Evaluation of the WRF-lake model at a large dimictic reservoir: A comparison with field data and another water temperature model

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Evaluation of the WRF-lake model at a large dimictic reservoir: A comparison with field data and another water temperature model

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Key Points:

- The WRF-lake model has imperfect surface simulation and worse simulation for deep layers, even with carefully chosen parameterization.
- Modifying the diffusion coefficient can only effectively improve the simulation of the WRF-lake model for deep layers, but not the surface.
- Inflow-outflow and topography, have a significant effect on the whole temperature profile and should be reasonably accounted for.

Abstract

The one-dimensional (1D) lake model, a submodule in the Weather Research and Forecasting (WRF) system (WRF-lake) was evaluated in a large dimictic reservoir, Miyun Reservoir, in northern China. Another 1D lake model, Minlake, which has been successfully applied in this reservoir and many other lakes/reservoirs, was applied as a reference. Simulated results showed that Minlake was able to reproduce the whole temperature profile of Miyun Reservoir accurately. For WRF-lake, although we used carefully chosen parameterization (the same surface absorption fraction, light attenuation coefficient and initial temperature as with Minlake, as well as modified surface roughness lengths), the model still had imperfect surface temperature simulation and completely inaccurate simulation in the deep layers. Several numerical experiments were carried out to study the impact of three factors (thermal diffusivity, inflow-outflow and topography) on the two 1-D models' performances, and we found: (1) Modifying the diffusion coefficient of WRF-lake can improve the simulation of deep layers but cannot influence the surface temperature. (2) Inflow-outflow and topography have a significant effect on the whole temperature profile. Overall, the WRF-lake model can be coupled with WRF when applied to reservoirs like Miyun, as it can reproduce surface water temperatures to some extent (Nash–Sutcliffe efficiency coefficient > 0.9). However, for better model performance in reservoir physical processes description and more extensive application to other reservoirs with larger flow rates or larger storage capacity, optimizing the parameterization for thermal diffusivity, inflow-outflow and topography needs to be done in future work.

1 Introduction

Water-atmosphere interactions over lakes and reservoirs can significantly affect local climate (Bates et al., 1993; Swayne et al., 2005; Leon et al., 2007; Adrian et al., 2009; Subin et al., 2012; Gerken et al., 2013, 2014; Gu et al., 2015, 2016; Steenburgh et al., 2017). Compared with land surfaces, water surfaces have low surface roughness, and larger heat capacity etc., tending to change air temperature, humidity and other meteorological elements (Bonan,1995; Samuelsson et al., 2010; Subin et al., 2012; Xu et al.,2016). For example, water is warmer than air in winter, causing more heat release into the atmosphere; conversely, water is colder than air in summer, causing more heat absorption from the atmosphere. (Krinner et al., 2003; Dutra et al., 2010; Wang et al., 2019) Therefore, the influence of water-atmosphere interactions on the surrounding environment has very important research value.

In recent years, the mesoscale numerical atmospheric model Weather Research and Forecasting (WRF) system has been widely applied to examine water-atmosphere interactions, forecast weather (Subin et al. 2012; Gu et al., 2015), and analyze large-scale hydrology (Skamarock et al., 2008). The WRF-lake model is a one-dimensional (1D) lake model included as a submodule in the WRF system (Cipagauta et al., 2014; Fang et al., 2017). The concept of WRF-lake was developed from Henderson-Sellers's eddy diffusion thermocline models (Henderson-Sellers et al., 1985), dividing the lake into several vertical layers and solving the 1D thermal diffusion equation (Hostetler et al., 1990; Hostetler et al., 1993; Bonan et al., 1995; Subin et al., 2012). Subin et al. (2012) added sediment, ice, and snow layers to WRF-lake, then parameterized the model based on the CLM4.LISSS scheme. Gu et al. (2015) found that WRF-lake could reproduce the surface water temperature accurately in shallow lakes but performed poorly in deep lakes (e.g., depth >50 m), because the model underestimated heat transfer between the lower and upper parts of deep lakes through unrealistic eddy diffusivity. Xiao et al. (2016) also found this poor performance in deep lakes when evaluating WRF-lake in the Laurentian Great Lakes, and improved it by adjusting the lake surface albedo and increasing the eddy diffusivity. Xu et al. (2016) evaluated the model over the Erhai Lake in southwestern China, testing the influence of surface radiation absorption, extinction of solar radiation in the water column, surface roughness, and the eddy diffusion coefficient, then adjusted these parameters for a better model performance. Fang et al. (2017) applied the model in Nam Co Lake (in Qinghai-Tibetan Plateau) and provided an improvement scheme for the vertical mixing calculation. Huang et al. (2019) evaluated the model in a deep lake and modified the light extinction coefficient, maximum water density setting and the surface roughness according to different seasons. After a series of modifications and improvements, it has been proved that WRF-lake can be applied to all kinds of natural lakes.

Reservoirs have more complex hydrological processes, and this is to a large extent because of inflow and outflow (Chen et al., 2015; Li et al., 2016; Xie et al., 2017). Reservoirs commonly undergo relatively large temporal variations with water storage and water surface elevation.

This can significantly influence the thermal processes in reservoirs (Li et al., 2016; Xie et al., 2017; Wang et al, 2019) and in turn have a significant impact on reservoir-atmosphere interactions (Samuelsson et al., 2010; Dutra et al., 2010; Deng et al., 2012; Xing et al., 2012; Stepanenko et al., 2013; Wang et al, 2019). However, there are few applications of WRF-lake to manmade reservoirs. Compared with natural lakes, manmade reservoirs have higher annual inflows and outflows, resulting in more complex hydraulic characteristics. Factors such as water level fluctuations and large flow rates may cause changes in water temperature structure simulation, then affect model performance (Owens et al., 1986; Straškraba et al., 1993; Owens et al., 1998; Nowlin et al., 2004; Li et al., 2010; Xing et al., 2012; Li et al., 2016). Therefore, whether WRF-lake can describe the physical processes of reservoirs with continuous inflows and outflows needs to be studied.

We evaluated WRF-lake with observed and simulated water temperatures for Miyun Reservoir, a large manmade dimictic reservoir in Beijing, China, under the conditions of the water level changing continuously. Moreover, we conducted a series of sensitivity tests to evaluate the influences of three factors (thermal diffusivity, through flow and topography) on model performance.

We also compared the simulation of WRF-lake with another 1D lake model, Minlake, which has ever been applied to Miyun Reservoir successfully (Zhu et al., 2015; Li et al., 2016). Minlake simulates vertical water temperature and dissolved oxygen distributions of lakes and reservoirs. This model was proposed by Riley for lake eutrophication studies and control strategies (Riley et al., 1987). Some versions of the model have been applied to some natural lakes and manmade reservoirs, being capable of simulating all hydraulic characteristics, e.g. Minlake96 (Fang et al., 1996), Minlake2010 (Fang et al., 2012) and Minlake2012 (Li et al., 2016). The latest Minlake version is the Minlake2012 model, containing a Chinese weather database and a spreadsheet interface. Thiery et al. (2013) evaluated the representation of a large, deep tropical lake, Kivu, in Africa, using this model. Li et al. (2016) applied the model to Miyun Reservoir in Beijing to study its water temperature stratification characteristics from 1998 to 2011. In another work, the Minlake model was applied to Miyun Reservoir and successfully simulated the stratification characteristics of water temperature and dissolved oxygen distributions with the water level declining between 1998 and 2011(Zhu et al., 2015). During the Middle Routine Project of the South-to-North Water Diversion of China, one-dimensional numerical simulation has played an important role in providing technical support. Therefore, we included Minlake to better characterize and understand the performance of WRF-lake.

This paper has the following objectives:

(1) To evaluate the application of WRF-lake in a large manmade dimictic reservoir, Miyun Reservoir;

(2) To study the effects of different elements (thermal diffusivity, through flow and topography) on the model performance of water temperature simulation.

2 Methods

2.1 Model description of WRF-lake

The WRF-lake model divides the water body into layers of uniform horizontal areas but varying vertical discretization. Thermal sources into the water body include longwave radiation, shortwave radiation, latent heat flux and sensible heat flux, with snow and ice influencing the net downward heat flux. Soil and bedrock under the water body are also represented (Figure 1).

