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Modelling of bubble plume destratification using DYRESM

Hengameh Moshfeghi, Amir Etemad-Shahidi and Jorg Imberger

ABSTRACT

North Pine Dam in Queensland, like other Australian reservoirs, stratifies in summer. Thermal stratification prevents the vertical transfer of heat and oxygen and deteriorates the water quality. Since North Pine Dam is a source of drinking water supply, bubble plume destratification system was chosen to counter the effects of stratification. A numerical model called Destrat was used to design a bubble plume system which destratifies the strongest observed stratification in the reservoir within 3 weeks. Field observations, however, showed that the destratification of North Pine Dam occurred slower than predicted by Destrat. Therefore, Destrat was modified for future applications by including the effect of solar radiation as a source of stratification. The Dynamic Reservoir Simulation Model (DYRESM) was then run to model the destratification of North Pine Dam. The results of this simulation were not in agreement with the field data as DYRESM overestimated the destratification caused by the bubble plume. A comparison of the field and simulated results indicated that the volume of water entrained by bubble plume in the DYRESM is overestimated. Reducing the entrainment coefficient of air bubbles produced a closer agreement between the field data and the simulation results.

Key words | artificial destratification, bubble plume, entrainment coefficient, North Pine Dam, simulation, water quality

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INTRODUCTION

In lakes and reservoirs, thermal stratification is a common phenomenon during summer. Solar radiation is absorbed by surface water and an upper warm and less dense layer (epilimnion) is formed. The epilimnion is well mixed because it is exposed to wind. On the other hand, the bottom layer (hypolimnion) remains cold and dense. Between these two layers there is a thermal gradient zone (metalimnion) which inhibits vertical mixing. This stratified zone controls the distribution of dissolved and suspended materials and therefore determines the water quality (Etemad-Shahidi & Imberger 2001). The oxygen is depleted by biological activities in the hypolimnion but the replenishment of dissolved oxygen is inhibited by thermal stratification. Consequently the bottom layer faces anaerobic conditions.

In order to inhibit or retard the water quality deterioration, the rate of vertical mixing should be increased by natural or artificial methods. Air bubbling, which is a continuous release of pumped air through the diffusers in the bottom of lakes, is an artificial destratification method. The rising air bubbles form a shear layer and entrain the surrounding water. In this way, the heavy bottom layer is lifted up and mixed with the lighter water in the top layer.

Destrat (Imberger *et al.* 1995) and DYRESM (Schladow & Hamilton 1997) are two models which can be used in the design of a bubble plume system and the simulation of its effect in lakes and reservoirs, respectively. The aim of this study was to evaluate the performances of these two models in a real case, North Pine Dam in Australia.

The study area is described in the following section. Then the numerical models and their governing equations are outlined. Following that, the results from numerical

