Research Report 2

Water Physico-Chemistry and Sediments of the Mallee Tract

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Final Report to MDBC

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Report Linkages

This individual Research Report forms a component of the larger report:

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Introduction

The physico-chemistry of a water body reflects catchment conditions and is paramount in determining whether an aquatic organism – with its particular life history and ecological tolerances – can persist. Poor water quality such as low dissolved oxygen concentrations, high electrical conductivity and extremes of pH can impact on biota such as native fish (Koehn and O'Connor, 1990), phytoplankton, zooplankton and macroinvertebrates (ANZECC, 2000; McCarthy *et al*., 2003). Physico-chemical changes can also influence the release of toxic elements from the sediment, such as aluminium and other metals at low pH (ANZECC, 2000). Eggs and juveniles may be particularly sensitive to poor water quality, such as larval fish tolerance to leachate (Gehrke, 1991). In addition, pesticides and other anthropogenic-derived contaminants can impact and bioaccumulate through the food chain.

Salinities exceeding 1000 $mg.L^{-1}$ may adversely affect aquatic biota (Hart *et al*., 1991), and may impact on the cycling of energy and nutrients in freshwater ecosystems (Nielsen *et al*., 2003). Electrical conductivities above 1000 $\mu S.cm^{-1}$ may switch off methanogenesis within wetland sediments, and levels above 10,000 $\mu S.cm^{-1}$ may result in a decrease in microbial diversity (Baldwin *et al*., 2002).

Elevated turbidity levels influence biota by diminishing the ability of an organism to find food visually, reducing photic depth and limiting primary production. High suspended solid concentrations may also increase stress to gill-bearing organisms through abrasion. Surface water nutrients are critical for microbial activity and for primary production through the growth and reproduction of benthic and planktonic algae and macrophytes.

Water quality is influenced by a multitude of often-interrelated factors including climate, flow, catchment characteristics, river regulation and local hydraulics. Weirs influence water quality by altering the hydraulic conditions (see Research Report 1) and create a low flow velocity environment that facilitates sedimentation of suspended solids (Thoms and Walker, 1993; Brizga, 2001). The loss of suspended particles from the water column lowers turbidity and increases photic depths, and alters the longitudinal transport of nutrients along the river (e.g. Brizga, 2001). Weirs have also elevated groundwater tables in the floodplain and altered groundwater movement, potentially contributing to increased electrical conductivities in the surface water (Walker and Thoms, 1993). Elevated groundwater levels may also impact upon floodplain soils (e.g. salinisation/acidification) and vegetation, and may result in changed water quality conditions during flood events.

Eight monitoring sites were selected along a 400 km reach of the Mallee Tract to separate the three weir pools from the free-flowing reaches, and allow the objectives of the study to be addressed.

Objectives

1. To measure surface water physico-chemistry at strategic points along the River Murray to examine the effects of weirs in the Mallee Tract.

2. To examine the relationships between the parameters examined.

Methods

Details of the eight riverine sites along the Mallee Tract of the River Murray (Thoms *et al.*, 2000) are provided in Table 1. The positions of these sites are shown in Figure 1.

Table 1. Details of the eight riverine study sites

Study Site	River km from sea	Easting	Northing	Character
Boundary Bend	1234	699033	6156081	Free-flowing
Yungera Island	1185	681163	6159589	Free-flowing
Euston WP	1118	661688	6170492	Lower Weir Pool
Hattah	994	629586	6173927	Free-flowing
Iraak	943	625879	6196672	Free-flowing
Mildura WP	887	607604	6216966	Lower Weir Pool
Apex Park	883	607393	6219543	Upper Weir Pool
Wentworth WP	834	585299	6224431	Lower Weir Pool

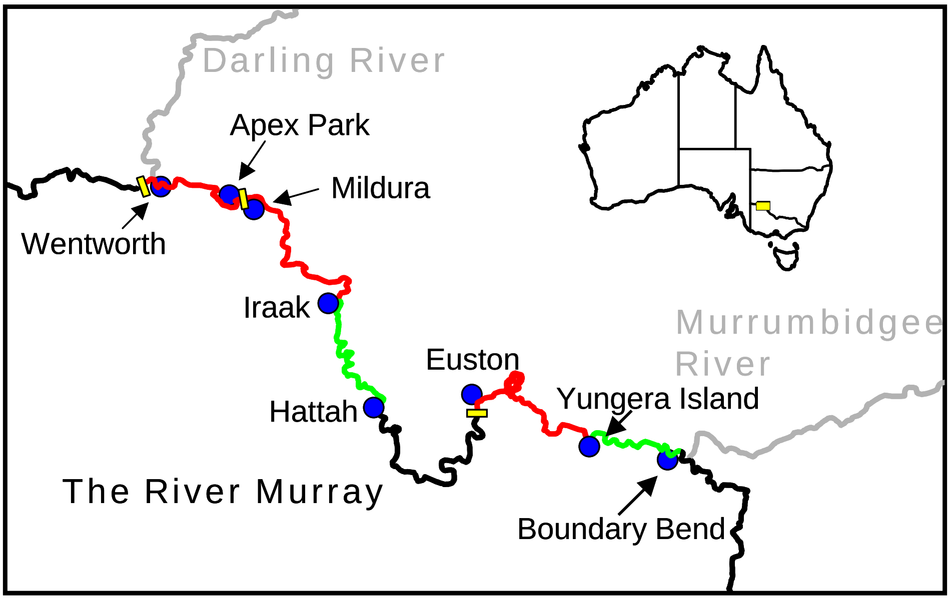


Figure 1. Study sites along the Mallee Tract of the River Murray. Weir pool and free-flowing study reaches are highlighted in red and green, respectively. The eight sampling sites (blue) and weirs (yellow) are highlighted.

Conceptual Design

As a body of water travels longitudinally along the river, the surrounding physical and chemical environment influences its water physico-chemistry. An examination of water physico-chemical parameters at the upstream and downstream points of the weir pool and free-flowing reaches allows changes to be measured, thereby allowing a comparison of the effects of weirs on water quality (Figure 2).

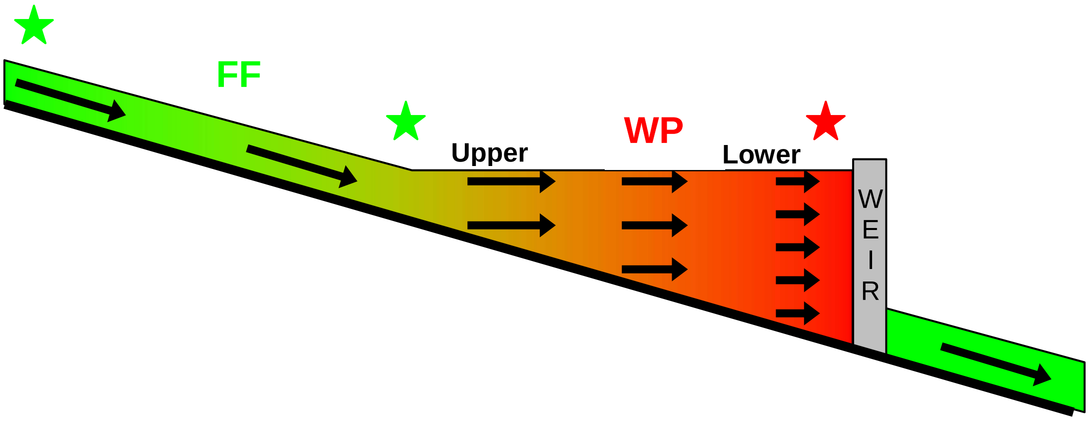


Figure 2. Schematic long section of a weir pool (WP) and free-flowing (FF) reach. Arrows show direction of flow and their lengths reflect the change in flow velocity as river depth increases. The sampling sites (stars) were located so as to allow changes in water quality to be assessed as water passes through the free-flowing and weir pool reaches.

Physico-Chemical Parameters

At each riverine site a relatively straight section of river was selected and three replicate points were established at approximately 25, 50 and 75% channel width along a transect spanning the river. At each replicate point physico-chemical parameters were measured at 1 m depth intervals of the water column with a Horiba U-10 Water Quality Checker (Australian Scientific Ltd.). The parameters included temperature (^{o}C), pH, turbidity (NTU), electrical conductivity (µS.cm^{-1} @25^{o}C), and dissolved oxygen (mg.L^{-1}). Flow velocity was also measured at the 50% replicate point on occasion at 0.5 m depth intervals to a maximum of 4.5 m with a Marsh-McBirney Inc. Flow Mate Portable Flowmeter.

A vertically integrated water sample was collected at each riverine replicate point by lowering and raising a 12 V bilge pump at a constant rate through the water column and collecting the pumped water in a 25 L container. The bilge pump was positioned inside a shallow bucket to prevent riverbed sediment contaminating the sample when the riverbed was contacted. Sub-samples were taken from each water sample for determinations of concentrations of oxides of nitrogen and filterable reactive phosphorus (0.01 L water sample filtered through a 0.45 µm filter), total nitrogen and total phosphorus (0.2 L), total suspended solids (0.5 L), phytoplankton chlorophyll (0.5 L), and phytoplankton species composition (0.6 L). All samples were kept cool in the field.

Sampling Times

Since time of day influences some water quality parameters (e.g. dissolved oxygen), sampling time was kept relatively consistent for a given site. Boundary Bend (08:30-10:30), Yungera Island (10:30-12:30) and Euston weir pool (12:30-15:00) were sampled in sequence on one day, and Hattah (08:00-10:00), Iraak (10:00-12:00), Mildura weir pool (12:00-14:00), Apex Park (14:00-16:00) and Wentworth weir pool (16:00-18:00) on the following day. This ensured that the upstream and downstream points for each defined weir pool and free-flowing reach were sampled sequentially.

Temperature Loggers

Temperature loggers (TidbiT StowAway) were deployed from 18/4/02 – 12/4/03 and logged temperature at 1 h intervals at the surface (ca. 0.3 m depth) and bottom (0.2 m from bottom) of the water column at Boundary Bend (FF), Euston (WP), Iraak (FF), Mildura (WP) and Wentworth (WP).

Light Climate

Light attenuation was measured on two occasions at various sites along the Mallee Tract to calculate the photic depth (depth to which 1% of surface irradiance penetrates). The photosynthetically active radiation (PAR, 400-700 nm) was measured at a deck sensor (LiCor 210SA) and underwater quantum sensor (LiCor 192SA; measuring downwelling irradiance) at 0.1

m depth intervals over 2 m, and logged to a Li-Cor LI-1000 DataLogger. Turbidity was measured simultaneously to allow the relationship between light attenuation and turbidity to be determined.

Suspended Solids

In the laboratory the suspended solid samples were shaken well and a known volume filtered through a pre-combusted and weighed GFF (47 mm) filter. The filter with encrusted sediment was dried to constant weight (overnight) at 80^{o}C, cooled and weighed. Filters were combusted in a muffle furnace (550^{o}C) for two hours, cooled then rewetted with distilled water to restore the waters of hydration. Filters were oven-dried to constant weight (overnight) at 80^{o}C, cooled and weighed, allowing the total suspended solids to be calculated in addition to the organic and inorganic fractions (APHA, 1995).

