Journal of Applied Mechanics Vol. 4, pp. 639-646 (August 2001) JSCE

Numerical Study on Wind-Driven Flow in Lake Yanaka

Guangwei Huang* and Hajime Ishida**

* Dr. of Eng., Associate Professor, Dept. of Civil Engineering, Kanazawa University, 2-40-20 Kodatsuno, kanazawa, 920-8667
** Dr. of Eng., Professor, Dept. of Civil Engineering, Kanazawa University, 2-40-20 Kodatsuno, kanazawa, 920-8667

In this study, a three dimensional hydrodynamic model is constructed to study wind-driven flow in Lake Yanaka. The characteristics of the wind field around the lake are analyzed, and the lake's responses to different wind forcing are revealed through the use of the 3-D model. In addition, we look into the difference between results from 3-D modeling and 2-D simulation to justify the use of 3-D modeling for this shallow lake. The information on flow structures obtained from the present study is useful for better understanding the lake's dynamics and for further study of water quality in the lake.

Key Words: Lake Yanaka, 3-D model, wind condition, flow pattern, bottom shear stress

1. Introduction

Lake Yanaka is a 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 end of the lake. Two tributaries are the Yata River (on the left), and the Watarase River (on the right).

In recent years, the eutrophication problem has surfaced up in Lake Yanaka [6]. 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. The dominant species are diatoms in spring and blue-green algae in summer. Since phytoplankton have long been known to respond to the advective physical processes operating at different spatial and temporal scales, development of a hydrodynamic model is the first step toward the goal of best management practice for the lake. In this study, a three dimensional model is constructed and validated with experimental and field data. Then it is used to study the lake's response to different forcing. In applying the model, particular attention is given to examining the variability of wind condition over the lake for the purpose of ensuring that the boundary forcing used to drive the model is a reasonable representation of the reality. Besides, 2-D simulations are also performed, and the results are compared with the 3-D model output. It is found that the flow patterns resulting from the 2-D calculation resemble the flow patterns of bottom layer obtained from the 3-D model, but significantly differ from surface layer flow patterns. The difference in bottom shear stress between 2-D and 3-D results is also examined. The magnitude of bottom shear stress is found to be practically independent of model dimension in this shallow lake; however, the difference in shear stress direction is appreciable between 2-D and 3-D cases.

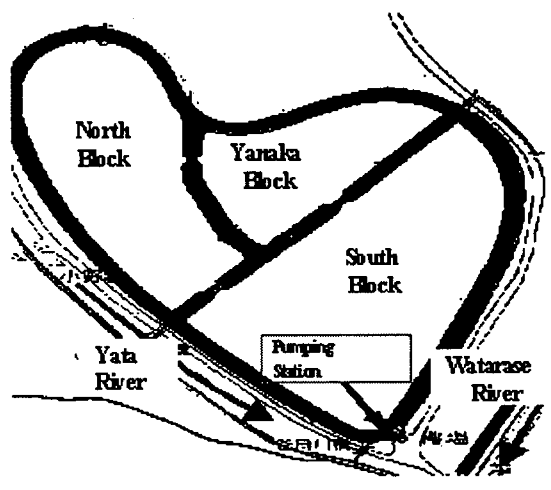

Fig.1 Lake Yanaka

2. Model description

The model used in this study is a three dimensional time-dependent hydrodynamic model, which assumes the hydrostatic pressure in the vertical. The resulting equations of motion in the Cartesian system are

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}= \\ fv+g\frac{\partial \eta}{\partial x}+\frac{\partial}{\partial z}(A_v\frac{\partial u}{\partial z})+\nabla\cdot(A_H\nabla u) \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial v^2}{\partial y}+\frac{\partial vw}{\partial z}= \\ -fu+g\frac{\partial \eta}{\partial y}+\frac{\partial}{\partial z}(A_v\frac{\partial v}{\partial z})+\nabla\cdot(A_H\nabla v) \tag{3}$$

where (u, v, w)=velocity components in (x, y, z)-directions; t=time, f=Coriolis parameter; η=water level; A_H=horizontal turbulent diffusion coefficient; A_v=vertical turbulent diffusion coefficient; ∇=gradient operator; $\nabla\cdot$ =divergence operator.
The vertical eddy viscosity is calculated using the k-ε model (Rodi, 1980), and the horizontal diffusion terms are modeled using the Smagorinsky formulation as below

$$A_H = C_s\Delta x\Delta y\times \\ [(\frac{\partial u}{\partial x})^2+(\frac{\partial v}{\partial y})^2+\frac{1}{2}(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})^2]^{1/2} \tag{4}$$

where C_s = Smagorinsky coefficient, which ranges from 0.01 to 0.5 in various applications.

To have a better computational resolution, the governing equations are recast 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[1], Mellor[4] and Sheng[8]. The curvilinear grid system designed for the present simulation is partially shown in Fig. 2 for the purpose of illustration. 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).

For numerical integration, the model employs the mode splitting technique (Simons[9], Madala and Piacsek[5]) to allow the calculation of water surface elevation separately from the three-dimensional calculation of the velocity and turbulence quantities. It basically divides a big integration time step into a number of computationally inexpensive small time steps, and updates the surface elevation every small time step while computing three velocity components and turbulence quantities only once every big time step.