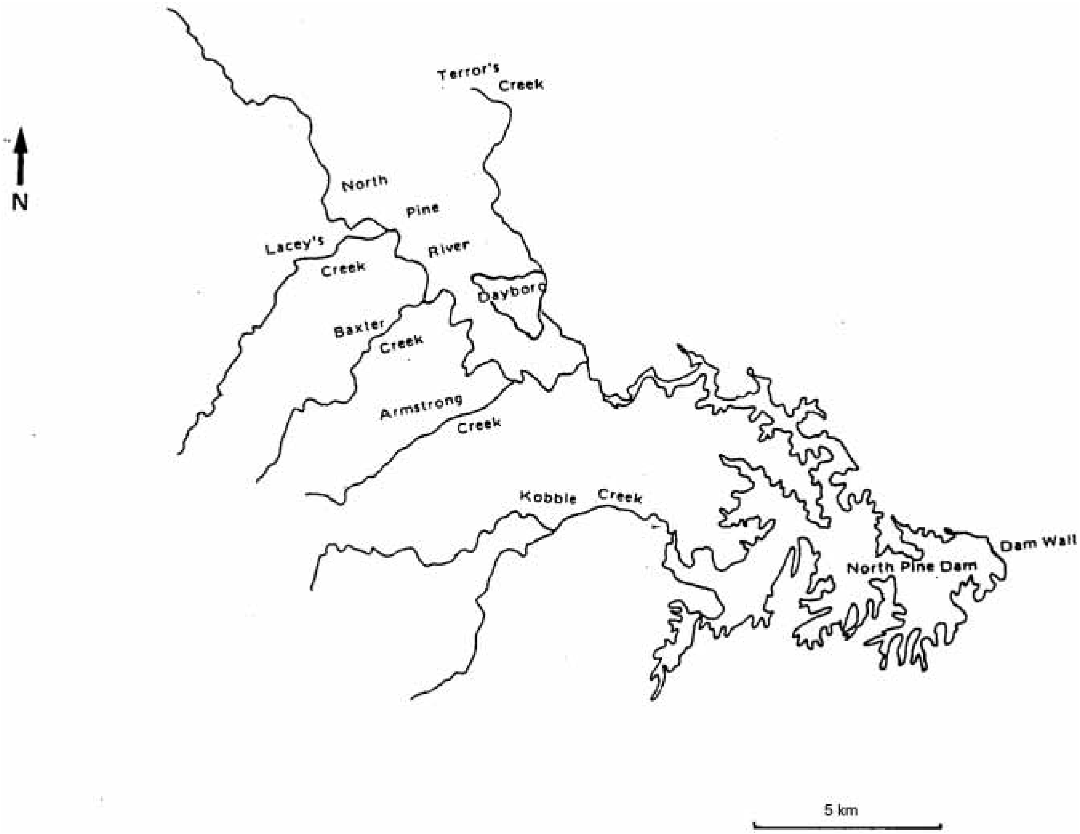

Figure 1 | Map of the North Pine Dam. The dam is located at 27°16′S and 152°56′E in Queensland, Australia.

simulations are discussed. The summary and conclusions of the study are mentioned in the last section.

STUDY AREA

North Pine Dam is located at 27°16′S and 152°56′E, in Queensland, Australia (Figure 1). The catchment area is about 347 km^2. The reservoir is designed to provide an average supply of 150,000 m^3 per day with a maximum of 230,000 m^3 per day (King 1979). Climate is subtropical with a mean summer temperature of 25°C and a mean winter temperature of 15°C. North Pine Dam has strong inter-annual variability in rainfall due to the El Niño Southern Oscillation (ENSO) events. Rainstorms cause large inflows and partial turnover in the reservoir (Moshfeghi & Imberger 1996). In this area, as in the rest of Australia, there is a low average annual rainfall and a high proportional loss by evaporation and transpiration. The average annual rainfall in the catchments is 1,169 mm with a mean pan evaporation of 1,400 mm per year (Webber 1955). The reservoir at full supply is 34.6 m deep with a mean depth of 9 m. The surface area is 21.36 km^2 and the volume is 203×10^6 m^3.

North Pine Dam is a shallow, warm monomictic lake, which means that complete mixing takes place in the lake once a year, during winter. The reservoir stratifies from October (mid spring) to May. Nevertheless, high inflows cause partial mixing during the wet season. In some years the dam can be meromictic or polymictic due to inflows mixing. The seasonal cycle of stratification in the dam is a function of both hydrographic and hydrological events. During stratification the hypolimnion becomes severely anoxic.

King & Everson (1978) estimated that there are 10 tonnes of total phosphorus and 6×10^4 kilograms of total nitrogen in vegetation prior to submergence. Therefore, there is a significant potential internal loading of these nutrients. Furthermore, intense subtropical summer rains combined with the erodible characteristics of Australian soils form runoff containing high concentrations of dissolved and particulate material. Oxygen depletion rates have been estimated at over 500 mg m^{-3} per day (Williams 1980). Extensive development in the catchments has brought about a rapid deterioration in water quality. North Pine Dam is a shallow reservoir with a high supply of nutrients, and is thus classified as productive and eutrophic.

The population of the species in the lake is directly affected by solar radiation, temperature and nutrients. North Pine Dam experiences cyanobacterial blooms in summer and diatom blooms in response to large inflows and seasonal turnovers. The algae blooms in summer change the conditions in the hypolimnion; light penetration and oxygen concentration decrease and the pH alters rapidly (Moshfgehi & Imberger 1996). The mean summer concentration of chlorophyll-a, in excess of 15 mg m^{-3} in the upper mixed layer of the reservoir during 1992–1994, is also indicative of the eutrophic condition of the dam (Moshfeghi & Imberger 1996).

BACKGROUND

Artificial destratification

Vertical stratification of reservoirs creates anoxic conditions in the hypolimnion and hence deteriorates the water quality. A bubble plume diffuser was applied to North Pine Dam to break the stratification. As the bubbles rise, they entrain the cold and dense ambient water and form a plume. The plume will rise until the mixture of air-water reaches its natural buoyancy where its density is equal to the density of surrounding water. At this stage the plume stops and the entrained water is detrained and ejects horizontally. This detrained water detaches from the air bubbles and therefore bubbles form a new plume and rise and entrain water again. In this way bubble plumes increase the rate of vertical exchange and enhance the mixing (Mc Dougall 1978).

