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Waterways Commission

WESTERN AUSTRALIA

REPORT TO THE WATERWAYS COMMISSION
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Water Quality of the Murray River Estuary
—Summary Report—

N. D'Adamo
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May 1985

**Centre for Water Research
The University of Western Australia
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INTRODUCTION

This report summarises the results of a study on the relationships between the hydrodynamics and biology of the lower reaches of the Murray River Estuary. Details of the study may be found in the main report (D'Adamo and Lukatelich 1985).

The Murray River is located approximately 70 km south of Perth, Western Australia, and flows to Peel Inlet through a delta where it divides into six tributaries (Fig. 1). Tidal influence extends to the Pinjarra Weir, 26 km upstream. The average depth is about 2 m, but is interrupted by many scour depressions near bends along the tidal portion of the river (Fig. 1).

Over the past 30 years, the loading of nitrogen in the Murray River has increased threefold while the phosphorus load has increased 50 times (Hodgkin *et al*. 1980). The increase in nitrogen load has been due mainly to the mineralisation of nitrogen from pasture legumes and increased use of nitrogenous fertilizers. The increase in phosphorus loading is correlated with the increased use of superphosphate on the coastal plain portion of the Murray River catchment.

This increase in nutrient loading resulted in a deterioration of the water quality of the Murray River. Algal blooms, water discolouration, unpleasant odours and sightings of dead fish (Waterways Commission File No. 8.3.1) have recently been recorded in the lower reaches of the Murray River. Past studies of the water quality of the Murray River (Lukatelich and McComb 1983) have shown that nutrient levels in the water are sufficiently high to potentially support algal blooms, and chlorophyll *a* levels of up to 178 $\mu g\ l^{-1}$ were measured during the study.

These water quality problems, along with recent interest in waterside developments along the lower reaches of the Murray River, provided the motivation for the present study.

The aims of the study were:

- To gain an understanding of the relationships between the hydrodynamics and the biology of the river.

- To integrate the analyses of the present study with the results of past studies (Lukatelich and McComb 1983; D'Adamo 1983) on the water quality of the Murray River.

- to determine the dominant mechanisms responsible for the build-up of stratification of the Murray River on seasonal time scales (50-100 days).

- To quantify the nature and order of importance of short time scale (< 10 days) perturbations to the stratification and to quantify their effect upon the horizontal transport of material.

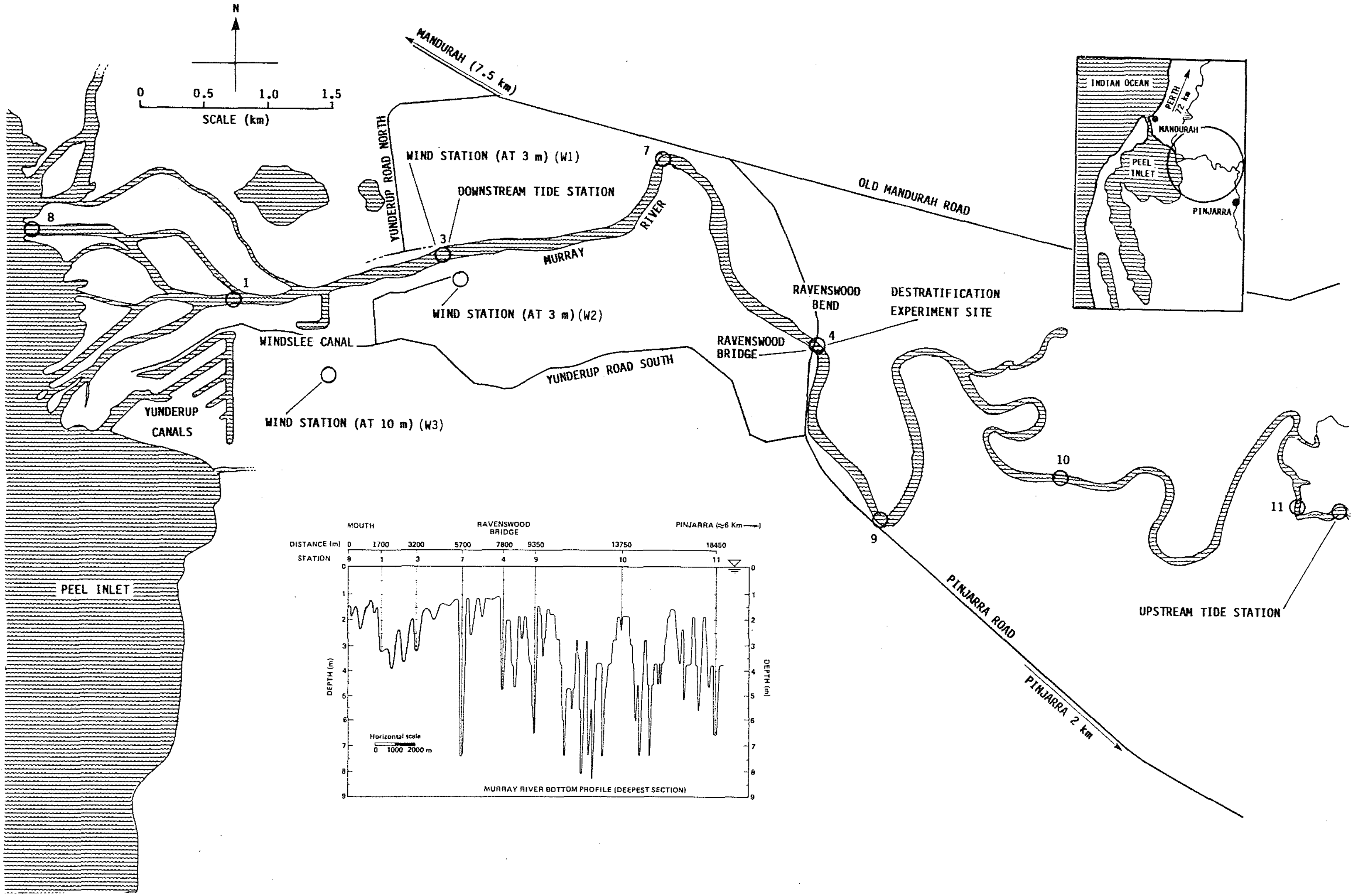


Figure 1 Map of the lower reaches of the Murray River, its local environs, data station labels and locations, and bottom profile

- To investigate, in detail, the potential of wind to destratify the water column.

- To investigate the potential of an artificial destratification technique to flush water from a local region and to quantify the hydrodynamic and biological response of the river to such a perturbation.

- To quantify the tidal behaviour of the Murray River during its estuarine phase and to determine the causes of, and relationships between the water level variations of the ocean, Peel Inlet and Murray River.

- To investigate the possible causes of recently reported fish kills in the lower reaches of the Murray River.

RESULTS

1. Tides at the Coast and in the Murray River

The periodic variation of water level in the Murray River is due mainly to the oceanic tidal variation which occurs at Mandurah. The oceanic tidal signal is transmitted to the Murray River, with amplitude attenuation and phase lag, via the Mandurah Channel and Peel Inlet (see Fig. 1).

The influence of tidal flows upon the mixing and structure of the salt wedge in the Murray River Estuary was investigated. In particular, the interaction between the complicated bottom topography (Fig. 1) and the tidal flow field was found to be an important mechanism for localised mixing resulting in density driven intrusive flows.

Astronomic tides, produced by the complicated pattern of gravitational forces exerted by the moon and sun on the earth, result in a maximum oceanic water level range of the order of 1 m. The astronomic tides are mainly diurnal with semi-diurnal tides only occuring for 3-4 days at a time when both the lunar and solar semi-diurnal components are near their maximum (Hodgkin and Di Lollo 1958).

Local meteorological forcings also influence water level along the coast. Southward propagating disturbances, known as continental shelf waves (Hamon 1966), are generally accepted to be generated by surface winds associated with meso-scale weather systems that regularly pass over the continental shelf region. These waves have periods of approximately 7 days and have a maximum range of approximately 0.3 m (Harrison 1983; Webster 1983).

The ocean also has an isostatic response of water level to barometric pressure. Sea level varies inversely with barometric pressure by approximately 1 cm per millibar. Barometric pressure variations of 10 to 20 millibars are commonly associated with the meso-scale weather systems that pass over the southwest coast of Western Australia with periods of approximately 7 days (D'Adamo 1983). Hence it may be expected that sea level variations of up to 0.2 m could be produced by the isostatic response of the ocean along the southwest coast to barometric pressure fluctuations.

Other meteorological forcings, such as typical daily onshore and offshore winds, and temperature fluctuations, will have a relatively small influence upon sea level. However, very strong winds, such as those generated by rare cyclonic depressions which pass along the southwest coast, have been found to influence water level at the coast by up to approximately 0.5 m (Hodgkin and Di Lollo 1958).

