Gravitational Flow in a Canal Estate

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SUMMARY Canal estates often experience problems with water quality due to poor circulation and flushing of the canal waters. Field measurements in the Yunderup Canals Estate (Peel Inlet, Western Australia) reveal the importance of both canal bathymetry and the effects of density gradients in the flushing process. Dredging of the entrance canal improved gravitationally driven flushing, leading to dramatic improvements in the flushing times for this estate.

1. INTRODUCTION

Canal estates have been popular for some time as residential areas with great potential for water-orientated recreation. At the same time these estates can be badly affected with water quality problems due to poor water circulation and flushing. The problems may be compounded in estates connected to estuaries which themselves have high nutrient levels. The combination of stagnant water due to poor flushing and high nutrient levels may result in algal blooms and the subsequent death and decay of the blooms leads to de-oxygenation of the water. This, in turn, can lead to fish kills and accelerated releases of nutrients from the sediments. Adequate circulation and flushing therefore needs to be ensured to eliminate these problems in canal estates.

Yunderup Canals Estate consists of six canals situated on the eastern side of the Peel Inlet (see Figure 1), approximately 70 km south of Perth. The entrance to the estate is to the south of the mouth of the Murray River where it joins Peel Inlet. A single channel cuts through the large tidal flats on the eastern shores of the Peel Inlet to connect the canals to the central

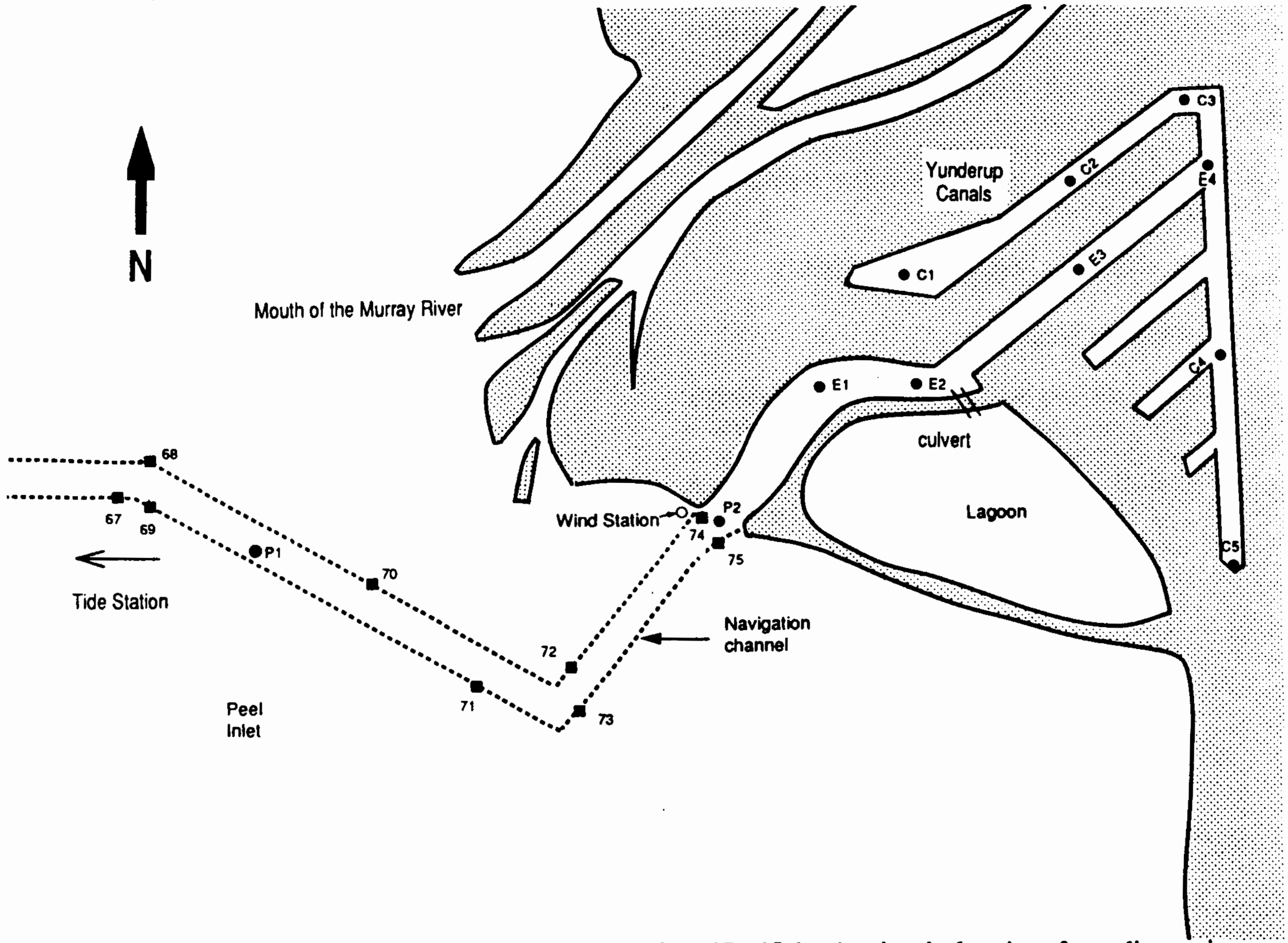

Figure 1 Plan view of the Yunderup Canals on the eastern side of Peel Inlet showing the location of sampling stations.

