with different patterns (Fig. 3.7 b, c). The model presented here has effectively predicted these variations, simultaneously for all time scales.

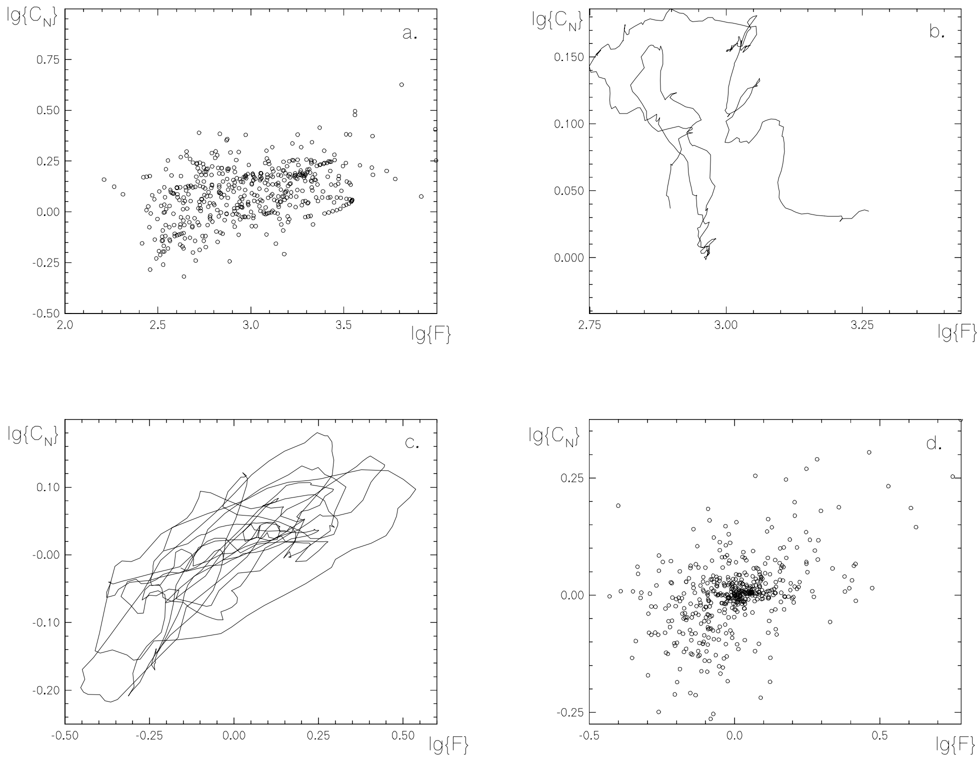

Figure 3.7. Observed total nitrogen concentrations C_N ($\mu g / \ell$) versus river discharge F ($M\ell / day$) in the Yarra River at Chandler Hwy from 1984 to 1993: (a) non-filtered data; (b) inter-annual variation with periods $\tau > 52$ weeks; (c) seasonal variation with periods $12 < \tau < 52$ weeks; (d) residual scatter plot.

3.4. 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. Even for an 11-year period for the Maribyrnong River and a 6-year period for Gardiners Creek with fixed model parameters (α, γ, w and $M(t = 0)$) the accuracy remained reasonable; the normalised error R for the chemical loads does not exceed 0.1 (10%), except for the prediction performed for lead (Sokolov and Black, 1995). The 0.15 (15%) error for the zinc load prediction in the Maribyrnong River is related to the low level of zinc concentration in the river which is comparable with the accuracy of measurements (in more than 90% of water samples, the concentration was lower than the level of detection).

Long-period changes in the watershed hydrochemical response may be determined by natural trends in biogeochemical and geomorphological processes within the local catchment, supplemented by alterations in the relative land uses. Identification of the events that may have led to the increased loading in the catchment and changes in the catchment response to chemical wash-off is beyond the scope of the present analysis. 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. This 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.

The lowest temporal scale resolved by the model is characterised by the duration of a storm event and can be estimated as the river time scale τ_0, associated with river flow. Thus, the developed model is effectively reproducing inter-annual and seasonal hysteresis simultaneously for all considered time scales. The resolved scale 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. The automated logging system continually recalculated storm characteristics, such as the beginning and end stages, and the stage maxima of streamwater response. The procedure resolved the short-term changes and allowed accurate calculation of averaged characteristics for a storm event.

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.

4. INPUTS TO PORT PHILLIP BAY FROM PATTERSON RIVER AND MORDIALLOC MAIN DRAIN

The Patterson River and Mordialloc Main Drain have been identified as one of the major sources of nutrients and toxicants to Port Phillip Bay (NSR Environmental Consultants 1993). The model outlined in Chapter 3 has been applied to estimate daily loads from these sources entering Port Phillip Bay for the period from 1988 to 1994.

4.1. Hydrological conditions

The Patterson River/Mordialloc Main Drain system is mainly fed by the waters of Dandenong and Eumemmerring Creeks (Fig. 4.1). Since the early 80's the low flows from Dandenong Creek are permanently diverted to Mordialloc Main Drain at Pillars Crossing while Patterson River mainly receives storm waters (DVA, 1990). The remaining waters in the Patterson River are from the Eumemmerring Creek. The other major inputs to Mordialloc Main Drain are the Heatherton Drain, Centre Swamp Drain and Settlement Drain, which account for about 10-15% of Mordialloc Main Drain discharge during dry weather conditions.

The median daily flow (representing dry weather base flow) of the Dandenong Creek at Hammond Road is 0.93 m^3/s for the period from 1988 to 1995 (Table 4.1). Further downstream, after receiving discharges from the Mile Creek (0.12 m^3/s) and Dandenong South Treatment Plant (0.4 m^3/s; DVA, 1990), the daily median flow at Greens Road accounts for 1.83 m^3/s. The remaining inputs to Patterson River/ Mordialloc Main Drain system come from the Eumemmerring Creek (0.26 m^3/s) and major drains in the Mordialloc Estuary (0.12 m^3/s; DVA, 1990). Under low flow conditions Dandenong Creek discharges are permanently diverted to Mordialloc Main Drain (1.83 m^3/s for the Dandenong Creek at Greens Road and 1.61 m^3/s for the Mordialloc Main Drain at Pillars Crossing), and under high flow conditions the remainder, between 5.43 m^3/s and 1.95 m^3/s in mean flows, feeds the Patterson River. The maximum flow in the Mordialloc Main Drain at Pillars Crossing never exceeded 9 m^3/s during this period.

Considering inter-annual variations in river flows (Fig. 4.2), the hydrological conditions of the Dandenong Valley are similar to those described for the Yarra River watershed, with a long-term increase in the Yarra River flow from 8 m^3/s in 1979-82 to up to 25 m^3/s in 1992-93 (see Chapter 5, Fig. 5.7). Similar to that trend, the mean annual flows of the Dandenong Creek rose from 3.5 m^3/s in 1988 to almost 7.5 m^3/s in 1992. A decrease in flows in the dry year of 1994 can be identified from both Yarra River and Dandenong Creek measured discharges.

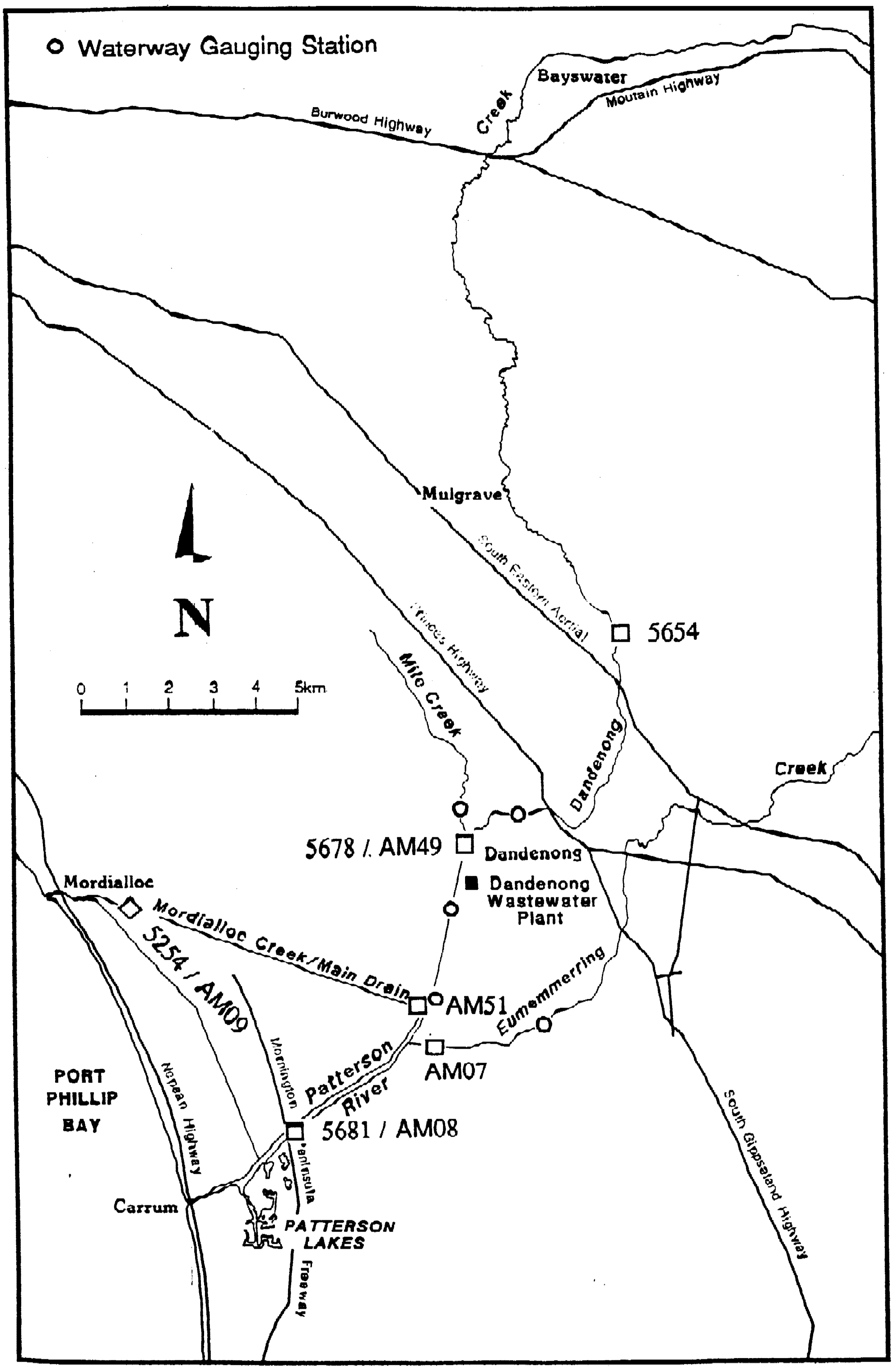

Figure 4.1. Dandenong Creek watershed and the location of the sampling sites.

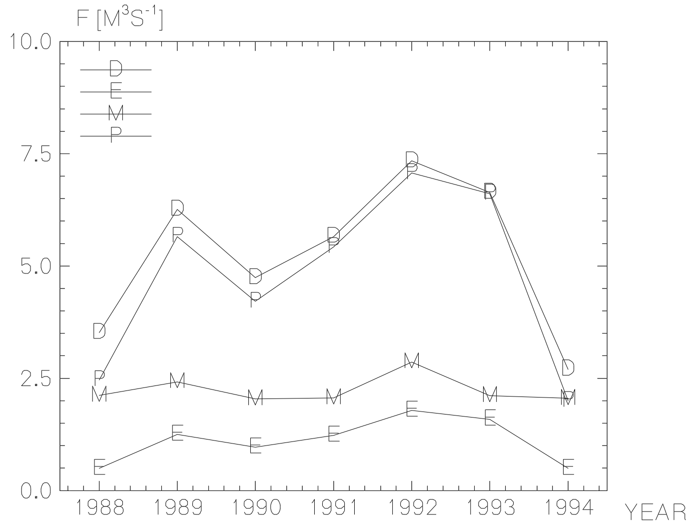

Figure 4.2. Mean annual river discharges during the period 1988-1994.
D - Dandenong Creek at Greens Road;
E - Eumemmerring Creek at Abbots Road;
M - Mordialloc Main Drain at Wells Road (estimated);
P - Patterson River at Mornington Peninsula Freeway (estimated).

Table 4.1: River flows

Stream	Mean flow (m^3s^{-1})	Median daily flow (m^3s^{-1})	0.2% flow exceedence (m^3s^{-1})	Maximum flow (m^3s^{-1})
Dandenong Ck at Hammond Rd, 1988-95	2.93	0.93	65	102
Dandenong Ck at Greens Rd, 1988-95	5.43	1.83	37	39
Mile Ck at Cheltenham Rd 1988-95	0.37	0.12	4	13
Mordialloc Ck at Pillars Crossing 1988-93	1.95	1.61	8	9
Eumemmerring Ck at Abbots Rd 1988-95	1.11	0.26	24	33

4.2. Estimation of loads and concentrations: 1988-1994

In order to account for the balances between flows and loads upstream and downstream of the diversion point at Pillars Crossing, the concentrations and loads for all water-quality variables have been estimated for the five sites: Dandenong Creek at Hammond Rd, Dandenong Creek at Olive Grove, Eumemmerring Creek at Worsley Rd, Mordialloc Main Drain at Wells Rd, and Patterson River at Mornington Peninsula Freeway. For the numerical predictions of water-quality variables we used equations (3.4) - (3.5). The model parameters and error analyses for all cases are summarised in Tables 4.2 and 4.3, and estimated annual loads and concentrations for the Mordialloc Main Drain and Patterson River are shown in Figs 4.3 - 4.19.

To estimate river flows for Mordialloc Main Drain at Wells Rd and Patterson River at Mornington Peninsula Freeway the following procedure has been adopted. The Patterson River discharge comprises Dandenong Creek storm water plus Eumemmerring Creek discharge:

$$F_{PR} = F_{GR} + F_{EC} - F_{PC}$$

where F_{PR} is the Patterson River discharge at Mornington Peninsula Freeway, F_{GR} is the Dandenong Creek discharge at Greens Rd, F_{EC} is the Eumemmerring Creek discharge at Abbots Rd, and F_{PC} is the Mordialloc Main Drain discharge at Pillars Crossing. In the cases where the discharge at Pillars Crossing exceeded the Dandenong Creek discharge at Greens Rd, it was assumed that the Patterson River received at least 0.4 m^3/s from the Dandenong Creek.

To calculate loads for the Mordialloc Main Drain it was assumed that they consist of loads generated in the Dandenong Creek catchment and coming from the Dandenong Creek at its diversion point and loads generated in the lower catchment of the Mordialloc Creek Estuary. The total discharge from the estuarine drain inputs was assumed to be equal to the discharge of the Mile Creek, the median flow of which is very close to the estimates provided by the Dandenong Valley Authority (DVA, 1990) for the total discharge of Mordialloc Estuary drains during dry weather.

The numerical prediction of water quality variables with fixed model parameters at all sites over the 7-year period of measurements produced in general had a high accuracy with normalised errors on average less than 5% for the nutrients and about 10% for the metals (Tables 4.2, 4.3). A low level of accuracy was obtained for cadmium (30-58%), total chromium (23-48%), lead (10-58%) and nickel (14-32%), where the number of water samples with concentration lower than the level of detection was about 55%, 40-50%, 15% and 10% of the total number of measurements respectively. The low level of accuracy for ammonium, orthophosphate ant total phosphorus for Mordialloc Main Drain probably related to discharge reduction and water quality improvement in effluent from the DSTP over the last seven years. The DSTP discharged to Dandenong Creek until 1 July 1994 after which it was diverted to the South East Purification Plant pipeline.

Table 4.2: Estimated mean concentrations and loads, and model parameters (1988-94).

Variable	Statistical characteristics		Model parameters		Accuracy
	$\langle C \rangle$ mg/L	$\langle Q^{-} \rangle$ kg/day	γ	w kg/m^2/s x 10^{12}	R
NO_X	0.752	242	1.05	1.3	0.04
	0.820	267	1.00	14	0.11
	2.19	163	0.80	6.3	0.06
	1.91	365	0.95	31	0.17
	1.59	502	0.90	13	0.15
NH_3	-	-	-	-	-
	0.109	28	1.00	0.76	0.11
	0.488	28	0.85	6.2	0.50
	4.94	698	0.55	-	0.60
	0.60	223	1.00	1.8	0.28
TKN	0.918	328	1.05	1.3	0.04
	1.17	412	1.05	31	0.02
	2.08	240	1.15	100	0.01
	7.67	1,171	0.60	48	0.52
	2.08	960	1.05	21	0.07
Total N	1.67	568	1.05	2.6	0.02
	2.01	669	1.05	42	0.01
	3.48	366	1.00	100	0.01
	9.72	1,590	0.70	92	0.37
	3.14	1,447	1.05	37	0.05
PO_4	0.067	11	0.95	0.17	0.15
	0.094	23	1.25	8.1	0.07
	1.05	43	0.70	9.4	0.07
	2.04	297	0.50	14	0.65
	0.38	134	0.95	3.3	0.20
Total P	0.154	42	0.95	-	0.04
	0.207	59	1.05	12	0.06
	1.33	69	0.75	12	0.02
	2.47	372	0.55	19	0.48
	0.56	201	0.95	4.0	0.06
NFR	32.7	17,600	1.10	2800	0.04
	35.9	23,800	1.10	210	0.05
	-	-	-	-	-
	60	14,100	1.35	1300	0.21
	61	32,700	1.10	1400	0.11
SS	-	-	-	-	-
	36.3	20,400	1.25	670	0.03
	42.5	7,400	1.30	570	0.01
	26.6	6,900	1.25	560	0.03
	56	36,100	1.20	690	0.07
Turbidity	31.1	16,300	1.00	2500	0.02
	38.8	19,600	1.10	1000	0.02
	46.5	8,600	1.25	630	0.01
	48	16,900	1.25	910	0.16
	61	35,800	1.15	1300	0.05

Note: The five numbers in each cell relate to Dandenong Ck. at Hammond Rd (top), Dandenong Ck. at Olive Grove, Eumemmerring Ck. at Worsley Rd, Mordialloc Ck. at Wells Rd, and Patterson River at Mornington Peninsula Fwy (bottom).