Hence, excluding the effect of rare event storms, the maximum influence of meteorological forcings upon coastal water level due to continental shelf waves plus direct pressure effects can be of the order of 0.5 m (Hodgkin and Di Lollo 1958).

The results in Fig. 2 present the amplitudes of the major components of the astronomic tidal signal at Warnbro (the ocean signal used in this study), Chimneys (in the Mandurah Channel) and Murray River (at station 3, see Fig. 1).

As indicated in Fig. 2 the tides at Warnbro are predominantly of the diurnal type. The sum total of the dominant astronomic constituents is 0.7 m. The raw Warnbro signal for the analysis period exhibits a maximum daily range of 1.1 m. This result reinforces Hodgkin and Di Lollo's (1958) conclusion that meteorological and hydrological influences can cause water level variations up to 0.5 m.

The major components of the astronomic signal showed varying degrees of amplitude attenuation from Warnbro to the Murray River caused by the geometrical properties and friction of the Mandurah Channel and Peel Inlet. The diurnal and semi-diurnal components showed a 60-90% attenuation in comparison to 20-40% for the longer period (> 14 day) components.

It was found that the diurnal signals for Warnbro and both the Murray River stations (see Fig. 1) were coherent, with the Murray River signal exhibiting a lag of approximately 4 hours relative to the Warnbro signal. By harmonic analysis it was shown that, for both Murray River stations, a daily tidal range due to the diurnal astronomic constituents was of the order of 0.10 m. As indicated in Fig. 3, changes in water level of between 0.05 and 0.20 m can occur in the Murray River over periods ranging from 3 to 10 hours. The sum contribution of the longer period components (> 14 days) to the tidal range in the Murray River was of the order of 0.35 m (Fig. 3).

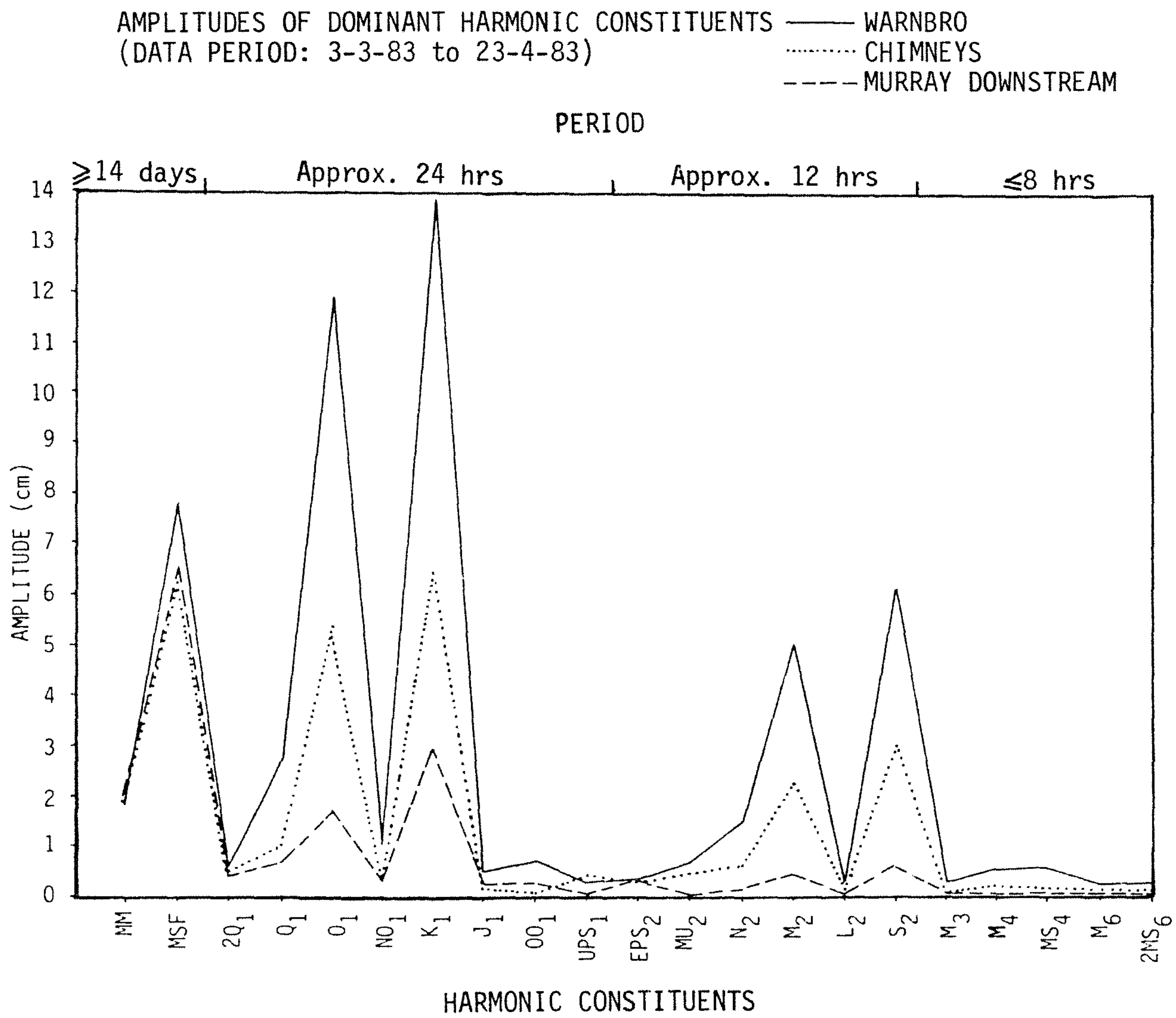


Figure 2 Amplitudes of dominant harmonic constituents of the tidal signal for Warnbro, Chimneys and Murray Downstream. Data period 3-3-83 to 23-4-83

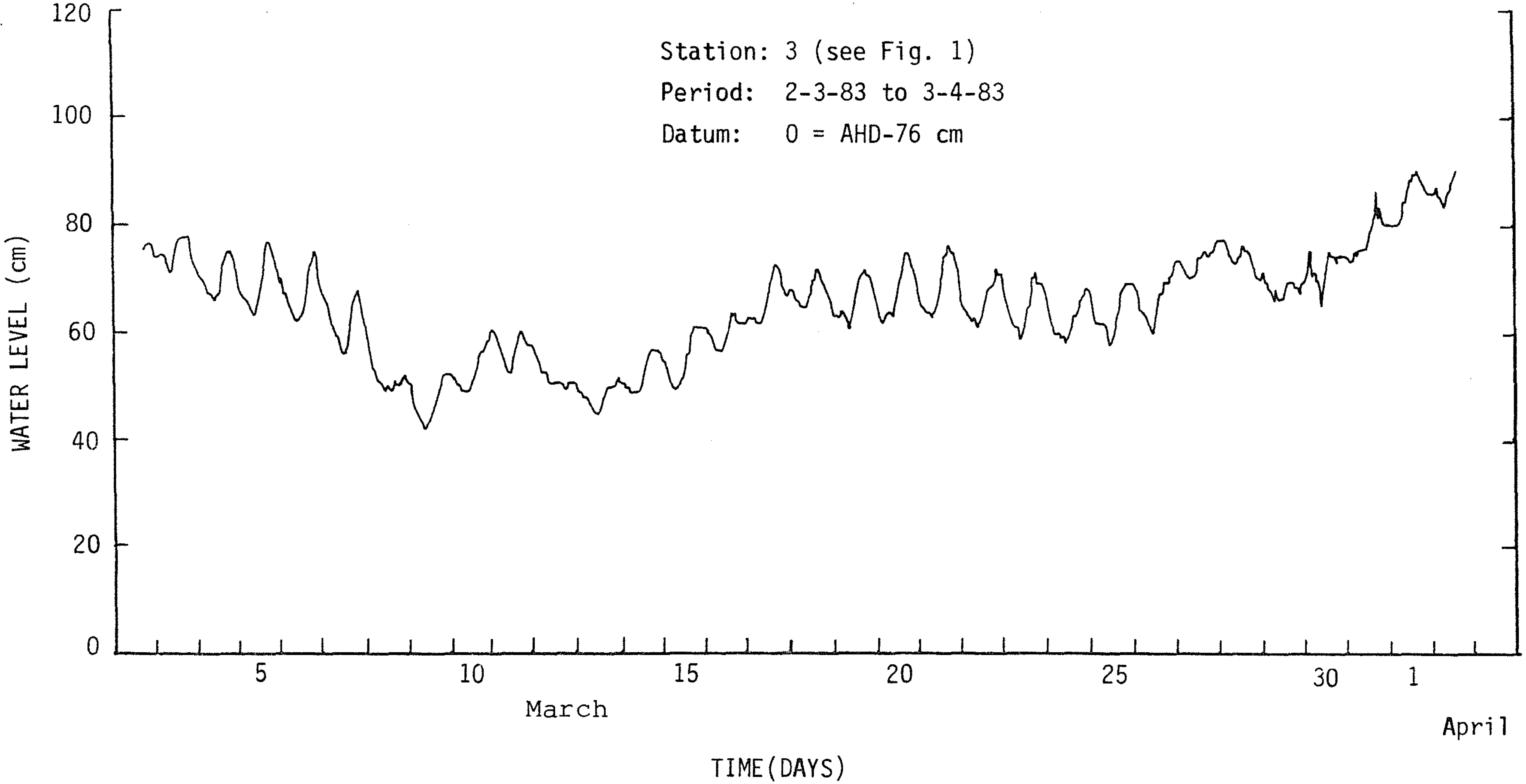


Figure 3 Water level variation at the Murray Downstream site (Station 3). Data period 2-3-83 to 3-4-83

The harmonic analyses performed on tidal data from both near the mouth and the head of the Murray River Estuary supported theoretical predictions in showing amplitude amplification of up to 40% towards the head. The amplification was due to the narrowing cross-sectional area of the river towards the head. The degree of amplification was found to increase with decreasing period of the harmonic component of the tidal signal.