Two field trips were undertaken, one before and one after the dredging, timed so as to match the prevailing meteorological and tidal conditions as closely as possible for each trip. This ensured that any changes in water quality and flushing behaviour could be attributed to the dredging of the entrance canal. The pre-dredge survey was carried out between 5 and 19 January 1990. The post-dredge survey was carried out between 6 and 25 April 1990.

A 20% Rhodamine WT aqueous solution was diluted with canal water and injected into the canals from a small boat. As the boat moved slowly around the canals, the Rhodamine solution was pumped through a diffuser which was oscillated in the vertical to facilitate even distribution of the dye solution over the entire depth of the canal waters. Samples of surface and bottom waters were then taken at intervals of about two or three days throughout each study period to determine the rate at which the dye concentration was reduced by exchange with the Peel Inlet waters. Samples were taken at stations E2 to C5 (Figure 1) at the surface and at two depths and the concentration of fluorescent dye in each sample measured using a fluorometer.

For selected periods during the two surveys, conductivity, temperature and depth (CTD) profiles or casts were taken at particular locations in the canal and the Inlet. The CTD probe was dropped through the water column at approximately 1 ms^{-1} whilst sampling at 50 Hz, yielding a record at 2 cm vertical depth intervals. The CTD data were taken over an approximately diurnal period during each survey with each transect or circuit of stations taking about thirty minutes to complete. Casts were made in the station order C1, C2, C3, E4, C4, C5, E3, E2, E1, P2, P1 (see Figure 1). The data was stored directly on a portable computer for subsequent processing [see Imberger and Chapman (1)].

Meteorological data and tidal data were collected during each field trip. Prevailing wind speeds and directions were measured at the entrance to the canals. Air temperature, wind speed and wind direction information were gathered at nearby Mandurah by the Bureau of Meteorology, and tidal information was provided from the W.A. Department of Marine and Harbours which operates a tidal gauge located in the Peel Inlet.

2.2. Data Analysis

2.2.1. Dilution rate

For each station, an exponential equation describing dye concentration as a function of time of the form $C(t) = C_0 e^{-t/T}$ was fitted to the data, where C_0 is the initial concentration of fluorescent dye and T is the e-folding time for the system (i.e. the time required for the concentration to drop to $C_0/e = 0.36C_0$). The e-folding time T was taken as the measure of the flushing rate.

While samples were taken at varying depths (approximately 0.5 m, 1 m and 1.5 m), flushing times for these different depths did not vary greatly. Station C5 was an exception in the post-dredge experiment, but as this station was at the end of one of the deepest parts of the canals, this result was not surprising. Since the differences in e-folding times were small over depth, the flushing times were averaged to produce a single value for each station. The north-south canal contained stations C3, E4, C4 and C5; the northern canal contained stations C1, C2 and C3; and the entrance canal contained stations E2, E3 and E4. Since the flushing times of stations in individual canal arms did not vary significantly, the values of flushing time for the stations were also averaged to produce a single value for each of the three main arms of the canal system. These results are shown in Table 1.

2.2.2. CTD profiling

Data collected by the CTD probe has been presented as a series of contour plots along the transect of the profiles (i.e.

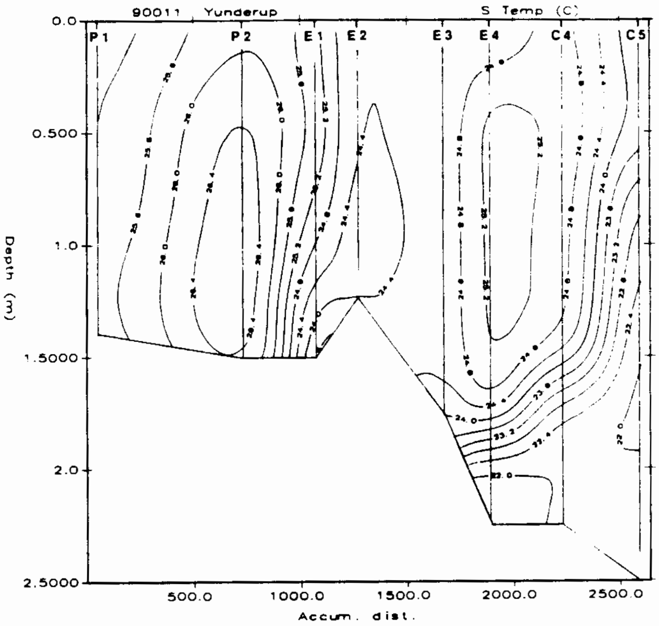

Figure 4 Temperature contours for January 11 1990 at time 1545 hours. Contour interval 0.4 °C. Vertical lines indicate station positions. Stations are P1, P2, E1, E2, E3, E4, C4 and C5, as shown on Figure 1.

