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Wind Induced Lake Circulation Model Application in the Lake Rudrasagar, Tripura (India)

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ABSTRACT

The goal of current paper is to follow the circulation pattern in lake Rudrasagar occurring during episodes of significant wind flow. An early established wind induced three dimensional lake circulation numerical models developed by Cocyigit and Falconer in the year 2004 has been applied to this lake, where a conventional sigma co-ordinate system was applied for following the bathymetry of the lake more accurately. This model was already tested against analytical solution and laboratory data and was successfully applied to Esthwaite Water, a small lake in Cumbria by the model designers. Application of this model in the lake Rudrasagar, West Tripura reveals some typical circulation patterns for different conditions. Numerical results were compared with measured velocity profile of the lake and the study reveals a fair agreement between them. Changes in the magnitude of velocity were also estimated along and across the wind axis for this lake and were found to be insignificant.

Keywords: Rudrasagar lake, wind induced circulation model, circulation patterns, sigma co-ordinates, velocity profile of lake

INTRODUCTION

Chemical and biological characteristics of any hydraulic basin is very much characterised by lake circulation processes [1-2]. Wind induced water movement might also be responsible for nutrient transport within the lake. Toxic algae may also accumulate in shoreline area of lakes and reservoirs by wind induced water movement process [3]. Prediction of wind induced circulation is very useful for management of any natural lakes and man-made reservoirs [4]. Circulation models may also be considered as a tool for planning of water pollution control strategy [5]. For well managements of natural lakes and man-made lakes Hydraulic Engineers are much more interested in analysing and predicting the mixing characteristics of wind induced lake circulation [4]. Due to invention of more and more powerful computers interest in theoretical study of circulation of water masses has become increasing day by day for the researchers. Wind may be considered as a direct or indirect mechanism causing circulation process in any lake. Wind stress on lake water surface causes turbulence, which is responsible for mixing in lake and so associated with material transport.

In this regard the numerical models are very useful for following the circulation and transport process in case of lakes. From literature survey it is revealed that during the last few decades two dimensional and three dimensional numerical models have been used by simulating the free surface flow [6-8] of lakes. Actually such models indirectly can also be able to describe a wide spectrum of processes in water science. Numerical simulations are very much important for following the lake water flow pattern. Our recent study is to follow the circulation pattern of Rudrasagar lake water under different conditions by using a well-established three dimensional lake circulation model.

Rudrasagar is a natural lake of Tripura (India), a hilly north-eastern state of India where the climate exhibits a strong seasonal rhythm. The climate of this state is generally warm and humid sub-tropical type. Five distinct seasons namely spring, summer, monsoon, autumn and winter are seen in this hilly state. Winds flow is generally very low in this state, though in monsoon period and in the last half of summer they are moderate. Winds are south-easterly during summer and also in post-monsoon season to some extent. While in post-monsoon period and early winter season wind blows towards the northerly direction and thereafter the southern-lies begin. Application of 3-dimensional air induced lake circulation model developed by Cocyigit and Falconer [9] in the lake Rudrasagar, Tripura is very much crucial for following the water circulation pattern of this lake as no such study on this lake has been reported earlier.

Study Area

Geographically the Rudrasagar lake ($23^0 29^/$ N and $90^0 01^/$ E) falls in Melaghar block under Sonamura Sub-division in west Tripura District, India. Hydro morphologically, it is a natural lake and at a distance of about 50 km from the state capital of Tripura. The satellite view of the study site is also shown in fig.1. The lake has three sources of in-flow namely Noacherra, Durlavnarayn cherra and Kemtali cherra. The lake is connected with the river Gumti through a connective channel namely Kachigang. During the period of measurement lake depth was found to vary from 2m to 6m, while the water basin area was found as 1.2 square kilometre. The actual field measurement sites within the lake water area [10] displaying the grid locations are representing in fig 2. Two sites are selected in open water (site A &B) for carrying out the circulation study.

