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# Modelling tracer dispersal and residence time in a reservoir

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**Abstract**

A quasi-two-dimensional, numerical, hydrodynamic model for the simulation of reservoir physics is described and used to evaluate the dispersal of tracers and the residence time of local parcels of water within a reservoir. In particular, tracers released in inflow sources are followed, and detention times (time for the inflowing water to reach the dam wall) are estimated. Several examples are given for Canning Reservoir in Western Australia revealing some interesting processes of dispersal.

*Key words:* Hydrodynamics; Mathematical modelling; Reservoir

## 1. Introduction

In any management decisions relating to the water quality in reservoirs, a knowledge of the way in which water moves in the lake is vital. In particular, the path taken by water which contains some contaminant which enters at a particular location, or the path followed by inflowing streams is of interest. An estimate of the time taken for such water to reach the vicinity of the outlets can be derived from this information.

In general, however, this information is not available for a particular reservoir or climatological scenario, other than in general terms. In this paper a mechanism is described which allows a first approximation to these movements to be obtained. A numerical model is described which can provide an estimate of the movements in the lake given some simple site-related characteristics and daily weather and inflow information. Once the model is verified for a given lake, various climatologi-

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cal scenarios and tracer locations can be modelled to provide an insight into general movements in the lake.

In order to illustrate this point, a quasi-two-dimensional, numerical, hydrodynamic model is used to investigate the movement of water in Canning Reservoir in Western Australia. Two sites are considered by using the model to follow tracers released at those points at different times. In addition, a record is retained of the time which each parcel of water has spent in the lake, allowing a map of local residence time to be compiled, giving a global picture of the origin of the water in different regions of the lake.

In certain circumstances, the time taken for water to reach the vicinity of the outlets may be very short, and examples of this are seen from the simulation results. Alternatively, an example is shown in which water which has been in the lake for a relatively long time still contains high concentrations of tracer due to it being situated in a quiescent region. Water entering the reservoir at other times may be rapidly dispersed. The desirable effect will of course depend upon the issue under consideration, but in all situations a model can be used to derive an understanding of the physical mechanisms at work.

In Section 2, a brief description of the numerical model is given, and its capabilities and limitations are outlined. The model is verified by comparison with data from the Canning Reservoir in Western Australia. Section 3 describes the simulations which were performed, considering the tracer studies and retention time studies separately, and Section 4 gives a short discussion of this work.

## 2. The model

The quasi-two-dimensional reservoir model (Hocking and Patterson, 1991) used in this work was developed from the one-dimensional reservoir model DYRESM, which has been verified on many occasions in the literature (Imberger et al., 1978; Hebbert et al., 1979; Ivey and Patterson, 1984; Keifer et al., 1993). The most recent example of such a verification is shown in Fig. 1, in which the isotherms in Canning Reservoir for a 14-month period between July 1986 and August 1987 (Imberger and Patterson, 1990; Hocking and Patterson, 1991) obtained from fortnightly field measurements (Fig. 1a) are shown together with the results of a simulation of the same period obtained using the model (Fig. 1b). The two-dimensional aspects of the new model are based in part upon the preliminary work of Jokela and Patterson (1985) One-dimensional models use the tendency of confined bodies of water in most regions of the world to stratify in density due to the action of the weather on the surface. Deviations from this horizontal layering are usually removed quite quickly by the tendency of patches of water which are not at a neutrally buoyant level to move toward that level, as they are heavier (or lighter) than the surrounding water. One-dimensional models assume that this adjustment occurs instantaneously.

The one-dimensional reservoir simulation model DYRESM uses a set of homogeneous, Lagrangian layers of variable size, which combine, expand, contract,

