2.2 HAWKESBURY-NEPEAN RIVER, NEW SOUTH WALES

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A nutrient budget has been prepared for the Hawkesbury-Nepean River using the LOICZ methodology (**http://data.ecology.su.se/MNODE/Methods/STOCH.HTM)**. The significant diversion from that methodology is that conductivity is used as the surrogate tracer for the salinity budget. Otherwise the methodology was followed. The budgets are divided into 'financial year' (July 1-June 30), for 1995-1996 and 1996-1997, because that is how the data are tabulated. The two years are reported separately to give some sense of interannual variability.

Site Area Description

The Hawkesbury-Nepean River system [Site No. 19.; 151.80E, 32.90S] is about 300 km long and drains a catchment area of approximately 22 000 km^2 (Figure 2.1; see Figure 1.1). The Hawkesbury-Nepean system can be divided into a fluvial and an estuarine section, with the mainstream receiving inflows from 14 large tributaries (SPCC 1983). Many of the tributary watersheds to the north and west are undeveloped, rugged and forested, whereas the flatter terrain to the west and south-west of Sydney, originally pastoral and agricultural land, is now generally urbanised.

The Nepean River, the fluvial section of the river, flows in a northerly direction from its headwaters in the Illawarra Range and is joined by the Avon, Cordeaux and Cataract rivers. Flowing north-west, it is joined by the Warragamba River and further downstream by Erskine and Glenbrook creeks before joining the Hawkesbury River at the Grose River junction near North Richmond.

The Hawkesbury River, the estuarine section of the river system, extends 140 km from the confluence of the mainstream of the Nepean and the Grose River to its outlet at Broken Bay. The Hawkesbury River is the largest section of water within the catchment. Saline intrusion occurs in the Hawkesbury River, but it is limited to reaches downstream of the Colo River junction (83 km from the coast) (SPCC 1983). Tidal movement in the Hawkesbury River is apparent upstream as far as its junction with the Grose River. A number of major tributaries, including the MacDonald and Colo Rivers and Mangrove, Cattai, Berowra and Cowan creeks flow into the Hawkesbury River between Windsor and Brooklyn.

Flow within the Hawkesbury-Nepean River system is significantly greater than the flow from the combined sewage treatment plant (STP) discharges. Based on average flow conditions, the contribution of STP discharges to the net flow of the Hawkesbury River ranges from approximately seven percent just below the confluence with the Grose River to 18 percent just below the junction with Eastern Creek. The contribution of STP discharge to flows in the Nepean River ranges from one percent at Penrith Weir, just above the junction with Boundary Creek, to eight percent just below the confluence with the unnamed creek into which the Winmalee STP discharges. Two STPs discharge into the upper reaches of Berowra Creek. This arm of the Hawkesbury-Nepean system can be separately budgeted, but that budget is not presented here.

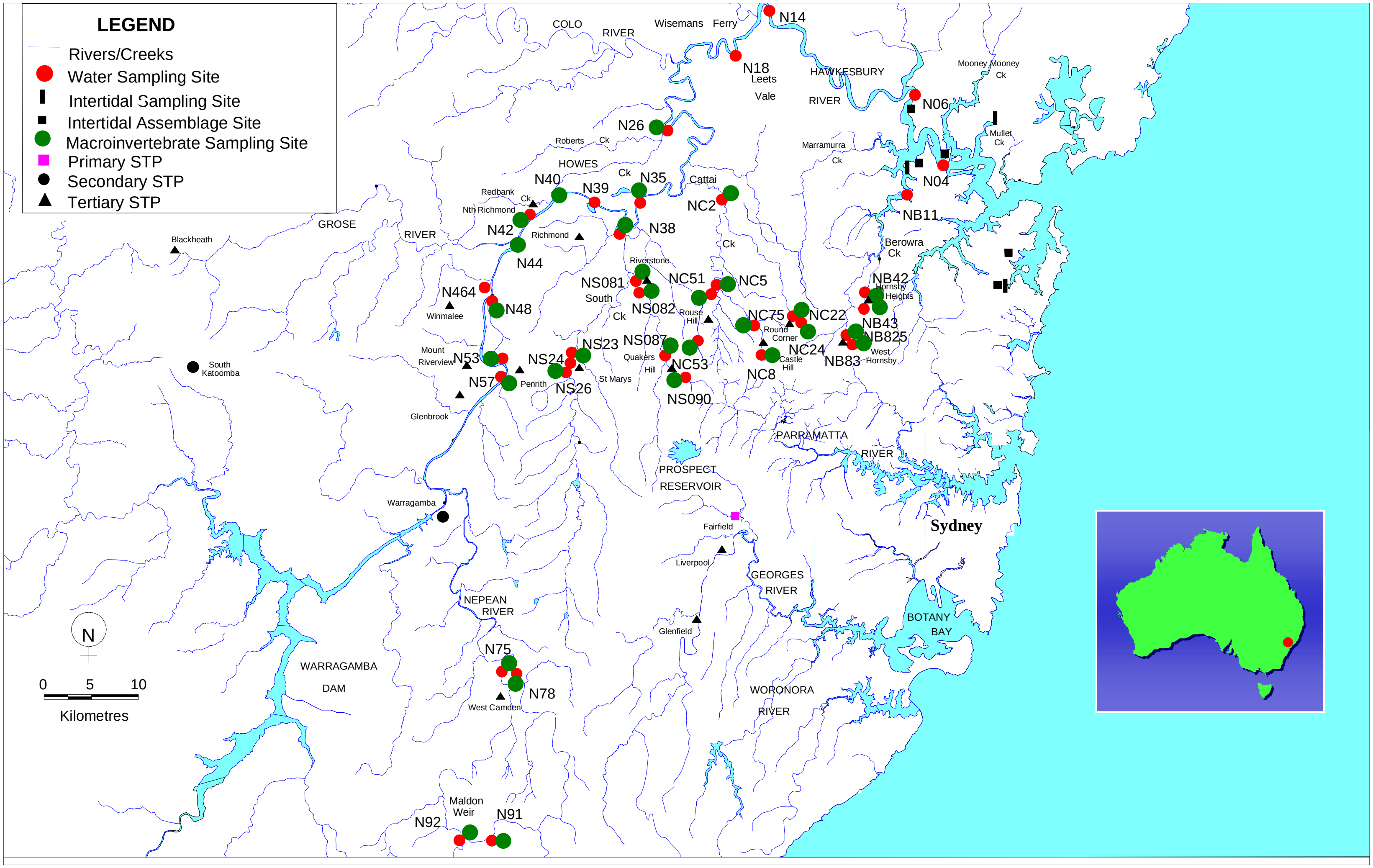

Figure 2.1 Hawkesbury-Nepean River system.

Flow in some tributary streams to the Hawkesbury-Nepean River, such as South, Eastern, Cattai and Matahil creeks, is dominated by STP effluent under dry weather conditions. The effluent contribution to flow ranges from a low of approximately six percent in the Warragamba River (below the dam) to a high of nearly 100 percent at Matahil Creek and Eastern Creek (downstream of the Riverstone and Quakers Hill STP discharges). Under wet weather conditions flow in these streams increases dramatically, and often the stream flow greatly exceeds the STP discharges.

The Hawkesbury-Nepean River system catchment can be divided into five different physiographic regions:

(1) the Blue Mountains Plateau;
(2) the Cumberland Lowlands;
(3) the Woronora Plateau;
(4) the MacDonald Ranges; and
(5) the Hornsby Plateau (Sydney Water 1991).

The Blue Mountains Plateau comprises most of the western side of the Hawkesbury-Nepean River from the Nepean Dam to Wisemans Ferry. It consists of a deeply incised, Hawkesbury sandstone surface that overlies Narrabeen sandstone. Numerous creeks draining the area flow into two of the primary tributaries to the Hawkesbury-Nepean River system, specifically the Grose and Coxs rivers. The vegetation consists mainly of open forest and woodland and is dominated by a variety of *Eucalyptus* species. Areas of heath occur on the exposed clifftops and areas of closed forest may be found in the deep valleys and protected slopes.