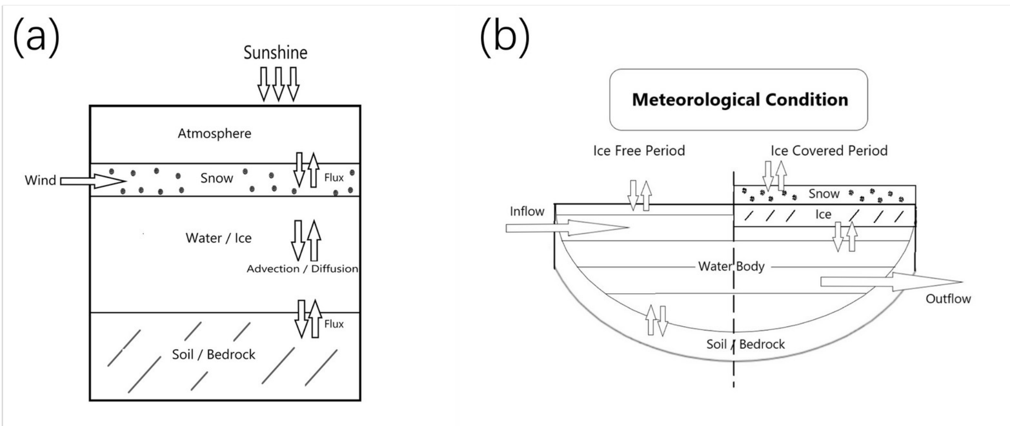

Figure 1. (a) Schematic of the WRF-lake model based on the original concepts of Subin et al. (2012); (b) Schematic of the Minlake model based on the original concepts of Li et al. (2016).

Thermal exchanges between water layers are described by solving the 1D unsteady thermal diffusion equation (Subin et al. 2012):

$$\frac{\partial T}{\partial t}=\frac{1}{A}\frac{\partial}{\partial z}\left(AK\frac{\partial T}{\partial z}\right)+\frac{1}{c_{liq}}\frac{d\varnothing}{dz} \quad (1)$$

where K is the diffusion coefficient of the water body, used to describe the heat exchange between layers, T is water temperature (°C), t is time (s), A is surface area of the control volume (m^2) (In WRF-lake model, A =1), c_{liq} is volumetric heat capacity of the water (J kg^{-1} K^{-1}), z is depth from the surface (m), and $\varnothing$ is the subsurface solar radiation heat source term (W m^{-2}) (Hostetler et al., 1990).

and $$K=K_m+K_e \quad (2)$$

where K_m is the molecular diffusion coefficient (1.433 × 10−7 m^2 s^{-1}), and K_e is the wind-driven eddy diffusion coefficient (Henderson-Sellers et al., 1983, 1985):

$$K_e=\frac{k w z}{P_0}e^{(-k^{*}z)}/\left(1+37R_i^2\right) \qquad T_g>T_f \quad (3)$$

$$K_e=0 \qquad T_g<T_f \quad (4)$$

where k is a coefficient (von Karman constant), w is wind speed (m s^{-1}), z is the depth of each layer (m), P_0 is neutral turbulent Prandtl number, R_i is gradient Richardson number, T_g is surface temperature (°C), and T_f is the freezing temperature of water (°C),

$$k^{*}=6.6\times(\sin\phi)^{1/2}u^{-1.84} \quad (5)$$

where ϕ is latitude.

Some earlier studies contended and modified the parameterization for K, which is defective in WRF-lake (Csanady et al., 1964, 1966; Sweers et al., 1970). Subin et al. (2012) found that the simulations were always improved by increasing the K value. Gu et al. (2015) found it was reasonable to multiply the K value by factors ranging from 10^2 to 10^5, and these factors became 10^2 when the depth was from 15m to 150m and the simulated surface temperature was higher than 4°C. Xu (2016) carried out a sensitivity test of diffusion coefficient and found the default *K* values were too large when applying WRF-lake in Erhai Lake. Fang et al. (2017) found that the weak vertical mixing in the WRF-lake model means a large amount of energy is stored in the shallow water, and. this was inferred as the cause of poor performance in deep-water temperature simulation. Wang et al. (2019) summarized the above researches and improved the parameterization of the *K* values by creating a new lake model, WRF-rLake, on the basis of the original WRF-lake. In our simulation, we also studied the effects of the *K* values on Miyun Reservoir water temperature simulation under conditions of the water level changing constantly (more in section 4.2).

Heat flux through the water surface is given by:

$$\beta S + L = H + E + G \quad (6)$$

where β is lake surface absorption fraction of net solar radiation S (W m^{-2}), L is net longwave absorbed radiation (W m^{-2}), H and E are sensible heat (W m^{-2}) and latent heat (W m^{-2}) from the water surface to the atmosphere, respectively, and G is heat from the water to the soil and bedrock (W m^{-2}).

Surface roughness lengths including momentum (z_{0m}), heat (z_{0h}) and water vapor (z_{0q}) are set to calculate the sensible heat and latent heat. In the default model settings, z_{0m}, z_{0h} and z_{0q} are set to 0.0024m for frozen lakes with resolved snow and 0.004m for frozen lakes without resolved snow. Some previous researches have proved that the default surface roughness lengths are often too large, so some modifications were made. Subin et al. (2012) provided settings of these three kinds of roughness lengths in another 1-D lake model (ColM-lake model) as follows: z_{0m} is set to 0.0024m for frozen lakes with resolved snow and 0.001m for frozen lakes without resolved snow, and

$$z_{oh} = z_{0q} = z_{0m} \exp\left(-0.13 R_0^{0.45}\right) \quad (7)$$

where R_0 is atmosphere roughness Reynolds number. Some researchers have applied this modification to WRF-lake and achieved better model performance (Wang et al.,2019; Huang et al., 2019). In our research, we also use this modification of surface roughness length setting.

2.2 Model description of MINLAKE2012

The Minlake model also divides the water body into vertical layers, but the horizontal areas vary with depth according to topographic data. During the ice formation period, snow and ice thickness are calculated. Unlike WRF-lake, Minlake calculates inflows and outflows, causing a constant changing of the water level and the water layer depths (Figure 1). The thermal exchange between water layers is also described by solving the 1D unsteady thermal diffusion equation (1), the same as with WRF-lake, but in Minlake, there is only the wind-driven eddy diffusion coefficient:

$$K = K_e \quad (8)$$

Compared with WRF-lake, Minlake has a different method to calculate the diffusivity; the K values are computed in two parts, epilimnion and hypolimnion, respectively (Riley et al., 1987, Li et al. 2016):

$$K = a w^{1.3} \quad \text{(in the epilimnion)} \quad (9)$$

¿ (in the hypolimnion) (10)

where K_{max} is the maximum K value of hypolimnetic, a is constant, taken to be 5.6 in Miyun Reservoir by Li et al. (2016), N is Brunt-Väisälä frequency. c_k is the minimum of the N values at the location of maximum K value of the hypolimnetic, usually taken to be 8.66×10^{-3}. K_{max} and N are expressed as:

$$K_{max} = a w^{1.3} \text{¿} \quad (11)$$

$$N = \left(\frac{g}{\rho} \frac{\partial \rho}{\partial z} \right)^{1/2} \quad (12)$$

where w is wind speed (m s^{-1}), g is acceleration of gravity (9.8 m s^{-2}), ρ is density (kg m^{-3}) of each layer, and z is lake depth (m).

Minlake models the dynamic lake water balance as:

$$\frac{dV(t)}{dt} = Q_I - Q_o + PA - EA + G \tag{13}$$

where $V(t)$ is the volume of the lake or reservoir (m^3), t is time (s), Q_I is inflow (m^3 s^{-1}), Q_0 is outflow (m^3 s^{-1}), P is rainfall (m s^{-1}), E is evaporation (m s^{-1}), G is net inflow from the underground water (m^3 s^{-1}), and A is surface area (m^2).

As for heat flux through the water surface, Minlake has the same equation as equation (6). There are also sources and sinks in the equation, which include longwave radiation, shortwave radiation, latent heat flux and sensible heat flux (Riley et al., 1987). Unlike WRF-lake, there is no surface roughness length in Minlake. Sensible heat and latent heat are calculated by equations which are functions of wind.