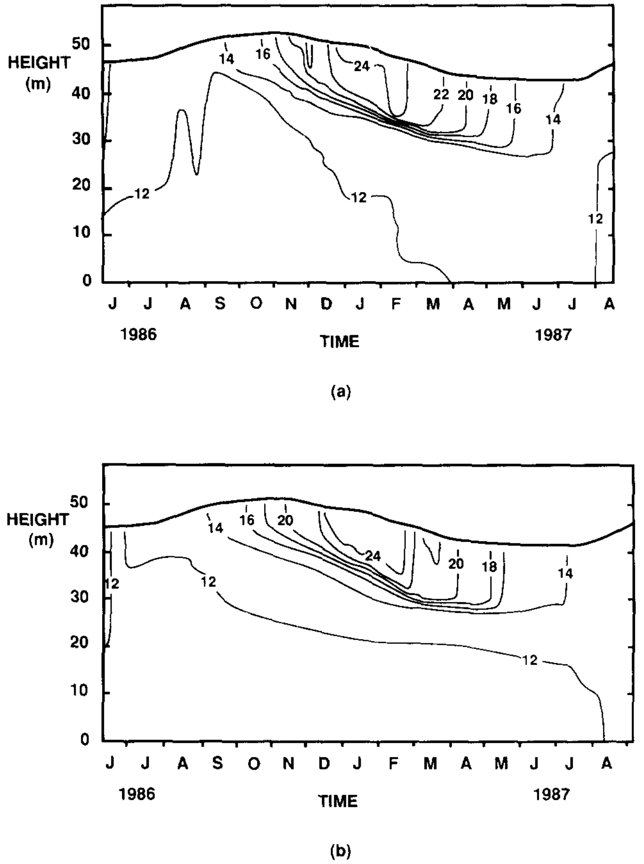



Fig. 1. Comparison of isotherms in Canning Reservoir over a 14-month period in 1986 between (a) field measurements, (b) simulations using the one-dimensional reservoir model, DYRESM.

move vertically and divide in response to the physical processes within the reservoir. The layers resolve the vertical temperature, salinity, and density structure of the lake. The background structure in the quasi-two-dimensional model is provided by the processes resolved by the one-dimensional model, and the laminar horizontal motions are calculated as perturbations to this background field.

An energy budget formulation is used to adjust the layer structure for the daily inputs of short- and long-wave radiation, air temperature, vapour pressure, rainfall, and wind speed. Several bulk aerodynamic formulae (TVA, 1972; Henderson-Sellers, 1986) are used to compute the transfer of heat, momentum and moisture across the air–water interface from these inputs. All of the inputs are assumed to be constant throughout the day with the exception of short-wave radiation, which is always zero for the second 12 h to account for the diurnal light–dark cycle. The geographical effect of variation of the number of daylight hours is accounted for by distributing the total incoming short-wave radiation over the modelled 12-h period.

This slight discrepancy causes negligible errors since the total energy budget for the day is still correct.

Evaporation is calculated, and inflow and withdrawal are added and removed respectively at the appropriate locations to complete the daily cycle (Imberger and Patterson, 1981; Imberger, 1982). Each of the one-dimensional physical processes is parameterised and modelled separately, and no calibration of the model is necessary when it is applied to a new lake, as the parameters associated with the processes have been determined from laboratory or field investigations, independent of the modelling exercise.

The use of Lagrangian layers and a variable time step allows the model to make the most efficient use of computer time. Layers are automatically concentrated to give maximum resolution near regions of greatest change, for example at the thermocline. Similarly, the time step is shortened when mixing activity driven by the surface inputs increases, and lengthened at times when there is little activity.

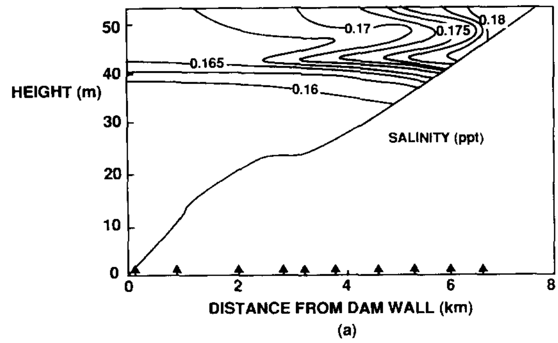
The adjustment of the layer structure is performed subject to a table of volumes and areas computed at every 10 cm depth. Thus layers move up and down within the confines of the reservoir boundaries, increasing their thickness if they happen to move vertically downward to a height where the area is smaller, and decreasing if they move upward. To maintain the desired range of layer sizes there are upper and lower bounds on both the thickness and volume of layers, and layers are split if they become too thick, or merged if they become too thin. The average layer thickness is around 1 m.