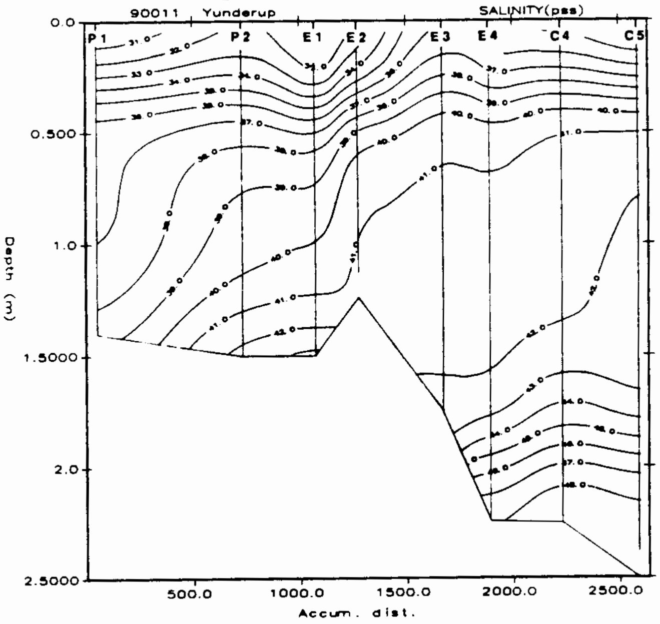

Figure 5 Salinity contours for January 11 1990 at time 1545 hours. Contour interval 1 pss. See Figure 1 for station locations.

basin of Peel Inlet. The main canal has a north to south alignment while the canal branches are orientated in a north-east to south-west direction in order to maximize the mixing due to summer sea breezes. Figure 1 also shows a man-made lagoon adjacent to the canal system, connected to the canals via a culvert with a one-way flap gate controlling the flow.

Planning approval for an extension of the canals required an examination of the flushing characteristics. The aim of the study programme was to identify the effect of deepening of the entrance channel on the flushing of the canal waters and to investigate whether a second entrance was warranted. The criterion used to determine if a second entrance was needed was the level of improvement (if any) in water quality as a result of deepening the entrance canal. If the canal water was judged to be of similar quality to that in the Peel Inlet, then the maximum improvement had occurred and a second entrance was not required. Aspects of the study programme involved dredging the entrance channel and monitoring the water in the canals both before and after dredging.

The assessment of the flushing of the canal water was divided into two parts:

(i) measurement of the flushing time of the system and
(ii) identification of the dominant exchange mechanism operating in the system.

The flushing time of the canals was determined by dosing them with a fluorescent dye and monitoring the subsequent dilution over time. Fine-scale conductivity and temperature profiles of the water column were used to identify the dominant flushing mechanism. This allowed the development of models for both the pre-dredged and post-dredged conditions. These models were used to interpret the flushing times measured with the dye studies. An understanding of the physical exchange processes occurring in this canal system should also be useful in ensuring acceptable flushing behaviour in other canal systems.

2. DESCRIPTION OF EXPERIMENT

2.1 Experimental Programme

The dredging of the entrance channel commenced in January 1990 and was completed at the end of March 1990. Figure 2 shows the pre-dredged and post-dredged bed profiles between the Inlet station P1 and the southern most canal station C5. A sill at the 1.25 km position obstructing the lower 0.5 m of the entrance canal is clearly shown and the removal of this sill was the objective of the dredging.

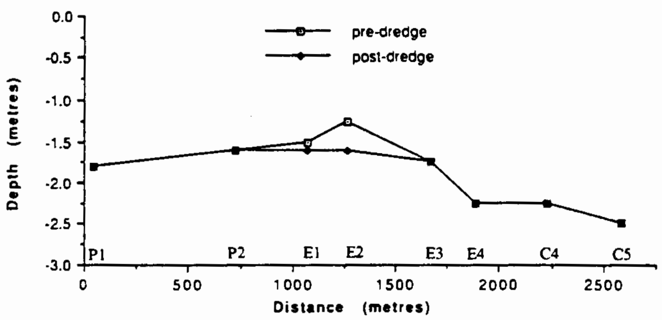

Figure 2 Pre-dredge and post-dredge canal bed profile where station positions are shown on Figure 1.