Table 4.3: Estimated mean concentrations and loads, and model parameters (1988-94).

Variable	Statistical characteristics		Model parameters		Accuracy
	$\langle C \rangle$ mg/L	$\langle Q^- \rangle$ kg/day	γ	W kg/m^2/s x 10^{12}	R
As	0.0013 0.0024 0.0027 0.0030	0.60 0.97 0.62 1.22	0.95 1.00 1.40 1.00	0.018 0.019 0.18 0.043	0.02 0.06 0.03 0.01
Cd	0.00024 0.00035 0.00043 0.00025	0.065 0.120 0.085 0.133	0.80 0.80 1.05 1.10	0.0022 0.0028 0.0077 0.0040	0.36 0.58 0.37 0.30
Cr	0.0023 0.0034 0.0070 0.0034	0.72 1.08 1.17 1.11	1.00 1.00 0.75 0.90	0.0065 0.0057 0.049 0.033	0.23 0.27 0.48 0.35
Hg	0.000024 0.000020 0.000022 0.000021	0.0045 0.0052 0.0041 0.0075	0.90 0.95 0.95 0.95	0.19e-3 0.19e-3 0.31e-3 0.20e-3	0.03 0.01 0.01 0.01
Ni	0.0027 0.0039 0.0075 0.0040	0.57 0.97 1.88 1.68	0.80 0.85 1.55 1.00	0.026 0.036 - 0.050	0.32 0.16 0.22 0.14
Pb	0.0069 0.0085 0.0156 0.0126	2.67 3.83 3.39 5.16	0.90 1.00 1.20 1.00	0.080 0.086 0.22 0.13	0.35 0.37 0.58 0.10
Cu	0.0053 0.0084 0.0117 0.0077	1.57 2.44 2.26 3.25	0.90 1.00 1.00 1.00	0.046 0.024 0.17 0.089	0.08 0.09 0.16 0.04
Zn	0.068 0.120 0.107 0.073	24 38 25 34	0.90 0.85 1.30 1.05	0.77 1.10 16 0.91	0.09 0.25 0.12 0.09

Note: The four numbers in each cell relate to Dandenong Ck at Hammond Rd (top), Dandenong Ck at Olive Grove, Mordialloc Ck at Wells Rd, and Patterson River at Mornington Peninsula Fwy (bottom).

The most pronounced changes occured in the concentration and load for ammonium and total kjeldahl nitrogen in Mordialloc Main Drain (Figs. 4.15, 4.16). Over the period the mean annual concentration for ammonium dropped from 12 mg/L in 1988 to 2 mg/L in 1994, thus the load in Mordialloc Main Drain contracted dramatically from 1400 kg/day to 300 kg/day. Further upstream in Mordialloc Main Drain at Pillars Crossing the reduction in mean annual concentration for the same period was from 14.3 mg/L to 2 mg/L. The concentration of ammonium in effluent from DSTP was 26 mg/L in 1989-1990 (DVA, 1990).

By contrast the annual concentration and load of orthophosphate and total phosphorus in Mordialloc Main Drain remained approximately constant over the period (Figs. 4.18, 4.19). Concentrations of PO_4 and total P in Mordialloc Main Drain (2.04 mg/L and 2.47 mg/L, Table 4.3) were more than 20 times higher than in Dandenong Creek at Olive Grove (0.094 mg/L and 0.207 mg/L) and is indicative that the major source of these species was the DSTP with an average concentration of orthophosphate in the effluent of about 7.5 mg/L (DVA, 1990). At the same time, these estimates for Mordialloc Main Drain are very close to those obtained for the period 1979-81 (NSR Environmental Consultants, 1993). Very high concentrations of orthophosphate and total P in the Eumemmerring Creek were also noted.

Because effluent from the DSTP was being discharged into Dandenong Creek and it was constantly diverted at low flows to Mordialloc Main Drain, the concentrations and loads for the Mordialloc Main Drain for all nutrients, except oxidised nitrogen and dissolved organic N, were higher then those estimated for the Patterson River.

The concentrations of the metals are generally higher in the Mordialloc Main Drain then in the Patterson River (Table 4.2, Figs. 4.3 - 4.10). However, because of difference in discharges, the loads of metals in Patterson River on average exceeded significantly the loads in the Mordialloc Main Drain, especially during wet years due to intensive runoff. The inter-annual variation in metals discharges from the Patterson River are entirely determined by changes in annual river flow. Among the toxicants, only mercury concentrations in both streams are the same (Fig. 4.7), though more than 90% of water samples had concentration of Hg lower than the level of detection. In considering trends in metal concentrations over the last 7 years, the most pronounced changes are the reduction in chromium (Fig. 4.5) and increase in arsenic (Fig. 4.3), nickel (Fig. 4.8) and zinc (Fig. 4.10) in the Mordialloc Main Drain at Wells Road.

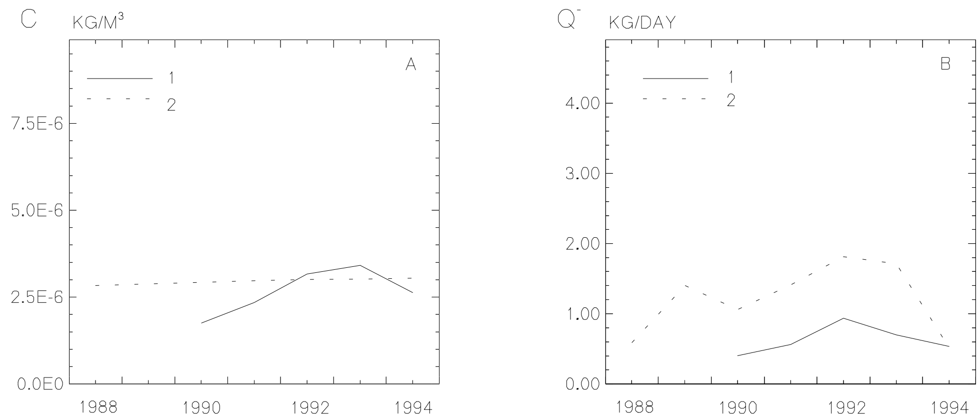

Figure 4.3. Predicted annual concentration (a) and load (b) for arsenic (As).
1 - Mordialloc Main Drain; 2 - Patterson River.

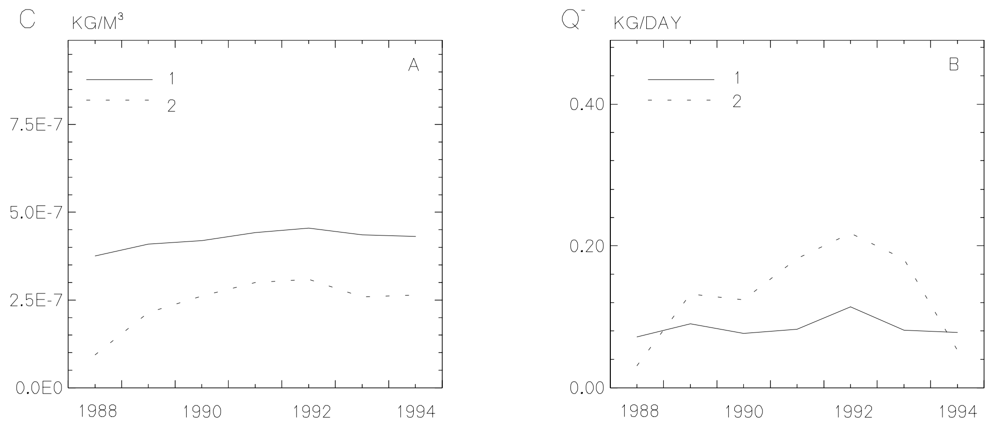

Figure 4.4. Predicted annual concentration (a) and load (b) for cadmium (Cd).
1 - Mordialloc Main Drain; 2 - Patterson River.

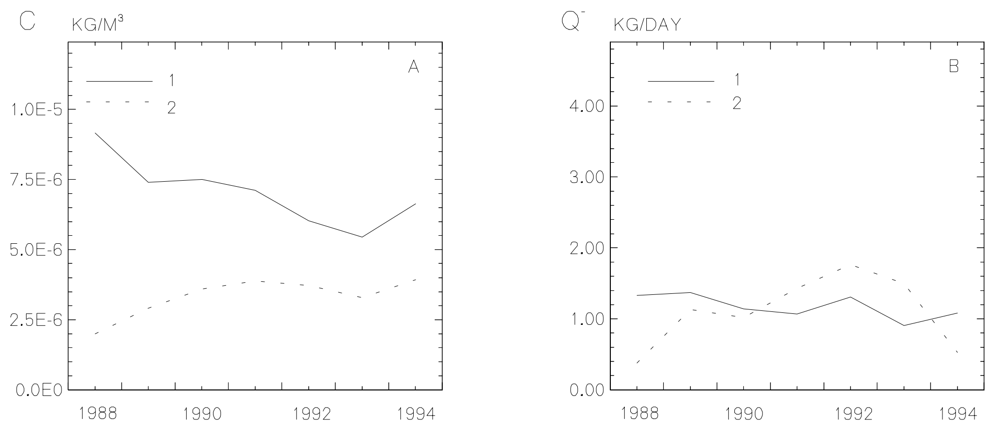

Figure 4.5. Predicted annual concentration (a) and load (b) for total chromium (Cr).
1 - Mordialloc Main Drain; 2 - Patterson River.

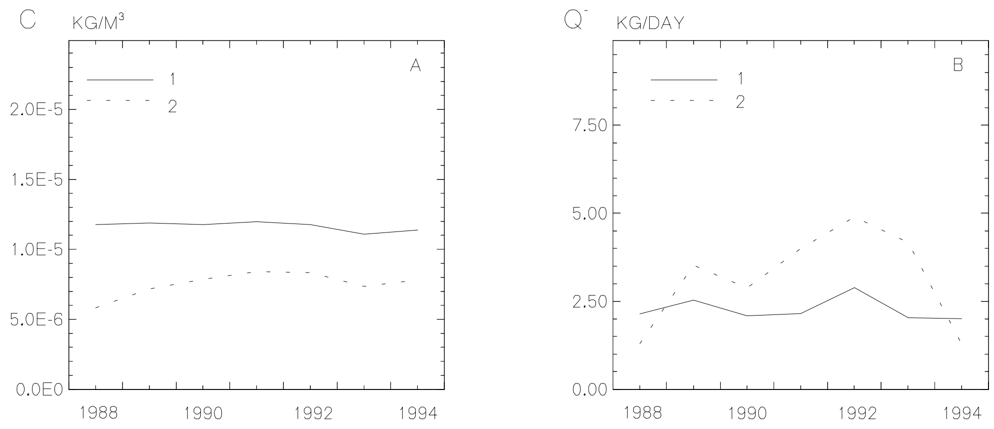

Figure 4.6. Predicted annual concentration (a) and load (b) for copper (Cu).
1 - Mordialloc Main Drain; 2 - Patterson River.

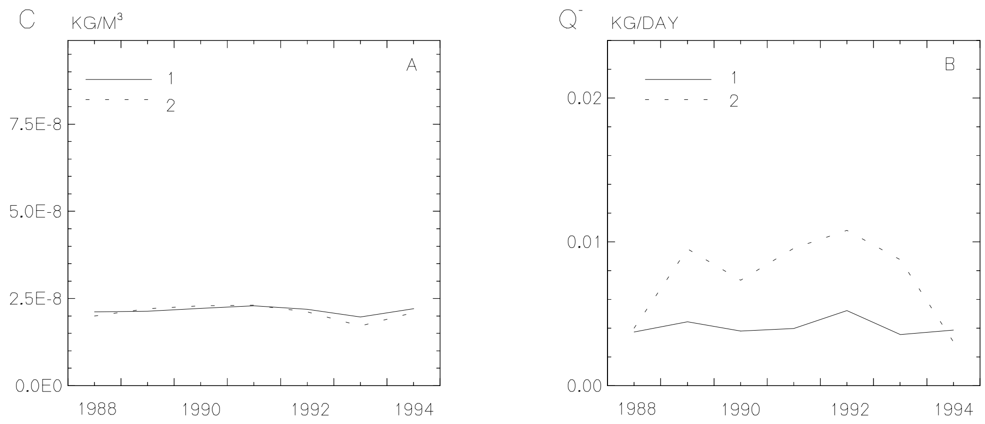

Figure 4.7. Predicted annual concentration (a) and load (b) for mercury (Hg).
1 - Mordialloc Main Drain; 2 - Patterson River.

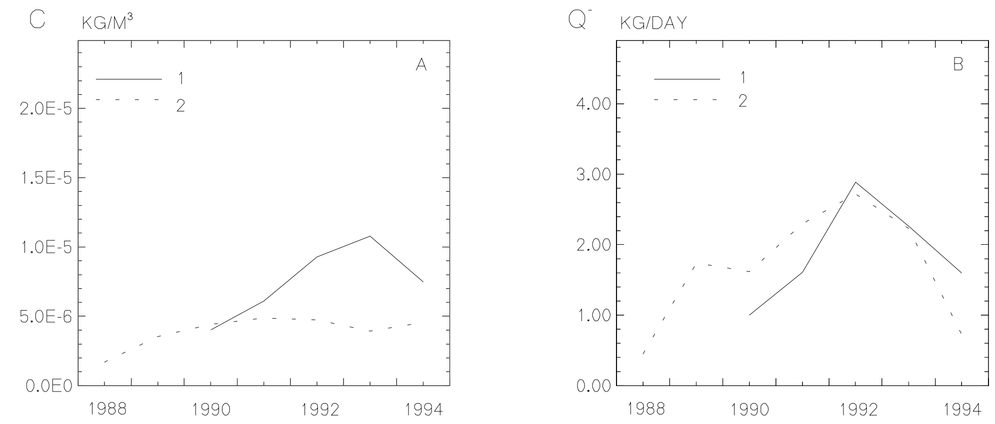

Figure 4.8. Predicted annual concentration (a) and load (b) for nickel (Ni).
1 - Mordialloc Main Drain; 2 - Patterson River.

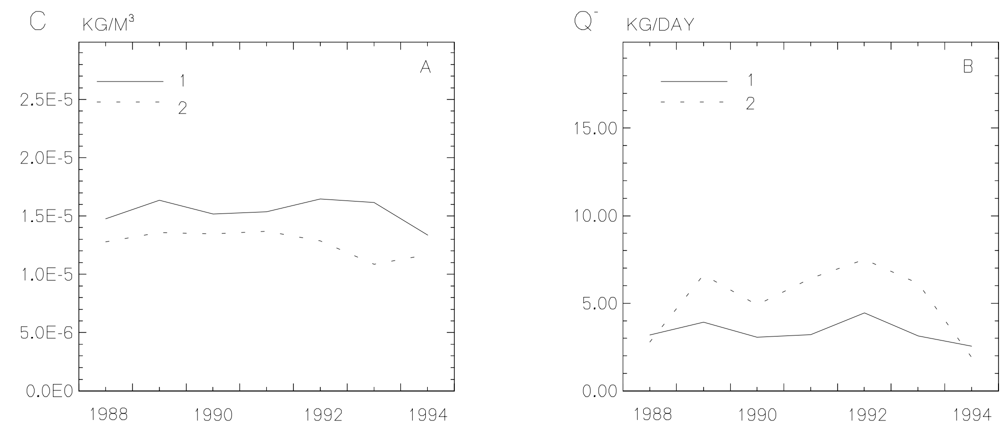

Figure 4.9. Predicted annual concentration (a) and load (b) for lead (Pb).
1 - Mordialloc Main Drain; 2 - Patterson River.

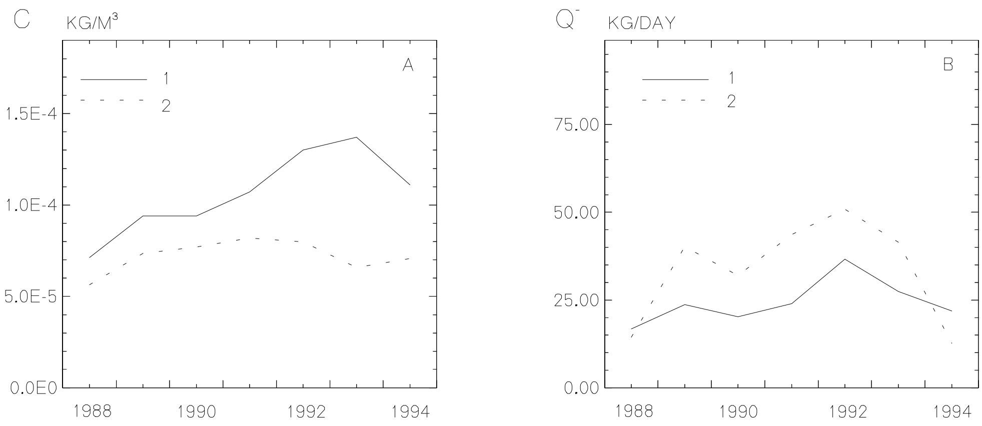

Figure 4.10. Predicted annual concentration (a) and load (b) for zinc (Zn).
1 - Mordialloc Main Drain; 2 - Patterson River.

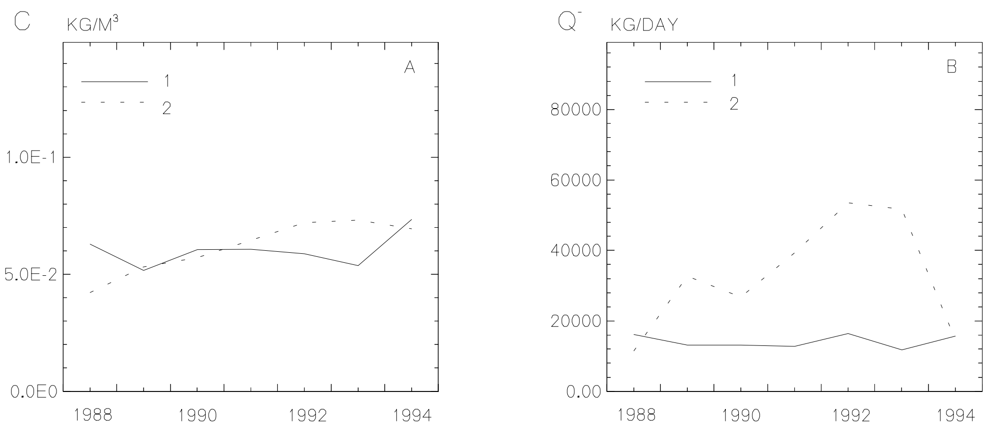

Figure 4.11. Predicted annual concentration (a) and load (b) for nonfiltrable residue (NFR). 1 - Mordialloc Main Drain; 2 - Patterson River.

