3-D simulation of flow in Lake Yanaka
谷中湖の三次元湖流解析

Guangwei Huang, Kanazawa University, 40-20 Kodatsuno 2chome, Kanazawa. E-mail: huang@t.kanazawa-u.ac.jp
Nobuyuki Tamai, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo. E-mail: tamai@hydra.t.u-tokyo.ac.jp

In this study, a three dimensional model is constructed for the simulation of flow in Lake Yanaka. Simulated flow patterns are in fair agreement with filed observation. The model is then used to study the lake's response to different forcing. The information on flow patterns obtained in this study is useful for further study of water quality in the lake.

1. Introduction

Lake Yanaka is part of the Watarase retarding basin. It is the first multi-purpose impoundment lake constructed in alluvial plain in Japan. The lake has a surface area of 4.5 km^2 and an average depth of six meters with seasonal changes of about three meters for flood control. It is divided into three blocks by levees and connected by gaps as depicted in Fig.1. Inflow and outflow are regulated at the pumping station located at the south tip of the lake. Two tributaries are the Yata River (on the left), and the Watarase River (on the right).

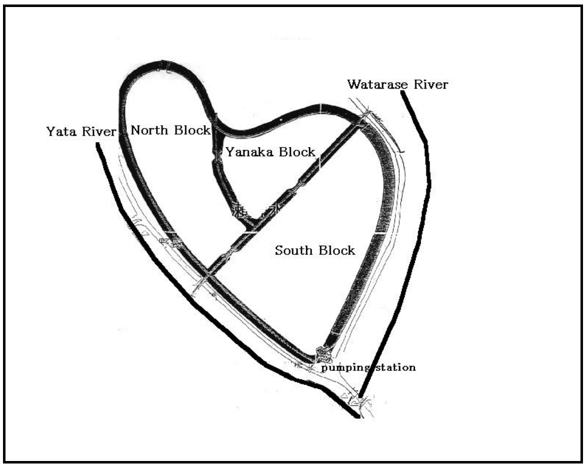

Fig. 1 Lake Yanaka

In recent years, the eutrophication problem has surfaced up in Lake Yanaka [1), 5)]. High inputs of nutrients led to excessive growth of phytoplankton. The concentration of chlorophyll a ranges from 50 μg/l to more than 250 μg/l. Since phytoplankton have long been known to respond the advective physical processes operating at different spatial and temporal scales, better understanding of hydrodynamics is a key to the development of better management strategy for the lake. In this study, a three dimensional model is used to study the lake's response to different forcing.

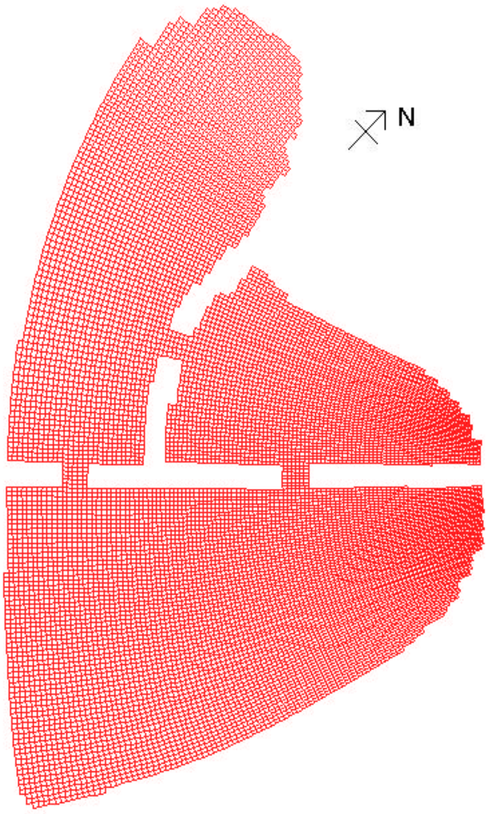

Fig. 2 Computational grid

2. Model description

The model used in this study is the three dimensional time-dependent hydrodynamic model, which assumes the hydrostatic pressure in the vertical. The vertical eddy viscosity is calculated using the k-ε model, and the horizontal diffusion terms are calculated using the Smagorinsky formulation. The governing equations are cast into a bottom-following sigma coordinate system in the vertical and boundary-fitted coordinate system in the horizontal. For details, readers are referred to Blumberg[2)], Huang[6)] and Sheng[6)]. The curvilinear grid system designed for the present simulation is shown in Fig. 2. The horizontal grid spacing ranges from 10m to 24m, and the aspect ratio is around 1.1 in most part of the lake, but reaches to 2 near the east corner. The vertical resolution is accomplished by dividing the depth into 10 non-uniform layers with smaller spacing near the surface and bottom (0.05×depth).