In order to resolve the two-dimensional structure in the new model, the layer structure was extended to include Lagrangian parcels within the vertical confines of the layers. Algorithms were written to enable the splitting and merging of the layers without losing this horizontal resolution.

Work in recent years has shown that horizontal transport in lakes and reservoirs is far greater than had been previously thought. Wind-driven circulation, inflow, and withdrawal have long been recognised as major sources of horizontal transport, but it is becoming increasingly clear that many other processes exist which are of great significance. The local geometry is a significant factor in many motions. Differential deepening due to wind sheltering, differential heating due to differing depths in sidearms or patches of higher turbidity, and upwelling, all have the potential to produce horizontal velocities of greater magnitude than previously thought. A review of these processes, and a discussion of the latest work is presented in Imberger and Patterson (1990).

The model to be used in this paper does not include all of the processes mentioned above, but rather concentrates on the inflow and withdrawal processes which are two major horizontal transport mechanisms at times of high flow, and are of great importance in answering the questions posed in the introduction. Each of the above processes creates horizontal density gradients which then relax, causing the horizontal motions. An algorithm is included in the model which relaxes these horizontal gradients.

As for the layers, maximum and minimum parcel sizes are set to prevent the formation of too many parcels, whilst retaining adequate resolution. New parcels



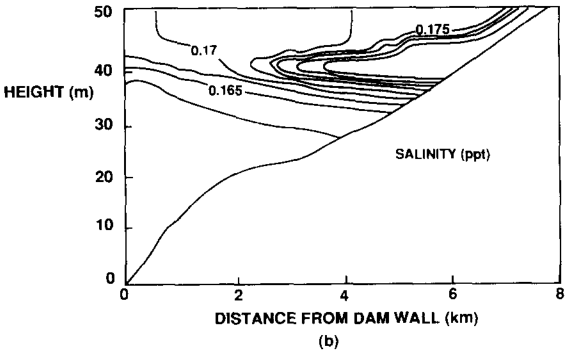




Fig. 2. Comparison of salinity contours on 28 October 1986 in Canning Reservoir from (a) field measurements, (b) simulation results using the two-dimensional model. The arrows in (a) indicate the locations at which profiles were taken.

may be created by the mixing of two layers, simulating local vertical mixing, or by the intrusion of a stream at its level of neutral buoyancy.

The main river is assumed to flow down the main basin, and hence begins its intrusion at the upstream end of the layers. The other inflow sources follow a path determined by the mean slope of their bottom, and hence may enter at a point in the middle of the reservoir. Water from these inflow sources is assumed to remain separate from the main layer and parcel structure of the model until it intrudes as a new set of parcels, as described in Hocking and Patterson (1988). Entrainment of reservoir water into the plunging inflow is computed as each parcel in the travel path is passed. Intrusion widths and lengths are computed as in the one-dimensional model, and the intrusions are distributed accordingly as a new set of parcels.

Withdrawal is calculated by computing an envelope from within which the water will come in each time step, based on the stratification and flow rate, as described in Hocking et al. (1988). Water is removed from within this envelope by removing parts or all of parcels within its bounds.

At this point in its development, the model is already of use for examining processes which drive motions in a reservoir. Fig. 2a shows an intrusion mapped in the Canning Reservoir using salinity measurements, and Fig. 2b shows a simulation of the same intrusion using the model. In Canning Reservoir, salinity levels are of insufficient magnitude to significantly influence the density, and consequently can be regarded as a tracer. The magnitude of values in the two plots differs because the inflow salinities were unavailable, and had to be estimated. The extent of the intrusion is predicted very accurately, despite occuring some 240 days after the beginning of the simulation. However, the model has not predicted the weak surface inflow which appears in Fig. 2a. This inflow has been mixed into the mixed layer in the model. Further verification is given in Hocking and Patterson (1991). The model can be seen to simulate both intrusion and underflow reasonably successfully, and can thus be used to examine the path of inflows.