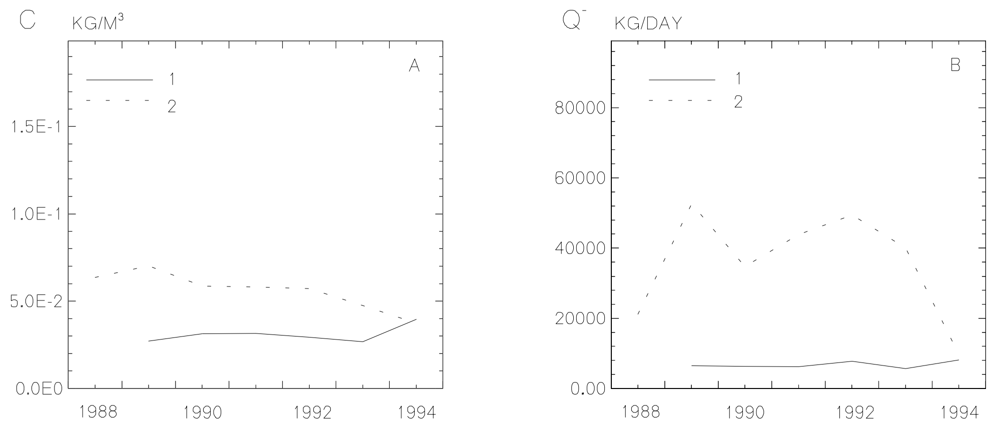

Figure 4.12. Predicted annual concentration (a) and load (b) for suspended solids (SS).
1 - Mordialloc Main Drain; 2 - Patterson River.

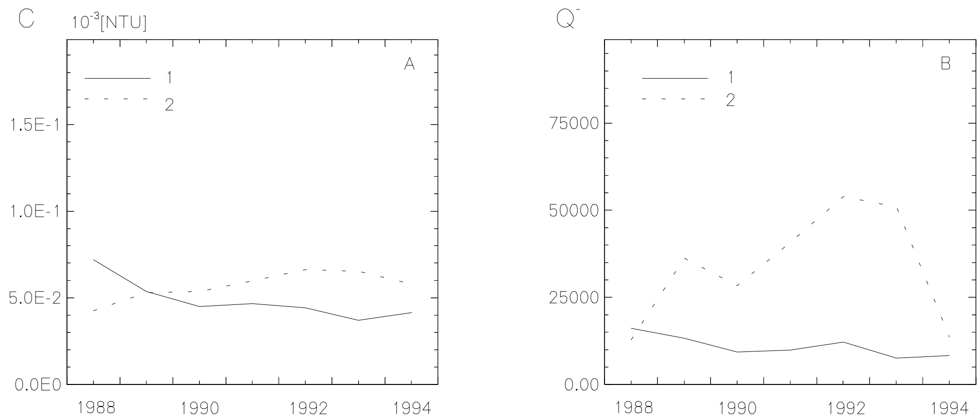

Figure 4.13. Predicted annual concentration (a) and load (b) for turbidity.
1 - Mordialloc Main Drain; 2 - Patterson River.

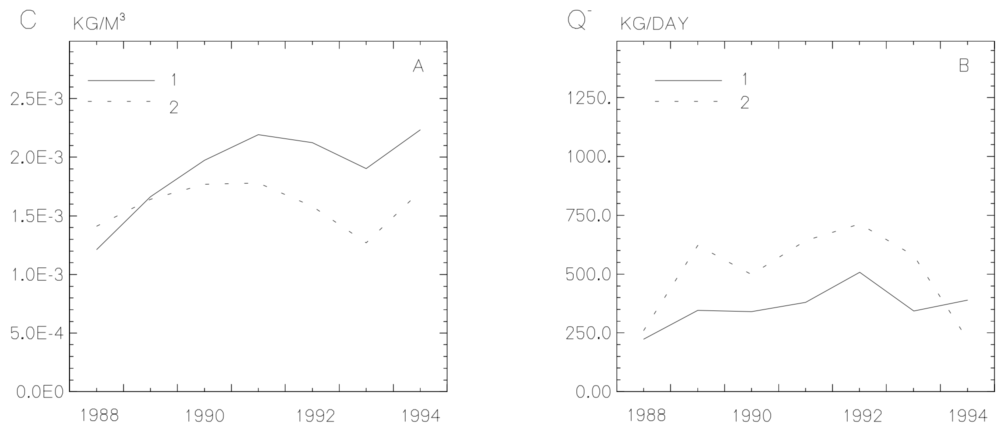

Figure 4.14. Predicted annual concentration (a) and load (b) for nitrate + nitrite (NO_x).
1 - Mordialloc Main Drain; 2 - Patterson River.

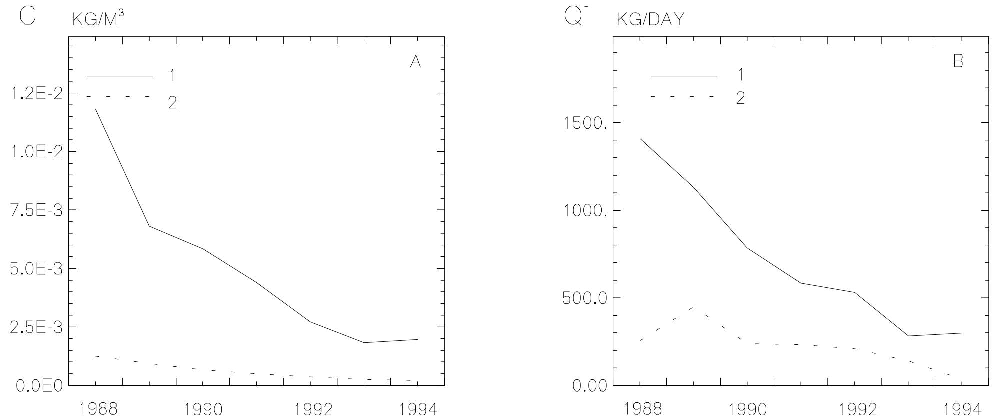

Figure 4.15. Predicted annual concentration (a) and load (b) for ammonium (NH_3).
1 - Mordialloc Main Drain; 2 - Patterson River.

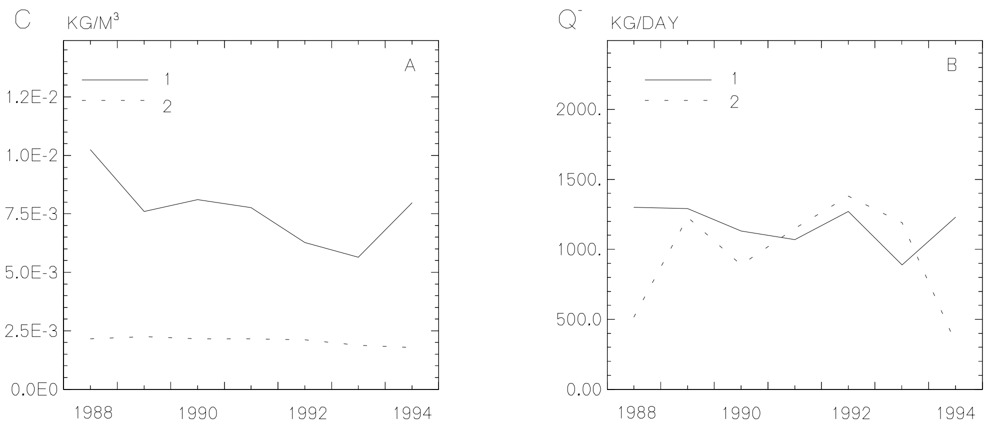

Figure 4.16. Predicted annual concentration (a) and load (b) for total kjeldahl nitrogen (TKN). 1 - Mordialloc Main Drain; 2 - Patterson River.

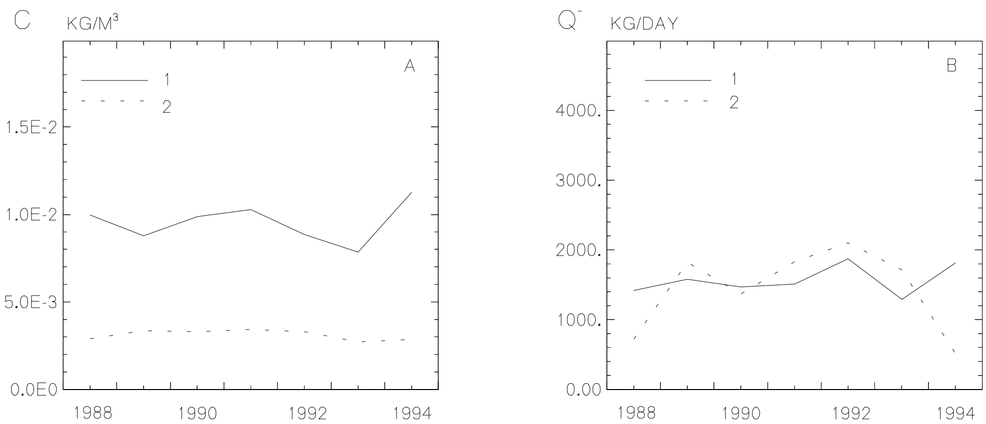

Figure 4.17. Predicted annual concentration (a) and load (b) for total nitrogen (NTOT). 1 - Mordialloc Main Drain; 2 - Patterson River.

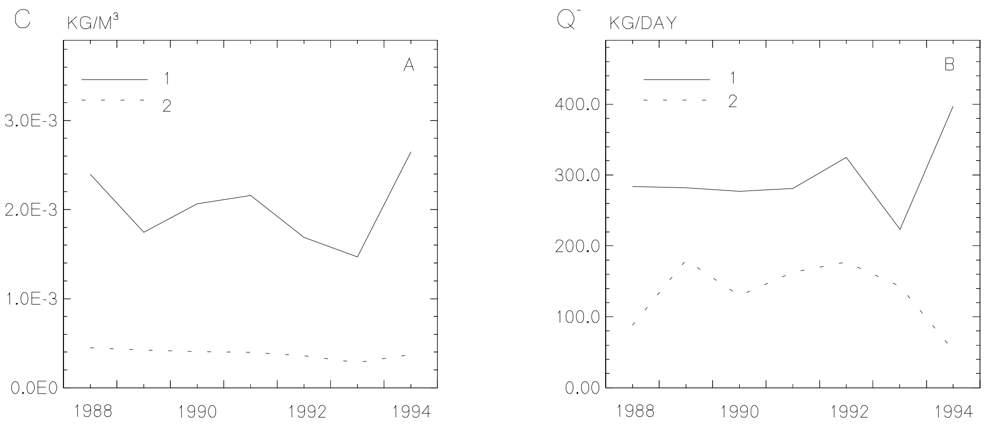

Figure 4.18. Predicted annual concentration (a) and load (b) for ortho-phosphate (PO_4). 1 - Mordialloc Main Drain; 2 - Patterson River.

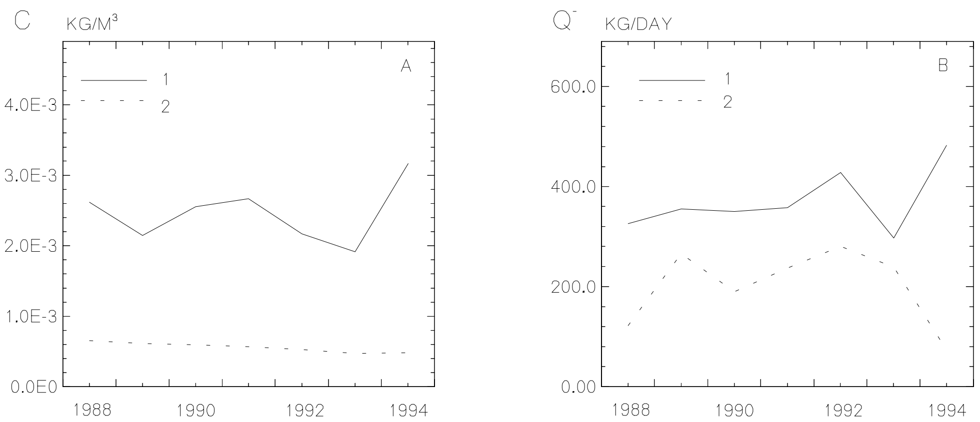

Figure 4.19. Predicted annual concentration (a) and load (b) for total phosphorus (PTOT). 1 - Mordialloc Main Drain; 2 - Patterson River.

5. INPUTS TO PORT PHILLIP BAY FROM THE YARRA RIVER

5.1. Study area

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 (Fig. 5.1).

Physiographic description

The Yarra is the major river running through the City of Melbourne, draining a middle part of Victoria into Port Phillip Bay (Fig. 5.1). The total area of the Yarra catchment is approximately 4,000 km^2 (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 km^2. Another principal tributary of the Yarra River which drains the inner south-eastern suburbs of Melbourne is Gardiners Creek (115 km^2), while Merri Creek (397 km^2) and Moonee Ponds Creek (145 km^2) drain the northern suburbs.

The Yarra River and Gardiners Creek catchments are underlain primarily by Palaeozoic sedimentary rocks - mudstone and sandstone. Soils of both catchments are dominated by soloths (yellow and red duplex soils) and alluvial soils. The Maribyrnong River catchment is underlain by Quaternary, some Tertiary, rocks (mainly olivine basalts) and in the valley by mudstone and sandstone. The soils in this area are classified as solodic (yellow-brown sodic duplex soils).

The precipitation is highly variable over the watershed from 1400-1500 mm per year in the upper part of the Yarra River catchment to 600-700 mm per year for the main part of the Maribyrnong River catchment. Rainfall generally increases with elevation above sea level. The influence of topography on rainfall differs between summer and winter because of the critical difference in the height of the cloud base between seasons. As a result, rain occurs more frequently in winter than in summer, but summer falls are generally heavier. The Yarra River catchment is characterised by a maximum rainfall in October and a minimum rainfall in January and June-July. For the Maribyrnong River basin, the wettest months are June-August while January is the driest.

January and February are the hottest months throughout Victoria, with average maximum temperatures around 20ºC. In winter, maxima range from below 10ºC in the high country to 13ºC in coastal areas. On the higher mountains, above 800 m (the upper part of the Yarra River catchment), much of the precipitation in winter is in the form of snow, with the snow season lasting from June to October.

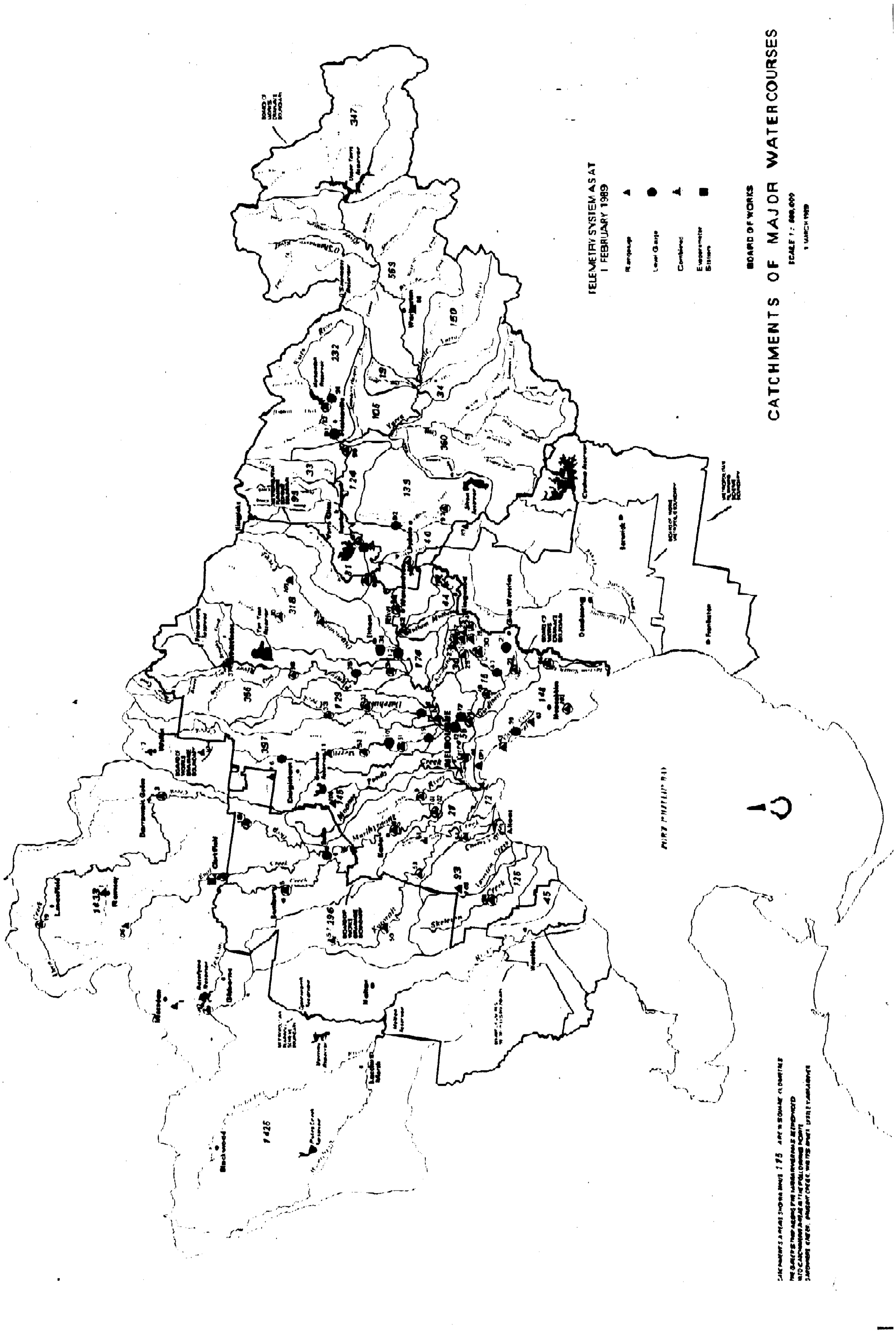

Figure 5.1. Yarra River watershed and the location of the sampling site.