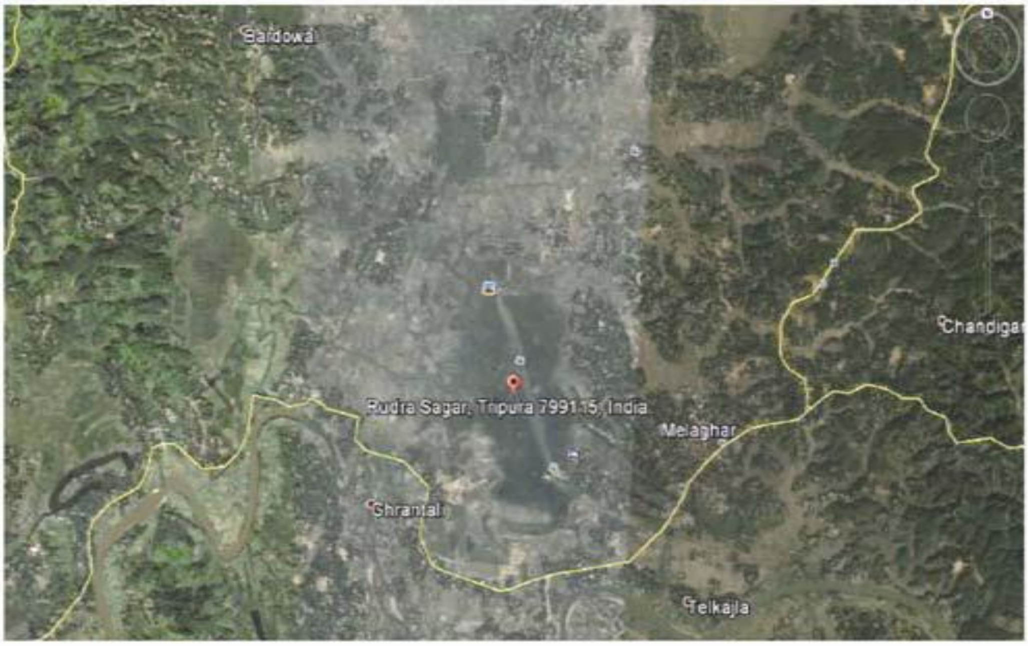

Fig.1 Satellite image of Rudrasagar Wetland, Tripura, India

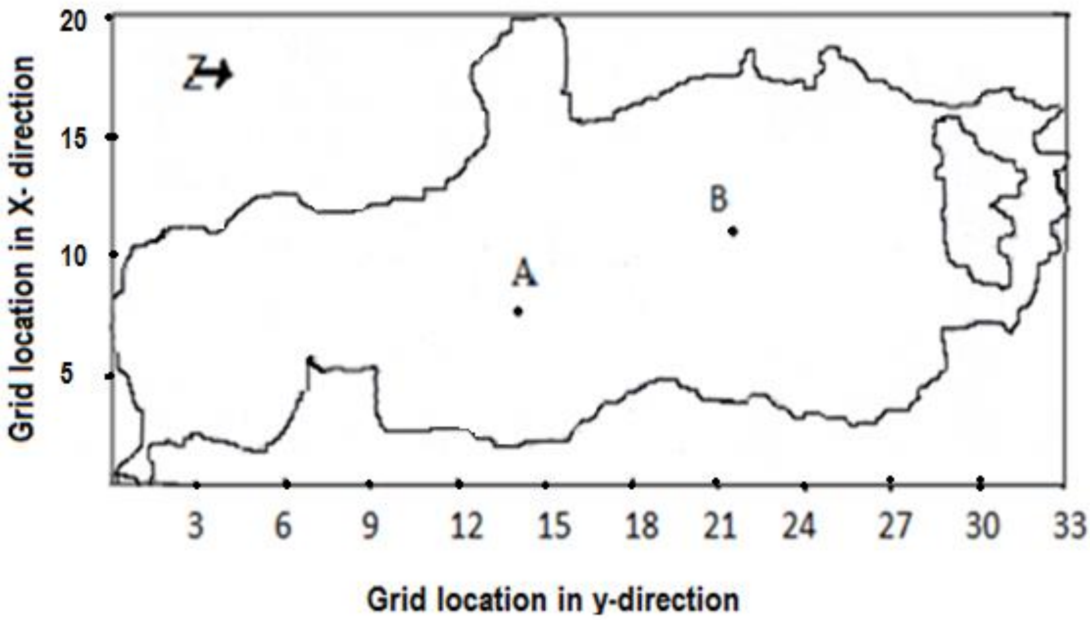

Fig. 2 Field measurement sites within Rudrasagar water

SAMPLING DETAILS AND INSTRUMENTATION

The data recording stations A and B are chosen for the purpose of comparison of open and comparatively deeper water velocity profiles for the lake. An Acoustic Current Profiler (ACP) was used for recording the velocity current data at an interval of 0.5 m depth. Data were stored in internal data logger of the device which is then manipulated in computer. The measurements were carried out for four week monitoring period in moon- soon season in the year of 2015, where there is an average wind flow recorded as 2.8m/sec south-easterly. A vane anemometer has been used for measuring wind speed and wind flow direction more precisely. The resolution of wind speed measurement is 0.1 m/s.

MATHEMATICAL FORMULATION USED IN THE MODEL

The mathematical model is based on the governing equations derived from mass and momentum conservation laws of fluid which are known as Reynolds-averaged Navier-Stokes equation. In this mathematical formalism pressure has been resolved in two components namely hydrostatic and hydrodynamic and the momentum equations are displayed introducing the eddy viscosity coefficient as:

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}= fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho}\frac{\partial q}{\partial x}+\frac{\partial}{\partial x}(v_h\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(v_h\frac{\partial u}{\partial y})+\frac{\partial}{\partial z}(v_v\frac{\partial u}{\partial z}) \quad (1)$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial vv}{\partial y}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho}\frac{\partial