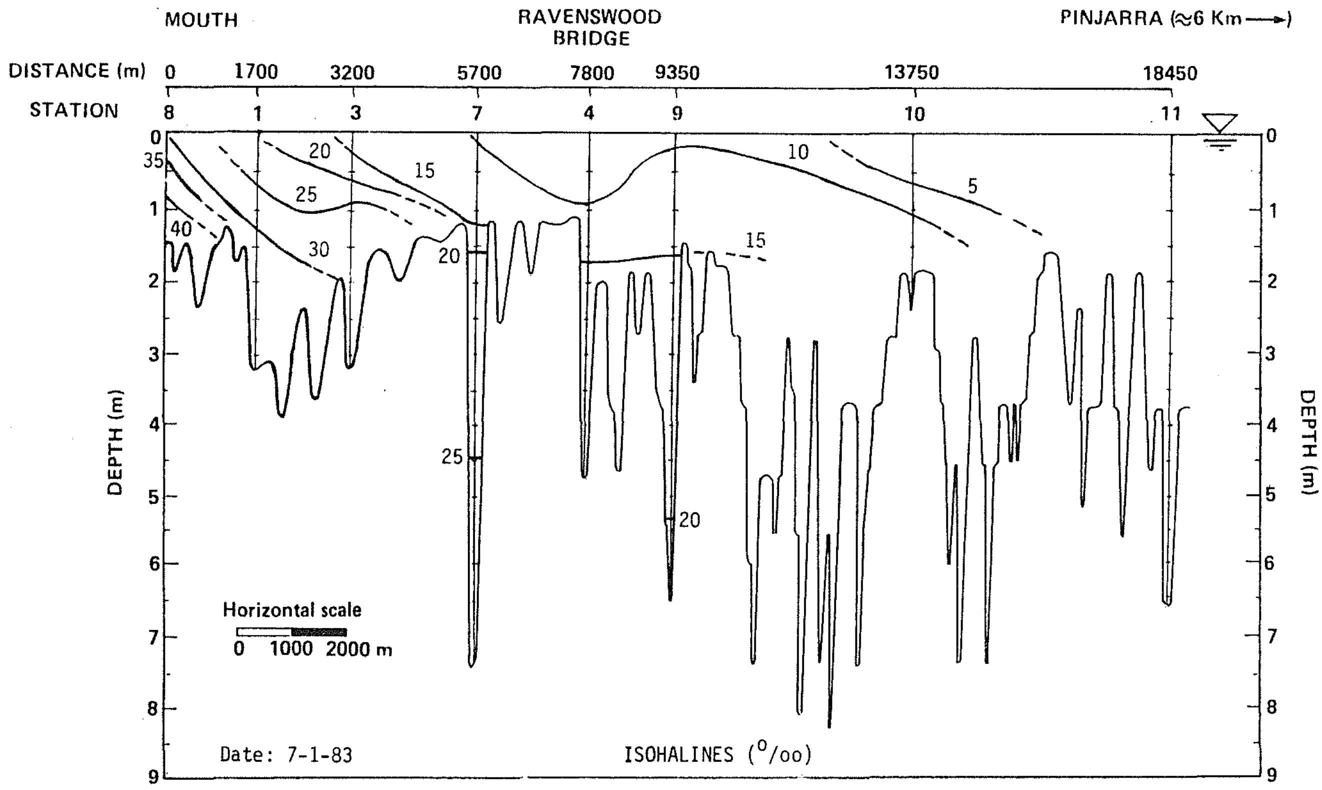
The amplitude attenuation caused by frictional damping of the tidal signal from the mouth of the river to the Murray Upstream station (see Fig. 1) was found to vary according to the period of the tidal component. The observed amplitude attenuation was approximately 20% for the long period components (> 14 days), approximately 30% for the diurnal components and approximately 40% for the semi-diurnal components.

In summary then, the oceanic tidal signal at Mandurah is predominantly diurnal with a typical daily range of approximately 0.3 to 0.9 m. This signal is transmitted to the mouth of the Murray River with approximately a 60-90% amplitude attenuation and 4 hour phase lag relative to Warnbro. The incident tidal signal at the mouth of the river has a daily range of approximately 0.1 m. The diurnal signal propagates upstream with an average phase lag of approximately 30 minutes occurring from the Murray Downstream site to the Murray Upstream site (see Fig. 1). Changes in water level of up to 0.2 m can occur in the Murray River over periods ranging from 3 to 10 hours.

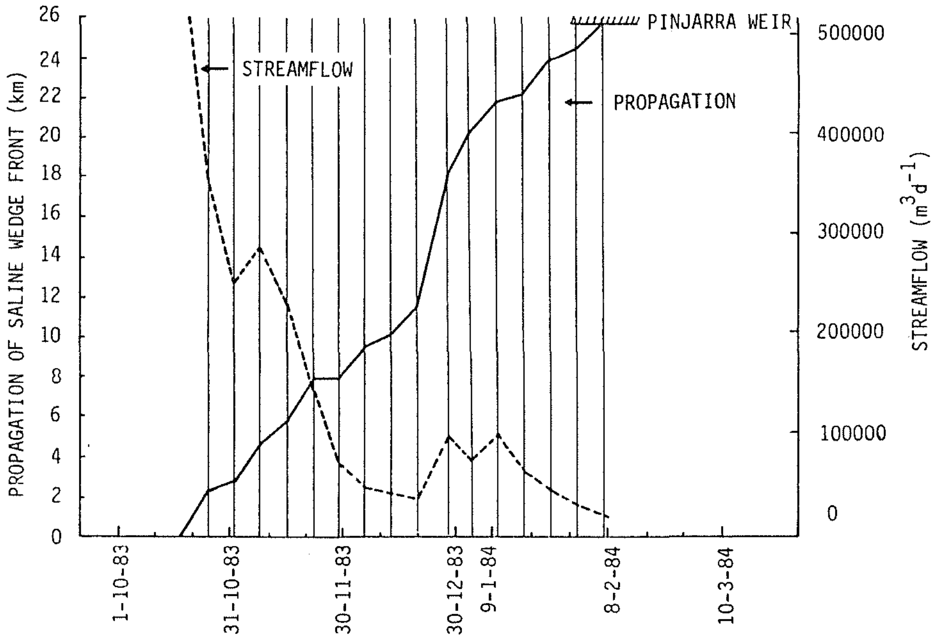
2. Seasonal Stratification of the Murray River

Past investigations of the hydrodynamic behaviour of the Murray River have found it to undergo a seasonal stratification cycle (Hodgkin, unpublished data; Lukatelich and McComb 1983; D'Adamo 1983). Subsiding winter discharge allows relatively saline (and therefore dense) Peel Inlet water to enter as a salt wedge through the mouth, reaching the Pinjarra Weir (26 km upstream) typically in 3-4 months. Two dominant parameters govern the propagation of the salt wedge on seasonal time scales (approximately 50-100 days). First, the density difference between the intruding Peel Inlet water and the fresh outflowing Murray River water, and second, the strength of the river discharge. A typical salinity stratification contour plot of the salt wedge for the Murray River is presented in Fig. 4a. The mean position of the salt wedge front is plotted along with streamflow variation for the 1983/1984 stratification period in Fig. 4b.

Table 1 presents a summary of the data gathered from 1969 to 1984 on the propagation of the salt wedge in the Murray River. For typical summer streamflow conditions (excluding rare event type storms) the salt wedge first enters the mouth when streamflow falls to 3-4 x 10^5 m^3d^{-1} and reaches the Pinjarra Weir by the time streamflow has fallen to approximately 1.5-3 x $10^4 m^3d^{-1}$ (Fig. 4b).



a) Contour plot of isohalines (lines of constant salinity, in parts per thousand (°/oo)) for 7-1-83.



b) Propagation of the salt wedge front from the mouth of the Murray River to the Pinjarra Weir and corresponding Murray River streamflow data.

