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TEMPERATURE DYNAMICS INVESTIGATION AT SMALL AND SHALLOW LAKES USING HYDRODYNAMIC MODEL

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A three-dimensional time-dependent hydrodynamic and heat transport model of Lake Binaba, a shallow and small dam reservoir in Ghana, emphasizing the simulation of dynamics and thermal structure has been developed. Most numerical studies of temperature dynamics in reservoirs are based on one- or two-dimensional models. These models are not applicable for reservoirs characterized with complex flow pattern and unsteady heat exchange between the atmosphere and water surface. Continuity, momentum and temperature transport equations have been solved. Proper assignment of boundary conditions, especially surface heat fluxes, has been found crucial in simulating the lake's hydrothermal dynamics. This model is based on the Reynolds Average Navier-Stokes equations, using a Boussinesq approach, with a standard $k - \varepsilon$ turbulence closure to solve the flow field. The thermal model includes a heat source term, which takes into account the short wave radiation and also heat convection at the free surface, which is function of air temperatures, wind velocity and stability conditions of atmospheric boundary layer over the water surface. The governing equations of the model have been solved by OpenFOAM; an open source, freely available CFD toolbox. As its core, OpenFOAM has a set of efficient C++ modules that are used to build solvers. It uses collocated, polyhedral numerics that can be applied on unstructured meshes and can be easily extended to run in parallel. A new solver has been developed to solve the hydrothermal model of lake. The simulated temperature was compared against a 15 days field data set. Simulated and measured temperature profiles in the probe locations show reasonable agreement. The model might be able to compute total heat storage of water bodies to estimate evaporation from water surface.

INTRODUCTION

Inalnd water bodies such as lakes and reservoirs are very important parts of the continental land surface[1]. Reservoirs or lakes are commonly built to store water for water supply, producing electricity or flood control[2]. In the management and operation of lakes and reservoirs, analysing and predicting the mixing characteristics and temperature profile are required[3]. Temperature is a very important parameter in water bodies. The changes in water temperature and the temperature stratification dynamics can have a profound effect in heat storage of lakes and water quality as well[4,5]. Understanding the heat storage in lakes and reservoirs is essential to estimate evaporation in energy budget methods which are widely used[6]. Moreover, the incorporation of turbulent transport phenomena in energy transfer in water bodies makes it important to understand the temperature distribution within water body[6]. However, measurements of heat exchange between the atmosphere and water surface are sparse. Experimental temperature profiles in lakes are available, but the vertical resolution often are not sufficient for assessing small-scale turbulence effects or investigating variations of water temperature induced by radiative forcing, air temperature as well as wind velocity in shallow waters. Small shallow lakes and reservoirs response to atmospheric conditions very fast. Accurate estimation of the heat transfer between the atmosphere and water is extremely important to model the temperature dynamics and stratification in the lakes[7].

Due to inabilities of 1-D and 2-D models in capturing mechanisms affecting temperature transport and mixing accurately, specially in morphometrically complex lakes and reservoirs, a number of three-dimensional models have recently been described[8,9,12,13]. Prediction of the flow field and temperature dynamics is possibleonly through fully 3-D models[15].

While numerous 3-D models have been described to characterize thermal dynamics in lakes, they have usually been applied to large and deep lakes where the representation of the boundary geometry is less critcal that the shallow small lakes[3]. According to the knowledge of the authors, there have been a little number of CFD simulations for temperature distribution in shallow small lakes.

The aim of this study was to develop a three-dimensional time-dependent hydrodynamic and heat transport model which is capable of simulating the effects of wind and atmospheric conditions over a complex bathymetry and to predict the circulation patterns as well as the temperature distribution in the water body. The simulated temperature profiles will be used to compute total heat storage of small shallow lakes and reservoirs in order to estimate evaporation from water surface.

DESCRIPTION OF STUDY SITE AND DATA COLLECTION

The study site is a small and shallow reservoir located in the Upper East region of Ghana. Lake Binaba (10° 53' 20" N, 00° 26' 20" W) is an artificial lake, used as a form of infrastructure for the provision of water. A natural stream has been dammed, storing and supplying water for domestic use and small-scale irrigation in the vicinity of Lake Binaba. The average area of the lake surface is 4.5 km^2 with the average and maximum depth of 3 m and 7 m, respectively. The air temperature fluctuates from 24 and 35 C, and the water surface temperature varies from 28 and 33 C [16].