Surface Water Nutrient Analysis

Nutrient analyses followed to the Lachat QuikChem Methods (1994) and were performed at a NATA-certified laboratory (MDFRC, Albury).

Ammonia-Nitrogen was reacted with alkaline phenol and hypochlorite to produce indophenol blue, which was intensified with sodium nitroprusside. Its absorbance was measured colorimetrically at a wavelength of 630 nm on a Lachat QuikChem 8000 Flow Injection Analyser (Method 31-107-06-1-C).

Oxides of Nitrogen was measured by reducing nitrate to nitrite by passing a buffered sample through a column of copper-coated cadmium. Total nitrite was converted to the diazonium salt by reacting with sulfanilamide. The 4-sulfanilamide benzenediazonium chloride then coupled with N-(1-naphthyl)ethylenediamine dihydrochloride to form a pink dye. Its absorbance was measured colorimetrically at a wavelength of 520 nm on a Lachat QuikChem 8000 Flow Injection Analyser (Method 31-107-04-1-C).

Filterable Reactive Phosphorus was measured by reacting orthophosphate in the sample with ammonium molybdate and potassium antimony tartrate in an acidic medium to form molybdophosphoric acid. This was reduced by ascorbic acid to give a molybdophosphoric blue complex whose absorbance was measured colorimetrically at 880 nm on a Lachat QuikChem 8000 Flow Injection Analyser (Method 31-115-01-1-C).

Total Nitrogen was measured by digesting the organic forms of nitrogen and ammonia to nitrate by an autoclaved base/acid ($NaOH-K_2S_2O_8$) persulfate oxidation procedure at 120^{o}C for 60 min. Nitrate was reduced to nitrite by passing a buffered sample through a column of copper-coated cadmium and total nitrite was converted to diazonium salt by reacting with sulfanilamide. The 4-sulfanilamide benzenediaxonium chloride then coupled with N-(1-naphthyl)ethylenediamine dihydrochloride to form a pink dye. Absorbance was measured colorimetrically at a wavelength of 880 nm on a Lachat QuikChem 8000 Flow Injection Analyser (Method 31-107-04-1-C).

Total Phosphorus was measured by digesting the organic forms of phosphorus to orthophosphate by an autoclaved base/acid ($NaOH-K_2S_2O_8$) persulfate oxidation procedure at 120^{o}C for 60 min. Orthophosphate was reacted with ammonium molybdate and potassium antimony tartrate in an acidic medium to form molybdophosphoric acid. This was reduced by ascorbic acid to give a molybdophosphoric blue complex, which was measured colorimetrically at a wavelength of 880 nm on a Lachat QuikChem 8000 Flow Injection Analyser (Method 31-115-01-1-C).

Riverbed Sediments

Riverbed sediment samples (0.2 L) were collected with an Eckman Grab sediment sampler at each site (three replicate points as for water samples). Sediments were oven-dried at 80^{o}C and the organic matter content determined from sediments from every second field trip. Approximately 5 g of dry sediment was added to a pre-weighed tray and oven-dried at 80^{o}C to constant weight (overnight). Samples were cooled, weighed, then combusted in a muffle furnace at 550^{o}C for four hours. Sediments were rewetted with distilled water to restore the lost waters of hydration, dried to constant weight (overnight) at 105^{o}C, then cooled and reweighed to allow the percentage of organic matter to be determined. The total nitrogen and total phosphorus concentrations of the sediments were also examined by randomly selecting 50 sediment samples for analysis. The organic matter content of these samples was measured to examine the relationships between sediment organic matter and nutrient content.

Results

Physico-Chemical Parameters

Temporal Variability

Temporal variations in water physico-chemistry were examined by averaging the parameters from all eight riverine sites for each time interval (Figure 3). The physico-chemistry of the surface water travelling along the River Murray varied considerably from August 2001-June 2003. Electrical conductivity (EC) decreased during the study period, likely as a result of greater proportions of water being sourced from low-EC upstream storages. Concentrations of NOx and FRP also followed this temporal trend. Dissolved oxygen followed a seasonal pattern with changes in water temperature, with higher concentrations in the colder months. Turbidity and suspended solid concentrations were variable over time, partly due to changes in flow, and were strongly correlated (see Figure 6).

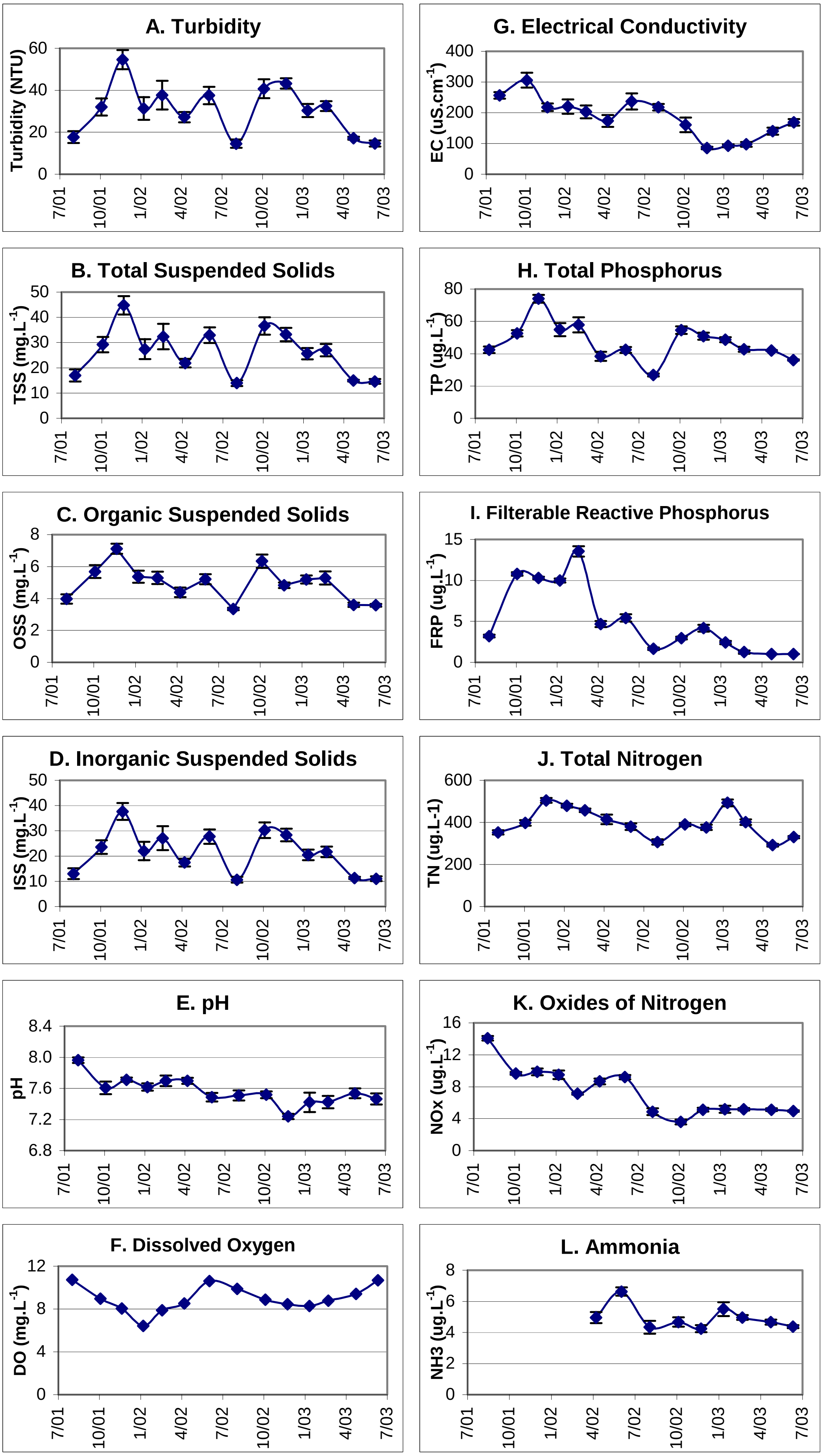


Figure 3. Temporal dynamics of surface water characteristics from August 2001-June 2003. Error bars = ± 1 S.E.

Spatial Variability

Sampling times for each particular site were averaged for each parameter to investigate spatial patterns in water physico-chemistry (Figure 4). Note that for each graph the free-flowing sites are highlighted in green, the weir pools in red, and the Apex Park site is highlighted in yellow because it is located downstream of the Mildura weir and it technically within the upper reach of the Wentworth weir pool. This spatial analysis reveals that physico-chemistry changes are occurring between specific sites along the Mallee Tract. For example, turbidity, suspended solids and total phosphorus each decrease between the site immediately upstream of the weir pool and the weir pool site. The lower flow velocity and consequent decrease in turbulence is likely facilitating the sedimentation of suspended solids within the weir pools. Sedimentation is also occurring in the free-flowing reach between Boundary Bend and Yungera Island, likely as a result of the increased channel width (and potentially lower flow velocity) in the River Murray downstream of the Murrumbidgee junction. The net sedimentation in this reach is inorganic material only.

Dissolved oxygen was relatively high across all sites, with the greatest concentrations occurring at Apex Park ca. 4 km downstream of the Mildura weir. It is likely that the aeration and mechanical mixing at this overflow weir has increased oxygen levels at this site. Electrical conductivity increased progressively along the Mallee Tract, with the greatest increases occurring downstream of Hattah.

