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DENSITY CURRENT SIMULATION USING THE CE-QUAL-W2 MODEL IN A DEEP SUBTROPICAL RESERVOIR UNDER VARIOUS STRATIFICATION CONDITIONS

CHOW M.F.[1*], TEO F.Y.[2]

[1] Associate professor, Discipline of Civil Engineering, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, Bandar Sunway, 47500 Selangor, Malaysia
[2] Associate professor, Faculty of Science and Engineering, University of Nottingham Malaysia, 43500, Semenyih, Selangor, Malaysia

(*) chow.mingfai@monash.edu

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ABSTRACT

Computer models are broadly used to simulate the hydrodynamic characteristics and water quality patterns under various conditions in reservoirs. The accuracy and reliability of model simulations often depend on the input parameter estimation and the availability of observed data. In this study, the two-dimensional hydrodynamic and water quality CE-QUAL-W2 (W2) model was used to simulate the water quality and density current patterns in the Fei-Tsui Reservoir in Taiwan. The model was calibrated and validated with a 3-year dataset of reservoir water level and water quality data at different depths of the reservoir. Plots and statistical measures between simulated versus observed results demonstrated that the W2 model can accurately simulate both spatial and temporal profiles of water quality parameters in a deep subtropical reservoir. The water quality coefficient values obtained from the model calibration and verification in this study are smaller than the values reported for similar reservoirs. The W2 model calibrated using the high-frequency dataset performs better in the water quality simulation. The occurrence of different types of density currents suggested that the water temperature distribution in the water column played an important role in the pattern of turbid runoff. The W2 model is recommended to be further used to evaluate future management strategies related to eutrophication control.

Keywords: Hydrodynamic model, Density current, Eutrophication, Reservoir, Subtropical

INTRODUCTION

Reservoirs have been widely used to satisfy multiple purposes, such as water supply, irrigation, flood control, hydropower generation and recreation (Afshar et al., 2009). In recent decades, water pollution in lakes and drinking water supply reservoirs has become a main concern for local environmental authorities and research scientists (Bowen, 2003; Baker and Dycus, 2004; Ye et al., 2007; Chang et al., 2015). Nutrient inflow, mainly nitrogen and phosphorus compounds, has enhanced the excessive growth of algae and phytoplankton in reservoirs (Chow et al., 2016). The eutrophication process damages ecosystem health, including algal blooms, hypoxia, odors, fish kills, deterioration of water quality and other serious environmental effects (Chow et al., 2011; Varol et al., 2012; Chow et al., 2013). Regarding the susceptibility of inland water bodies, the management and protection of freshwater resources in many countries have received great attention in recent decades (Cole and Wells, 2000; Chung and Oh, 2006; Debele et al., 2008; Diogo et al., 2008). The eutrophication process is primarily influenced by hydrodynamic environmental factors, such as temperature, salinity, carbon dioxide and biodiversity of microbes, as well as nutrient enrichment (Ehteram et al., 2019). Thermal stratification will significantly affect the vertical mixing and nutrient level of a reservoir by changing the cycling process, primary production, biochemical reactions and dissolved oxygen contents (Etemad-Shahidi et al., 2009). Therefore, effectively modeling the eutrophication processes in the reservoir must include modeling the hydrodynamic processes that take place in the reservoir. Computer models are normally used to simulate the hydrodynamic characteristics and water quality patterns under different conditions in reservoirs. Among these models, the CE-QUAL-W2 (hereafter W2) model is a well-known two-dimensional, laterally averaged model that has been widely applied in many deep stratified reservoirs worldwide for predicting the transport mechanisms of flow, chemical constituents and biological reactions in a waterbody (Garvey et al., 1998; Gunduz et al., 1998; Gelda and Effler, 2007; Fai et al., 2015). The W2 model is popular for predicting the effects of catchment management control measures on water quality and ecosystem status (Kornecki et al., 1999; Hu et al., 2008; Fai et al., 2015; Huang and Lo, 2015). In previous studies, the W2 model was often calibrated by comparing the simulated and field data and generated a set of calibrated input parameters based on individual reservoir characteristics (Tilzer and Goldman, 1978; Thomann, 1982; Mc Kee et al., 1992; Kurup et al., 2000; Sullivan et al., 2003; Sullivan and Rounds, 2005; Nielsen, 2005; Kuo et al., 2006; Liu et al., 2008; Najah, et al., 2021).

The accuracy of a calibrated model always depends on the quality and resolution of the field dataset. To obtain accurate water quality assessments in deep water reservoirs, full-depth parameter profiles are often needed. Reliable parameter estimation is essential for ensuring the reliability and validity of a hydrodynamic and water quality model. A successfully validated model can be utilized to assess the effects resulting from reservoir operations, catchment activities and bathymetric changes. In this study, the performance of the W2 model calibrated and validated using a comprehensive high-frequency water quality dataset was investigated. Furthermore, this model was also applied to simulate the thermal stratification pattern and movement of turbidity currents in the Fei-Tsui Reservoir. Recently, several studies have examined the consequences of the density currents that appear at the bottom of dam reservoirs based on bathymetric surveys (Remini, 2018; 2019).

MATERIAL AND METHODS

Study Site

The Fei-Tsui Reservoir (24°54’33' N, 121°34’48' E) is a deep stratified drinking water supply reservoir located in Shiding District, New Taipei City, Taiwan (Fig. 1). The Fei-Tsui Reservoir has a surface area of 10.24 km^2 with mean and maximum depths of 39.68 m and 113.5 m, respectively. Generally, the Fei-Tsui Reservoir has an average water residence time of 150 days (Chow et al., 2016). Most areas of the reservoir watershed are enclosed by secondary subtropical forests. In addition, a few tea plantations are established on mountain slopes near the riverine regions of the Fei-Tsui Reservoir. The land use percentages of the Fei-Tsui Reservoir watershed for forest, agricultural, water body, grassland, bare soil, building, orchard and farmland are 88.43%, 3.86%, 3.53%, 1.20%, 1.11%, 0.98%, 0.45% and 0.44%, respectively. The Fei-Tsui Reservoir is fed by five major inflows: the Bei-Shih stream, Dai-Yu stream, Jia-Gua stream, Hou-Keng-Tsz stream and Huo-Shao-Zhang stream. Since 1987, the Fei-Tsui Reservoir Administration Bureau has monitored and collected high-frequency hydrological data (e.g., daily inflow, outflow, water volume) and water quality data, which consist of 30 parameters.