The measurements includes atmospheric parameters(air temperature, wind speed at 2 m above the water surface, wind direction and relative humidity, incoming shortwave radiation, and water temperature profile, that is utilised for validation the model. Atmospheric measurements and water thermistor string were located at the point near the dam body, where the lake depth is around 6.8 m. The mentioned parameters were recorded in 15 minutes time intervals.

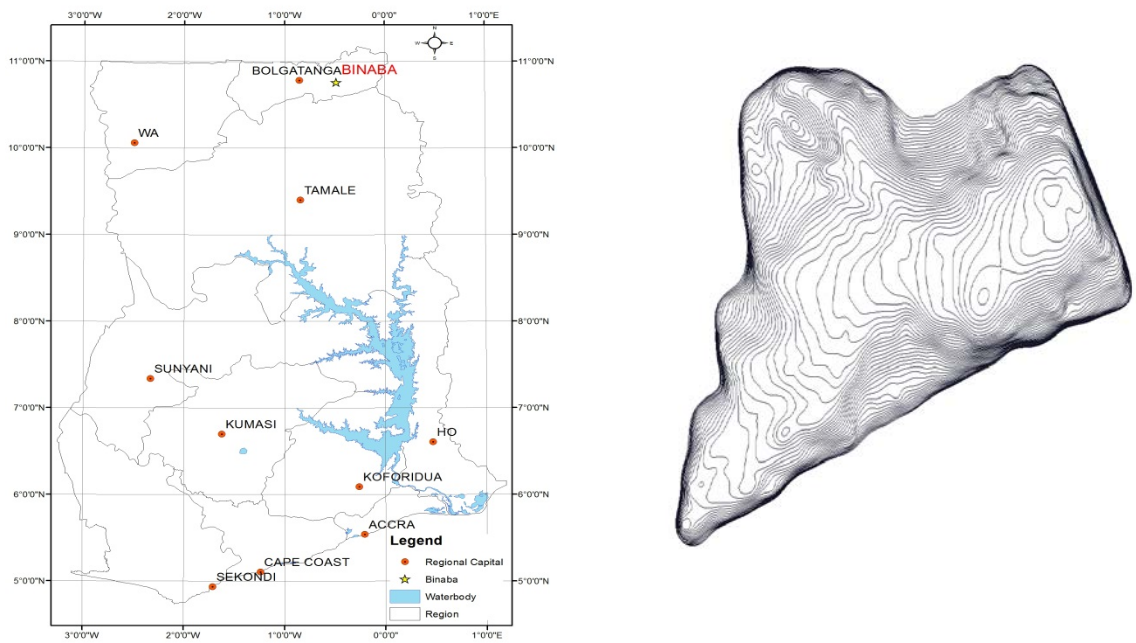

Figure 1. a)Location of Lake Binaba in the Upper East region of Ghana. b) Bathymetry map of the lake with depth contours.

MATHEMATICAL MODEL

Governing Equations

The flow field in a morphometrically complex small lake is solved with the incompressible RANS(Reynolds Averaged Navier-Stokes) equations:

- The water can be assumed to be incompressible[17], and the constant-density continuity equation can be written as

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

- The constant-density(except in the gravity term) momentum equations using Boussinesq approach can be written as

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(u_j u_i\right) - \frac{\partial}{\partial x_j}\left\{ \nu_{eff}\left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_j}\right) - \frac{2}{3}\left(\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}\right]\right\} = \frac{-\partial p}{\partial x_i} + g_i\left[1 - \beta\left(T - T_{ref}\right)\right] \tag{2}$$

where u_i is the velocity component, p pressure, T temperature, $\nu_{eff} = \nu_0 + \nu_t$ is the effective kinematic viscosity, with ν_0 and ν_t denoting molecular and turbulent viscosoty, repectively, g_i the gravity acceleration vector, T_{ref} a reference temperature(T_{ref}=25 C) β the coefficient of exapnsion with temperature of the fluid and is the delta of Kronecker. The Boussinesq approximation is valid under the assumption that density differences are sufficiently small to be neglected, except where they appear in term multiplied by g_i. In the model, for incompressible flows the density is calculated as a linear function of temperature.

Temperature(Internal Energy) Equation

The temperature(instantaneous internal energy) in the water body is calculated from the energy conservation equation for incompressible flows[19]:

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j}\left(Tu_j\right) - \kappa_{eff}\frac{\partial}{\partial x_k}\left(\frac{\partial T}{\partial x_k}\right) = S_T \qquad (3)$$

where T is temperature in water, κ_{eff} effective heat transfer coefficient and S_T is heat source term in lake. Changing in temperature in water body might occurs mainly due to heat exchange across the air-water interface. Accurate estimation of heat fluxes is extremely important in the simulating of temperature dynamics in the water body[15]. Atmospheric heat fluxes include incoming short-wave(solar) and long-wave(atmosphere) radiations, outgoing long-wave radiation, conductive heat at the free surface and evaporation heat flux. Computationally, all of these terms except for incoming shortwave radiation are considered at the water surface as boundary conditions.

