MORPHOMETRY AND STRATIFICATION OF THE BENTS BASIN SCOUR POOL, NEPEAN RIVER, NSW.

L.M. Turner and W.D. Erskine
School of Geography, University of NSW, Sydney NSW 2052.

ABSTRACT

The Bents Basin scour pool is a large hole eroded into the bed of the Nepean River where it flows through the Lapstone Structural Complex at the downstream end of the Bents Basin sandstone gorge. The scour pool has a surface area of 17500 m^2, a volume of 157 400 m^3, a mean depth of 9.0 m, a maximum depth of 22.8 m and is an oval-shaped cone. While the capacity-inflow ratio is only 0.00054 and indicates that pool volume is very small in relation to the mean annual flow, the scour pool is not flushed for time periods up to 12 months long. Thermal stratification was measured between mid-January and March 1996 when the thermocline was usually at a depth of 10 m. Temperature differences of between 9.6 and 14.7°C were measured between the surface and the bottom at times of stratification. Density differences of 2 kg/m^3 were calculated as a result of thermal stratification. Oxygen stratification was measured between January and April 1996 when the oxycline varied between depths of 7 and 12 m. Anoxic conditions were usually recorded below the oxycline. Oxygen stratification resulted in a large increase in total phosphorus concentrations, due to the release of sediment-bound phosphorus. Cation concentration did not vary with depth. Datalogging on 6-7 March 1996 proved that both thermal and oxygen stratification persisted throughout the night. Stratification was recorded between mid-January and March/April 1996 because climatic and hydrologic conditions were not capable of generating sufficient turbulence to mix and hence destratify the scour pool. Current water quality monitoring programs on the Nepean River by government agencies are flawed because they do not sample the whole water column, only surface waters. As a result, these programs present a biased assessment of current conditions during summer.

INTRODUCTION

Many limnologists have concluded that persistent thermal stratification rarely occurs in streams, rivers and estuaries because flow is usually turbulent enough to cause complete mixing (for example, Baxter, 1977; Williams, 1981; Horne and Goldman, 1994). As a result, many of the water quality problems associated with the formation and persistence of thermal stratification in lakes, such as oxygen depletion in the deeper layers causing hypolimnetic anoxia and the consequent increase in ammonia, hydrogen sulfide, iron, manganese and phosphorus concentrations (Bayly and Williams, 1973; Petts, 1984; 1986; Horne and Goldman, 1994), have been rarely reported in rivers. Nevertheless, salt and thermal stratification have been recently recorded on some Australian rivers (Anderson and Morison, 1989; Cameron and Jekabsons, 1992). The development of stratification in the majority of dams and lakes is dependent on water depth (Hutchinson, 1957; Wetzel, 1975). The deeper the water body, the greater the chance that it will persistently stratify (Preece, 1996).

Although the Nepean River has been deepened substantially by dredging for construction sand (Warner, 1983; Erskine, 1997; Erskine and Green, 1997), water quality monitoring and modelling programs do not acknowledge that stratification may occur (for example, Qin *et al.*, 1994; Qin and Fisher, 1994; Sivakumar and Musavi Jahromi, 1995). The environment Protection Authority (1994) found little change in temperature with depth in the tidal Hawkesbury River and, therefore, concluded that the whole water column was well mixed throughout the Hawkesbury-Nepean River. However, Erskine and Green (1997) reported well developed thermal and oxygen stratification on the Nepean River in the Cobbitty Weir Pool during summer as a result of significant deepening due to dredging.

The Nepean River is characterised by a series of alternating bedrock and alluvial reaches (Warner, 1983; Erskine, 1997). There are many deep, natural scour pools in the bedrock reaches (Warner, 1983; Saynor and Erskine, 1993). Flow regulation and interbasin water transfers for Sydney's water supply have greatly reduced both flood peak and baseflow discharges on the Nepean River below Pheasants Nest (Sammut and Erskine, 1995), thus increasing the probability of stratification in these deep pools (Erskine, 1997). The purpose of this paper is to present the results of a preliminary study on the formation and persistence of stratification in one of these deep pools at Bents Basin (Figure 1). The morphometry of this deep pool, the effects of thermal and oxygen stratification on total phosphorus and cation concentrations as well as the influence of ambient climatic and hydrologic conditions on mixing are also discussed.

BENTS BASIN SCOUR POOL.

The Bents Basin scour pool is a large hole eroded where the Nepean River debouches from the Bents Basin bedrock gorge onto Quaternary alluvium. Erskine (1997) classified the Nepean River into a series of homogeneous reaches based on geomorphic criteria. The scour pool is located at the boundary of this Bents Basin gorge and Wallacia alluvial reach. This boundary coincides with Herbert and Clark's (1991) Lapstone Structural Complex which, at Bents Basin, is either a monoclinal fold or a fault with a throw of 150 m. This Complex is currently thought to be a horst resulting from collapse of the Cumberland Basin rather than by uplift of the Blue Mountains Plateau (Herbert and Clark, 1991). While the Lapstone Structural Complex may have been active since the Triassic (Herbert and Clark, 1991), its present geomorphic expression relates to movements about 12 million years ago (Bishop *et al.*, 1982). The Bents Basin gorge is cut into Triassic Hawkesbury Sandstone which, although usually horizontally bedded, dips steeply in an exposure on the right bank of the scour pool. A large, high bar has been deposited immediately downstream of the scour pool from the sediment either eroded from the floor of, or transported into and through, the scour pool. The upstream gorge, the scour pool and the downstream bar are all located within the Bents Basin State Recreation Area.

SCOUR POOL MORPHOMETRY.

Figure 2 shows the contours of the scour pool. Permanent Mark 81102 with a Reduced Level of 44.36 m Australian Height Datum (AHD) was used as the origin of the survey. Water level at the time of survey (16-19 August 1996) was RL 27.22 m AHD. The contours of the scour pool were determined by lead line at fixed 5 m intervals on a series of transects between surveyed end points. A total of 265 spot depths was used to construct Figure 2. Although an earlier bathymetric map had been produced by the Sydney Water Board from echo-sounder traces undertaken in 1985, it was not used here because both the pool outline and contours were not representative of current conditions.

There is a rapid increase in depth to the minimum level of RL 5.7 m AHD which is located 80 m downstream of the inflow point. This part of the scour pool is cut into sandstone and is often veneered by large sandstone boulders. The left bank of the pool is very steep next to the deepest point. A concave upwards bed profile characterises the rest of the scour pool away from the deepest point.