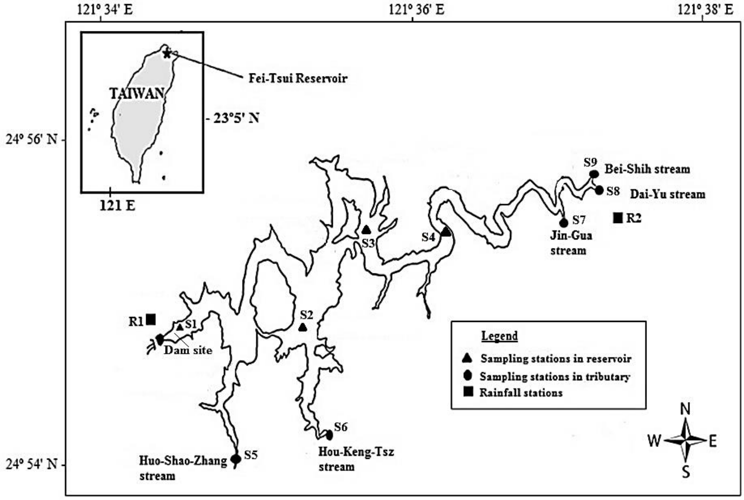

Figure 1: Location of the Fei-Tsui Reservoir and sampling stations

Modeling Approaches

A two-dimensional, laterally averaged hydrodynamic and water quality model W2 is applied to simulate the thermal stratification and turbidity density current in the Fei-Tsui Reservoir. A bathymetry file that consists of the lengths of longitudinal segments, vertical depths of layers, and average widths of reservoir cross-sections is developed for the computational grid in the W2 model. The W2 model is capable of quantifying the free surface elevation, hydrostatic pressure, density, horizontal and vertical velocities, and constituent concentrations. The W2 model user can specify up to 21 constituents for water quality simulations.

The CE-QUAL-W2 model solves the mean transverse equations, which include momentum in the x-direction, momentum in the z-direction, continuity equation, state equations and water surface elevation equation, using the finite difference method. These equations are shown in Equations 1-5. In the state equation, the density is a function of water temperature (TW), total dissolved solids concentration (ØTDS), and suspended solids concentration (ØSS) (Wells 2020a, b):

$$\frac{\partial UB}{\partial t}+\frac{\partial UUB}{\partial x}+\frac{\partial WUB}{\partial z}=g\,B\sin\alpha+g\,B\cos\alpha\frac{\partial n}{\partial x}-\frac{g\,B\cos\alpha}{\rho}\int_{\pi}^{z}\frac{\partial p}{\partial x}dz+\frac{1}{\rho}\frac{\partial B\tau_{xx}}{\partial x}+\frac{1}{\rho}\frac{\partial B\tau_{xz}}{\partial z}+q\,BU_x \tag{1}$$

$$\frac{\partial p}{\partial z}=p\,g\cos\alpha \tag{2}$$

$$\frac{\partial UB}{\partial x}+\frac{\partial WB}{\partial z}=qB \tag{3}$$

$$\rho=f(T_w,\theta_{TDS},\theta_{SS}) \tag{4}$$

$$\frac{\partial B_n n}{\partial t}=\frac{\partial}{\partial x}\int_n^h UBdz-\int_n^h qBdz \tag{5}$$

where

x and *z* = horizontal and vertical coordinates
B = width of the waterbody
U = horizontal mean transverse velocity
W = vertical mean transverse velocity
ρ = water density
t = time
p = pressure
g = gravitational acceleration
q = inlet and outlet flow rate
α = slope of waterbody bed

dz and *dx* = thermal elements in the *x* and *z* directions
τ_{xx} and τ_{xz} = turbulent shear stress in the *x* and *z* directions
β_η = water surface width that varies with time and location
η = water surface elevation
h = depth

This model simulates the average temperature for the vertical depth profile of the reservoir body by considering the inflow, outflow, solar radiation, and surface heat exchange conditions. The surface heat exchange process is characterized by using an equilibrium temperature approach in the W2 model. Spatial and temporal variations are allowed for longitudinal diffusion. The W2 model is able to estimate the vertical diffusion coefficient based on the vertical gradient of the longitudinal velocities, water densities, and decay of surface wind shear. First-order kinetics with temperature-dependent coefficients are used to simulate the decay and decomposition processes in the model. Hydrodynamics, loading, and outflow are updated in the W2 model simulation at each computational time step. On the other hand, water quality simulations can be updated less frequently since most biochemical processes require longer time steps than hydrodynamic processes (Wells, 2005).

Usually, computer models need calibration and validation to prove their capabilities in simulating real situations (Xu et al., 2007). The calibration of the W2 model started from the (1) water surface level, (2) temperature profile, and (3) water quality. The input coefficients for the W2 model are adjusted accordingly during the calibration process. After that, the model was validated by running a new set of data. Finally, the simulation results were interpreted by using statistical and graphical aids.

Model Performance Analysis

The model simulation results are analyzed by using statistical equations to quantify the errors in the model calibration and verification results. The model performance was evaluated by the absolute mean error (AME), root mean square error (RMSE) and normalized objective functions (NOFs), as shown in Eqs. 6 to 8 (Xu et al., 2007):

$$\text{AME}= \frac{X_{iobs}\text{-}X_{iprd}}{N} \tag{6}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(X_{iobs}-X_{iprd}\right)^2}{N}} \tag{7}$$

where N = number of simulated data, X_{iobs} = ith observed value of parameter X, and X_{iprd}=ith simulated value of parameter X.

$$NOF = \frac{RMSE}{\bar{X}} \tag{8}$$

where RMSE is the root mean square error and $\overline{X}$ is the mean of the observed values. The ideal value for NOF is 0.0 but is acceptable for a range from 0.0 to 1.0 when site-specific data are available for calibration (Wu et al., 2004).

Model Segmentation

The Fei-Tsui Reservoir water body is represented by the W2 model in a grid that consists of longitudinal segments and vertical layers (Fig. 2). The Fei-Tsui Reservoir has a length of 21 kilometers, and the maximum depth is 113.5 m. The structure of the Fei-Tsui Reservoir is divided into 19 longitudinal segments from upstream to downstream. The number of vertical layers is set as 6 at the most upstream and increases to 54 near the outlet of the dam. For the full water supply level at the dam site, each layer is 2 meters in depth. In the longitudinal direction, the first segment is taken as the upstream boundary, and the last segment (19th) is the downstream boundary. The second segment is 600 meters in length, and the lengths of the remaining segments are 1200 meters. In the z direction, the first layer is considered the boundary of air and surface water, and the deepest layer is the boundary of water and the bottom sediment. The inflows of the Fei-Tsui reservoir include one main branch and 3 tributaries. The entire water column was divided into 480 cells. In this study, the Bei-shih stream and Dai-Yu stream converge to the main branch inflow. Three main tributaries are identified as the Jin-Gua stream, Hou-Keng-Tze stream and Huo-Shao-Zhang stream, which are located in the 3rd, 14th and 17th segments, respectively. The 2-D grid system of the Fei-Tsui Reservoir in the W2 model is illustrated in Fig. 2.