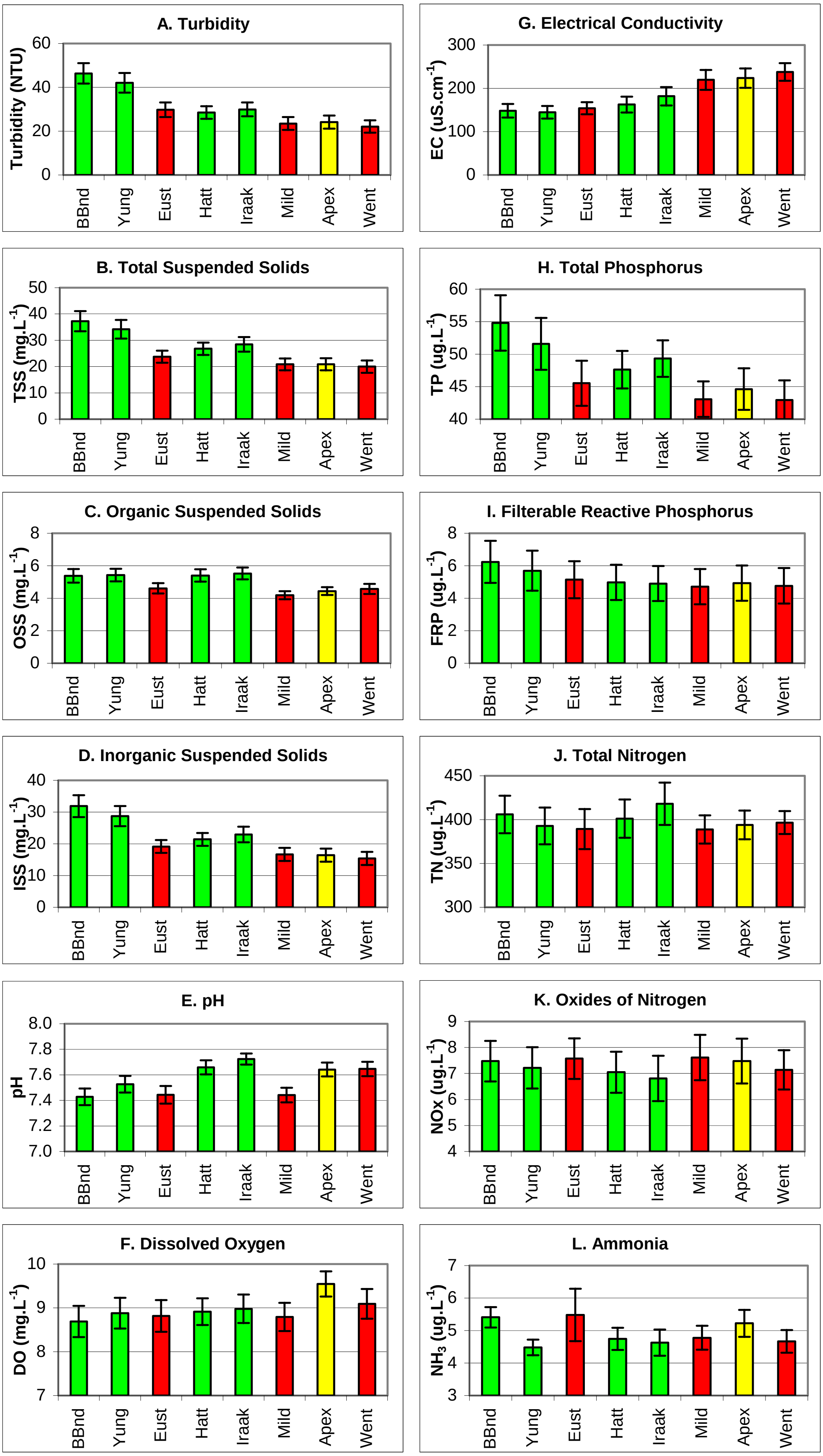


Figure 4. Spatial patterns of surface water characteristics from August 2001-June 2003. Free-flowing (green), weir pool (red) and top of Wentworth weir pool (yellow) sites are highlighted.

Reach Changes

To investigate in more detail the changes revealed in the spatial investigation, and to examine specifically the 50-60 km weir pool and free-flowing reaches, the **changes** in water physico-chemistry were investigated along the five defined reaches (detailed in Conceptual Design in the Methods section). This entailed selecting a reach and subtracting the value of a particular parameter at the upstream end of a reach from the value at the downstream end of that reach. A positive number indicates that the reach being examined increased the water physico-chemical parameter, and hence may be considered to be acting as a **source** for that parameter, whilst a negative number indicates that the reach is acting as a **sink**. An example is provided for total suspended solids (TSS). If on a particular day the concentration of TSS in the water column is 34.2 mg.L^{-1} at Yungera Island (immediately upstream of Euston weir pool) and 23.8 mg.L^{-1} at Euston (downstream end of Euston weir pool), the -10.4 mg.L^{-1} figure indicates that the weir pool has acted as a sink for TSS and 10.4 mg.L^{-1} of TSS has settled from the water column to the riverbed of the weir pool.

An ideal situation would be to apply the above design to a body of water as it passes along the river through the different reaches. A more practical approach is to sample particular sites on multiple occasions to build a picture of the patterns of change and to obtain a measure of the variability between sampling occasions, as was done here. The resulting graphs highlight the changes that occur along the free-flowing (green) and weir pool (red) reaches (Figure 5).

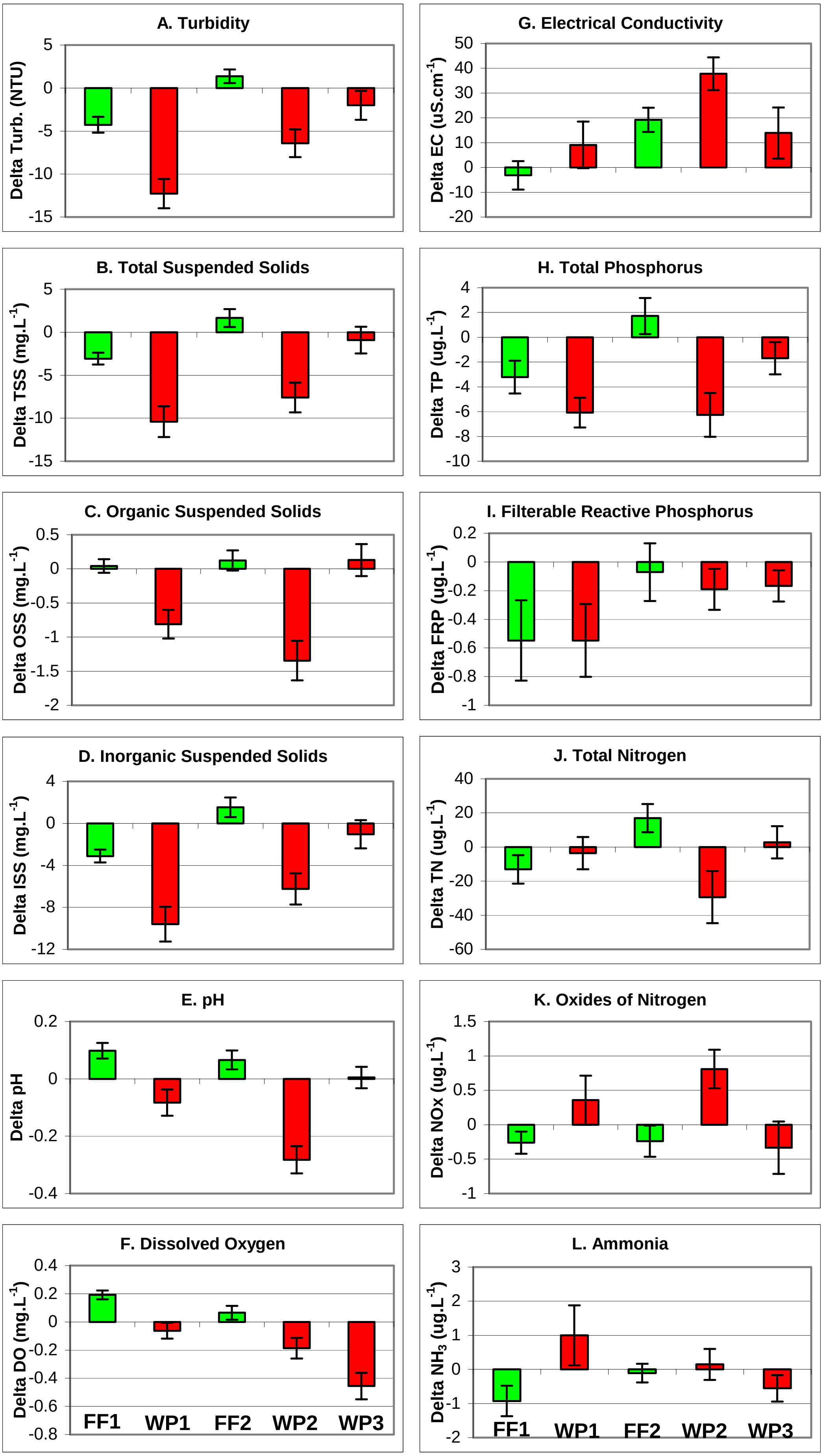


Figure 5. Mean changes in water quality parameters within the free-flowing (green) and weir pool (WP) reaches. FF1=BBend-Yung, WP1=Yung-Eus, FF2=Hatt-Irak, WP2=Irak-Mda, WP3=Apex-Went.

Water Physico-Chemistry Relationships

Turbidity and total suspended solids (TSS) concentrations along the Mallee Tract were strongly and positively correlated (Figure 6). Total Phosphorus concentrations were also well correlated with TSS (Figure 7), whilst total nitrogen concentrations were most strongly correlated with the organic suspended solids (Figure 8). Given the demonstrated sedimentation of suspended solids into the weir pools, this represents a substantial loss of nutrients from the water column to the riverbed, and this is evident from the nutrient-rich weir pool sediments (see Figure 10).

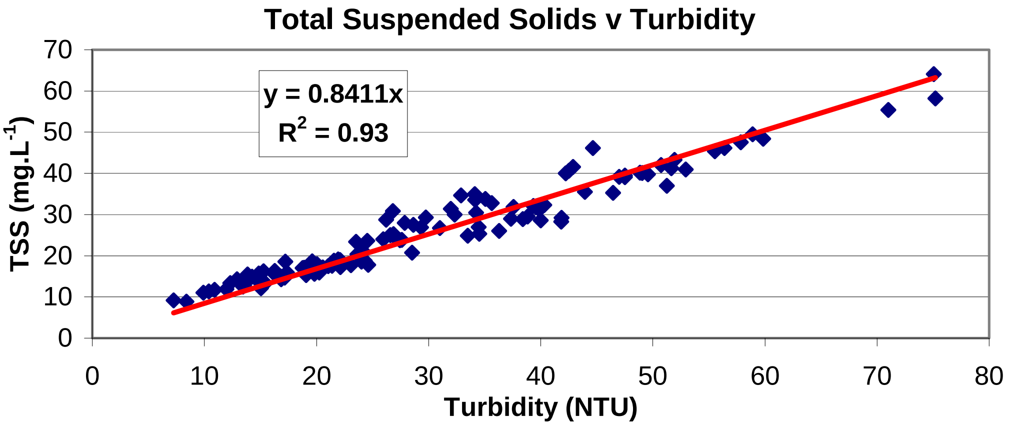


Figure 6. Total Suspended Solids v Turbidity for all river sites in the Mallee Tract, August 2001 – June 2003.

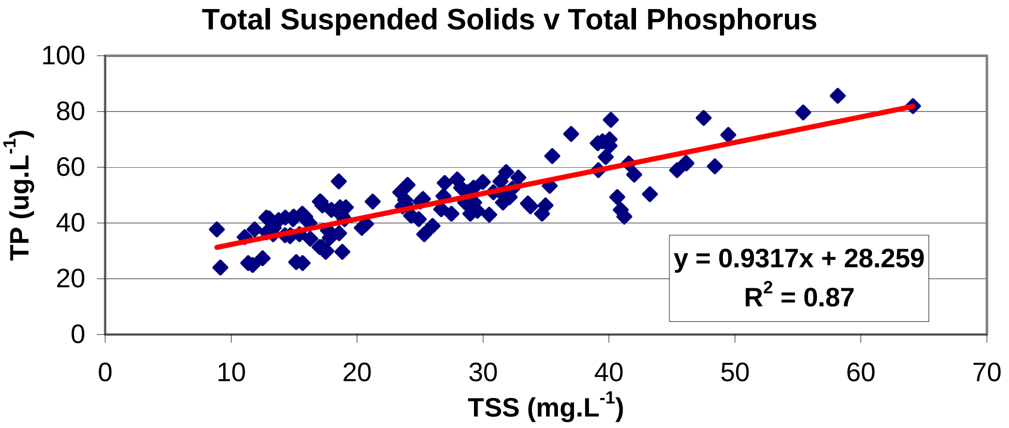


Figure 7. Total Suspended Solids v Total Phosphorus for all river sites in the Mallee Tract, August 2001 – June 2003.