TABLE I
Flushing Times Determined from Pre-Dredge Survey

Canal arm	Slope of Line (t^{-1})	e-folding time in days
northern	0.15478	6.2
north/south	0.22058	5.2
entrance	0.19220	4.2
average	--	5.4

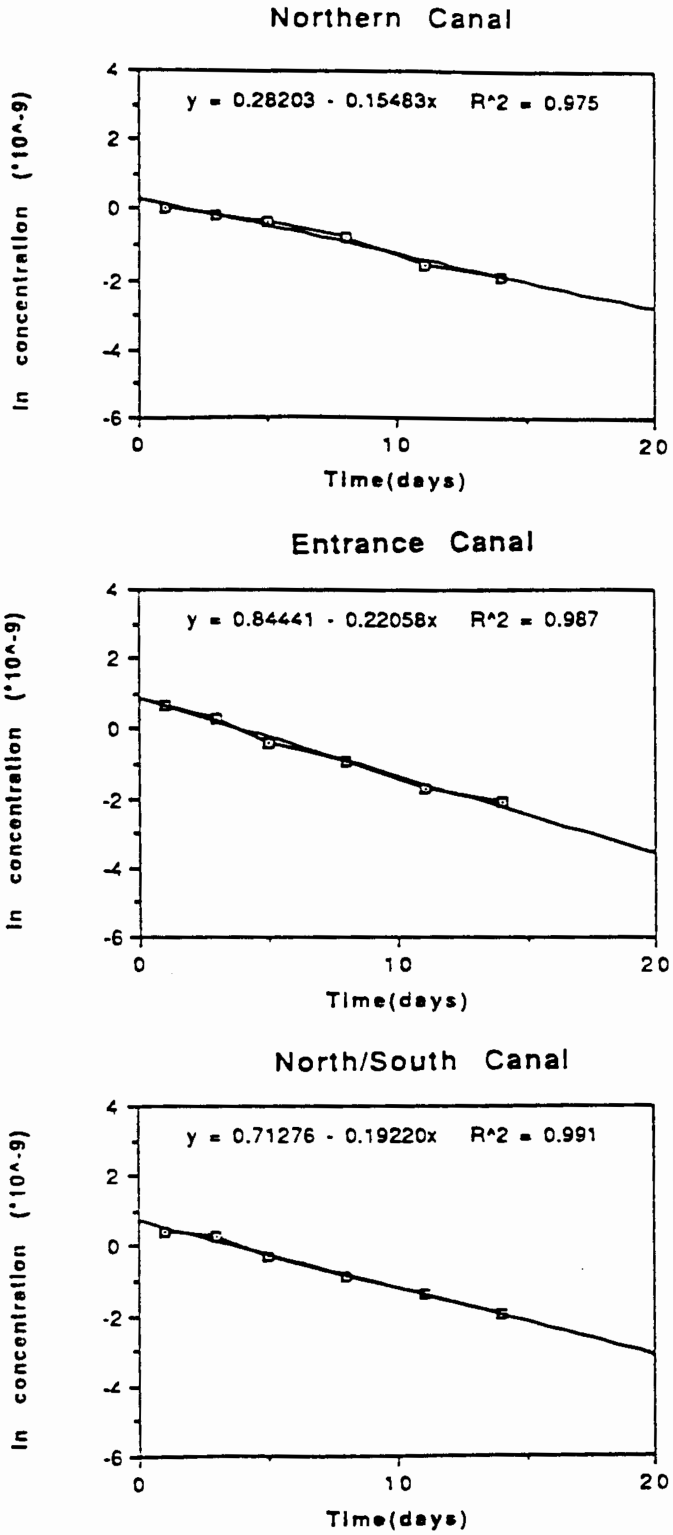

Figure 3 Averaged dye concentrations versus time for the three arms of the canals for the pre-dredge survey.

into the canal system. Tidal data from the Department of Marine and Harbours indicates that the flap gate only opens about once every two weeks. The net effect is thus a periodic or pulsed injection of saline water into the canals.

A time series at approximately 2 hourly intervals shown in Figure 6 displays a strong flow of relatively fresh water moving into the canals in the surface layers with the incoming tide. This flow can be tracked in Figures 6a, 6b, 6c and 6d by the successive displacement of the highlighted isopycnal $\sigma_T = 28$ kg/m^3 (where $\sigma_T = \rho - 1000$ kg/m^3). This isopycnal was a convenient marker dividing the incoming water from the canal water. Note also the lack of movement of the $\sigma_T = 31$