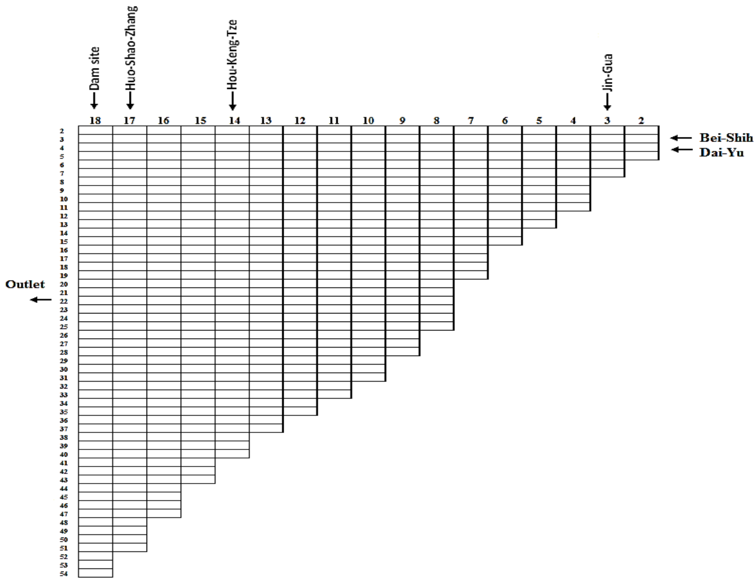

Figure 2: Grid representation for the Fei-Tsui reservoir model

RESULTS AND DISCUSSION

Hydrodynamic calibration results

The W2 model was first calibrated for water surface elevation with 2004 and 2005 data and verified with 2006 data, as shown in Fig.3. The time-variable water surface elevations were used to estimate the reservoir outflow through a water mass balance. The water mass balance in the reservoir was calibrated by tuning the bathymetric dimensions until the simulated water surface level matched the observed dataset. Figs.3(A)-(C) show that the time-variable water surface elevations were reproduced successfully in 2004, 2005 and 2006. The AME and RMSE for 2004, 2005 and 2006 are 0.21 m and 0.36 m, 0.21 m and 0.36 m, and 0.31 m and 0.23 m, respectively. The model was able to correctly reflect the large storms of February and August in 2004, July 2005 and September 2006. The draw-down and refill periods of the reservoir were also clearly addressed.

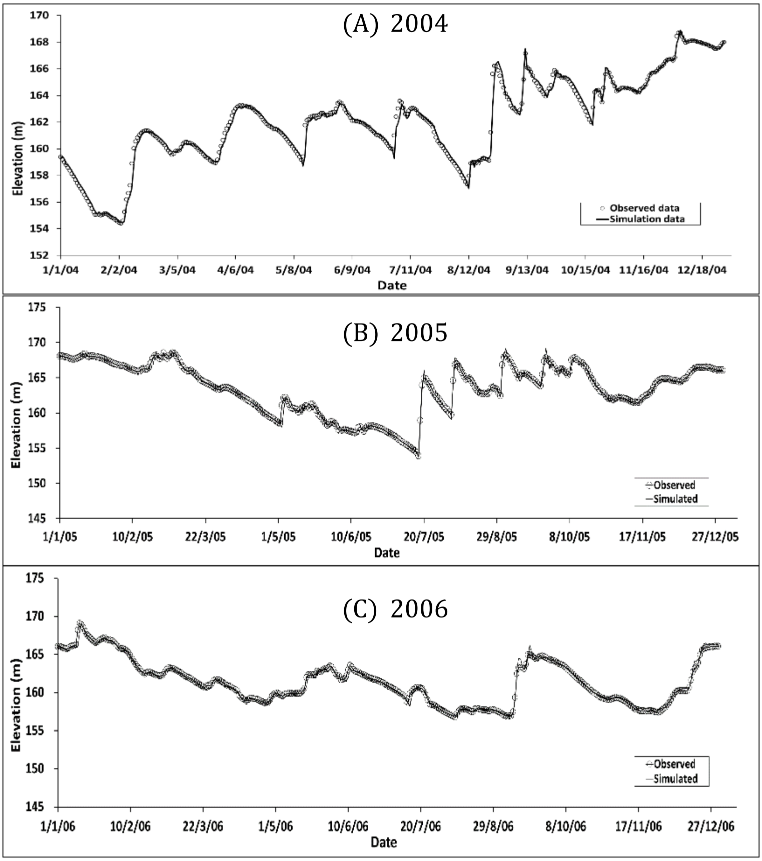

Figure 3: Model predicted vs. observed water level for (A) 2004, (B) 2005 and (C) 2006 in the Fei-Tsui Reservoir

Both the longitudinal and vertical variations in water temperature were used to further evaluate the hydrodynamic performance of the W2 model. Temperature calibration was performed using data collected at stations 1, 2, 3 and 4, as shown in Fig. 1. Fig. 4 shows the longitudinal and vertical profiles of the simulated and measured water temperatures at different depths during the calibration periods in 2004 and 2005. The results showed that the model is capable of simulating the thermal variation both longitudinally and vertically well. The input parameters that need to be calibrated are the wind sheltering coefficient (WSC), Chezy coefficient (FRICC) and sediment heat exchange coefficient (CBHE). The calibrated WSC, FRICC and CBHE values of 0.9, 70 and 7.0 x 10^8, respectively, were found to be optimal for the Fei-Tsui reservoir. The statistical results for the calibration of the longitudinal and vertical profiles of temperatures are presented in Table 1. The AME and RMSE for the observed and simulated water temperatures were 0.61 and 0.82, respectively. A pronounced stratification was observed in the Fei-Tsui Reservoir waterbody during the summer period and underwent significant overturning starting from the end of fall. The stratification process minimized the vertical exchange of nutrients in the water column of the reservoir. The thermocline is located at approximately 10 to 60 m below the water surface, and 14 °C differences are observed between the surface and lower layers of the water body.