q}{\partial y}+\frac{\partial}{\partial x}(v_h\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(v_h\frac{\partial v}{\partial y})+\frac{\partial}{\partial z}(v_v\frac{\partial v}{\partial z}) \quad (2)$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial vw}{\partial y}+\frac{\partial ww}{\partial z}=-\frac{1}{\rho}\frac{\partial q}{\partial z}+\frac{\partial}{\partial x}(v_h\frac{\partial w}{\partial x})+\frac{\partial}{\partial y}(v_h\frac{\partial w}{\partial y})+\frac{\partial}{\partial z}(v_v\frac{\partial w}{\partial z}) \quad (3)$$

here, x,y,z are the Cartesian coordinates along east. north and upward direction respectively and u,v,w are the velocity components along these directions respectively. z=0 is taken for undisturbed water surface and η is the water surface above horizontal datum. q represents the fluid density, f is the coriolis parameter and v_h and v_v representing the kinematic eddy viscosity coefficients in horizontal and vertical directions respectively.
Equation for mass conservation may be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Integrating the equation (4) over the depth and applying Lebnitz rule, free surface evolution equation may be obtained as

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\left[H\int_{-1}^{0} u d\sigma\right]+\frac{\partial}{\partial y}\left[H\int_{-1}^{0} v d\sigma\right]=0 \quad (5)$$

where, H represents the total depth of water column.
In order to define bed and surface boundaries accurately, the sigma coordinate system is used in the vertical direction and thereby fitting the numerical mesh with the free surface and bed accurately. Details of the transformation and resulting equations may be obtained in the works of modelling approach done by Kocyigit group [9].