Figure 4 Isohaline contour plot (7-1-83) and salt wedge propagation and streamflow data for the Murray River (1983/1984)

Typically, the salt wedge begins to be eroded when streamflow rises again to approximately $2 \times 10^5 m^3 d^{-1}$ and is completely flushed into Peel Inlet when streamflows reach approximately $1 \times 10^5 m^3 d^{-1}$ (Table 1).

Table 1 Approximate propagation and flushing rates of the salt wedge for the Murray River: 1969-1984.

Period	Streamflow when the salt wedge first enters the mouth ($m^3 d^{-1}$)	Streamflow when the salt wedge reaches the Pinjarra Weir ($m^3 d^{-1}$)	Time averaged rate of change of position of salt wedge front during entry ($m\ s^{-1}$)
<u>During falling streamflow periods (after winter)</u>			
6.11.70 - 30.1.71	3×10^5	3×10^4	3.5×10^{-3}
11.11.71- 19.2.72	4×10^5	3×10^4	2.95×10^{-3}
2.2.82 - 16.3 82 (after flooding)	3×10^5	3×10^4	7.0×10^{-3}
late 1982 - 30.1.83	?	1.6×10^4	?
25.10.83 - 7.2.84	4×10^5	2×10^4	2.8×10^{-3}

Period	Streamflow when salt wedge begins to be flushed by river discharge ($m^3 d^{-1}$)	Streamflow when salt wedge completely flushed into Peel Inlet ($m^3 d^{-1}$)	Time averaged rate of change of position of salt wedge front during flushing ($m\ s^{-1}$)
<u>During increasing streamflow periods (after summer)</u>			
27.1.82 - 23.1.82 (during flooding)	2.2×10^4	3×10^7 (peak)	$0(300 \times 10^{-3})$
8.6.82 - 3.8.82	2×10^5	9×10^5	5.3×10^{-3}

Peel Inlet has a yearly bottom salinity range of approximately 10-50^{o}/oo for all but a few weeks during winter, when it is strongly influenced by the freshwater inputs from the Murray, Serpentine and Harvey Rivers. Peel Inlet water is exchanged with the ocean, predominantly by tidal flows, via the Mandurah Channel. The salinity of the ocean water entering through the Channel is approximately 35^{o}/oo. However, Peel Inlet water near the mouth of the Murray River was hypersaline (up to 45^{o}/oo) during January to May of 1983. The shallow nature of Peel Inlet leads to significant evaporative increases of salinity, and the gradual increase in density of Peel Inlet water near the mouth of the Murray River leads to a gradual increase in the density of water flowing into the Murray River as a density current. This water propagates upstream, along the bottom, and spills into the deep holes (Fig. 1), from which it displaces and replaces resident water.

The mean position of the salt wedge is determined by a force balance between the driving baroclinic pressure gradient (due to longitudinal density difference) and the retarding force induced by the opposing streamflow. However, variation in the daily tidal forcing results in significant short term deviations in the steady state position of the salt wedge.

The daily tidal variation can lead to appreciable short term increases in the flow speed of the salt wedge along the bottom, especially near the mouth. Bottom flows of up to 0.30 ms^{-1} have been recorded and it is probable that such flows result in bottom shear mixing over sills. This results in localised regions of mixed water which can intrude into the adjacent stratification as subsurface intrusions. Such intrusions were identified from current metering during 1982 to occur regularly in the lower 4 km reach of the river. As shown by the typical set of vertical velocity profiles presented in Fig. 5, the jets were generally up to 0.75 m thick and had associated speeds up to 0.10 ms^{-1}. Their occurrence was most prevalent during rising tides.

The meandering nature of the river (Fig. 1) and spatial variation in the degree of topographic sheltering, largely from houses and trees along the river alignment, result in significant blocking of the wind and shading of the sun in localised regions of the river. This leads to spatial variability in the degree of wind mixing and solar heating which occurs at the water surface. Hence, a common scenario resulting from a daily wind or heating event is the occurrence of localised regions of mixed or heated water residing alongside unaffected water. Thus, adjacent regions of water of differing density, caused by either salinity differences (from mixing) or temperature differences (from solar heating) result. This will lead to gravitational spreading of the less dense water over the surface, while below the surface there will be an underflow of denser water as intrusions. One such intrusion was identified to occur on May 11 1983 by conductivity-temperature-depth (CTD) monitoring and is indicated by the warm temperature wedge in the temperature contour of Fig. 6. These flows can have typical speeds between 0.02 and 0.10 ms^{-1} and thicknesses between 0.2-0.6 m.

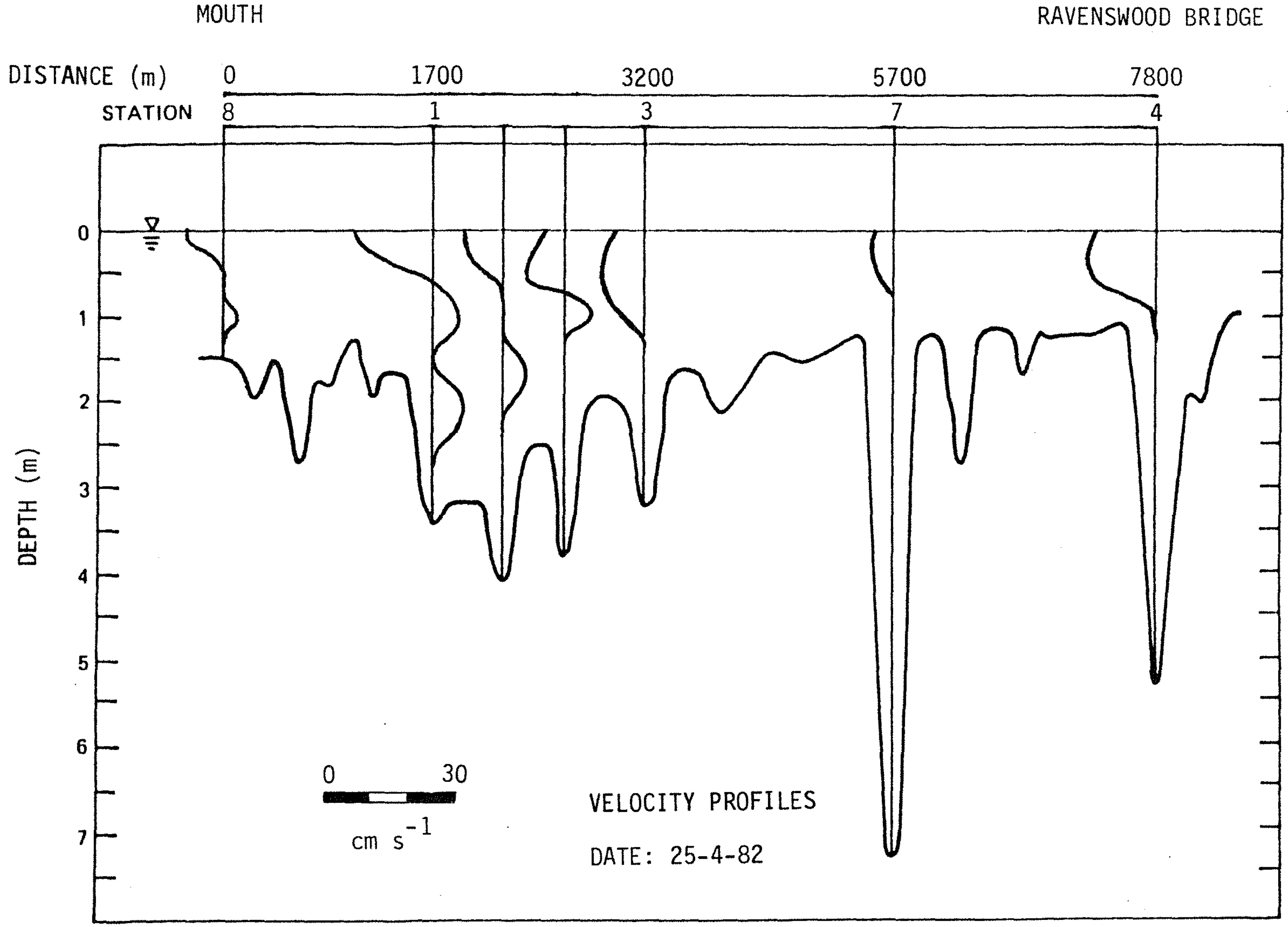


Figure 5   Vertical flow velocity profiles for the Murray River, 25-4-82 (after D'Adamo, 1983)

Temperature, dissolved oxygen and salinity data from station 3
Wind data from wind station W3