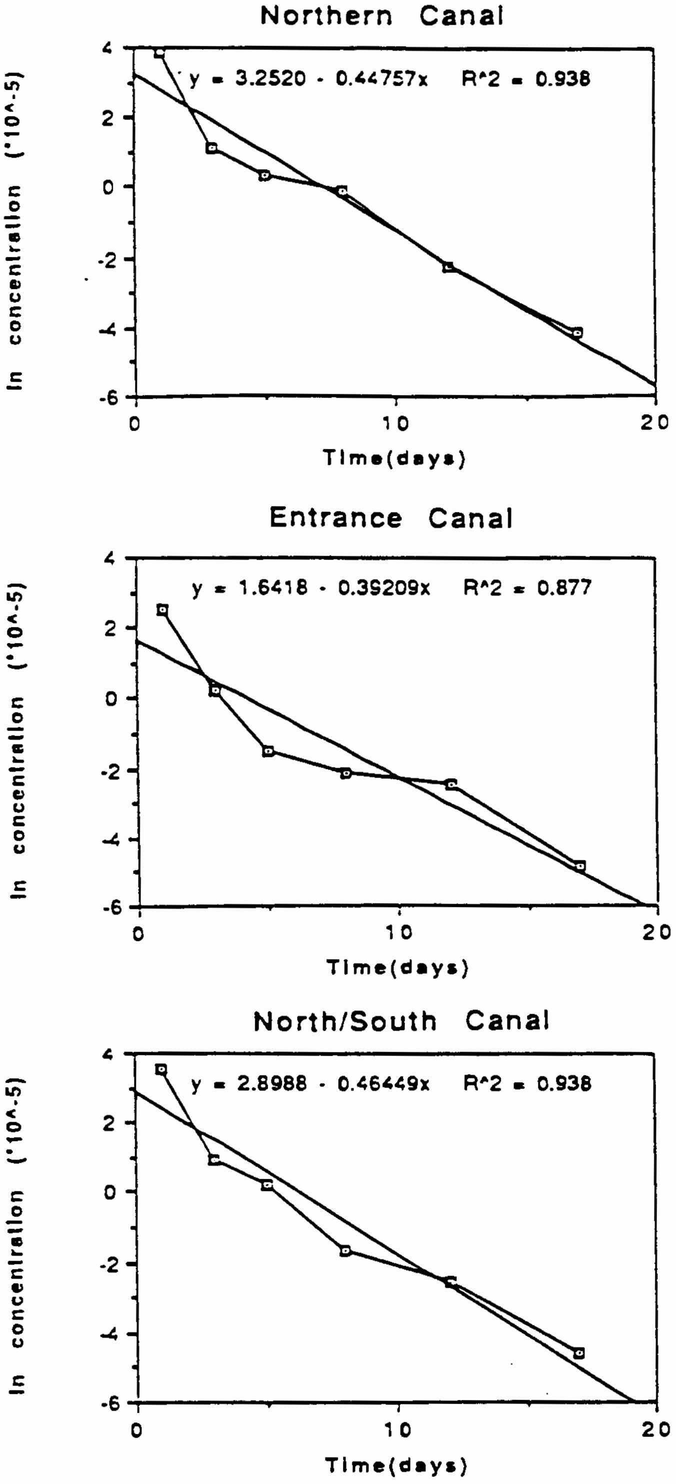

Figure 7 Averaged dye concentrations versus time for the three arms of the canals for the post-dredge survey.

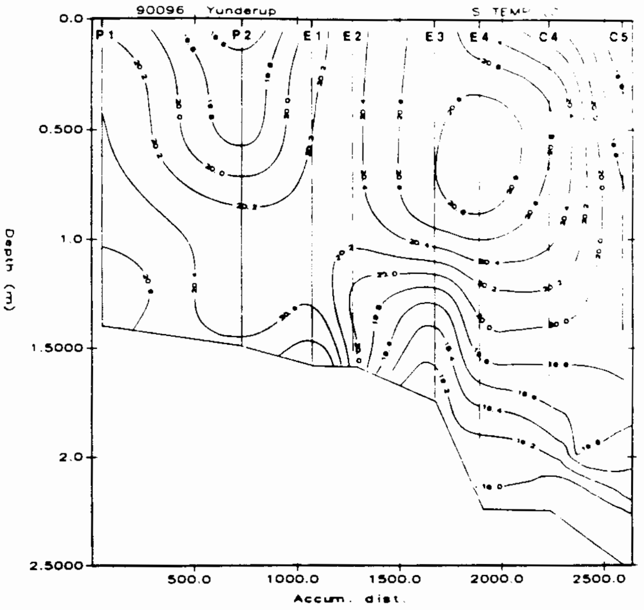

Figure 8 Temperature contours for April 6 1990 at time 2115 hours. Contour interval 0.2 °C. See Figure 1 for station locations.

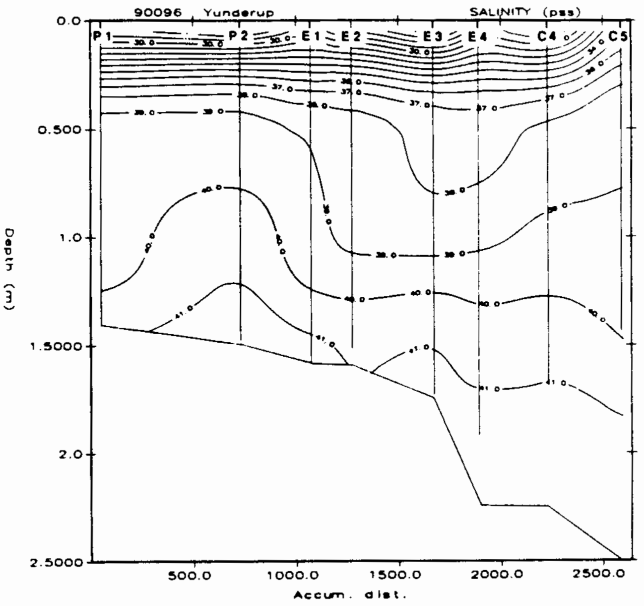

Figure 9 Salinity contours for April 6 1990 at time 2115 hours. Contour interval 1 pss. See Figure 1 for station locations.

