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Numerical study of the hydrodynamic and sediment transport process in a subtropical water reservoir: The impacts of storms and winds

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Abstract: A three-dimensional (3D) numerical model was developed to investigate the thermodynamic and sediment processes in a subtropical drinking water reservoir. Data-driven models were also established to generate the inflow conditions. The modelling outputs revealed that climatic forces such as storms and winds significantly impact lake stratification and mixing processes. The sediment transport is driven by storm events, during which sediment delivery to the reservoir is dominated by allochthonous flux. The sediments are transported from riverine zones to transition zones and finally to lacustrine zones. It is estimated that sediment accumulation could have reached 100,000 kg during the largest storm event in February 2015. The winds can lead to a strong vertical water cycle, especially at the centre of the reservoir, and strong winds result in bed erosion in shallow regions. The outcomes of this paper benefit future research by providing a modelling approach for understanding the hydrodynamics of lakes and reservoirs under a variable climate, and also the local water utility by providing insights for an improved management of the reservoir of this study.

Article Highlights:

- Coupled data-driven and numerical model of a shallow water reservoir
- Storm and winds have significant impacts on the lake stratification and mixing processes.
- Sediment transport dominated by allochthonous flux during storm.
- Strong winds result in the bed erosion in shallow regions of the lake.

Keywords: *Lake dynamics; Numerical modelling; Sediment transport; Water treatment*

1. Introduction

Aquatic systems in reservoirs are dynamic, complex and influenced by both internal and external forces and processes. The interaction between meteorological, hydrological, hydrodynamic, thermodynamic and ecological processes may influence water quality within a reservoir temporally and spatially, in both horizontal and vertical directions [1,2]. Water temperature and sediment concentration are two important parameters that influence water quality in aquatic ecosystems [3-7]. Water temperature in lakes affects chemical reaction rates, the dissolved oxygen (DO) content of water, aquatic flora and fauna growth rates and mortality [3]. Sediments in water, on the other hand, can affect the physical and chemical environments of the water column through their transport [8]. Sediment transport also influences the cycling of nutrients through the adsorption and desorption of dissolved nutrients in the water column [9]. Achieving and maintaining constant high water quality standards is an essential requirement to fulfil various demands in relation to reservoirs [10]. The variation in water temperature and sediment concentration not only affects the water quality but also results in spatial and temporal gradients in a number of physical processes, such as sediment erosion and deposition [4,11]. It is necessary to understand the spatial and temporal variation of the thermal structure and sediment transport processes, especially during and after storm events, since during these events there is more disruption to the lake systems [12-14]. Complex numerical models are often applied to fully capture these changing dynamics [12,15]. With decreased computational costs and improvements in computational power, coupled three-dimensional (3D) hydrodynamic and water quality models are increasingly being used [16].

Several studies have been conducted to simulate the thermal structure and sediment transport processes using numerical models in recent years. Weinberger, Vetter [5] calibrated and validated a hydrodynamic model to simulate the vertical thermal distribution in Lake Ammersee, Germany. The simulated results indicated that climate change had led to an

extended duration of stratification and a lack of mixing as a result of higher water temperatures in line with other recent studies [17]. Jin et al. [18] used a hydrodynamic and sediment transport model to simulate the sediment resuspension and transportation caused by wind-driven currents and waves in Lake Okeechobee, United States, during storm events and hurricanes among others. The simulation indicated that near surface velocities were affected by the wind conditions and they matched the predominant wind directions. Li et al. [19] developed a hydrodynamic model and a distributed catchment hydrological model to simulate spatial water level differences in Poyang Lake, China. The results revealed a satisfactory agreement with field observations, and both models accurately simulated seasonal changes in the lake surface area. Such models extend the understanding of reservoir systems and enhance the interpretation of spatially and temporally incomplete field measurements. Models are an essential tool to support decision making, especially in lakes or reservoirs that supply drinking water [16,20-22].

In Tingalpa reservoir, that is a small subtropical Australian reservoir, previous studies found that heavy rainfall, especially occurring after a dry period, led to dramatic accelerated water mixing and significantly influenced water quality [23]. The water temperature and turbidity variation in the vertical direction were also studied in this reservoir as part of the same study. However, the 3D hydrodynamic characteristics of the thermal structure and partial sediment processes, such as sediment deposition and erosion, remain unknown. Therefore, in the present study, a complex 3D hydrodynamic and sediment transport model was developed to evaluate the seasonal variation of water temperature and sediments and to assess the impact of storm events on the reservoir. Such a 3D model would enable to understand the impact of storm events and winds on thermal structure and sediment transport over time and discover the variation of water temperature and sediment in different locations of the reservoir.

2. Study site and monitoring data

Tingalpa Reservoir is a subtropical reservoir located in South-Eastern Queensland, Australia (153.18°E, 27.53°S), as displayed in Fig. 1. This reservoir provides approximately 20% of the water supply to Redland City, which currently has a population of around 150,000 inhabitants. The reservoir is bounded by the Leslie Harrison Dam (LHD), which was completed in 1968. The surface area is 470 ha at full capacity, and the catchment area covers 87.5 km². The main inflows are from Tingalpa Creek from a south-western direction and Stockyard Creek from a south-eastern direction. An intake tower, located on the north-eastern side of the reservoir, withdraws the raw water and redirects it to the Capalaba Water Treatment Plant (WTP). The dam is managed by Seqwater, the main bulk water supplier in the South-East Queensland region. Seqwater commenced a dam improvement program in 2014 and reduced the water level in Tingalpa Reservoir to ensure the upgrade works could be completed. After the reduction of the water levels, the full supply capacity in August 2014 was lowered from 24,868 ML to 13,206 ML, with a water level of 16 mAHD.

Fig. 1 (located here)

The bathymetry of the lake was measured using a Tritech SeaKing Dual Frequency Profiler, and is presented in Fig. 1. The water depth varies from 2m to 16m. A vertical profiling system (VPS) was installed in the Tingalpa Reservoir 500 m from the dam wall in 2013, as depicted in Fig. 1. Such systems consist of a buoy, with a probe system connected to a set of water quality sensors that are automatically winched up and down the water column to measure water quality variables, including water temperature, DO, turbidity, pH, conductivity, chlorophyll a, fluorescent dissolved organic matter and blue-green algae counts. The VPS collects these water quality data for the full vertical profile from the surface to the depth of 13m

and transmits the collected data via telemetry to the Seqwater datasets. This situ measurement is made at a 1-hour interval and data stored every 1m.