3 Study area, field data and model settings

3.1 Study area

Miyun Reservoir (40°25′N–40°37′N, 116°80′E–117°10′E) is the largest reservoir in northern China, with a volume of 4.375×10^9 m^3 at the maximum storage water level of 154m above sea level (ASL). Correspondingly, the maximum water depth is 43.5m and the maximum water area is 1.88×10^8 m^2. (Chen et al., 1998). The climate of the reservoir basin is moderate continental, being hot and wet in summer, and cold and dry in winter (Liang et al., 2005). Miyun Reservoir is an important water source for the Beijing region, accounting for 60% of the area's total water supply. Before 2014, the main recharge of the reservoir came from the Chaohe River and the Baihe River. Between 1998 and 2011, the annual inflow was between 1.5×10^8 m^3 to 1.1×10^9 m^3 (average value was 4×10^8 m^3), and the maximum inflow rate in 1998 was 766 m^3/s. Because of the large water demand in this period, the reservoir's water level decreased significantly, for example, there was an approximate water level decline of 15m in

1999 (Zhu et al., 2015). After the Middle Routine Project (MRP) for the South-to-North Water Diversion Project was put into operation, Miyun Reservoir began to store excess water and its water level recovered. As a large water ecosystem, Miyun Reservoir is an important part of the ecological environment in Beijing city (Chen et al., 1998). The construction and impoundment of a reservoir can influence the surrounding environment, such as the meteorological, hydrological and ecological characteristics (Deng et al., 2012; Subin et al., 2012; Gu et al., 2015; Li et al., 2016; Jiang et al., 2018). Some studies have indicated that this manmade reservoir might be exacerbating climate warming in surrounding areas (Xia et al., 2007; Ma et al., 2010; Bao et al., 2012; Li et al., 2016). Therefore, increasing attention has been paid to the study of its water temperature.

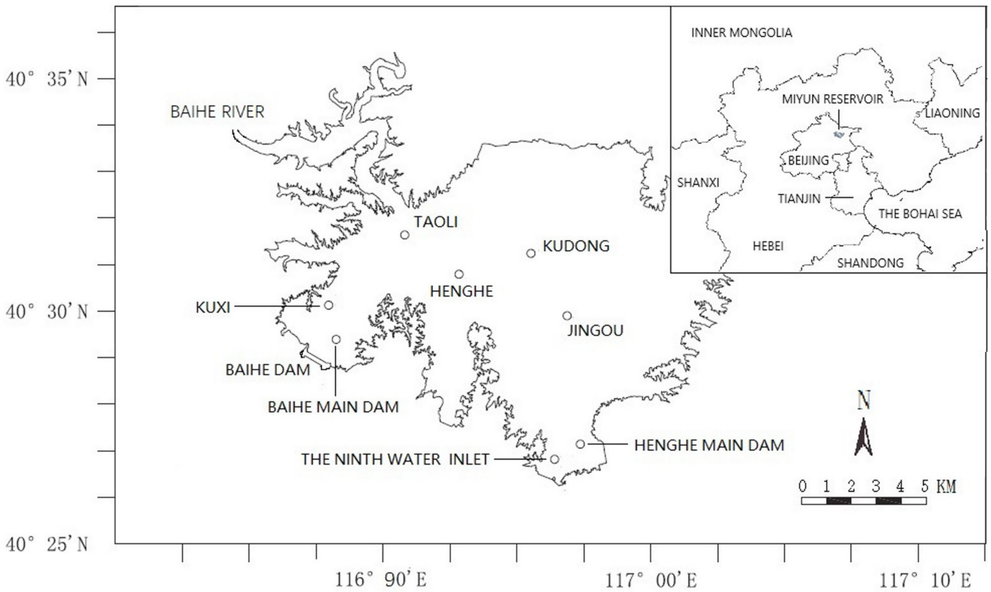

Figure 2. Location of Miyun Reservoir. The circles show the locations of the eight temperature observation stations.

3.2 Model configuration and input data

Model configuration and initialization are based on measured conditions and previous researches:

1) The initial depth of the reservoir is set to 39m. (In both WRF-lake and Minlake)
2) The layer division scheme is as follows: In WRF-lake, according to previous researches, for a lake of which the depth is less than 50m, it is reasonable to set 5 layers for snow and 10 layers (the top layer is set to 0.1m depth and the other 9 layers account for the remaining depths) for ice and water (Gu et al., 2015; Wang et al., 2019). In Minlake, there are 8 small depth layers for calculating the depth of snow and ice, and 10 layers for the other depths (Li et al., 2016).
3) The lake surface absorption fraction is set to 0.4. (Default in both WRF-lake and Minlake)
4) The light attenuation coefficient for 1D lake models has proven to be reasonable between $0.13m^{-1}$ and $3m^{-1}$ in previous researches (Gu et al., 2015; Wang et al., 2019). In our study, it was set to $0.43m^{-1}$ according to the calibration of Li et al. (2016) for Miyun Reservoir (In both WRF-lake and Minlake).
5) The surface roughness length setting is as the modification of Subin et al. (2012) (In WRF-lake).
6) The location of the outlet is 15m above the bottom of the reservoir (In Minlake).
7) At the beginning of a year, the water temperature of the whole reservoir is close to 4°C; therefore, for both WRF-lake and Minlake, we set this uniform initial temperature (4°C) for the whole lake column and use the first six years of simulation as a warming up period (In both WRF-lake and Minlake).

Our study period covers 1 January 1998 to 31 December 2011, 14 years in total. The meteorological data driving the model simulations, including downward shortwave and longwave radiation (W m^{-2}), atmospheric temperature (°C), atmospheric wind speed in the east and north directions (m s^{-1}), precipitation (mm s^{-1}),and atmospheric specific humidity (kg kg^{-1}), were acquired with 1-day temporal resolution from the China Meteorological Data Sharing Service System. The radiation data were from the Beijing Weather Station (39°48 ′N, 116°28 ′E), and the other data were from the Miyun Weather Station (40°23 ′N, 116°52 ′E).

The Minlake model additionally required hydraulic data and topographic data, with the former indicating daily inflow and outflow rates (m^3 s^{-1}) and monthly average inflow water temperatures (°C) observed by the Xiahui Hydrological Station and the Zhangjiafen Hydrological Station, and the latter indicating the area-depth curve and volume-depth curve of Miyun Reservoir from the Haihe Basin Water Information System (Zhu et al., 2015; Li et al., 2016).