The Cumberland Lowlands extend eastward from the Blue Mountains Plateau and, with the exception of the Razorback Range, consist of low-lying, gently undulating plains and low hills on Wianamatta Group shales and sandstones. Stretching east of the Hawkesbury-Nepean River system, the Cumberland Lowlands are flanked by the Woronora Plateau in the south, the Hornsby Plateau in the north-east and MacDonald Ranges in the north-west. It is an extensive floodplain area that includes the drainage catchment of South and Eastern creeks.

The region is comprised of creeks and their associated floodplains, alluvial terraces, and some intermediate slopes and undulating land. Very little original vegetation remains as a result of land clearing for agricultural and/or residential use. Open forest, woodland, riverine and pasture are the primary vegetation types found in the region.

The Woronora Plateau lies east and south of the Cumberland Lowlands. It is a deeply dissected sandstone plateau with Wianamatta Group shales occurring as thin lenses. Upland swamps are a common feature towards the coast. The major vegetation formation found in the Woronora Plateau, which occupies most the Sydney Water catchment areas at Nepean, Avon, Cordeaux and Cataract dams, is woodland and open forests. Heaths, including paroo lily, snake grass, and fuller shrubs (she-oak and heath banksia) also grow on the Woronora Plateau.

The MacDonald Ranges are located in the north-east and consist of steep, rugged hills with narrow crests and valleys on Hawkesbury sandstone. Low, open forests of Sydney peppermint, *Eucalyptus piperita* and smooth-barked apple, *Angophora costata*, inhabit the steeper slopes of the MacDonald Ranges, whilst the drier ridges support a low woodland dominated by red bloodwood, scribbly gum and narrow-leaved stringy bark gum.

The Hornsby Plateau, which is similar in form to the Woronora Plateau, is dominated by undulating to rolling plateau surfaces on Hawkesbury sandstone with Wianamatta Group shale caps on some crests. Areas of natural vegetation are generally represented by either national parks or Sydney Water catchment areas.

The Hawkesbury-Nepean River system is used for a variety of agricultural, industrial and recreational activities. The upper river reaches have been dammed and supply much of Sydney's drinking water, plus lesser amounts used for agriculture, industry and other needs. The river is also used for both primary (e.g., swimming) and secondary (e.g., boating) recreation. The number of people participating in these activities is likely to increase with additional future urban development.

Over 60 percent of the Hawkesbury-Nepean River system catchment is forested; it includes parts of nine national parks. Agricultural land comprises approximately 30 percent of the area, supporting activities such as cattle and sheep grazing, dairying, irrigated horticultural crops and intensive pig and poultry production; less than 10 percent is developed for urban and industrial use (Sydney Water 1991).

Industrial development within the Hawkesbury-Nepean River system is limited and generally located within sewage catchments served by the West Camden, Penrith and St Marys STPs (NSW EPA 1994). Industrial discharges to the sewer system are regulated by Sydney Water's Trade Waste Policy. The primary industries in the region include textiles, paint production, electroplating and metal finishing and the manufacture of pharmaceuticals and organic chemicals. A few industries between Menangle and Spencer are involved with the extraction of sand, gravel and other materials. Extraction of sand and gravel is concentrated in the Agnes Banks/ Londonderry and Penrith Lakes areas, while extraction from the river bed material is currently only undertaken at Windsor, Freemans Reach and Menangle. Coal mining also occurs in the upstream areas.

The climate of the Hawkesbury-Nepean catchment is strongly influenced by the Tasman Sea to the east and the Blue Mountains to the west (Sydney Water 1991). The headwaters of the Cox, Grose, Nepean and Nattai rivers and the coastal area near Broken Bay receive the highest rainfalls (annual rainfall ranges from 1000 to 1600 mm). Most of the remaining catchment is located within a rain shadow created by the higher coastal plateau; here annual rainfall ranges from 650 to 750 mm (Sydney Water 1991).

Throughout the region, rainfall occurs primarily in the summer with an average summer maximum of 261 mm at Penrith, ranging to a winter low of 154 mm at Richmond. Rain falls over the region about 10-11 days per month throughout the spring and summer, but decreases to about 6 days per month in winter.

Diurnal and seasonal temperature ranges within the area vary considerably. Maximum summer temperatures average between 26-28°C (maximum 40°C), while minimum winter temperature averages between 2.6-5.9°C (minimum -5°C). Prevailing winds originate from the north-east in spring and summer and from the south-west in autumn and winter (Sydney Water 1991).

Sewage Treatment Plants
In the late 1980s a strategy was developed to reduce the impacts of STPs by reducing the phosphorus levels, oxygen demand and ammonia levels of the effluent. Upgrades to treatment processes ensured that the levels of phosphorus were lowered, thereby reducing eutrophication of the receiving waters. Nitrification processes were installed at the STPs, which meant that the effluent was oxygenated and ammonia was transformed to oxidised nitrogen (mostly as nitrate) (NSW EPA 1994). More recent, additional upgrades at the STPs further reduce phosphorus and nitrogen levels in the effluent.

Data Sources
Monthly data are collected at a number of sites along the Hawkesbury-Nepean River and its tributaries. These data are for a range of dissolved nutrients and physico-chemical parameters. The averages of these data have been used to calculate the nutrient fluxes. Inflows from streams to the main river are gauged and daily flows have been used to calculate an average daily flow. Similarly, flows from sewage treatment plants are gauged each day. The loads of nutrients from the STPs have been calculated using these flows and the average annual nutrient concentrations obtained from daily nutrient monitoring data. A complete series of water, salt and nutrient budgets, including the stoichiometric analysis, is presented for financial year 1995-1996 (July 1-June 30). To give a sense of interannual variation in the budget results, a summary table is also presented for N and P fluxes in the year 1996-1997.

The river has been divided into several reaches representing the freshwater, fresh tidal and estuarine sections (see Figure 2.2). The fluxes from each reach of the river have been presented and it has been assumed that the river is well mixed in each reach.

Results
Complete budgetary data are presented for the 1995-1996 financial year, using annual mean data (Figures 2.3-2.5). There has been no attempt to determine the errors about these means. A summary table of non-conservative fluxes is presented for that year (Table 2.9), as well as 1996-1997 (Table 2.10). The DIP and DIN budgets for the two years are summarised in Tables 2.9 and 2.10.