Daily outflow discharge data from 2014 to 2016 were also obtained from Seqwater, including the outflow volume to the Capalaba WTP and the water from the LHD. Water samples for the determination of suspended solid concentrations were collected on a monthly basis by Seqwater. Suspended solid sediment concentrations during the period from 2014 to 2016 were measured at two sampling points (marked as ‘a’ and ‘b’ in Fig. 1) and at the inflow monitoring station (marked as ‘c’ in Fig. 1). In addition, daily water level data from 2014 to 2016 were collected near the dam wall from Seqwater. Weather conditions, such as the hourly air temperature, hourly wind speed and direction, hourly relative humidity, hourly evaporation and daily precipitation, were collected from the Australian Bureau of Meteorology from 2014 to 2016.

3. Methodology

This study employed a modelling framework consisting of both hydrodynamic and sediment transport models, which are enforced by the inflow conditions predicted by data-driven models. The hydrodynamic model was first used to simulate flow and temperature variation in the lake. The coupled sediment model was then applied to estimate the distribution of sediment concentration along the lake from extreme events.

3.1 3D hydrodynamic model

To investigate the hydrodynamics and thermal structure in the Tingalpa Reservoir, a 3D time-dependent hydrodynamic model MIKE 3 FM [24], was applied. The MIKE 3 FM model is based on the numerical solution of the 3D incompressible Reynolds-averaged Navier-Stokes equations under the Boussinesq and hydrostatic assumptions [24]. The model included continuity, momentum, temperature, salinity and density equations and utilised a turbulence closure scheme. A horizontally unstructured and flexible grid was applied, with larger cells in

flat areas and smaller cells in narrow channels. The grid cells were triangular, ranging in area from 3,000 to 4,000 m² and totalling 1,204 in the study domain. In the vertical direction, the variable sigma co-ordinates formulated by Song, Haidvogel [25] were adopted. The top 10 m in the vertical direction were divided into five levels with uniform interval. The bottom layer was discretised into z-levels with a 1-m interval. To guarantee the stability of the numerical simulation, the time step was determined to be 12 s to ensure that the maximum Courant number was less than 5 [26].

The model was set up to simulate the flow and the variations of the water temperature in Tingalpa Reservoir continuously over the period 2014–2016. Initially, on, a uniform distributed temperature of 28.28°C was assumed along the whole Reservoir. The daily discharge rates were specified as the boundary condition at the dam, located in the northeast of the reservoir, as depicted in Fig. 1. The model was driven by hydrometeorological conditions (wind and precipitation on the lake surface) and the heat exchange between the atmosphere and the lake. The bed resistance was described by a constant roughness height of 0.05 m, which was obtained from the results reported previously [11]. The horizontal and vertical eddy viscosities were simulated using the mixed Smagorinsky and k - ε formulation [24].

3.2 Sediment transport model

To investigate sediment transport in the Tingalpa Reservoir, a mud transport model was coupled with the hydrodynamic model. The sediment model includes the transport and deposition processes of fine-grained materials. The suspended sediment are divided into a number of size classes, for size k , the following sediment transport equation is solved:

$$\frac{\partial c_k}{\partial t} + u \frac{\partial c_k}{\partial x} + v \frac{\partial c_k}{\partial y} + (w - w_k) \frac{\partial c_k}{\partial z} = \frac{\partial}{\partial x} \left(D_{Hk} \frac{\partial c_k}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_{Hk} \frac{\partial c_k}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_{V_k} \frac{\partial c_k}{\partial z} \right), \quad (1)$$

where, subscript k designated the variable associated with sediment size class k , c_k is the sediment concentration (g/m³); t is time (s); (x, y, z) are the Cartesian coordination; u , v and w are the

velocity components (m/s) along the Cartesian coordinates x, y, z , respectively; w_k is the settling velocity (m/s); D_{Hk} and D_{Vk} are horizontal and vertical diffusivities (m^2/s).

The suspended sediment concentration (SSC) measured at point b (in Fig. 1) in January 2014 was used as the initial value. The sediment transport model was utilised to simulate cohesive and fine sand sediments. According to the field measurement, the cohesive sediment in the Tingalpa Reservoir typically has grain sizes of 0.035 mm, which account for 94% of total sediment. Based on Stokes' law, the settling velocity of the cohesive sediment is roughly 1.09×10^{-5} m/s, which is so small that sediment settling can be neglected. The fine sand sediment has a grain size of 0.081 mm with a settling velocity of 5.71×10^{-4} m/s. Time dynamic sediment concentrations were used at the open boundary of Tingalpa Creek and Stockyard Creek and at the sink point, as described in Section 3.4. The proportion of the cohesive and fine sand sediments in the reservoir water was assumed to be the same as that in the creek water. In terms of the total sediment concentration at the boundary, it was assumed that 94% of the sediments were cohesive sediments and 6% of the sediments were fine sand sediments. The initial bed of sediment was defined as one layer with a 1-m bed thickness and consisted of 90% fine sand sediments and 10% cohesive sediments.

3.3 Data-driven models for inflow conditions

The inflow from Tingalpa Creek, located at the upstream of the Tingalpa Reservoir (Fig. 1), is the major open boundary condition. The only available monitoring data close to this site include the volume flow rate (q), water level (h), water temperature (T), turbidity (C_t), DO, pH and conductivity collected by the Queensland Department of Environment and Resource Management at an hourly interval from 2009 to 2012. The stream-monitoring site is upstream of the Tingalpa Creek and is about 2 km from point c in Fig. 1. The creek water quality was measured by probes at the surface layer of the water. Rainfall is daily data, while water level in the creek is hourly data. In order to analyse the regression between rainfall and water level,

daily water level data (mean daily water level) is used in this study. Fig. 2 indicates that heavy rainfall led to the increase in the water level in the Tingalpa Creek catchment.