Generally, three types of plume may form in a linearly stratified flow. The type of the plume depends on the relative strength of stratification and air flow rate (Asaeda & Imberger 1993). The optimum value of the air flow rate is the rate which produces one ejection at the water surface. In North Pine Dam the diffuser has several clusters in order to avoid interaction of bubble plumes, which reduces the efficiency (Robertson *et al*. 1991). Furthermore, the diffuser is placed 1 m above the bottom to prevent the disturbance of bottom sediments and the transport of nutrients to the surface.

Using Destrat software

Destrat (Imberger *et al*. 1995) was used to calculate the specifications of the bubble plume. This program calculates the power requirement, the optimum flow, the diffuser length and the number of clusters. The program is based on a partial double-plume model described by Asaeda & Imberger (1993). The behaviour of the bubble plume is controlled by three non-dimensional numbers (Lemckert *et al*. 1993)

$$M_H = \frac{Q_B\, g}{4\pi\alpha^3 H\, {u_s}^3} \tag{1}$$

where, M_H is a number that represents the source strength to the total pressure head, Q_B is the volumetric air flow rate from the air diffuser at the air diffuser depth pressure ($m^3\ s^{-1}$), g is the gravity, α is the entrainment coefficient, H is the air diffuser depth and u_s is the slip velocity of the bubbles relative to the rising plume (0.3 m s^{-1}).

The second number is:

$$P_N = \frac{N^3 H^4}{Q_B\, g} \tag{2}$$

where, N is the buoyancy frequency and P_N is the plume number that represents the effect of stratification compared with the source strength based on H.

The third non-dimensional number is:

$$H_R = \frac{H}{H_T} \tag{3}$$

where, H_R is the pressure head ratio and H_T is the total pressure head (including atmospheric pressure head at diffuser depth).

The highest possible mixing efficiency will minimize the operating cost. Therefore, it is necessary to calculate Q_B which yields a flow with maximum efficiency (Q_B^*).

To design an efficient aerator system that destratifies the stratification, two flow rates are calculated:

$$Q_M = \frac{Q_B{}^*}{M_H{}^*} = \frac{4\pi\alpha^2 H u_s{}^3}{g} \quad (4)$$

$$Q_P = P_N{}^* Q_B = \frac{N_e{}^3}{g} \quad (5)$$

Where, N_e is the equivalent buoyancy frequency for the linear stratification; P_N^* and M_H^* are the values of P_N and M_H at maximum mixing efficiency.

To calculate N_e, the model computes the density distribution using the temperature and salinity profiles. Then the potential energy of the stratification is calculated using N_e. The equivalent buoyancy frequency for the linear stratification is determined by equating the actual stratification profile and equivalent linear profile of potential energy.

The next step is the estimation of P_N^* from the numerical scheme of Asaeda & Imberger (1993) using the following equation:

$$P_N^* = 10^{(0.871(\ln Q_R) + 2.38 + 0.97H_R - 0.18H_R^2)} \quad (6)$$

where, $Q_R = Q/Q_M$.

Subsequently the corresponding air flow rate per diffuser port is calculated using the following equation:

$$Q_B{}^* = \frac{H^4 N^3}{P_N{}^* g} \quad (7)$$

Then the power required by each plume, the number of clusters, the total air flow rate and diffuser length for each system are calculated using the above-mentioned parameters. Finally, the total pressure drop and head loss are estimated to determine the power required by each system. In addition, the air flow rate of each system at atmospheric pressure can be easily estimated by multiplying the air flow rate by H_T/H_A.

USING DYRESM SOFTWARE

DYRESM is the physical part of the DYRESM-WQ (Dynamic Reservoir Simulation Model, Water Quality version), which is a coupling of hydrodynamic and water quality models described in detail by Schladow & Hamilton (1997) and Hamilton & Schladow (1997). In brief, it is a one-dimensional model which simulates the vertical distribution of temperature and salinity in lakes (horizontal homogeneity). This assumption is based on the density stratification usually found in lakes and reservoirs in which lateral and longitudinal variations in density are negligible.

The one dimension assumption is valid when $L_N \gg 1$, $L_{N,I} \gg 1$, $F_o \ll 1$ and $R \gg 1$; where, L_N is the ratio between restoring force and distributing force introduced by the wind (Imberger & Patterson 1990), $L_{N,I}$ is the ratio between restoring force and disturbing force introduced by plunging inflow, F_o is the ratio between outflow disturbing force and restoring force and R is the ratio between Rossby radius of deformation and lake dimensions.