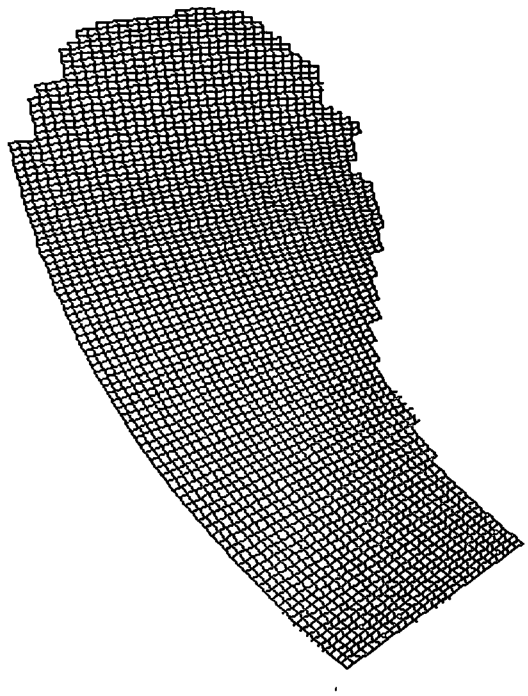

Fig. 2 Computational grid in the North Block

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 field data for 1996, which were recorded at a nearby meteorological observation station. The results 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.
- The probability of wind direction for the whole year of 1996 is shown in Fig. 3. 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. 4. 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.

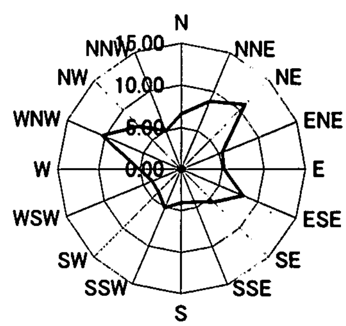

Fig.3 Wind rose based on hourly data of 1996

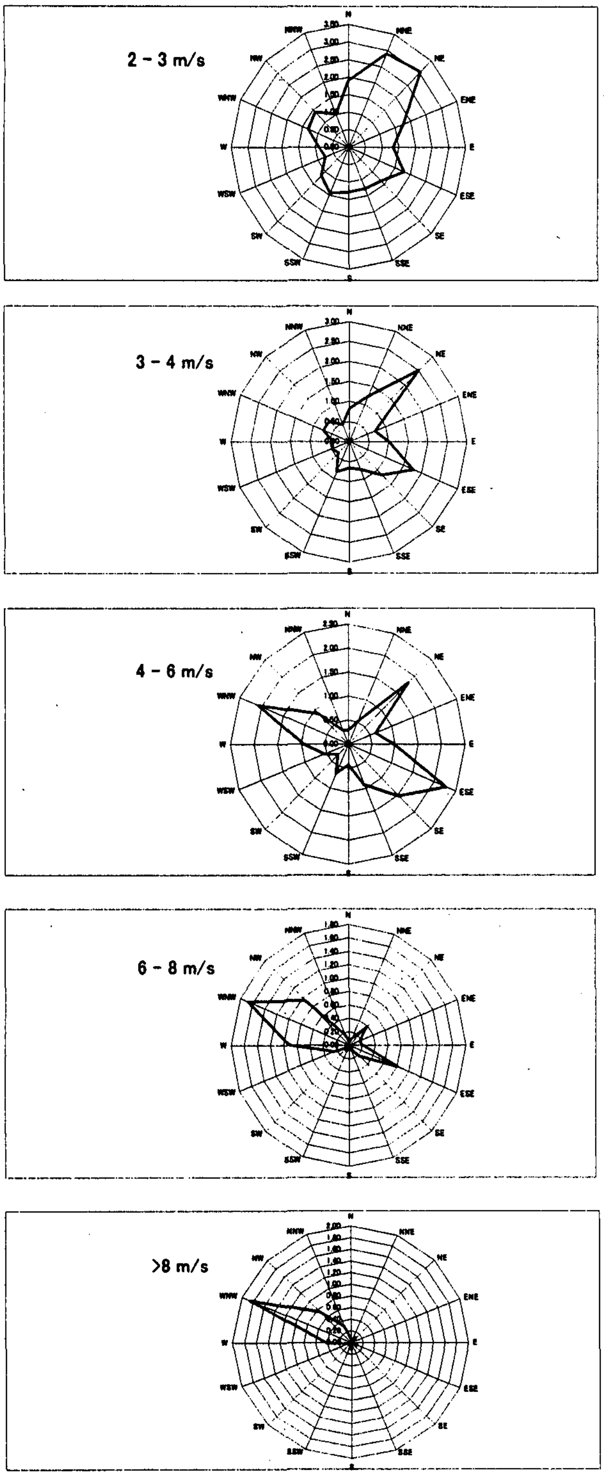

Fig. 4 Association of wind speed with direction

The wind shear stress acting on the water surface is usually expressed by a quadratic form as

$$\tau_{sx} = \rho_a \cdot c_f \cdot W_X \cdot \sqrt{W_X^2 + W_Y^2} \tag{5}$$

$$\tau_{sy} = \rho_a \cdot c_f \cdot W_Y \cdot \sqrt{W_X^2 + W_Y^2} \tag{6}$$

where τ_{sx}, τ_{sy} are surface stress in x, y direction, respectively. C_f is the wind drag coefficient, and its value is give to be 0.0026 in this study. W_x, W_y are wind velcocity components measured 10 m above surface.