Table 1 lists the values of a number of morphometric parameters which were calculated according to the procedures and formulae in Bayly and Williams (1973) and Timms (1992). These parameters were derived for lakes and may not be directly applicable to scour pools on a river. While the minimum level of RL 5.7 m AHD (a depth of 21.52 m) was determined during the transect surveys, lower levels, with the deepest being RL 4.42 m AHD (a depth of 22.8 m), were recorded during water quality measurements at points not on the surveyed transects. According to Timms (1992), the relative depth of most lakes is generally 0.1%, with smaller, deeper lakes having higher values. The higher the value, the more stable is the resultant thermal stratification. A relative depth of 14.4% is very high and indicates a high potential for thermal stratification in the Bents Basin scour pool. The outline of the scour pool approximates a circle, given a shoreline

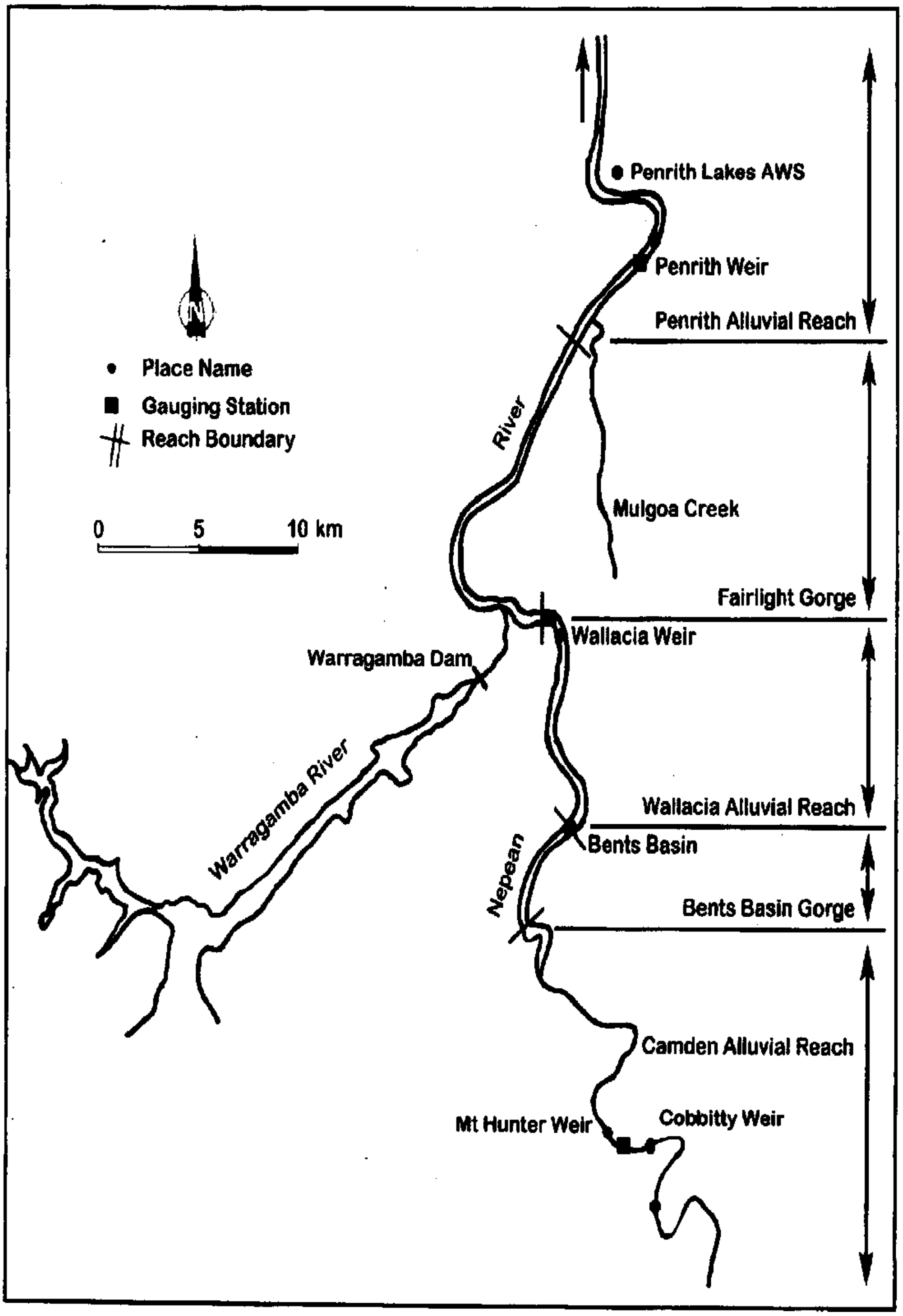

Figure 1: Nepean River between Camden and Penrith showing the location of the Bents Basin scour pool near Wallacia and Erskine's (1997) channel reaches.