TABLE II
Flushing Times Determined from Post-Dredge Survey

Canal Arm	Slope of Line (t^{-1})	e-folding time in days
northern	0.44757	2.2
north/south	0.39209	2.5
entrance	0.46449	2.2
average	-	2.3

from station P1 to station C5). The raw data was adjusted for the vertical separation of the probe's sensors and the data were corrected in order to match sensor response times [Fozdar et al. (2)]. The salinity values were calculated from temperature, conductivity and pressure, and density from temperature and salinity using the UNESCO (3) formulae.

3. DISCUSSION OF RESULTS

3.1 Pre-dredged Case

Figure 3 shows the results of the dye experiments in each of the three arms of the canal, and the flushing times determined from exponential fits to the data are summarized in Table I; the flushing times ranged from 4 to 6 days. It is important to point out that the dye samples were collected in the top 1.5 m and so did not include the high salinity water lodged in the depression at station C5 in Figure 5 above.

Figures 4 and 5 show a typical set of contour lines of constant temperature and salinity for January 11, 1990, during the late afternoon. The contoured data is dominated by very strong density stratification and clearly show trapping of highly saline, very dense water in the deep closed ends of the canals. This was particularly noticeable at the southern end of the north-south canal at station C5 where saline water in excess of 48 pss was found. Oxygen concentrations below 2 mg/L were measured at depth, clearly showing that the strong stratification had inhibited vertical mixing.

The likely source of this very salty water is the shallow lagoon located adjacent to the canals and the Peel Inlet (see Figure 1) which becomes hypersaline due to evaporation. Measurements in the lagoon during March 1990 showed salinities there were in excess of 55 pss, while salinity on the canal entrance side of the culvert was measured at around 40 pss. Flow through the culvert connecting the lagoon and canal is controlled by a one-way flap gate that opens when the canal water level is higher than the lagoon water level. Once the flap gate is open, the large difference in salinity would result in two-way flow between the lagoon and the canal with dense saline lagoon water flowing along the base of the culvert, and the lighter, less saline canal water flowing into the lagoon near the surface of the culvert. Since the outlet of the culvert is on the east side of the obstructing sill (Figure 1), the salty slug of lagoon water would then flow unobstructed