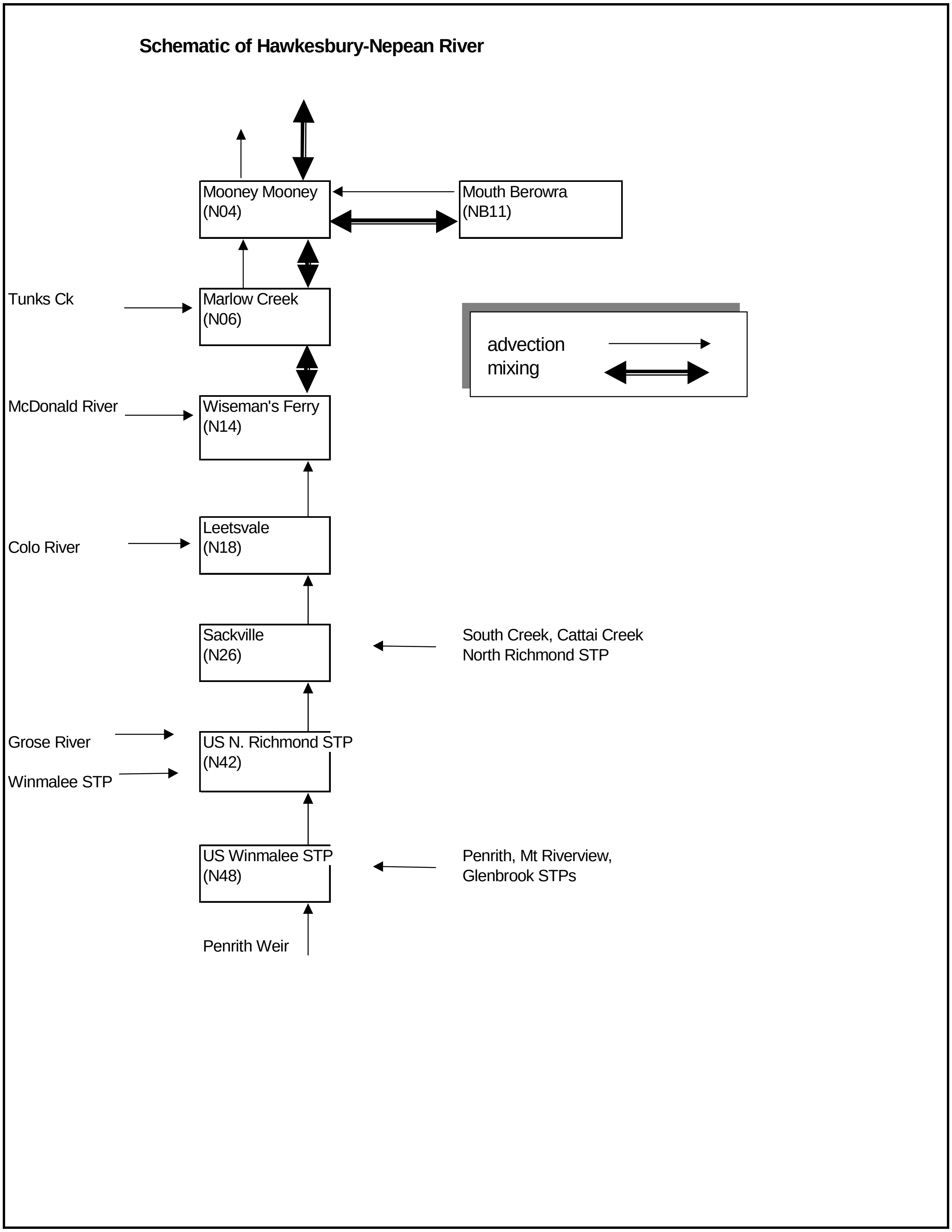

Figure 2.2 Schematic diagram for the Hawkesbury-Nepean River system.

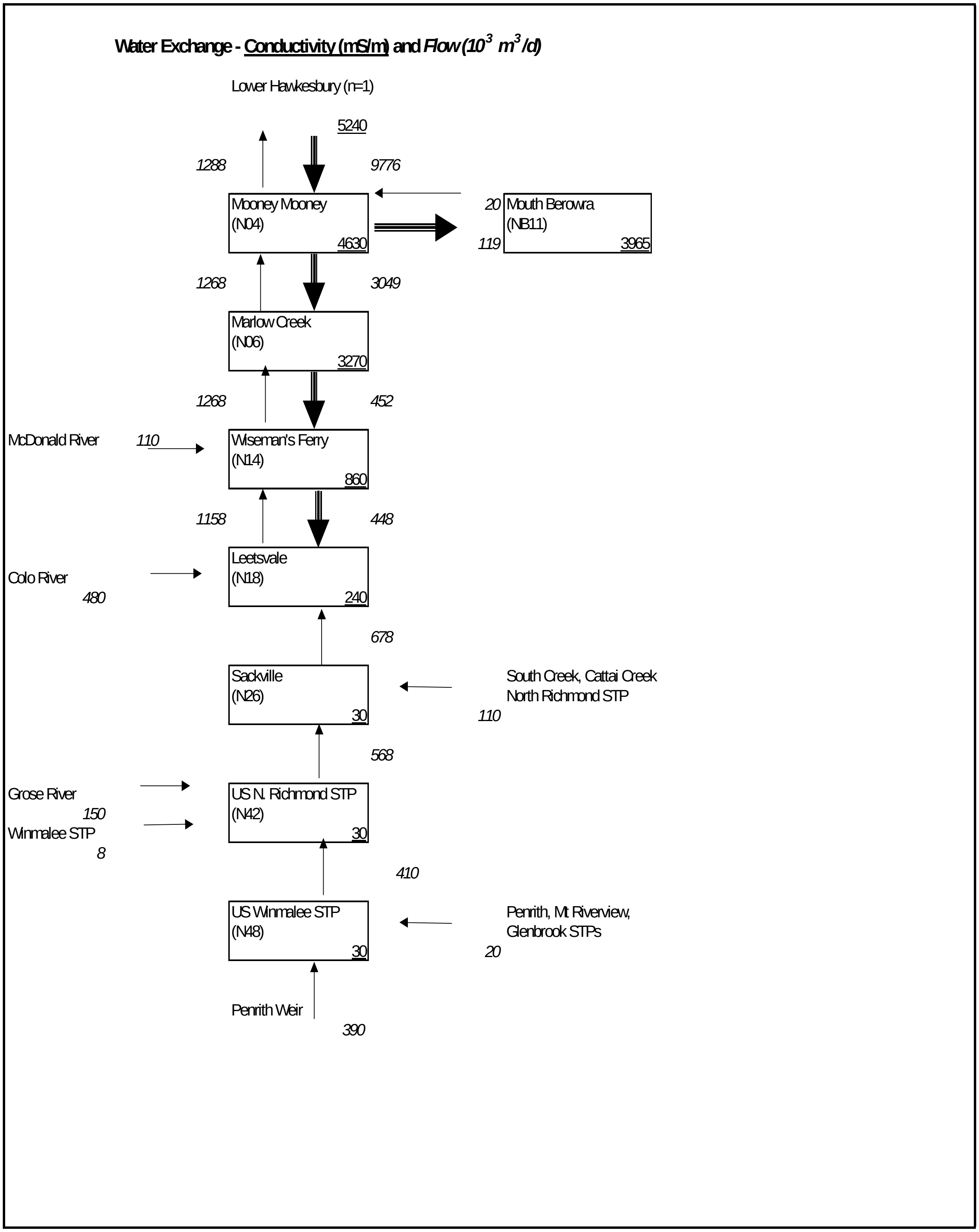

Figure 2.3 Summary of the water and salt balance during 1995-1996, for the Hawkesbury-Nepean River system.