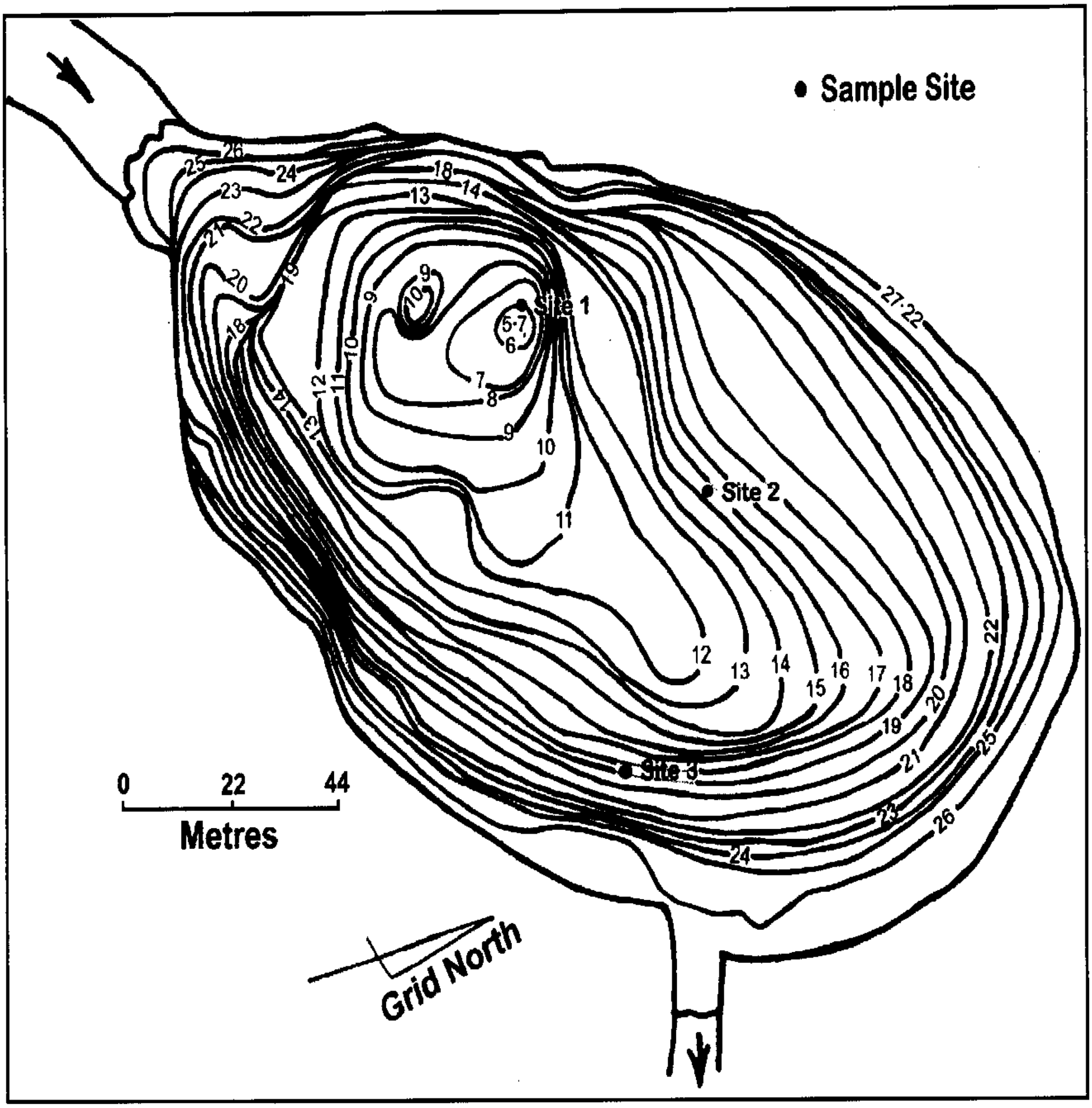

Figure 2: Contours in metres to Australian Height Datum of the Bents Basin scour pool. Location of the water quality monitoring sites is also shown.

Table 1: Morphometric and hydrologic characteristics of the Bents Basin scour pool.

Volume (m^3)	157 400 (157.4 ML)
Surface Area (m^2)	17 500
Mean Depth (m)	9.0
Maximum Depth (m)	21.52 (22.8)
Relative Depth (%)	14.4
Maximum Length (m)	209
Maximum Width (m)	114
Mean Width (m)	84
Shoreline Development	1.15
Volume Development	1.25
Capacity: Inflow Ratio	0.00054
Mean Water Residence Time (hrs)	4.7
Maximum Water Residence Time (months)	12
% Time Daily Flow < 157 ML/d	86% or 314 days/year
% Time Monthly Flow < 157 ML	19.4% or 2.3 months/year

development value of 1.15 (a circle has a value of 1.0). The shape of the scour pool, based on a volume development value of 1.25, approximates a cone.

The five hydrologic parameters in Table 1 were calculated using streamflow data at the downstream Wallacia gauging station for the period 1917-1984 (Curtis, 1985). The capacity: inflow ratio is the volume of the scour pool divided by the mean annual flow. A value of 0.00054 indicates that the pool volume is very small in relation to the mean annual flow. This would suggest relatively frequent flushing. The mean water residence time is the time for the mean daily discharge (804 ML/d) to displace the total volume of the pool (157.4 ML), assuming complete mixing. The maximum water residence time is the longest time period during which the cumulative monthly flow was less than 157.4 ML. This occurred between November 1965 and October 1966 and indicates that the scour pool can experience long periods without flushing. Based on daily flows, discharge is less than 157.4 ML/d for an average of 314 days/annum and the time that monthly flows are less than 157.4 ML/month is, on average, 2.3 months/annum. Therefore, there are long time periods when stratification may develop due to poor flushing of, and lack of turbulence in, the scour pool. Furthermore, all of the above calculations are based on the assumption that a flow at least equal to the volume of the scour pool is required for complete mixing. However, our field measurements indicate that a much larger flow is, in fact, required. Therefore, the above estimates of flushing times must be viewed as minima.

STRATIFICATION OF THE SCOUR POOL.

Methods.

Detailed depth profiles of pH, electrical conductivity, dissolved oxygen and temperature were measured at multiple depths throughout the water column at three sites (Figure 2) using a YEO-KAL 611 Intelligent Water Quality Analyser between January and August 1996. This submersible data logger was calibrated immediately before use according to the user manual. A glass electrode was used to determine pH, a four platinum electrode cell to measure conductivity, a Clark type membrane covered polargraphic sensor with an in-built stirrer to measure dissolved oxygen and a PN junction in a stainless steel sleeve to determine temperature. Datalogging of all water quality parameters was also carried out over a 24 hour period between 6 and 7 March 1996 at site 1 to determine whether stratification persisted throughout the day and night. Two YEO-KAL 611 submersible data loggers were used, one at the surface and one near the bottom. Both were fixed in place to stop drifting.

On 20 March 1996 water samples were obtained at 1 m depth increments from the top to the bottom of the water column at site 2 with an instantaneous water sampler (a modified Vandorm bottle). All samples were kept at or below 4°C until analysed in the laboratory, as recommended by the American Public Health Association (1992). Total phosphorus was determined by a modified acid digestion method of the American Public Health Association (1992). The modifications were that sodium carbonate was substituted for sodium hydroxide to neutralise acidity and P-nitrophenol indicator was used to detect the neutral end point of the digested solution. Total phosphorus concentrations were then determined using a UNICAM 8625 UV Light/VIS Spectrometer. Calcium, magnesium, sodium and potassium concentrations were determined by adding a strontium chloride suppressant to the water samples before using a UNICAM SolAAr 929 Atomic Absorption Spectrometer.

Seasonal Variation in Stratification.

Thermal stratification characterised by an epi-, meta- and hypolimnion occurred at both sites with a water depth greater than 10 m (i.e. sites 1 and 2). At these sites, a well developed thermocline persisted until the end of March (Figure 3), while at site 3, where depths were less than 10 m, isothermal conditions were always recorded throughout the study period. At site 1, temperature differences varied from 9.6 to 14.7°C between the surface and a depth of 20 m during times of thermal stratification, while the differences at site 2 varied from 10.2 to 13.2°C.