The physics of DYRESM are based on the following processes: (1) surface heat and mass transfer; (2) energetics of the surface layer; (3) vertical diffusion in the hypolimnion; (4) inflow dynamics; (5) outflow dynamics; and (6) air bubble plume dynamics. The reservoir is divided into a series of horizontal layers of variable size which can expand, contract, amalgamate, divide and move up or down according to the physical processes represented in the reservoir. The model operates on a fixed daily time step, which begins with the input of inflow, outflow and meteorological data. A sub-daily time step is also determined by heat and velocity of the surface mixed layer. The water quality component of DYRESM-WQ follows the pattern of physical mixing processes. Unlike the physical component of the model, the biochemical coefficients need to be calibrated.

Air bubble destratification sub-model of DYRESM

DYRESM models a simple, single core plume. The motion of the bubble plume is determined from three differential equations of conservation of mass, momentum and buoyancy (Patterson & Imberger 1989).

Conservation of mass for the plume becomes:

$$\frac{d(b^2w)}{dz} = 2\alpha bw \tag{8}$$

where, z is the height, w is the centreline vertical velocity at height z and b is the effective radius of plume. The entrainment coefficient, α, is based on the Taylor's hypothesis that the velocity of inflow of diluting water into a jet is proportional to the maximum mean velocity in the jet at the level of inflow. This is true for a fair air bubble plume which is a buoyant jet. Hence, $\alpha = u_e\, w^{-1}$ where u_e is the entrainment velocity.

Conservation of momentum for the plume:

$$\frac{d}{dz}\left(\frac{1}{2}b^2w^2\right) = \lambda^2 b^2 g'_m(z) \tag{9}$$

where, $g'_m(z)$ the centreline density anomaly is given by:

$$g'(r,z) = \frac{-g(\rho - \rho_0)}{\rho_0} = g'_m(z)\exp(-r/\lambda b)^2 \tag{10}$$

where, ρ_0 is the background density at height z, ρ is the density of the air-water mixture, r is the radial coordinate of the plume, λb is the characteristic width for the buoyancy profile and λ (0.3) is the ratio of buoyancy thickness to momentum thickness (Poon 1985). Equation (10) basically shows a Gaussian distribution for density anomaly which becomes 0.37 of $g'_m(z)$ when r becomes equal to λb.

Conservation of buoyancy for the plume:

$$\frac{d}{dz}\left(\frac{\lambda^2 b^2 w g'}{1+\lambda^2}\right) = -b^2wN^2 + \frac{d}{dz}\left[\frac{Q_0P_a w}{(H_T - z)(\pi\rho_0)(w+u_b)}\right] \tag{11}$$

where, Q_0 is the air flow rate at the surface pressure and u_B is given by:

$$u_B = u_s(1+\lambda^2) \tag{12}$$

The first term in the right-hand side of Equation (11) incorporates the effect of stratification and the second term shows the effect of gas expansion and bubble slip velocity on buoyancy flux.

Equations (8–11) are solved by the Runge-Kutta method with initial conditions obtained from power series solution of the above-mentioned equations for the case of no stratification (McDougall 1978). For a starting value of small x, where $x = z/H_T$, the initial conditions are given by:

$$b = 2\alpha H_T x\left[0.6 + 0.01719\frac{x^{1/3}}{M^{1/2}} - 0.002527\frac{x^{2/3}}{M^{2/3}} + x\left(0.04609 - 0.000031\frac{1}{M}\right)\right] \tag{13}$$

$$w = u_b\frac{m^{1/3}}{x^{1/3}}\left[1.609 - 0.3195\frac{x^{1/3}}{M^{1/3}} + 0.06693\frac{x^{2/3}}{M^{2/3}} = x\left(0.4536 - 0.0105\frac{1}{M}\right)\right] \tag{14}$$

$$g' = \frac{Q_0P_a(\lambda^2+1)}{\lambda^2 b^2 (H_T - z)(w+u_B)\pi\rho_0} \tag{15}$$

where,

$$M = \frac{Q_0P_a(\lambda^2+1)}{4\pi\alpha^2\rho_0 H_T{}^2 u_B{}^3} \tag{16}$$

In DYRESM, the bubbler subroutine uses finer resolution layers than the main program and the time step is also fixed at 15 minutes.