Incoming shortwave radiation is included in the source term(S_T) that allows the radiation to be absorbed through a finite distance in the upper layers of the model water column rather than only at the air-water interface. The heat source term using Lambert-Beer low is written as:

$$S_T\left(z,t\right) = \frac{1}{\rho_0 C_p}\eta I_0 \exp\left(-\eta z\right) \qquad (4)$$

where is the extinction or absorption coefficient for solar radiation in water($\eta \approx 0.3$), I_0 is the net short-wave radiation at the water surface and z is downward vertical distance from the water surface. The light extinction coefficient(η) theoretically is a function of wave length, temperature and water turbidity[15]. Different values for η have been reported that is ranges between 0.02 and 2 m^{-1} for clear natural waters[15]. Usually a linear relationship between the extinction coefficient and the secchi depth is used for inland water bodies. For this study, an absorption coefficient of $\eta \approx 0.3$ was used.

Numerical Simulation

The model improvements explained in the last section, were implemented in OpenFOAM. As its core, OpenFOAM has a set of efficient C++ modules that are used to build solvers. It uses colocated, polyhedral numerics that can be applied to unstructured meshes and can be easily extended to run in parallel. To respect the structure of the original code, a new turbulence model based on original $k-\epsilon$ and a new heat transfer solver is defined. This solver is an unsteady state and incompressible heat transfer solver that considers buoyancy effects in the momentum equation.

OpenFOAM allows one to choose which specific solver should be used for each of the equations describing the system. Due to the transient conditions of flow in the lake, an adaptive time-stepping technique based on Courant numbers was used. In this study, the maximum value of *Cr* was adopted to 0.5. As the Cournat number increase the model will be more unstable[18].

Boundary Conditions

During the simulation period, meteorological and water temperature measurements are available. At the water surface the heat diffused away from the lake surface equals the net surface heat flux(H_{net}) which is described by the following equation(Neumann Type):

$$\rho_0 C_p \kappa_{eff} \frac{\partial T}{\partial z} = H_{net} \tag{5}$$

The net heat exchange between atmosphere and water surface includes four heat flux terms:

$$H_{net} = H_{LA} + H_{LW} + H_S + H_E \tag{6}$$

where H_{LA} is the long-wave(atmospheric) radiation from atmosphere, H_{LW} is the long-wave (atmospheric) radiation from the water surface, H_S and H_E are the sensible heat flux and latent heat flux between the lake surface and atmosphere, respectively.

It should be mentioned that H_{net} does not include the short-wave radiation. This term is included in temperature equation(Eq. (3)) as a source term.

This boundary condition is updated at every time step and the new value is used to the simulations. Of the surface heat transfer terms, only the incoming shortwave radiation is directly measured. The rest of the surface terms are calculated within the model at each time step by using standard formulations.

The used temperature boundary condition is an implicit boundary condition on water surface that needs the result of the model to estimate the boundary condition. Using this boundary condition, the model doesn't need to have the water surface temperature measurements. On the other boundaries, the zero heat flux for temperature were imposed[15].

NUMERICAL RESULTS AND DISCUSSION

A large number of calculations was undertaken during the different phases of the development. The calculations were run for a simulation time of a total time of 2 days(1728 00 seconds). The flow field in the lake is unsteady and highly three-dimensional due to the influence of the reservoir bathymetry, and dynamic atmospheric conditions. The flow is coupled with energy, and therefore changes in temperature resulted in an unsteady velocity distribution. The flow near the bottom tended to follow the bathymetry. Positive heat flux during the day warmed the water body. Long-wave radiation along with a lower air temperature cooled the surface layer after sunset.