Fig. 2 (located here)

The available measurements of rainfall and the estimates of the daily water level from 2009 to 2012 were applied to develop a regression involving the rainfall and water level following:

$$h_i = a_1 R_i + b_1 R_{i-1} + c_1 R_{i-2} + d_1, \quad (2)$$

where R is the rainfall, i represents the current day, $i-1$ represents 1 day earlier, $i-2$ represents 2 days earlier, and a_1 , b_1 , c_1 , d_1 are regression coefficients. It was found that the best multivariate linear regression was based on the factors $a_1 = 2.72 \times 10^{-4}$, $b_1 = 6.80 \times 10^{-5}$, $c_1 = 1.69 \times 10^{-5}$ and $d_1 = 0.14$, with an R^2 of 0.55 during the period 2010–2012.

Chowdhury et al. [27] developed a rating curve to convert the continuous water level from the pressure transducers into discharge in Tingalpa Creek. According to the data analysis, an exponential relationship (Fig. 3a) was found to estimate the stream discharge as a boundary condition which can be applied in the hydrodynamic model, the relationship can be written as :

$$q = a_2 e^{b_2 h} + c_2 e^{d_2 h}, \quad (3)$$

where q is the volume discharge rate (m^3/day) in Tingalpa Creek, h is the water level (m) in Tingalpa Creek, and a_2 , b_2 , c_2 , d_2 are regression coefficients. The best fitted factors are $a_2 = 69,090$, $b_2 = 1.098$, $c_2 = -83,350$ and $d_2 = -0.39$, with $R^2 = 0.94$.

Fig. 3 (located here)

A strong correlation between the air temperature and creek water temperature was also found. The linear regression models between the air temperature (daily minimum, daily

maximum and daily mean) and water temperature were developed. The correlation between the minimum air temperature and the water temperature was stronger in Fig. 3b, so the minimum air temperature (T_{air}) data and estimates of the daily water temperature (T_{water}) in Tingalpa Creek were applied according to Eq. (4):

$$T_{water} = a_3 T_{air} + b_3, \quad (4)$$

in which the regression coefficients $a_3 = 0.75$ and $b_3 = 7.13$, with R^2 of 0.88.

The SSC at inflow locations was measured and recorded monthly by Seqwater. However, the monthly measured data were not frequent sufficiently to describe the sediment variations during storm events. The sediment rating curve was therefore developed using Eq. (5)

$$C_s = a_4 \times q^{b_4}, \quad (5)$$

in which a_4 is the rating coefficient, and b_4 is the rating exponent. It was found that the best rating curve was obtained with an R^2 of 0.75, based on the factor $a_4 = 0.46$ and $b_4 = 0.36$, which was close to a value of 0.4, as suggested by Ciesiolka et al. [28]. The sediment rating curve was applied to estimate the SSC of inflow conditions during storm events in 2015, as demonstrated in Fig. 4.

The water turbidity, C_t , at the VPS station (as marked in Fig. 1) was measured hourly and recorded in nephelometric turbidity units. The SSC (C_s in mg/L) at a water depth of z is estimated using

$$C_s = a_5 + b_5 \log(C_t) + c_5 z, \quad (6)$$

where C_s is the SSC (mg/L) at VPS station, C_t is the water turbidity (NTU) at the VPS station, z is the water depth (m), $z = 10$ means the water depth of 1m and $z = 1$ is the water depth of 10m. When the regression coefficients $a_5 = 2.14$, $b_5 = 1.78$ and $c_5 = -0.049$, the model achieved the best regression with an R^2 of 0.62.

Fig. 4 (located here)

The overall model structure was composed by data-driven models for inflow conditions, a hydrodynamic model and a sediment model. The overview of the models and their inputs and outputs are presented in Fig. 5.

Fig. 5 (located here)

3.4 Atmospheric conditions and other boundary conditions

The hourly air temperature, sum of daily rainfall and weekly wind conditions (wind speed and wind direction) are presented in Fig. 6. Fig. 6a reveals that the air temperature exhibited seasonal variation during the study period: the maximum air temperature was 38°C in the summer, and the minimum air temperature was 8°C in the winter. During a period of February 2015, heavy rainfall in excess of 100 mm per day occurred at the Tingalpa Reservoir. Fig. 6c indicates that northeast and southwest winds are dominant; such winds have the longest wind fetch.

Fig. 6 (located here)

The SSCs measured in Tingalpa Creek were input as boundary conditions in Tingalpa Creek and Stockyard Creek, and the simulation period in this study was 1 January 2014 to 1 January 2016. The sediment rating curve following Eq. (5) was applied to estimate the SSCs in the creeks during storm events in 2015. Fig. 7 indicates the SSCs in Tingalpa Creek and at measuring station d. The SSCs at point b are assumed to be the same as that at the outflow water of the reservoir.

Fig. 7 (located here)

3.5 Model calibration

The model was calibrated for both the hydrodynamic and sediment transport modules. The simulation ran from 2014 to 2016 based on the model configuration described above. The heat exchange coefficients for the evaporative heat loss were determined, and the constant and wind coefficients in Dalton's law were calibrated at 1.5 and 0.9, respectively, based on the measured evaporation data. To accurately reproduce the water temperature of the surface layer, the light extinction coefficient in the heat exchange module was calibrated at 3.0. The critical shear stresses of deposition for cohesive sediments and fine sand sediments were 0.03 and 0.10, respectively, and the shear stresses of erosion for different types of sediments were calibrated at 0.3. The simulated results were validated in terms of the water level, temperature and SSC. The statistical errors were estimated, as defined in the following equations:

$$RMSE = \sqrt{\frac{\sum(\eta_{obs} - \eta_{sim})^2}{n}}, \quad (7)$$

$$R^2 = \left(\frac{\sum(\eta_{obs} - \overline{\eta_{obs}})(\eta_{sim} - \overline{\eta_{sim}})}{\sqrt{\sum(\eta_{obs} - \overline{\eta_{obs}})^2} \sqrt{\sum(\eta_{sim} - \overline{\eta_{sim}})^2}} \right)^2, \quad (8)$$

where η_{obs} and η_{sim} represent the observation and simulation data, respectively; $RMSE$ is the root mean square error; R^2 is the coefficient of determination; n is the number of the record; and $\overline{\eta_{obs}}$ and $\overline{\eta_{sim}}$ represent the observed and simulated mean values.