NUMERICAL ANALYSIS METHOD

Fractional step method was adopted for solving the 3-D free surface flow equations in two steps.Θ-method [11] was adopted for discretising the gradient of surface elevation in the horizontal momentum equations and the horizontal velocities in the surface equation. For getting the discretised form of the equations, a conventional staggered mesh system was applied. The centre of the cells was numbered with indices i ,j, *k* , where i=1,2,….I ,j =1,…..J and k=1,…..,K with k=1 for the surface cell and k=K for the bed cell. For a comprehensive representation of the bathymetry the u velocity was defined at (i+1/2, j, k),v velocity at (i,.j+1/2,k) and the vertical velocities w and ω were defined at the node (i,j, k -1/2).The hydrodynamic pressure term q was defined at the node (i, j, k) ,the surface elevation η was defined at the cell centre(i, j) and the water depth H(x, y)was taken at the centre of each grid side i.e at (i+1/2,j)and (i, j+1/2).The free surface equation after discretisation procedure can be expressed as [9]:

$$\begin{aligned}&\eta_{i,j}^{n+1}-g\theta^2\frac{\Delta t^2}{\Delta X^2}\left\{\left[(\Delta\sigma)^T A^{-1}\Delta\sigma\right]_{i+1/2,j}^{n}\left(\eta_{i+1,j}^{n+1}-\eta_{i,j}^{n+1}\right)-\left[(\Delta\sigma)^T A^{-1}\Delta\sigma\right]_{i-1/2,j}^{n}\left(\eta_{i,j}^{n+1}-\eta_{i-1,j}^{n+1}\right)\right\}\\&-g\theta^2\frac{\Delta t^2}{\Delta Y^2}\left\{\left[(\Delta\sigma)^T A^{-1}\Delta\sigma\right]_{i,j+1/2}^{n}\left(\eta_{i,j+1}^{n+1}-\eta_{i,j}^{n+1}\right)-\left[(\Delta\sigma)^T A^{-1}\Delta\sigma\right]_{i,j-1/2}^{n}\left(\eta_{i,j}^{n+1}-\eta_{i,j-1}^{n+1}\right)\right\} \quad (6)\\&=\delta_{i,j}^{n}-\frac{\Delta t}{\Delta X}\left\{\left[(\Delta\sigma)^T A^{-1}G\right]_{i,j+1/2}^{n}-\left[(\Delta\sigma)^T A^{-1}G\right]_{i,j-1/2}^{n}\right\}\end{aligned}$$

In 2nd step the new velocity fields $u^{n+1}_{i+1/2,j,k}, v^{n+1}_{i,j+1/2,k}$ and $w^{n+1}_{i,j,k+1/2}$ have been introduced and these are connected with intermediate velocity fields ($\tilde{u}^{n+1}_{i+1/2,j,k}, \tilde{v}^{n+1}_{i,j+1/2,k}$ and $\tilde{w}^{n+1}_{i,j,k+1/2}$) and the gradient of hydrodynamic pressure correction term q as:

$$u^{n+1}_{i+1/2,j,k} = \tilde{u}^{n+1}_{i+1/2,j,k} - \frac{\Delta t}{\Delta x}\left(q^{m+1}_{i+1,j,k} - q^{m+1}_{i,j,k}\right) \tag{7}$$

$$v^{n+1}_{i+1/2,j,k} = \tilde{v}^{n+1}_{i+1/2,j,k} - \frac{\Delta t}{\Delta Y}\left(q^{m+1}_{i,j+1,k} - q^{m+1}_{i,j,k}\right) \tag{8}$$

$$w^{n+1}_{i+1/2,j,k} = \tilde{w}^{n+1}_{i+1/2,j,k} - \frac{\Delta t}{H^n_i \Delta\sigma_{k+1/2}}\left(q^{m+1}_{i,j,k} - q^{m+1}_{i,j,k+1}\right) \tag{9}$$