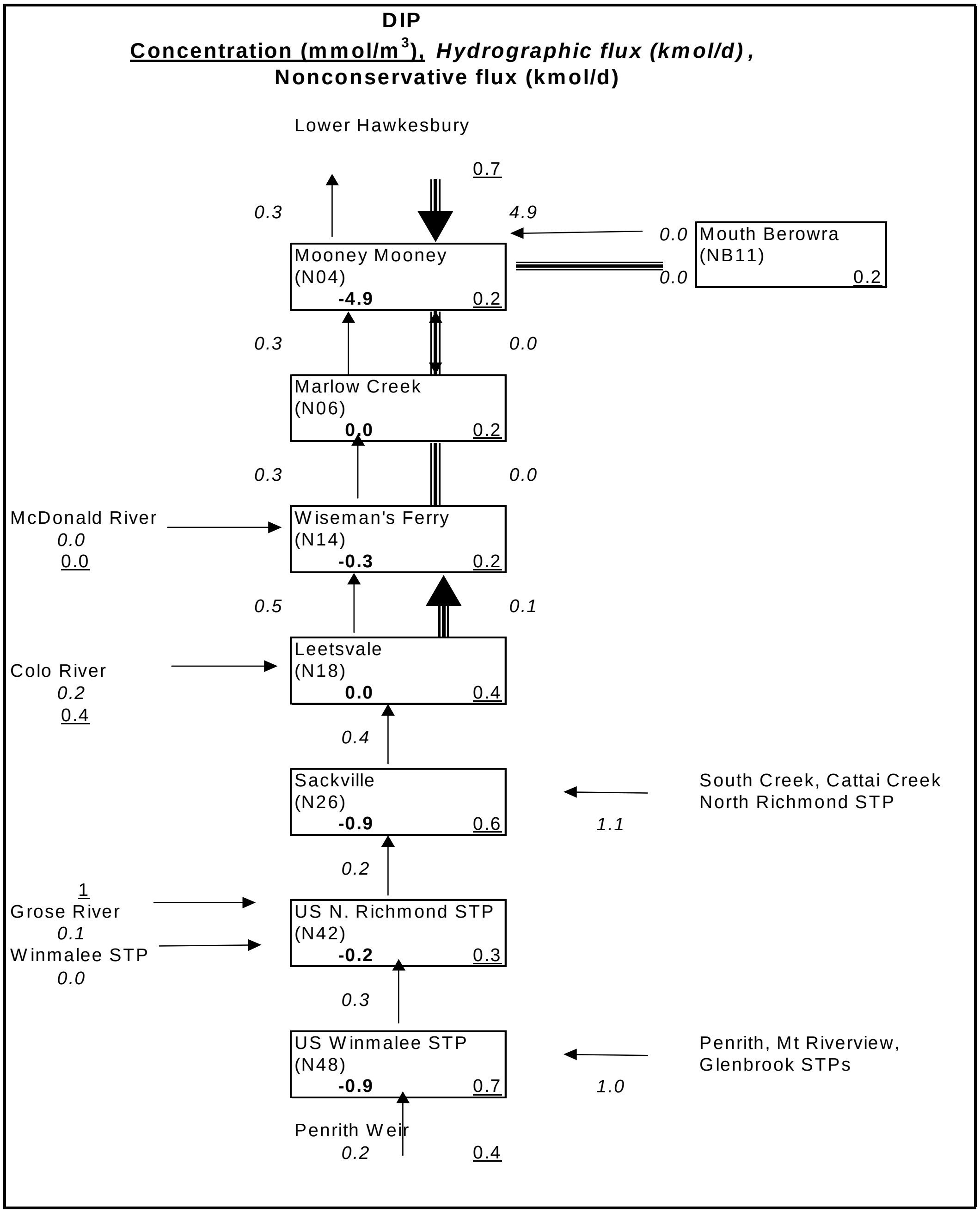

Figure 2.4 Summary of the DIP balance during 1995-1996, for the Hawkesbury-Nepean River system.

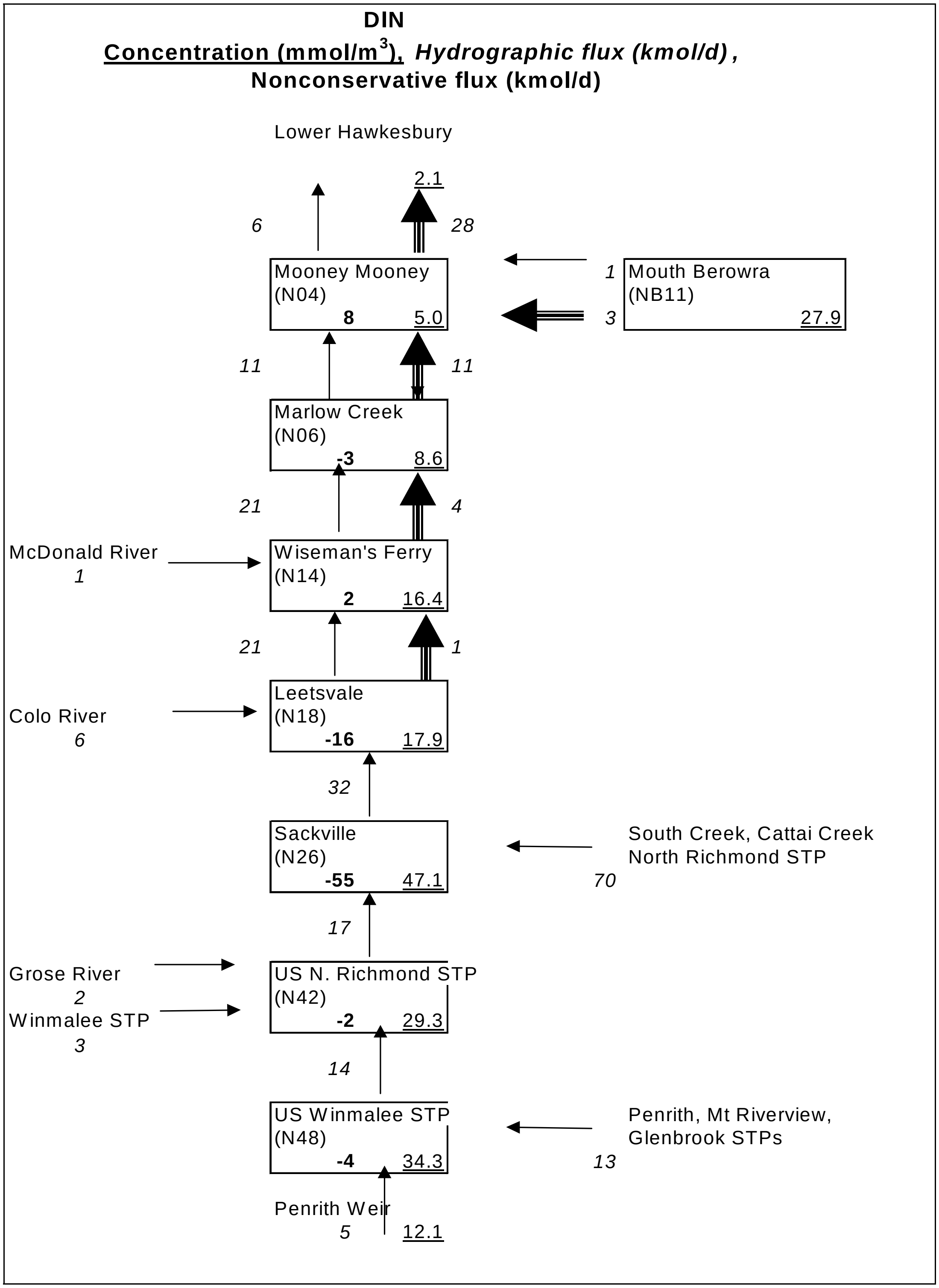

Figure 2.5 Summary of the DIN balance during 1995-1996, for the Hawkesbury-Nepean River system.

Table 2.9 Non-conservative DIP and DIN fluxes in the Hawkesbury-Nepean River system for the year 1995-1996. (Biogeochemical performance is inferred from LOICZ stoichiometric arguments.)

	Location	DP kmol d^{-1}	DN kmol d^{-1}	(p-r) kmol d^{-1}	(nfix-denit) kmol d^{-1}
↑	(N04)	-4.9	8	523	87
	(N06)	0.0	-3	0	-3
estuary	(N14)	-0.3	2	32	7
tidal fresh	N18	0.0	-16	0	-16
↑	N26	-0.9	-55	95	-41
river	N43	-0.2	-2	21	1
	N48	-0.9	-4	95	10

	Area km^2	DP mmol m^{-2} d^{-1}	DN mmol m^{-2} d^{-1}	(p-r) mmol m^{-2} d^{-1}	(nfix-denit) mmol m^{-2} d^{-1}
Lower estuary	25	-0.2	0.2	21	3.4
Upper estuary	9	0.0	-1.6	4	-1.0
River, Tidal fresh	10	-0.2	-6.8	24	-2.9

Table 2.10 Non-conservative DIP and DIN fluxes in the Hawkesbury Nepean River system for the year 1996-1997. (Biogeochemical performance is inferred from LOICZ stoichiometric arguments.)