3. Wind forcing

Since the lake is shallow, wind should be a major driving force for the water movement in the lake. The wind conditions over the lake are analyzed based on the observational data for 1996. They are summarized below.

- Wind magnitudes between 1-6 m/s account for 80% of the data.
- Wind magnitudes between 1-3 m/s account for 50% of the data.
- Monthly average and maximum instantaneous speeds are shown in Fig. 3. The monthly average decreases, but the maximum increases from January to December.
- The probability of wind direction for the whole year of 1996 is shown in Fig. 4. Three predominant directions can be identified. They are WNW, NE and ESE.
- Next, correlation between wind speed and direction is classified as shown in Fig. 5. It can be seen clearly that high wind speeds are frequently associated with the WNW direction, while the average winds mainly blow from the northeast.

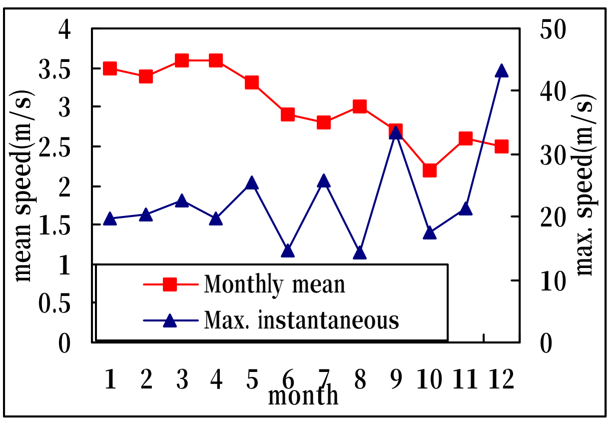

Fig. 3 Wind speed for 1996

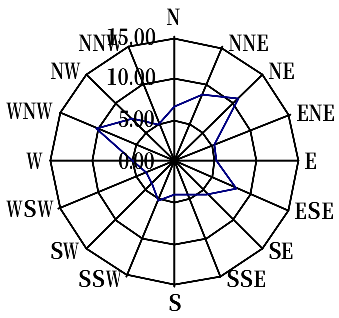

Fig. 4 Wind rose based on hourly data for 1996

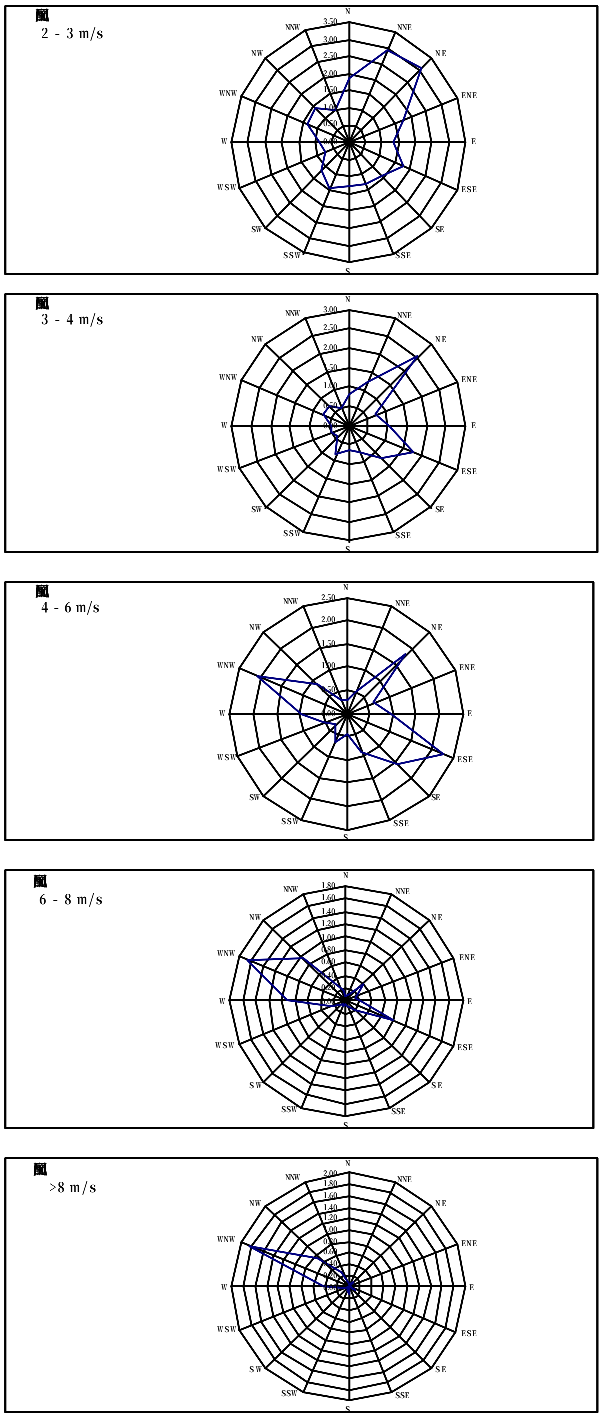

Fig. 5 Association of wind speed with direction

4. Model validation

The model is first checked against a simple case. That is the wind-induced flow in a closed basin. Simulation results are compared with the experimental data of Baines and Knapp[3]. The simulated velocity profile is in good agreement with the experiment except the portion near the bottom where the experiment exhibited a distinct peak. Details of this comparison are omitted here due to the space limitation. Next, we try to validate the model against the field observation in Lake Yanaka. The flow observation was conducted with ADCP (Acoustic