As the wind blows from land onto the water surface, the velocity distribution in the air boundary layer will have to adjust itself to a new roughness, representative of the water surface. The adjustment will generate an internal boundary layer, which grows in thickness with distance from lakeshore. Therefore, if the wind fetch is sufficiently long, the wind velocity measured over land should be adjusted before it is substituted into (5) and (6). To see if such a modification is necessary for Lake Yanaka, wind field measurement was conducted in November 1997. Wind velocities at three sites around the lake, as depicted in Fig.5, were recorded continuously for three days. The wind data from the three sites and the nearby meteorological station are shown in Fig.6.

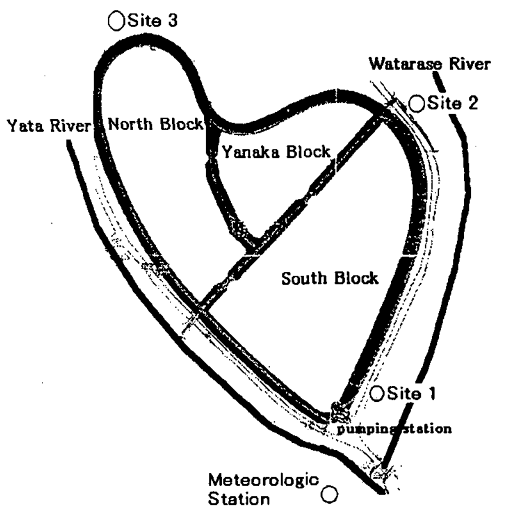

Fig.5 Wind observation locations

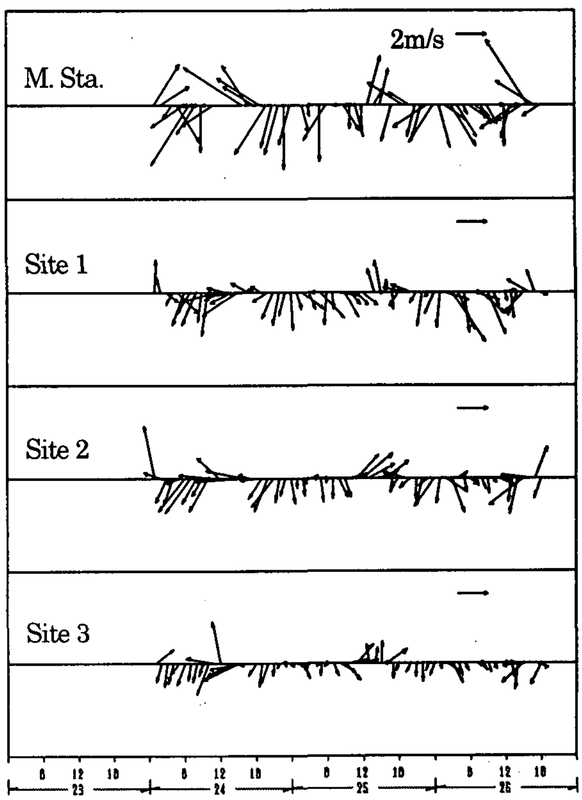

Fig.6 Observed wind around the lake (1997)

It can be seen from Fig.6 that the wind directions were quite the same among the four sites. Nevertheless, the magnitudes of wind speed at the three sites along the lakeshore were somewhat lower than that at the meteorological station that is approximately 300m away from the south end of the lake. In August 1998, wind field measurement was conducted again to examine the extent to which wind speed might be altered over the lake. Figure 7 shows the wind profiles at the center of the lake and at the site 3. At the height of 10m above the surface, the wind velocity at the lake center was less than that at site3 around the noon. However, wind velocity at the center was higher than that at site3 in the late afternoon. The differences were 9% and 13%, respectively. Normally, one would expect the wind speed to be increased due to the reduction in roughness. The decrease in wind speed over the lake surface during the daytime was likely to be caused by thermal instability. As shown in Fig.8, the air temperature over the lake was unstably stratified, and higher than that over the land. The thermally induced upward motion of air might lead to a reduction in horizontal velocity. In the late afternoon, the stratification was gone; the wind speed over the lake was higher than that over the land as expected.

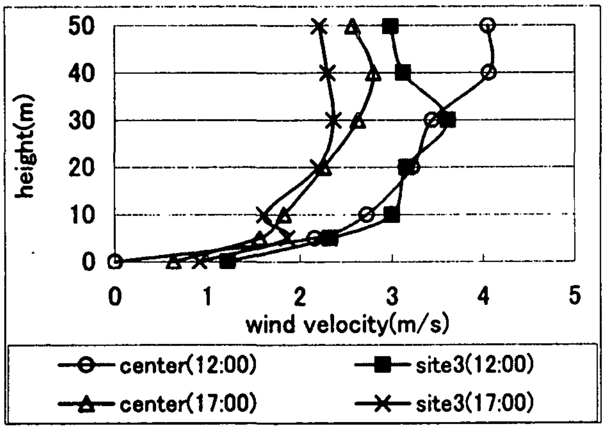

Fig.7 Measured wind profile (1998)