In mid-January 1996, oxygen stratification was well developed at sites 1 and 2, with an oxycline at a depth of 10 m (Figure 4). The oxycline then rose to 8 m in March before falling to 13 m in April. The greatest oxygen difference between surface and bottom waters was 12.8 mg/L in April, while the average difference was 8 mg/L for January and March (Figure 4). Anoxic conditions were recorded below the oxycline from January to April (Figure 4). Anoxic conditions started at a depth of 11m in January, 10 m in March and 13 m in April. Destratification had occurred by 17 May at site 1 and a slight oxycline had reformed by 13 August. Site 3 was only oxygen stratified on 1 March 1996.

Electrical conductivities were essentially constant throughout the whole water column at all sites on all occasions. Therefore, salt stratification never occurred in the Bents Basin scour pool.
Water density for all temperature and conductivity measurements was calculated using equations A3.1 and A3.2 in Gill (1982). Figure 5 shows the density profiles at site 2 for all measurements. Thermal stratification resulted in large density differences of about 2 kg/m^3 between the epi- and hypolimnion. Once isothermal conditions were recorded, these density differences ceased. The change in density at a depth of about 11 m between January and March 1996 coincided with the thermocline (Figure 5) and was clearly great enough to inhibit mixing.

Daily Variation in Stratification.

Diel variations in water quality were measured between 1145 hrs on 6 March and 1145 hrs on 7 March 1996 at depths of 0 and 15 m. Surface dissolved oxygen concentrations only varied between 5.6 and 5.8 mg/L, temperature ranged from 23.3°C at 0700 hrs on 7 March to 27.1°C at 1615 hrs on 6 March 1996 (Figure 6) and electrical conductivity remained constant. Surface temperatures rose during the afternoon of 6 March, fell after sunset and then increased after 1015 hrs on 7 March. At a depth of 15 m, dissolved oxygen concentration, temperature and electrical conductivity remained constant. Clearly thermal and oxygen stratification persisted throughout the whole day (Figure 6).

Total Phosphorus and Cations.

Figure 7 shows the total phosphorus profile at site 2 on 20 March 1996. Concentrations increased from 0.075 mg/L at the surface to 0.093 mg/L at a depth of 15 m. Clearly, concentrations increased below the oxycline in the anoxic zone (Figure 7), due to internal loading by the release of sediment-bound phosphorus under anoxic conditions (Erskine and Saynor, 1996).

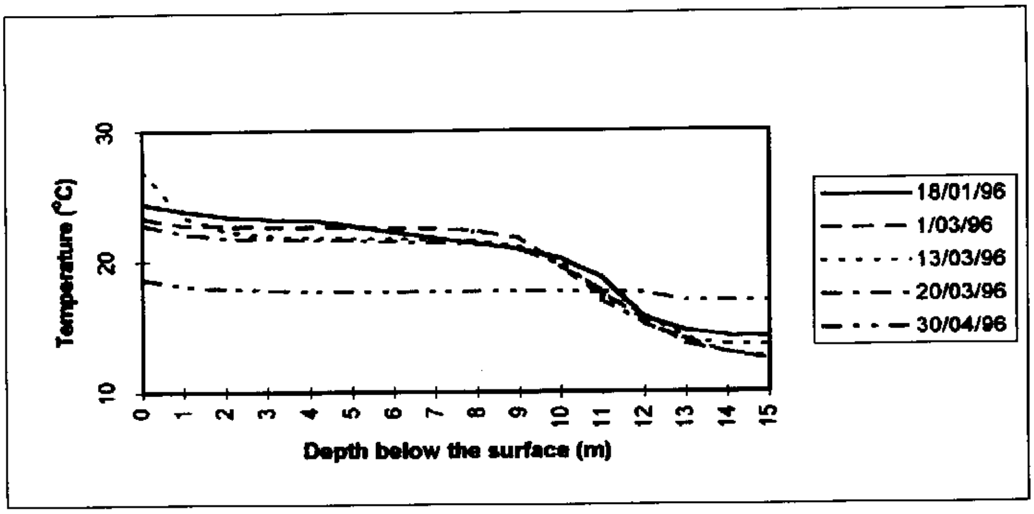

Figure 3: Temperature profiles at site 2 in the Bents Basin scour pool.

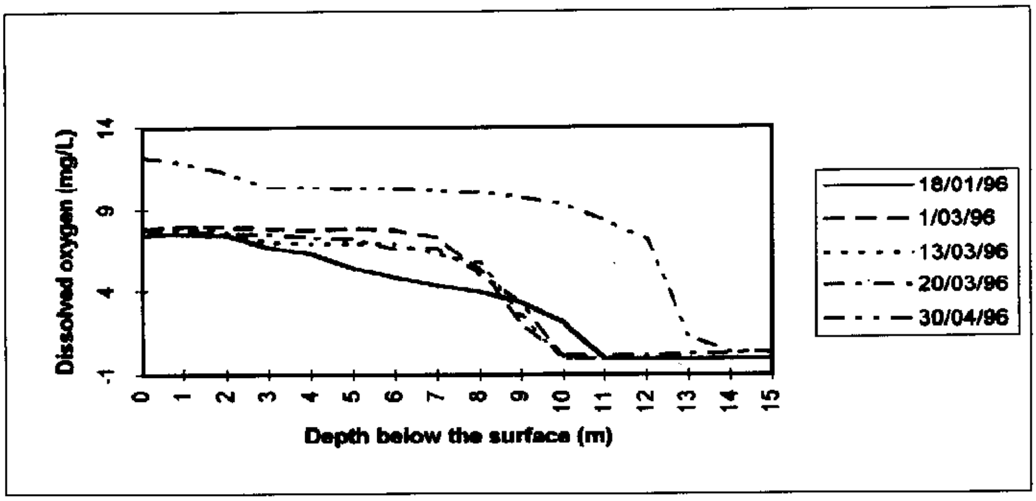

Figure 4: Dissolved oxygen profiles at site 2 in the Bents Basin scour pool.