For computing the hydrodynamic pressure correction term the new velocity terms have been introduced into the discretised incompressibility equation to get the finite difference Poisson equation as:

$$\frac{\Delta t}{\Delta x^2}\Delta\sigma^n_{1+1/2,j,k}\left(q'^{n+1}_{i+1,j,k} - q'^{n+1}_{i,j,k}\right) - \frac{\Delta t}{\Delta x^2}\Delta\sigma^n_{1+1/2,j,k}\left(q'^{n+1}_{i,j,k} - q'^{n+1}_{i-1,j,k}\right) + \frac{\Delta t}{\Delta y^2}\Delta\sigma^n_{1,j+1/2,k}\left(q'^{n+1}_{i,j+1,k} - q'^{n+1}_{i,j,k}\right)$$
$$-\frac{\Delta t}{\Delta y^2}\Delta\sigma^n_{1,j+1/2,k}\left(q'^{n+1}_{i,j,k} - q'^{n+1}_{i,j-1,k}\right) + \frac{1}{\Delta\sigma^n_{i,j,k-1/2}}\left(q'^{n+1}_{i,j,k-1} - q'^{n+1}_{i,j,k}\right) - \frac{1}{\Delta\sigma^n_{i,j,k+1/2}}\left(q'^{n+1}_{i,j,k} - q'^{n+1}_{i,j,k+1}\right)$$
$$= \frac{1}{\Delta x}\left[\Delta\sigma^n_{i+1/2,j,k}\widetilde{u}^{n+1}_{i+1/2,j,k} - \Delta\sigma^n_{i-1/2,j,k}\widetilde{u}^{n+1}_{i-1/2,j,k}\right] + \frac{1}{\Delta y}\left[\Delta\sigma^n_{i,j+1/2,k}\tilde{v}^{n+1}_{i,j+1/2,k} - \Delta\sigma^n_{i,j-1/2,k}\tilde{v}^{n+1}_{i,j-1/2,k}\right] + \left[\widetilde{w}^{n+1}_{i,j,k-1/2} - \widetilde{w}^{n+1}_{i,j,k+1/2}\right] \tag{10}$$

Equation (10) can be solved by iterative method with the help of conjugate gradient concept and thereby obtaining the pressure correction term the final velocity field at the new time level can be evaluated.

MODEL APPLIED IN RUDRASAGAR LAKE

This model has been applied successfully in the natural lake Rudrasagar. The sediment particles transported along with the flow coming from three evergreen sources of inflow and settles on the bed of lake influencing a change in lake depth. The bathymetry of the lake has been considered for getting its effect on wind-induced lake circulation patterns. Horizontal velocity field has been predicted for surface layer with a wind speed of 3m/sec considering the coriolis acceleration and without coriolis acceleration which are shown in fig.3 and fig.4 respectively.

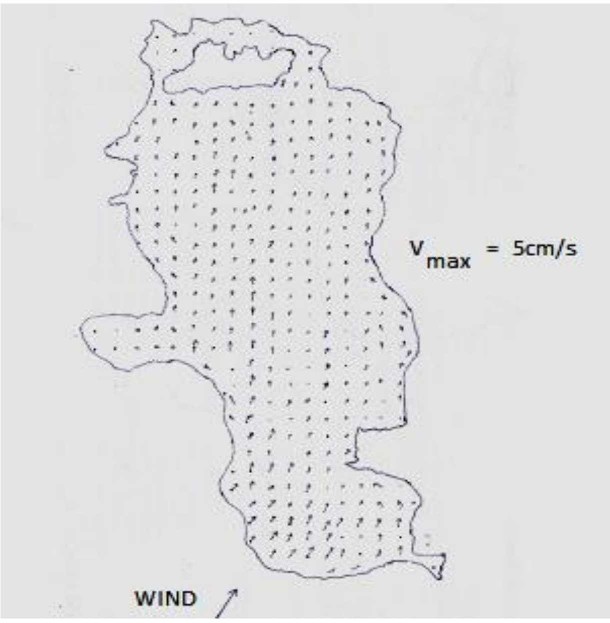

Fig. 3 Predicted horizontal velocity field of Lake Surface layer with a wind speed of 3m/s considering Coriolis acceleration