	Location	DP kmol d^{-1}	DN kmol d^{-1}	(p-r) kmol d^{-1}	(nfix-denit) kmol d^{-1}
↑	(N04)	-3.5	-8	370	48
	(N06)	0.2	38	-21	35
estuary	(N14)	-0.2	3	21	6
tidal fresh	N18	0.1	-9	-11	-11
↑	N26	-0.4	-59	42	-53
river	N43	-0.6	-4	64	6
	N48	-0.9	-6	95	8

	Area km^2	DP mmol m^{-2} d^{-1}	DN mmol m^{-2} d^{-1}	(p-r) mmol m^{-2} d^{-1}	(nfix-denit) mmol m^{-2} d^{-1}
Lower estuary	25	-0.1	1.2	14	3.3
Upper estuary	9	0.0	0.4	1	-0.5
River, Tidal fresh	10	-0.2	-7.7	22	-3.9

Stoichiometric inferences are presented for both the river and the estuarine system, although the river-based stoichiometry is unlikely to be realistic because of inorganic reactions in this region. Above Sackville, the major source of dissolved inorganic P is sewage treatment plants, with a relatively small contribution from non-point sources. Most of the discharged phosphate is taken up as either organic or inorganic particulates close to the sewage treatment plants. Only about 20% of the phosphate introduced to the river above Sackville is transported below Sackville. For the estuary itself, the major source of DIP is the coastal ocean rather than the sewage treatment plants. Above Sackville, the major source of nitrogen to the river is from the STPs (90%). About 20% of the N introduced to the river from non-point and STP sources reaches the estuary. Most of the remainder is interpreted to be lost to denitrification.

The calculated (*p-r*) result for the lower estuary over the two years averages +18 mmol m^{-2} d^{-1}, with minor interannual variability. The upper estuary (*p-r*) is near 0, and the rate averaged over the whole estuary for two years is +14 mmol $m^{-2}d^{-1}$. There is a strong suggestion of an internal source of N (nitrogen fixation) in the lower estuary. The possible source of this nitrogen may be from a significant area of mangroves in the lower estuary. The upper estuary is a slight nitrogen sink (denitrification). The whole-estuary average rate of (*nfix-denit*) is +2.3 mmol m^{-2} d^{-1}.

2.3 LAKE ILLAWARRA, NEW SOUTH WALES

Cathee Miller and John Morrison

Study Area Description

Lake Illawarra (Site No.20.; 150.83E, 34.50S) is located on the south-east coast of Australia, approximately 8 km south of central Wollongong (see Figure 1.1). Lake Illawarra is a Late Pleistocene barrier estuary, with the barrier causing restricted connection to the ocean via a channel of approximately 3.7 km in length, with an average width of less than 200 m (Figure 2.6). The channel is mobile in both location and cross section, due to natural coastal processes involving winds, waves and currents (Standing Committee on Public Works 1996). The lake entrance is heavily shoaled and closes intermittently. Engineering works are currently planned to maintain an open entrance (Lake Illawarra Authority (LIA), personal communication 1997).

Some system information on Lake Illawarra is given in Table 2.11.

Table 2.11 System data for Lake Illawarra

Dimensions:	
Maximum length:	7.3 km
Maximum width:	5.5 km
Surface area:	35 km^2
Foreshore length:	40 km
Maximum depth:	3.8 m
Average depth:	1.8 m
Volume:	63 x 10^6 m^3
Catchment:	
Area	235 km^2
Land uses:	
Forest/undeveloped	87 km^2
Rural	94 km^2
Residential/ Commercial	54 km^2
Main Freshwater Sources:	
Macquarie Rivulet	39% of catchment
Mullet Creek	27%
Duck Creek	7%
Other creeks	27%
Fisheries:	
Finfish	140 000 kg yr^{-1} (mullet, flathead, bream, luderick)
Prawns	30 000 kg yr^{-1}

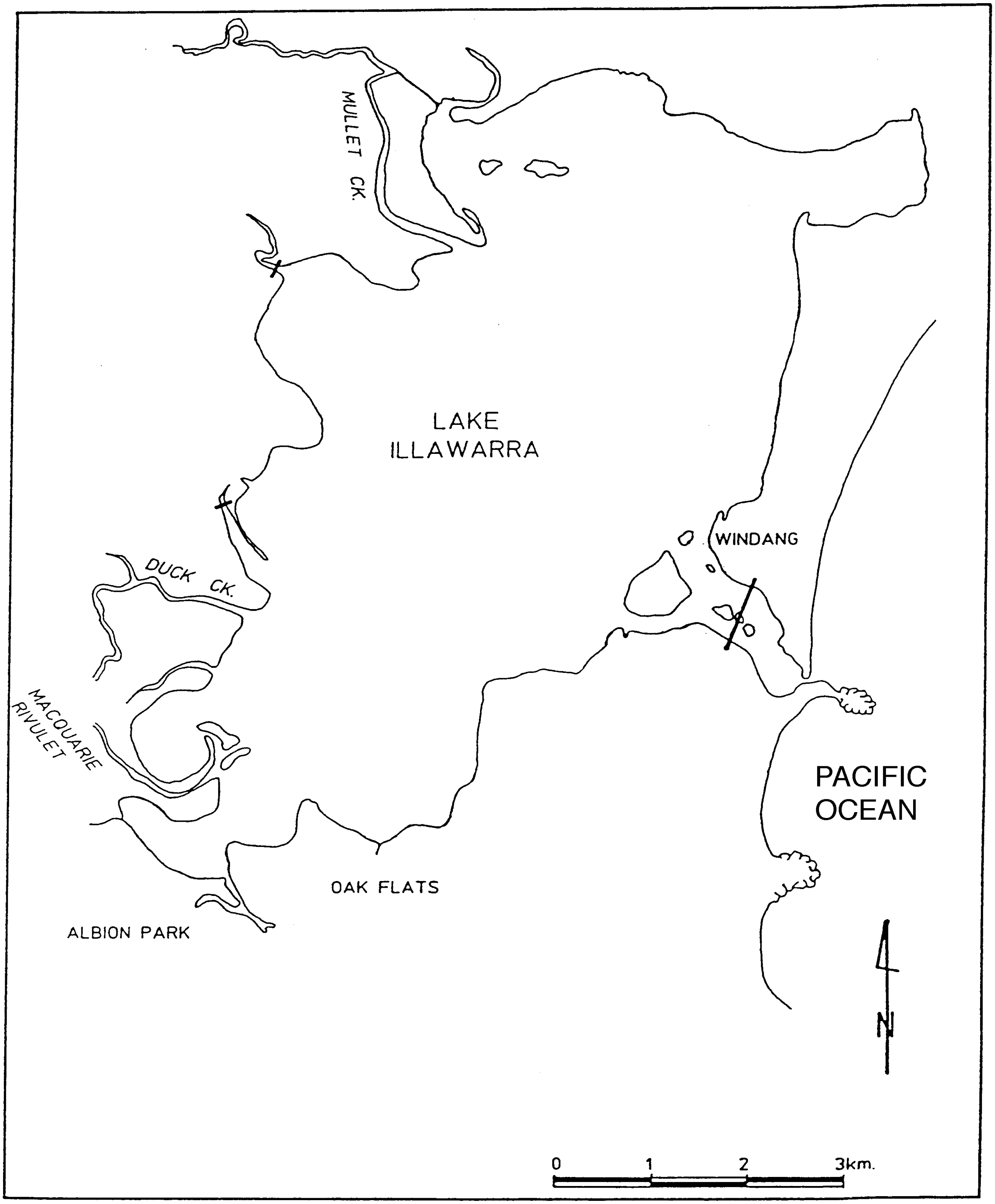

Figure 2.6 Site map of Lake Illawarra.