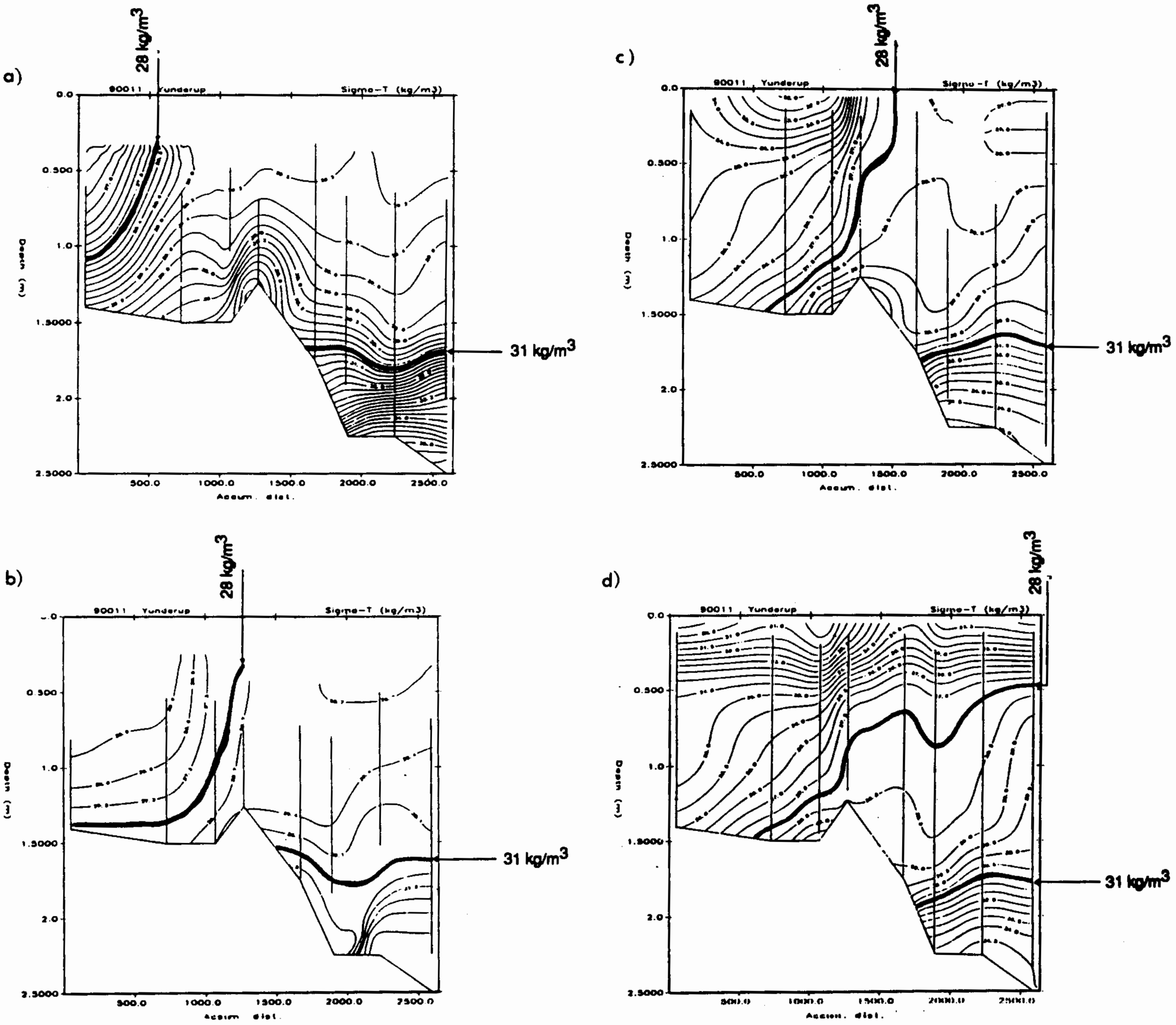

Figure 6 Density contours for January 11 1990. Times are: a) 0945 b)1200 c) 1415 d) 1545. See Figure 1 for station locations.

show the flushing timescale to about one half of the initial value, indicating that dredging had increased the effectiveness of the gravitationally driven flushing.

Figures 8 to 10 are typical of the contours produced from the CTD data collected from the post-dredge survey. In the top 0.4 m there is a thin, strongly stratified layer which was likely due to local freshwater input from the Inlet. Below this thin layer, it is clear from comparing Figures 5 and 9 that, as result of dredging, the pocket of hypersaline water at the end of the canals has been removed. As shown in the time series in Figure 10, there are only very small vertical density gradients in the bottom waters, indicating efficient flushing to the bottom of the canals. There are, however, longitudinal density differences of about 2 kg/m^3 between the Peel Inlet station P1 and station C5 which will drive a gravitationally driven exchange flow in the canals.

4. DISCUSSION

The effectiveness of the exchange of waters in the canals thus appears to be controlled by two factors: the depth of the sill, and the magnitude of the density gradient between the canals and the Inlet. The sill depth determines the depth to which the exchange is effective and controls the volume of dense water trapped in the system as in the pre-dredge case. The post-dredge data did not identify dense saline water at depth to the extent found previously, implying effective mixing to a depth of at least 1.75 m (the increased depth of the sill). Exchange flows driven by a longitudinal density gradient can be of two types, depending on the force balance.

a) a viscous - buoyancy force balance [Imberger (4)]

$$u = 0.01 \left(\frac{g}{\rho_0} \frac{\Delta\rho}{L} \frac{h^3}{K_v} \right) \qquad (3)$$

b) an inertia - buoyancy force balance [Turner (5)]

$$u = 0.5 \left(\frac{g}{\rho_0} \Delta\rho h \right)^{1/2} \qquad (4)$$

where u is the longitudinal velocity of water, g is the gravitational acceleration , $\Delta\rho$ is the longitudinal density difference (2 kg/m^3), ρ_0 is the reference density, L is the length of the canal cross-section (~3000 m), h is the height of the water column (2 m) and K_v is the vertical eddy diffusivity [1 x 10^{-5} m^2/s - a typical value from Fischer et al. (6)].

Substituting the above values into equations (3) and (4) gives the following values for velocity:

a) u = 0.05 m/s implying the flushing time is
T ~ L/u = 16 hours

b) u = 0.1 m/s implying the flushing time is
T ~ L/u = 8 hours.

Both balances yield flushing timescales shorter than the tidal period of 24 hours. Hence when longitudinal density gradients are present, gravitationally driven flows governed by either force balance will flush the canals very efficiently. The expanse of tidal flats outside the canals is a seasonal generator of hypersaline water and, combined with inputs from both the ocean and rivers, leads to the constant presence of density gradients between the canals and Inlet and hence the likelihood of density driven flows.

5. CONCLUSIONS

In the pre-dredge case the sill in the entrance canal was an effective barrier to longitudinal flow over the total vertical cross-section. Field data clearly show trapping of dense, saline water in the deeper ends of the canals with limited vertical mixing and a dye injection study yielded a flushing time of 5.4 days for the fluid above this dense pocket. After the entrance canal was dredged the clarity of the water improved significantly. The data showed a reduction in the volume of highly saline water near the closed ends of the canals and a dye injection study indicated the flushing timescale was reduced to only 2.3 days. Longitudinal horizontal density gradients between the Inlet and the canal ends driving a gravitational inflow appeared the dominant mechanism for flushing of the canal waters.

6. ACKNOWLEDGEMENTS

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kg/m^3 line over the entire period, indicating the persistence of a stagnant pool of hypersaline water at the closed ends of the canals; the dye samples did not include this deep water.