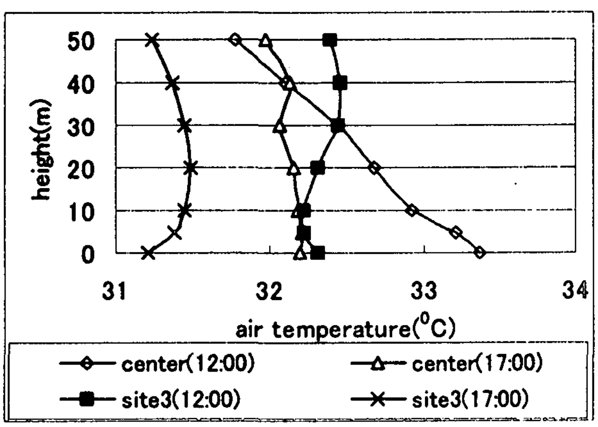

Fig.8 Measured temperature profile (1998)

Based on these observations, it can be concluded that the wind over the lake was altered in magnitude due to both mechanical and thermal causes. However, there is no sign that wind directions were significantly changed over the lake. In light of these findings, it appears to be preferable to carry out on-site meteorological measurement in order to have reliable model input.

4. Model validation

The model is first checked against a simple case. That is the wind-induced flow in a closed basin. Numerical results are compared with the experimental data of Baines and Knapp[3] in Fig.9. The simulated velocity profile is in good agreement with the experiment except the portion near the bottom where the experiment exhibited a distinct peak.

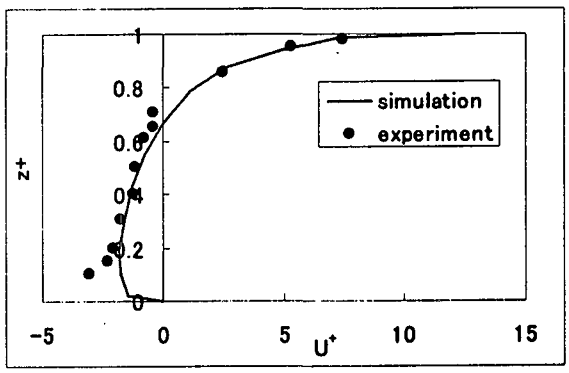

Fig.9 Comparison with experiment

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 frequency was 1200KHz. The sampling density was horizontally five points in each block, and vertically nine to thirteen layers according to the local depth. The water depth at the time of measurement was approximately 5m on average. The meteorological conditions including wind speed and direction were also measured simultaneously. To calibrate this type of model, it is common to adjust the Smagorisky coefficient and the standard bottom friction coefficient to obtain best fit with measurement (Blumberg[2]). However, sensitivity studies indicate that the model output is more sensitive to the bottom friction coefficient than the Smagorisky coefficient for the present case. Therefore, only is the bottom friction coefficient used as a calibration parameter, and the value of C_s is given to be 0.01. The simulated and observed flow patterns of the surface layer at the time of 12:00, October 6 are given in Fig.10 and 11. They are in fairly good agreement. The flow patterns of both simulated and observed at the depth of 4m are shown in Fig.12 and 13. As can be seen, the deep layer flow pattern is also reasonably resolved although there are some points where difference in flow direction is noticeable. Considering uncertainties of various kinds in filed measurement, the model output is deemed to be acceptable.