Doppler Current Profiler) in October 1998. The sampling density was horizontally five points in each block, and vertically nine to thirteen layers according to the local depth. The meteorological conditions including wind speed and direction were also measured simultaneously. To obtain good results, it is common for this type of flow simulation to adjust the Smagorisky coefficient or the bottom roughness. Sensitivity studies indicate that the model output is less sensitive to the Smagorisky coefficient than the bottom roughness for the present case. Therefore, only is the bottom roughness used in model calibration. The simulated and observed flow patterns of the surface layer at the time of 12:00, October 6 are given in Fig. 6 and 7 (note that the lake is rotated clockwise by 44^0C for computational convenience). They are in fairly good agreement. The flow patterns of both simulated and observed at the depth of 4m are shown in Fig. 8 and 9. As can be seen, there is some difference in flow direction. Comparisons for other time are similar. That is to say, the surface layers were fairly well resolved, but discrepancy developed in the deep part of the lake. We believe that this difference is caused by the inflow. During the field measurement, water was being taken into the lake from the Yata River and Watarase River. By coupling the hydrodynamic model with a water temperature model, our preliminary simulation indicates that the flow in the deep layer could be deflected if the plunge flow takes place. However, due to the lack of accurate data on inflow rate and water temperature, we are not able to take this effect into consideration at this moment. We plan to carry out filed measurement to clarify this issue.