RESULTS AND DISCUSSIONS

DYRESM was previously run and calibrated for North Pine Dam. The simulation was from July 1992 to July 1994 (Moshfeghi & Imberger 1996). The output of Destrat (aerator specifications) was used as the input file for DYRESM to predict the effect of destratification on North Pine Dam. The simulation showed that the reservoir would be stratified in a few days without having the bubbler on (Figure 2(a)). The aerator system started running on 15 October 1995. DYRESM was run for 2 months, starting on 1 October 1995 and simulated results were

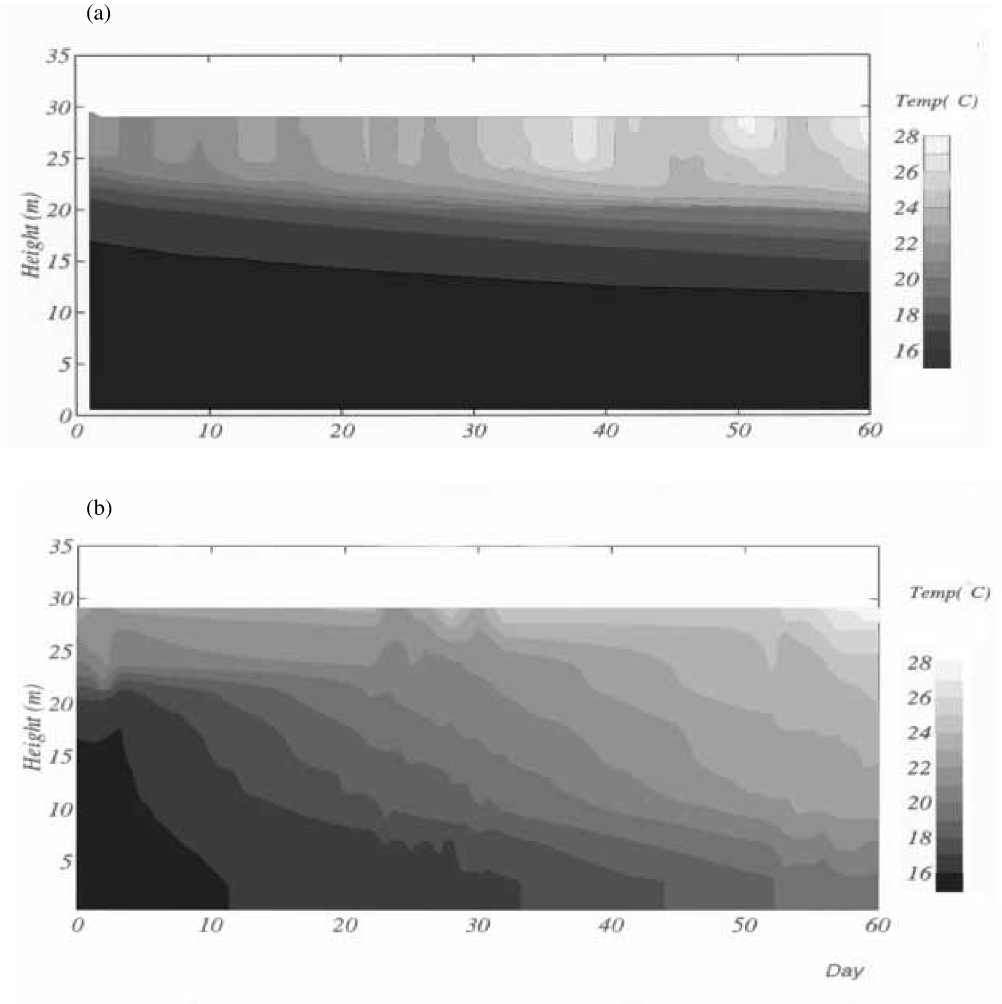

Figure 2 | Temperature contours (a) simulated with the bubbler off showing the possible strong stratification; (b) field measurements with the bubbler on showing the destratification.

compared with the field data collected by a thermistor chain. The aim of the simulation was to model the thermal stratification and therefore the water quality was not simulated.

Although a safety factor of two was taken into account for the design of bubblers, the field data showed that the destratification period of North Pine Dam was longer than 3 weeks (Figure 2(b)). Investigation of the problem revealed that the effect of solar radiation on the increase in potential energy was missing in the Destrat calculations. Therefore, the Destrat was modified to consider the effect of solar radiation. The bubbler specifications used as an input to DYRESM were: air flow rate: $0.33\,m^3\ s^{-1}$, number of ports: 323, length of diffuser: 1,100 m and location above bottom: 4 m. These numbers are not exactly the same as the outputs of Destrat due to some installation and operational problems.