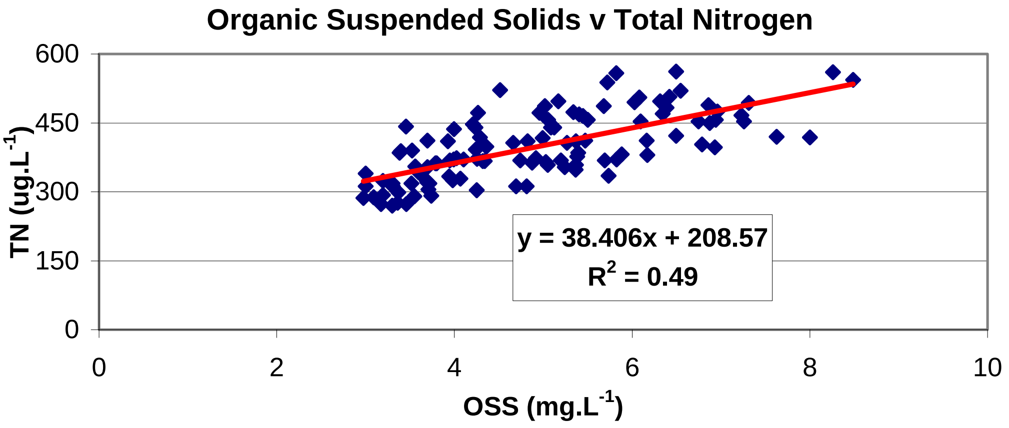


Figure 8. Organic Suspended Solids v Total Nitrogen for all river sites in the Mallee Tract, August 2001 - June 2003.

Loads

Knowledge of the riverine flows along the Mallee Tract on each sampling occasion and the sampling methodology employed (vertically integrated) allows loads to be calculated for different water quality parameters. The mean daily loads are summarised for the three weir pools and two free-flowing reaches from August 2001-June 2003 (Table 2).

Table 2. Mean Loads (all tonnes.d^{-1}) of suspended solids and nutrients for each reach.

Reach	TSS	ISS	OSS	TN	TP
BBend-Yung (FF)	-18.02	-18.49	0.47	-0.084	-0.022
Yung-Eus (WP)	-78.09	-72.59	-5.50	-0.054	-0.043
Hatt-Iraak (FF)	17.85	16.38	1.47	0.122	0.016
Iraak-Mild (WP)	-45.64	-37.87	-7.78	-0.162	-0.037
Apex-Went (WP)	-8.25	-8.55	0.30	-0.006	-0.011

TSS = total suspended solids, ISS = inorganic suspended solids, OSS = organic suspended solids, TN = total nitrogen and TP = total phosphorus.

The free-flowing reach from Hattah to Iraak was the only riverine section to act as a source of sediment. Sedimentation occurred in the remaining reaches and showed a longitudinal gradient in the weir pools, with the greatest rate of sedimentation occurring in the Euston weir pool and the least in the Wentworth weir pool. The greatest sedimentation of organic matter occurred in the Mildura weir pool, with net sedimentation of organic matter not occurring in the Wentworth weir pool. This pattern highlights the longitudinal stripping of suspended solids from the water column, particularly in the Euston and Mildura weir pools.

The sedimentation rates in the Euston and Mildura weir pools were largely dictated by the river flow, where higher flows resulted in greater suspended loads entering the weir pool and greater quantities of suspended sediments settling from the water column (Figure 9). It would be expected that when flows exceed a particular threshold (beyond the flow conditions of this study period) the increased turbulence would re-suspend the soft riverbed material and a net export of suspended sediments from the weir pools would occur. Weir manipulations offer some opportunity to increase the flow velocity within weir pools although the flow at the time of drawdown is also important in determining the net export of sediment (McCarthy *et al*., 2004). A net export of sediment from the *system* may only occur if the weirs are managed in an integrated manner and downstream weirs are manipulated as well.

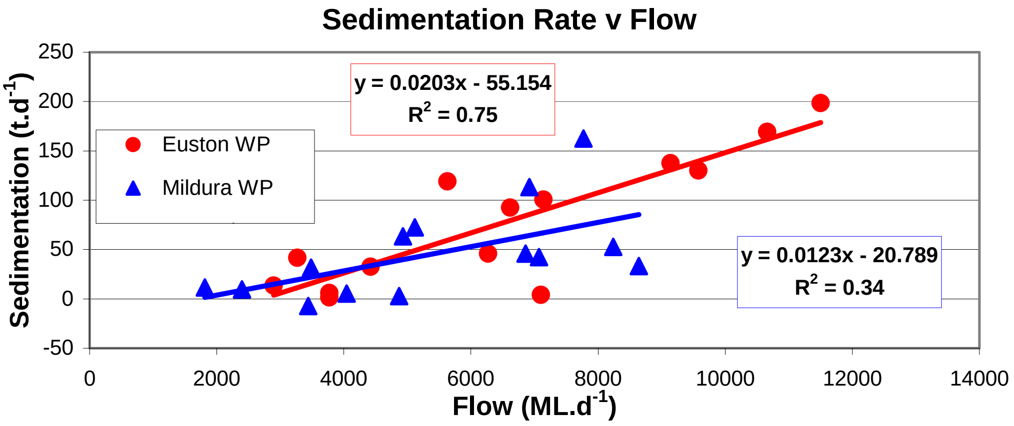


Figure 9. Daily sedimentation rates in the Euston and Mildura weir pools under different flow conditions, August 2001 – June 2003.

Riverbed Sediments

Riverbed sediments from the Euston, Mildura and Wentworth weir pools contained a consistently higher percentage of organic matter compared to the free-flowing sites (Figure 10A). The riverbed sediments of the weir pools were predominately fine and rich in both nitrogen (Figure 10B) and phosphorus (Figure 10C) compared to the sand-dominated sediments at the free-flowing sites.

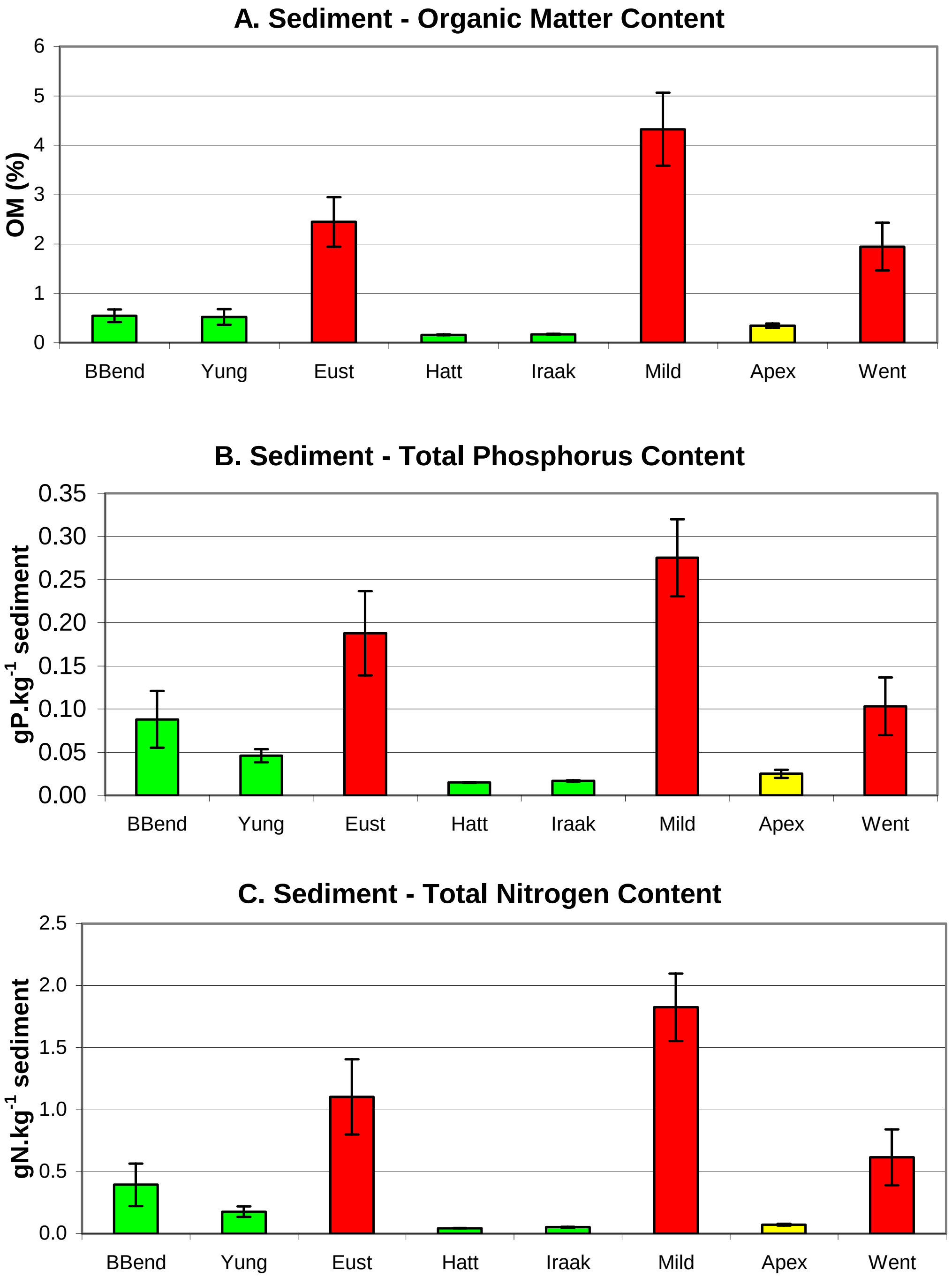


Figure 10. Riverbed sediment characteristics at free-flowing (green), weir pool (red) and at Apex Park (yellow) sites from August 2001 – June 2003: (A) Organic Matter content, (B) Total Phosphorus content, and (C) Total Nitrogen content. Error bars = ± 1 S.E.

The organic matter content of the benthic sediments was very strongly and positively correlated with the concentrations of total nitrogen and total phosphorus within the sediments across all sites (Figure 11).

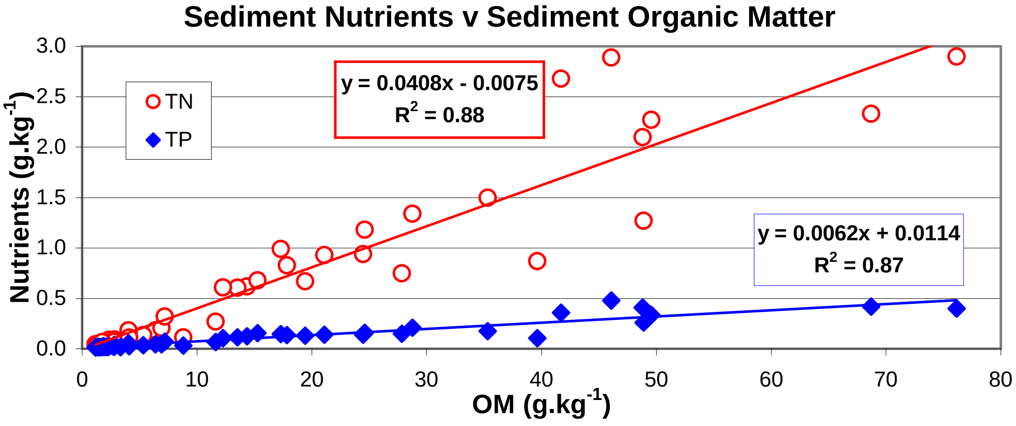


Figure 11. Organic matter content of riverbed sediments v total nitrogen and total phosphorus sediment concentrations.