Table 5.1: River flows

Stream	Mean flow (m^3/s)	Median daily flow (m^3/s)	0.2% flow exceedence (m^3/s)	Maximum flow (m^3/s)
Yarra River: Chandler Hwy - 1979-95	15.97	8.43	168	218
Maribyrnong River - 1980-95	3.40	0.79	120	415
Moonee Ponds Creek - 1990-95	0.90	0.63	11	17
Merri Creek - 1980-95	1.09	0.20	28	99
Gardiners Creek - 1980-95	0.87	0.29	17	50

The median daily flow of the Yarra River is almost 8.5 m^3/s. The flow at Chandler Hwy (Fig. 5.1) 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 m^3/s (February) to 31 m^3/s (September). The annual flows for the same period are in the range 4.7 to 28.5 m^3/s, with a mean annual flow of 15.97 m^3/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 m^3/s 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.

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.

5.2. Estimation of upstream 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.

Two examples of the numerical simulations for TKN in the Yarra River and total P in the Maribyrnong River using equations (3.4)-(3.5) are presented in Figs. 5.2 and 5.3, and the estimation of the model parameters and error analyses for all cases are summarised in Tables 5.2 and 5.3.

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 5.2). 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 5.3). 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. For the period from 1988 to 1995 the highest average concentration of ammonium was found in Gardiners Creek (0.181 mg/L), while the highest average level of orthophosphate was estimated for Moonee Ponds Creek (0.107 mg/L; Table 5.3).

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 (Fig. 5.4), 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 (Fig. 5.7), the chemical loads of these metals in the river (Fig. 5.8) 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 (Figs. 5.5, 5.6). These changes cause the constant elevation in total P loads during the last 15 years (Fig. 5.9). 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 (Fig. 5.10).

It should be noted, that the temporal changes in discharges, concentrations and loads for most of the water quality variables are characterised by large sub-annual variability. In the majority of cases, the empirical distributions are strongly positively skewed, and the sampling mean values exceed mode and median values considerably. In this respect, the estimations based on the field measurements with an inadequate sampling strategy may tend to underestimate (or overestimate) loads. Utilisation of flow weighted mean concentration for load calculations does not appear to resolve the problem. Indeed, for correlated processes x and y

$$\langle xy \rangle = \langle x \rangle \langle y \rangle + \sigma_x \sigma_y \rho_{xy};$$

where $\langle x \rangle$ and $\langle y \rangle$ are the mean values, σ_x and σ_y are the standard deviations, and ρ_{xy} is a correlation coefficient. Thus, for correlated processes with high variance (discharge and concentration), the loads estimations should be based on the flow weighted mean concentrations. However, distortions in empirical distributions created due to inadequate sampling cause significant errors in load estimations (Fig. 5.11).

Table 5.2: Estimated mean concentrations and loads, and model parameters (1979-87).

Variable	Statistical characteristics		Model parameters		Accuracy
	$\langle C \rangle$ mg/L	$\langle Q^- \rangle$ kg/day	γ	w kg/m^2/s x 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

Note: The three numbers in each cell relate to Yarra River (top), Maribyrnong River (middle), and Gardiners Creek (bottom).

Table 5.3 Estimated mean concentrations and loads, and model parameters (1988-95).

Variable	Statistical characteristics		Model parameters	Accuracy
	$\langle C \rangle$ mg/L	$\langle Q^- \rangle$ kg/day	γ	R
NO_X	0.67 0.80 1.36 0.66 0.78	1,080 156 133 73 92	1.15 0.80 1.20 1.20 1.15	0.16 0.24 0.31 0.03 0.25
NH_3	0.044 0.078 0.102 0.140 0.181	90 25 19 8 21	1.25 1.00 1.95 0.80 1.15	0.22 0.13 0.19 0.12 0.52
TKN	0.77 0.99 1.84 1.24 1.11	2,020 486 218 182 131	1.55 1.15 1.50 1.15 1.15	0.19 0.02 0.79 0.03 0.19
NTOT	1.32 1.67 3.19 1.75 1.91	3,120 630 350 250 224	1.45 1.05 1.40 1.15 1.15	0.14 0.02 0.62 0.01 0.14
PO_4	0.044 0.031 0.107 0.075 0.040	59.1 8.0 12.9 9.4 6.0	0.85 0.90 1.50 1.10 1.30	0.74 0.32 0.84 0.04 0.28
PTOT	0.136 0.083 0.233 0.162 0.149	270 60 30 26 19	1.35 1.30 1.60 1.20 1.20	0.44 0.04 0.71 0.01 0.31
Cu (Yarra R.)	0.0038	7.6	1.20	0.33
Pb (Yarra R.) (Maribyr. R.)	0.0074 0.0032	14.7 1.0	1.20 1.40	0.52 0.19
Zn (Yarra R.)	0.0356	59	2.15	0.47
NFR (Yarra R.) (Maribyr. R.)	68 27	169,700 49,900	1.60 1.65	0.14 0.04
SS (Moonee Ponds) (Merri Creek) (Gardiners Ck.)	36 23 65	8,350 7,300 9,740	2.15 1.50 1.30	0.19 0.03 0.46
TURB	52 61 21 27 72	125,200 42,500 5,360 9,600 9,100	1.40 1.30 2.25 1.55 1.20	0.26 0.12 0.09 0.04 0.24

Note: The five numbers in each cell relate to Yarra River (top), Maribyrnong River, Moonee Ponds Creek, Merri Creek and Gardiners Creek (bottom).

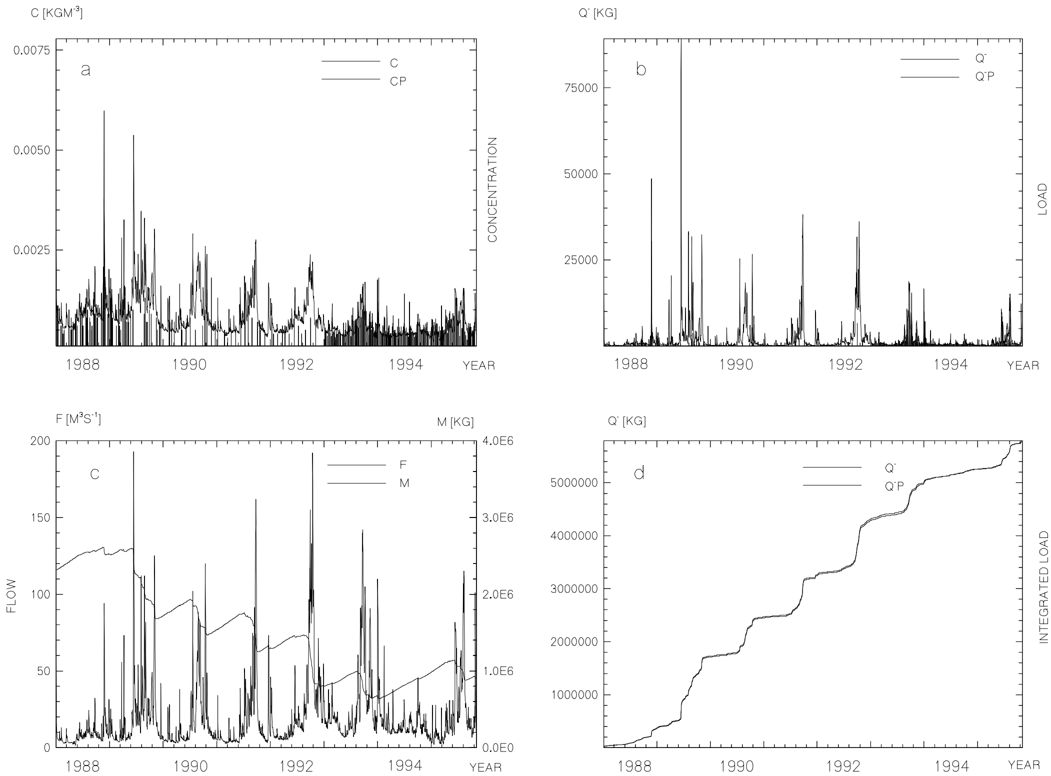

Figure 5.2. Time evolution of modelled parameters for TKN in the Yarra River during the period 1988-1995.

(a) observed (thin line) and predicted (thick line) concentrations; (b) observed (thin line) and predicted (thick line) loads in the river; (c) river discharge (thin line) and total mass of chemical element in the catchment (thick line); (d) observed (thin line) and predicted (thick line) time integrated loads in the river. Notably, the agreement between model and data is very close and the predicted and observed curves mostly coincide.

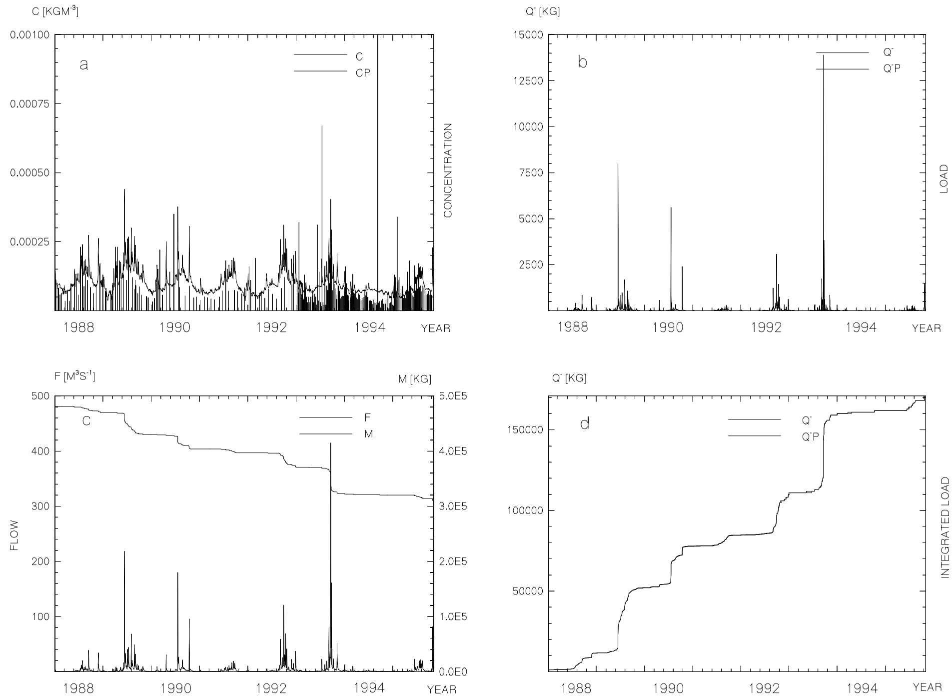

Figure 5.3. Time evolution of modelled parameters for total P in the Maribyrnong River during the period 1988-1995.

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

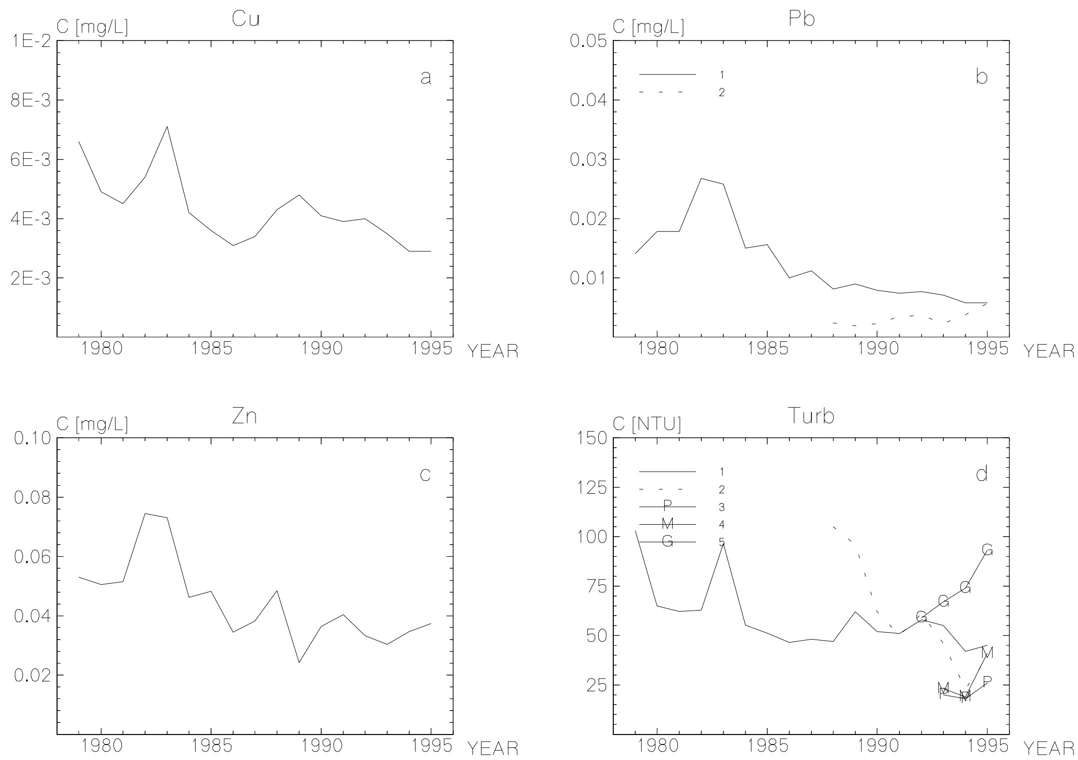

Figure 5.4. Predicted annual concentration: (a) copper; (b) lead; (c) zinc; (d) turbidity. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

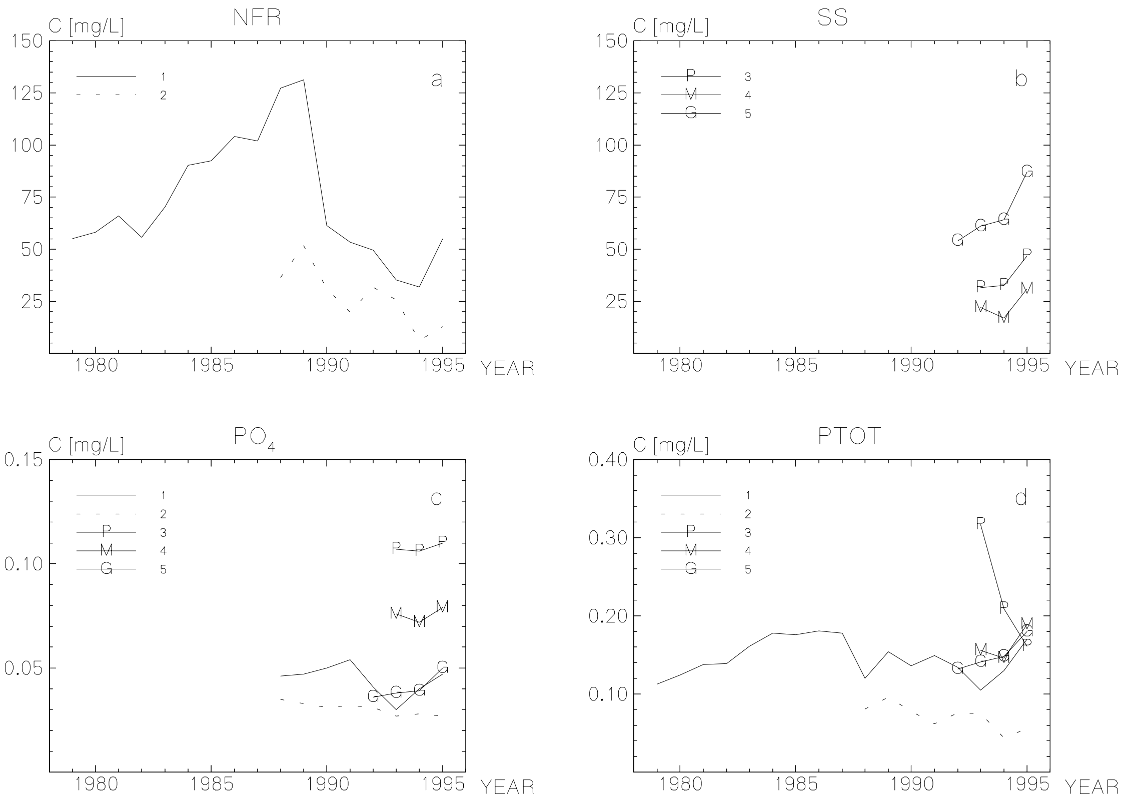

Figure 5.5. Predicted annual concentration: (a) non-filtered residue; (b) suspended solids; (c) orthophosphate; (d) total P. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

