Modeling of Lake Wind Profile for Estimating Water Surface Evaporation Using Land-based Meteorological Data

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The Big Question

Can we use land-based meteorological data to estimate evaporation from a nearby water surface?

Introduction

Evaporation from reservoirs and small lakes plays an important role in water management. Evaporation is difficult and expensive to measure experimentally over the water surface. For operational purposes, it would be attractive if evaporation from a lake could be estimated with acceptable accuracy from standard meteorological data taken at nearby land-based stations. Here, the modeled wind profile is used to estimate evaporation from the water surface using the aerodynamic approach.

CFD Model of Air Flow in ABL

A CFD model (Reynolds Averaged Navier–Stokes Equations,RANS) was used to simulate the wind profile over the water surface with land-based measurements. The flow in ABL(Atmospheric Boundary Layer) is assumed to be viscous, steady, incompressible, turbulent and indifferently stratified:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{V}\right) = 0$$

$$\frac{\partial}{\partial t}\left(\rho \vec{V}\right) + \nabla.\left(\rho \vec{V}\vec{V}\right) = -\nabla p + \nabla.(\tau) + \rho \vec{g}$$

$$\frac{\partial (\rho C_v T)}{\partial t} + \nabla.(\rho C_p T) = \nabla.(K_T \nabla T)$$

where p is air pressure, $\vec{V}$ wind velocity in three directions (u, v, w) , T temperature and ρ air density. The equations are solved with $k-\varepsilon$ turbulence closure using 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 colocated, polyhedral numerics that can be applied on unstructured meshes and can be easily extended to run in parallel[3][4].

Boundary Conditions

Solving RANS equations with the $k-\varepsilon$ approach needs specified boundary conditions.

- Inlet Boundary Conditions[1]:

$$u = \frac{u_*}{\kappa} ln\left(\frac{z+z_0}{z_0}\right)$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\sqrt{C_1 ln\left(\frac{z+z_0}{z_0}\right) + C_2}$$

$$\varepsilon = \frac{u_*^3}{\kappa(z+z_0)}\sqrt{C_1 ln\left(\frac{z+z_0}{z_0}\right) + C_2}$$

$$\frac{\partial p}{\partial x} = 0 \qquad (\texttt{fixedGradient}^{\circledast})$$

- Outlet Boundary Conditions:

$$\frac{\partial}{\partial x}(u, v, w, k, \varepsilon) = 0 \quad and \quad \texttt{p=fixedValue}^{\circledast}$$

- Top Boundary Conditions:

$$\frac{\partial}{\partial z}(u, v, k, \varepsilon) = 0 \quad and \quad w = 0$$

- Land-Water Boundary Conditions[2]:

$$\vec{V} = (0, 0, 0)$$

$$k = WallFunction(\texttt{kqRWallFunction}^{\circledast})$$

$$\varepsilon = WallFunction(\texttt{epsilonWallFunction}^{\circledast})$$

$$\mu_t = WallFunction(\texttt{nutRoughWallFunction}^{\circledast})$$

$$p = \texttt{zeroGradient}^{\circledast}$$

$^{\circledast}$ defined boundary conditions in OpenFOAM

Verification the Model

The results of the model verified by Wind Tunnel measurements[1].