Land use within the catchment has changed greatly since first European settlement in the early 1800s, with the region shifting from predominantly agricultural to merging industrial, with relatively recent increases in urban and recreational usage of the area. The population living around the lake has increased from about 10,000 in the 1950s to about 95,000 in the late 1990s. The region is now completely sewered, but septic tanks dominated until the mid-1980s with significant overflows into the lake during storms. Some overflow from sewage pumping stations has occurred and the Lake Illawarra Authority is attempting to manage overflow sites by the introduction of artificial wetlands.

The lake is very shallow and has been infilling since its creation, roughly 6000 years ago. It has a maximum depth of 3.5 m and an average depth of 1.8 m, the north-eastern segment being particularly shallow (Kanamori 1976). Hean and Nanson (1985) estimate that since European settlement 25 000-100 000 m^3 of sediment are transported to the lake floor annually. Sediment analysis has shown this is up to 50 times greater than prior to European settlement.

The volume of water in Lake Illawarra is estimated to be 6.3×10^7 m^3. Kanamori (1976) estimated the volume of flood and ebb tide to be 1.9×10^5 m^3 and 7.8×10^5 m^3 respectively, giving a mean volume of 4.9×10^5 m^3, which accounts for 0.8% of the lake's volume. Therefore, allowing for tidal exchange only, he estimated the turnover rate of the lake to be 62.5 days. This is a gross simplification, not taking into account freshwater inflows, tidal variation, tidal penetration and entrance conditions.

The tidal range in the lake proper varies from 0.03 m under a heavily-shoaled entrance to 0.1 m under scoured-entrance conditions for an average ocean range of 1.1 m (Kanamori 1976). A 1.83 m tide recorded at Port Kembla showed a fluctuation of only 2.5 cm at Windang Bridge and was barely noticeable beyond Berkeley boat harbour on the south coast of the Lake, because of elevated lake water level compared with the sea (this elevation is 25-30 cm).

The area is classified as a temperate coastal environment, with temperatures moderated by the ocean. The expected rainfall in the area depends mainly on elevation. Average rainfall levels at Port Kembla to the north of the lake and Albion Park to the south are 1 151 and 1 231 mm (National Environmental Consulting Services 1997). Rainfall on the south-western escarpment, at an elevation of approximately 350 m, is about 1 600 mm per annum. Occasional heavy rainfall comes from mild cyclonic storms but otherwise rainfall is generally consistent throughout the year, with heaviest rain in late summer and autumn (Hean and Nanson 1985). Bureau of Meteorology rainfall data from 1974 to 1997 provides the following average rainfall percentages for the seasons:

Summer:	25.5%
Autumn:	30.1%
Winter:	21.8%
Spring:	22.6%

Storm events are an important feature of the catchment and lake behaviour, with major storm events occurring almost every year. Figure 2.7 shows the average monthly rainfall figures from 1974 to 1997, with maximum and minimum temperatures in Wollongong recorded from 1991. Figure 2.8 shows annual rainfall levels experienced in Wollongong, from 1974 to 1997 (Bureau of Meteorology, Canberra 1974 - 1997).

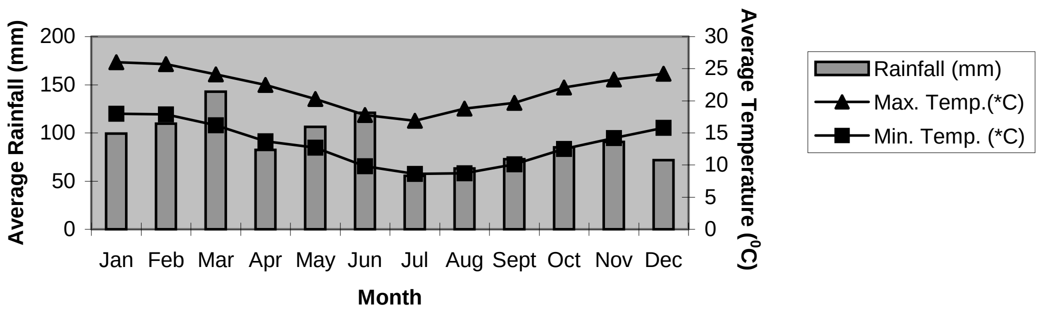

Figure 2.7 Average monthly rainfall and temperature in Wollongong from 1974 to 1997. (Data from Bureau of Meteorology Monthly Reports, 1974 – 1997. Temperature data for Wollongong was only available in this report from 1991.)

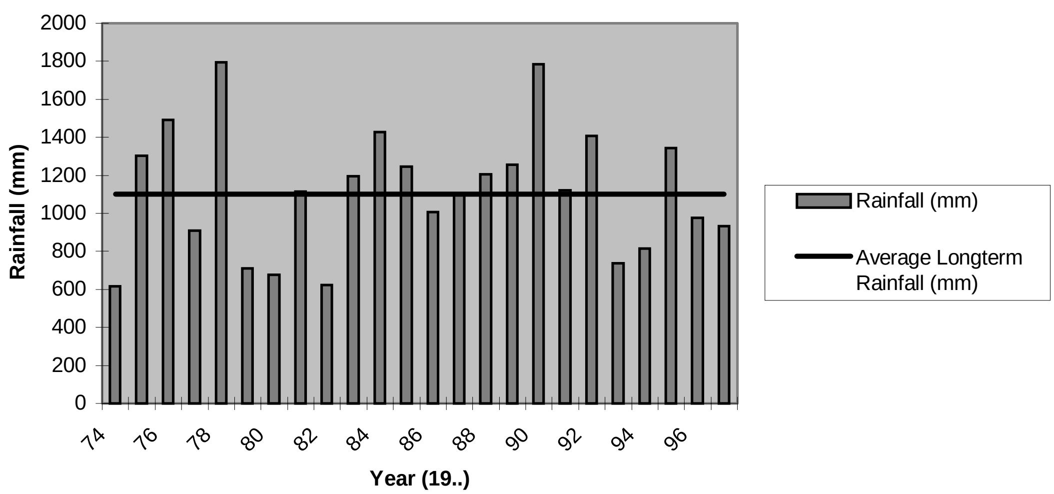

Figure 2.8 Annual rainfall recorded in Wollongong from 1974 to 1997. (Data from Bureau of Meteorology Monthly Reports, 1974–1985.)

Three types of winds are evident at Lake Illawarra. In the summer months, strong north-easterly winds are prevalent. In the winter months, strong westerly to south-westerly winds are experienced (LIA 1995). Clarke and Elliot (1984) suggest the strong winds at Lake Illawarra create wind-driven circulation that results in a well-mixed lake water body, on the most part exhibiting little variation in vertical or horizontal movement.

The Lake Illawarra Authority regularly dredges, partly to maintain lake depth and partly to remove nutrient-rich sediments, with about 30 000 m^3 being extracted each year. Macroalgal harvesting has been going on since the late 1980s, with an average of 2000 tonnes dry matter removed each year (LIA 1998).

The lake is an important economic and recreational resource, with both commercial and recreational fishing activity. Yachting, water skiing and sailing attract large numbers of both local residents and tourists.

Legislative control rests with the Lake Illawarra Authority, established by the NSW Parliament in 1988, with membership from NSW government departments (Department of Land and Water Conservation – DLWC; Environmental Protection Agency – EPA; Fisheries), local government (Wollongong City Council, Shellharbour City Council) and community representatives.

Data Sources

As Lake Illawarra has been affected by local population increases and land use changes, including industrial development, a significant body of data has been collected. Only a very limited component of the data is suitable for use in LOICZ nutrient budgeting, with information being obtained from the Lake Illawarra Authority, the NSW Government (DLWC, EPA), Sydney Water Corporation, Wollongong City Council, ELCOM/Pacific Power/Integral Energy, University of Wollongong, and several consultancy reports.