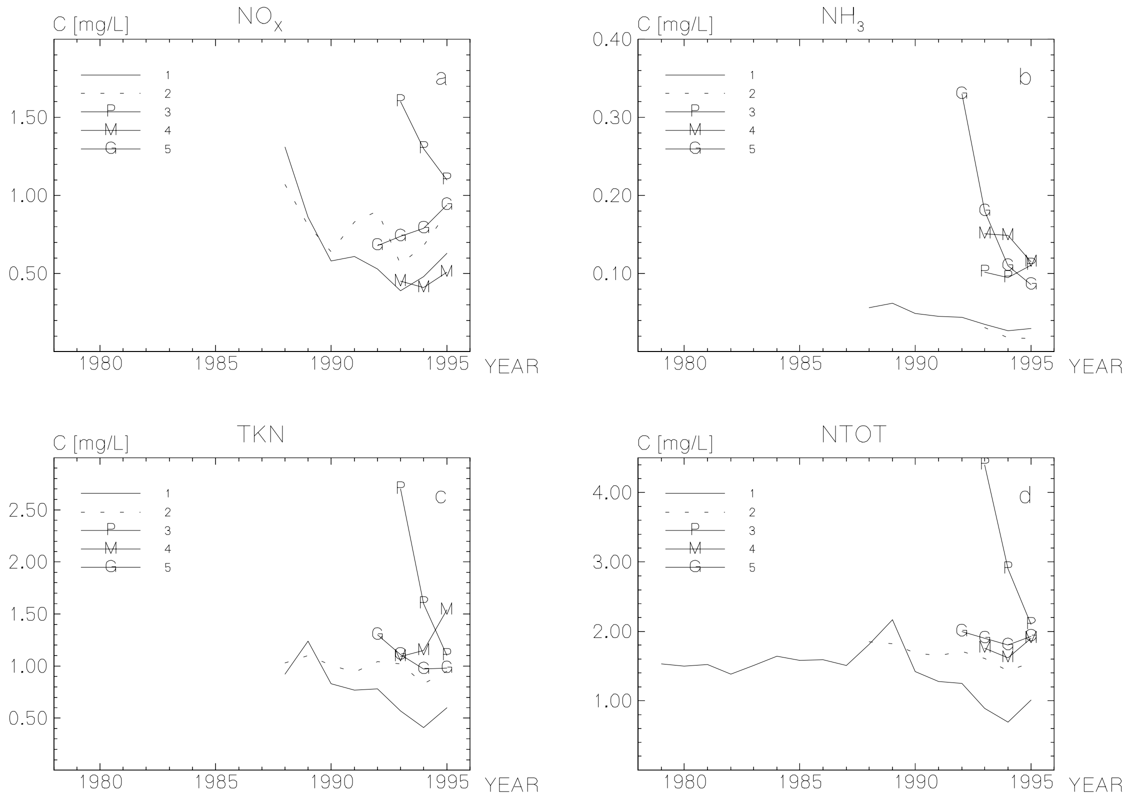

Figure 5.6. Predicted annual concentration: (a) oxidised N; (b) ammonium; (c) kjeldahl N; (d) total N. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

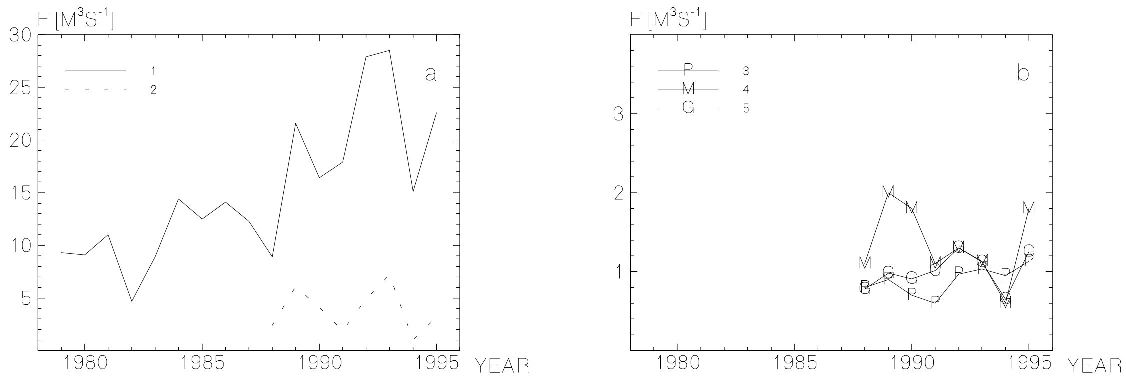

Figure 5.7. Mean annual river discharge. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

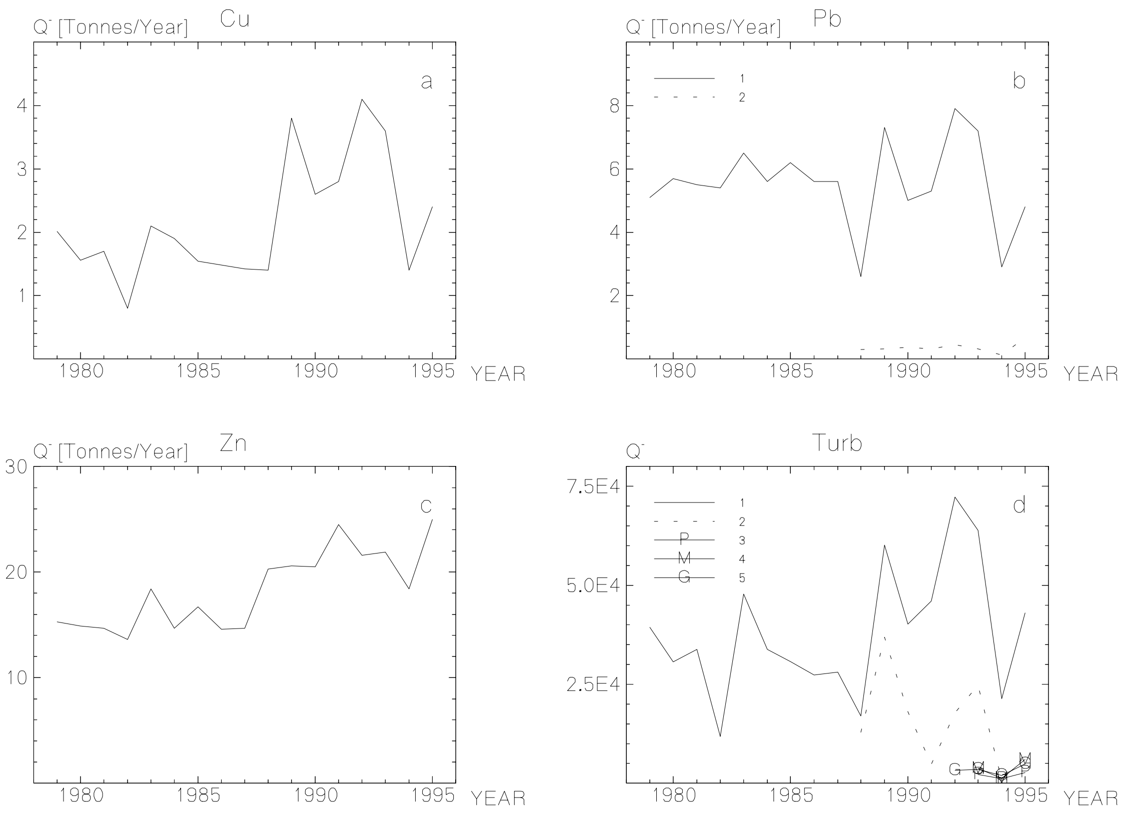

Figure 5.8. Predicted annual load: (a) copper; (b) lead; (c) zinc; (d) turbidity.
1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

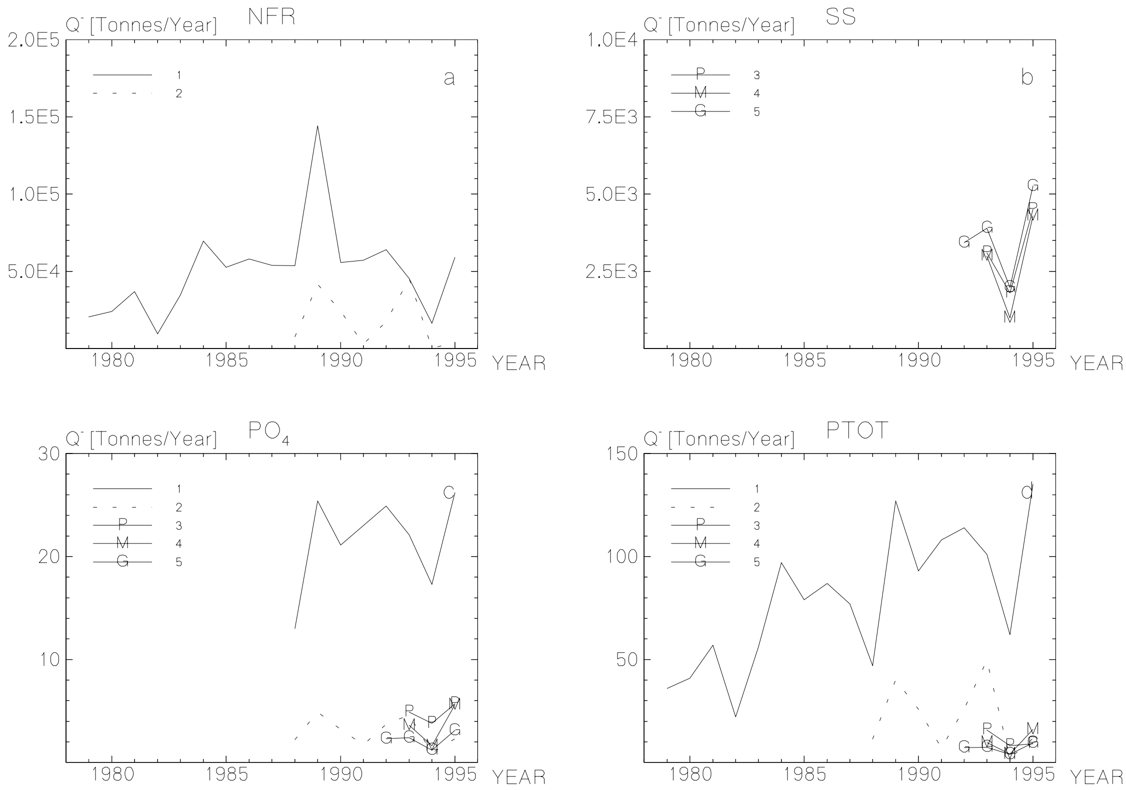

Figure 5.9. Predicted annual load: (a) non-filtered residue; (b) suspended solids; (c) orthophosphate; (d) total P. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

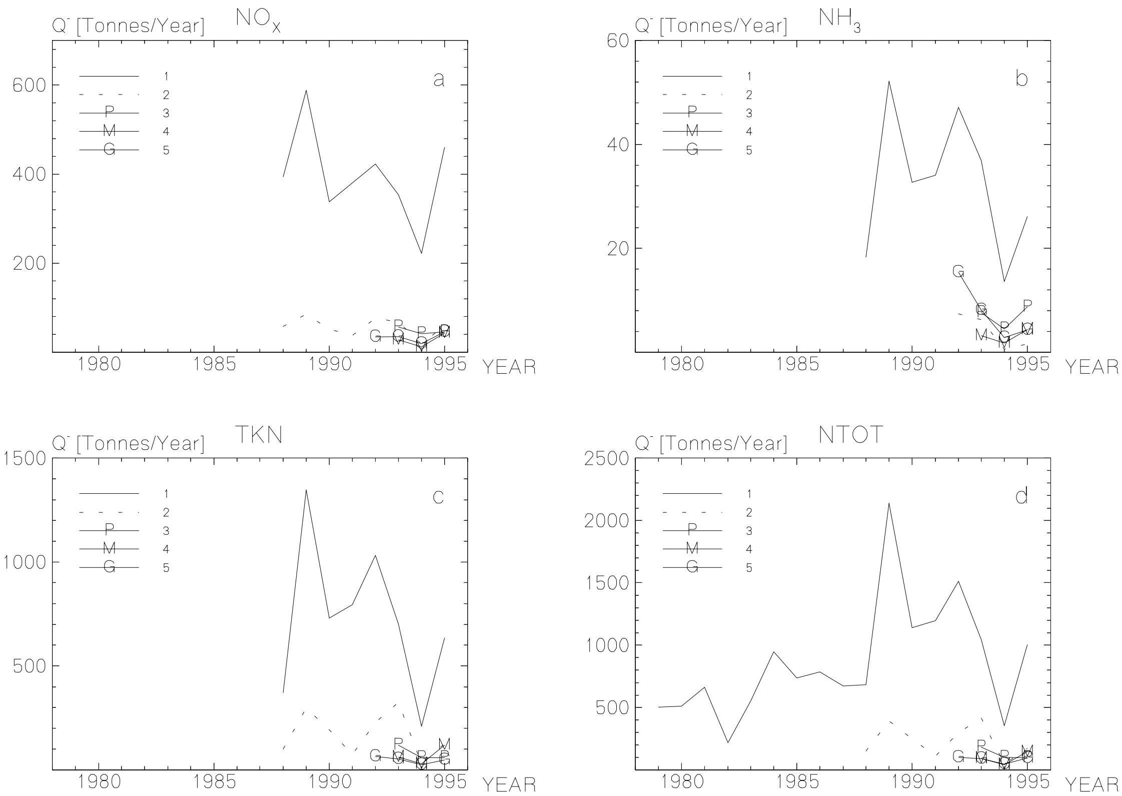

Figure 5.10. Predicted annual load: (a) oxidised N; (b) ammonium; (c) kjeldahl N; (d) total N. 1 - Yarra River; 2 - Maribyrnong River; 3 - Moonee Ponds Creek; 4 - Merri Creek; 5 - Gardiners Creek.

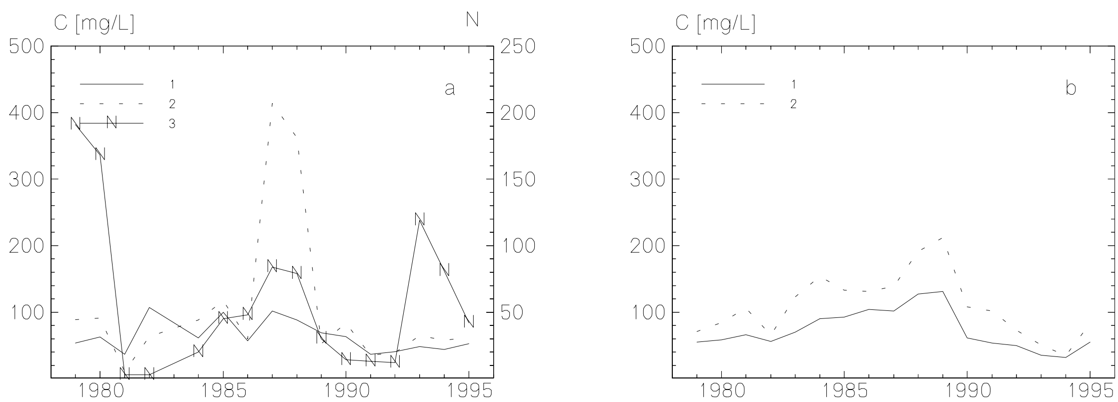

Figure 5.11. Comparison between mean annual concentration (1) and flow weighted mean annual concentration (2) for non-filtered residue.
(a) - observed concentration; (b) - predicted concentration; 3 - number of measurements (N).

5.3. Total loads at Westgate Bridge

To estimate total loads of nutrients and toxicants derived from the Yarra River, the historical upstream measurements have been related to those downstream at Westgate Bridge, near the entrance to Port Phillip Bay. The six month measurement program implemented in 1995 at Westgate Bridge resulted in continuous observations of river discharges and water quality variables from five depth levels with a more intensive sampling strategy during high flow events.

Hydrological structure and circulation in the Yarra Estuary

The analysis of the hydrological structure and circulation in the Yarra Estuary has shown that typical temperature, salinity and density distributions are characterised by a three-layer vertical structure (Black *et al.*, 1994, Sokolov and Black, 1994). The Yarra River discharge and local runoff during storm events determines the salinity and thickness of the surface layer. The average salinity of the top 0.5 m layer ranges from 3 to 12 ‰ under medium flow conditions with a discharge of about 20 m^3s^{-1} at Chandler Hwy and from 15 to 25 ‰ under low flow conditions with a discharge of under 10 m^3s^{-1} (Fig. 5.12). The thickness of the surface layer varies from 1.0-1.5 m to 0.25-0.75 m respectively.

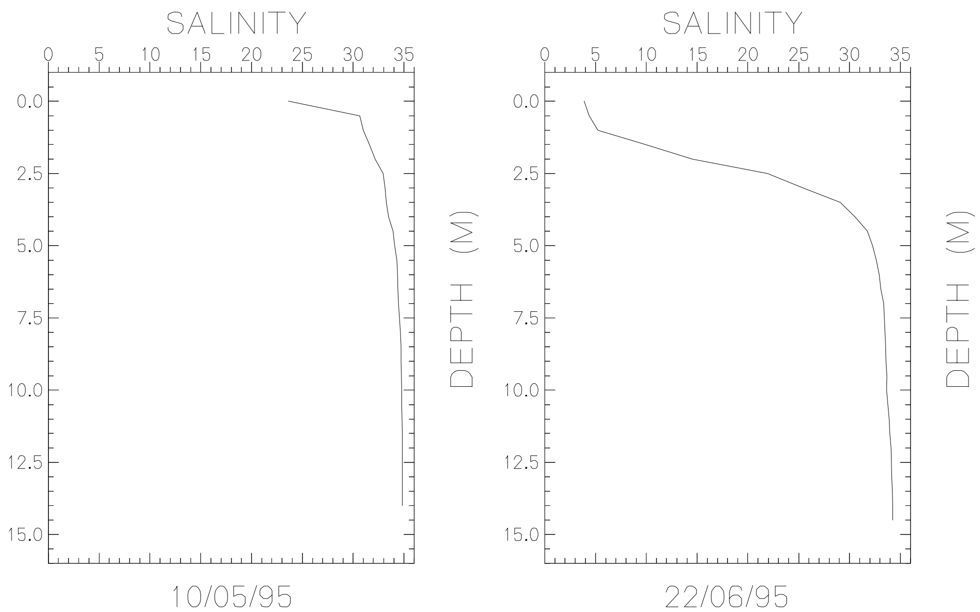

Figure 5.12. Typical vertical distribution of salinity near Westgate Bridge during low (left panel) and high (right panel) flow events.

A very pronounced halocline (and pycnocline) within the subsurface layer isolates the upper, low-salinity water from the more saline lower layer. Salinity increases rapidly from 5-15 ‰ to 28-32 ‰. The lower boundary of the halocline is located at depths from 1.0-1.5 m to 3.5 -5.0 m with respect to river discharge. In the deep zone, salinity and density increase more slowly with depth, and the salinity maximum occurs close to the bottom. The density of water is determined mainly by salinity, so the vertical density profile is similar to the salinity profile. The deep layer water is formed in Port Phillip Bay, and annual variation in the salient temperature characteristic for the deep layer and Port Phillip Bay is closely allied (Black *et al.*, 1995).