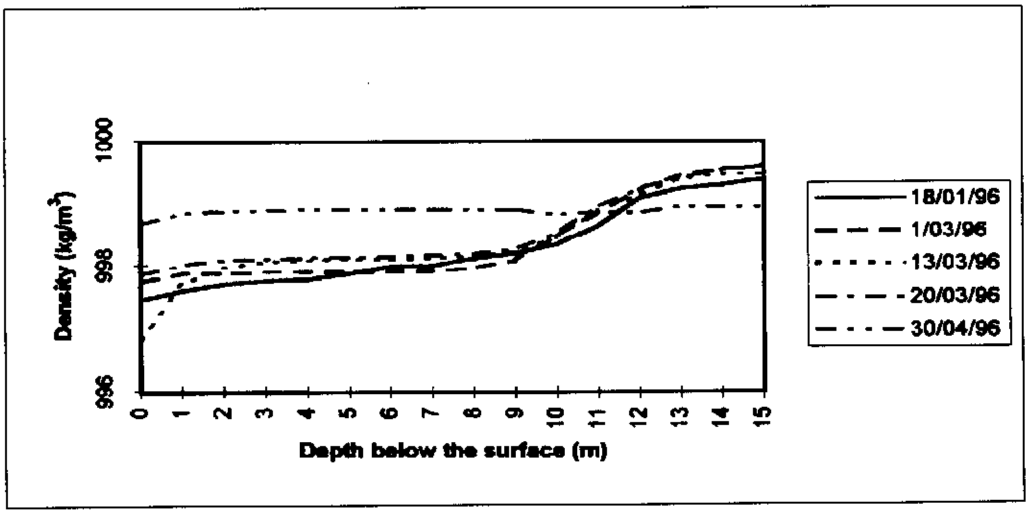

Figure 5: Density profiles at site 2 in the Bents Basin scour pool.

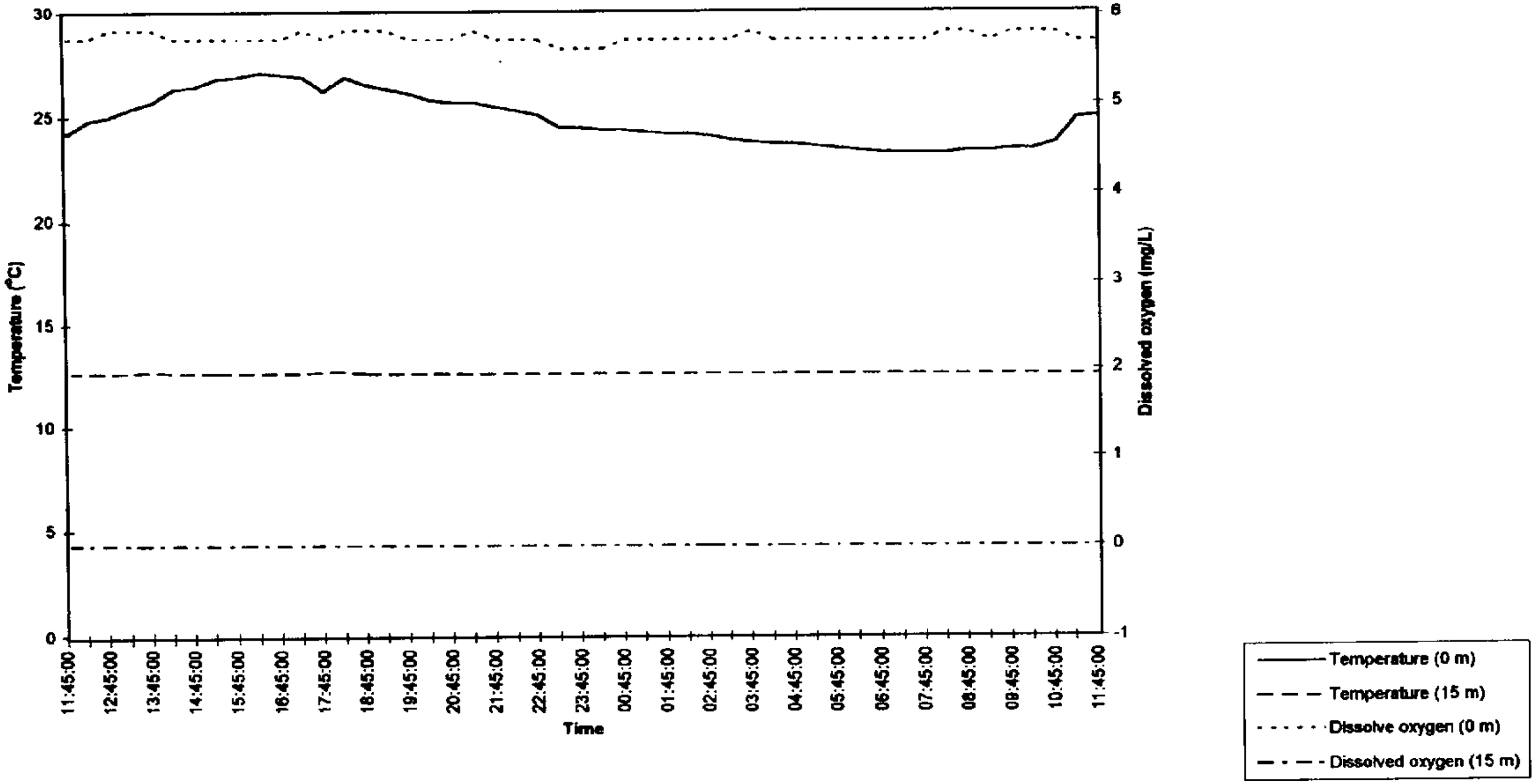

Figure 6: Diel variations in temperature and dissolved oxygen between 1145 hrs on 6 March and 1145 hrs on 7 March 1996 at depths of 0 and 15 m at site 1 in the Bents Basin scour pool.