Table 1: Statistical results for calibration of longitudinal and vertical profiles of temperatures

Station		**1**			**2**			**3**			**4**	
Date	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF
16 Aug 2004	1.02	1.31	0.06	1.06	1.23	0.05	1.62	1.75	0.07		-	0.05
14 Sep 2004	1.00	1.74	0.08	0.50	0.65	0.03	0.72	0.87	0.04	0.79	0.99	0.04
5 Oct 2004	0.78	1.31	0.06	0.66	1.07	0.05	0.25	0.30	0.01	0.95	1.35	0.06
9 Nov 2004	0.64	1.15	0.05	0.25	0.28	0.01	0.15	0.16	0.01	0.07	0.08	0.01
11 Jan 2005	0.52	0.59	0.03	0.52	0.54	0.03	0.51	0.51	0.03	0.61	0.61	0.03
15 Mar 2005	0.28	0.35	0.02	0.19	0.22	0.01	0.15	0.15	0.01	0.10	0.10	0.01
12 Apr 2005	0.22	0.31	0.02	0.33	0.40	0.02	0.46	0.63	0.03		-	0.02
10 May 2005	0.25	0.30	0.02	0.47	0.72	0.04	0.67	0.96	0.05	0.68	0.97	0.05
14 Jun 2005	0.66	1.15	0.06	0.94	1.41	0.07	0.97	1.49	0.07	0.12	0.15	0.01
12 July 2005	0.89	1.39	0.07		-		1.16	1.71	0.07	0.67	0.77	0.03
mean	0.63	0.96	0.05	0.55	0.72	0.03	0.67	0.85	0.04	0.50	0.63	0.03

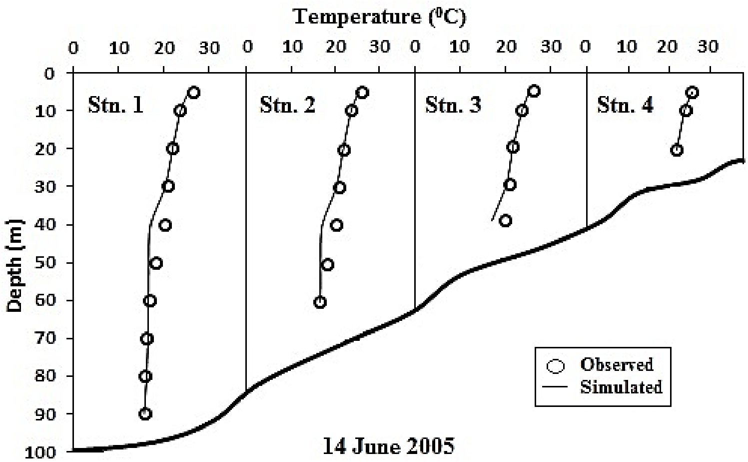

Figure 4: Calibration assessments of vertical profiles of temperature from upstream to downstream

Water Quality Calibration Results

Water quality data, including total suspended matter (TSM), dissolved oxygen (DO), chlorophyll a (Chl-a), ammonium (NH_4), nitrate-nitrite (NO_3) and phosphate (PO_4), were collected and analyzed to characterize the water quality in the Fei-Tsui Reservoir. Vertical profiles of water quality parameters were observed monthly at the dam site, and these reliable datasets were applied to examine the water quality simulation in the W2 model. Numerous model runs were conducted to calibrate the water quality model parameters. Fig. 5 shows the observed and predicted results of TSM, DO, Chl-a, NH_4, NO_3 and PO_4 at different depths at the dam site in 2005. The distribution of Chl-a is influenced by complex factors such as temperature, availability of light, nutrients, and hydrodynamic mixing processes. Nutrient dynamics are of crucial importance to the water quality components of the model. The calibration procedure requires consideration of the balance between phytoplankton growth and depletion of available nutrients from the water column. The final model calibration was achieved by adjusting the parameter values within the specified ranges so that the estimated time series water quality values mimicked the observed series. Table 2 presents a summary of the statistical results for water quality model calibration. The results revealed that the model predictions and field measurements are in reasonable agreement. Some discrepancies between the modeled and observed results show that the model still needs some improvements to simulate the full vertical profile of the reservoir. The calibrated input coefficients and constants for the water quality modeling are listed in Table 3. Generally, all parameter values calibrated for the Fei-Tsui Reservoir fall within the general ranges reported in the literature, as presented in Table 3. These values can therefore be used for W2 modeling in reservoirs with the same climate.

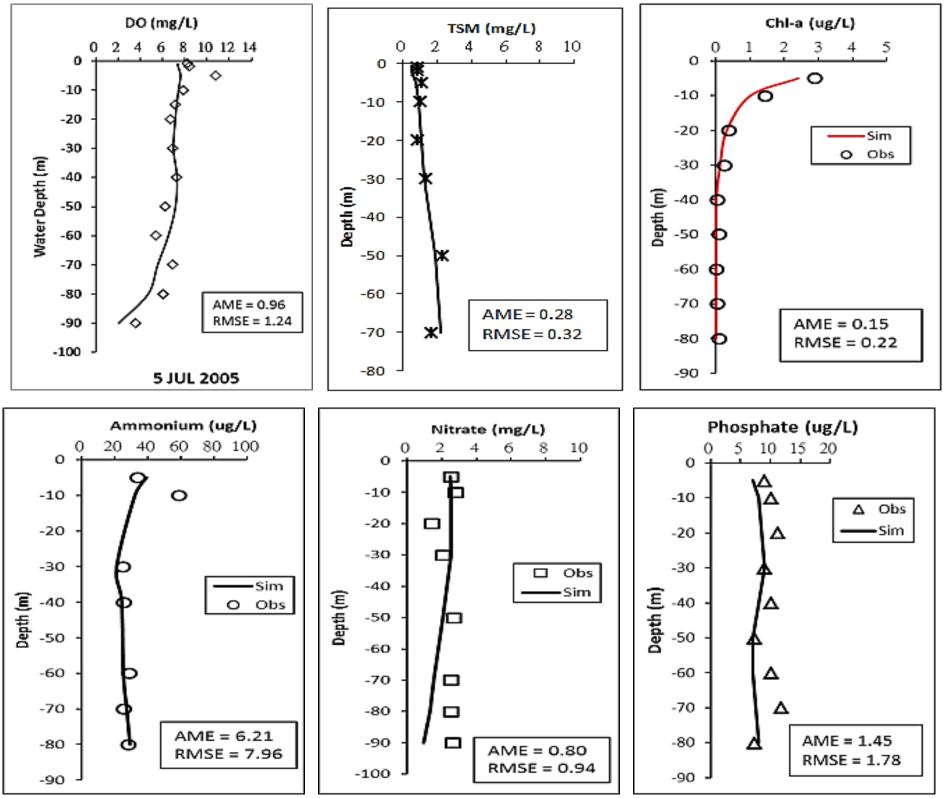

Figure 5: Measured versus simulated vertical temperature, DO, TSM, Chl-a, NH_4, NO_3 and PO_4 at various depths below the water surface at the dam site

Table 2: Statistical results of model calibration for monthly water quality parameters