A comparison between the simulated and measured daily water levels at the LHD is provided in Fig. 8. The comparison displays reasonable agreement. The $RMSE$ between the simulated and observed water levels was 0.04 m. The simulated water level generally matched the observed water levels with $R^2 = 0.99$. The variations in water levels indicate that the model was able to effectively reflect the varying flow conditions in Tingalpa Reservoir.

Fig. 8 (located here)

Fig. 9 (located here)

The time series of the water temperature (Fig. 9a) depicts the temperature comparison between the observation and simulation for 2014–2015 at the surface layer of the water. The seasonal trend of the measured data was readily recognisable. The simulated and measured water temperatures revealed that the hydrodynamic model overestimated the water temperatures during early summer at the surface. To assess the performance of the model, the *RMSE* and R^2 of the temperature were calculated with the values of 1.31°C and 0.96 respectively, which show a good agreement. The simulated vertical profiles generally agreed with those observed at the VPS station (Fig. 9b).

The model produced reliable results during storm events in 2015 (Fig. 10a), and the simulated and observed SSCs matched. In addition, there was a slight difference between the simulated and measured SSCs in May, although the magnitude was similar. The slight difference between the simulated and measured data may have resulted from the long intervals between the field measurements, for example, because the monthly measured data may miss peaks in the SSC during storm events at the outflow conditions. The vertical profiles of the SSC are depicted in Fig. 10b. The simulated vertical profiles matched the observed profiles at the VPS station. Overall, the numerical model used in the study made reasonable predictions regarding the water level, SSC and vertical distribution of the temperature.

Fig. 10 (located here)

4. Results

4.1 The influence of storm events on the water temperature

In the Tingalpa Reservoir, the storm season lasts from January to May. During the study period, four storm events were analysed (Table 1). As displayed in Table 1, the rainfall intensity varied

from 0.31–2.41 mm/h. The rainfall was the most intense during the second storm, and the third storm had the longest rainfall duration.

Table 1 The meteorological characteristics of the storm events during the study period

Parameter	Event 1	Event 2	Event 3	Event 4
Time period	19/01/2015– 29/01/2015	20/02/2015– 26/02/2015	22/03/2015– 03/04/2015	30/04/2015– 03/05/2015
Rainfall magnitude (mm)	66.6	288.8	162.4	223.4
Storm duration (h)	216	120	312	94
Rainfall intensity (mm/h)	0.31	2.41	0.52	2.38

To analyse the influence of the storms on the hydrodynamics, the numerical model was established to simulate the thermal structure of the reservoir in the four storm events in 2015. The February storm featured high rainfall intensity, so the simulation results during this period are representative of the storm's influence on the thermal variations. The simulation results indicate that the surface water temperatures during the storm (Fig. 11b and 11c) were much lower than those before and after the event (Fig. 11a and 11d). As displayed in Fig. 11a, the overall horizontal water temperatures measured between 28.46°C and 28.98°C before the storm. Fig. 11b reveals that the colder water from the Tingalpa Creek and Stockyard Creek led to decreases in the water temperature near the southeast and southwest. The cold inflow plume from the creeks mainly spread towards the east and west sides of the lake because of the effects of the large river runoff and short residence periods. The temperature at the centre of the reservoir was 28°C, and the water temperature near the inflow boundary declined to less than 27°C, as indicated in Fig. 11c. After the peak inflow discharge, the water temperature returned

to the initial state, as displayed in Fig. 11d. Therefore, as illustrated in Fig. 11, the water temperature decreased due to the effects of the large runoff and colder inflow plume. After the storm, under the influence of the air temperature, the surface water temperature returned to its original state before the storm.

Fig. 11 (located here)

To indicate the thermal reaction to the cold plume during the storm, three locations were chosen to represent the lacustrine, transition and riverine zones in the reservoir (see Fig. 12). The coordinates of the three locations are 27°33'32.4"S, 153°11'26.16"E; 27°32'33.3816"S, 153°10'53.094"E; and 27°31'52.014"S, 153°10'35.7888"E. The time series of the water temperatures at these three locations are displayed in Fig. 12. This figure indicates that the surface and bottom water temperatures at three locations ranged between 27°C and 29°C, and the vertical temperature differences between the top and bottom layers were the same at three locations before the storm on 18 February 2015. Because the riverine zone was close to the cold plume, the water temperature at this zone decreased first on 19 February. Fig. 12a, Fig. 12b and 12c demonstrate that the transition location was influenced by the cold plume 1 day after 19 February, and the water temperature at the lacustrine location started to decrease 2 days after 19 February. It is noteworthy that the water temperature decreased from above 28°C to approximately 26.5°C in the surface water at the lacustrine zone, and the bottom layers of the water decreased from 27.5°C to approximately 25°C in this area. Fig. 12 depicts when the flood runoff flowed into the reservoir with small amounts of discharge on 24 February; the water temperature in the top and bottom layers at the riverine and transition zones gradually increased, resulting in the re-establishment of the initial thermal structure. However, the bottom water temperature at the lacustrine zone required a long time to increase back to the original status. The recovery times of the bottom water temperatures at the riverine, transition and lacustrine zones were 4, 8 and 12 days, respectively. After the storm, the thermal structure in the reservoir

was controlled by the atmospheric conditions; after 3 March, the surface water exhibits diurnal variations.

Fig. 12 (located here)

The above analysis demonstrated that the inflow plume played a vital role in the heat exchange of the reservoir during the storm. The cold inflow plume with a higher density tends to move downwards and decrease the water temperature in the deep waters. The cold inflow plume was determined by the heavy rainfall and the decrease in the air temperature. As visible in Fig. 13b, the water temperature in Tingalpa Creek and Stockyard Creek decreased from 25.3°C to 24.0°C. Additionally, high inflow and outflow current speeds can accelerate the horizontal mixing and transport processes, especially in shallow areas. Fig. 13c reveals how the current speeds near the inflow and outflow locations increased during the storm.