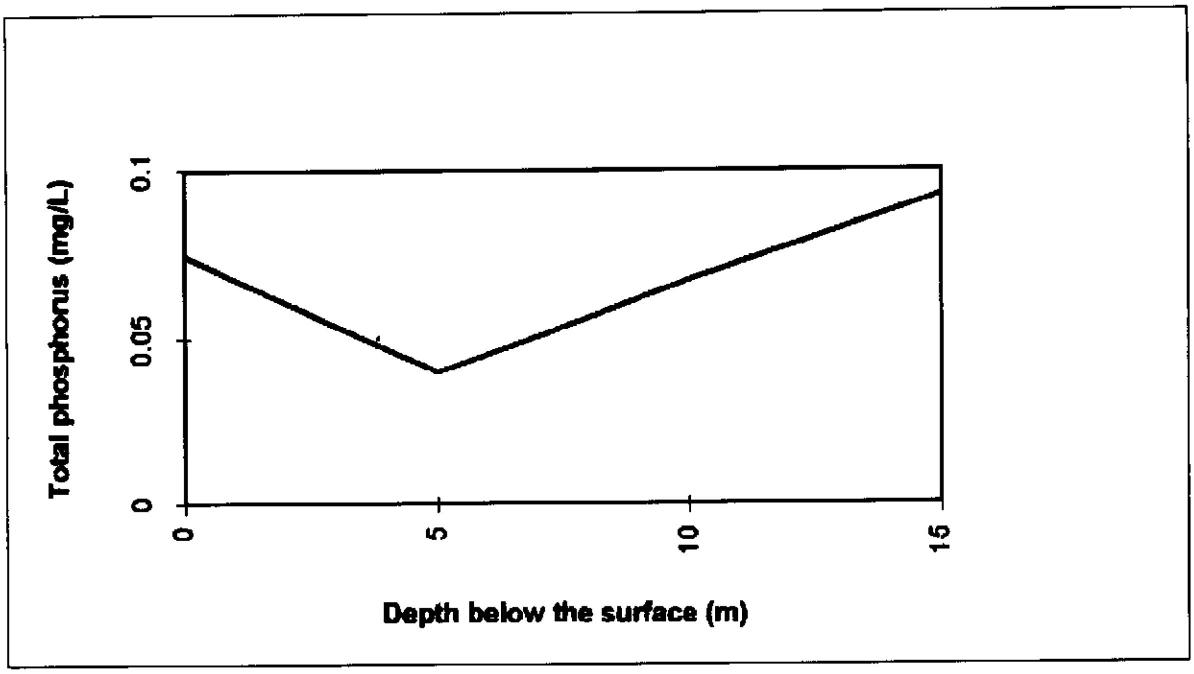

Figure 7: Total phosphorus concentration profile on 20 March 1996 at site 2 in the Bents Basin scour pool.

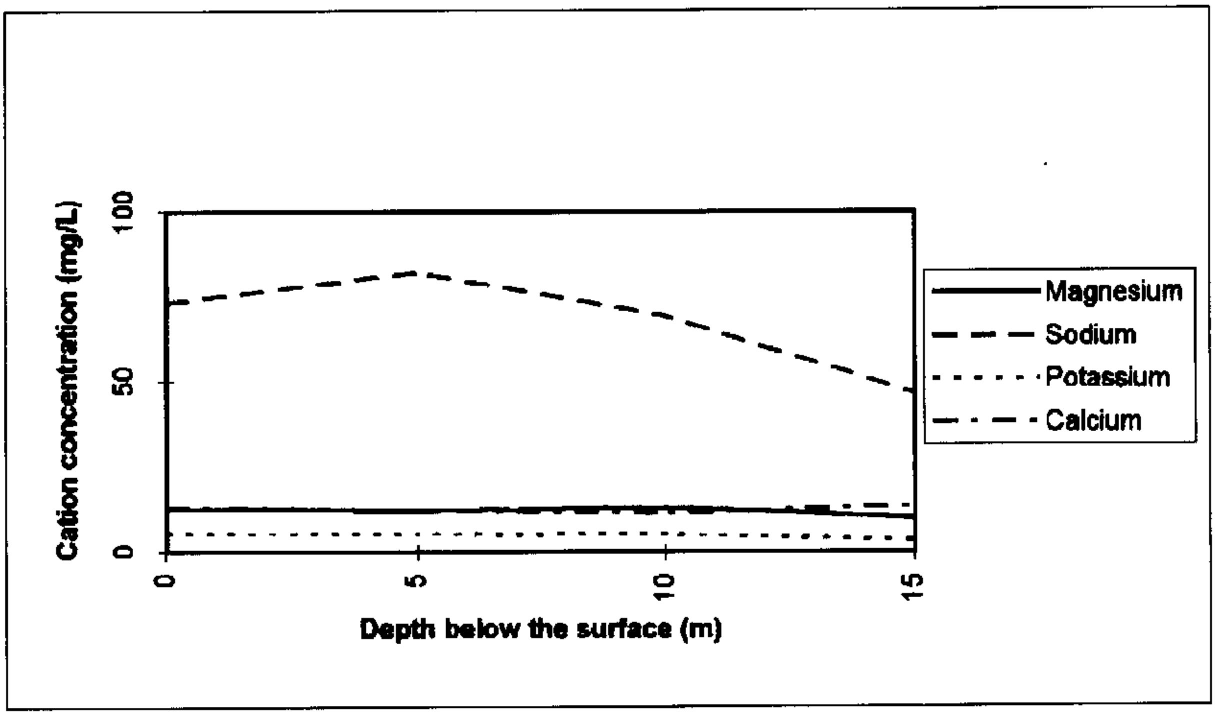

Figure 8: Cation concentration profile on 20 March 1996 at site 2 in Bents Basin scour pool.

Table 2: Climatic conditions at the Penrith Lakes automatic weather station during the water quality measurements at Bents Basin

Date	Maximum Temperature (C°)	Minimum Temperature (C°)	Maximum Temperature on previous day (C°)	Minimum Temperature on previous day (C°)	1500 hrs wind speed (Km/hr)	1500 hrs wind speed on previous day (Km/hr)	Rainfall (mm)	Rainfall on previous day (mm)
18 January 1996	32.2	18.0	23.4	18.1	9 NE	2 E	0	0.2
1 March 1996	N/R	16.6	20.5	18.1	9 N	17 S	0	9
13 March 1996	30.9	15.0	27.9	15.8	13 NE	11 N	N/R	0
20 March 1996	27.1	N/R	N/R	15.6	N/R	15 NE	0	N/R
30 April 1996	N/R	13.4	N/R	8.8	17 ENE	13 NNE	0	0
17 May 1996	18.7	13.1	N/R	11.1	13 SSW	N/R	0	0
13 August 1996	24.7	4.1	N/R	2.3	N/R	21 W	0	0

N/R - No record.

Table 3: Mean daily discharge at Mt Hunter and Wallacia gauging stations during the water quality measurement at Bents Basin.

Date	Mt Hunter Mean daily discharge (ML/d)		Wallacia Mean daily discharge ML/d	
	Day of Sampling	Day Before	Day of Sampling	Day Before
18 January 1996	28	33	31	35
1 March 1996	8	8	11	6
13 March 1996	10	12	N/A	11
20 March 1996	8.7	9.0	6	7
30 April 1996	7.0	13	0	0
17 May 1996	38	43	30	33
13 August 1996	N/A	N/A	N/A	N/A

N/A - Not available

Figure 8 shows the uniform cation profiles at the same site on the same day. While K$^+$ had the lowest concentrations, Na$^+$ had the highest throughout the whole water column. Unlike phosphorus, cation concentrations did **not** reflect thermal and/or oxygen stratification.