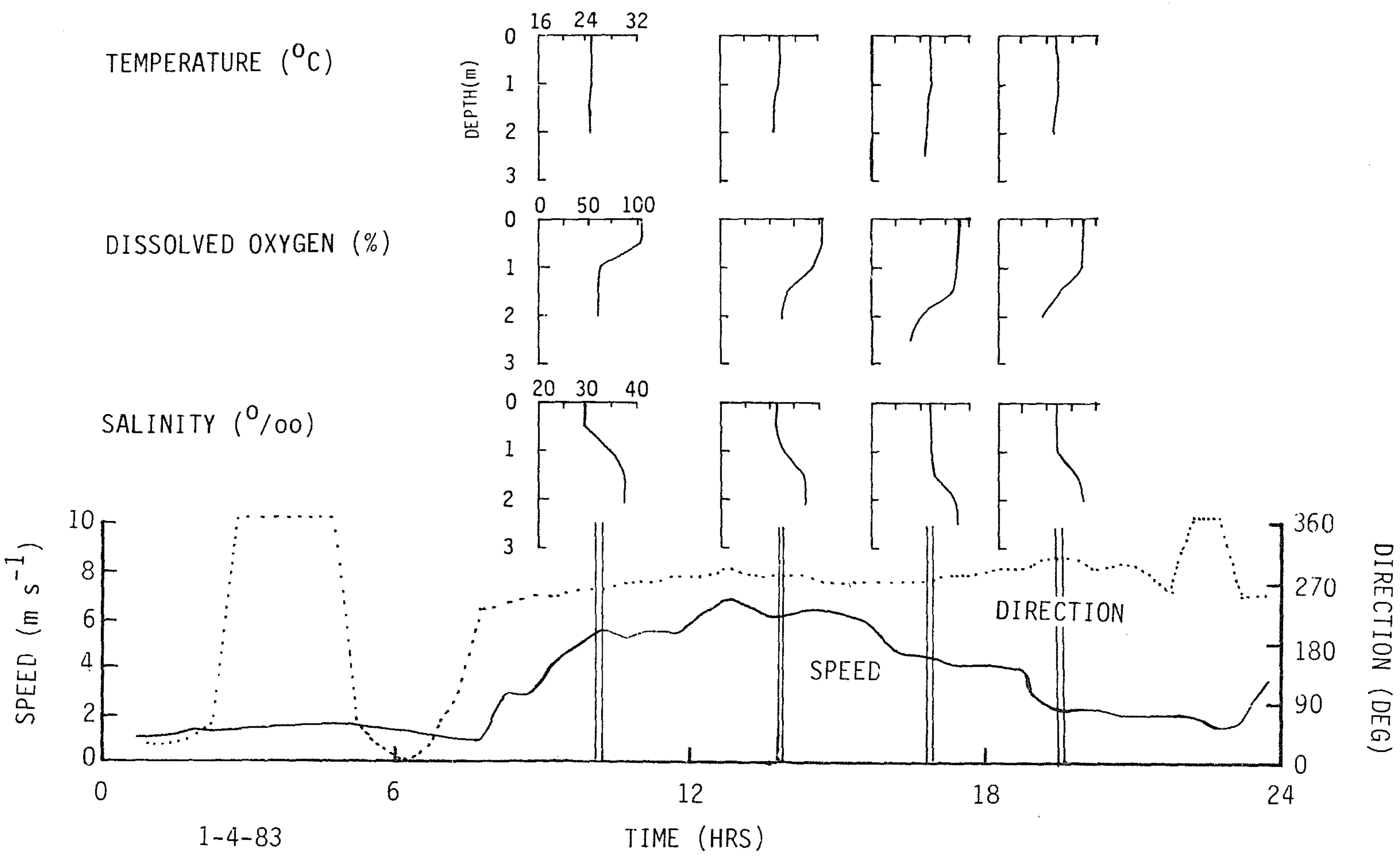


Figure 7 Temperature, dissolved oxygen and salinity profiles for Station 3 and corresponding wind velocity data, 1-4-83 (after DCE, 1983)

b) a relatively strong wind (5-7 ms^{-1}), aligned parallel to the river and blowing for about 5 hours or more, is required to mix the surface down to 1.5-2.0 m;

c) the sheltering effect of local topography strongly influences the degree of deepening. Winds of up to 7 ms^{-1}, blowing perpendicular to a stretch of the river well sheltered by trees and houses, appeared to mix the surface down to at most 0.5-1.0 m.

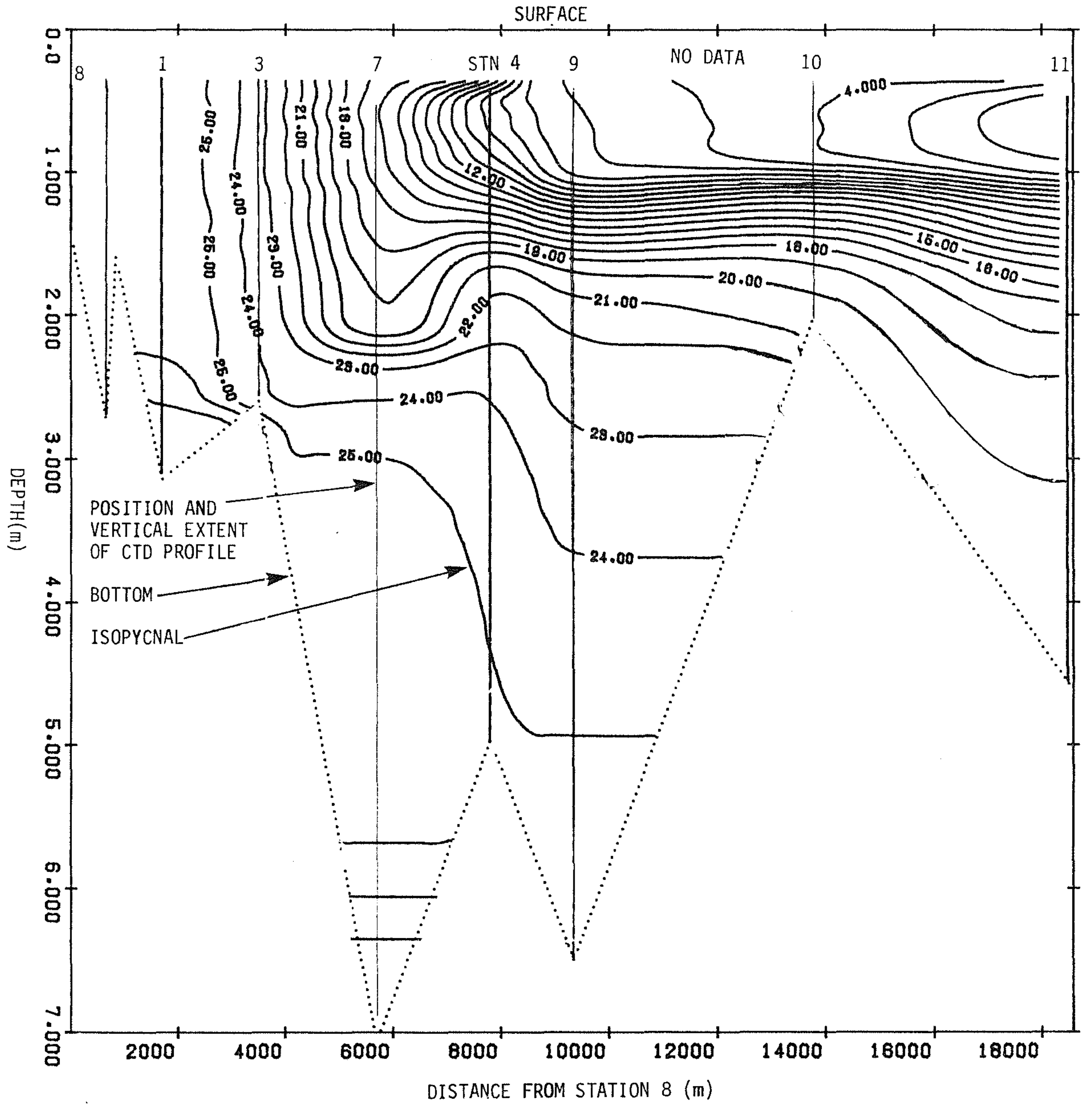
Complete destratification occurred only when there were winds of greater than approximately 7 ms^{-1} along the lower 4 km reach of the river. Further upstream, the reduced effective fetch length, due to the meandering nature of the river, along with topographical sheltering appear to restrict the deepening potential of winds of this strength to approximately 1.0 m. This is illustrated by the density contour plot in Fig. 8, which shows the result of wind mixing in the river during a severe storm (wind speeds up to 12 ms^{-1}) on May 12, 1983. After such mixing events the density structure of the river will relax by density current flows and strong stratification will be re-established in times scales of approximately 1 day.

In conclusion, the most important factors governing the potential of winds to cause surface deepening are the strength of the initial stratification, the speed and relative direction of the wind with respect to river alignment, the fetch length and the degree of topographical sheltering to the wind along the river banks. Deepening is thus patchy and localised, leading to horizontal intrusions of mixed regions.

4. Hydrodynamic Effects of Artificial Destratification

Local artificial perturbation of the water column in stratified water bodies has been used in the past to alleviate water quality problems directly related to stratification.