Fig. 13 (located here)

4.2. Simulation results for the suspended sediments during the peak inflow condition

The rainfall amount during the main storm events is displayed in Fig. 14a. The start times of these storms were 19 January, 20 February, 22 March and 30 April (**Table 1**). The suspended sediment loads from the LHD from January to July 2015 were calculated using $\gamma(t) = C_s(t)Q(t)$, where γ is the suspended sediment release and loads, C_s is the SSC, and Q is the flow discharge rate.

Fig. 14 (located here)

Fig. 14b depicts the daily suspended sediment loads from Tingalpa Creek and Stockyard Creek and the sediment release from the LHD, which were simulated in the sediment model. These four storms were primarily caused by heavy rainfall, with large quantities of sediments

flowing into Tingalpa Creek and released from the LHD. **Table 2** demonstrates that the sediment loads from the inflow creeks are 7.17×10^4 kg during the first storm and more than 2.0×10^5 kg in the other three storms. As depicted in Fig. 14, the SSC revealed significant variation in spatial distribution. The SSC at the riverine zone experienced an earlier and larger increase during storm events than those in the transition and lacustrine zones. This observation can be explained by the influence of the inflow conditions; the riverine zone is close to the inflow boundary and more likely to be influenced by the SSC from the inflow creeks. The transport of the sediments occurred from the riverine zone to the transition zone and finally to the lacustrine zone. From Fig. 14c, it was found that the SSCs at the transition and riverine zones sharply declined after the peak of the second storm event. The reason for this decline is that the peak of the SSC sinking from the LHD was later than that of the SSC loading from the inflow creeks. Combined with **Table 2**, it can be demonstrated that the average increasing rate of the SSC in the reservoir water correlates with the rainfall intensity. The correlation is because the runoff with high SSC, produced by the heavy rainfall, flows into the reservoir, and leads to the higher increasing rate of SSC in the reservoir water. **Table 2** demonstrates that the lag time from the rainfall peak to the SSC peak was 18 hours in the second storm, which indicates that an intense storm also led to the short lag time from the rainfall peak to the SSC peak in the lacustrine zone. Moreover, during the third storm, due to the long rainfall duration, the SSC at the riverine zone continuously increased, and its peak was late to the SSC in the lacustrine zone. In addition, due to the large accumulation of sediment during the four storms, the SSC in the lacustrine zone exhibited a growing trend over the whole period. Finally, after May 2015, the atmospheric and hydrologic conditions tended to be stable, so the SSCs at different points became consistent following these storms.

Table 2 Relevant parameters in Tingalpa Reservoir during four storm events

Parameter	Event 1	Event 2	Event 3	Event 4
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Sediment loads from inflow creeks (kg)	7.17×10^4	2.11×10^5	2.14×10^5	2.18×10^5
Accumulation of sediment loads (kg)	3.69×10^4	1.04×10^5	9.71×10^4	1.05×10^5
Average increasing rate of sediment concentration in the lacustrine zone (mg/L/hour)	2.69×10^3	1.69×10^2	4.61×10^3	9.06×10^3
Peak of sediment concentration in the lacustrine zone (mg/L)	5.15	8.10	7.84	9.37
Lag time from the rainfall peak to the SSC peak in the lacustrine zone (h)	156	18	72	24
Lag time from the SSC peak in the riverine zone to the SSC peak in the lacustrine zone	90	41	−288	66

The numerical model described previously was utilised to characterise the dynamics of the sediments within the lake and thus to assess the contribution of the storms. As revealed in Fig. 15a, high concentrations (red) occurred only in the vicinity of the creek mouth. Because of the large amount of runoff into the reservoir, the high concentration occurred approximately 2,000 m away from the Tingalpa Creek after 16 hours (Fig. 15b). However, the sediment concentrations did not change from IP5 to IP7 between 6 a.m. and 10 p.m. Fig. 15c depicts that at the peak water level, the SSC near Tingalpa Creek (IP2–IP4) decreased to 0.095 kg m^{-3} and the SSC near the LHD (IP6–IP7) increased to 0.090 kg m^{-3} . The water column was well mixed after the event, and the SSC ranged from 0.091 kg m^{-3} to 0.097 kg m^{-3} in the whole vertical direction. The model results for the flow velocity support that advection is the main process of

sediment transport within the Tingalpa Reservoir during storm events. Overall, the modelling results also reveal that catchment runoff was the main source of the SSC during this period.

Fig. 15 (located here)

To analyse the variation in the water temperature and suspended sediment during peak discharge, the vertical distribution of the simulated temperatures and SSCs on 21 February are plotted in Fig. 16.

Fig. 16 (located here)

A sudden decrease in water depth was observed between IP5 and IP6, when the water in the upper layers rapidly flowed up to the surface and the water in the lower layers flowed to the bottom. This water was cold with high concentrations of suspended sediment. Because this water had transported the sediment to adjacent areas of deep depth, the water in these areas decreased in temperature. The cold water led to a decrease in water temperature at the bottom layer; at the same time, this water brought suspended sediments to the deep layer. As depicted in Fig. 16c and d, the transported sediment led to an increase in suspended sediments at every depth during the peak discharge. It was also observed that the deep-water temperature decreased under the influence of cold flows. However, only the water temperature of the surface layer increased because of the increase in air temperature from 8 to 12 p.m.

4.3. The influence of wind conditions

To indicate the thermal reaction to the wind conditions, the simulated horizontal and vertical variations of the thermal structure under the east wind were analysed. The continuous east wind blew from 9 a.m. to 6 p.m. on 28 November 2014, with the wind speed varying from 1 m/s to 5 m/s. The simulated lake-wide circulation patterns varied between the top and bottom layers of the water column (Fig. 17). The water temperatures at the northeast, southeast and southwest edges were high, suggesting that the shallow areas were well mixed. The velocity

magnitude of the bottom currents was greater than that of the surface currents, and the bottom currents in the lake's centre moved in different directions. This behaviour suggests there was a water transport cycle present in the vertical direction of the lake, with water moving from the east to west areas and then being transported to the bottom. Water in the bottom layers moved from west to east, and the water temperature in the west littoral zone was higher than in the middle of the lake. However, vertical water transport did not mix water well in these areas. The bottom layer velocities were reduced in a vortex that occurred in the littoral zone. Water withdrawals near the dam wall influenced the circulation pattern at the top and bottom of the water column.