A number of problems were identified with the data, including:

- inconsistent reporting of parameters measured;
- spasmodic collection of data, both temporally and spatially;
- much dry weather data, few representative data for wet weather;
- raw data not included in reports and thus not able to be scrutinised;
- methodology often not included, so comparison of data difficult;
- some data in obscure documents, often difficult to access;
- little groundwater information available;
- no coherent programs linking catchment data and lake data measurements.

Sufficient information, however, was available to compile an adequate budget as a first approximation. To determine if seasonal effects were being dramatically hidden by such an approach, wet and dry season budgets were also prepared and compared to the overall annual data. A sensitivity analysis on the influence of salinity was also completed.

Results

<u>Water and salt budget</u>

Average precipitation at Lake Illawarra is 1100 mm (Hean and Nanson 1985). Bureau of Meteorology data taken for Wollongong 1974 to 1997, as seen in Figure 2.8, agree with this value.

Daily evaporation is typically 1 mm in winter and 4 mm in summer (Standing Committee on Public Works 1996). Wollongong City Council and The University of Wollongong (1976) found the following figures for average monthly evaporation:

Estimated Evaporation (mm)												
J	F	M	A	M	J	J	A	S	O	N	D	Year
117	108	111	89	72	55	55	63	74	88	98	110	1040

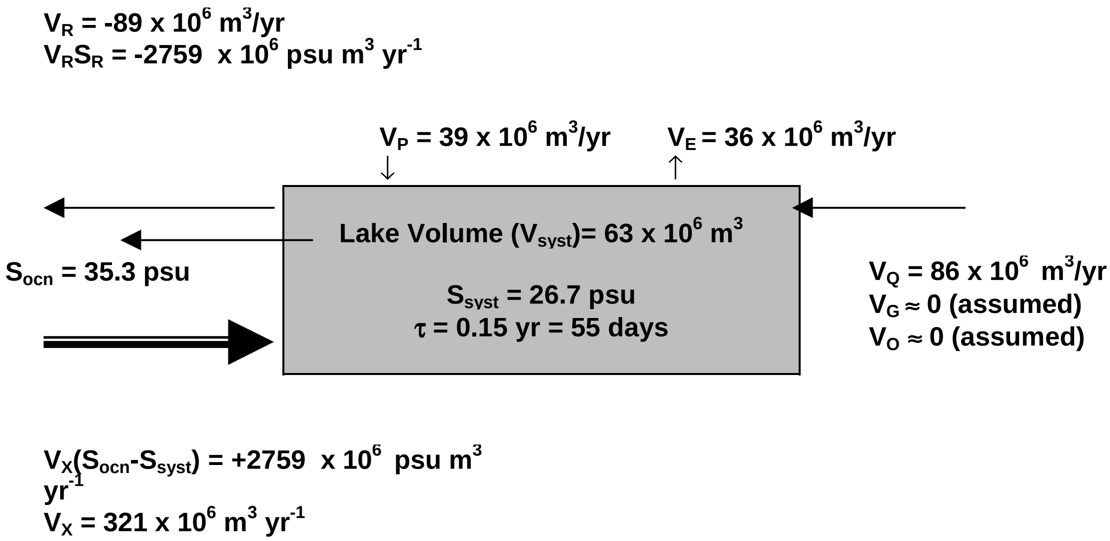

Figure 2.9 Water and salt budgets, Lake Illawarra.

The above evaporation figures may be elevated as they do not allow for cloud and fog (at higher altitude), both of which reduce evaporation (WCC and UOW 1976). However, they are indicative of Lake Illawarra, considering the lake is only 25-30 cm above sea level.

LIA (1995) found runoff average (between wet and dry years) to be 86 x 10^6 m^3 yr^{-1}. This is in line with Kanamori data, where Macquarie Rivulet was gauged and found to have a runoff of 42 x 10^6 m^3, and the total catchment runoff value was estimated as double this value at 80 x 10^6 m^3.

Groundwater contribution is assumed as negligible; it is expected the water would surface prior to reaching the lake and thus would be included in the surface runoff (V_Q).

V_O is assumed to be zero. No other sources of water contribute to the lake system.

The Public Works Department Lake Illawarra Hydrographic Survey General Plan (1988) was used to determine if the estimated volume was appropriate, using a volume (squares-method) analysis.

Salinity in precipitation and runoff is expected to be zero or so small as to be insignificant to the salinity budget (Gordon *et al.* 1996). The salinity in Lake Illawarra can range from 6.9 to 42 psu (ELCOM 1987). The former is experienced in wet weather, where freshwater flow has a diluting effect, and the latter in dry weather, where evaporation is the major determinant of salinity concentration.

The Standing Committee on Public Works (1996) and LIA (1995) reported that the average salinity of the lake is 33 psu. From further assessment of data, we consider that this salinity value is too high to be used as an average. These figures have mostly been derived from recent reports conducted during relatively dry periods (ELCOM 1984, Collie 1991, Simeoni *et al.* 1995 and Ferguson *et al.* 1995). Other studies which have reported much lower levels of salinity in the Lake Illawarra system were generally conducted over a more 'normal' (i.e., ≥ 1100 mm) rainfall conditions, or over a longer time and taking more climatic cycles into account: Anderson and Storey (1981) recorded an average salinity of 28.6 (24/3/76 to 12/8/76); Kanamori (1976) recorded an average salinity of 24.7 (7/4/72 to 21/1/74); and Brown (1968) recorded salinity near Tallawarra Power Station about weekly (2/1/57 to 17/8/65), with an average value of 26.7 psu.

Brown's (1968) average has been used in this budget as it covers the most extensive time period, although the values at the former Tallawarra Power Station site may not be fully representative of the salinity in Lake Illawarra in general.

Ocean Salinity = 35.3 psu (ERM McCotter & Associates 1994)

Residual salt flux $(S_R) = \dfrac{S_{\text{ocean}} + S_{syst}}{2}$ = 31 psu

Residual flow is negative, indicating flow from the system. Under these conditions, mixing (V_X) is likely to transport salt into the system.

Exchange Time (τ) $= \dfrac{V_{syst}}{V_x + |V_r|}$ = 56 days

This value compares with estimates by the Lake Illawarra Authority where from an exchange rate of about 1 million $m^3\,d^{-1}$, an exchange time of 63 days was calculated (G. Clarke, personal communication 1997).

<u>Dissolved inorganic phosphorus budget</u>

ELCOM (1984 and 1987) data were two consistent data sets for system phosphorus concentration; the average of these has been used in the model (1.9 mmol m^{-3}).

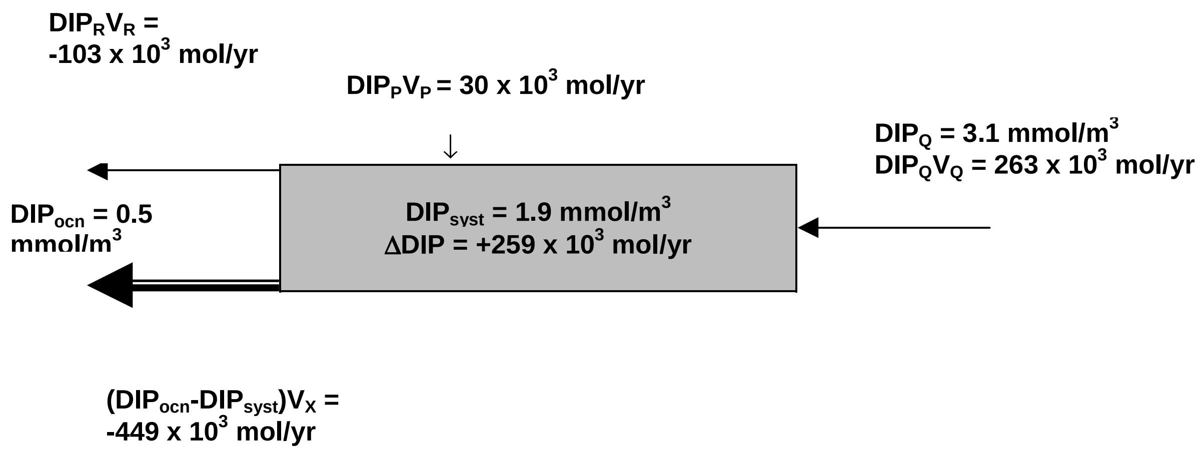

Figure 2.10 DIP budget, Lake Illawarra.