Month	DO			TSM			Chl-a			NH_4			NO_3			PO_4		
	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF
Jan	0.61	0.68	0.11	0.69	0.79	0.29	0.13	0.18	0.87	-	-	-	0.98	0.99	0.41	1.5	1.53	0.38
Feb	0.44	0.52	0.07	1.25	1.31	0.63	0.58	0.73	1.15	-	-	-	0.57	0.59	0.26	1.52	1.91	0.28
Mar	0.64	0.89	0.11	1.12	1.19	0.50	0.81	1.35	1.01	5.58	6.21	0.16	0.31	0.34	0.14	2.59	3.05	0.37
Apr	1.86	0.52	0.13	0.64	0.74	0.61	0.39	0.53	0.79	15.19	16.01	0.28	0.26	0.35	0.15	0.88	1.14	0.15
May	1.03	1.12	0.13	0.75	0.90	0.43	0.07	0.10	0.17	12.48	14.63	0.32	0.51	0.55	0.26	1.36	1.49	0.36
Jun	0.77	0.98	0.17	0.49	0.56	0.48	0.25	0.40	0.39	8.30	9.30	0.30	0.64	0.69	0.28	1.39	1.59	0.49
Jul	0.96	1.24	0.20	0.28	0.32	0.26	0.15	0.22	0.38	6.21	7.96	0.25	0.80	0.94	0.4	1.45	1.78	0.2
Aug	0.90	1.07	0.16	1.44	2.19	0.36	0.31	0.42	0.70	5.95	6.90	0.25	0.59	0.72	0.32	1.1	1.13	0.43
Sep	1.09	1.20	0.21	2.64	4.05	0.55	0.50	0.68	0.61	4.06	4.35	0.22	0.86	1.02	0.43	1.36	1.41	0.35
Oct	0.97	1.09	0.20	0.78	0.92	0.33	0.83	1.04	0.93	6.6	8.04	0.46	0.88	1.04	0.43	1.04	1.11	0.32
Nov	0.40	0.70	0.13	0.49	0.51	0.34	0.26	0.47	0.32	-	-	-	0.8	1.02	0.46	4.38	4.9	1.74
Dec	0.75	1.16	0.20	0.23	0.39	0.25	0.29	0.47	0.58	-	-	-	-	-	-	2.9	2.97	1.03
mean	**0.87**	**0.93**	**0.15**	**0.90**	**1.16**	**0.42**	**0.38**	**0.55**	**0.66**	**8.05**	**9.18**	**0.28**	**0.65**	**0.75**	**0.32**	**1.79**	**2.00**	**0.51**

- data not available

Table 3: Calibrated hydrodynamic parameters from different studies and the present study

Parameter	Description	Units	Calibrated value					
			Debele et al. (2008)	Kuo et al. (2006)	Afshar & Saadatpour (2009)	Wu et al. (2004)	Chang et al. (2015)	This Study
AX	Horizontal eddy viscosity	m^2/s	1.0	1.0	1	1.0		1.0
DX	Horizontal eddy diffusivity	m^2/s	1.0	1.2	1	1.0		1.0
Chezy	Bottom frictional resistance	m^2/s	70					70
Beta	Solar radiation fraction absorbed at the water surface	-	0.45		0.45			0.45
EXH20	Solar radiation extinction- water	m^{-1}	0.25	0.28	0.4	0.28		0.45
WSC	Wind sheltering coefficient	-	1.0		0.85			0.9
SOD	Zero order sediment oxygen demand	-	1.5	0.3	1.8	0.3		0.5
AG	Algal growth rate	day^{-1}	1.3	1.9	0.34	1.1	1.3	2
AR	Algal dark respiration rate	day^{-1}	0.02		0.03			0.07
AE	Algal excretion rate	day^{-1}	0.02	0.03	0.03	0.03		0.01
AM	Algal mortality rate	day^{-1}	0.05	0.02	0.02	0.02		0.008
AS	Algal settling rate	day^{-1}	0.09	0.09	0.035	0.09	0.05	0.005
AHSP	Phosphorus half-saturation coefficient	$g\ m^{-3}$	0.03	0.005	0.043	0.005	0.0038	0.003
AHSN	Nitrogen half-saturation coefficient	$g\ m^{-3}$	0.11		0.32		0.022	0.014
ASAT	Light saturation	$W\ m^{-2}$	125	350		350	55	400
ALGP	Phosphorus-to-biomass ratio	-	0.023		0.012			0.01
ALGN	Nitrogen-to-biomass ratio	-	0.08		0.08			0.08
ALGC	Carbon-to-biomass ratio	-	0.45		0.45			0.45
ACHLA	Algae-to-chlorophyll a ratio	-	130		115			
NH4DK	Ammonium decay rate	day^{-1}	0.12	0.03	0.01	0.03	0.5	0.02
NH4R	Sediment release rate of ammonium	Fraction of SOD	0.05				0.03	0.001
PO4R	Sediment release rate of phosphorus	Fraction of SOD					0.023	
NO3DK	Nitrate decay rate	day^{-1}	0.68	0.04	0.08	0.04	0.03	0.001
SS	Suspended solids settling rate	$mday^{-1}$					1.0	

Table 4: Statistical results of model validation for monthly water quality parameters

Month	WT			DO			TSM			Chl-a			NO_3			PO_4		
	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF	AME	RMSE	NOF
Jan	0.70	0.81	0.04	0.87	0.94	0.14	0.21	0.23	0.16	0.44	0.48	0.48	0.18	0.20	0.13	1.63	1.77	0.55
Feb	0.78	0.92	0.05	1.40	1.51	0.21	0.38	0.47	0.48	0.82	1.04	0.87	0.15	0.15	0.10	1.57	1.82	0.46
Mar	0.87	0.92	0.05	1.55	1.62	0.22	0.37	0.44	0.40	0.46	0.63	0.45	-	-	-	0.88	1.02	0.43
Apr	1.04	1.22	0.07	1.62	1.77	0.23	0.52	0.56	0.35	0.23	0.36	0.30	0.53	0.54	0.46	0.93	0.97	0.40
May	1.11	1.22	0.07	1.28	1.37	0.19	0.37	0.41	0.28	0.47	0.71	0.49	0.10	0.16	0.11	0.90	1.16	0.51
Jun	1.02	1.09	0.06	1.58	1.71	0.23	0.34	0.37	0.25	0.36	0.61	0.60	0.28	0.33	0.19	0.94	1.11	0.54
Jul	0.83	1.01	0.05	0.81	0.97	0.16	0.59	0.65	0.37	0.23	0.35	0.23	-	-	-	0.98	1.17	0.48
Aug	0.62	0.82	0.04	1.20	1.32	0.20	0.95	1.07	0.45	0.43	0.73	0.40	0.51	0.59	0.45	1.43	1.57	0.90
Sep	0.94	1.03	0.05	1.25	1.38	0.27	0.61	0.73	0.58	1.00	1.51	0.81	0.38	0.46	0.45	1.22	1.36	0.61
Oct	0.70	0.85	0.04	1.11	1.25	0.26	0.20	0.22	0.26	0.75	1.44	0.60	0.43	0.47	0.34	1.02	1.17	0.61
Nov	0.95	0.96	0.04	1.12	1.22	0.22	0.46	0.51	1.05	0.62	1.03	0.74	0.22	0.33	0.40	2.55	2.76	1.30
Dec	0.45	0.61	0.03	0.57	0.75	0.14	-	-	-	0.19	0.24	0.36	-	-	-	2.44	2.47	1.27
mean	0.83	0.96	0.05	1.20	1.32	0.21	0.45	0.51	0.42	0.50	0.76	0.53	0.31	0.36	0.29	1.37	1.53	0.67