Two facilities are available in the model for the investigation of water movement, in addition to the temperature, salinity and density values. The first is the local 'retention time' of each parcel, an estimate of the time passed since that parcel was at a location defined by the user, either an inflow source or some point within the storage, or simply the time since the water entered the reservoir. When parcels are mixed, the residence time of the new parcel is taken to be the younger of the two previous parcels, subject to the condition that the smaller parcel comprise at least 10% of the combined volume. This residence function thus provides a general picture of the dispersal of water in the lake. The second method for examining water movement is provided by the tracer facility, in which a fixed amount of tracer can be 'released' at any specified location, either on a single day, or over several days. The concentration of this tracer in each parcel is monitored as the model proceeds. At present the tracers are assumed to be non-diffusive.

No comparison of the model with field tracer studies have been performed, but the success of the model in predicting the behaviour shown in Figs. 1 and 2, and in Hocking and Patterson (1991), is evidence that the model is of some use in its current form to investigate the properties of inflow and withdrawal in a reservoir.

## 3. Simulation and results

Canning Reservoir is a small (length 10 km, storage $50 \times 10^6$ m$^3$), domestic supply reservoir situated 50 km south-east of the city of Perth in Western Australia. It is fed by the main Canning River, a number of smaller streams, and a diversion of a stream from downstream of the reservoir into the reservoir itself. This diversion, the Kangaroo Gully Contour Channel (KGCC), enters the reservoir, and simply runs down the side of the reservoir basin about 500 m from the dam wall.

In order to illustrate the points discussed in the opening remarks of this paper, two sites were chosen for investigation. The first site was chosen to be in the KGCC near the dam wall, and the second, for contrast, was chosen to be on the banks of the main inflow source, the Canning River, about 7 km upstream. In fact we could have chosen any site, and it need not have been part of an inflow. To motivate the study, we shall suppose that both the Canning River and the KGCC pass through farmland, and consequently have a very high nutrient content. The

Canning River has a daily flow up to $20 \times 10^4$ $m^3$/day and inflow temperatures at this time of the year are around 17°C. The flow in the KGCC is about one tenth of the flow of the Canning River at the time of year over which the simulations were conducted. The inflow decreases significantly over this period dropping to almost zero over the summer. Simulations were run from 11 June 1986 to 28 February 1987, which covers the period from late winter, when the reservoir is well mixed, through the seasonal stratification into late summer (see Fig. 1).

### 3.1. Tracer studies

In the simulations, the flows from the KGCC were seen to plunge to a range of depths from the bottom to the top of the reservoir at various times. In the early part of the simulations, the level of the intrusion was very sensitive to the temperature of the inflowing water, because of the low level of stratification in the main basin (see Fig. 1). As the reservoir began to stratify, the intrusions began to occur at a more consistent level, usually near the thermocline.

Tracers placed in this inflow at regular intervals in the model showed that water entering the surface mixed layer spread quite rapidly upstream, reaching the far end of the main basin (2–3 km from the dam wall) within 3 or 4 days of entering, although the highest concentrations remained near the dam wall. Subsequent inflows which plunged through this initial patch were seen to entrain low levels of this tracer and carry it deeper into the hypolimnion. Water entering the hypolimnion, either by this process or directly, was found to remain almost stagnant for long periods unless disturbed by another inflow. The dominant mode of dispersal of this deeper water would therefore be turbulent diffusion, until the surface mixed layer deepened to this depth, or until the seasonal overturn.

Fig. 3 shows one example of the way in which water flowing from the KGCC is dispersed. A model tracer was released each day for 4 days beginning on 8 August 1986. Fig. 3a shows the situation on 9 August 1986, just after the start of the tracer release. Two intrusions are clearly evident near to the dam wall and at a depth just beneath the thermocline, which is quite weak. Fig. 3b shows the situation on 18 August, 10 days after the first inflow of tracer. Contour levels shown are at 5, 10, 50 and 100 units of tracer (in Fig. 3a the '10' contour has been omitted for clarity). The result of one mechanism for dispersal can be clearly seen. Other inflows from minor streams have plunged through the initial region and entrained some of the tracer, which has then been carried deeper into the reservoir. Despite this, the initial patch remains at a high level of concentration. More detailed plots reveal that there has been some very low-level entrainment of the tracer into the mixed layer where it is quite rapidly dispersed.