Thermal Stratification

Complete hourly records (18/4/02 – 12/4/03) of surface water temperature were obtained at Euston and Wentworth, and bottom water temperature at Boundary Bend, Iraak and Mildura. Partial records were obtained at the remaining five site/positions due to the loss of loggers.

Temperatures ranged from a minimum of 8.1°C (Boundary Bend bottom logger, 0900, 2/7/02) to a maximum of 30.3°C (Wentworth surface logger, 1200, 24/1/03). At the yearly temporal scale, mean river temperatures (all loggers combined) changed in line with air temperature changes (air temperatures shown as 5-day moving averages) (Figure 14).

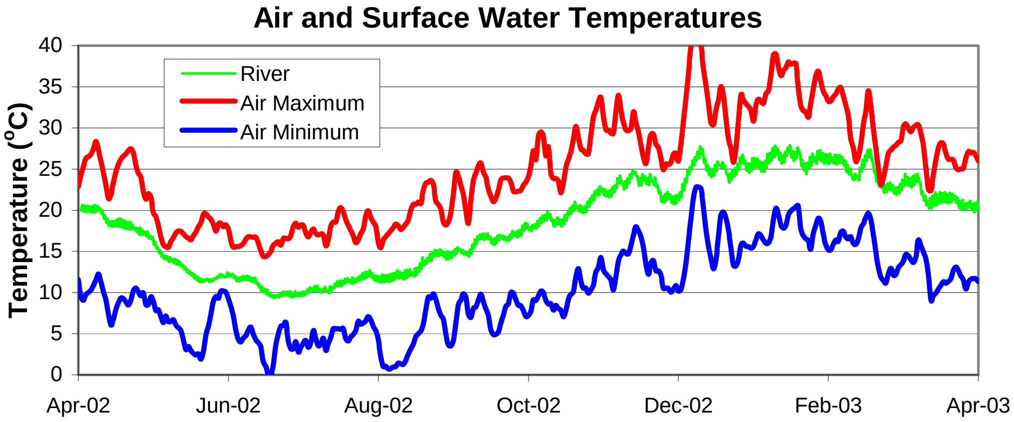
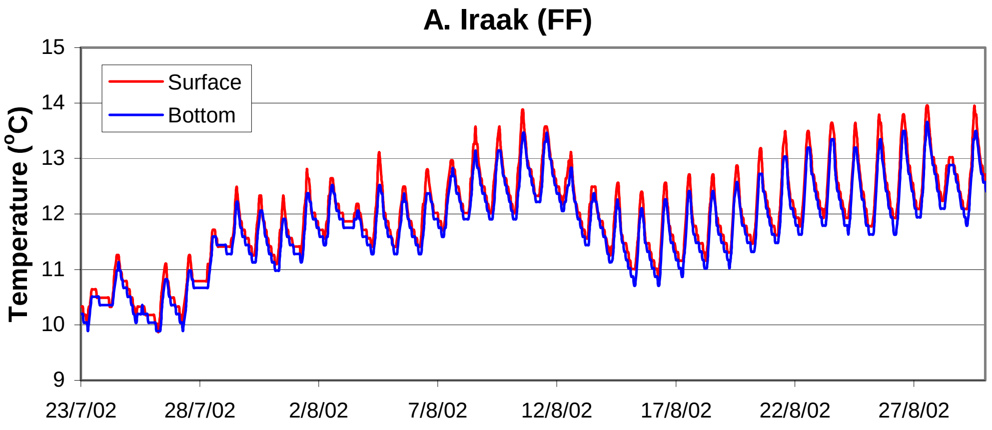
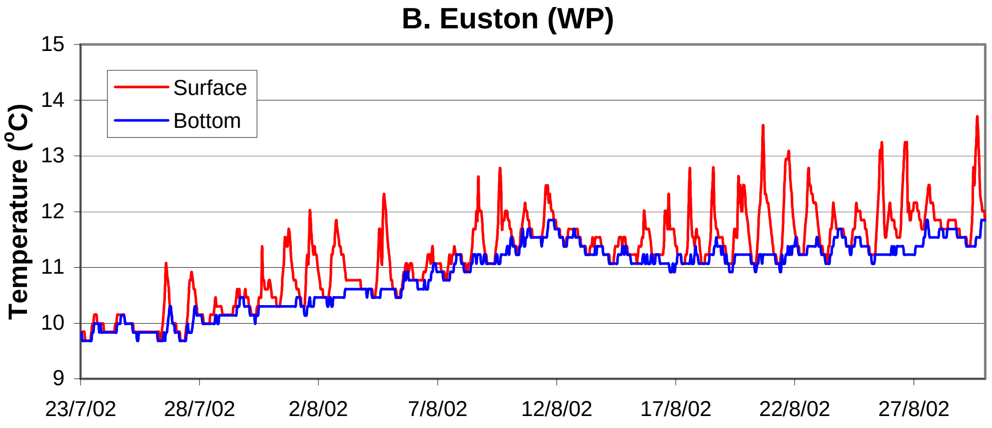


Figure 12. Mean hourly river temperatures and the daily maximum and minimum air temperatures (5-day running averages) at Mildura weather station from 17/4/02-12/4/03.

Periods when information from surface and bottom loggers was obtained simultaneously revealed that the weir pools underwent considerable diurnal thermal stratification relative to the free-flowing sites throughout the year. The period 23/7/02 – 30/8/02 is shown for three sites (Figure 13). Note that persistent (day and night) stratification occurred in the Euston and Wentworth weir pools on one day in late August 2002.





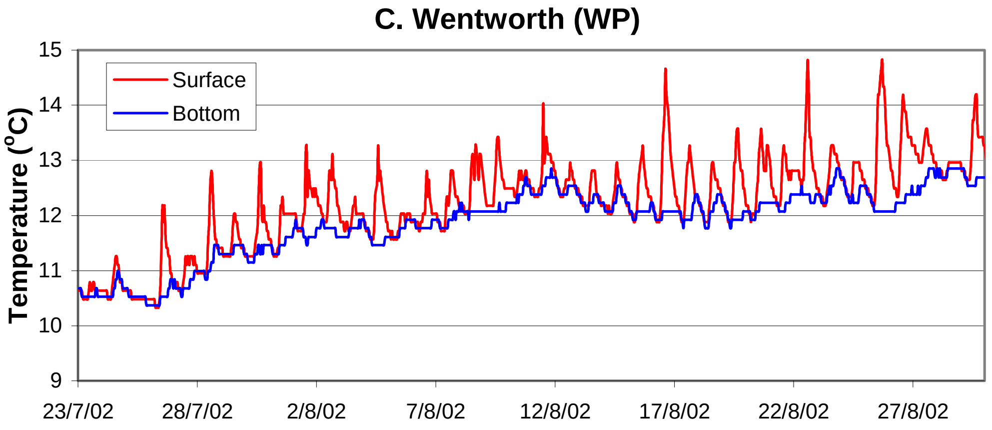


Figure 13. Hourly surface and bottom temperatures at (A) Iraak (FF), (B) Euston (WP) and (C) Wentworth (WP) from 23/7/02-30/8/03.

A comparison of the bottom water temperatures at Boundary Bend and Euston reveals the lag effect in temperature change between weir pools and free-flowing areas (Figure 14). As air temperatures lowered, water temperatures at the free-flowing site were more responsive to change and lowered more rapidly than for the Euston weir pool. Weir pool temperatures often lagged by several days and were up to 2^{o}C warmer at these times. When air temperatures increased, free-flowing sites typically warmed at a greater rate than for the weir pool sites. This pattern is due to the greater volumes of water in the weir pools having a higher thermal buffering capacity than the shallower free-flowing sites.

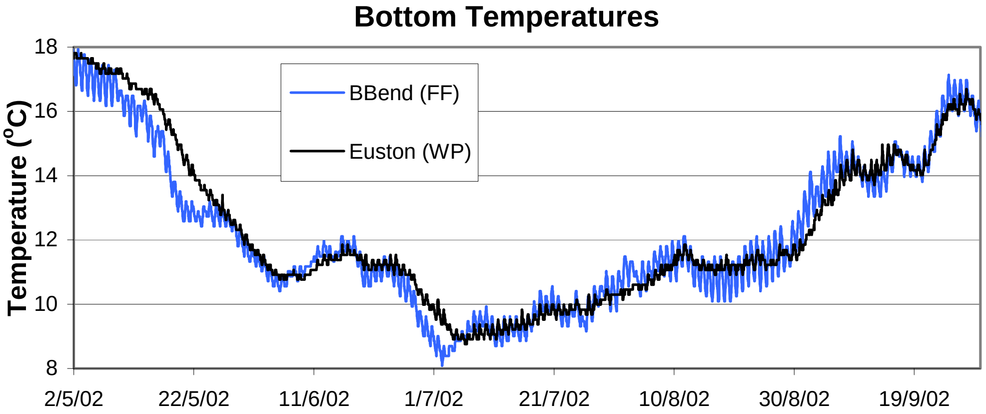


Figure 14. Hourly bottom temperatures at Boundary Bend (FF) and Euston (WP) from 2/5/02 – 29/9/02. Note the relative lag in thermal change and reduced daily temperature range in the Euston weir pool.

Daily stratification patterns were examined further by obtaining the temperature difference between the surface and bottom loggers for each hour and plotting against time of day for a 5-6 week period in July/August 2002 and January/February 2003 for the Wentworth (WP) and Iraak (FF) sites (Figure 15). The Wentworth weir pool underwent diurnal thermal stratification for both of these periods, with greater stratification in the January/February period when the maximum mean daily temperature difference between the surface and bottom exceeded 2°C.