This suggests the use of a simple volumetric flushing model. If it is assumed that on each tidal cycle a gravitational current exchanges a certain volume of water, then the dilution factor K is given by :

$$K = \frac{\text{volume of water exchanged per cycle}}{\text{total volume of water}} \qquad (1)$$

If we assume the exchange volume is mixed with the canal water then after one cycle an initial concentration C_0 would be reduced to KC_0. The data in Table I indicates a pre-dredge condition average flushing timescale of 5 days, which means that $K^5C_0 = 0.36C_0$ and hence $K = 0.82$. Since the average depth of the canals is about 2 m, and if the depth of fresh water entering the canal and mixing on each tidal cycle is denoted by h, then

$$K = 0.82 = \left[\frac{2}{2+h}\right] \qquad (2)$$

leading to a value for h = 0.44 m. As seen in Figure 6, the system is clearly not mixed to homogeneity on each cycle so that the above value for h is an underestimate. Given the typical diurnal tide in Peel Inlet is about 0.1 m, a value much smaller than this figure for h, the above result implies that buoyancy-driven gravitational or baroclinic flows must be the dominant exchange mechanism.

3.2 Post-dredged Case

Figure 7 summarizes the results of the dye experiment conducted during the post-dredge survey. While the results suggests some non-uniformity of the flushing process, flushing times determined from best fits to the data are shown in Table II. Comparison of the flushing times in Table I and Table II

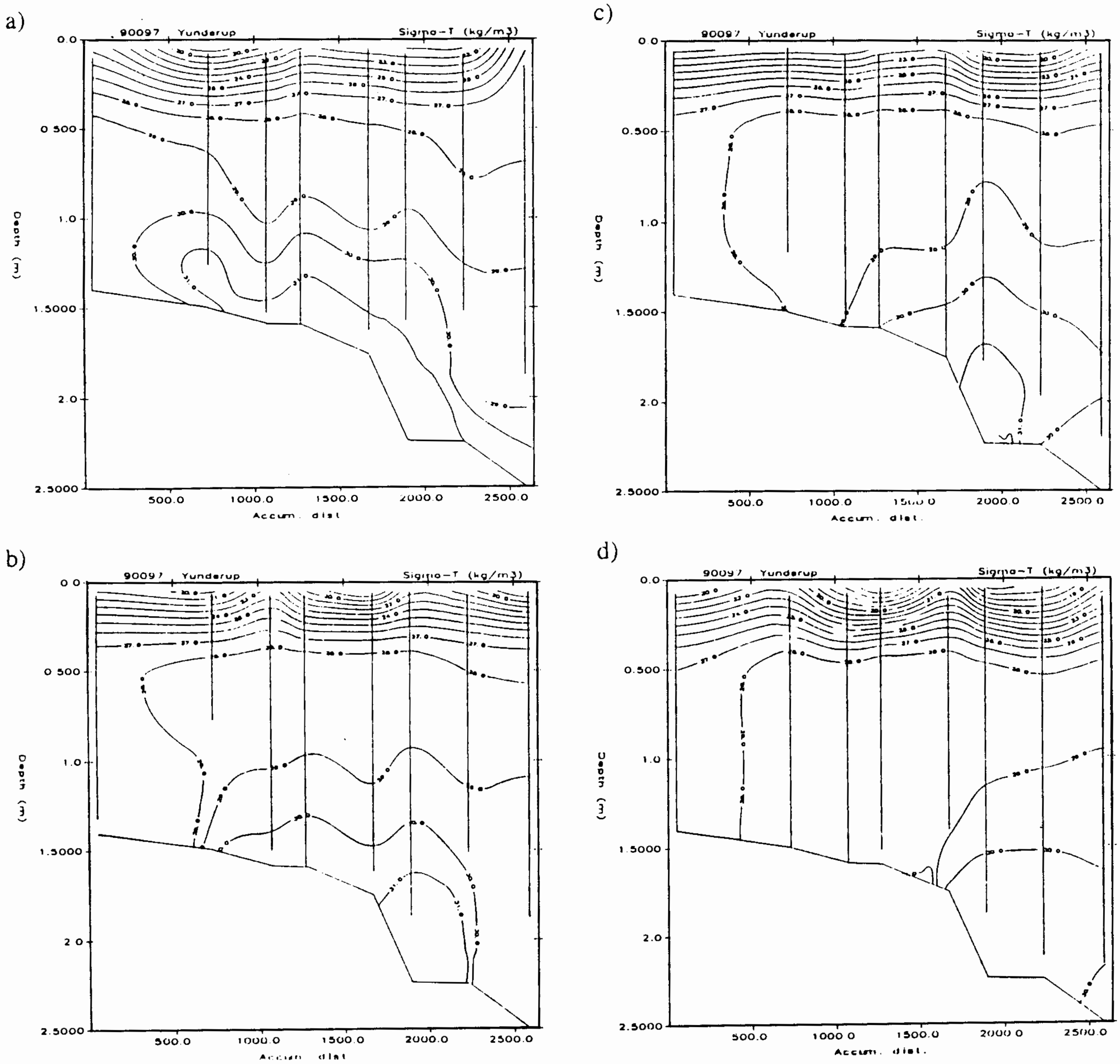

Figure 10 Density contours for April 7 1990. Times are: a) 0715 b)1000 c) 1410 d) 1725. See Figure 1 for station locations.

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