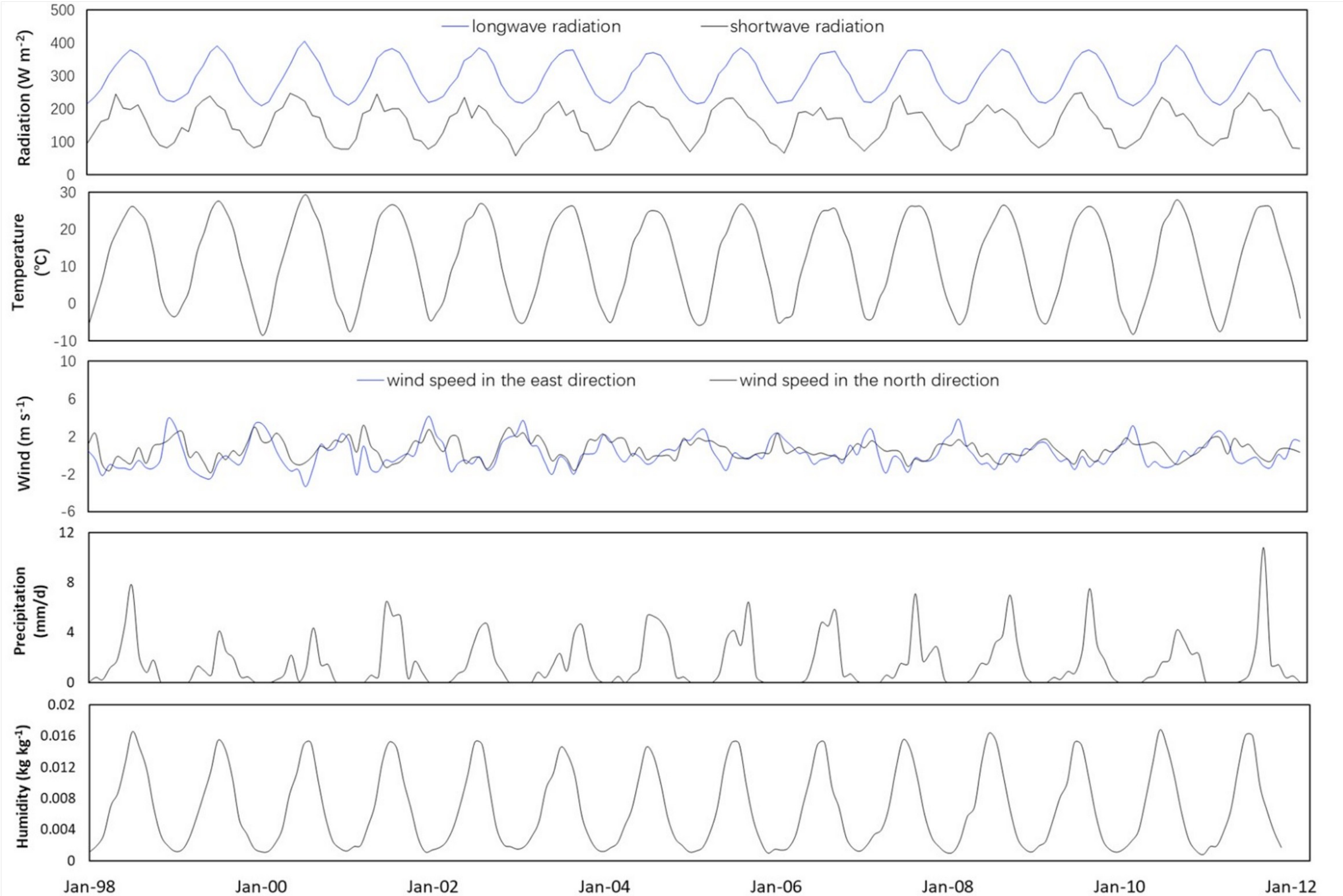
longwave radiation
shortwave radiation
Radiation (W m-2)
0
100
200
300
400
500
Temperature (℃)
-10
0
10
20
30
wind speed in the east direction
wind speed in the north direction
Wind (m s-1)
-6
-2
2
6
10
Precipitation (mm/d)
0
4
8
12
Humidity (kg kg-1)
0
0.004
0.008
0.012
0.016
0.02
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Jan-12

Figure 3. Monthly average meteorological data from 1998 to 2011.

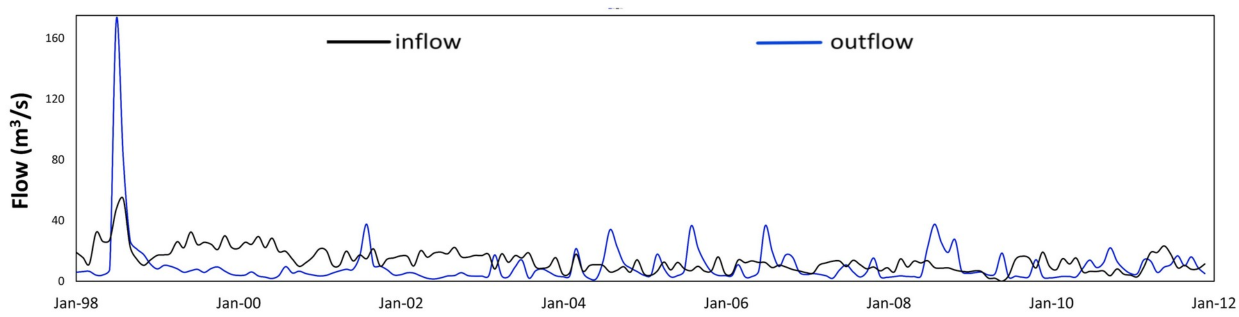

Figure 4. Monthly inflow and outflow rates from 1998 to 2011.

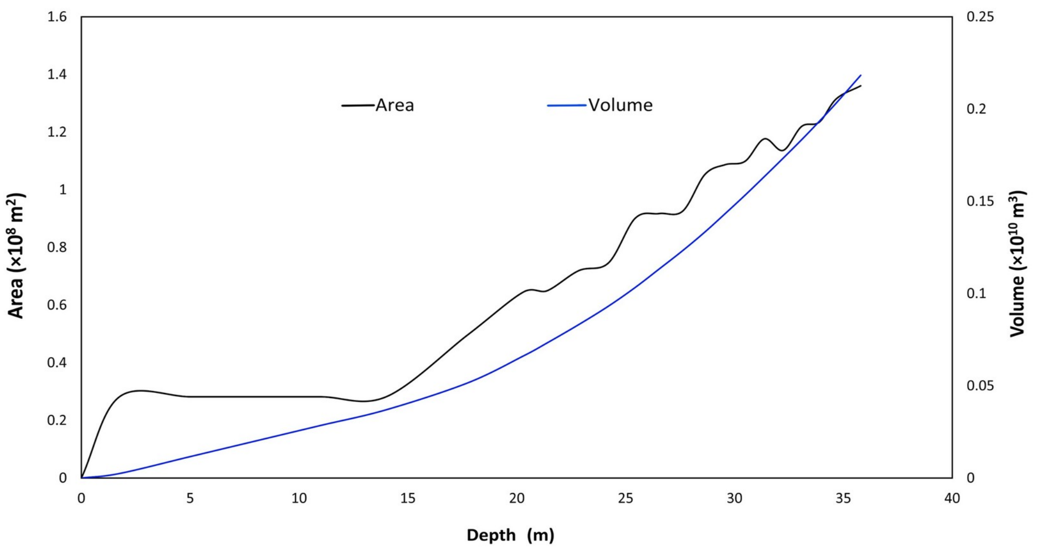

Figure 5. Area-Depth curve and Volume-Depth curve for Miyun Reservoir.

3.3 Field data

The field data for this study were acquired from the Miyun Reservoir Management Department. There are eight observational stations: Taoli, Henghe, Kudong, Kuxi, Baihe Main Dam, Henghe Main Dam, Ninth Water Inlet, and Jingou Station (Figure 2). The data from these stations were averaged for comparison with simulated results, since the models do not represent horizontal spatial heterogeneity. The water temperature data were measured at three depths, including surface, middle, and bottom. The surface water temperature data were averaged data of all these eight stations (except 2005, which was only measured at Baihe station). The middle and bottom water temperature data were averaged data of only five stations (Baihe, Kuxi, Chaohe, Shuijiu and Henghe), measured at half and bottom depth of each station only during ice-free periods (April-October).

3.4 Experiment scenarios

We designed a series of experiment scenarios to explore the influence of different elements (thermal diffusivity, inflow-outflow and topography) on model water temperature simulation (Table 1). M0 and W0 are the initial Minlake model and the initial WRF-lake model, respectively, and represent baseline simulations.

We removed the inflow-outflow submodule of Minlake in M1. M1 is designed to examine the role of non-equilibrium water depth resulting from differences in inflow-outflow. Scenario M2 is the Minlake model without the inflow-outflow submodule and with a uniform area of topography, which is designed to explore the influence of topography.

W1 is a scenario based on WRF-lake with larger *K* values (×10 (5-15m); ×100 (15-25m); ×1000 (25-39m)), and this scenario can reflect how the diffusion coefficient (*K* value) affects the simulation of WRF-lake.

Table 1. Design of different experiment scenarios

Experiment scenario	**Description**
M0	The initial Minlake model
M1	The Minlake model without inflow-outflow
M2	The Minlake model without inflow-outflow

	and topography
W0	The initial WRF-lake model
W1	The WRF-lake model with *K* values (×10 (5-15m); ×100 (15-25m); ×1000 (25-39m))

4 Results and discussions

4.1 Comparison of the results by original WRF-lake and Minlake (W0 and M0)

Figure 6 shows the measured and simulated water surface elevation from 1998 to 2011. As seen in this figure, the water surface elevation simulated using Minlake agreed well with the observed (Figure 6). While the water surface elevation simulated using WRF-lake remained unchanged over the 14 years. This is because WRF-lake does not have an inflow-outflow submodule, nor does it take into account precipitation or evaporation.