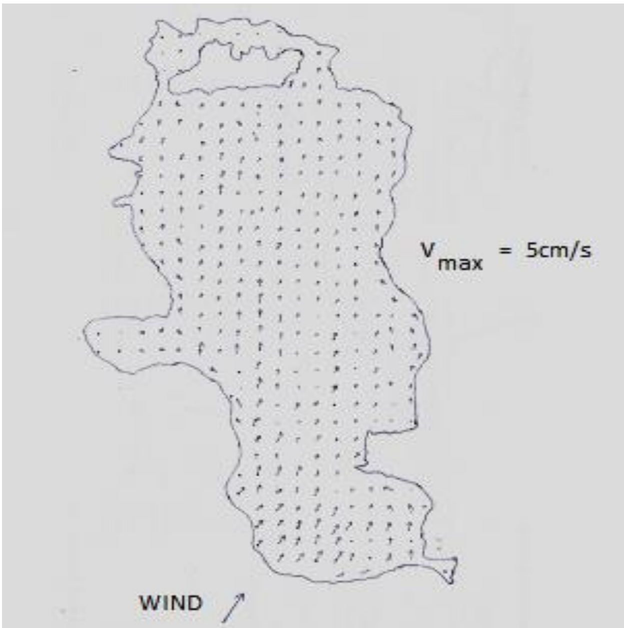

Fig. 4 Predicted horizontal velocity field of Lake Surface layer with a wind speed of 3m/s without considering Coriolis acceleration