- *data not available*

Water Quality Validation Results

Validation is required to determine the validity of previously calibrated input coefficients by using a new set of field data collected independently and under different ambient conditions (Wu et al., 2004). Measured hydrodynamic and water quality data on a monthly basis in 2006 were used to validate the simulated results at the dam site. As shown in Fig. 6, the vertical profiles of the simulated and measured results revealed the similarity of both sets of data. PO_4 concentrations were slightly overpredicted. The model slightly underpredicts the Chl-a concentration in the upper layers of the water column at the dam site. Table 4 presents a summary of the statistical results of the AME and RMSE between the model results and field measurements. Plots and statistical analysis between simulated versus observed parameter concentrations demonstrated that the W2 model can accurately simulate both the spatial and temporal distributions of most water quality parameters.

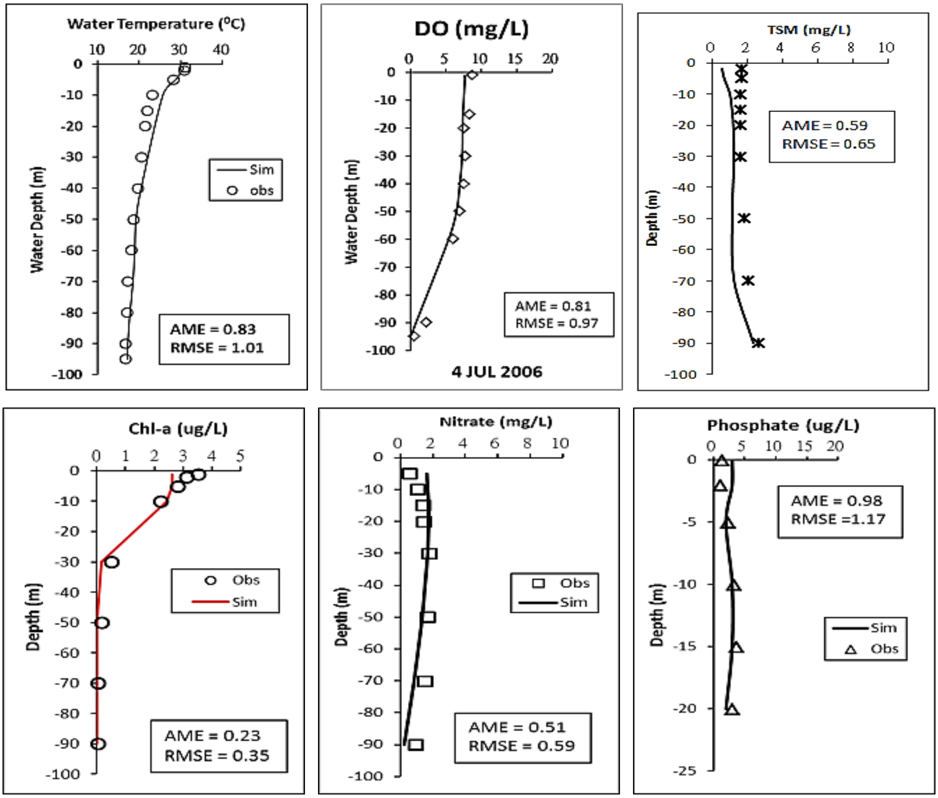

Figure 6: Measured versus simulated vertical temperature, DO, TSM, Chl-a, NH_4, NO_3 and PO_4 at various depths below the water surface at the dam site (July 2005)

Density Current Simulations

The validated W2 model is used to simulate the density current within the Fei-Tsui Reservoir during the typhoon event. The spatial and temporal distributions of density currents were detected by the total suspended matter concentration and water temperature layers. The typhoon event occurred from September 30 until October 14, 2013, as shown in Fig. 7. Two heavy storms occurred on 2nd October and 8th October 2013 with rainfall depths of 106.9 mm and 154.9 mm, respectively. The first density current from upstream to downstream started to be observed on 6th October at depths ranging from 8 m to 28 m below the water surface layer, as shown in Fig. 8a. The concentration of fine particles in the density current was approximately 6.5 mg/L at the entrance to the reservoir, while the concentration was reduced to 2.5 mg/L upon arrival at the dam site. The solid particle concentration in the density current showed a significant positive correlation (r = 0.73) with most of the chemical parameters. During the autumn season, the Fei-Tsui Reservoir water body experiences a stratification process with higher temperatures in the surface layer and lower temperatures in the bottom water layer. Early rainfall events bring the turbid flow from upstream to the dam site of the reservoir. The inflow temperature is relatively similar to the temperature of the surface water layer within the reservoir body. Therefore, the density current forms an overflow pattern. However, heavy rainfall from October 8 to October 14, 2013, brought greater inflow stream water with lower temperature into the reservoir. The cold inflow water forms an underflow density current followed by an intrusion interflow into the water column of the reservoir, as shown in Fig. 8b. A higher TSM concentration was observed in the middle layer, which was approximately a factor of 2 higher than that of the upper layer. The intrusion interflow occurs within the 60 m depth of the uniform temperature layer in the water column. The simulation result indicates that the plunging point for this underflow (the point at which the dense water plunges below the lighter water) occurred 15 km from the dam site. The occurrence of different types of density currents suggested that the water temperature distribution in the water column played an important role in the pattern of turbid runoff. The movement of the density current mainly depends on the temperature profile within the reservoir water body, inflow water temperature, location and changes in the flushing discharge rate of the withdrawal outlet. To enhance reservoir water quality management, dam operations can be optimized by simulating the impacts resulting from changes in these variables.