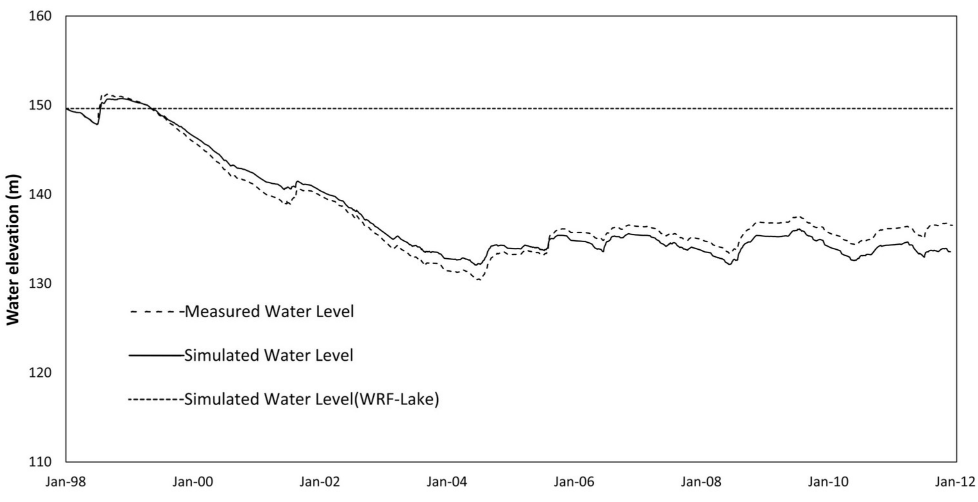

Figure 6. Water surface elevation from 1998 to 2011

The comparisons between simulated water temperature of Minlake (M0) and field data at different depths are shown in Figure 7. Here the surface, middle and bottom refer to vertical position at 0% depth, 50% depth and 100% depth, respectively. During ice-covered periods, the depth of ice cover is not included in the water depth, and the surface refers to the water right beneath the ice cover. The agreement between the field data and model simulation was evaluated as NSE (Nash–Sutcliffe model efficiency) coefficient (Figure 7(a) to Figure 7(c)). The NSE of Minlake between simulated and observed surface water temperature is 0.98, which suggests that Minlake can simulate the variation of the surface temperature accurately. The Minlake model can also describe the temperature at the middle depth (NSE = 0.76) and the bottom (NSE= 0.20). The simulation in Figure 7 shows that Minlake is reasonable to serve as a reference for WRF-lake in simulating water temperature of Miyun Reservoir.

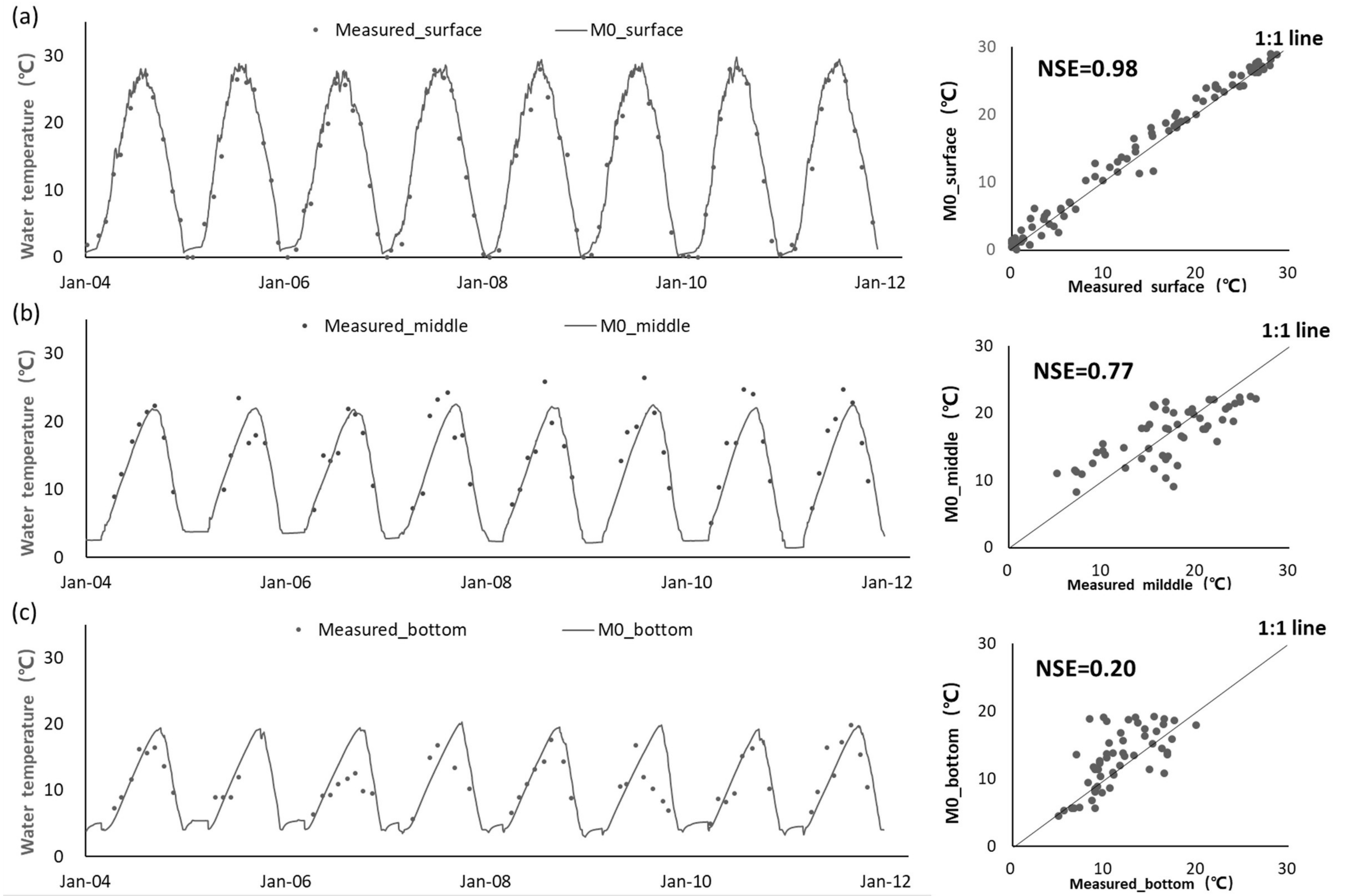
(a)
Measured_surface
M0_surface
Water temperature (℃)
Jan-04
Jan-06
Jan-08
Jan-10
Jan-12
NSE=0.98
1:1 line
M0_surface (℃)
Measured surface (℃)
(b)
Measured_middle
M0_middle
Water temperature (℃)
NSE=0.77
1:1 line
M0_middle (℃)
Measured milddle (℃)
(c)
Measured_bottom
M0_bottom
Water temperature (℃)
NSE=0.20
1:1 line
M0_bottom (℃)
Measured_bottom (℃)

Figure 7. Field data and simulation results of Minlake (M0) at different depths (i.e., surface, middle and bottom).

Our field data are limited to three depths, surface, middle and bottom. However, WRF-lake is unable to describe the water level fluctuation, so we cannot compare the middle and bottom simulated temperatures of WRF-lake with those of Minlake and the measured data directly. Therefore, we chose three depths including 0m (surface), 10m and 20m under the water surface to compare the simulated temperatures of WRF-lake and Minlake (Figure 8). The WRF-lake model can also describe the surface water temperature variation, with the NSE being 0.92, even without considering the inflow, outflow, topography and water level changes. This data-model agreement of the surface layer is essential for coupling this lake model with the WRF system, and meanwhile indicates that the main influencing factors of the surface temperature are meteorological elements, rather than the hydraulics or topographic elements. However, compared with Minlake, the surface layer simulation of WRF-lake is still flawed, having a lower temperature (e.g. about 2°C lower in summer). Moreover, in the deep-water layers (10m depth and 20m depth), a more inaccurate simulation occurred in WRF-lake, having a significantly lower temperature. In conclusion, WRF-lake simulated lower temperatures than the actual situation in the whole profile of Miyun Reservoir, and the lower temperature simulation was more obvious in the deep-water layers. The reason for this lower temperature simulation is discussed in the following three sensitivity tests (from section 4.2 to section 4.4).