DYRESM was then run to simulate the temperature profile of the reservoir with the bubbler on. Figure 3 shows a poor agreement between the field measurements (Figure 2 (b)) and the simulation. Basically, DYRESM overestimated the destratification process and mixing happened fast. The sensitivity of the DYRESM to the bubbler specifications was tested by changing the major parameters.

Figure 4 displays the simulation results if the bubbler was 1 m above the bottom of the reservoir. The results

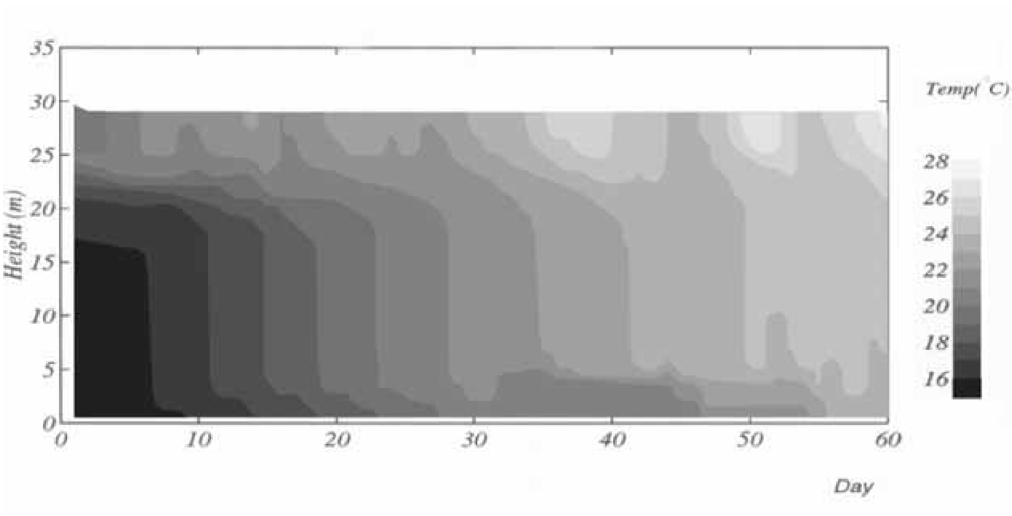

Figure 3 | Original simulated temperature contours using DYRESM with bubbler on; note the rapid mixing of the water column.

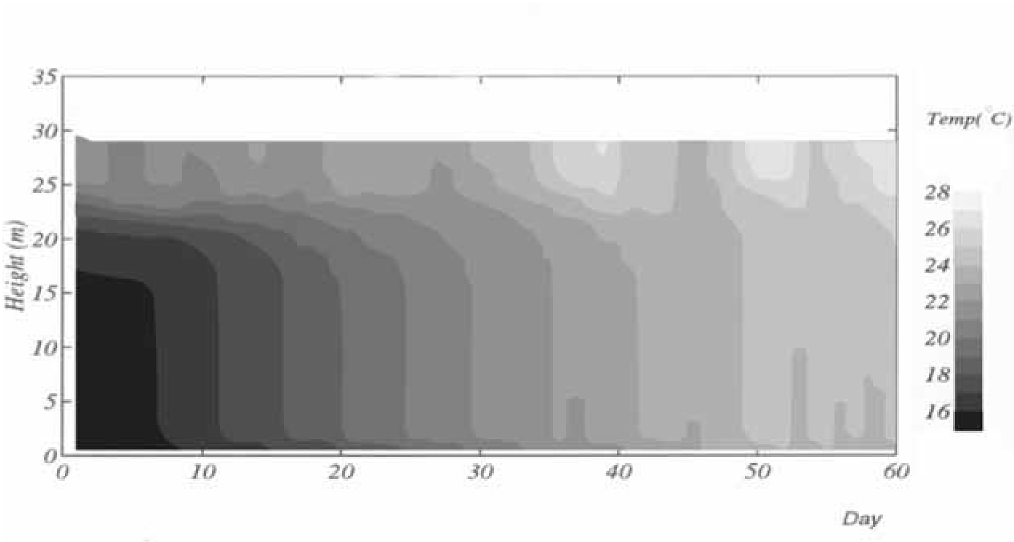

Figure 4 | Simulated temperature contours when the bubbler is located 1 m above the deepest part of the lake instead of 4 m. No major difference is observed compared with the original simulation.