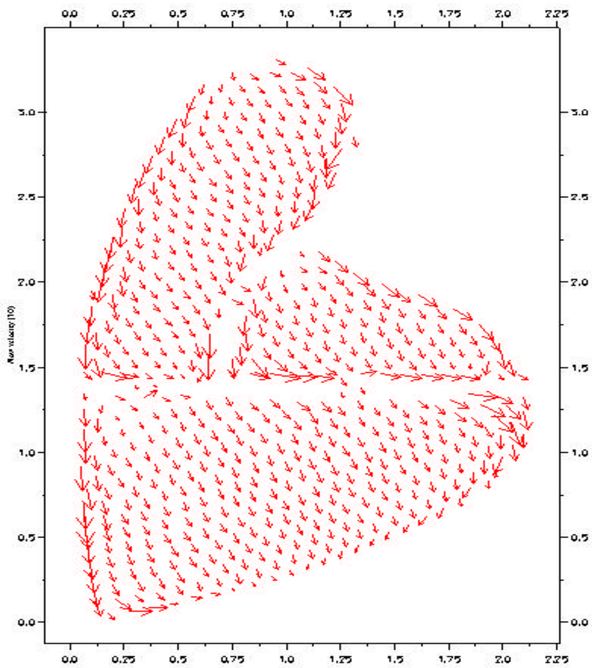

Fig. 6 Simulated flow pattern at the depth of 1.5m

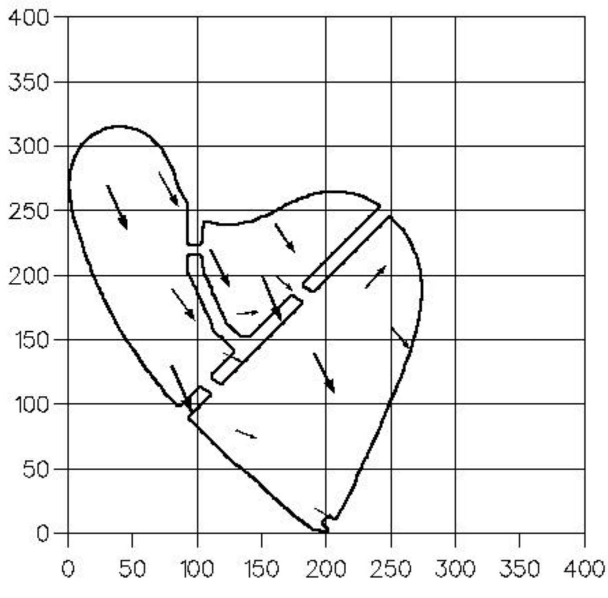

Fig. 7 Observed flow pattern at the depth of 1.5m

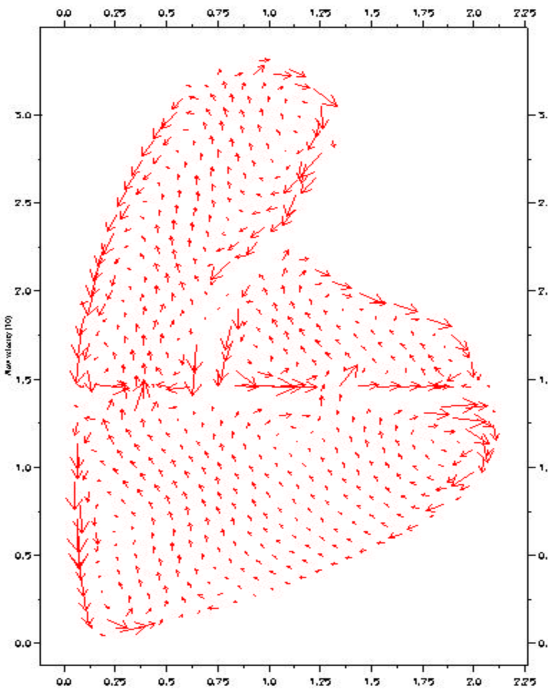

Fig. 8 Simulated flow pattern at the depth of 4m

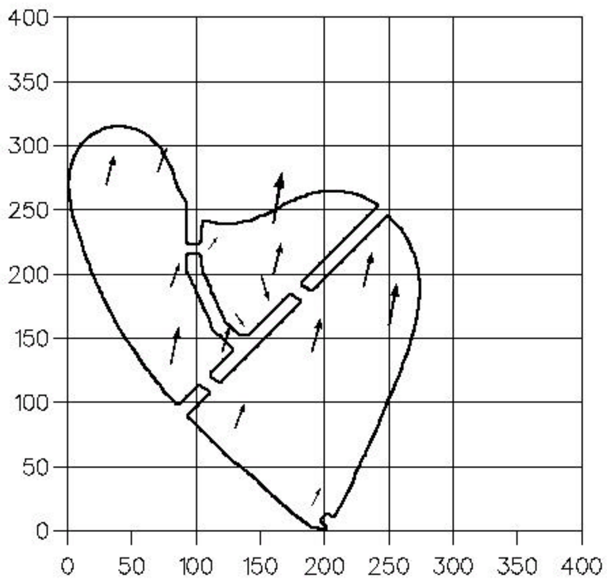

Fig. 9 Observed flow pattern at the depth of 4m

5. Lake's response to different forcing

By using the afore-mentioned model, the Lake's response to different forcing is investigated. Given a NE wind of 5m/s, Figs. 10 and 11 show the simulated flow patterns in the first and sixth layers, respectively. Several types of circulation can be identified through examining the figures. Firstly, the vertical circulation may be recognized since the surface layer follows closely the wind direction, and a return flow forms under certain depth. Secondly, horizontal circulation can be clearly observed since the flow direction near the shore is opposite to that in the inner region of the lake as seen in Fig. 11.