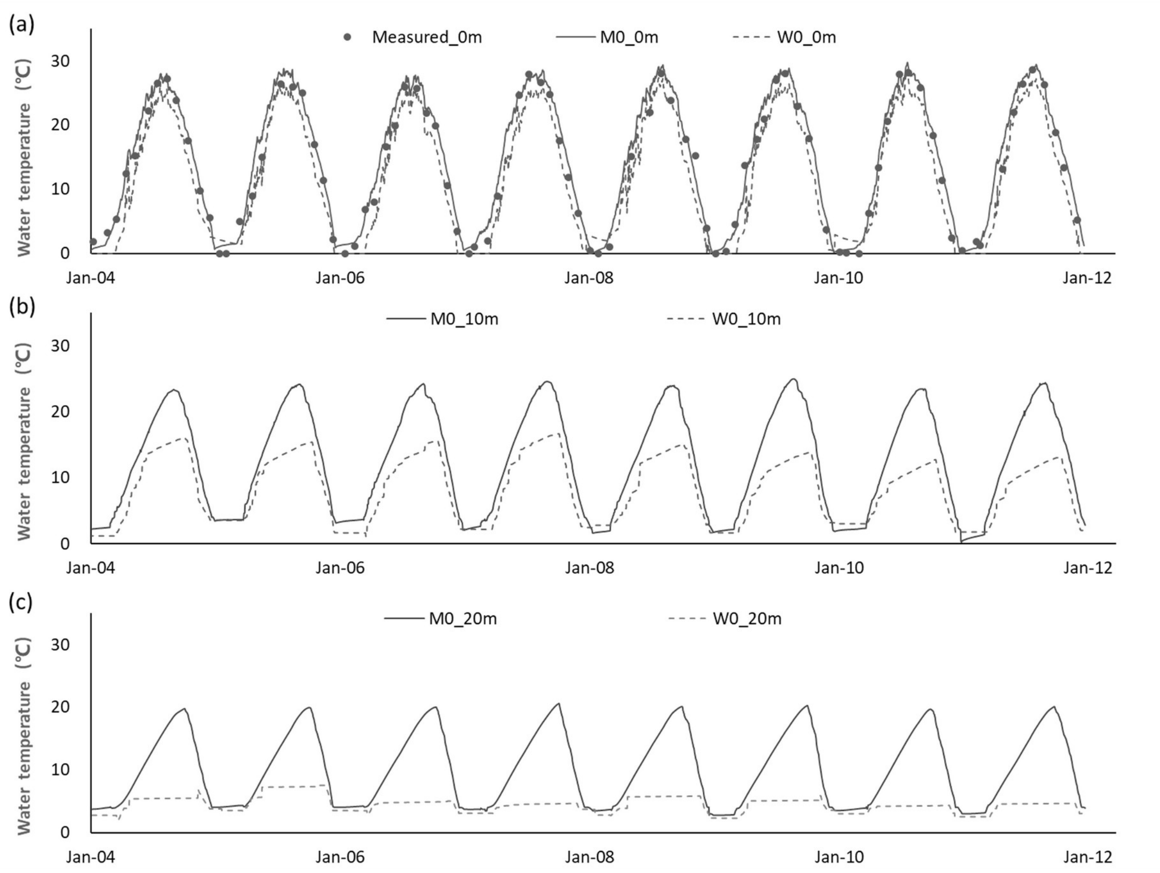

Figure 8. Simulated water temperature of original WRF-lake (W0) and Minlake (M0) at different depths (i.e., 0m, 10m and 20m).

4.2 Effects of the diffusion coefficient (*K*)

The diffusion coefficients (*K*) are also expected to influence the simulated water temperature. For a thermally stratified reservoir, the mixing process can be suppressed by stratification, and the diffusion coefficient will change accordingly with the mixing degree of the water body. As mentioned in section 2.1, the diffusion coefficients are often underestimated in WRF-lake. We surmised that bias between the simulated temperature of the two models was because of WRF-lake underestimating the *K* values of the water body. We chose 6 months from May to October (strong stratification period) in 1998, and compared the monthly average *K* values calculated by scenarios M0 and W0 (Figure 9). In the shallow water, the *K* values of the two models were relatively close, and WRF-lake even produced larger *K* in September and October. However, the *K* values of W0 fell off rapidly with the water depth increasing, being far less than those of M0, and were only of the same order of magnitude of molecular diffusivity (10^{-7} m^2s^{-1}). In contrast, the *K* values of M0 remained at about 10^{-5} m^2s^{-1} in the deep water. Clearly, the excessive attenuation of diffusion coefficient with depth by WRF-lake is one of the main reasons for insufficient mixing in deeper water.

Thus, a test was carried out to multiply the *K* values of WRF-lake by 10 from 5m to 15m depth, by 100 from 15m to 25m, and by 1000 from 25m to the bottom. The simulated results W1 are compared with those of M0 and W0 (Figure 10).