The tidal range determines the variation of the deep layer salinity. Above the deep layer, the tidal variation in salinity is affected by vertical mixing due to shearing in the surface and subsurface layers and baroclinic advection. Intensification of the tidal changes in salinity was observed during the periods under low Yarra River discharge conditions when the difference in density between surface layer and deep zone was the lowest. In turn, the decrease in stratification may reduce the gradient Richardson number to the critical value and cause internal vertical mixing because of shear instability (Sokolov & Black, 1994). The velocity shear itself is varying during the tidal cycle, thus the salinity of the mixed layer at the top part of the water column will coincide with intensity of the vertical mixing.

The currents in the Yarra Estuary are characterised by two pronounced layers; ebb (negative) currents prevail near the surface, and flood (positive) currents appear near the bottom (Fig. 5.13). Currents do not usually exceed 25 $cm \cdot s^{-1}$. The core of maximum ebb currents is always located in the top measurement layer at 1.5 m depth.

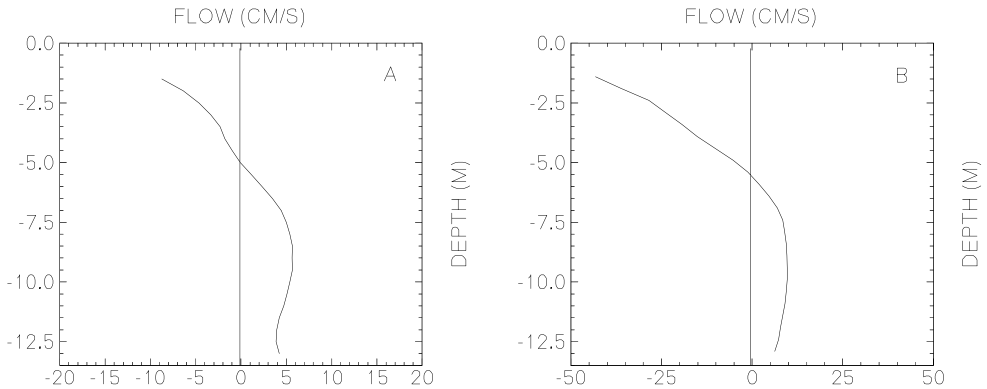

Figure 5.13. Typical velocity profile at Westgate Bridge averaged over the tidal cycle. (a) low flow conditions; (b) high flow conditions.

The tidal current directed upstream in the lower layer is strongest in a core zone at about 7.5 -10 m depth. This flow creates upward movement at the upper boundary of the core and downward movement at the lower boundary (Fig. 5.14 a). When combined with downward vertical movement associated with the river flow in the surface layer, a zone of convergence occurs near 2.5 m depth throughout the tidal cycle. This corresponds to the lower boundary of the halocline (pycnocline) where the vertical gradients are about 1 ‰·m^{-1}.

If a river discharge into an estuary is connected to a nearly tideless sea, the fresh water overrides the salt water and flows as a nearly undiluted layer into the sea. Salt water intrudes underneath the fresh water layer in the form a wedge. If there is some tide the wedge moves back and forth; the more the wedge motion the more kinetic energy is available to break down the interface and turbulently mix the fresh and saline layers. The river may be thought of as a source of a deficit of potential energy, and the tide as a source of kinetic energy to overcome the deficit. More precisely, the river is a source of buoyancy determined by the difference in density between the river and ocean water.

A longitudinal salinity distribution in an estuary creates a longitudinal pressure gradient even if the estuary is vertically well mixed. The pressure gradient will drive a current tending to bring the isohalines towards the horizontal. Internal flows driven by density variations are called baroclinic circulation. The tide-driven flows above are barotropic flows.

Spatial variability of hydrological characteristics in the Yarra Estuary (Sokolov & Black, 1994) indicates that in an estuarine river entrance the small-scale vertical mixing for the spring tidal range occurs at the moment of maximum shearing in both the ebbing and flooding phases. The turbulent energy spectrum $S(k) \sim k^{-5/3}$, and the flow in the range from 2 cm to 1 m can be characterised as fully turbulent. The eddy viscosity coefficients calculated for the spring tide range from 10^{-4} m^2s^{-1} to 10^{-1} m^2s^{-1} and, in general, are characterised by a gradual increase from the surface to the bottom, with a well-pronounced maximum in the sub-surface layer at the lower boundary of the pycnocline at 2-4 m depth, and often a second maximum near the bed (Fig. 5.14 b).

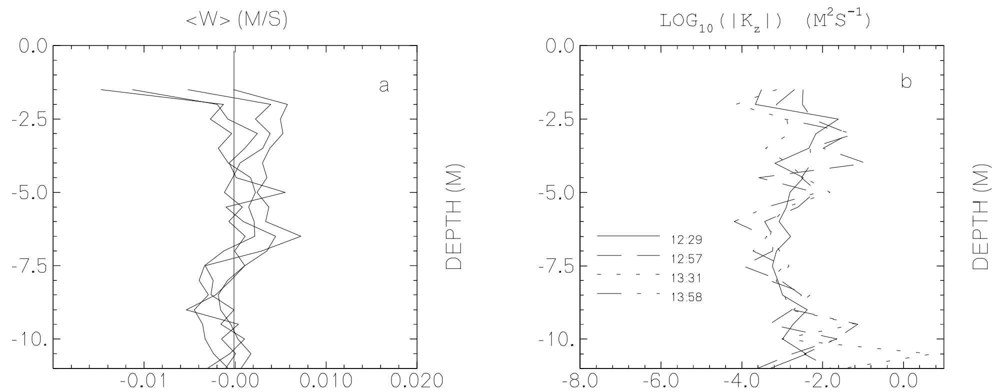

Figure 5.14. Typical (a) vertical velocity and (b) eddy viscosity coefficient profiles at Westgate Bridge.

Internal small-scale mixing is associated with a Kelvin-Helmholtz instability. The general conditions for instability are determined by gradient Richardson number and the variation of shear with depth. Rayleigh's result for homogeneous inviscid fluids states that there must be a point of inflexion in the velocity profiles for instability to occur. Another general condition obtained by Miles is a sufficient condition which states that in inviscid continuously-stratified flow is stable to small disturbances if $Ri >> 1/4$ everywhere in the flow.

High-resolution estimates of Ri can be obtained by considering the vertical distribution of Brunt-Väisälä frequency calculated using the high resolution temperature and salinity measurements (Fig. 5.15). Typically, the vertical distribution of $Ri(z)$ suggests that internal small-scale mixing occurs in the whole water column, excluding the zone near the sharp halocline, a natural barrier between fresh river flow and saline tidal flow (Fig. 5.15 b). At the moment of maximum shearing in both the ebbing and flooding phases, even under low river flow conditions, there is evidence of internal mixing in the halocline as well (Fig 5.15 a).

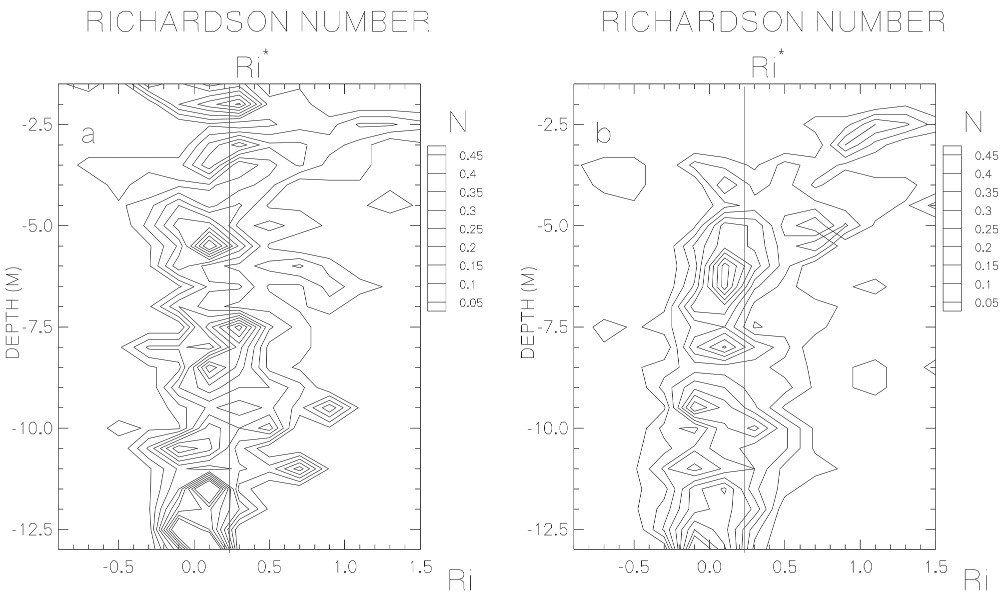

Figure 5.15. Vertical distribution of Richardson number $Ri(z)$ through the water column at Westgate Bridge at the time of maximum shearing in the pycnocline (a) and at the middle of the flood phase (b). The vertical line at $Ri = 1/4$ represents the threshold.

The large-scale dynamics of the river and tidal flow establishes a transverse mixing with a regular spatial structure. This structure exists during the whole tidal cycle and consists of four counter-rotating main zones (cells) with different signs of vorticity, and these cells are associated with river flow, lower boundary of the pycnocline, tidal flow and bottom layer. The sign of rotation for each cell appears to be determined by the inertial momentum due to a corner in the river at the measurement site. The main cells are characterised by internal variations of vorticity intensity. As the tidal cycle progresses, each main cell can be represented by several cells with lesser horizontal lengths, but with the same sign of rotation as the main cell.

The superposition of river and tidal flows during the whole tidal cycle maintains a zone of convergence near 2.5 m depth, which corresponds to the lower boundary of the pycnocline. Thus, at this level, there is a balance between the convergence of fresh and salt water and the mixing due to interfacial internal waves. The convergence and mixing appears to be the main mechanism that maintains the high stratification in an estuary.

Changes to the hydrological structure at tidal frequencies are accompanied by diurnal and low-frequency oscillations. Usually, the diurnal changes in water temperature are moderate and appear only in the top 1.5 m of the water column. However, in summer the temperature changes due to absorption of solar radiation can reach 2.5 °C and penetrate down to the lower boundary of the pycnocline (Black *et al*., 1995). Low-frequency oscillations are able to create significant changes in the absolute values, but do not significantly alter the structure.

Calculation of river discharge in Yarra Estuary at Westgate Bridge using 1995 field measurements

Calculations of river discharges at Westgate Bridge were based on the continuous velocity measurements recorded with a single bottom-mounted Acoustic Doppler Current Profiler (ADCP) and a S4 current meter deployed nearby in the surface layer. The pilot studies at Westgate Bridge undertaken in 1993 showed that a single velocity profile taken far enough from the river bank was highly correlated with currents at the same level averaged across the whole section. This occurred for all three sets of measurements which spanned the low (Fig. 5.16) to high flow regime (Fig. 5.17). The estimated correction parameters for side effect were adopted for present river discharge calculations.

The daily averaged velocity measurements in the surface layer at Westgate Bridge recorded using a S4 current meter are well-correlated with the total Yarra River discharge comprising discharges at Chandler Hwy and from major tributaries: Maribyrnong River, Merri Creek, Gardiners Creek and Moonee Ponds Creek (Fig. 5.18).

Current recorded with a bottom-mounted ADCP was sampled with a 10 Hz maximum pinging rate and 1 min averaging interval with 0.5 depth cell size through the whole water column, excluding the top 1.5 m layer. To remove high-frequency variability and tidal oscillations in current measurements, the data has been averaged using a 1 hour period of averaging, and tidal oscillations have been filtered using digital low-frequency filter. The original velocity data offers an opportunity for further analysis, and contains valuable material for a study of mixing processes and tidal circulation in a "salt-wedge" estuary.

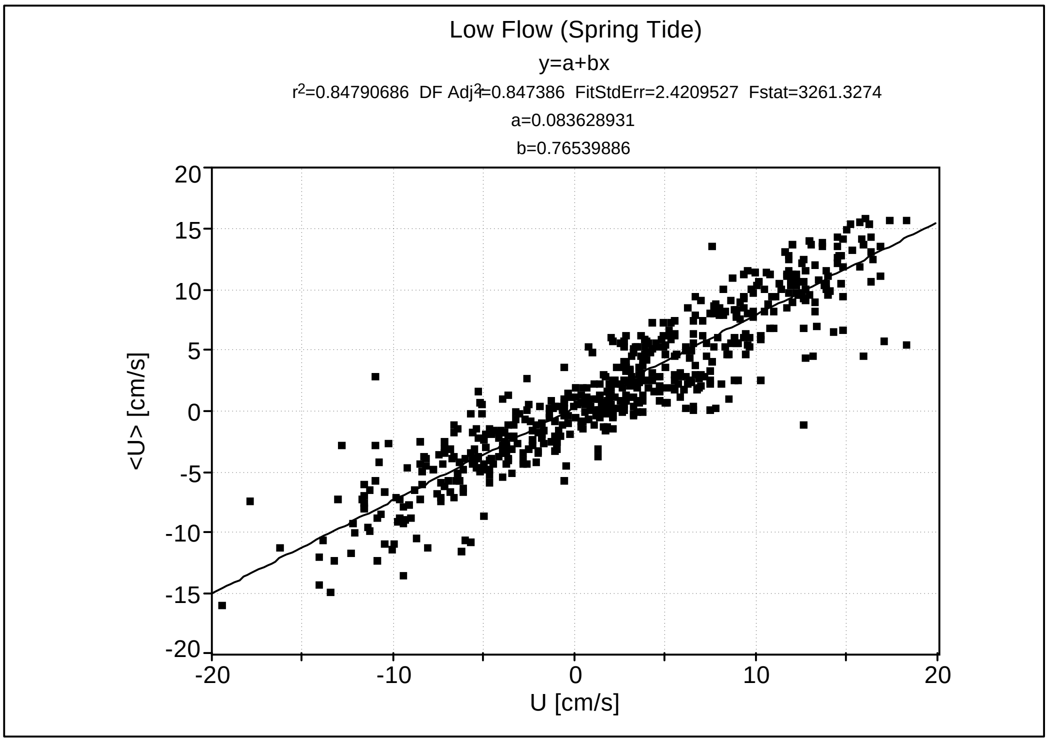

Figure 5.16. Current at location of bottom-mounted ADCP versus current at the same depth averaged across the section (low flow conditions).

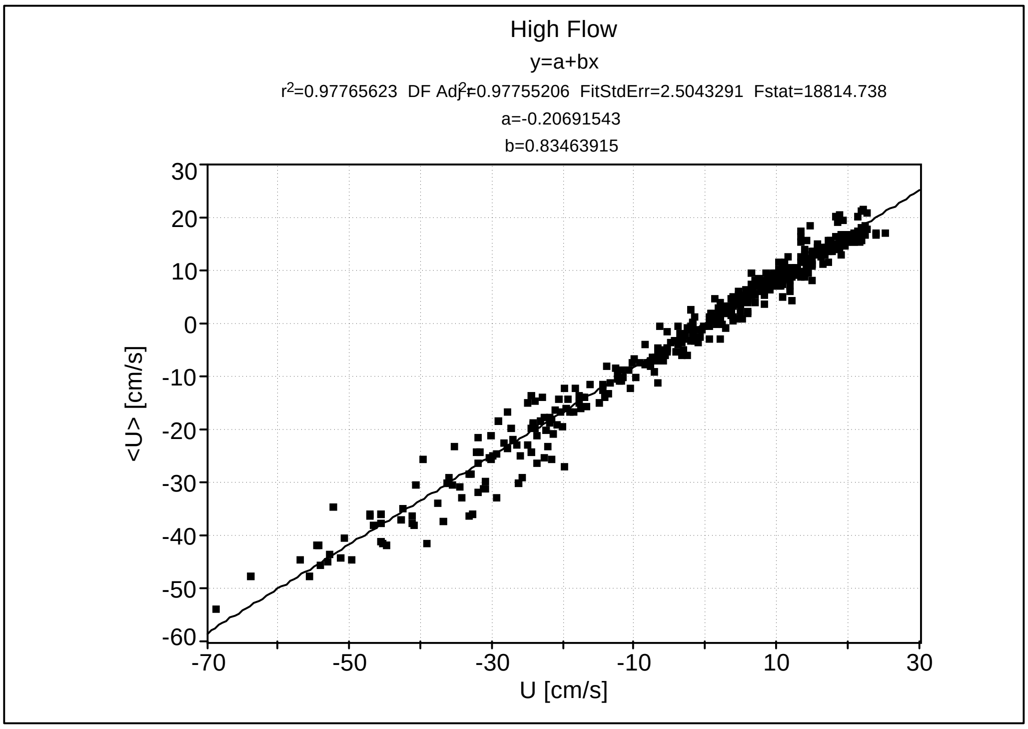

Figure 5.17. Current at location of bottom-mounted ADCP versus current at the same depth averaged across the section (high flow conditions).

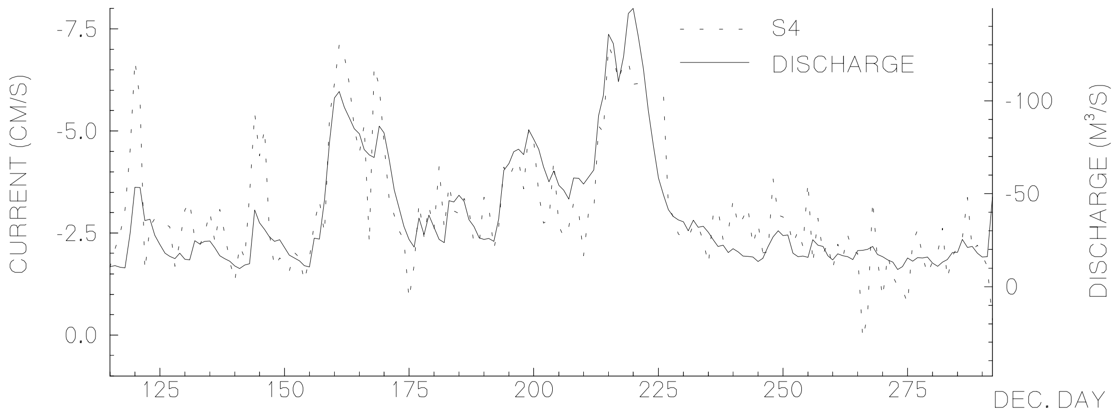

Figure 5.18. Current measured at location near a channel marker # 36 at a depth of 0.8 m (S4 current meter) and total Yarra River discharge (May-October, 1995).