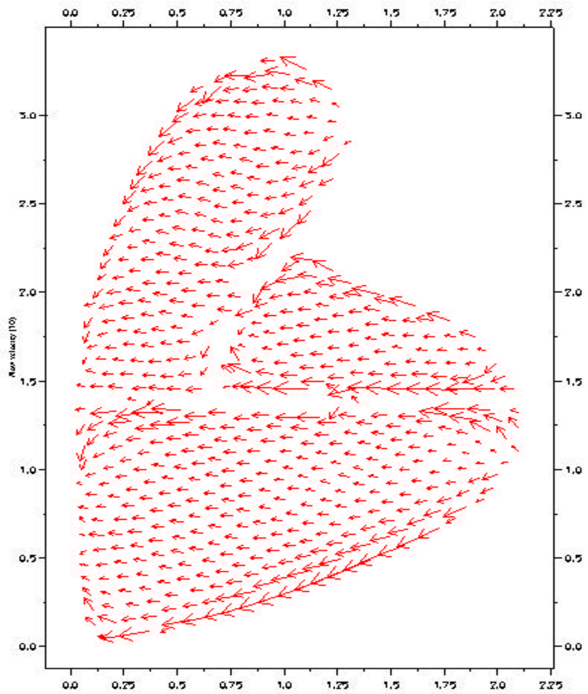

Fig. 10 Flow pattern in the surface layer under a NE wind

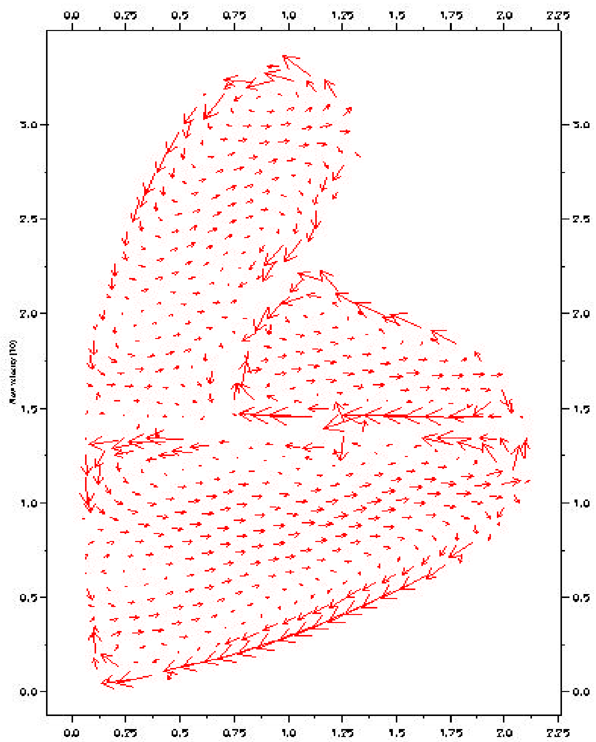

Fig. 11 Flow pattern in the sixth layer under a NE wind

Given an east wind of 5 m/s, Fig. 12 shows the simulated flow pattern in the eighth layer. Three swirls in the South Block may be identified from the figure, a long and narrow clockwise swirl along the left bank of the block, a relatively small counterclockwise one in the right corner, and another one in the middle of the block. Besides, two eddies may be recognized in both the North Block and Yanaka Block. This suggests that at least seven sampling points are needed for water quality measurement under such a circumstance because different swirl may carry different properties for water quality.

Next, we consider an unsteady wind that changes from N to NW in direction and from 9.9 to 8 m/s in magnitude in two hours. It is indeed a real recording on May 5. 1996. The simulated flow pattern at the end of the two-hour period is shown in Fig.13. A predominant feature in this case is that the North Block is split by two large eddies from the middle.

Since WNW is one of the dominant wind directions over the lake, we have investigated the distribution of the vertical velocity near the bottom under a WNW wind of 5 m/s. As shown in Fig.14, the area of up-drift is larger than that of down-drift. The effect of this distribution on the vertical transport of nutrients shall be a subject of further study.