Average precipitation contains 0.8 mmol m^{-3} total phosphorus, of which 95% is as DIP (LIA 1995).

Total Phosphorus Inflow = 263 x 10^3 mol yr^{-1} (LIA 1995). This approximates an inflow P concentration of 3.1 mmol m^{-3}. Phosphorus in the ocean is approximately 0.8 mmol m^{-3} (LIA 1995) of which only 60% is available as orthophosphate, *viz.*, 0.48 mmol m^{-3}.

Outward transport occurs via both residual flow and mixing, in excess of the estimated inflow contributed by rainfall and catchment runoff. Thus, there appears to be an internal source of DIP contributing approximately 260 x 10^3 mol yr^{-1} (~0.01 mol m^{-2} yr^{-1}). Davey (1994) and Woodward (1986) suggested this source is sediments recycling processes. Others suggest that recycling contributes >80% of the system phosphorus during non-event periods (Sydney Water 1998).

<u>Nitrogen budget</u>

Information on nitrogen in the lake system is not easily accessible because of the both array of nitrogen species and analytical methods applied to historical measurements, including:

- Total Nitrogen
- Total Kjeldahl Nitrogen
- Total Uncombined Ammonium
- Nitrogen oxides i.e., nitrate and nitrite.

For the purposes of this budget ELCOM (1984) data were utilised. DIN_{syst}=2.4 mmol m^{-3}.

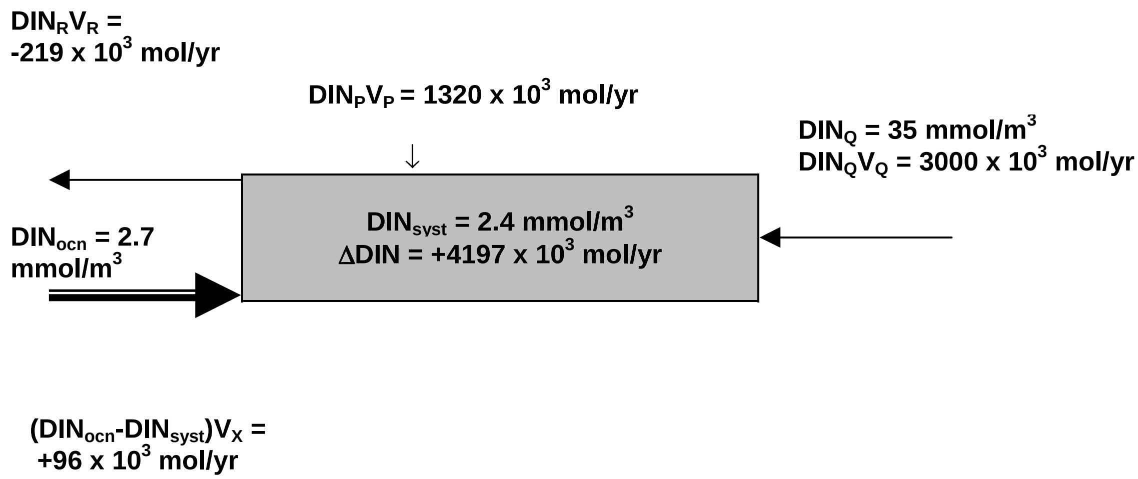

Figure 2.11 DIN budget, Lake Illawarra.

Average precipitation contains about 36 mmol m^{-3} nitrogen, of which 95% is available as DIN (LIA 1995) thus ~34 mmol m^{-3}.

Total Nitrogen Inflow = 10^6 mol yr^{-1} of which DIN is estimated to contribute 30% (LIA 1995). This equals a DIN delivery of approximately 3 x 10^6 mol yr^{-1}, and as catchment inflow is averaged at 86 x 10^6 m^3 yr^{-1}, concentration is approximately 35 x 10^{-3} mol m^{-3}.

Total nitrogen in the ocean is reported as approximately 18 mmol m^{-3} (LIA 1995), of which only 15% is DIN, i.e., ~2.7 mmol m^{-3}. Therefore, the outward DIN flux is at least an order of magnitude lower than the influx of nitrogen from the catchment. Consequently, there appears to be a sink for DIN in this system and fits the previous report of Lake Illawarra being a nitrogen limited system (LIA 1995). However, flux measurements are needed to consolidate these first estimates.

Stoichiometric Calculations According to the LOICZ Guidelines

Carbon:Phosphorus Stoichiometry

$\Delta DIC = \Delta DIP \times (C:P)_{part}$

$= 259 \times 10^3 \text{ (mol yr}^{-1}) \times 106$ (assuming plankton dominance of primary production)

$= 2.75 \times 10^7 \text{ mol C yr}^{-1}$

Net Ecosystem Metabolism

$(p\text{-}r) = -2.75 \times 10^7 \text{ mol y}^{-1} = -0.8 \text{ mol m}^{-2}\text{ yr}^{-1}$

$= -2.2 \text{ mmol m}^{-2}\text{ d}^{-1}$

The system appears to be net heterotrophic, according to the LOICZ approach.

Net primary production in Lake Illawarra has been estimated at about 101 mol m^{-2} d^{-1} (Ian Webster and Phillip Ford, CSIRO, personal communication 1998), which suggests that (*p-r*) is about 2% of the primary production and the P/R ratio is about 0.98.

<u>Nitrogen:Phosphorus Stoichiometry</u>

$$
\begin{aligned}
(nfix\text{-}denit) &= \Delta DIN_{obs} - \Delta DIN_{exp} = \Delta DIN - \Delta DIP \times (N{:}P)_{part} \\
&= (-4197 \times 10^{3}) - (259 \times 10^{3}) \times 16 \\
&= -8341 \times 10^{3} \text{ mol yr}^{-1} \\
&= -0.24 \text{ mol m}^{-2} \text{ yr}^{-1} = -0.7 \text{ mmol m}^{-2} \text{ d}^{-1}.
\end{aligned}
$$

This rate of net denitrification compares with reports from similar systems (Seitzinger, 1988). These estimates assume that plankton dominate primary production. In Lake Illawarra there is significant productivity both of seagrasses (*Zostera* and *Ruppia*) and macroalgae. These macrophytes will contribute to a slightly different C:N:P ratio than phytoplankton for estimating the organic material, but these changes have been ignored in this analysis.

Sensitivity Analyses

An attempt was made to estimate budgets for the Lake in two seasons, one wet and one dry, each lasting for 6 months. In dry weather, the residence time of freshwater more than doubles and the exchange time is reduced by 70%. This leads to a ΔDIP of +645 x 10^3 mol yr^{-1} and a ΔDIN of -2600 x 10^3 mol yr^{-1}. Under wet weather conditions, the freshwater residence time is reduced and the exchange time is increased, whereby ΔDIP is calculated to be -12 x 10^3 mol yr^{-1} and ΔDIN to be -4612 x 10^3 mol yr^{-1}. The combination of these seasonal budgets yields a similar outcome as that estimated above for an annual budget.

It should be noted that there is some difficulty in determining an appropriate mean salinity for this system and that the calculated residence times and nonconservative fluxes are, as expected, sensitive to the salinity values chosen.

Conclusion

LOICZ budgets have been developed for Lake Illawarra and the results obtained from carrying out the modelling exercise are in line with observations on the Lake. The Lake would appear to be losing nitrogen by denitrification, and is a system that is a net producer of DIC by respiration.