Fig. 17 (located here)

Fig. 18 presents the vertical thermal variance from IP8 and IP9 on 28 November 2014. The water temperature at IP8 is higher than at IP9 at the same depth. For the flow direction, the surface water to the water depth of 2 m flowed in the same direction as the wind direction, and the water below 2 m flowed in the reverse direction. Moreover, the water temperature at the bottom layers of the water, below a depth of approximately 6 m, was not affected by the wind-induced flow.

Fig. 18 (located here)

Models with constant strong wind conditions (southwest wind with a 20 m/s wind speed and northeast wind with a 20 m/s wind speed) and no wind condition were built to understand the strong wind's effects on the sediment transport during storm events, especially at the riverine zone, and the difference in sediment variations between the monitored wind and no wind conditions. The simulated result (Fig. 19) reveals that the SSCs at the VPS station without wind conditions were roughly the same as those with observed wind conditions. The result also indicates that before and after the storm event, the simulated total SSC sharply increased under

the strong northeast and southwest wind conditions. The main source of the increased sediment was bed erosion in the shallow terrain. Fig. 20 demonstrates that the bed at the shallow terrain (southwest of the reservoir) was eroded under the strong winds, which contributed to the increase in suspended sediment. This shallow area had a water depth of 1 m on 17 February 2015, so the sediment could easily transfer from the bed to the water column in this area. The maximum simulated erosion of the shallow areas of the reservoir was up to $3.29 \times 10^{-4} \text{ kg/m}^2/\text{s}$. During the storm, due to the relatively low SSC flowing into the reservoir, the simulated total SSC at the VPS station decreased to the minimum value of $1.29 \times 10^{-2} \text{ kg/m}^3$ to $1.42 \times 10^{-2} \text{ kg/m}^3$.

Fig. 19 (located here)

Fig. 20 (located here)

5. Discussion

By comparing the water temperature during the storm events to the thermal variations before and after the storm, the simulated results depicted in Fig. 11 and Fig. 12 indicate that the inflow plume significantly affects the thermal structure in the Tingalpa Reservoir. The cold plume causes a decrease in the water temperature of the reservoir. The water in the shallow basin could return to the original state after 4 days of the storm. However, the water temperature in the deeper basin required approximately 12 days to return to the original status. This phenomenon can be explained because during the storm event, the cold inflow plume with a relatively higher density underflows to the deepest basin. The long duration of the thermal stratification hinders vertical mixing, so the deep water needs a long period to recover to the original status. The same phenomenon was also described by Irwin, Pickrill [29].

The time series of the suspended sediment load (Fig. 14) reflects that the sediment delivered to the reservoir was dominated by the allochthonous flux during the storm events

[30]. The temporal pattern of the sediment loads closely resembled that of discharge, as fluctuation mainly depends on streamflow variability. The storm events have considerable effects on sediment transport [31], as a high-intensity rainfall event could transport the bulk of the sediment load to the lake. In addition, a linear regression (Fig. 21) was identified between the rainfall intensity and the average increasing rate of the SSC in the reservoir water during the four storm events.

Fig. 21 (located here)

The near-surface velocities mostly matched the predominant wind direction [18], and a water cycle in the vertical direction of the lake was identified. To analyse the extent of the monitored wind conditions' influence on the sediment concentration variance during storms, a model without wind conditions was established. The simulated results reveal that the SSCs at the VPS station without wind conditions were roughly the same as those with wind conditions from Fig. 19. The results indicate that the sediment concentrations were primarily influenced by the sediment loads from the inflow creeks and less affected by the wind conditions during the storms. Moreover, the models with constant strong wind conditions (southwest wind with a 20 m/s wind speed and northeast wind with a 20 m/s wind speed) were also built. The results (Fig. 20) revealed that the current directions were the same as the wind directions at the surface layer. The main source of the increased sediment is the bed erosion, and the strong winds result in the transport of sediment from the bed to the water column in the shallow regions.

The hydrodynamic model coupled with the sediment model is used to investigate the lake dynamics and the water quality in a water source (e.g., to estimate the sediment concentrations at the drinking water intake and to identify periods of high risks). This modelling approach can be used to test various scenarios to examine, for example, the influence of different storm conditions or wind conditions on sediment transport and even to provide short-term forecasts. The ability to reliably estimate the thermal stratification and sediment

concentrations is highly beneficial for the Tingalpa Reservoir water operators, as it can lead to a more proactive raw water management.

6. Conclusion

In this study, a 3D hydrodynamic model coupled with a sediment transport model was developed to investigate the thermal structure and sediment transport in the Tingalpa Reservoir. To improve the accuracy of the inflow conditions, data-driven models were used to define the boundary conditions of the 3D model. After the model calibration, acceptable performance was achieved in simulating the water temperature and sediment concentrations both temporally (i.e. through time series analysis) and spatially (i.e. throughout the water column).

Through the validated 3D numerical model, the analysis of the thermal structure and sediment transport in the reservoir extended from observation points to the entire reservoir, and both the spatial and temporal variations were analysed and discussed. The simulation results indicated that the inflow plume significantly affects the thermal structure during storm events. The comparison of the simulated water temperature during and after the storms revealed that the cold inflow plume can mix the shallow water and underflow to the deep water, cooling deeper waters for a long time (approximately 14 days). After the storm, the thermal structure in the upper layers of water quickly returned to the previous ranges within 4 days. However, deeper waters required relatively longer periods (12 days) to return to the original state. The study also found that storm events have considerable effects on sediment transport. During storm events, sediment delivery to the reservoir was dominated by allochthonous flux, and the sediment accumulation could have reached 100,000 kg in the largest storm event. Sediments were transported from the riverine zone to the transition zone and finally to the lacustrine zone during the storms. An analysis of the influence of wind on water movement was also conducted. Due to the prolonged easterly wind conditions, the surface water flowed towards western areas of the lake. However, the bottom water was less affected by the prolonged wind. Moreover,

strong wind affects the surface currents and leads to bed erosion in shallow regions. Overall, the results shed light on the thermodynamics and sediment processes in the Tingalpa Reservoir and provided immediate estimates of the sediment state during extreme events. These model results provide a range of time-saving benefits for water quality operational management and decision making.