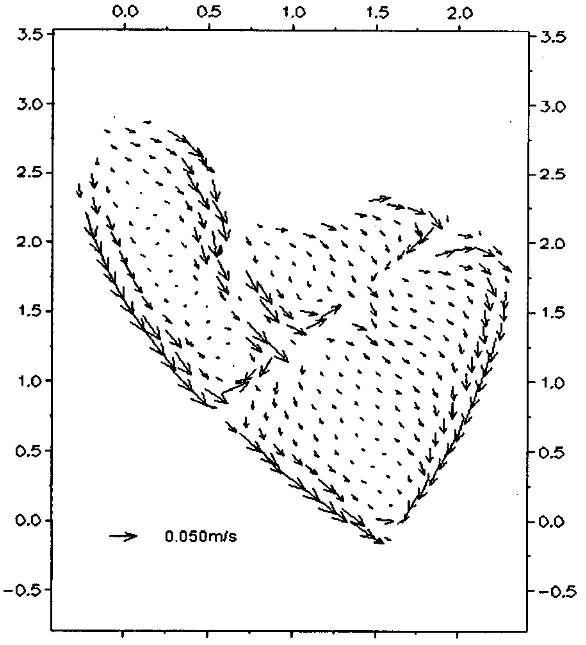

Fig.10 Simulated flow pattern at the depth of 1.5m

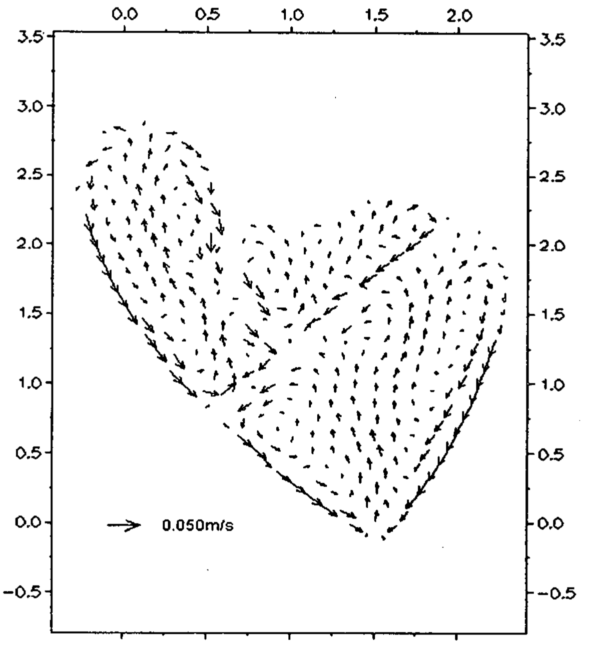

Fig12 Simulated flow pattern at the depth of 4m

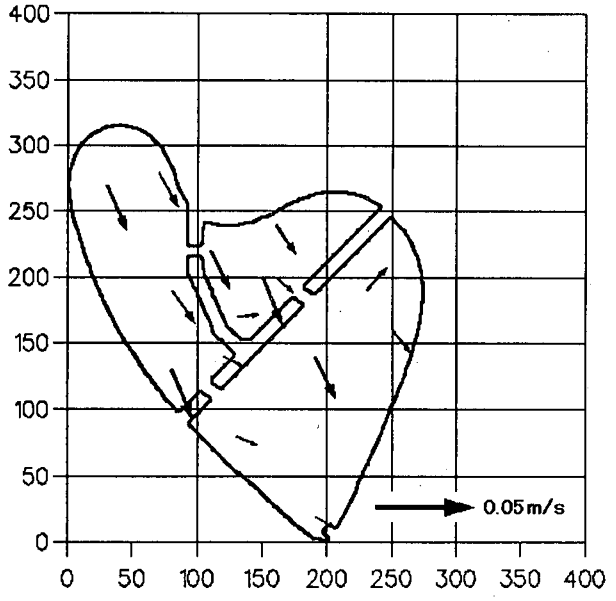

Fig.11 Observed flow pattern at the depth of 1.5m

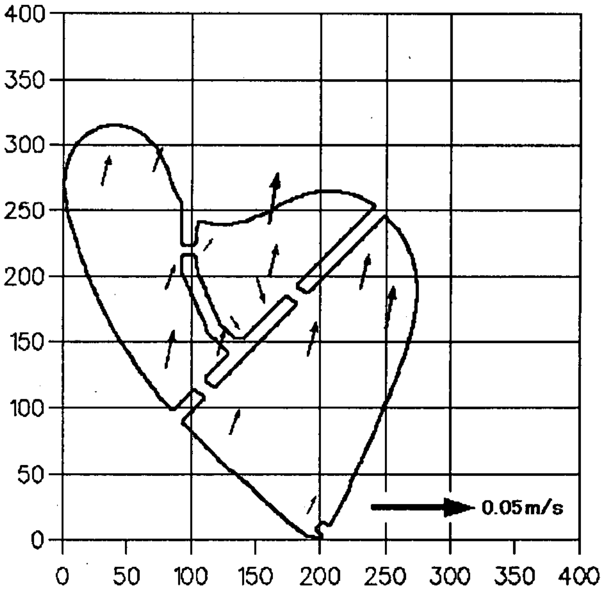

Fig.13 Observed flow pattern at the depth of 4m

5. Lake's response to different forcing

The Lake's response to different forcing is investigated with the 3-D model described above. Given a NE wind of 5m/s, Figs. 14 and 15 show the simulated flow patterns in the surface and bottom layer, respectively. Some characteristics of the flow field can be identified through examining the figures. Firstly, flow directions in the surface layer are very different from that in the bottom layer. Flow in the surface layer follows closely the wind direction, and near the bottom, the return current can be clearly seen in the middle part of each block, particularly, around the center of the South Block. Secondly, two undercurrent circulation cells in the South Block can be recognized since the flow directions near the shoreline are opposite to that in the inner region of the lake as seen in Fig.15.

Given an east wind of 5 m/s, Fig.16 shows the simulated flow pattern near the bottom. In the South Block, two horizontal underwater swirls are located at two ends, while a return flow moves meanderingly in the middle area. The swirl at the southeast end is clockwise and big in size, while the one at the northeast end is counterclockwise and relatively small. Besides, two underwater eddies may be recognized both in the North and Yanaka Block from Fig.16. The two eddies in the North Block split the block more or less equally into two parts. On the left hand side is a clockwise eddy, while on the right hand side is a counterclockwise eddy. In the Yanaka Block, a big eddy with a length scale of the block size and a small corner eddy characterize the underwater flow pattern. Based on the above observation, one may conclude that at least, six horizontal sampling points, three for the South Block, two for the North Block, and one for the Yanaka block are needed for water quality measurement under such a circumstance because different swirl may carry different properties of water quality.