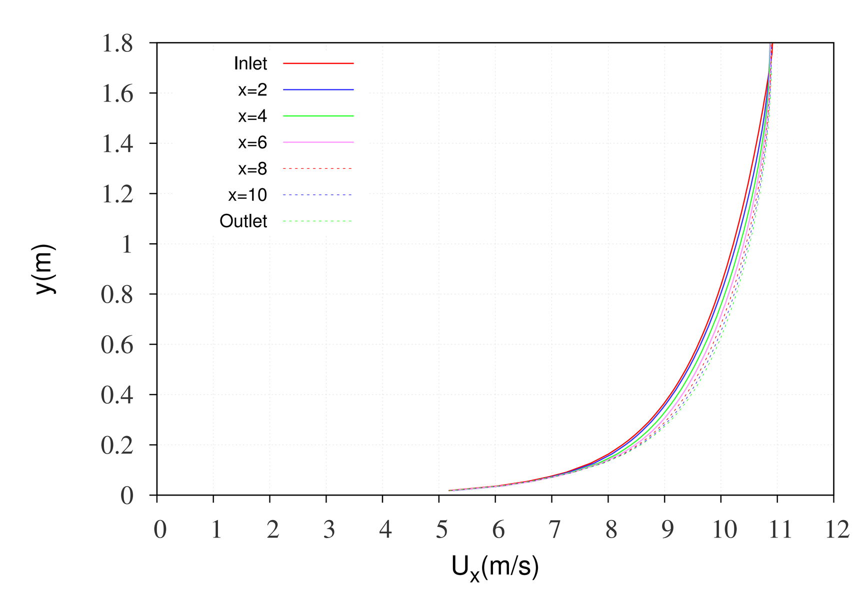

Figure 1: Mean velocity profile at different downstraem distances (verification test)

Numerical Results

The model was run for two different large-scale problems in 2-D. In case (I), the bottom surface is homogeneous(land surface) with a constant roughness length ($z_0 = 0.1m$). In the second case(II), the bottom surface is not homogeneous and includs two different surfaces(land and water) with different roughness length values.

- CASE (I)

Domain Length(L) =10,000 m — Domain Height(H) = 500 m

Roughness Length of Land Surface(z_0)= 0.1 m

Friction Velocity (u_*)= 0.912 m/s

- CASE (II)

Domain Length(L) =10,000 m — Domain Height(H) = 500 m

Length of Land Surface(L_L) =5,000 m

Length of Water Surface(L_W) =5,000 m

Roughness Length of Land Surface(z_{0L})= 0.1 m

Roughness Length of Water Surface(z_{0W})= 0.001 m

Friction Velocity (u_*)= 0.912 m/s

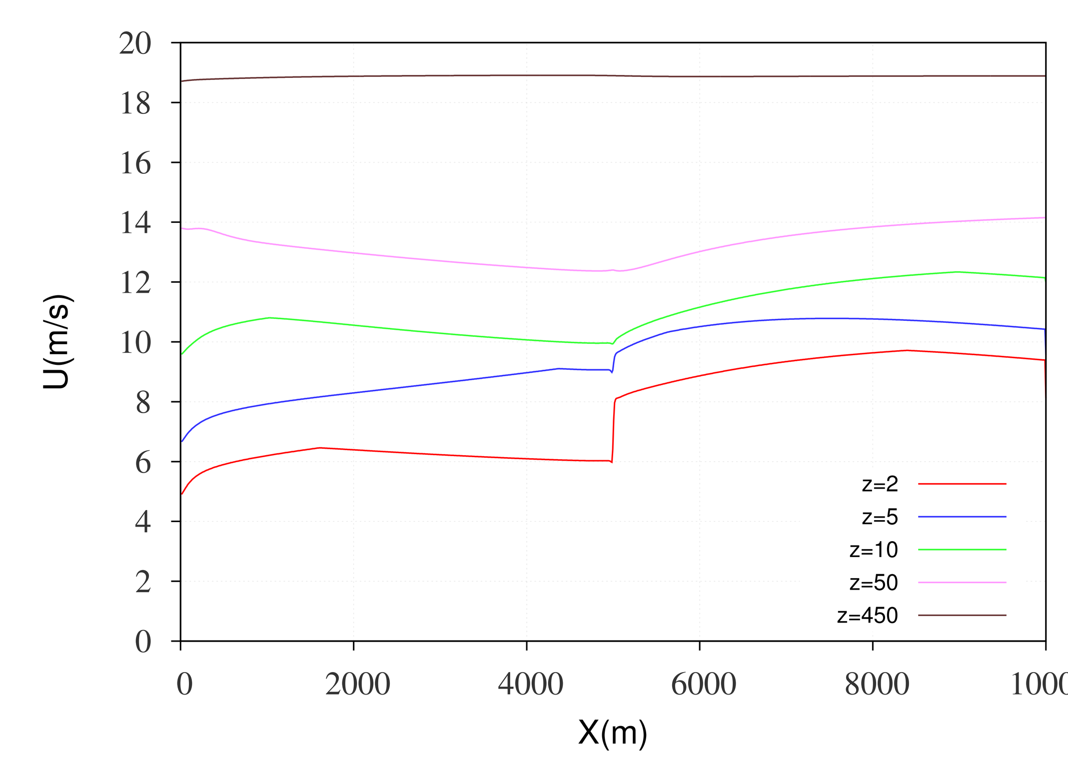

Figure 2: Wind velocity values at different downstream distances (fetch) in CASE (II)

Sharp change in roughness length from land to water surface affects the wind velocity profile. The upwind surface characteristics(land) influences the wind velocity values over the lake. Figure 3, shows the effects of the sharp roughness length change in wind velocity.