Simulations conducted of the injection of tracers at the upstream site showed similar behaviour in intrusion level to the near wall site. Intrusion of the inflows occurred over a range of depths when the reservoir was weakly stratified, but became more consistent as stratification became more pronounced.

Two examples for this site are shown in Figs. 4 and 5. Fig. 4 shows the fate of an intrusion near the surface from tracers released between 30 June and 3 July 1986.

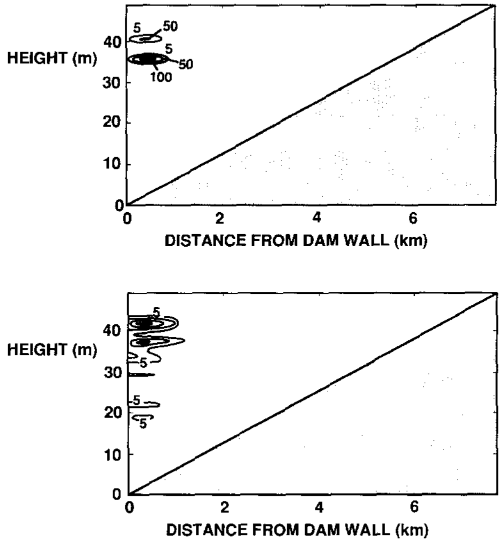



Fig. 3. Contours of tracer concentration on (a) 9 August, and (b) 18 August 1986, for a tracer released from the KGCC over 4 days between 8–11 August 1986. Contour levels are 5, 10, 50, 100 units.

Two days later, on 5 July (Fig. 4a), the tracer has travelled at low levels to within 2 km of the dam wall. This is about the distance at which the Canning River enters the main basin of the reservoir: Contour levels are at 5, 10, 15, 20 and 25 in this figure. A reasonably concentrated patch remains near the original location. Under the influence of wind mixing and subsequent inflows, the tracer has spread throughout the mixed layer by the time of the second plot, Fig. 4b, which shows the situation on 15 July, 10 days later. There is evidence of an intrusion beneath the level of the thermocline, which is very weak at this time of the year. There is also evidence of very low levels of tracer carried into the deeper parts of the lake, although as above they do not show on the scale of this plot. The spread of the tracer throughout the surface mixed layer has taken less than two weeks.

Fig. 5 shows a second example of tracers released at the upstream site between 19 July and 22 July. Fig. 5a shows the situation on 29 July. Contour levels are 8, 16, 32, 64. A major intrusion which occurred during the period of the release of tracer is evident, and a later inflow has entrained some of the tracer and intruded 7–8 m beneath the original. Fig. 5b shows 3 August, on which it is clear that later inflows have plunged through the original intrusions and carried the tracer to the deep. In addition, a region of high concentration remains near the location of the original intrusion, though it is slightly higher as subsequent deep inflows have raised the water level slightly.

These examples show that a substance entering the hypolimnion may remain at quite high levels of concentration for a considerable time, and show some circumstances in which it may be transported, which are not immediately obvious. Water in the mixed layer is much more rapidly dispersed, but may still remain at quite high concentrations in isolated patches.

### 3.2. Residence time studies

The definition of theoretical residence time in the reservoir context is an estimate for the time which any inflowing water spends in the lake before it is withdrawn. It is usually computed in the average sense, i.e. as the total volume divided by the amount withdrawn in a single day, and provides a global estimate for the time any parcel of water spends in the lake before it is withdrawn. It is not clear, therefore, exactly how long any particular parcel spends in the reservoir. Using the simulation model, single parcels of water can be followed as they move in the water body, and a record can be assigned to each as to how long it has been in the lake, or if it is desired, the time since that parcel of water was at a single, specified location. Thus, after some time in a given simulation, a map can be drawn of the time which each parcel has spent in the reservoir, and an estimate of the age of the water being withdrawn can be obtained.