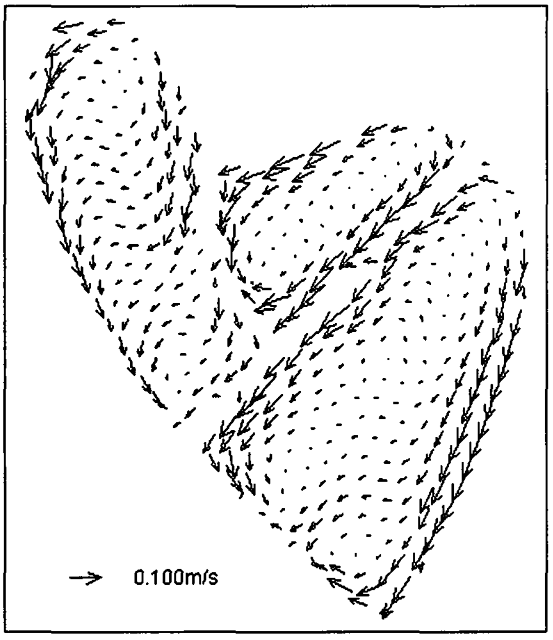

Fig.14 Flow in the surface layer under a NE wind

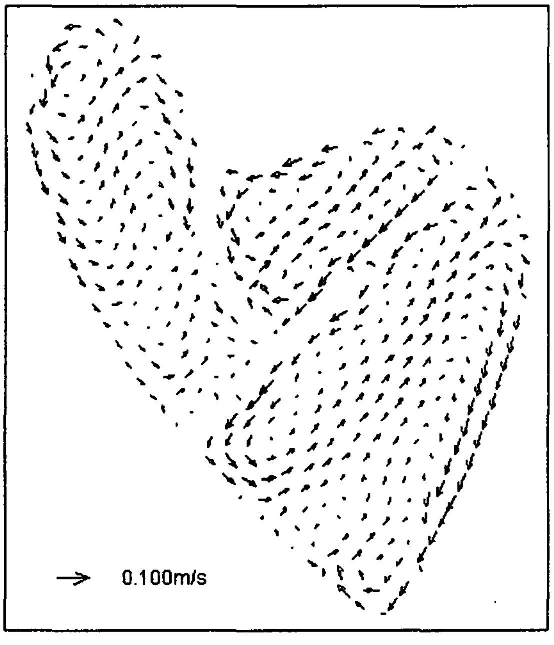

Fig.15 Flow in the bottom layer under a NE wind

Under a WNW wind of 5 m/s, the flow pattern near the bottom is shown in Fig.17. It is surprisingly quite similar to that under an E wind of 5m/s except that the flow direction is reversed.

Because the lake is shallow, the wind-induced resuspension of sediment particles is of particular interest for water quality management. To get some rough idea about the vertical transport in the lake, we have investigated the distribution of the vertical velocity near the bottom under different wind conditions. Fig.18, 19 show the distributions of vertical velocity 0.5m above the bottom under the WNW and E wind of 5m/s, respectively. Comparing Fig.18 with Fig.17, one may realize that in the North Block, the area of up-drift (dark part) is associated with the horizontal counterclockwise eddy on the left side, while the area of down-drift (gray part) is associated with the clockwise eddy on the other side. Under the E wind, the distribution of vertical velocity in the North Block also looks correlated with the horizontal flow structures. Besides, it should be observed that the down-drift regions under the WNW wind, and vice versa replace the up-drift regions under the E wind.