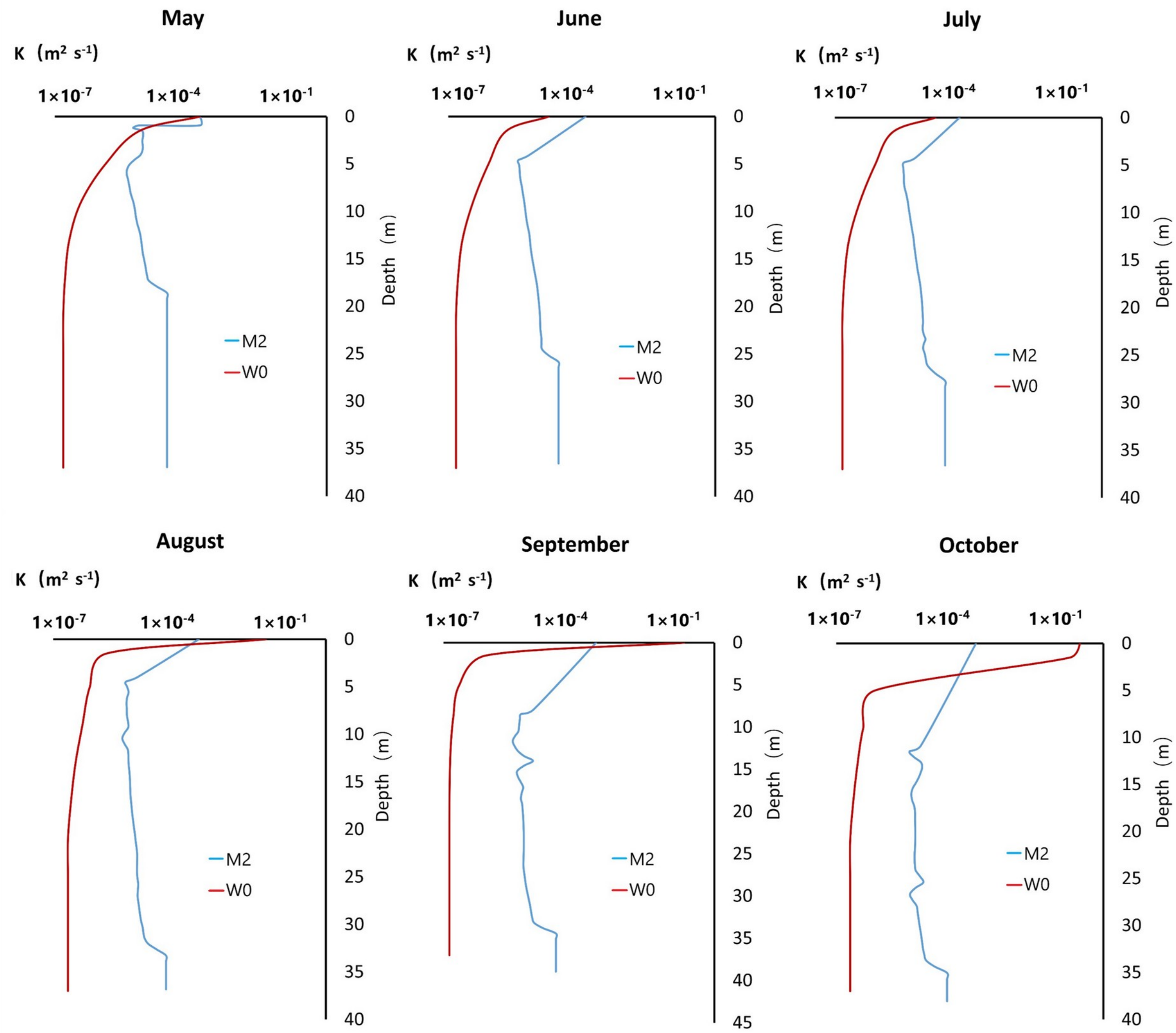

Figure 9. Monthly average *K* values of M0 and W0 from May to October in 1998

In this comparison (Figure 10(a) to Figure 10(c)), we found the underestimated vertical mixing resulted in worse performance of the 1D models. For the deep layers, there may be stronger mixing processes that equations (2), (3) and (4) are unable to capture. Therefore, when we multiplied the *K* values by a factor larger than 1, which increased the mixing degree of the water body, it resulted in higher and more reasonable temperatures for deeper water. However, larger K values did not influence the simulation of WRF-lake at the surface, with the surface temperature remaining basically unchanged. This finding accords with previous studies which argued that for shallow lakes with depths less than 50m, current parametrization of diffusivity is sufficient for surface water temperature simulation and one does not need to enlarge the parameters. (Martynov, et al., 2010; Gu, et al., 2015; Wang et al., 2019).

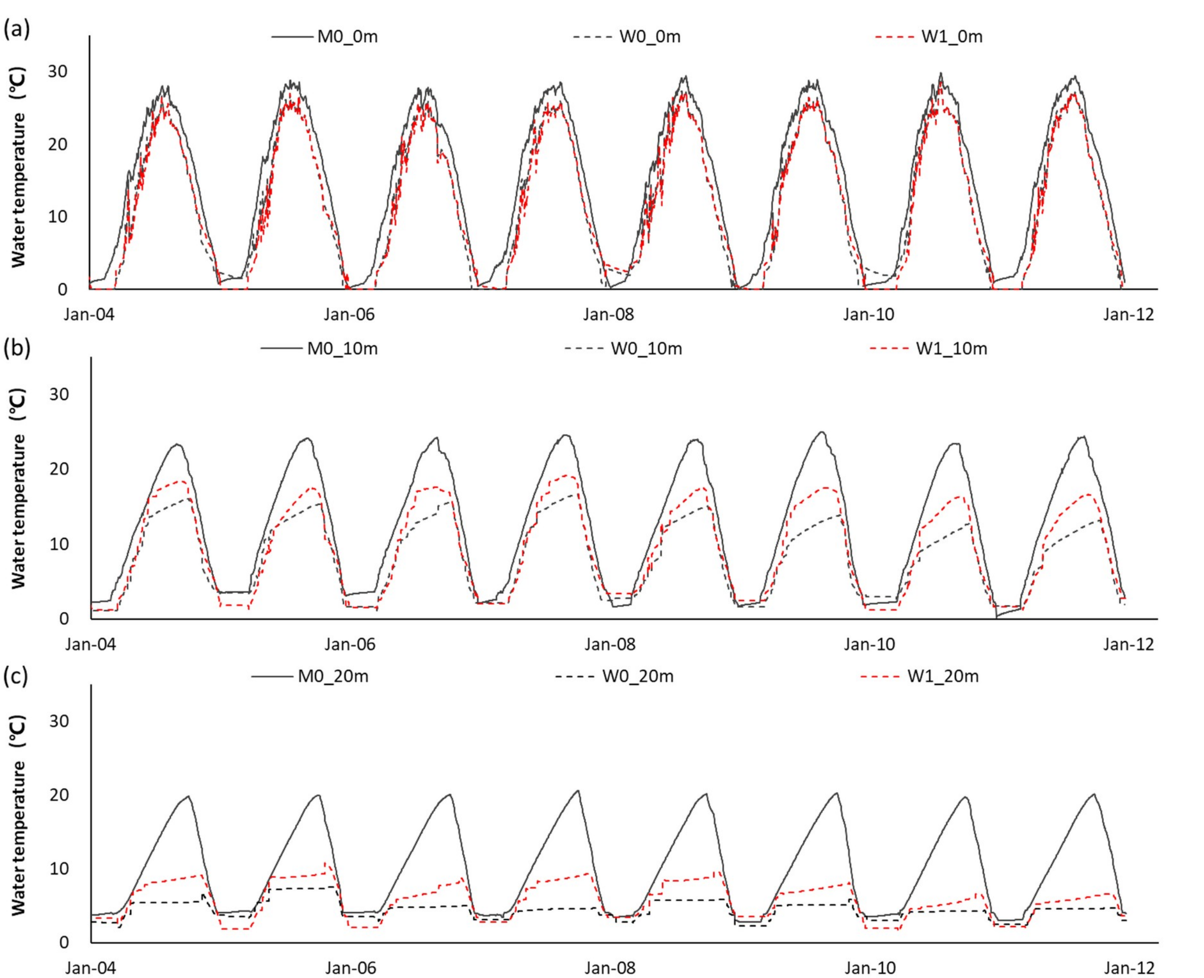

Figure 10 Simulated water temperature at different depths (i.e., 0m, 10m and 20m) including the results of WRF-lake with a better K values' modification (W1). (i.e., M0, W0 and W1)

4.3 Effects of inflow-outflow

We performed a sensitivity test with Minlake (M1) by removing the inflow-outflow submodule to study the effects of inflow-outflow. Besides the surface (0m) of the reservoir, we again chose two other depths (10m and 20m). We then compared the new simulation results of M1 (blue lines) with those of M0 and W1 (Figure 11(a) to Figure 11(c)).

After we removed the inflow-outflow submodule, we found the peak levels of the blue lines lower than that of the black lines at all three depths (Figure 11(a) and Figure 11(c)), particularly at 10m and 20m depths, suggesting that M1 simulated lower water temperature and the results were closer to W1. We next calculated the monthly outflow temperature minus inflow temperature between 2004 and 2011. The results (Figure 12) show that the outflow temperature was lower than the inflow temperature in summer.

Moreover, the flow rate in summer was always high. Therefore, more heat stayed in the reservoir and obviously lower annual maximum water temperature occurred, which is consistent with the simulated temperature of M0 and M1. In winter, the outflow temperature was higher than the inflow temperature, however, the air temperature and the inflow rate were quite low, so the surface temperature remained close to 0°C and the interior temperature remained close to 4°C.Therefore, removing the inflow-outflow scheme only has a small influence on winter water temperature simulation.

This sensitivity test proves that the inflow-outflow scheme is a non-ignorable influence element of accurate simulation for the whole temperature profile.

4.4 Effects of topography

A sensitivity test was then carried out to explore the influence of the topographic elements on 1D model water temperature simulation. Topographic features are considered in Minlake, with different water areas at different depths. However, areas of all layers in WRF-lake are uniform. In this experiment, we removed the inflow and outflow from Minlake, and set the surface area as a uniform area in the whole reservoir, and re-ran the simulation (red lines) of temperature at different depths (Figure 11).

The simulated temperature decreased a little at the surface (0 m), and decreased clearly at 10m and 20m depths. From the results (Figure 11(a) and Figure 11(c)), we can see that the red lines are always lower than the blue lines, which resulted from a vertically uniform lake area setting. The differences in deep-water layers were also expected, because a larger water area accounts for less temperature increase with the same heat source input. In winter, the surface temperature still remained close to 0°C and the interior temperature still remained close to 4°C for the same reason mentioned in section 4.2. Moreover, the new simulated temperature of M2 also became closer to that of WRF-lake (W1).

This sensitivity test proves that topography scheme is also a non-ignorable influence element for accurate simulation for the whole temperature profile.