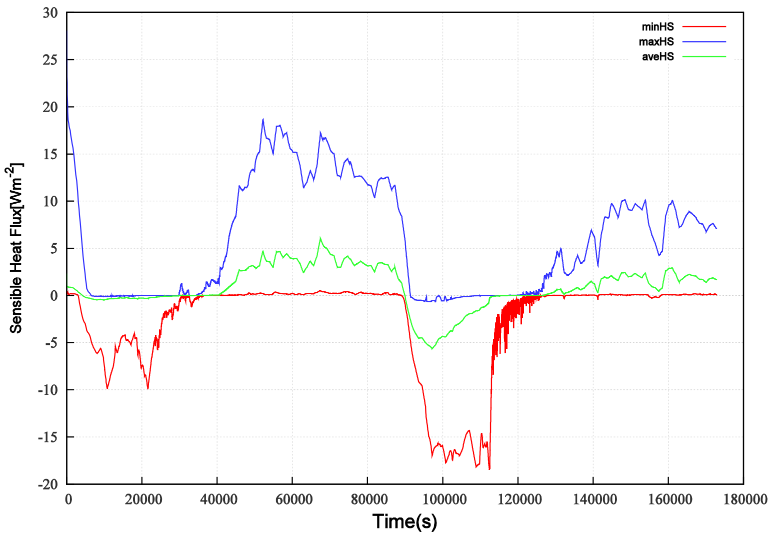

Figure 2. Maximum, minimum and average values of sensible heat flux over the water surface

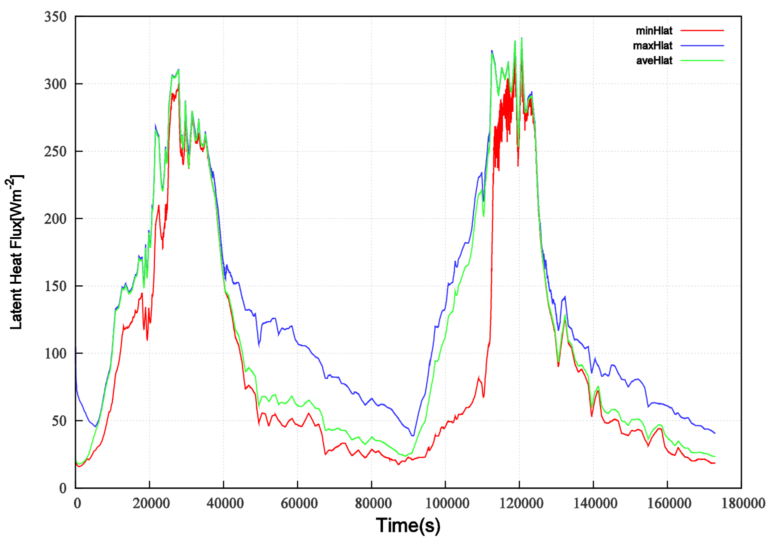

Figure 3. Maximum, minimum and average values of calculated latent heat flux over the water surface

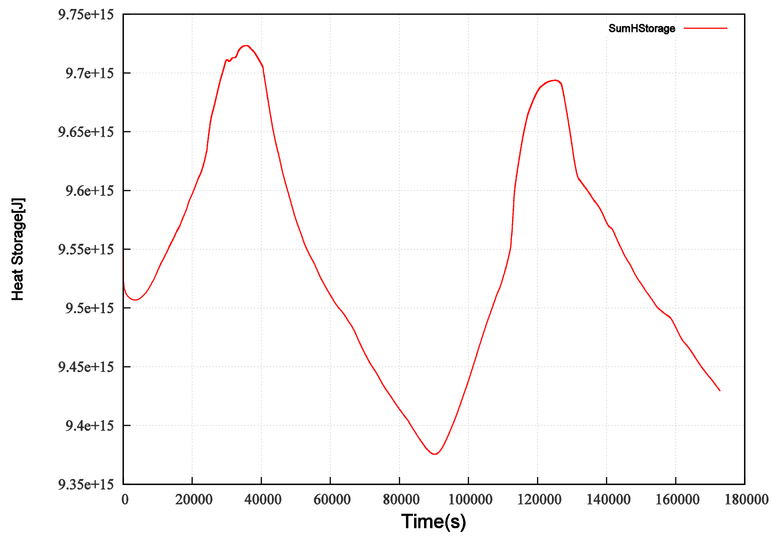

Figure 4. Calculated heat storage of lake to use in evaporation estimation from water surface

CONCLUSIONS

An unsteady three-dimensional numerical model was developed to study the hydrodynamics and temperature dynamics in the Lake Binaba. The model is based on the open-source code OpenFOAM, and solves the incompressible RANS equations with the Boussinesq approximation. The turbulence was modeled with a $k-\epsilon$ model with wall functions. Solar radiation and convective heat transfer at the free surface were incorporated into the model. The main conclusions are as follows: (1) The flow pattern in the lake is three-dimensional and coupled with temperature. (2) The incorporation of wind-induced turbulence improves the temperature predictions in the lake.

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