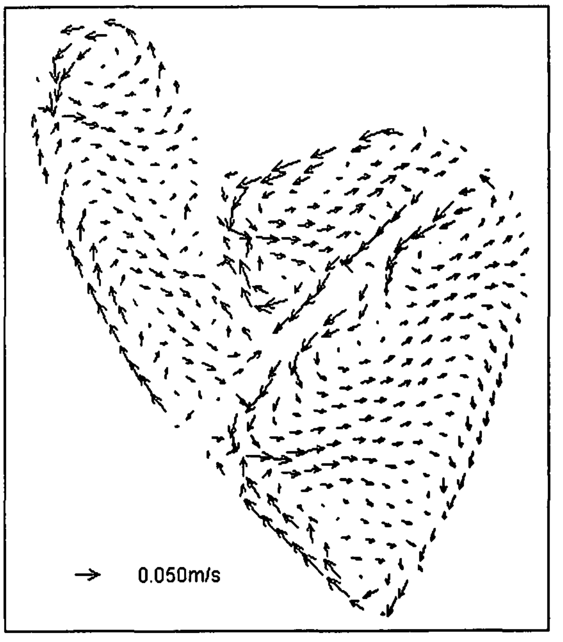

Fig.16 Flow in the bottom layer under an E wind

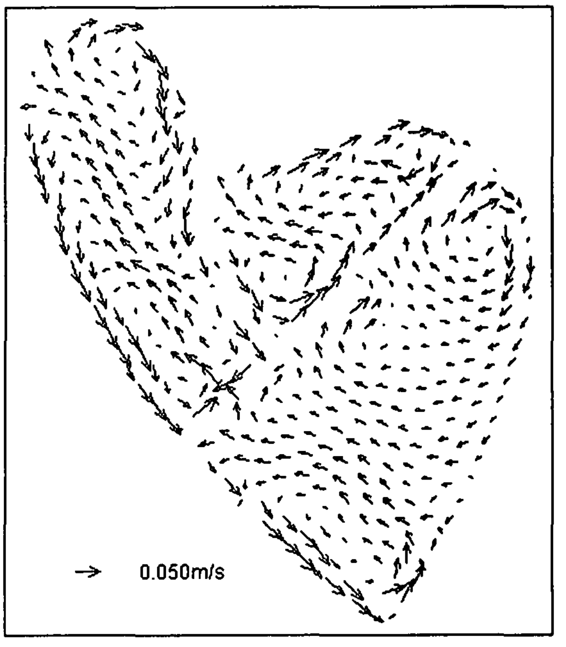

Fig.17 Flow in the bottom layer under a WNW wind

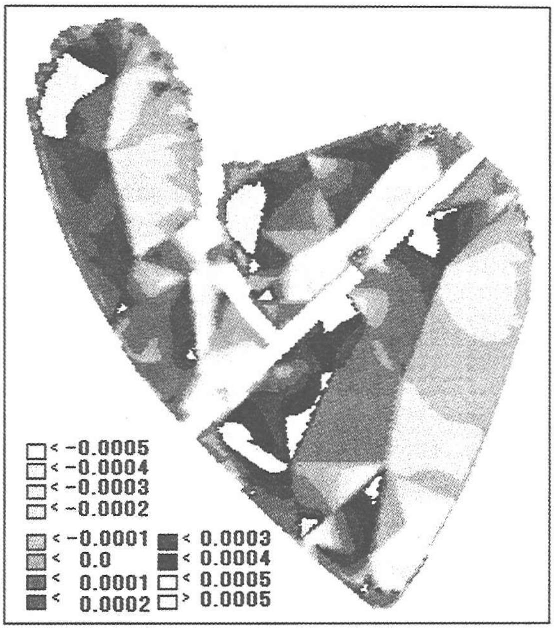

Fig.18 Vertical velocity near the bottom under a WNW wind

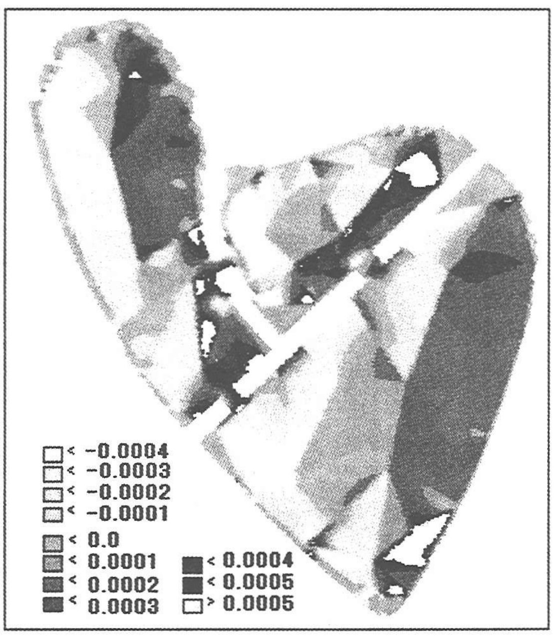

Fig.19 Vertical velocity near the bottom under an E wind

A remarkable difference between the two cases lies in the location of relatively high upward velocity. As can be seen from Fig.18 and 19, under the WNW wind, there is a patch of relatively strong vertical velocity close to the north end. Under the E wind, however, this patch disappears; instead, a patch of relatively strong upward velocity takes place around the south end. The effect of such distributions on the vertical transport of nutrients shall be a subject of further study.

6. Comparison between 2-D and 3-D simulations

For shallow lakes, 2-D depth-integrated approach works remarkably well in many applications. 3-D modeling is certainly useful in understanding 3-D flow structure, however, it is roughly an order of magnitude more expensive in computer time compared to 2-D modeling. Since Lake Yanaka is a shallow lake, a question arises naturally as to whether the 3-D modeling is necessary for the lake. To answer this question, 2-D simulations are performed and are compared with 3-D results. Figure 20 shows the flow field obtained from 2-D simulation under a NE wind of 5m/s. By comparing it with Fig.10 and 11, one may notice that the depth-integrated flow pattern in the South and Yanaka Block is similar to the bottom layer flow pattern of 3-D simulation, but significantly different from that in surface layer. In the North Block, the 2-D flow pattern is neither similar to the bottom layer nor to the surface layer. Along the NE direction, the width of the North Block is smaller than that in the South and Yanaka Block, resulting in relatively lower degree of shallowness in the North Block than the other two blocks. Consequently, 3-D modeling is more needed in the North Block under a NE wind. By the same token, under a NNW wind, 3-D modeling may be desirable for the Yanaka Block.

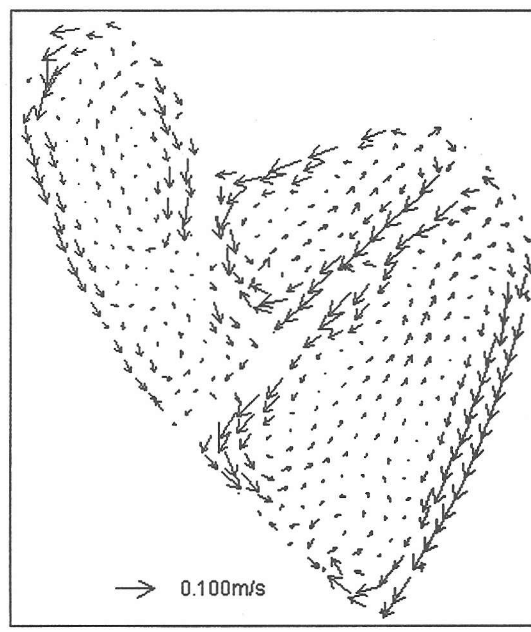

Fig.20 2-D flow field under a NE wind

Next, the bottom shear stress is examined for a number of different wind input. It is found that the distribution of magnitude of bottom shear stress is virtually the same between 2-D and 3-D simulations (not shown). Nevertheless, the directions of bed shear stress across the lake bottom are dependent on model dimension as illustrated by the contour maps of direction in Figs.21, 22. Under an ESE wind of 3m/s, the directions of 2-D bed shear stress are deviated from that of 3-D stress by more than 30^0 in the middle of the South Block.