To obtain an empirical relationship between the measured at Westgate Bridge current and total Yarra River discharge, the velocity profiles were reconstructed using a polynomial approximation (Sokolov, 1995)

$$U(z) = az^3 + bz^2 + cz + d;$$

where

$$a = -4\frac{\tilde{F}_{TD}}{z_0^4} - \frac{2}{3}\frac{b}{z_0};$$

$$b = 6\frac{z_0}{h^2}\frac{\tilde{F} + \tilde{F}_{TD}\left(\frac{h^4}{z_0^4} - 2\frac{h^2}{z_0^2}\right)}{2hz_0 - h^2 - z_0^2};$$

$$c = -az_0^2 - bz_0;$$

$$d = 0;$$

where z is the distance from the river's bed, z_0 the elevation of the velocity reverse level; h the total depth. Scaled discharges $\tilde{F}_{TD} = F_{TD}L^{-1}$; and $\tilde{F} = FL^{-1}$; are defined, where L is the width of the river; and F_{TD}, F the tidal and net river discharges respectively (Fig. 5.19).

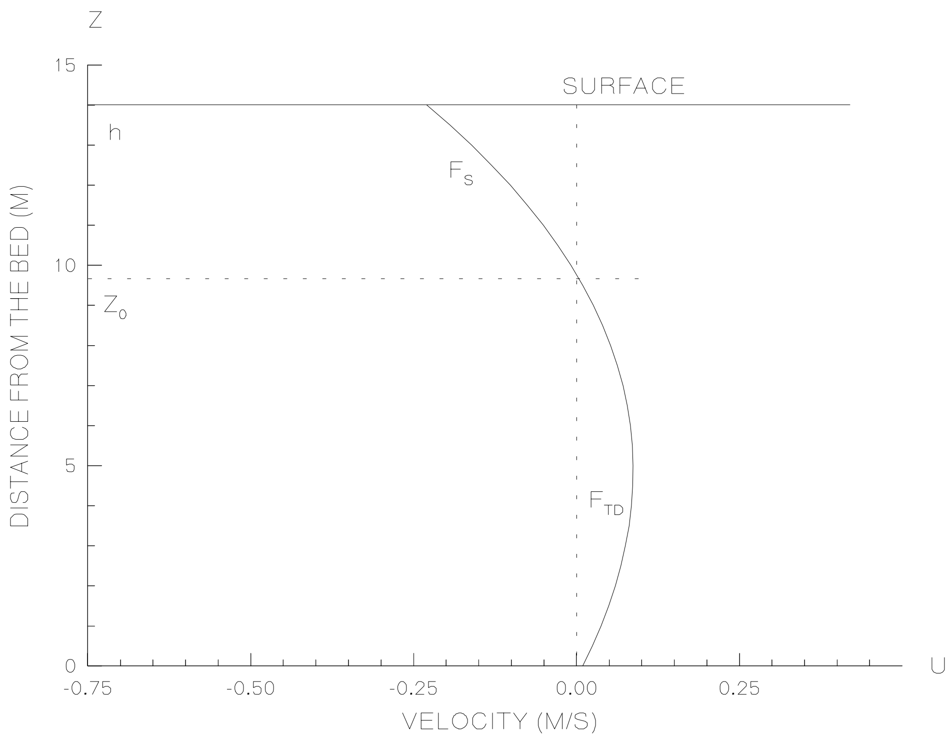

Figure 5.19. Polynomial approximation of velocity profiles in Lower Yarra (Sokolov, 1995).

The coefficients a, b, c and d can be found at each time step n solving the system of linear equations

$$A_n x_n = f_n;$$

where

$$A_n = \begin{bmatrix} z_1^3 & z_1^2 & z_1 & 1 \\ z_2^3 & z_2^2 & z_2 & 1 \\ z_3^3 & z_3^2 & z_3 & 1 \\ z_4^3 & z_4^2 & z_4 & 1 \end{bmatrix}_n ; \quad x_n = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}_n ; \quad f_n = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}_n ;$$

and u_i are the measured velocities at specified levels z_i.

Then, the reconstructed velocity profiles have been integrated, and the relationships between total upstream Yarra River flow F and the tidal F_{TD}, fresh water F_S and net river F_{NET} discharges at Westgate Bridge have been obtained independently

$$F_{TD} = 77.48 - 0.171F \;\left[m^3 s^{-1}\right]$$

$$F_S = -79.98 + 1.21F \;\left[m^3 s^{-1}\right]$$

$$F_{NET} = -2.32 + 1.045F \;\left[m^3 s^{-1}\right]$$

Note, that in the above empirical equations the water flux, associated with tidal flow, is directed upstream and positive, and the flux, related to river discharge, is directed downstream and negative.

The results are well in accordance with expectations. The net river flux is very close to the combined upstream Yarra River discharge. The fresh water flux comprises the river discharge plus entrained Port Phillip Bay water because of vertical mixing. The mean dilution in the top 5 m layer in the Yarra Estuary at Westgate Bridge varies from about 10:1 to 1.5:1, when the river discharge spans the range from the low (~ 10 m^3s^{-1}) to high (~200 m^3s^{-1}) flow regime. In the deeper layer the tidal water flux directed upstream is about 80 m^3s^{-1} increasing under high river discharge conditions. More precisely, the tidal flux is a residual tidal flux induced as a baroclinic response in estuarine circulation by the longitudinal pressure gradient. When the discharge of fresh water delivered by the river is increasing, it will intensify the internal flows driven by bigger longitudinal pressure gradient resulting in greater water fluxes.

It should be noted, that the above empirical equations are the subject of significant short-period deviations due to the non-linear nature of the estuarine circulation resulting in ignored phase lags between upstream river discharge and the water fluxes in the lower estuary. The remotely induced low-frequency oscillations could be another source of discrepancy. However, the relationships should work well for the balance calculations.

Measured water-quality variables in the Yarra Estuary at Westgate Bridge in 1995

In general, the typical vertical distribution of nutrient and metal concentrations in the Yarra Estuary is characterised by higher levels near the surface decreasing with depth. This is indicative that the major source of various species in the estuary is related to the Yarra River flow. However, there are several features in the vertical distributions, which should be stressed. The most pronounced difference between the near-surface and the deeper water concentrations occurs for nitrite, nitrate, ammonium, silicate and metals (iron and lead). The statistical characteristics of water-quality variables for the Yarra Estuary at Westgate Bridge measured in 1995 are presented in Table 5.4.

By contrast, orthophosphate is distributed uniformly through the water column. Moreover, the higher concentration of orthophosphate in the Yarra Estuary compared with upstream concentrations indicates that another major influx of orthophosphate in the estuary is determined by the deeper water source.

To confirm the last statement, the original data set has been subdivided (Table 5.5). The median (typical) concentrations of species in the Yarra Estuary were determined for the low flow conditions and during high flow events: 14-21 June, 14-19 July and 2-16 August (Fig. 5.20). Under low flow conditions, then the influx of nutrients from the Yarra River is small, and orthophosphate gradually increases with depth. Elevation in the river flow mainly resulted in a reduction in concentration in the surface layer. However, the surface layer orthophosphate influx during high flow events is still 5 times above the low flow load.

Table 5.4 The statistical characteristics of water-quality variables for the Yarra Estuary at Westgate Bridge (1995). Units for all variables are in mg/L.

Variable	Depth (m)									
	0.1		1.5		3.5		8.0		12.0	
	mean	std	mean	std	mean	std	mean	std	mean	std
NO_2	0.0076	0.005	0.0033	0.003	0.0012	0.001	0.0005	0.001	0.0005	0.001
NO_3	0.464	0.307	0.153	0.157	0.033	0.031	0.008	0.014	0.005	0.013
NO_X	0.471	0.312	0.156	0.159	0.034	0.032	0.009	0.015	0.006	0.014
NH_3	0.074	0.035	0.044	0.042	0.020	0.016	0.011	0.016	0.011	0.019
TKN	0.490	0.227	0.305	0.191	0.187	0.061	0.163	0.038	0.162	0.041
NTOT	0.961	0.439	0.460	0.337	0.221	0.089	0.172	0.051	0.167	0.053
PO_4	0.078	0.049	0.085	0.045	0.074	0.020	0.069	0.015	0.069	0.017
PTOT	0.117	0.047	0.110	0.045	0.091	0.023	0.086	0.020	0.086	0.021
SiO_4	1.564	0.490	0.813	0.452	0.371	0.122	0.252	0.072	0.236	0.069
TOC	6.83	4.10	3.93	3.36	2.18	0.42	1.84	0.26	1.83	0.25
Fe	0.741	0.296	0.099	0.030	0.063	0.018	0.071	0.058	0.123	0.127
Pb	0.0038	0.0029	0.0004	0.0002	0.0002	0.0001	0.0002	0.0001	0.0002	0.0002
SS	17.39	17.29	10.92	12.89	6.21	3.21	7.78	5.73	7.52	4.64
TPH	0.0411	0.028	0.0016	0.002	0.0031	0.004	0.0006	0.001	0.0037	0.008

Table 5.5 Median concentrations at Westgate Bridge during low and high flow conditions (1995). Units for all variables are in mg/L.

Variable	Depth (m)									
	0.1		1.5		3.5		8.0		12.0	
	low	high	low	high	low	high	low	high	low	high
NO_2	0.0063	0.0069	0.0023	0.0039	0.0011	0.0010	0.0004	0.0004	0.0004	0.0005
NO_3	0.254	0.530	0.057	0.318	0.021	0.032	0.004	0.006	0.002	0.003
NO_X	0.262	0.536	0.060	0.321	0.023	0.033	0.004	0.006	0.003	0.004
NH_3	0.050	0.058	0.022	0.036	0.017	0.014	0.007	0.008	0.008	0.010
TKN	0.314	0.698	0.212	0.502	0.175	0.188	0.170	0.155	0.153	0.165
NTOT	0.588	1.283	0.263	0.823	0.201	0.226	0.172	0.160	0.155	0.168
PO_4	0.061	0.036	0.071	0.058	0.072	0.060	0.074	0.059	0.074	0.061
PTOT	0.085	0.109	0.090	0.092	0.088	0.078	0.092	0.076	0.090	0.076
SiO_4	1.44	2.00	0.52	1.37	0.31	0.39	0.21	0.29	0.20	0.29
TOC	3.7	11.4	2.7	6.1	2.2	2.1	1.9	1.7	2.0	1.8
SS	4.6	36.2	4.9	20.0	4.0	9.0	5.9	6.2	6.6	5.3

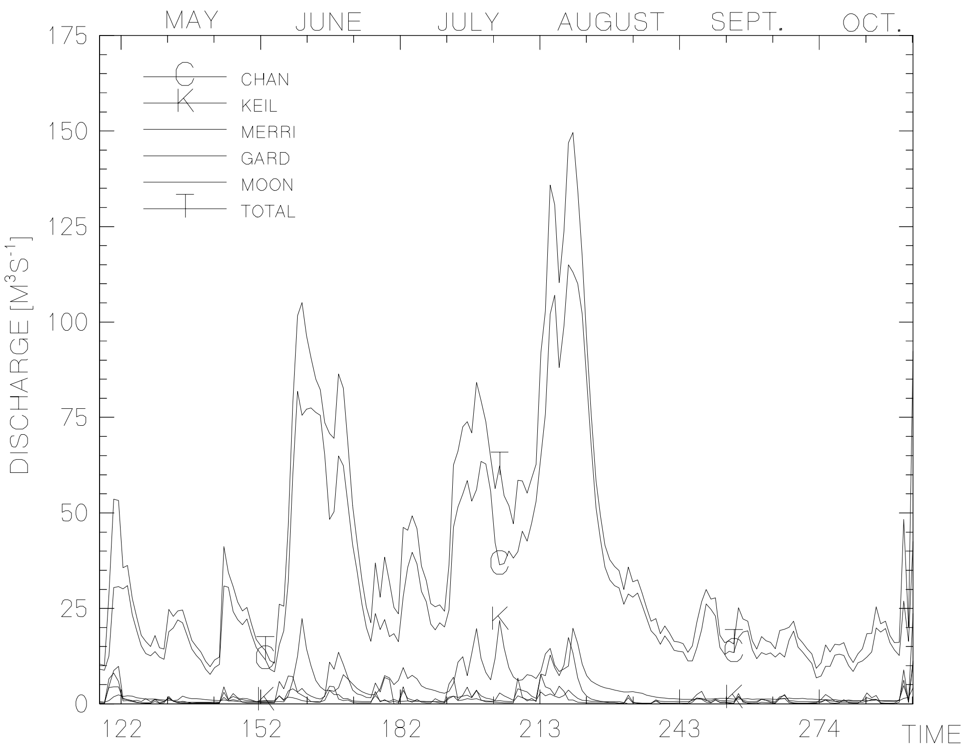

Figure 5.20. Measured discharges of the Yarra River and the major tributaries.

Higher concentrations of ammonium were also found in Yarra Estuary compared with those recorded in the Yarra River. This can be the case, when significant loading of ammonium occurs within the CBD of Melbourne. Another indication was presented in the "Victoria Dock Re-Development Water Quality Investigation" (Black *et al*., 1995), where very high concentrations of ammonium (up to 0.110 mg/L) were found in the bottom layer under medium river flow conditions.

The vertical distribution of total suspended solids has the most pronounced difference in concentrations between low and high flow conditions. If for the low flow regime the concentration of total suspended solids is increasing with depth from 4.6 mg/L near the surface to 6.6 mg/L at 12 m depth, then during storm events, the surface concentration is about 7 times higher than concentration near the river's bed. The time evolution of SS concentrations measured during a single storm event is presented in Fig. 5.21.

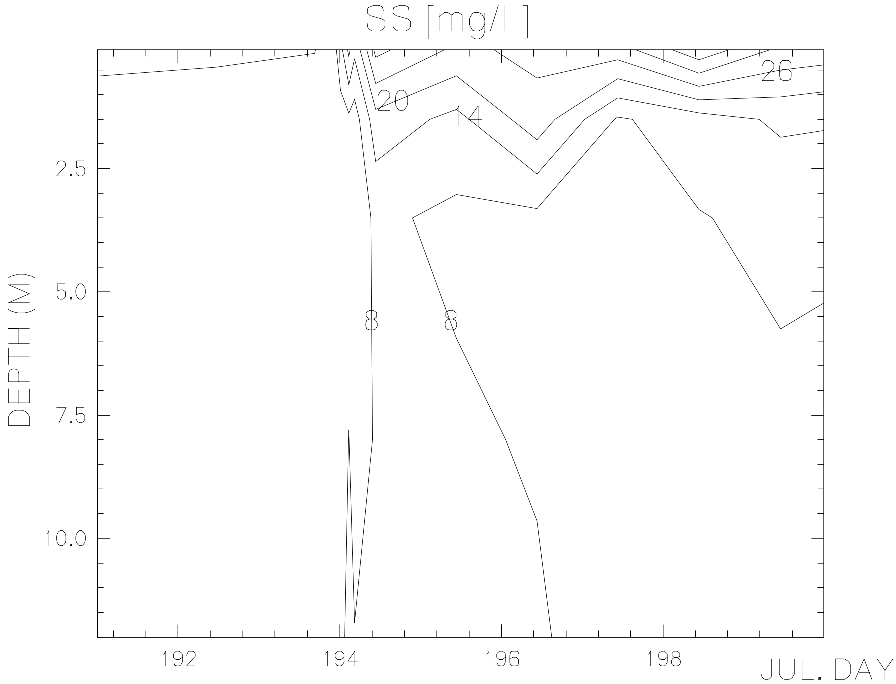

Figure 5.21. Measured concentrations of total suspended solids during a single storm event: 12-19 July, 1995.

At the time of arrival of the first spill of storm water on the 14th of July, the surface water, highly contaminated by SS, was mixing downward, reaching the lower boundary of the pycnocline several hours later. The intense internal vertical mixing in the upper water column is in agreement with the results of internal mixing conditions obtained from hydrological measurements discussed in the previous section. The elevation of total suspended solids concentrations near the river's bed during high flow events testifing to resuspension of the bed sediments due to an intensified deeper layer flow directed upstream, and flocculation and precipitation of colloidal material further downstream are the major processes. These processes are most pronounced during periods of low discharges, when the external influx of total suspended solids from the Yarra River is low (Table 5.5).

Under low river discharge conditions the elevated concentrations of nutrients (except orthophosphate) and metals are usually limited by the surface layer, sharply decreasing downward in the pycnocline below 1.5 m depth (Table 5.4). This is again an indication, that typically, internal vertical small-scale mixing occurs in the whole water column, excluding the zone near the sharp halocline, a natural barrier between fresh river water and saline Port Phillip Bay water below (Fig. 5.15 b). Only at the moment of maximum shearing in both the ebbing and flooding phases an internal mixing in the halocline may occur.

Calculation of chemical fluxes in Yarra Estuary at Westgate Bridge

To relate the nutrients and SS loads entering Port Phillip Bay to those estimated upstream, the measurements of water-quality variables recorded over six months at Westgate Bridge in 1995 were adopted to estimate daily loads in the estuary using equations (3.4)-(3.5). The concentrations of measured species were recalculated using reconstructed velocity profiles $U(z)$ to obtain mean concentrations in the surface fresh water layer with discharge F_S

$$\overline{C} = \frac{1}{F_S} \int_{z_0}^{h} C(z) U(z) L(z) dz$$

where $C(z)$ are the measured concentrations through the vertical, $L(z)$ is the width of the river, z_0 is the elevation of the velocity reverse level (Fig. 5.19), and *h* is the elevation of water surface above the river's bed.

An example of the numerical simulations for total suspended solids at Westgate Bridge is presented in Fig. 5.22 and the estimations of the model parameters and error analyses for all cases are summarised in Table 5.6. In general, the normalised error R for predicted chemical loads does not exceed 20-25%. The error of almost 50% for orthophosphate and ammonium once again (see previous section) certifies that in the Yarra Estuary there are additional sources of these species, which do not relate to direct influx from the Yarra River.