We now look at some of the results obtained using this facility in the model in the above simulations. Some features of great interest emerged, and the following general pattern evolved. When the reservoir was stratified, and the withdrawal was

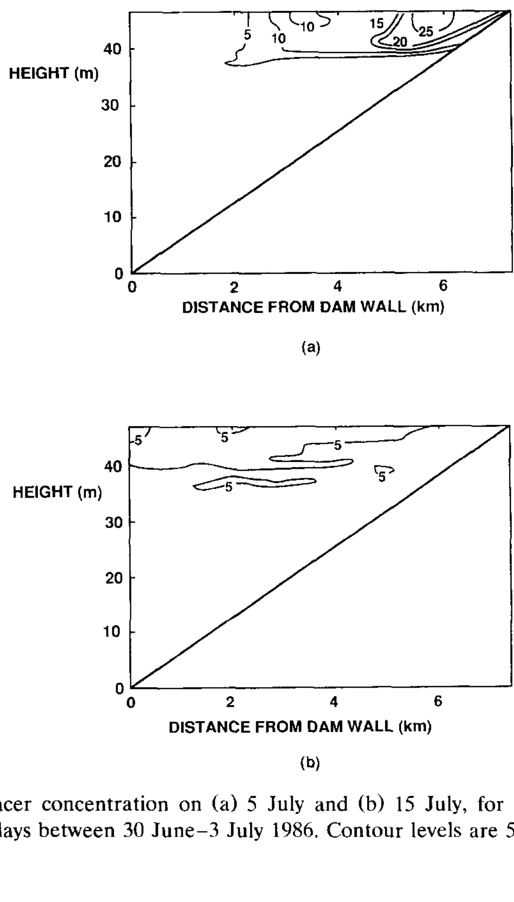



Fig. 4. Contours of tracer concentration on (a) 5 July and (b) 15 July, for a tracer released in the Canning River over 4 days between 30 June–3 July 1986. Contour levels are 5, 10, 15, 20, 25 units.

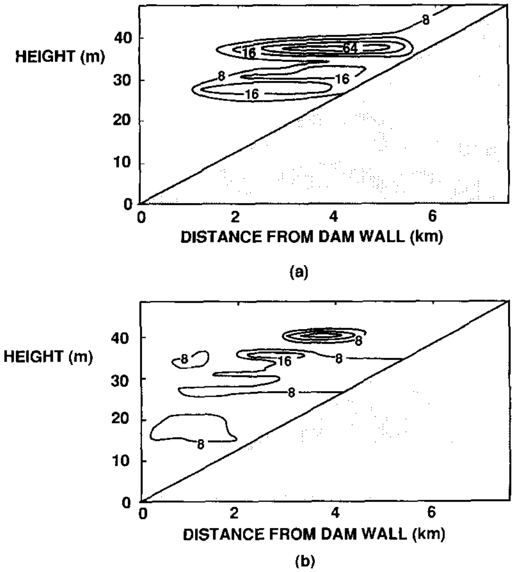



Fig. 5. Contours of tracer concentration on (a) 29 July and (b) 3 August 1986, for a tracer released in the Canning River over 4 days between 19–22 July 1986. Contour levels are 8, 16, 32, 64 units.

being made above the level of the thermocline, the water in the hypolimnion remained untouched for long periods. Thus warm river water, entering above the thermocline, flowed along the reservoir and was withdrawn relatively quickly. In this situation, an estimate for the actual retention time would be obtained by dividing the volume above the thermocline by the withdrawal in a day, since the water beneath the thermocline plays virtually no role in the through-flow cycle. Conversely, if withdrawal is being made from beneath the thermocline, and inflows are entering the surface layer, actual retention time of that inflowing water may be greatly increased.

If the inflowing water is travelling deep into the lake, then it may stay for long periods before being withdrawn, although it will depend upon the level of intrusion, since water near the top of the hypolimnion may be entrained into the mixed layer and then may be withdrawn. If withdrawal is from beneath the thermocline, the water may remain for long periods, unless it happens to intrude horizontally at a level at or just below the level of the outlets, in which case it may travel across the whole reservoir in a band only a few metres deep, thus greatly reducing the usual travel time for that particular inflow.