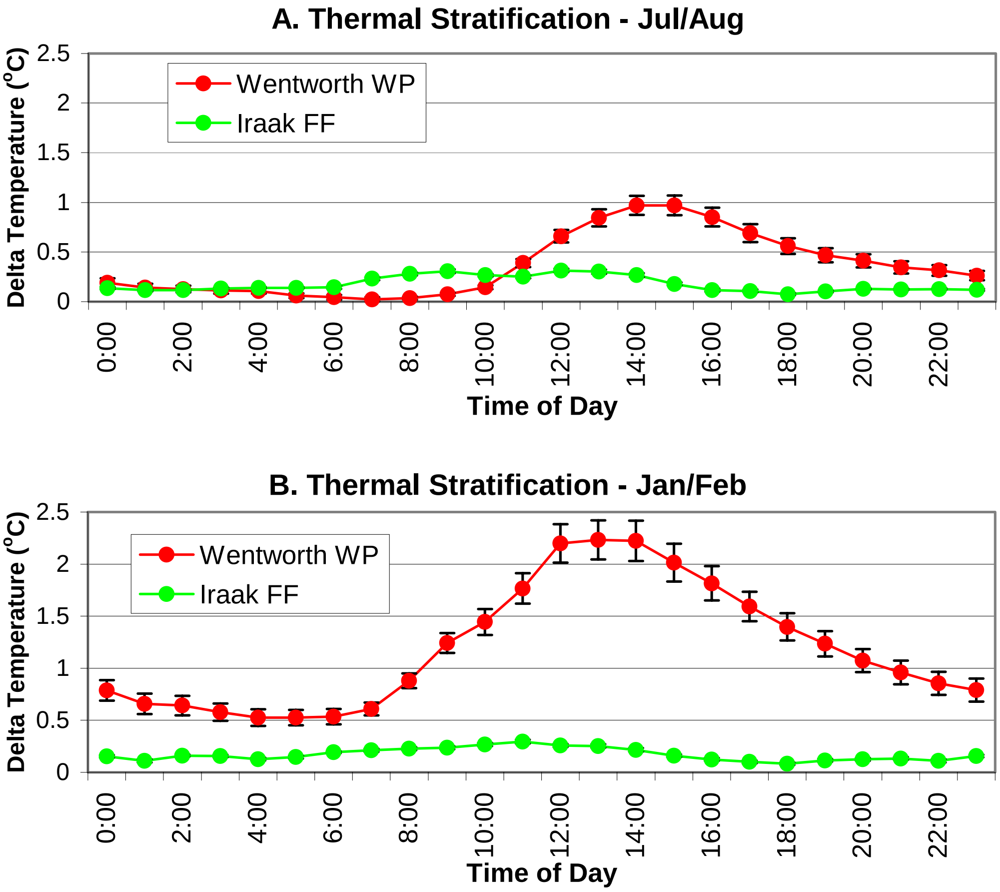


Figure 15. Mean hourly thermal stratification at Wentworth (WP) and Iraak (FF) from (A) 23/7/02-30/8/02 and (B) 23/1/03-28/2/03. Error bars = ± 1 S.E.

The greater volume of water in the weir pools compared to the free-flowing reaches would result in a reduced range of daily temperature change in the weir pools (given the thermal buffering effect and assuming mixed conditions where heat is dissipated evenly throughout the water column). This effect is particularly pronounced at the bottom of the water column (Figure 16A). However, the diurnal daily thermal stratification in weir pools partially offsets this for the surface water, with the range of surface temperatures actually exceeding the daily free-flowing temperature range during the hottest months of January to March (Figure 16B). These changes may have implications for benthic biota reliant on temperature cues and potentially for microbial processes as well.

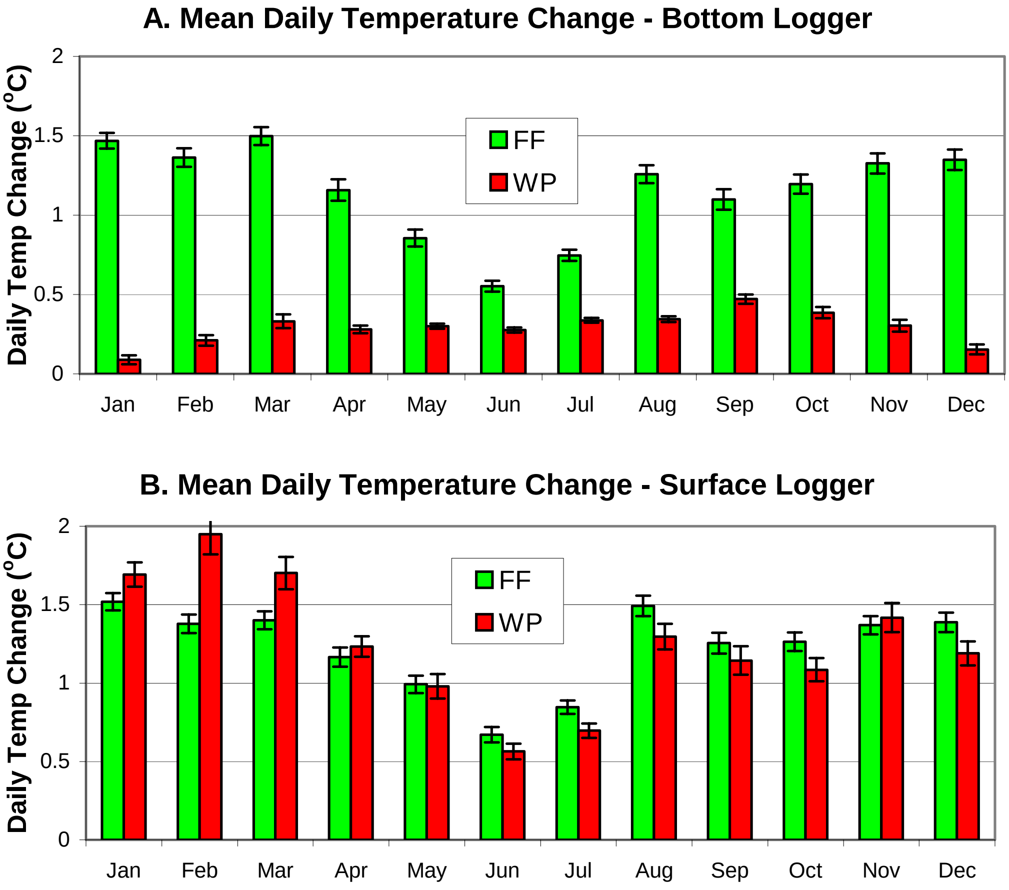


Figure 16. Mean daily temperature changes for each month at (A) bottom and (B) surface of the water column in free-flowing (green) and weir pools (red). Error bars = ± 1 S.E.

Dissolved Oxygen Stratification

Dissolved oxygen concentrations in the water column of weir pools also stratified, with a clear gradient of decreasing dissolved oxygen concentration with increasing depth. The differences between the oxygen concentrations at 1 m depth and at the bottom of the water column (0.3 m from the riverbed) were examined for each site by averaging across times (Figure 17A), and revealed much greater oxygen stratification in the weir pools than the free-flowing sites. The weir pool and free-flowing sites were separated and examined over time (Figure 17B), which further revealed that the greatest stratification occurred in the weir pools during the warmer months of the year.

Given the strong influence of temperature on dissolved oxygen concentrations, it is conceivable that the observed differences in dissolved oxygen (mg.L^{-1}) were due to temperature changes alone, with percentage oxygen saturation actually remaining stable throughout the water column. To test this, the oxygen concentration (mg.L^{-1}) at each depth was converted to % saturation (based on the formula of 100% oxygen saturation at sea level = –3.4145Ln(temperature at that depth) + 19.248). The strong stratification of dissolved oxygen in the weir pools remained (data not shown), demonstrating that temperature did not account for the high degree of oxygen stratification recorded in the weir pools.

The lowest DO concentration recorded at each of the Euston, Mildura and Wentworth weir pools from the 14 sampling events was 5.18 mg.L^{-1} , 3.98 mg.L^{-1}, and 2.41 mg.L^{-1} , respectively. These concentrations were recorded on 7/1/02 (Euston) and 8/1/02 (Mildura and Wentworth) at the bottom of the water column (0.3 m above the sediment).

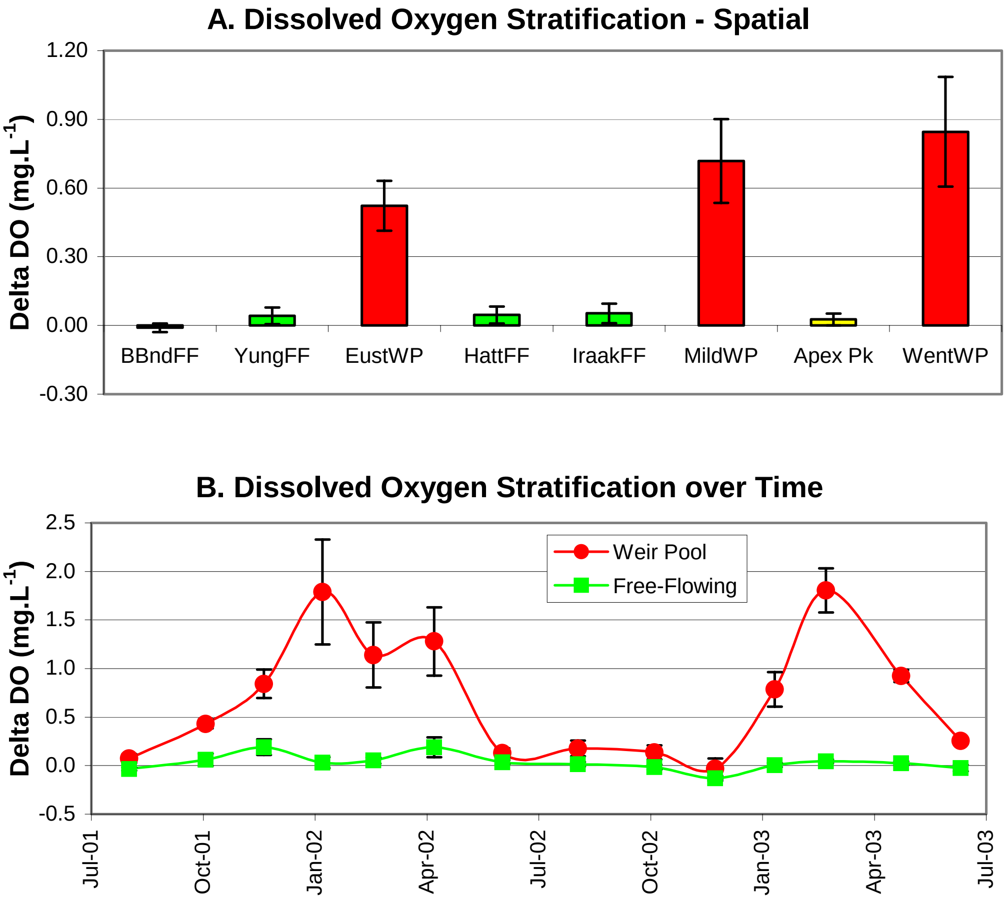


Figure 17. Dissolved oxygen stratification across (A) sites and (B) times at the weir pool and free-flowing sites of the Mallee Tract. Error bars = ± 1 S.E.

pH Stratification

pH decreased in the water column of the weir pools with increasing depth. The differences between the pH at 1 m depth and at the bottom of the water column (0.3 m from the riverbed) were examined for each site by averaging across times (Figure 18A), and revealed much greater stratification of pH in the weir pools than the free-flowing sites. The weir pool and free-flowing sites were separated and examined over time (Figure 18B), further revealing that the greatest stratification occurred in the weir pools during the warmer months of the year.

The lowest pH recorded during this study period was 6.48 at each of the Euston and Mildura weir pools on 14/1/03 and 15/1/03, respectively. The depths at which the readings were made were 7.0 m (Euston) and 6.6 m (Mildura). The highest pH measurement was 8.67 and was taken immediately below the surface of the water at Wentworth on 26/2/03.