Further, the predicted daily loads at Westgate Bridge for 1995 were related to upstream loads estimated for the same period. The adopted relationships are presented in Table 5.7, and results for TKN, total P and ammonium are shown in Figures 5.23 - 5.25. In general the correlation between combined upstream loads and loads in Yarra Estuary is high, resulting in r^2 adjustment of about 85-95%. However, as expected, the relationships obtained for orthophosphate, and partially, for ammonium, are very noisy. Closer examination of Fig. 5.25, which presents the relationship for ammonium, shows at least two regimes in flux generation in the estuary.

More importantly, the relationship for nutrients is close to logarithmic and in the intermediate range of high flow events loads in the Yarra Estuary exceed the combined upstream loads, indicating that there is an additional influx of nutrients generated downstream of Chandler Hwy. By contrast, the relationship obtained for total suspended solids is exponential, testifying to processes of flocculation and precipitation of colloidal material in the estuary being of major importance.

As a final step the combined daily upstream loads for the Yarra River predicted for the period 1988-1995, using the empirical equations, were converted into total loads entering Port Phillip Bay. A summary of statistical characteristics calculated for empirical distributions of loads and concentrations is presented in Table 5.8. Because of the limited data set used for estimation of relationships between upstream and total loads, there is an uncertainty, from a statistical point of view for the range of very high loads. Thus, if in this interval the estimations of upstream loads obtained for nutrients exceeded those calculated in the estuary, it was assumed that these loads are at least equal. A similar hypothetical assumption was adopted for total suspended solids, that during very high flow events, the combined upstream loads do not exceed total loads.

The available data shows that comparing the average annual discharges from the Yarra River with estimates for other surface inputs (Patterson River/Mordialloc Main Drain and Western Treatment Plant (Murray, 1995)), the Yarra River is one of the major sources of nutrients (except ammonium) and metals in Port Phillip Bay (Table 5.9). Equally important, in contrast to the WTP, discharges from the Yarra River are characterised by very intense sub-annual variability resulting in high extreme daily loads. For example the estimated maximum discharge of total suspended solids peaked at almost 27,000 tonnes/day during a notable storm event in June 1989, when the combined Yarra River flow reached 412 m^3/s mark. This estimate exceeds the mean daily load by more than 100 times. Thus in terms of impact on the Port Phillip Bay environment, the Yarra River inputs can be treated as significant short-term perturbations.

Table 5.6 Estimated mean concentrations and loads, and model parameters for the Yarra Estuary at Westgate Bridge in 1995.

Variable	Statistical characteristics		Model parameters	Accuracy
	$\langle C \rangle$ mg/L	$\langle Q^- \rangle$ kg/day	γ	R
NO_X	0.197	2,440	1.30	0.21
NH_3	0.044	504	0.85	0.49
TKN	0.316	3,950	1.65	0.19
NTOT	0.512	6,370	1.50	0.15
PO_4	0.080	870	1.85	0.49
PTOT	0.170	1,170	0.80	0.35
TOC	4.56	58,200	2.00	0.19
SiO_4	0.887	10,670	1.05	0.25
SS	11.8	171,210	3.10	0.09

Table 5.7. Estimated relationship between upstream total loads and loads in Yarra Estuary at Westgate Bridge in 1995. The best fit was obtained using power equation $y = a + bx^c$. *) The adopted formula for orthophosphate is $y = a + b(\ln x)^2$. All loads measured in [kg/day].

Variables	Model parameters			r^2 adjustment
	a	b	c	
NO_X	-2054	65.57	0.567	0.87
NH_3	-2226	1790	0.096	0.75
TKN	-1523	150.6	0.468	0.96
NTOT	-4192	227.5	0.464	0.93
*PO_4	543	24.09	-	0.16
PTOT	-1891	1423	0.142	0.94
SS	23409	0.0029	1.429	0.85

Table 5.8 Statistical characteristics of concentrations and loads in Yarra Estuary at Westgate Bridge estimated for the period 1988-1995.

Variable	Concentration (mg/L)					Load (tonnes/day)				
	med	mean	std	90%	max	med	mean	std	90%	max
NO_X	0.085	0.134	0.111	0.300	1.08	0.66	1.50	2.02	3.50	33.30
NH_3	0.045	0.044	0.017	0.066	0.141	0.366	0.430	0.305	0.85	5.01
TKN	0.214	0.279	0.277	0.550	3.88	1.72	3.36	6.24	7.00	123.0
NTOT	0.275	0.402	0.390	0.850	5.23	2,170	4.79	8.29	12.0	160.0
PO_4	0.111	0.112	0.024	0.146	0.168	0.894	0.923	0.146	1.12	1.70
PTOT	0.135	0.134	0.023	0.160	0.478	0.966	1.179	0.686	1.80	17.00
SS	5.1	13.8	32.2	30	753.7	38.2	202	909	500	26800

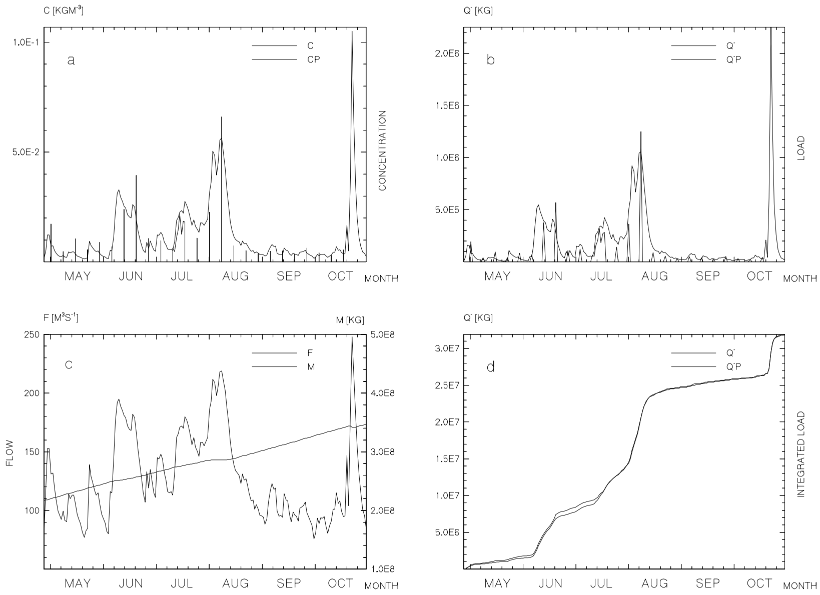

Figure 5.22. Time evolution of modelled parameters for total suspended solids at Westgate Bridge in 1995.
(a) observed (thin line) and predicted (thick line) concentrations; (b) observed (thin line) and predicted (thick line) loads in the river; (c) river discharge (thin line) and total mass of chemical element in the catchment (thick line); (d) observed (thin line) and predicted (thick line) time integrated loads in the river.

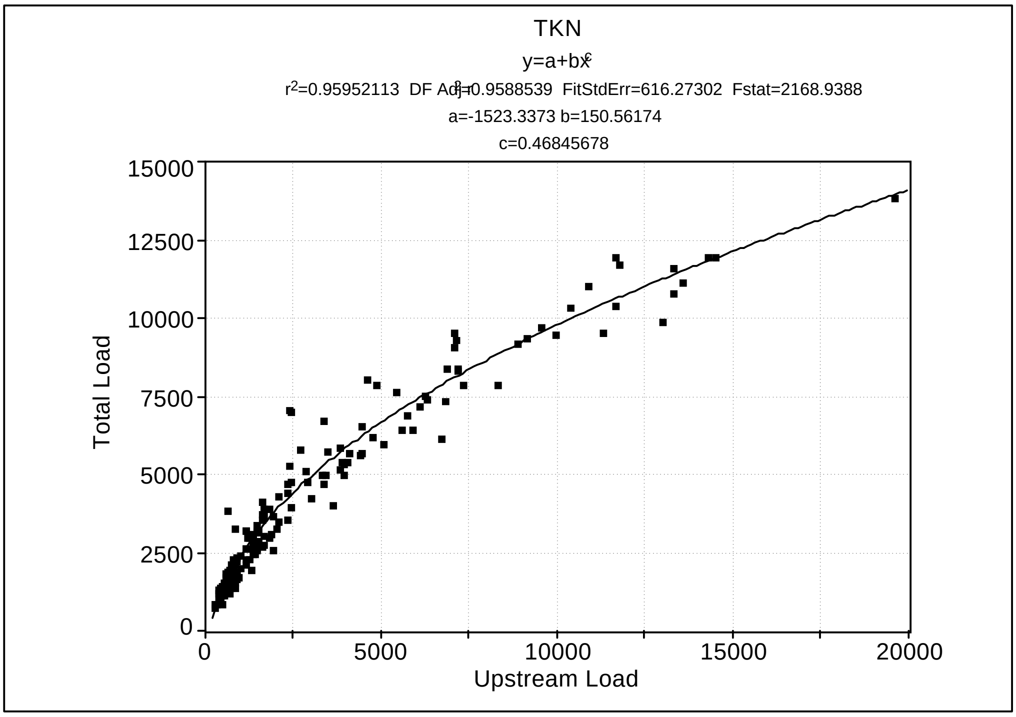

Figure 5.23. Estimated relationship for TKN between upstream total loads and loads in the Yarra Estuary at Westgate Bridge in 1995. The best fit was obtained using power equation $y = a + bx^c$. All loads measured in [kg/day].

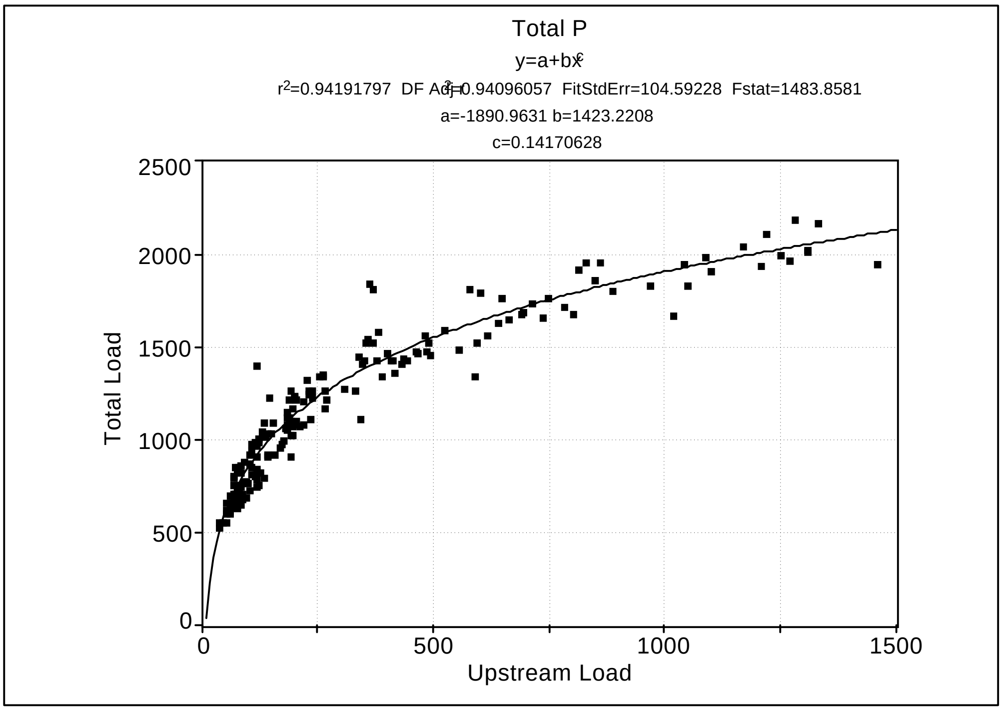

Figure 5.24. Estimated relationship for total P between upstream total loads and loads in the Yarra Estuary at Westgate Bridge in 1995. The best fit was obtained using power equation $y = a + bx^c$. All loads measured in [kg/day].

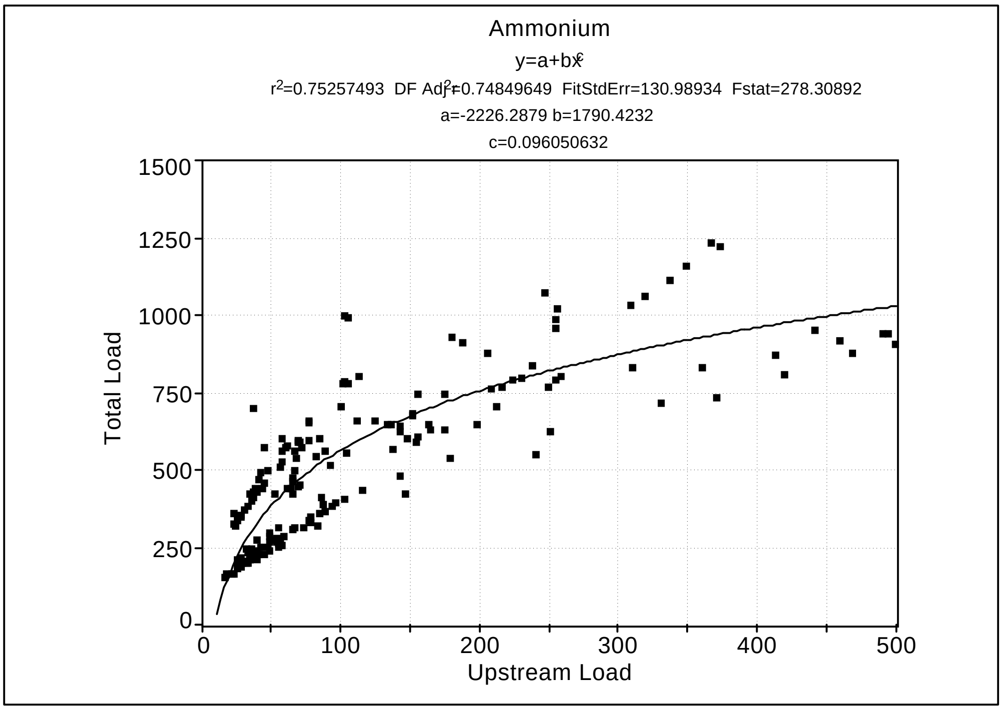

Figure 5.25. Estimated relationship for ammonium between upstream total loads and loads in the Yarra Estuary at Westgate Bridge in 1995. The best fit was obtained using power equation $y = a + bx^c$. All loads measured in [kg/day].

Table 5.9: Mean annual loads (tonnes/year).

[1] Estimate for 1995. Upstream loads; [2] Yarra River + Maribyrnong River; [3] Yarra River.

Variable	Yarra Estuary	Patterson River/ Mordialloc Creek	WTP
Flow (km^3/year)	3.480	0.221	0.150
NO_X	548	317	253
NH_3	157	336	2,386
DIN	705	653	2,639
Organic N	1,070	442	1,019
TKN	1,227	778	3,405
Total N	1,775	1,095	3,658
PO_4	337	157	759
Total P	431	209	941
Organic C	21,260[1]		5,957
As		0.7	
Cd		0.08	
Cr		0.8	3.9
Cu	2.8[3]	2.0	2.7
Hg		0.004	
Ni		1.3	4.9
Pb	5.7[2]	3.1	1.1
Zn	21.5[3]	21.5	5.8
SiO_4	3,897[1]		
SS	73,800	15,700	

6. SUMMARY

The numerical prediction of water quality variables for the Dandenong Valley catchment at all sites over the 7-year period of measurements, with fixed model parameters had, in general, a high accuracy with normalised errors on average less than 5% for the nutrients and about 10% for the metals.

The low level of accuracy for ammonium, orthophosphate and total phosphorus for Mordialloc Main Drain probably related to discharge reduction and water quality improvement in effluent from the Dandenong South Treatment Plant over the last seven years. This fact is exhibited in concentration and load reduction for ammonium and total kjeldahl nitrogen in the Mordialloc Main Drain. During seven years the mean annual concentration for ammonium has been reduced from 12 mg/L in 1988 to 2 mg/L in 1994, thus the load in Mordialloc Main Drain contracted dramatically from 1400 kg/day to 300 kg/day respectively.

By contrast the annual concentration and load of orthophosphate and total phosphorus in Mordialloc Main Drain remained approximately constant over the period. Concentrations of PO_4 and total P in the Mordialloc Main Drain (2.04 mg/L and 2.47 mg/L) were more than 20 times higher than in Dandenong Creek at Olive Grove Rd (0.094 mg/L and 0.207 mg/L), which indicates that the major source of these species was the DSTP with an average concentration of orthophosphate in effluent of about 7.5 mg/L (DVA, 1990). At the same time, these estimates for the Mordialloc Main Drain are very close to those obtained for the period 1979-81 (NSR Environmental Consultants, 1993).

The concentrations of the metals are generally higher in the Mordialloc Main Drain than in the Patterson River. However, because of difference in discharges, the loads of metals in Patterson River on average significantly exceeded the loads in the Mordialloc Main Drain, especially during wet years due to intensive runoff. The inter-annual variation in metals discharges from the Paterson River is entirely determined by the changes in annual river flow.

For the numerical predictions of water-quality variables for the Yarra watershed, 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.

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 nutrients concentrations was characterised by a gradual increase from 1979-82 to 1987-89, followed by slight decrease for total P and a much steeper reduction for total N. These changes caused 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 the 80's, and were reduced to 750 tonnes/year in the mid-90's.

To estimate total loads of nutrients and toxicants derived from the Yarra River, the historical upstream measurements have been related to those downstream at Westgate Bridge, near the entrance to Port Phillip Bay. The relationship for nutrients is close to logarithmic and for the intermediate range of high flow events the loads in the Yarra Estuary exceed combined upstream loads, indicating that there is an additional influx of nutrients generated downstream of Chandler Hwy. By contrast, the relationship obtained for total suspended solids is exponential, testifying that the processes of flocculation and precipitation of colloidal material in the estuary are of major importance.

The available data shows that comparing the average annual discharges from the Yarra Estuary with estimates for other surface inputs (Patterson River/Mordialloc Main Drain and Western Treatment Plant (Murray, 1995)), the Yarra River is one of the major sources of nutrients (except ammonium) and metals in Port Phillip Bay. In contrast to the WTP, the discharges from the Yarra River are characterised by very intense sub-annual variability resulting in high daily loads during heavy rainfalls.

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