CLIMATIC AND FLOW CONDITIONS.

To determine the effects of air temperature, wind speed, rainfall and streamflow on the development and persistence of stratification, relevant data were collected for the nearest stations. Penrith Lakes automatic weather station was the closest meteorologic station and Mt Hunter and Wallacia were the closest river gauging stations (Figure 1). Table 2 summarises air temperatures, wind speeds and rainfall on the day of sampling and on the previous day. Only wind speed at 1500 hrs is included in Table 2 because it is usually the highest recorded during the day. Table 3 summarises discharge on the day of sampling and on the previous day.

Thermal stratification was well developed during January and March when maximum and minimum air temperatures exceeded 20.5 and 15.0°C, respectively. Isothermal conditions were recorded when maximum and minimum air temperatures were less than 24.7 and 13.4°C, respectively.

Climatic and streamflow conditions during the period of thermal and oxygen stratification were not capable of generating sufficient turbulence to mix and hence destratify the scour pool. This is to be expected because wind speed (<18 km/hr) and rainfall (< 10mm/day) were low and streamflows were very low (<36ML/d) when stratification was recorded. It must also be emphasised that the Lapstone Structural Complex will protect the Bents Basin scour pool and so the climatic data at Penrith Lakes represent more severe conditions than would have been experienced on site. According to the Environment Protection Authority (1994), the upper limit of low flows on the Nepean River at Penrith is 300 ML/d. Qin *et al.* (1994) adopted a limiting value of 60 ML/d to define low flow at Wallacia. The 300 ML/d threshold was only exceeded during the study period between 6 and 8 January, and between 6 and 9 May 1996. However, strong stratification had formed by 18 January 1996. The 60 ML/d threshold was not exceeded during February, March and April 1996. Therefore, the combination of scour pool morphometry and ambient climatic and hydrologic conditions was suitable for the development and persistence of stratification in the scour pool between mid-January and March/April.

DISCUSSION AND CONCLUSIONS.

Thermal stratification characterised by a well-developed epi-, meta- and hypolimnion was recorded in the Bents Basin scour pool where depths exceeded 10 m between mid-January and March 1996. Measurements elsewhere on the Nepean River (Cobbitty Weir pool) by the authors (Turner and Erskine, 1997) indicate that thermal stratification starts in early November under low flow conditions. Well-developed oxygen stratification in the Bents Basin scour pool was recorded at depths between 7 and 12 m between mid-January and April 1996. Measurements in the Cobbitty Weir pool indicate that oxygen stratification starts in October under low flow conditions. Anoxic conditions were usually present below the oxycline. For an oxycline depth of 10 m in the Bents Basin scour pool, anoxic conditions cover 7500 m^2 or 43% of the scour pool area and 105 000 m^3 or 67% of the total scour pool volume. Phosphorus concentrations increased below the oxycline due to internal loading by the desorption of orthophosphate (PO_4^{3-}) from the bottom sediments and organic material under anoxic conditions (Erskine and Saynor, 1996). The distribution of the different species of orthophosphate is pH dependent; for the pHs measured in the scour pool, dihydrogen phosphate ($H_2PO_4^-$) and monohydrogen phosphate (HPO_4^{2-}) are the most important (Erskine and Saynor, 1996). Surface adsorption reactions of orthophosphate are rapid, generally occurring on time scales of minutes to days, whereas the slower solid state diffusion reactions operate at time scales of months to years (Oliver, 1993; Horne and Goldman, 1994). Stratification did not impact on the vertical distribution of cations.

The interaction of the following three sets of factors result in the formation and persistence of stratification in the Bents Basin scour pool:

i) the scour pool morphometry,
ii) ambient climatic conditions, and
iii) low streamflows.

The scour pool is a very deep, oval-shaped cone which is conducive to the formation of stable, persistent thermal and oxygen stratification. This stratification will develop when increasing solar radiation during late spring heats the epilimnion so that its density is about 2 kg/m^3 less than the hypolimnion. Stratification persists right through summer when winds are not strong enough to induce mixing and/or streamflows are too low to generate the turbulence to effect mixing. Further work is required to define the climatic and hydrologic conditions which cause mixing. Turnover occurs in autumn when decreasing solar radiation results in epilimnetic cooling and the sinking of the thermocline through the hypolimnion. The onset and breakdown of oxygen stratification before and after thermal stratification, respectively suggests that the two are not causally related (Turner and Erskine, 1997). Episodic summer turnover will recycle phosphorus from the hypolimnion to the surface, thus providing nutrients for phytoplankton. Current discussions on environmental streamflows in the Nepean River must consider thermal and oxygen stratification and the flows required for destratification, especially as our measurements have found stratification in **every** weir pool which we have sampled (Turner and Erskine, 1997).

Current water quality guidelines for the Nepean River for the maintenance of aquatic ecosystems stipulate a maximum total phosphorus concentration of 0.05 mg/L (Qin *et al.*, 1994). Figure 7 demonstrates the problems of collecting surface samples to determine total phosphorus concentrations, as is the current practice of government agencies. At the very least, depth integrated samples, as used in suspended sediment transport studies (see Sammut and Erskine, 1995), **must** be collected. As this is not done, the present water quality data base for the Nepean River does not provide accurate information on water quality for stratified conditions (Anderson and Morison, 1989; Sammut *et al.*, 1994). All summer data (November to March) should be discarded and the monitoring program redesigned.

The Australian and New Zealand Environment and Conservation Council (ANZECC) (1992) guidelines for the protection of aquatic ecosystems fixate on effluent inputs to rivers. It is recommended that the maximum temperature of a river should not **increase** by more than 2°C above natural conditions. Thermal stratification and cold hypolimnetic releases from dams are totally ignored for reasons that remain obscure to us. Longer reaches of rivers are impacted by cold bottom releases from dams than by the discharge of heated effluent from power stations and industry! It is also recommended by ANZECC (1992) that dissolved oxygen concentrations in rivers should exceed 6 mg/L, although 4 mg/L have been adopted for the Nepean River (Qin *et al.*, 1994). Nevertheless, it is obvious from Figure 3 that these thresholds are not exceeded throughout most of the water column when oxygen stratification is present. Existing assessments of water quality in the Nepean River are biased to a best possible situation by ignoring stratification.

The development of hypolimnetic anoxia reduces the biologically available habitat and severely impacts on benthic organisms (Anderson and Morison, 1989). Benthic fish, in particular, must live in a greatly reduced area when 67% of the total scour pool volume (oxycline depth of 10 m) is unsuitable for them.