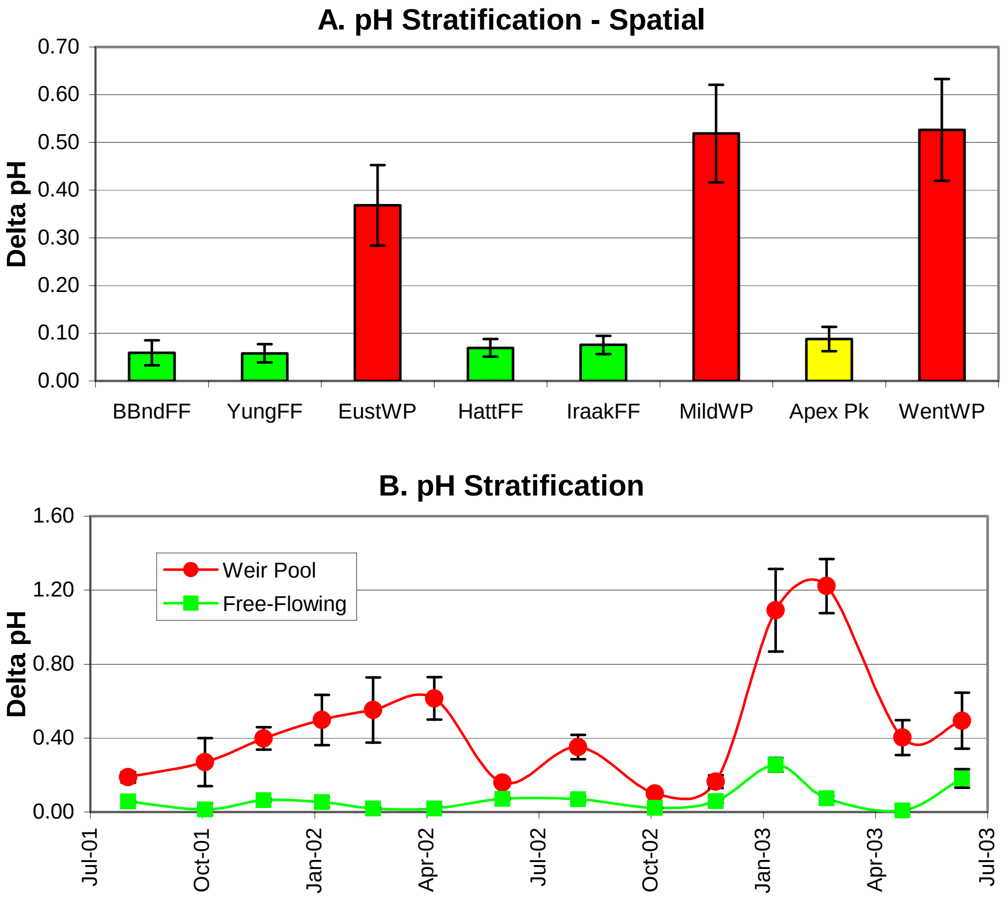


Figure 18. pH stratification across (A) sites and (B) time at the weir pool and free-flowing sites of the Mallee Tract. Error bars = ± 1 S.E.

Light Climate

Light attenuation and turbidity along the Mallee Tract were strongly correlated (Figure 19).

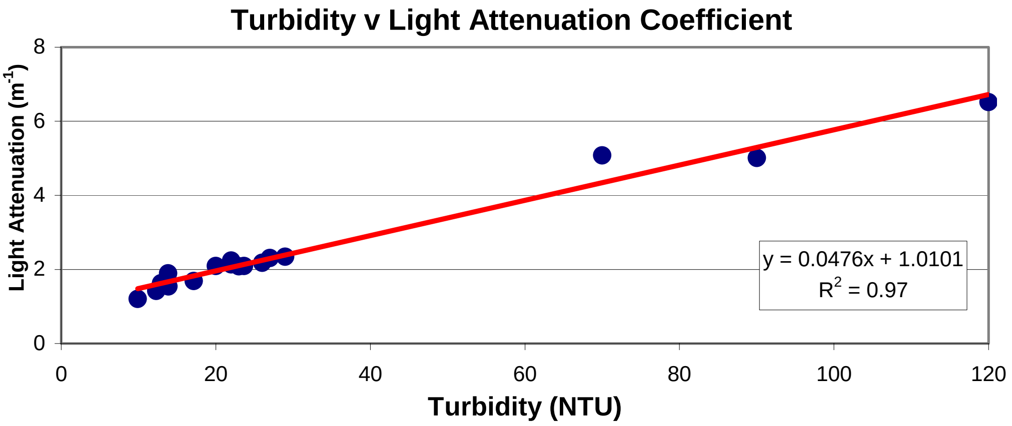


Figure 19. Relationship between light attenuation coefficient (K) and turbidity (NTU) in the Mallee Tract of the River Murray.

The photic depth (the depth to which 1% of surface irradiance penetrates) was also calculated and its relationship with turbidity is shown in Figure 20. The strength of this relationship provides justification for estimating photic depths at sites within the Mallee Tract based on turbidity measurements. The relationship reveals that photic depths of 1.5-3 m were typical from August 2001 – June 2003.

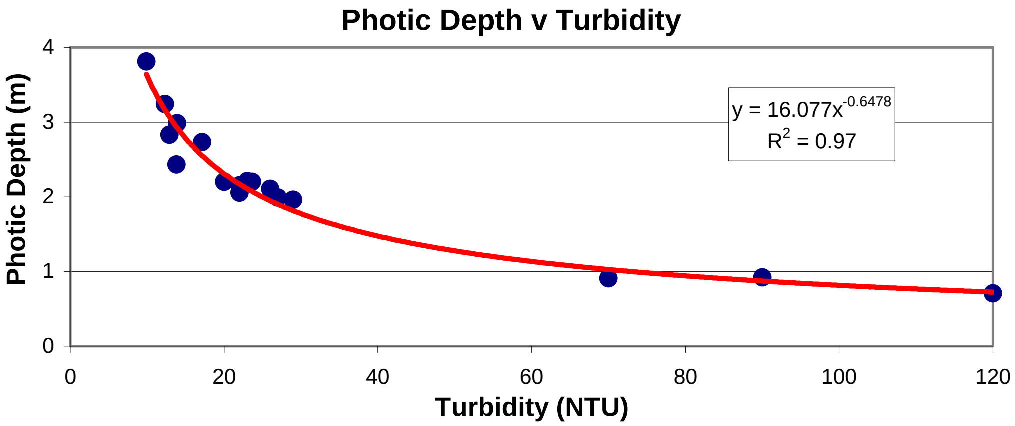


Figure 20. Photic depth (m) v turbidity (NTU) along the Mallee Tract.

The proportion of the water column receiving light influences the proportion of time phytoplankton are able to photosynthesise and is therefore an important measure when considering primary production potential. Whilst weirs have increased the photic zone by promoting the sedimentation of suspended solids, they have also increased the water depth resulting in a net reduction in the proportion of the water column receiving light relative to the free-flowing sites (Table 3).

Table 3: Proportion of water column receiving light

Site	Mean Turbidity[1] (NTU)	Mean Photic Depth[2] (m)	Mean River Depth[3] (m)	Water column receiving light (%)
Boundary Bend (FF)	46.3	1.34	2.13	63
Yungera Island (FF)	42.1	1.43	2.13	67
Euston (WP)	29.8	1.78	6.88	26
Hattah (FF)	28.5	1.84	2.13	86
Iraak (FF)	30	1.78	2.13	83
Mildura (WP)	23.5	2.08	5.68	37
Apex Park	24.1	2.05	2.13	96
Wentworth (WP)	22.1	2.16	5.33	41

Notes and assumptions: [1]Mean turbidity based on 14 site visits during study period; [2]Photic depth calculated from turbidity based on formula in Figure 20; [3]Mean depths based on 14 site visits to the four free-flowing sites during study period (2.13m) plus weir elevation (Table 1 in Research Report 1).

Discussion

The comparison of weir pools and free-flowing reaches in the Mallee Tract of the River Murray revealed that weirs exert a considerable influence on water physico-chemistry. The changed hydraulic conditions have promoted sedimentation and reduced turbidity, interrupted the longitudinal transport of nutrients along the river, changed the riverbed sediment composition, increased the photic depth, and altered the temperature, dissolved oxygen and pH profiles in the water column.

Turbidity and Suspended Solids

The low flow velocities of weir pools have reduced turbulent flow and facilitated the sedimentation of organic and inorganic solids from the water column. Based on the 14 sampling trips conducted, the greatest mean sedimentation occurred in the Euston weir pool (78 $t.d^{-1}$) followed by the Mildura (46 $t.d^{-1}$) and Wentworth (8 $t.d^{-1}$) pools. Given that the 14 sampling trips covered the range of flow conditions experienced during the two year period, these figures likely represent reasonable estimates of sedimentation for the period. This longitudinal pattern of sedimentation accords well with the description by Walker (2003) of weirs acting as a series of filters in the Lower Murray. Being located upstream of the Lower Murray Tract, and given the sequence of sedimentation rates, it is probable that the rates of sedimentation in the Mallee Tract are considerably greater than those occurring in the Lower Murray, although river channel erosion/adjustment remains ongoing in at least some areas (Thoms and Walker, 1993), and Darling River inputs require consideration.

In addition to the sedimentation measured in the weir pools, sedimentation of inorganic material also occurred in the free-flowing reach of the River Murray below the Murrumbidgee confluence (18 $t.d^{-1}$). This may be attributable to the widening of the River Murray below the confluence (Research Report 1) and possibly a greater cross-sectional area and lower flow velocity in this reach. An alternative view is that the Yungera Island site (67 km upstream of the Euston weir) was located *within* the upper portion of the Euston weir pool, and that sedimentation had occurred in the weir pool upstream of this site. The Euston weir elevates the water level to a greater degree (4.75 m) than other weirs (ca. 3.5 m), and the upstream point at which the Euston weir pool ceases is unclear. However, the finding of fine and relatively nutrient rich sediments at Boundary Bend (well upstream of the Euston weir pool but below the Murrumbidgee confluence) provides evidence that sedimentation is occurring as a result of the altered channel form.

A review of water quality monitoring of the River Murray by Mackay *et al*. (1988) revealed a progressive decrease in turbidity from downstream of the Wakool River junction (median 40 NTU) to Euston (30 NTU) and Merbein (23 NTU). This pattern was consistent over a wide range of flow conditions from 1978-1986. This study of turbidity and suspended solids confirms the sedimentation occurring in the Mallee Tract and reveals that it is the weir pools (particularly Euston and Mildura) where the sedimentation is predominately occurring. There is little data available to reveal the fate of these sediment loads. Do they become re-suspended during high flow events? If so, what impact will these greater sediment loads have on sedimentation rates in wetlands and on the floodplain? What are the impacts of elevated turbidity levels on biota?