7. Conclusions

The main findings of the present work may be stated as following:

1) A 3-D hydrodynamic model is constructed for Lake Yanaka, which shall be a useful tool for better managing this deteriorating lake.
2) The lake's responses to different wind conditions are investigated with the 3-D model. Various circulation patterns are revealed, and some similarity is found between the flow filed under a WNW wind and that under an E wind. Such a similarity might be interesting to both theoretic researchers and practical engineers.
3) The wind speed over the lake may be increased due to the reduction in surface roughness. On the other hand, the wind speed over the lake could be decreased if an unstable stratification exists over the water surface. Besides, field measurements show no sign of significant change in wind direction over the lake.
4) The necessity of 3-D modeling for Lake Yanaka is justified through the comparison between 2-D and 3-D simulation results.
5) The obtained information on the lake's hydrodynamics will help at better understanding the water quality issues, and at determining the significant locations for future measurements of water quality parameters in the lake.

ACKNOWLEDGMENT:

The first author would like to express gratitude for the support by the Upper Tone River Working Office, and to thank Prof. Tamai at the University of Tokyo, and Prof. Kawahara at the Kagawa University for their professional advice.

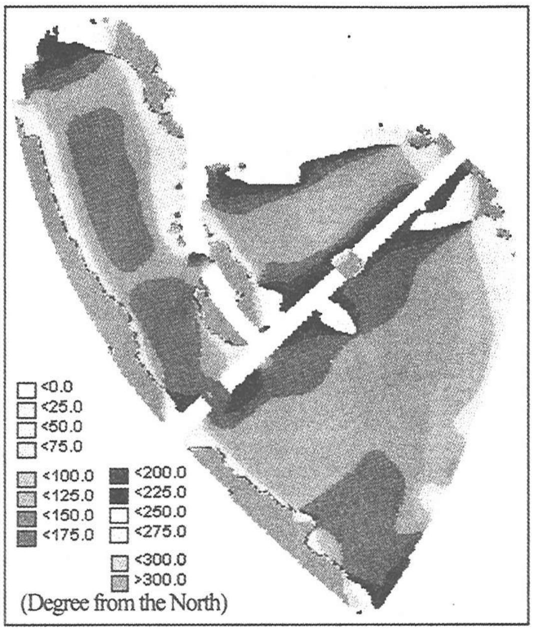

Fig.21 Contour map of direction for 3-D bed shear stress

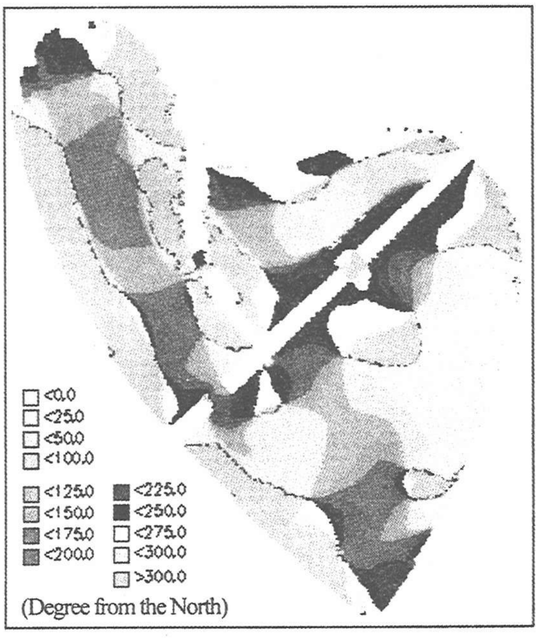

Fig.22 Contour map of direction for 2-D bed shear stress

References

1) Blumberg, A.F., and Mellor, G.: A description of a three dimensional coastal ocean circulation model, N. S. Heaps, ed., American Geophysical Union, Washington, D.C., 1987.
2) Blumberg, A.F., Liaqat, A.K., and John, P.S.: Three-Dimensional Hydrodynamic Model of New York Harbor Region, J. Hydr. Div., ASCE, Vol. 125, No. 8, 799-816, 1999.
3) Baines, W.D., and Knapp, P.E.: Wind driven water currents, J. Hydr. Div., ASCE, Vol. 91, No. 2, 205-221, 1965.
4) Mellor, G.L., and Blumberg, A.F.: Modeling vertical and horizontal diffusivities with the sigma coordinate system, Mon. Wea. Rev., Vol. 113, 1380-1383, 1985.
5) Madala, R.V., and Piacsek, S.A.: A semi-implicit numerical model for baroclinic oceans, J. Comput. Phys., Vol. 23, 167-178, 1977.
6) Huang, G.W., and Tamai, N.: Limnological studies in Lake Yanaka, Annual J. of Hydraulic Engineering, JSCE, Vol. 44, 1107-1112, 2000.
7) Huang, G.W., and Tamai, N.: 3-D simulation of flow in Lake Yanaka, Proc. of 14th Symposium on Computational Fluid Dynamics, CD-ROM, 2000.
8) Sheng, Y.P.: Evolution of a three-dimensional curvilinear-grid hydrodynamic model for estuaries, lakes and coastal waters: CH3D, Estuarine and coastal modeling, ed., Malcolm L. Spaulding, N.Y., ASCE, 40-47, 1992.
9) Simons, T.J.: Verification of numerical models of Lake Ontario, Part I, circulation in spring and early summer, J. Phys. Oceanogr., Vol. 4, 507-523, 1974.
10) Rodi, W.: Turbulence models and their applications in hydraulics: a state of the art review, IAHR, Delft, 1980.

(Received: April 20, 2001)