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REFERENCES.

American Public Health Association (1992) *Standard Methods for the Examination of Water and Wastewater.* 18th Edition, American Public Health Association, Maryland.

Anderson, J.R. and Morison, A.K. (1989) Environmental flow studies for the Wimmera River, Victoria. Part C. Water quality and experimental releases. *Arthur Rylah Institute for Environmental Research Technical Report Series No. 75*

Australian and New Zealand Environment and Conservation Council (1992) *Australian Water Quality Guidelines for Fresh and Marine Waters.* Australian and New Zealand Environment and Conservation Council, Canberra.

Baxter, R.M. (1977) Environmental effects of dams and impoundments. *Annual Review of Ecology and Systematics*, 8:255-283.

Bayly, I.A.E. and Williams, W.D. (1973) *Inland Waters and their Ecology.* Longman, Hawthorn.

Bishop, P., Hunt, P. and Schmidt, P.W. (1982) Limits to the age of the Lapstone Monocline, NSW - a palaeomagnetic study. *J. Geol. Soc. Aust.*, 29:319-326.

Cameron, M. and Jekabsons, M. (1992) *Salinity in the Glenelg and Wannon Rivers, Victoria.* Department of Conservation and Natural Resources, Victoria, Portland.

Curtis, B.R. (1985) *Upper Nepean River Stream Gauging Data.* Metropolitan Water Sewerage and Drainage Board Report No. GSB 9026.

Environment Protection Auithority (1994) *Water Quality, Hawkesbury-Nepean River System, June 1990 to June 1993.* Environment Protection Authority, Chatswood.

Erskine, W.D. (1997) Environmental impacts of extractive industries on the Hawkesbury-Nepean River, NSW. *Proceedings Hawkesbury Bicentenary Conference, 1794-1994, The Hawkesbury: Past, Present and Future, University of Western Sydney, 10-12 September 1994*, in press.

Erskine, W.D. and Green, D. (1997) Geomorphic effects of extractive industries and their implications for river management: the case of the Hawkesbury-Nepean River, NSW. In: S.O. Brizga and B.L. Finlayson (eds.), *River Management in Australia*. Wiley, Chichester, in press.

Erskine, W.D. and Saynor, M.J. (1996) *The Influence of Waterway Management on Water Quality with Particular Reference to Suspended Solids, Phosphorus and Nitrogen*. Broken River Management Board and Department of Conservation and Natural Resources, Victoria, Wangaratta.

Gill, A.E. (1982) *Atmosphere and Ocean Dynamics*. Academic Press, New York.

Herbert, C. and Clark, N.R. (1991) Structural geology. In: D.C. Jones and N.R. Clark (eds.), *Geology of the Penrith 1:100,000 Sheet 9030*. NSW Geological Survey, Sydney, pp.87-94.

Horne, A.J. and Goldman, C.R. (1994) *Limnology*. 2nd Edition. McGraw-Hill Inc., New York.

Hutchinson, G.E. (1957) *A Treatise on Limnology. Volume 1. Geography, Physics and Chemistry*. Wiley and Sons, New York.

Oliver, R.L. (1993) Phosphorus dynamics and bioavailability in turbid waters. In: D. Simon (ed.), *Proceedings of the National Workshop on Phosphorus in Australian Freshwaters*. Land and Water Resources Research and Development Corporation Occasional Paper No. 03/93:93-103.

Petts, G.E. (1984) *Impounded Rivers. Perspectives for Ecological Management*. Wiley and Sons, Chichester.

Petts, G.E. (1986) Water quality characteristics of regulated rivers. *Progress in Physical Geography*, 10:492-516.

Preece, R. (1996) *Pindari Reservoir. Impacts of Enlargement and Management on Stratification Behaviour and Water Quality*. Unpublished Master of Applied Science Thesis, University of New South Wales.

Qin, D. and Fisher, I. (1994) Sensitivity analysis for the SALMON model of the upper Nepean River. *Water Down Under 94, Adelaide, 21-25 November, 1994, Vol. 1*, Institution of Engineers Australia National Conference Publication 94/10, pp.609-612.

Qin, D., Fisher, I. and Maheswaran, M. (1994) Prediction of impacts on water quality in the Nepean River due to proposed effluent and dam release. *Water Down Under 94, Adelaide, 21-25 November, 1994, Vol. 1*, Institution of Engineers Australia National Conference Publication 94/10, pp.315-319.

Sammut, J. and Erskine, W.D. (1995) Hydrological impacts of flow regulation associated with the Upper Nepean Water Supply Scheme. *Australian Geographer*, 26:71-86.

Sammut, J., White, I. and Melville, M.D. (1994) Stratification in acidified coastal floodplain drains. *Wetlands (Australia)*, 13:49-64.

Saynor, M.J. and Erskine, W.D. (1993). Characteristics and implications of high-level slackwater deposits in the Fairlight Gorge, Nepean River, Australia. *Australian Journal of Marine and Freshwater Research*, 44:735-747.

Sivakumar, M. and Musavi Jahromi, S.H. (1995). Analysis of phosphorus in the Nepean River using turbidity and electrical conductivity. *The Second International Symposium on Urban Stormwater Management 1995, Melbourne, 11-13 July 1995, Vol. 2*, Institution of Engineers Australia, National Conference Publication No 95/03, pp.503-508.

Timms, B.V. (1992) *Lake Geomorphology*. Gleneagles Publishing, Adelaide.

Turner, L.M. and Erskine, W.D. (1997). Thermal, oxygen and salt stratification in three Weir pools on the Nepean River. *Proceedings on Science and Technology in the Environmental Management of the Hawkesbury-Nepean Catchment, 10-11 July 1997, University of Western Sydney, Nepean, Kingswood,* *Institution of Engineers Australia, National Conference Publication NCP 97/01 and Geographical Society of New South Wales Conference Papers No.14, 87-92.*

Warner, R.F. (1983) Channel changes in the sandstone and shale reaches of the Nepean River, NSW. In: R.W. Young and G.C. Nanson (eds.), *Aspects of Australian Sandstone Landscapes.* Australian and New Zealand Geomorphology Group Special Publication No. 1:106-119.

Wetzel, R.G. (1975) *Limnology.* Saunders, London.

Williams, W.D. (1981) Inland aquatic systems: an overview. In: A. Keast (ed.), *Ecological Biogeography of Australia.* Dr W. Junk, The Hague, pp.1080-1099.