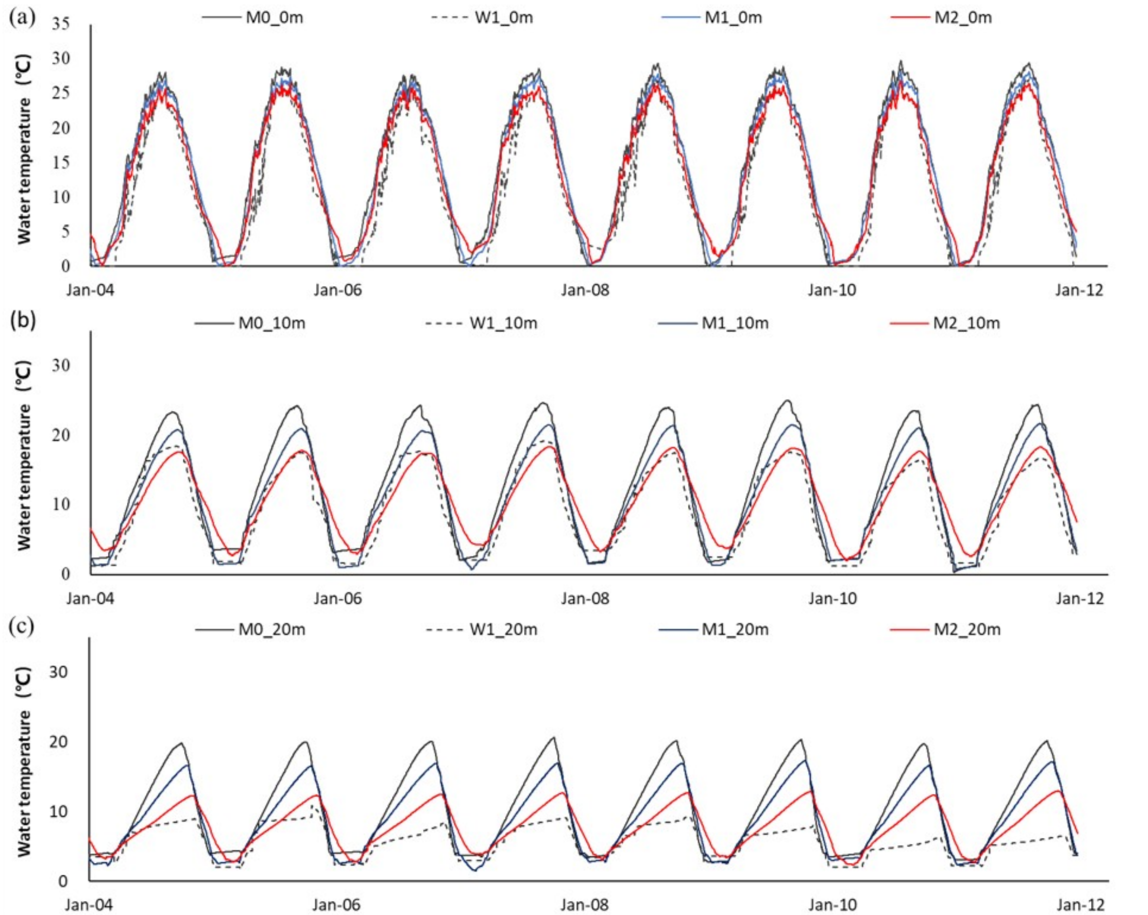

Figure 11. Simulated water temperature at different depths (i.e., 0m, 10m and 20m), including the results of Minlake without inflow-outflow (M1) and Minlake without inflow-outflow and topography (M2). (i.e., M0, W0, M1 and M2)

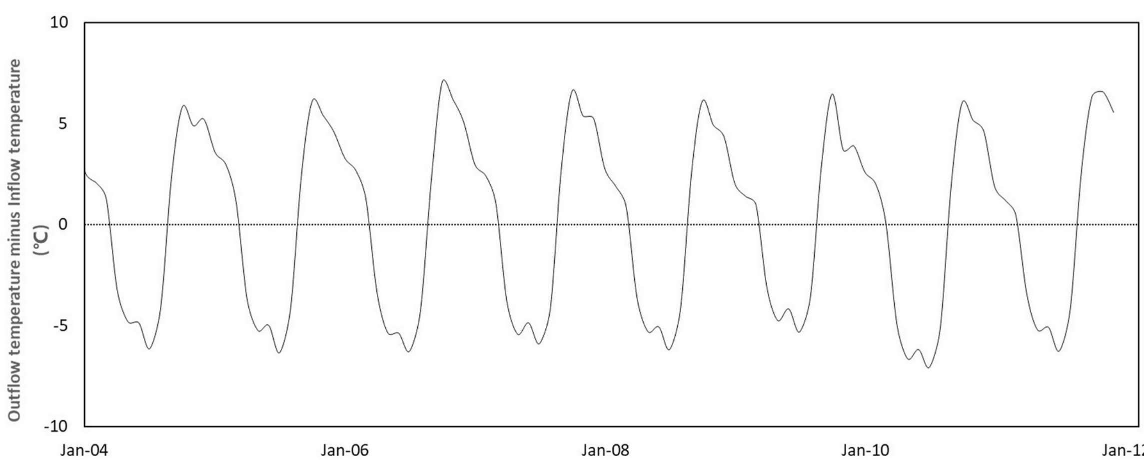

Figure 12. Outflow temperature minus inflow temperature between 2004 and 2011

4.4 Summary of these sensitivity tests

We ran a series of sensitivity tests on the basis of WRF-lake and Minlake to study the influence of diffusivity, inflow-outflow and topography on the 1D model water temperature simulation in Miyun Reservoir. After we provided modified K values, WRF-lake performed better in deep-water layers, but the surface temperature remained unchanged. After we removed the inflow-outflow submodule and the topography scheme of Minlake, we found the simulations of Minlake were obviously closer to those of WRF-lake in both surface and deep-water layers. Therefore, we can conclude that:

1) Modifying the diffusion coefficient of WRF-lake can improve the temperature simulation for deep-water layers but not for the surface;
2) The inflow-outflow scheme can influence the whole water temperature profile simulation, and the influence increases with the increase of depth.
3) The topography scheme can influence the whole water temperature profile simulation, and the influence increases with the increase of depth.

5 Summaries and conclusions

In this study, the applicability of a one-dimensional (1D) water temperature model, WRF-lake, was evaluated at a large manmade dimictic reservoir (Miyun Reservoir) in northern China. Another 1-D lake model, Minlake, which had been successfullyapplied in this reservoir and many other lakes/reservoirs, was used for comparison. Observed water temperatures at 8 stations between 1998 and 2011 were acquired as field data for reference. Moreover, we ran a series of sensitivity tests to study the influence of diffusivity, inflow-outflow and topography on the 1D model water temperature simulations in Miyun Reservoir. Based on these results, the following conclusions can be drawn:

1) Although we provided carefully chosen parameterization (the same surface absorption fraction, light attenuation coefficient and initial temperature as with Minlake, as well as modified surface roughness lengths), WRF-lake still has imperfect surface temperature simulation and evidently inaccurate simulation in the deep-water layers.
2) The values of the diffusion coefficient are underestimated in WRF-lake. Multiplying the diffusion coefficient (K value) by 10 for the shallow water, 100 for the middle and 1000 for the bottom of WRF-lake can improve the simulation for deep layers, but cannot influence the surface temperature.
3) Disabling the inflow-outflow and topography scheme of Minlake markedly brings the two models' (Minlake and WRF-lake) simulations closer in both surface and deep-water layers, meaning that the inflow-outflow schemes and the topography schemes are non-ignorable influence elements for accurate simulation for the whole temperature profile.
4) With the increase of the water depth, the contribution of meteorological elements (the most important influence elements at the surface) on water temperature variation decreases, and those of hydraulics elements (inflow-outflow, diffusivity) and topography increase.

Though unable to describe the complete physical processes and the whole temperature profile of a reservoir, WRF-lake can be coupled with WRF climate system to some extent, as its NSE of surface temperature simulation is more than 0.9. But for better descriptions of the physical processes, for more accurate water-atmosphere heat exchange calculation and more extensive application to other reservoirs with larger flow rates or larger storage capacity, its parameterization for throughflow, topography and thermal diffusivity needs further exploration. The applicability of the WRF-lake model at more reservoirs and lakes with varied depths and terrains also needs to be studied.

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