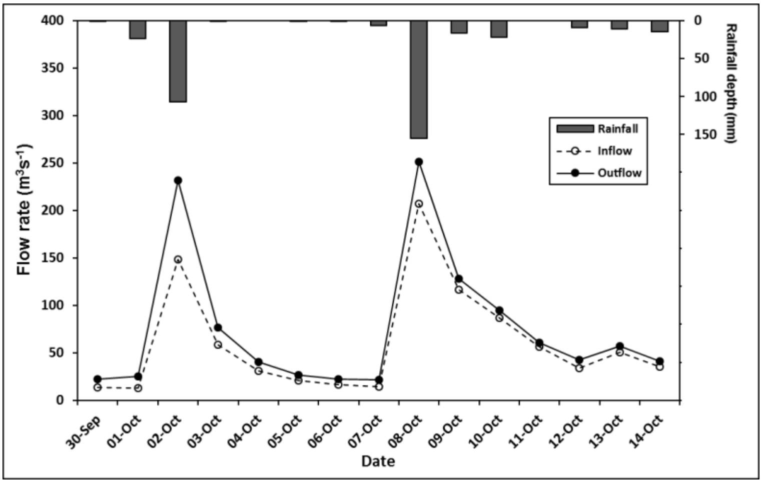

Figure 7: Daily variations in inflow, outflow and rainfall at the Fei-Tsui Reservoir during the typhoon storm event in October 2013

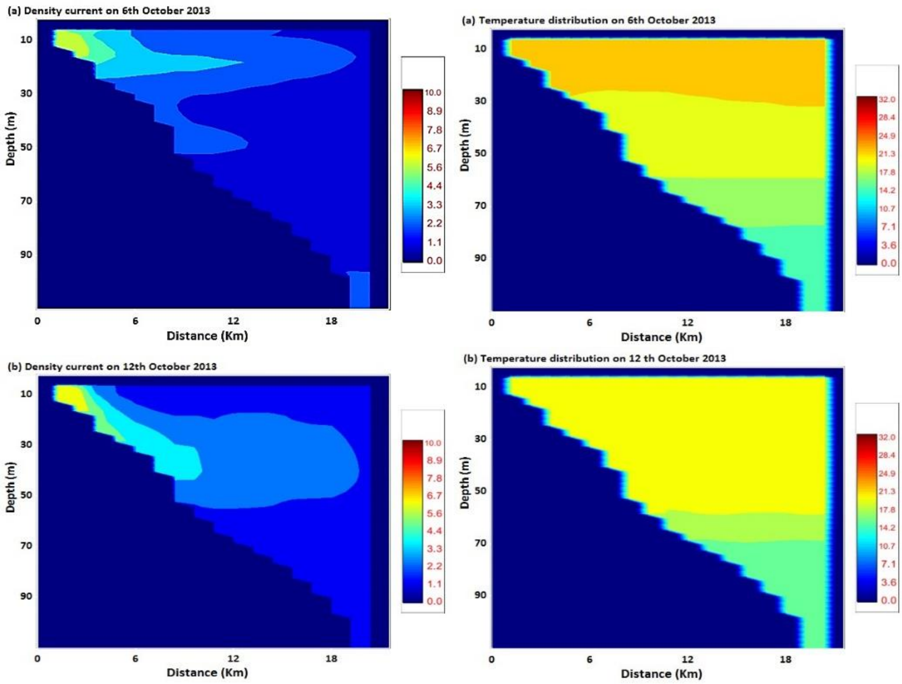

Figure 8: Simulations of density currents and temperature distributions in the Fei-Tsui Reservoir water body during (a) 6th October 2013 and (b) 12th October 2013

CONCLUSIONS

A two-dimensional hydrodynamic and water quality model, namely, CE-QUAL-W2, was configured and applied for hydrodynamic and water quality modeling in the Fei-Tsui Reservoir. The model was calibrated and verified with data from 2004, 2005 and 2006 in the Fei-Tsui reservoir. The hydrodynamic model is able to accurately simulate the temporal and spatial distributions of temperature in the water column. The model results closely reproduce the measured full vertical profiles of temperature in the Fei-Tsui Reservoir. Thermal stratification in the Fei-Tsui Reservoir was well predicted with the depths of the thermocline in each year. The W2 model successfully simulates the spatial and temporal concentration distributions of major water quality parameters such as TSM, DO, Chl-a, NH_4, NO_3 and PO_4. Generally, good fits between the simulated and observed results demonstrated that the W2 model is capable of simulating various hydrodynamic and water quality parameters in the Fei-Tsui Reservoir. The water quality coefficient values obtained from the model calibration and verification in this study are smaller than the values reported for similar reservoirs. The W2 model calibrated using the high-frequency dataset performs better in the water quality simulation. The occurrence of different types of density currents suggested that the water temperature distribution in the water column played an important role in the pattern of turbid runoff. The W2 model is recommended to be further used to evaluate future management strategies related to eutrophication control.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

AFSHAR A, SAADATPOUR M. (2009). Reservoir eutrophication modelling, sensitivity analysis, and assessment, application to Karkheh Reservoir, Environmental Engineering Science, Vol. 26, Issue 7, pp.1227-1238.

BAKER T, DYCUS D. (2004). Use of monitoring information to identify and implement water quality improvement, In: National monitoring conference, Chattanooga, TN, USA, May, pp. 17–20.

BOWEN J.D., HIERONYMUS J.W. (2003). A CE-QUAL-W2 Model of Neuse Estuary for total maximum daily load development, Journal of Water Resources Planning and Management, Vol. 129, Issue 4, pp.283–294.

CHANG C.H., CAI L.Y., LIN T.F., CHUNG C.L., LINDEN L.V.D., BURCH M. (2015). Assessment of the impacts of climate change on the water quality of a small deep reservoir in a humid-subtropical climatic region, Water, Vol. 7, pp.1687-1711.

CHOW M.F., SHIAH F.K., LAI C.C., KUO H.Y., WANG K.W., LIN C.H., CHEN T.Y., KOBAYASHI Y., KO C.Y. (2016). Evaluation of surface water quality using multivariate statistical techniques: a case study of Fei-Tsui Reservoir basin, Taiwan. Environmental Earth Sciences, Vol. 75, Article number 6.

CHOW M.F., YUSOP Z. MOHAMED M. (2011). Quality and first flush analysis of stormwater runoff from a tropical commercial catchment, Water Science and Technology, Vol.63, Issue 6, pp.1211-1216.

CHOW M.F., YUSOP Z., TORIMAN M.E. (2013). Level and transport pattern of fecal coliform bacteria from tropical urban catchments, Water science and technology, Vol. 67, Issue 8, pp.1822-1831.

CHUNG S.W., OH J.K. (2006). Calibration of CE-QUAL-W2 for a monomictic reservoir in monsoon climate area, Water science and technology, Vol. 54, Issue 12, pp.1291-1298.

COLE T.M., WELLS S.A. (2000). Workshop Notes on Hydrodynamic Modeling with Application to CE-QUAL-W2, Portland State University, Portland, Oregon, USA.

DEBELE B., SRINIVASAN R., PARLANGE J.Y. (2008). Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins, Environmental Monitoring and Assessment, Vol.13, pp.135-153.