indicate that the modified simulation is slightly different from the original simulation (Figure 3). Therefore, it was concluded that DYRESM is not very sensitive to small changes in the bubbler height. Figure 5 shows that if the air flow rate is decreased by 30%, the destratification of the reservoir will be very slow. This is due to the fact that when the air flow rate is small, the plume will not rise sufficiently and intrusion occurs. Therefore less water will be entrained and the aerator system will be less efficient. The results show that the change in the air flow rate does not affect the sharpness of the isotherms significantly and the change in the air flow rate is not responsible for the difference between the field and simulation results. Figure 6 shows that decreasing the number of ports by

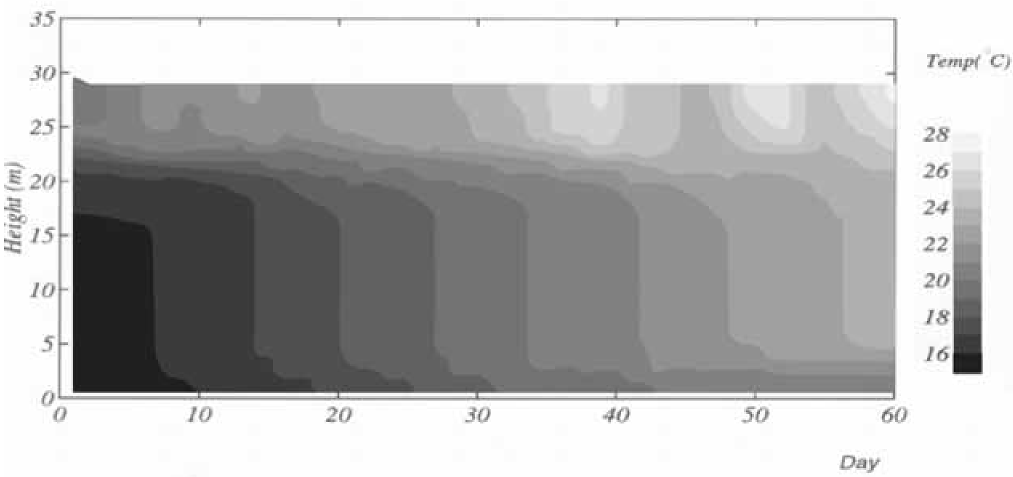

Figure 5 | Simulated temperature contours when the air flow rate is reduced to 0.22 $m^3 s^{-1}$. Vertical mixing still happens rapidly.

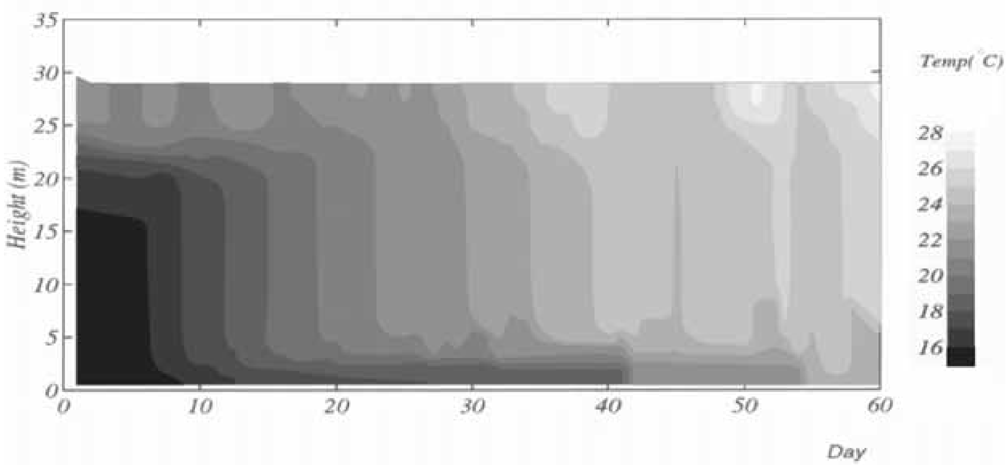

Figure 6 | Simulated temperature contours when the number of the ports is reduced from 323 to 215. Destratification still happens faster than the observed trend.

33% (due to possible clogging) accelerates the destratification process. This result is very similar to the result obtained by increasing the air flow rate (not shown). This is because when the number of ports decreases, the air flow rate from each port will increase.