The applicability of artificial destratification methods to improve water quality for lakes and reservoirs was the subject of a symposium in Melbourne, Australia in 1979 (Burns and Powling 1981). As pointed out in Burns and Powling (1981), vertical density stratification results from thermal stratification of the water column in the temperate climatic regions of the world, though in the Murray River the vertical density stratification is due to strong salinity gradients. Very often this results in a stably stratified water column which resists vertical mixing by environmental forcings such as wind, tides and hydrological mechanisms. Hence, the pycnocline between the less dense upper layer (epilimnion) and the dense lower layer (hypolimnion) acts as a physical barrier to vertical mass transport. This situation often results in the hypolimnion being cut off from the surface



Contour plot of isopycnals (lines of constant density, in σ_t units - density with respect to fresh water, kg m^{-3}) from the mouth to Station 11.
Data collected between 0900 and 1500 hours on 12-5-83 as conductivity-temperature-depth (CTD) profiles.
Winds at Station W3 during this period were approximately 10 m s^{-1}.

Figure 8 Isopycnal contour plot of the Murray River from the mouth to Station 11, 12-5-83 mixing current and being denied a replenishment of dissolved oxygen required to compensate for oxygen consumption by normal biological activity. As a result, this water tends to anoxia with its associated water quality problems.

Past design investigations for canals in the Murray River have advised the use of artificial flushing mechanisms to complement the natural flushing mechanisms known to operate in stratified canals. Artificial flushing by means of intrusive gravity currents set up by local destratification of the water column was investigated as part of this study.

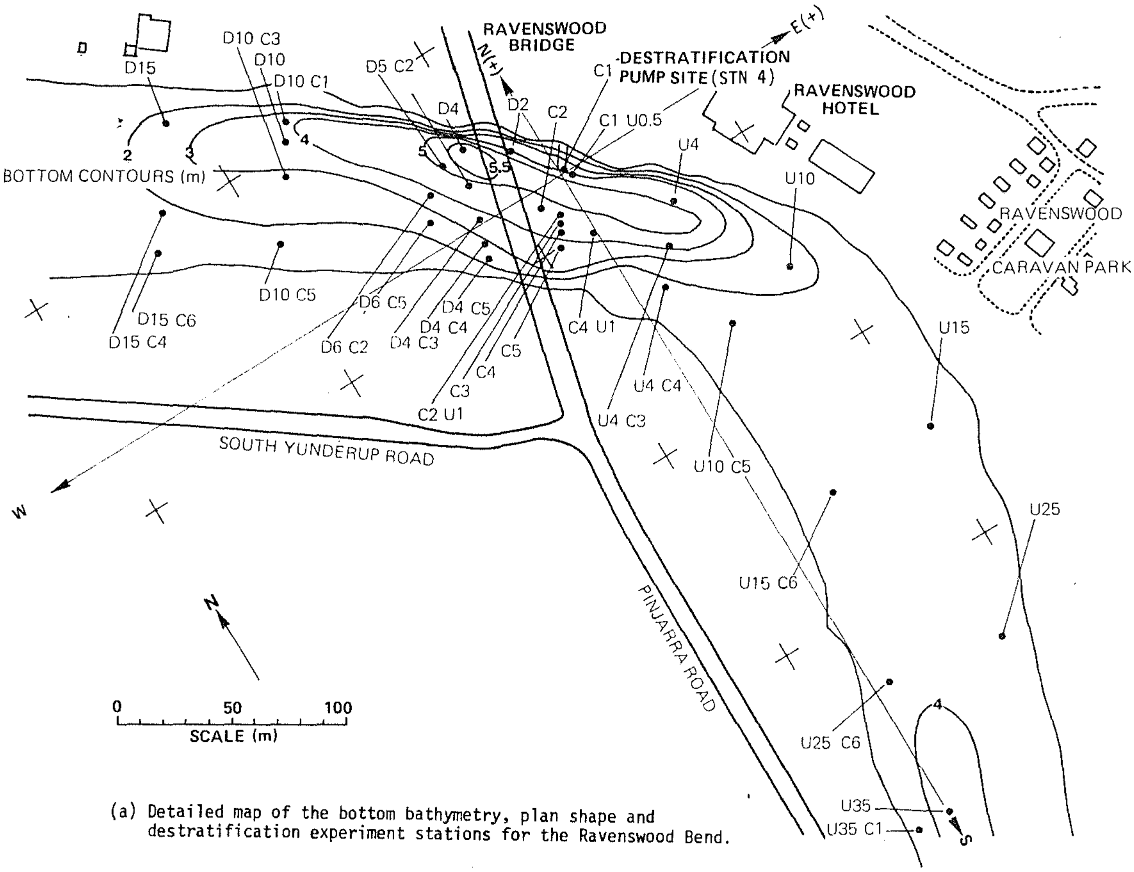
The relatively deep and strongly stratified region of the river at station 4 (Fig. 1) was used as the site for the destratification experiment. Figure 9a presents the bottom contour of this river bend and Fig. 9b presents the field set up for the experiment.

A submersible propeller pump (220 mm diameter) was attached at a depth of 3.5 m to a model frame secured to a jetty (Fig. 9b). The pump was used to jet water from the bottom to the surface for a period of approximately 10 hours. The jet entrained adjacent water and broke the surface in a zone of intense mixing (Fig. 9b). The mixed region at the surface comprised of water derived from the entire water column and so the density of the mixed region was intermediate to the densities of the surface and bottom waters. The continual pumping drove a transport of the surface mixed region from the pump jet both upstream and downstream as intrusive gravity currents. These gravity currents had speeds of about 0.02-0.05ms^{-1} and thicknesses of some 0.2-0.5 m, and occurred between depths of 0.6 and 1.2 m. Figures 10a and 10b present the respective density and temperature contours of the study region, showing the stratification of these two parameters during the experiment.

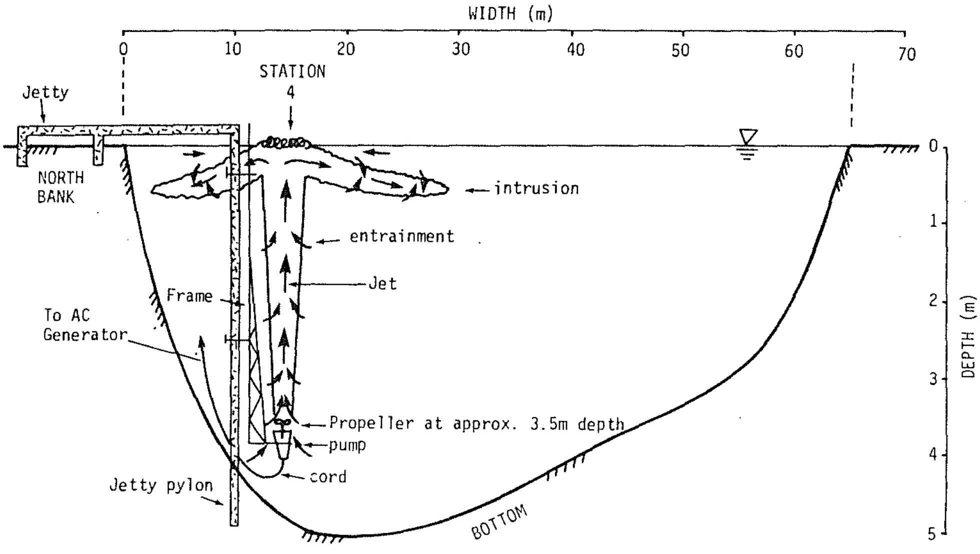
Figure 10a shows the strong density variation, from nearly fresh at the surface to approximately sea water salinity at the bottom. The weakened stratification between 0.6 and 1.2m indicates the pump forced intrusion of relatively weakly stratified water.

The temperature contour (Fig. 10b) shows two relatively low temperature isotherm wedges, pointing both upstream and downstream away from the pump site. These wedges represent the pump forced intrusion of lower temperature water.