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References:

1. Missaghi S, Hondzo M (2011) 3D water quality modeling of a morphologically complex lake, sensitivity and uncertainty analyses, and examples of model applications. In: 19th International Congress on Modelling and Simulation-Sustaining Our Future: Understanding and Living with Uncertainty, MODSIM2011, 2011. pp 3747-3753
2. Leon LF, Smith RE, Romero JR, Hecky RE (2006) Lake Erie hypoxia simulations with ELCOM-CAEDYM.
3. Gooseff MN, Strzepek K, Chapra SC (2005) Modeling the potential effects of climate change on water temperature downstream of a shallow reservoir, Lower Madison River, MT. *Climatic Change* 68 (3):331-353. <https://doi.org/10.1007/s10584-005-9076-0>
4. Yu Y, Zhang H, Lemckert C (2017) Sediment transport in a shallow coastal region following severe flood events. *Environmental Fluid Mechanics* 17 (6):1233-1253. <https://doi.org/10.1007/s10652-017-9546-8>
5. Weinberger S, Vetter M (2012) Using the hydrodynamic model DYRESM based on results of a regional climate model to estimate water temperature changes at Lake Ammersee. *Ecological Modelling* 244:38-48. <https://doi.org/10.1016/j.ecolmodel.2012.06.016>
6. Jin K-R, Ji Z-G (2005) Application and validation of three-dimensional model in a shallow lake. *Journal of waterway, port, coastal, and ocean engineering* 131 (5):213-225. [https://doi.org/10.1061/\(asce\)0733-950x\(2005\)131:5\(213\)](https://doi.org/10.1061/(asce)0733-950x(2005)131:5(213))
7. Zhang H, Chan E-S (2003) Modeling of the turbulence in the water column under breaking wind waves. *Journal of oceanography* 59 (3):331-341. <https://doi.org/10.1023/A:1025567911110>
8. Ji Z-G, Hamrick JH, Pagenkopf J (2002) Sediment and metals modeling in shallow river. *Journal of Environmental Engineering* 128 (2):105-119. <https://doi.org/10.1007/s10584-005-9076-0>
9. Cerco CF, Cole T (1993) Three-dimensional eutrophication model of Chesapeake Bay. *Journal of Environmental Engineering* 119 (6):1006-1025. [https://doi.org/10.1061/\(asce\)0733-9372\(1993\)119:6\(1006\)](https://doi.org/10.1061/(asce)0733-9372(1993)119:6(1006))
10. Bertone E, Stewart RA, Zhang H, O'Halloran K (2015) Analysis of the mixing processes in the subtropical Advancetown Lake, Australia. *Journal of Hydrology* 522:67-79. <https://doi.org/10.1016/j.jhydrol.2014.12.046>
11. Sokolova E, Pettersson TJ, Bergstedt O, Hermansson M (2013) Hydrodynamic modelling of the microbial water quality in a drinking water source as input for risk reduction management. *Journal of hydrology* 497:15-23. <https://doi.org/10.1016/j.jhydrol.2013.05.044>
12. Hodges BR (2000) Numerical Techniques in CWR-ELCOM (code release v. 1). CWR Manuscript WP 1422.
13. Wu T, Qin B, Brookes JD, Yan W, Ji X, Feng J (2019) Spatial distribution of sediment nitrogen and phosphorus in Lake Taihu from a hydrodynamics-induced transport perspective. *Sci Total Environ* 650:1554-1565. <https://doi.org/10.1016/j.scitotenv.2018.09.145>
14. Schernewski G (2003) Nutrient budgets, dynamics and storm effects in a eutrophic, stratified Baltic Lake. *Acta hydrochimica et hydrobiologica* 31 (2):152-161. <https://doi.org/10.1002/ahch.200300479>
15. Missaghi S, Hondzo M, Melching C (2013) Three-dimensional lake water quality modeling: sensitivity and uncertainty analyses. *Journal of environmental quality* 42 (6):1684-1698. <https://doi.org/10.2134/jeq2013.04.0120>
16. Ji Z-G (2017) Hydrodynamics and water quality: modeling rivers, lakes, and estuaries. John Wiley & Sons. <https://doi.org/10.1002/9781119371946>
17. Bertone E, Stewart R, Zhang H, O'Halloran K (2014) Numerical study on climate variation and population growth impacts on an Australian subtropical water supply reservoir. Paper presented at the 11th International Conference in Hydroinformatics, New York, 17-21 August 2014
18. Jin K-R, Hamrick JH, Tisdale T (2000) Application of three-dimensional hydrodynamic model for Lake Okeechobee. *Journal of Hydraulic Engineering* 126 (10):758-771. [https://doi.org/10.1061/\(asce\)0733-9429\(2000\)126:10\(758\)](https://doi.org/10.1061/(asce)0733-9429(2000)126:10(758))
19. Li Y, Zhang Q, Yao J, Werner AD, Li X (2013) Hydrodynamic and hydrological modeling of the Poyang Lake catchment system in China. *J Hydrol Eng* 19 (3):607-616. [https://doi.org/10.1061/\(asce\)he.1943-5584.0000835](https://doi.org/10.1061/(asce)he.1943-5584.0000835)
20. Bedri Z, Corkery A, O'Sullivan JJ, Alvarez MX, Erichsen AC, Deering LA, Demeter K, O'Hare GM, Meijer WG, Masterson B (2014) An integrated catchment-coastal modelling system for real-time water quality forecasts. *Environmental modelling & software* 61:458-476. <https://doi.org/10.1016/j.envsoft.2014.02.006>
21. Arhonditsis GB (2009) Useless arithmetic? Lessons learnt from aquatic biogeochemical modeling, vol 1. *Modelling of Pollutants in Complex Environmental Systems*.
22. Ali A, Lemckert CJ, Zhang H, Dunn RJ (2013) Sediment dynamics of a very shallow subtropical estuarine lake. *J Coastal Res* 30 (2):351-361. <https://doi.org/10.2112/jcoastres-d-12-00255.1>
23. Wang X, Zhang H, Bertone E, Stewart RA, O'Halloran K (2019) Analysis of the Mixing Processes in a Shallow Subtropical Reservoir and Their Effects on Dissolved Organic Matter. *Water* 11 (4):737. <https://doi.org/10.3390/w11040737>
24. DHI (2017) MIKE 3 Flow Model, Hydrodynamic Module, Scientific Documentation. DHI Water & Environment, Horsholm.