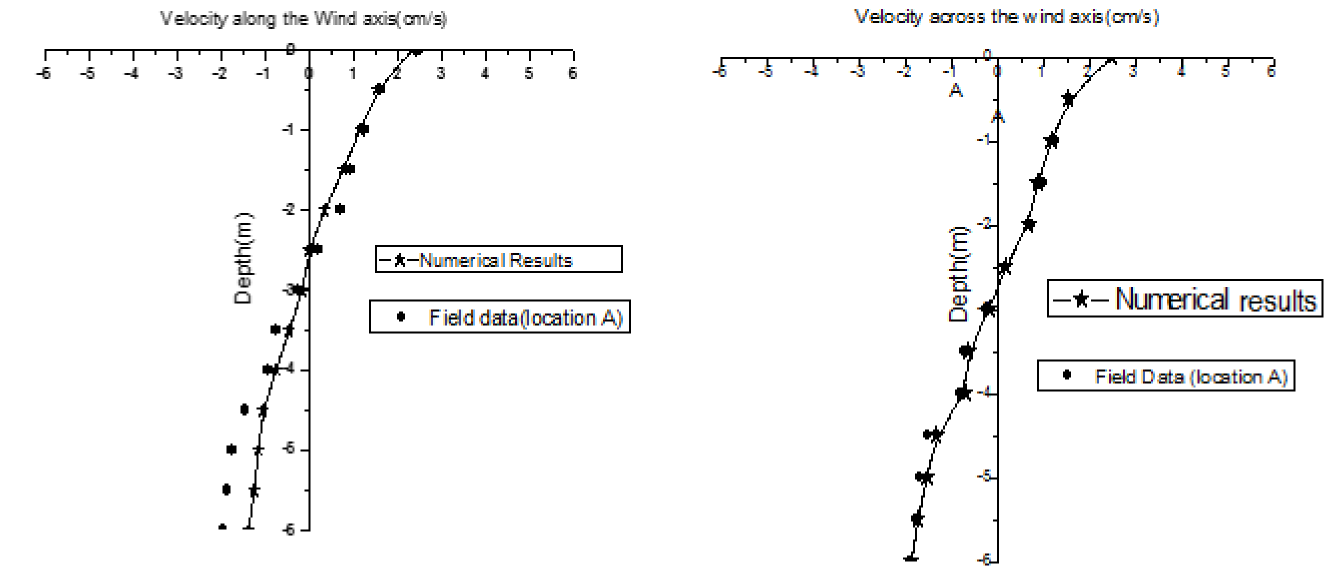

Fig.5 (a) Predicted and measured velocity profiles at site A in open water

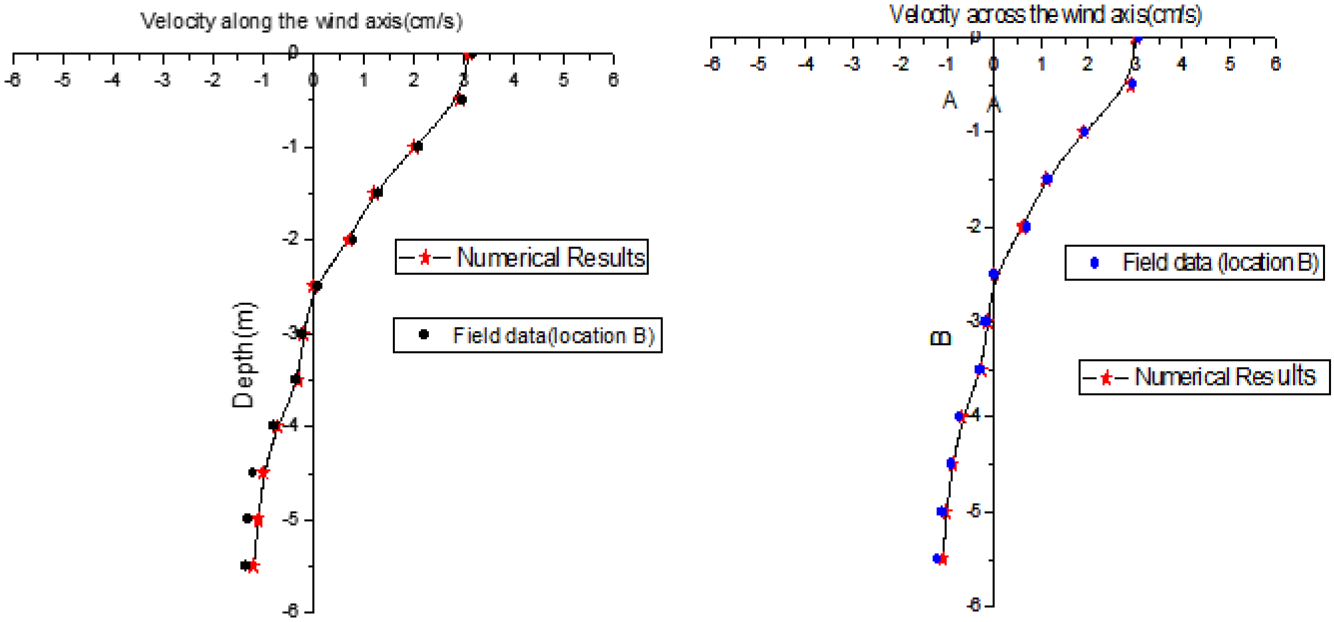

Fig. 5 (b) Predicted and measured velocity profiles at site B in open water

RESULTS AND DISCUSSION

Study of predicted and measured velocity profiles in open water for a wind speed of 3m/sec in sites A and B reveals that there exists a fair agreement between numerical model result and field data. Moreover, it has been observed that velocity components along and across the wind axis in each of the two sites are not much more different. This suggests that Coriolis force has a poor influence on lake circulation phenomena for this small lake. Fig.3 and fig.4 also suggests that predicted horizontal velocity field of lake surface layer is almost remains unaffected when Coriolis force is taken in to consideration. In both of the two figures it has been observed that the numerically predicted result is less than the observed value. The bathymetry of lake, wind speed and wind directions are the main parameters affecting any lake circulation process. For the lake Rudrasagar, it has also been observed that the wind speed and wind direction influences the circulation of this lake significantly.

CONCLUSION

Application of three dimensional lake circulation model induced by air, applied in the lake Rudrasagar of Tripura have explored some typical circulation pattern which may be helpful for the study of nutrient transport within the lake and also for planning of water pollution control strategy of the lake. It is to be mentioned that the effect of hydrodynamic pressure component is to be investigated on the circulation patterns of the entire lake to have an idea of overall circulation pattern more accurately, which is to be done in our next phase of study. For better performance of the model it is also wise to perform studies in near shore regions of lake water also.

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