Nutrient Transport

The positive correlation of nitrogen and phosphorus with suspended solids reveals that substantial quantities of nutrients are being deposited on the riverbed of the weir pools during the relatively low flows experienced throughout this study. This is strongly supported from an examination of riverbed sediments. At the Euston weir pool, estimates of phosphorus and nitrogen depositions over the study period are 43 $kgP.d^{-1}$ and 54 $kgN.d^{-1}$. At the Mildura weir pool, sedimentation occurred at the estimated rates of 37 $kgP.d^{-1}$ and 162 $kgN.d^{-1}$. The deposition of phosphorus in the Euston weir pool alone exceeds by an order of magnitude the annual phosphorus reduction target (1.1 - 1.6 $t.y^{-1}$) entering the River Murray from the entire Mallee catchment area as a result of irrigated horticulture and stormwater inputs (SMEC,

2001) and highlights the need for land and river managers to consider the effects of weirs in the transport of nutrients from catchments.

The internal loading of phosphorus within the weir pool sediments is an important management issue because the phosphorus may become released - particularly during periods when the hypolimnion becomes anoxic (Webster *et al*., 2001) – and fuel nuisance algal growth. Nitrogen is less conservative than phosphorus and has the potential to be lost through denitrification from the anoxic riverbed sediments. Other biota may also be utilising these nutrients – particularly microbes within the sediments.

The movement of other pollutants, such as heavy metals and pesticides, also requires consideration given that these are transported in association with sediment particles (Baldwin *et al*., in prep.) and are therefore likely components of the weir pool riverbed sediments. It is probable that the fine sediments (and associated nutrients and pollutants) are exported from the weir pools during high flow events; an adequate temporal resolution of sampling during these events would be required to avoid missing or underestimated their potential export.

The estimated contribution of 122 kg.d^{-1} of nitrogen to the surface waters in the reach between Hattah and Iraak may be due to groundwater inputs. Two pieces of evidence support this. First, electrical conductivity also increased substantially between these sites. Second, increased total nitrogen concentrations were recorded in the Mildura weir pool during the 3.5 m drawdown of the Mildura weir pool in 2001 when groundwater inflows to the river channel increased (McCarthy *et al*., 2004), suggesting that nitrogen concentrations may be high in the groundwater of this region.

The estimated daily sedimentation of 5.5 t.d^{-1} and 7.8 t.d^{-1} of organic matter into the Euston and Mildura weir pools, respectively, represents a considerable loss in organic carbon travelling along the river. This loss has strong implications for river health because the longitudinal transport of carbon is likely important in maintaining the ecological integrity of lower reaches as stressed in the River Continuum Concept (Vannote *et al*., 1980). The importance of lateral (floodplain) inputs of organic material, as argued in the Flood Pulse Concept (Junk *et al*., 1989), would have been limited due to the flows remaining in-channel throughout the study period. The relative contribution of autochthonous carbon production to the food web of the Mallee Tract, as emphasised in the Riverine Productivity Model (Thorp and Delong, 1994), remains unclear but may be an important source of carbon in this region (Gawne *et al*., 2002).

Water leaving the Mallee Tract and entering the Lower Murray during low flow periods carries lower concentrations of nutrients as a result of the sedimentation in weir pools along the Mallee Tract. Whether these levels are lower than those typical of pre-regulation conditions remains unknown given the anthropogenic changes to catchment conditions upstream (e.g. land clearance) and the inherent difficulties of statistically testing a highly variable system (Mackay *et al*., 1988). Contributions from the turbid and nutrient-rich Darling River also influence water quality in the Lower Murray, and the Wentworth weir, Menindee Lakes Storage Scheme, and other weirs along the Darling River system have altered sediment transport mechanisms in this system as well.

Riverbed Sediments

Riverbed sediment characteristics reflect well the measured patterns of sedimentation occurring in the different river reaches of the Mallee Tract. The riverbed sediments at weir pool sites were fine clays and silts and contained a high organic matter, phosphorus and nitrogen content relative to the free-flowing sites. Of the sediments at the free-flowing sites, those at Boundary Bend and Yungera Island typically contained higher proportions of silts and clays than Hattah and Iraak (and Apex Park), and had a correspondingly higher organic matter and nutrient content.

Total phosphorus and total nitrogen concentrations in the sediments were strongly correlated with sediment organic matter content. These relationships were very similar to samples collected in the Mildura and Euston weir pools in 2001 (McCarthy *et al*., 2004), demonstrating that the measurement of organic matter content may be a cost-effective way of estimating the phosphorus and nitrogen content of sediments.

The change in sediment character from predominately sand to fine silts and clays has a large impact on biota persisting on the riverbed. Macroinvertebrate communities would be expected to have changed as a result of the altered sediments but were not examined in this study. The distribution of larger macroinvertebrates such as Murray Crayfish and river mussels have likely been restricted as a result of increased regions of riverbed comprising soft, fine sediments. Nutrient cycling and microbial processes have also likely changed.

Water Physico-Chemistry

Temperature

Diurnal thermal stratification was a year round phenomenon in weir pools but did not occur in the free-flowing areas despite the low flow conditions during the study period (Research Report 1). Thermal stratification, therefore, is not a feature typical of the Mallee Tract but an effect of weirs. The diurnal thermal stratification in the weir pools typically broke down overnight (particularly in winter), but became persistent on occasion in the weir pools during the warmer months.

The thermal stratification and greater water volume of the weir pools altered the daily temperature fluctuations in different parts of the water column. Temperatures at the at the top and bottom of the water column were consistently similar at the free-flowing sites due to turbulent mixing, and each section of the water column underwent the same daily range in water temperature change. In contrast, temperatures in the bottom of the water column of weir pools remained nearly constant day and night, with surface water temperatures generally fluctuating to a smaller extent than at the free-flowing sites. However, high solar irradiance in the summer months produced strong thermal stratification in the weir pools and resulted in a greater daily temperature range at the water's surface.

On a weekly temporal scale, weir pool temperatures changed at a slower rate relative to the free-flowing sites. This lag effect arising from the greater water volume of the weir pools was also noted previously for the Mildura weir pool and Iraak sites (McCarthy *et al*., 2004).

Dissolved Oxygen

Dissolved oxygen (DO) remained high and relatively consistent through the water column of the free-flowing sites at a given time. In contrast, DO in the water column of the weir pools stratified during the warmer periods. The lowest DO concentration recorded during the study period was 2.41 mg.L^{-1} immediately above the sediment at the Wentworth weir pool during January 2002. Dissolved oxygen concentrations as low as 0.31 mg.L^{-1} have been recorded during summer monitoring of the weir pools of the Mallee Tract (MDFRC, unpublished data). These low oxygen conditions may prevent biota such as macroinvertebrates from persisting in the deeper sections of the weir pool and could potentially result in anoxic conditions above the sediments where chemicals such as phosphorus may be liberated into the water column (Webster *et al*., 2001).

pH

pH in the Mallee Tract was typically slightly alkaline, with levels remaining within range of 7.0-8.1 over the study period (mean of entire water column). pH displayed a similar stratification pattern to dissolved oxygen, with greatest stratification occurring in the weir pools during the summer months. pH at the surface commonly exceeded 8 but pH consistently lowered with increasing depth. pH levels are influenced by photosynthetic activity (ANZECC, 2000; Mackay *et al*., 1988), with the consumption of carbon dioxide during photosynthesis increasing pH levels. This is consistent with the higher pH measurements within the photic zone where algal photosynthesis is occurring. This is particularly evident in the weir pools where vertical mixing is limited.

Mackay *et al*. (1988) described a steady increase in pH along the Mallee Tract. This trend was evident from Boundary Bend to Iraak, with the greatest mean pH levels occurring at Hattah and Iraak. These higher pH levels correlate well with the higher phytoplankton biomass at these sites (Research Report 3), which are likely related to the increased nitrogen levels in this region.

Electrical Conductivity

Increases in electrical conductivity (EC) were greatest in the Mildura weir pool reach, with large increases in salinity also occurring in the free-flowing reach from Hattah to Iraak. The river channel of the Mallee Tract winds through ancient marine and lake sediments where strong connectivity (low impedance) between the surface and groundwater systems is a feature in some areas (e.g. Beaton, 1980; SKM, 1999). It is likely that the increased levels of salt, nitrogen and phosphorus are attributable to groundwater inflows from these natural connections. Irrigated horticulture on land adjacent to these reaches may be contributing to these results given the documented elevated groundwater mounds in these irrigated regions (Mackay *et al*., 1988; SKM, 1999).

Comparison to 1978-1986

Water quality results obtained at Euston (means) were compared with data from this same area from 1978-1986 where applicable (data shown as our mean value v Mackay *et al*. 1988 mean value). Turbidity (30 v 34) and pH (7.4 v 7.1) were similar to the longer-term average, whilst electrical conductivity (154 v 270) and the nutrients total phosphorus (46 v 94), filterable reactive phosphorus (5 v 19), total nitrogen (389 v 510) and oxides of nitrogen (8 v 74) were all much lower than the longer-term values. It is likely that the drought-induced low flows and possibly the sourcing of water from upstream storages may explain some of these findings, particularly the low EC and dissolved nutrient concentrations.

ANZECC Guidelines

The ANZECC (2000) water quality guidelines provide trigger levels (thresholds that, when exceeded, stimulate further investigation) for lowland rivers in south-eastern Australia. The thresholds utilised were for slightly disturbed ecosystems.

Electrical conductivity ranged from 74 - 402 µS.cm^{-1} during the period of study and remained within or below the 125 -2200 µS.cm^{-1} guideline. EC levels increased above 402 µS.cm^{-1} outside of the sampling times (ca. 700 µS.cm^{-1} at Mildura during the 2003 Mildura weir pool drawdown; McCarthy *et al*., 2004) but remained well within the guideline range.

Turbidity at the most upstream site (Boundary Bend) exceeded the 6-50 NTU guideline on seven of the 14 sampling occasions. Due to the sedimentation described previously for the Mallee Tract, Euston exceeded 50 NTU on one occasion and sites downstream of Euston remained below 50 NTU during the study period.

Total phosphorus exceeded the ANZECC (2000) threshold of 50 µg.L^{-1} on eight of the 14 sampling occasions. Total phosphorus was often highest in the upstream sites, but occasionally exceeded the threshold at all sites throughout the Mallee Tract. As the concentration of total phosphorus is considerably lower than the mean values obtained at Euston from 1978 -1986 (Mackay *et al*., 1988), these levels likely do not reflect atypical conditions for this area.

Total nitrogen exceeded the threshold of 500 µg.L^{-1} on four of the 14 sampling occasions, with a maximum concentration recorded of 562 µg.L^{-1}. Levels were considerably lower than for the period 1978-1986 (Mackay *et al*., 1988).

The maximum filterable reactive phosphorus concentration recorded during the study period was 17 µg.L^{-1} (ANZECC threshold 20 µg.L^{-1}). Similarly, the maximum nitrous oxides and ammonia concentrations were 15 µg.L^{-1} (ANZECC threshold 40 µg.L^{-1}) and 12 µg.L^{-1}, respectively.

Mean dissolved oxygen (DO) concentrations in the water column fell below the ANZECC (2000) lower limit of 85% saturation on two of the 14 sampling occasions. However, DO concentrations lower in the water column of the weir pools occasionally decreased to much lower concentrations, with hypolimnion dissolved oxygen levels of 46% and 28% saturation being recorded in the Mildura and Wentworth weir pools, respectively, on 8 January 2002.

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