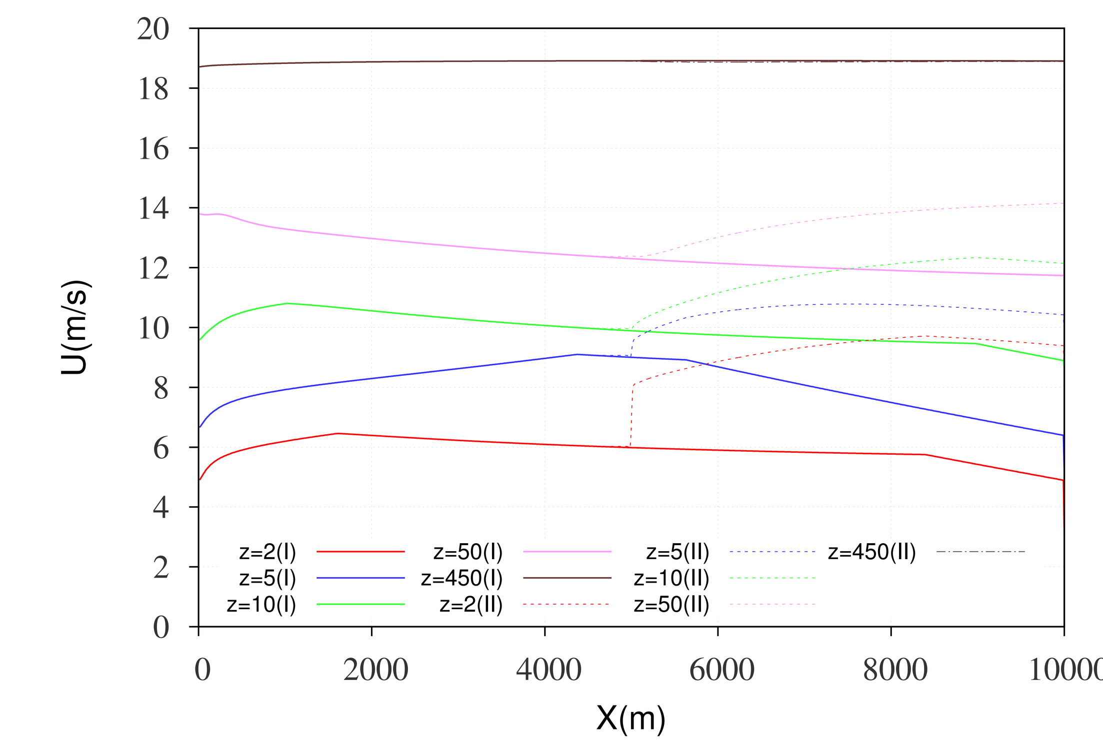

Figure 3: Comparison of wind velocity values at different downstream distances (fetch) in CASE(I) and CASE(II)

Conclusions and Outlook

The flow parameters over the water surface are estimated using the measured parameters over the land surface. By considering the upwind land surface characteristics and that of water surface (such as roughness length), the model's results can be implemented in estimating evaporation methods that need wind velocity values.

References

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[2] B. Blocken, T. Stathopoulos, J. Carmeliet "CFD simulation of the atmospheric boundary layer: wall function problems ", Atmospheric Environment **41** (2007), 238-252.

[3] J.P. O'Sullivan, R.A. Archer, R.G.J. Flay "Consistent boundary conditions for flows within the atmospheric boundary layer ", Journal of Wind Engineering and Industrial Aerodynamics **99** (2011), 65-77.

[4] http://www.openfoam.org/