25. Song Y, Haidvogel D (1994) A semi-implicit ocean circulation model using a generalized topography-following coordinate system. *Journal of Computational Physics* 115 (1):228-244. <https://doi.org/10.1006/jcph.1994.1189>
26. MIKE D (2010) MIKE 3 flow model, hydrodynamic and transport module, scientific documentation. Hørsholm, Denmark: DHI Water Environment Health.
27. Chowdhury R, Gardner T, Gardiner R, Chong M, Tonks M, Begbie D, Wakem S Catchment hydrology modelling for stormwater harvesting study in SEQ: from instrumentation to simulation. In: Science Forum, 2010.
28. Ciesiolka C, Coughlan K, Rose C, Escalante M, Hashim GM, Paningbatan Jr E, Sombatpanit S (1995) Methodology for a multi-country study of soil erosion management. *Soil Technology* 8 (3):179-192. [https://doi.org/10.1016/0933-3630\(95\)00018-6](https://doi.org/10.1016/0933-3630(95)00018-6)
29. Irwin J, Pickrill R (1982) Water temperature and turbidity in glacially fed Lake Tekapo. *New Zealand journal of marine and freshwater research* 16 (2):189-200. <https://doi.org/10.1080/00288330.1982.9515962>
30. Braun C, Hardy DR, Bradley RS, Retelle MJ (2000) Streamflow and suspended sediment transfer to Lake Sophia, Cornwallis Island, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research* 32 (4):456-465. <https://doi.org/10.2307/1552395>
31. Cogley JG, McCann S (1976) An exceptional storm and its effects in the Canadian High Arctic. *Arctic and Alpine Research* 8 (1):105-110. <https://doi.org/10.2307/1550613>

Fig.1 Monitoring sites in the Tingalpa Reservoir. In the background, the bathymetry (mAHD) of the reservoir is presented

Fig.2 Daily water level and rainfall in the Tingalpa Creek catchment

Fig.3 a The exponential regression between the daily water level and daily flow discharge in the Tingalpa Creek catchment and **b** the linear regression between the minimum air temperature and mean water temperature in a daily interval

Fig.4 The relationship between flow discharge and sediment concentration in the Tingalpa Creek

Fig.5 The integrated model structure

Fig.6 Time series of meteorological parameters in the Tingalpa Reservoir from 2014 to 2016: **a** hourly air temperature, **b** daily rainfall and **c** weekly wind conditions

Fig.7 Measured suspended solid concentrations in Tingalpa Creek and at measuring point b

Fig.8 Simulated versus observed water levels 2014–2015

Fig.9 a Comparison of the simulated and observed temperatures and **b** validation of the vertical SSC profiles between the numerical model and field measurement at the VPS station (blue: 10 August 2014, yellow: 25 January 2015)

Fig.10 a The simulated and measured SSC (mg/L) in the period January 2015–July 2015 at sampling point a; **b** the validation of the vertical SSC profiles between the numerical model and field measurement

Fig.11 The simulated horizontal variation of the surface water temperature and velocity distributions during Cyclone Marcia in Tingalpa Reservoir on 18, 21, 22 and 24 February 2015. The colour contours represent the degrees Celsius (°C)

Fig.12 The simulated surface and bottom water temperatures at the riverine zone **a**, the transition zone **b** and the lacustrine zone **c** of the Tingalpa Reservoir from 17 February 2015 to 10 March 2015

Fig.13 a Hourly rainfall (mm) and hourly simulated surface elevation (m), **b** hourly air temperature and inflow water temperature ($^{\circ}\text{C}$) and **c** hourly simulated current speed in the Tingalpa Creek (TC) and Stockyard Creek (SC) and near the dam (m/s)

Fig.14 **a** Hourly rainfall (mm), **b** hourly sediment loads from Stockyard Creek and Tingalpa Creek and the daily sediment releasing from the LHD (kg) and **c** simulated suspended sediment concentration at the riverine, transition and lacustrine zones, Tingalpa Reservoir, January-July 2015

Fig.15 The simulated vertical variation of the total suspended sediment concentration in the fourth storm event from IP1 to IP7. The vertical transection represents the contour of the sediment concentration and the vector of the flow velocity **a** at 6 a.m. on 30 April, **b** at 10 p.m. on 30 April, **c** at 3 a.m. on 2 May and **d** at 9 a.m. on 4 May

Fig.16 The simulated vertical variation in temperature in the second storm event **a** at 8 a.m. on 21 February and **b** at 12 p.m. on 21 February from IP5 to IP6. The simulated vertical variation of the suspended sediment in the second storm event **c** at 8 a.m. on 21 February and **d** at 12 p.m. on 21 February. The vectors represent the flow velocity

Fig.17 a Simulated top cell-averaged velocity and temperature field (10 a.m. to 1 p.m.) on 28 October 2014 and **b** the simulated bottom cell-averaged velocity and temperature field (10 a.m. to 1 p.m.) on 28 October 2014; the vectors represent the flow velocity

Fig.18 a The simulated vertical variation of temperature at 10 a.m. on 28 November 2014 and **b** the simulated vertical variation of temperature at 3 p.m. on 28 November 2014

Fig.19 The time series of the modelled total sediment concentration under the observed wind, no wind, northeast wind and southwest wind conditions at the VPS station (the total SSC under observed wind was the same as that under no wind, the blue line is overlapped under the red line)

Fig.20 a The simulated surface distribution of total SSC at 8 a.m. on 17 February 2015 under northeast winds and **b** simulated horizontal variations of the total SSC at 8 a.m. on 17 February 2015 under southwest winds; the vectors represent the flow velocity

Fig.21 The relationship between the rainfall intensity and the gradients of SSC variation in Tingalpa Reservoir from January 2015 to May 2015