DIOGO P.A., FONSECA M., COELHO P.S., MATEUS N.S., ALMEIDA M.C., RODRIGUES A.C. (2008). Reservoir phosphorous sources evaluation and water quality modeling in a trans-boundary watershed, Desalination, pp.200-226.

EHTERAM M., GHOTB, S., KISI O., NAJAH AHMED A., HAYDER G., MING FAI C., KRISHNAN M., ABDULMOHSIN AFAN H., EL-SHAFIE A., (2019). Investigation on the potential to integrate different artificial intelligence models with metaheuristic algorithms for improving river suspended sediment predictions, Applied Sciences, Vol. 9, Issue 19, Article number 4149.

ETEMAD-SHAHIDI A,, AFSHAR A., ALIKIA H., MOSHFEGHI H. (2009). Total dissolved solid modeling; Karkheh reservoir case example, International Journal of Environmental Research, Vol. 3, Issue 4, pp.671–680

FAI C.M., BAKAR M.F., ROSLAN M.A., FADZAILAH F.A., IDRUS M.F., ISMAIL N.F., SIDEK L.M., BASRI H., (2015). Hydrological performance of native plant species within extensive green roof system in Malaysia, ARPN Journal of Engineering and Applied Sciences, Vol. 10, Issue 15, pp.6419-6423.

GARVEY E.J., TOBIASON M., HAYES WOLFRAM E, RECKHOW D.A., MALE J.W. (1998). Coliform transport in Pristine Reservoir: modeling and field studies. Water science and technology, Vol. 37, Issue 2, pp.137-144.

GELDA R.K., EFFLER S.W. (2007). Testing and application of a two-dimensional hydrothermal model for a water supply reservoir: implication of sedimentation, Environmental Engineering Science, Vol. 6, Issue 1, pp.73–84.

GUNDUZ O., SOYUPAK S., YURTER C. (1998). Development of water quality management strategies for the proposed Isikli Reservoir, Water science and technology, Vol. 37, Issue 2, pp.369-376.

HU G., WANG L.A., YUAN H., BAO L., OU YO. (2008). Release of N, P from submerged soil in the bottom part of shore-area in Three Gorges Reservoir, Resources and Environment in the Yangtze Basin, Vol. 17, Issue 5, pp.122-126, (in Chinese).

HUANG T.C.C, LO K.F.A. (2015). Effects of Land Use Change on Sediment and Water Yields in Yang Ming Shan National Park, Taiwan, Environments, Vol. 2, Issue 1, pp.32-42.

KORNECKI T.S., SABBAGH G.J., STORM D.E. (1999). Evaluation of Runoff, Erosion, and Phosphorus Modeling System: SIMPLE, Journal of the American Water Resources Association, Vol. 35, pp. 807-820.

KUO J.T., WANG Y.Y., LUNG W.S. (2006). A hybrid neural-genetic algorithm for reservoir water quality management, Water Research, Vol. 40, pp.1367-1376.

KURUP R.G., HAMILTON D.P., PHILLIPS R.L. (2000). Comparison of two-dimensional, laterally averaged hydrodynamic model application to the Swan River Estuary, Mathematics and Computers in Simulation, Vol. 51, Issue 6, pp.627-638.

LIU W.C, CHEN W.B, KIMURA N. (2008). Impact of phosphorus load reduction on water quality in a stratified reservoir-eutrophication modeling study, Environmental Monitoring and Assessment, Vol. 159, pp.393–406.

MC KEE C.P, THACKSTON E.L., SPEECE R.E, WILSON D.J., CARDOZO R.J. (1992). Technical Report No.42, Modeling of water quality in Cheatham Lake. Environmental and Water Resources Engineering, Vanderbilt University, Nashville, USA.

NAJAH A., TEO F.Y., CHOW M.F., HUANG Y.F., LATIF S.D., ABDULLAH S., ISMAIL M., EL-SHAFIE A. (2021). Surface water quality status and prediction during movement control operation order under COVID-19 pandemic: Case studies in Malaysia, International Journal of Environmental Science and Technology, Vol. 18, Issue 4, pp.1009-1018.

NIELSEN E.J. (2005). Algal Succession and Nutrient Dynamics in Elephant Butte Reservoir, M.Sc. Thesis, Brigham Young University, Provo, Utah, USA.

REMINI B. (2018). The density current in the Foum El Gherza dam (Algeria), Larhyss Journal, No 35, pp. 87-105. (In French)

REMINI B. (2019). The current density: a natural phenomenon that manifests in arid regions, Larhyss Journal, No 40, pp. 165-194. (In French)

SULLIVAN A.B., JAGER H.I, MAYERS R. (2003). Modeling white sturgeon movement in a reservoir: the effect of water quality and sturgeon density, Ecological Modelling, Vol. 167, Issues 1–2, pp.97–114.

SULLIVANW A.B., ROUNDS S.A. (2005). Report on Modeling Hydrodynamics, Temperature and Water Quality in Henry Hagg Lake, Oregon 2000-2003, USA.

THOMANN R.V. (1982). Verification of water quality models, Journal of Environmental Engineering, Vol. 108, Issue 5, pp. 923–940.

TILZER M.M., GOLDMAN C.R. (1978). Importance of mixing, thermal stratification and light adaptation for phytoplankton productivity in Lake Tahoe, California Nevada, Ecology, Vol. 59, Issue 4, pp.810 - 821.

VAROL M., GOKOT B., BEKLEYEN A, SEN B. (2012). Spatial and temporal variations in surface water quality of the dam reservoirs in the Tigris River basin, Turkey, Catena, Vol. 92, pp.11-21.

WELLS S.A. (2005). Surface Water Hydrodynamic and Water Quality Models: Use and Misuse. In: 26th Annual Water Law Conference, San Diego, California, USA.

WELLS, S.A. (2020a). CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.2.2, user manual part 2, hydrodynamic and water quality model theory," Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon, USA.

WELLS, S.A. (2020b). CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.2.2, user manual part 4, model examples. Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon, USA.

WETZEL R.G. (2001). Limnology, Lake and river systems, 3rd ed., Academic Press, San Diego, USA.

WU R.S., LIU W.C., HSIEH W.H. (2004). Eutrophication Modeling in Shihmen Reservoir, Taiwan, Journal of Environmental Science and Health, Part A, Vol. 39, Issue 6, pp.1455-1477.

XU Z., GODREJ A.N., GRIZZARD T.J. (2007). The hydrological calibration and validation of a complexly linked watershed–reservoir model for the Occoquan watershed, Virginia, Journal of Hydrology, Vol. 345, Issue 3-4, pp.167–183.

YE C., XU Q.J., KONG H.N., SHEN Z.M., YAN C.Z. (2007). Eutrophication conditions and ecological status in typical bays of Lake Taihu in China, Environmental Monitoring and Assessment, Vol. 135, Issues 1-3, pp.217–225.