Figure 11 presents time series plots of temperature profiles collected 20 m downstream of the pump site, both immediately prior to and during the destratification pumping. Profile 1 was collected just before the start of pumping, and shows a localised warm temperature region with maximum temperature of approximately 22.4^{o}C, a thickness of approximately 0.5 m and occurring at a depth of 0.6 m. The pump was turned on at 2206 hours. Profiles 3 to 9 show the alteration to the pre-existing temperature structure by the forced intrusion. The low temperature indentation at 0.9 m depth in profile 3 became more pronounced with time during the six

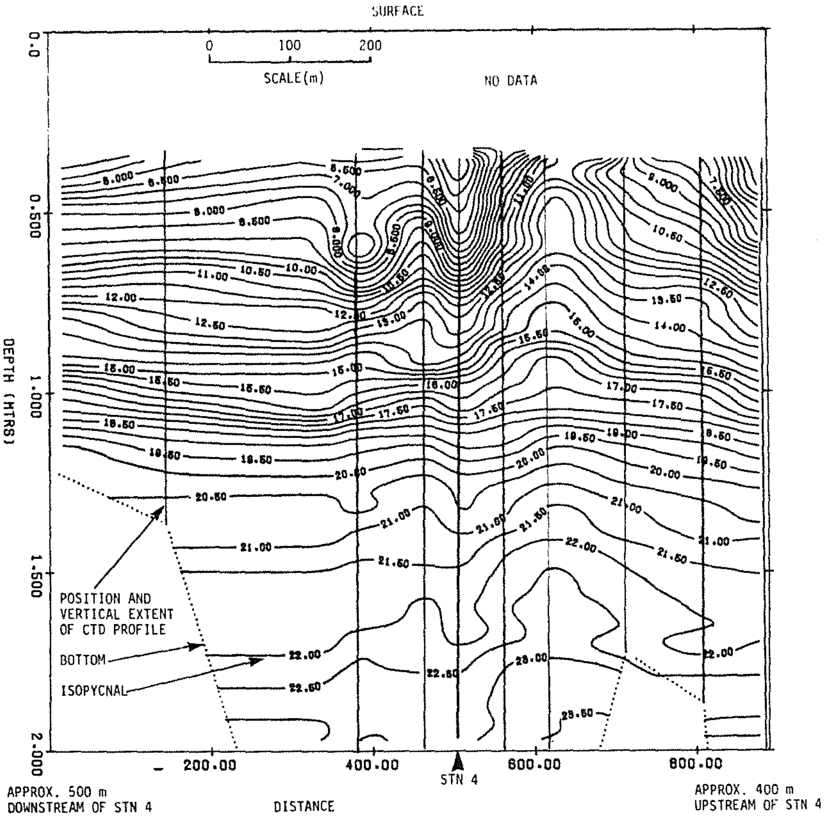


(a) Detailed map of the bottom bathymetry, plan shape and destratification experiment stations for the Ravenswood Bend.

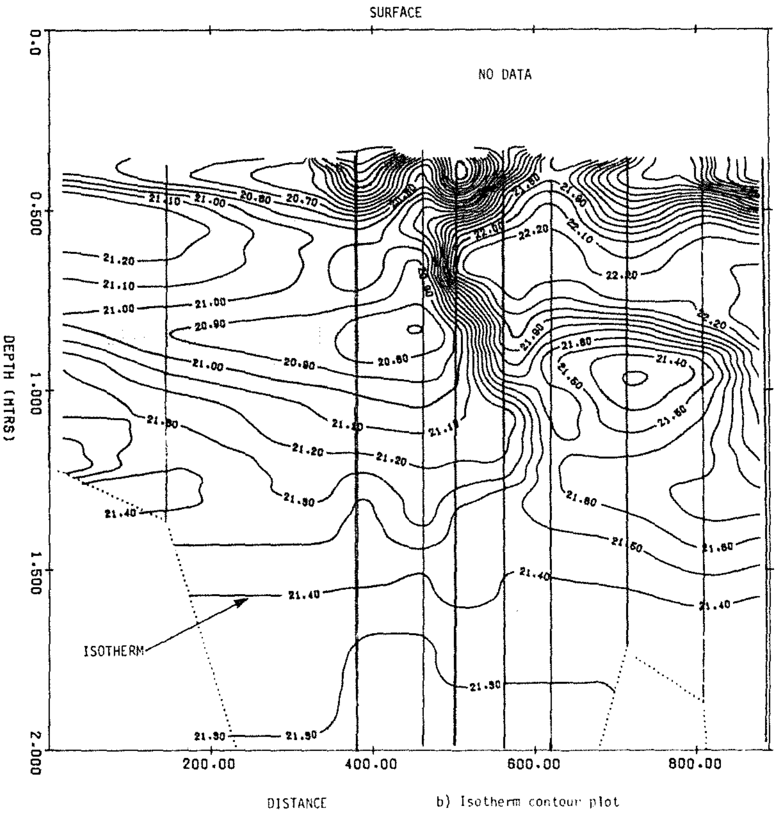


(b) Cross-sectional schematic of field set up for the destratification experiment: Ravenswood Bend (Station 4), 9-5-83 to 12-5-83.

Figure 9 Destratification experiment study site and field equipment set-up, 9-5-83 to 12-5-83



a) Isopycnal contour plot



b) Isotherm contour plot

Contour plots of isopycnals (lines of constant density, in σ_t units - density with respect to fresh water, kg m^{-3}) and isotherms (lines of constant temperature, ^oC).

Data collected during destratification experiment between 0450 and 0520 hours on 11-5-83 as conductivity-temperature-depth (CTD) profiles.

Figure 10 Isopycnal and isotherm contour plots of the destratification experiment study region, 11-5-83

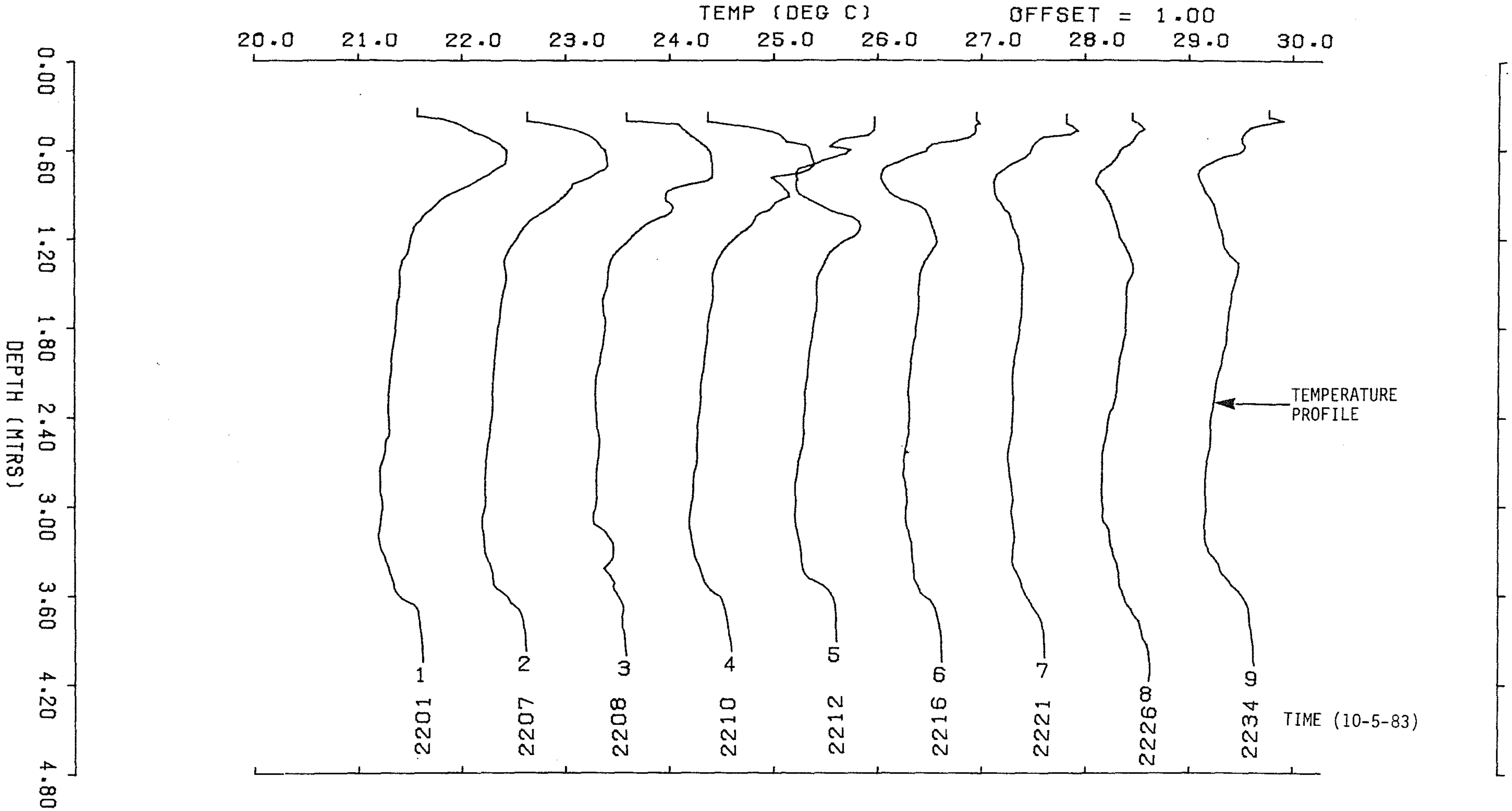


Figure 11 Time series of temperature profiles from conductivity-temperature-depth (CTD) data collected at Station D2 (20 m downstream of destratification experiment pump site: Station 4) before and during the destratification pumping, 10-5-83

succeeding profiles. By 2234 hours the warm water region, which had existed previously, had been almost completely annulled by the forced intrusion of relatively low temperature water between the depths of 0.4 and 1.3 m.