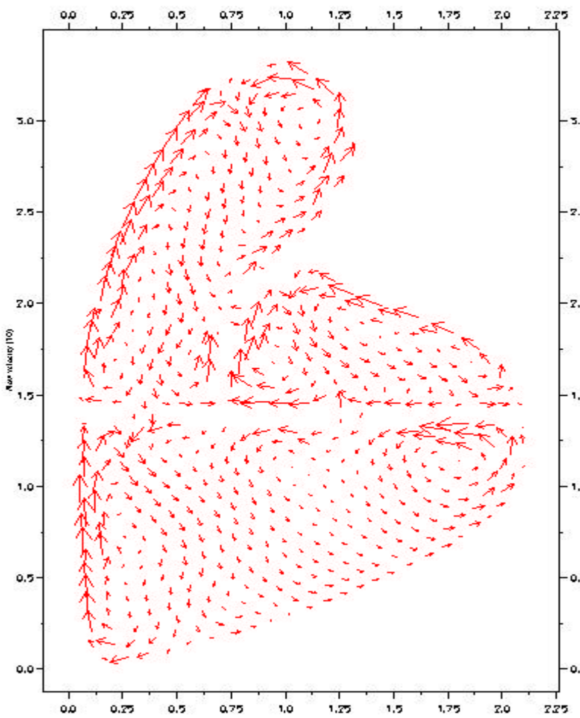

Fig. 12 Flow pattern in the eighth layer under an E wind

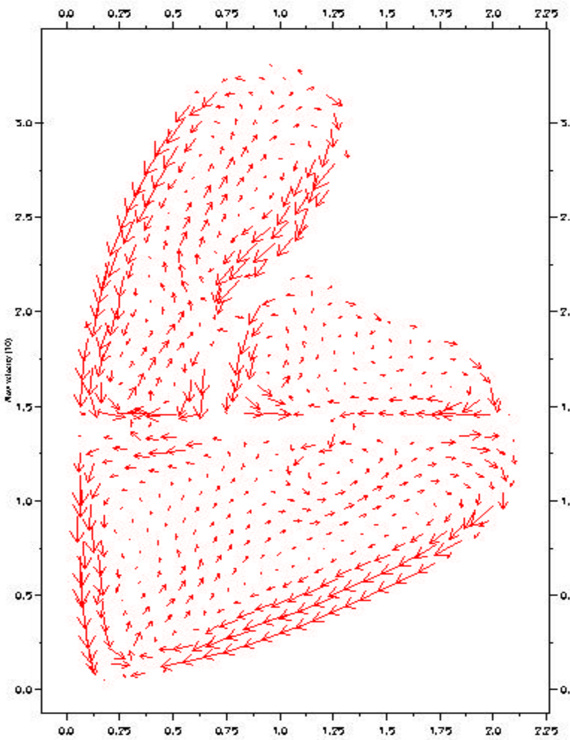

Fig. 13 Flow pattern in the fifth layer under an unsteady wind

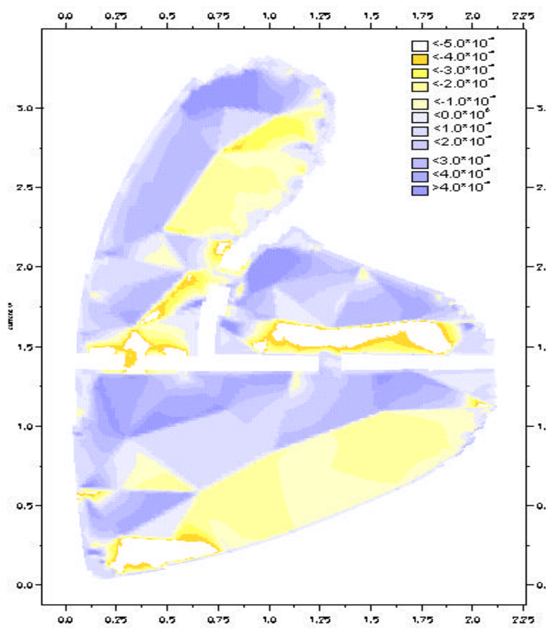

Fig. 14 The distribution of vertical velocity near the bottom

6. Concluding remarks

Characteristics of the flow circulation in Lake Yanaka is studied with a three dimensional model. The significance of the present work may be stated as following:

1) The information on the hydrodynamics of the lake will help at better understanding the water quality issues such as

phytoplankton accumulation and resuspension. It can also be used to calculate the volume fluxes between blocks, which is required if mass balance of nutrients in each block is to be sought.

2) The various circulation patterns revealed in this study will also help determine the significant locations for future measurements of water quality parameters.

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