The results from the above tests show that the disagreement between the field data and simulation results was not due to the possible inaccuracy in the input data. Therefore, the source code of the bubbler subroutine in DYRESM was investigated and the entrainment coefficient (0.083) was multiplied by 0.1, 0.2 and 0.3. Figure 7 shows the DYRESM outputs when the entrainment coefficient is multiplied by 0.2 (closest result). The simulated temperature corresponds closely to the field data within the thermocline (Figure 2(b)) and overall trend of destratification is well predicted. It

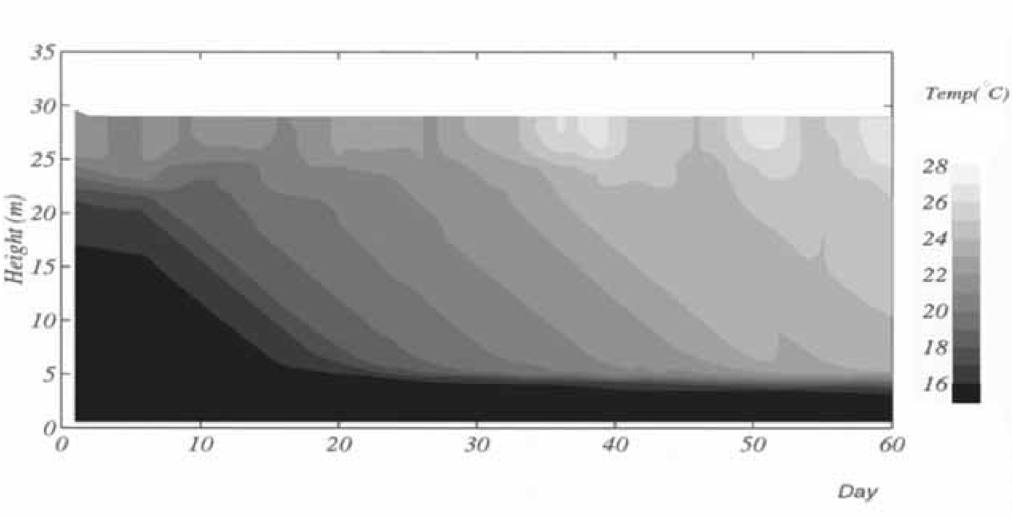

Figure 7 | Simulated temperature contours when the original entrainment coefficient is multiplied by 0.2. Simulated temperature structure within the thermocline is in close agreement with the field data.

should be mentioned that the bubbler does not mix the bottom 4 metres. The slight difference may be due to a number of different reasons such as missing data on the outlet elevations, inflow volumes and the inflow temperatures. In addition, the simple plume and 1-D assumptions used in the model may have contributed to the difference observed. Note that no site-specific adjustment was done for the hydrodynamic module and the results are obtained independently from water quality simulation. There might be some biological reasons for the observed discrepancies. The mono-molecular layers stemming from the plankton organisms might affect the entrainment process. Furthermore, the plankton cause more attenuation of the light (Hamilton & Schladow 1997) and therefore change the thermal structure. However, DYRESM-WQ is not a coupled model and cannot consider effects of the biological processes on the physical processes.

The constant value of 0.083 is hard coded in the DYRESM. This value for the entrainment coefficient has been proposed by some investigators. However, Milgram (1983) showed that the entrainment coefficient is not constant and is a function of bubble Froude number. Therefore, the correct estimation of the entrainment coefficient needs to be incorporated in the model in the future. While investigating Destrat, it was observed that there are some problems which need to be resolved. For instance, the entrainment coefficient is also used in Destrat with a value of 0.083. Logically, decreasing the entrainment coefficient means that the volume of water entrained by the air bubble is smaller. Therefore, a higher air flow rate is required to destratify the lake. Nevertheless, in practice, when the entrainment coefficient in Destrat is decreased, the computed air flow rate for destratification decreases.

SUMMARY AND CONCLUSIONS

This study was carried out in the North Pine Dam to investigate the accuracy of Destrat and DYRESM. Destrat was used to derive the design specifications of the bubbler system and DYRESM was run to predict the effect of bubbler on the reservoir destratification. There are two major conclusions from this study. Firstly, when the field and simulated results were compared it was observed that DYRESM overestimated the mixing rate of the bubbler system. A sensitivity analysis showed that the discrepancy between the field and simulated results was not due to possible inaccuracies in the input data. When the source code was examined it was found that the value of the entrainment coefficient which relates the velocity of inflow of diluting water into the plume to the maximum mean velocity in the plume, was too large. It was also found that the entrainment coefficient should be multiplied by a factor of 0.2 to give a close agreement between the field and simulated results. From this study it was concluded that, in order to obtain a better simulation of the entrainment process, the entrainment coefficient estimation in the bubble plume subroutine of the DYRESM needs to be improved.

Secondly, it was found that Destrat underestimates the required air flow rate to destratifiy the reservoir within the assigned period of time. The reason was that the effect of solar radiation was missing from the initial calculations.

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