Fig. 6a shows a residence time map for Canning Reservoir 54 days into the simulation, in late winter (3 August 1986). At this time the reservoir is only very weakly stratified. The map shows that the inflows are travelling downward to a range of depths before intruding, and the most recent inflow from Canning River can be seen travelling down the drowned river valley. The water near the surface is around 2 weeks old, indicating that the colder inflowing water is not flowing near

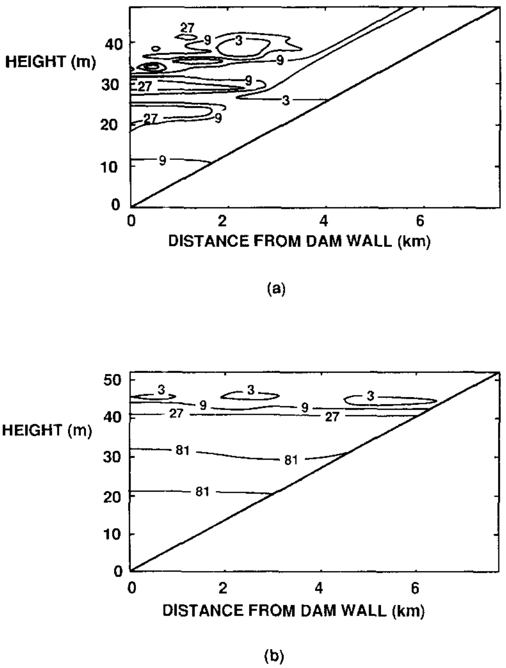



Fig. 6. Typical contours of local residence time for Canning Reservoir on (a) a winters day (3 August 1986) and (b) a mid-spring day (28 October 1986).

the surface. Water is being quite rapidly diluted as it enters because of the low resistance to mixing provided by the weak density gradient. It is difficult to show this quantity very clearly using a contour plot, since the residence times in a small region can vary considerably. However the plot does show that apart from small localised regions 'young' water is present throughout the water body.

Fig. 6b shows a residence time map of the Canning Reservoir at a time 140 days into the simulation in mid-spring (28 October, 1986), when the reservoir has been stratified in density for some time, and the inflows have warmed sufficiently to be flowing over the surface. In contrast to the winter picture, all of the most recently arrived water can be seen in the mixed layer, and because of the barrier to mixing provided by the thermocline, it remains in this surface layer. The base of the thermocline clearly shows as the level beneath which all of the parcels are tagged as being greater than 27 days old.

## 4. Discussion

The results of the simulations highlight several factors of importance in a consideration of water dispersal, and hence water quality, in a reservoir.

Water introduced to the surface mixed layer may quite rapidly be diluted and spread through the mixed layer within 5 to 10 days, usually at low levels of concentration. In the tests for the KGCC, a region of high concentration remained near the injection point, while for the Canning River, a region of high concentration created by the initial injection drifted toward the dam wall under the influence of inflows, reaching the dam wall within 10 days. In another example, a region of high concentration remained at an upstream location for a long time as later inflows passed underneath it.

Laminar processes such as flow due to differential heating, differential deepening or wind-driven circulation, which are not included in the model, could enhance or decrease the speed of travel, but are unlikely to alter the qualitative behaviour.

Water entering the hypolimnion is shown by the model to be driven mainly by the inflow and withdrawal processes, since it is sheltered from the surface weather conditions by the thermocline. Inflows may either carry nutrients or pollutants directly, or they may pass through regions containing them and entrain some en route. They may carry a parcel with high concentration all the way across the reservoir without significant dilution. In addition, large flows of water under concentrated patches may raise the level of such patches by several metres, as shown in the final example. Conversely, withdrawal can draw concentrated patches directly toward the outlets, or it may withdraw water underneath such patches, causing them to fall to the level of the outlets.

The model has provided a picture of some of the possible behaviour patterns for nutrient rich or contaminated water introduced at two sites on the Canning Reservoir. Water from the upstream site does take longer to reach the vicinity of the outlets, and could be dispersed by an isolated mixing event en route, but could equally reach the dam wall in concentrations reduced very little from the original. Further simulations using different input data to simulate a wide range of weather and flow conditions can be easily performed to provide a more complete picture of the behaviour of water released at the two sites, or indeed any other sites of interest.

The examples given show the power of the use of numerical modelling in a general examination of water quality, or to answer specific questions about water movement or pollutant dispersal in a lake. These can be tested over a variety of different climatic scenarios to give an indication of how a particular reservoir behaves in many different conditions.

## Acknowledgements

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