The forced intrusion could not be detected after 10 hours had elapsed from the cessation of pumping. Natural flow mechanisms such as tidal flows or gravitational currents were therefore strong enough to either annul or replace the forced intrusion in relatively short time scales (of the same order as the set up time, 10 hours).

5. Water Quality

The water quality of the river is strongly influenced by the hydrodynamic characteristics of the seasonal salt wedge. Both vertical distribution of hydrodynamic processes and biological variables are effectively divided into two distinct regions at a depth of approximately 1 m. In general, this depth defines the lower limit of the photic zone and the centre of the high density gradient region, above which regular wind mixing and gravitationally driven currents dominate the hydrodynamics, and below which density stratification persists.

Generally, dissolved oxygen levels are relatively high (> 5 mg l^{-1}) in the upper 1 m of the water column, and this is primarily a consequence of the following factors, net photosynthetic oxygen production, turbulent diffusion of oxygen into the surface waters as a result of regular wind mixing and horizontal advection of oxygen rich waters by gravitational spreading currents which originate from localised surface mixed regions.

Below 1 m light limits photosynthesis and biological oxygen demand exceeds the rate of introduction of oxygen into this region by diffusive and advective processes. Low dissolved oxygen levels (< 0.5 mg l^{-1}) near the bottom facilitate release of nutrients from the sediments. This contributes to the eutrophic conditions of the lower reaches of the Murray River.

At relatively shallow sites (e.g. station 10), light penetration and mixing extend to the bottom on a regular basis. The water is therefore typically oxic, which restricts the release of nutrients from the sediments. Further, sediment nutrient loads are lower at the shallow sites than at the deeper sites, probably due to more active sediment transport at the shallow sites by physical processes.

The effect of the salt wedge was clearly seen at Station 11. On the first two sampling trips (December 16, 1982; January 7, 1983) there was little vertical salt stratification at this site, and there was little difference between surface and bottom oxygen levels (Fig. 12). By January 27, the salt wedge had reached this station, and there was a large difference between surface and bottom oxygen levels. On February 17 the water was highly stratified and the bottom water deoxygenated (Fig. 12). The salt wedge clearly maintains the low bottom oxygen levels by restricting vertical mixing.

Surface pH was generally much higher than at depth. Below the halocline, respiration exceeds photosynthesis and hence there is net carbon dioxide production, which lowers pH. The effect of the salt wedge on pH was clearly seen at Station 11 (Fig. 12). As for dissolved oxygen, there was little difference between surface and bottom pH until the water became stratified (Fig. 12).

There was also horizontal stratification of pH at depth (Fig. 12). The pH of the bottom water decreased with increasing distance upstream, except at station 10. As the salt wedge moved upstream the concentration of carbon dioxide in bottom water increases and pH falls. As the salt wedge moved over the shallower sections of the river (e.g. station 10) the bottom pH increases due to increased photosynthetic activity at depth and vertical mixing.

The salt wedge has a marked influence on ammonium and phosphate concentrations in the Murray River, and this is related to its influence on bottom oxygen levels. Sediment nutrient release rates are known to increase ten-fold under anoxic conditions (e.g. Holdren and Armstrong 1980). Density-driven flushing of nutrient rich interstitial water may also partly account for the high bottom ammonium and phosphate concentrations.

Surface ammonium and phosphate concentrations were generally, uniformly low at all sites (Fig. 13). At depth, the concentrations increase spectacularly at the deeper sites on most occasions (Fig. 13). Nitrate concentrations were very low in the bottom water on all occasions; the oxidation of ammonium to nitrate is inhibited by the anoxic bottom conditions.

Intensive sampling has shown that peak chlorophyll levels often occur near the halocline (Fig. 14). This is probably due to photoinhibition at the surface, and high nutrient levels below the halocline.

Turbulence in the vertical scale has two competing effects with respect to primary production. It enhances production by causing the upwelling of nutrients, but when it causes the mixed layer depth to exceed the compensation depth it decreases primary production by mixing some of the biomass below the photic zone. The balance of these two effects may be important in determining the level of primary production in the Murray River.

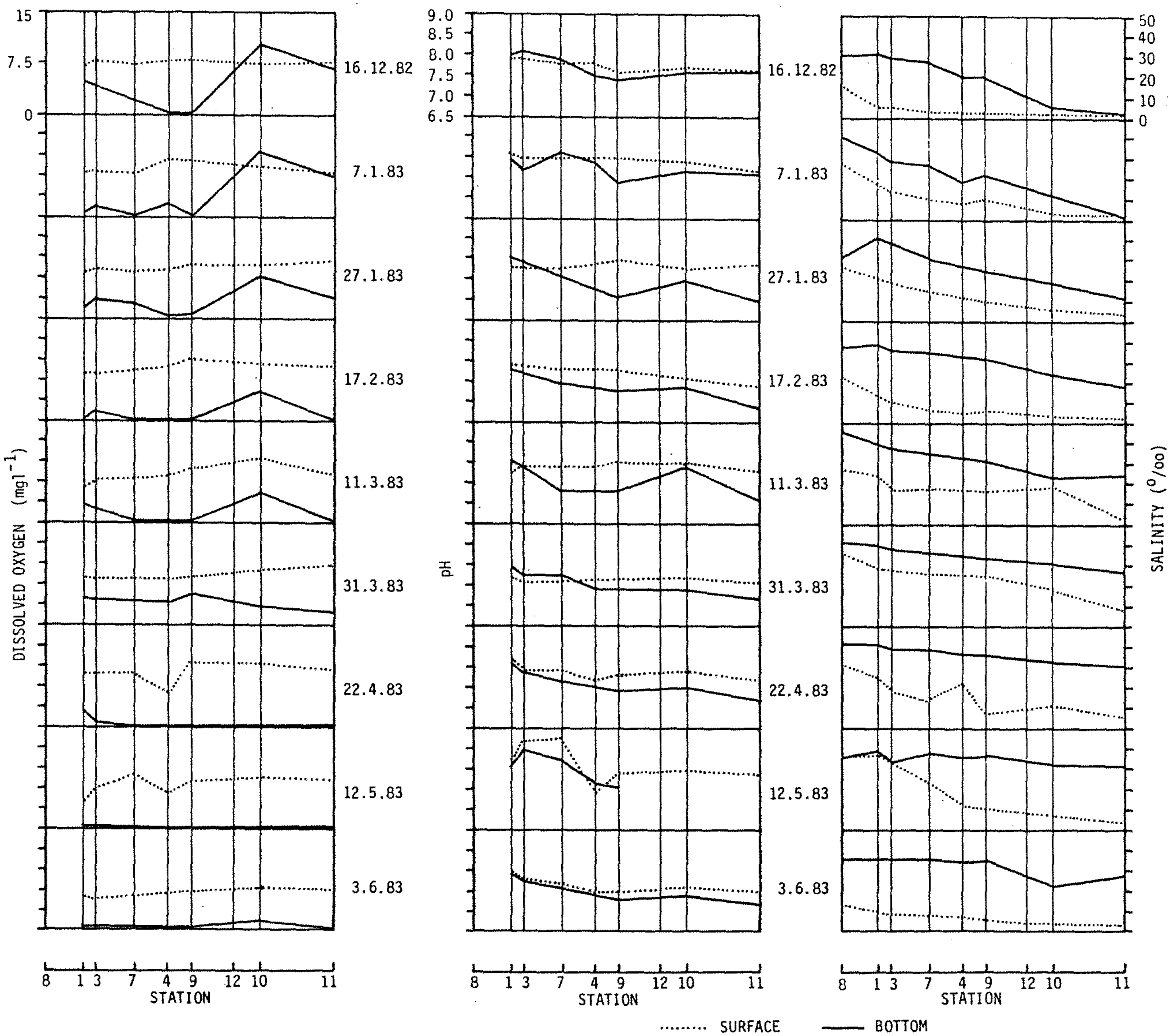


Figure 12 Dissolved oxygen, pH and salinity data. Surface and bottom variation along study route from 16-12-82 to 3-6-83

RECOMMENDATIONS

Inflows through the river mouth are increasingly denser as summer progresses, and therefore must persistently displace bottom waters (which have high nutrient concentrations) from deep sites further upstream. However, shallower regions of the river exhibit relatively low concentrations of nutrients. It would benefit the understanding of the nutrient dynamics of the river to quantify the processes involved in the release and uptake of the nutrients. This could be achieved by tracking a control volume of river water during its propagation upstream. Most attention must be focused on the spatial and temporal resolution of the data collection.

Further, it is recommended that any addition to topographical sheltering (buildings, trees etc.) be given due consideration with regards to probable effects upon wind speeds and hence wind mixing of surface waters.

The river tends to show effects of eutrophication in the low flow period. Further nutrient inputs should be limited, as water quality is at present at critical levels. Any further developments likely to lead to associated increases in nutrient loading or physical perturbations to the density structure of the river should be closely examined because of their possible effects on water quality.

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