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A wind driven three-dimensional pollutant transport model

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Abstract

This paper describes a computer program that can be used to simulate three-dimensional wind driven pollutant transport under different environmental conditions. The model uses the three-dimensional governing equations for wind-induced circulation in lakes as determined from the Reynolds stress equations. The governing equations are approximated by the control volume method on the Arakawa-C staggered grid. The model accounts for inflows and outflows from major tributaries and the Coriolis effect. A semi-implicit difference scheme is used for the barotropic pressure, the Adams–Bashford scheme for the temporal terms and the weight averaged Donor-cell scheme for the advective terms. The central difference scheme, of second order accuracy in space, is used for the diffusive term. The functionality of the model is demonstrated using two simple test basins under a single source and constant wind conditions. In addition the applicability of the model to a nearshore, multiple source, variable wind case is illustrated.

Keywords: Wind induced circulation; Control volume; 3-D pollutant transport; Turbulence closure; Stratified; Coriolis effect; Finite difference; Reynolds stress equations

Software availability

Name of software:	IDOR3D
Developer:	I.K. Tsanis and H. Shen
First available:	1998
Hardware requirements:	PC or Unix
Software requirements:	DOS and/or Windows
Program language:	Fortran
Program size:	300 KB
Availability:	free (executable file)

1. Introduction

Accurate analysis of the transport and mixing of pollutants entering waterways is becoming increasingly important under urbanization of shorelines and the requirement for clean and safe drinking water. This is particularly true for the Great Lakes System in North America which acts as the recipient of pollutants and as the source of fresh drinking water. As a result a number of pollutant transport models have been developed and applied to these lakes over the last several years. Detailed reviews of these models can be found in Cheng and Smith (1989) and Schwab (1992) and include both two- and three-dimensional representations, wind setup and pollutant transport under rigid-lid theory, long-wave theory and Ekman flow theory (Wu, 1993). The IDOR3D model, described herein, is another such model that has been applied on several occasions to Lake Ontario. The IDOR3D model simulates three-dimensional wind driven circulation using the Reynolds stress equations on a cartesian based grid. The model accounts for inflows and outflows from major tributaries and the Coriolis effect. To outline the program and its applicability this paper has been divided into three major sections: the first discusses the numerical methods

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behind the computations; this is followed by a description of the IDOR3D model; and subsequently by practical applications. A GIS pre-processor developed by Naoum et al. (2004) is used to prepare ASCII input files for the IDOR3D model.

2. The wind driven circulation method

The three-dimensional governing equations for wind-induced circulation in lakes were derived from the Reynolds equations using the following assumptions:

- Incompressibility: for lakes the water can be assumed to be incompressible, allowing for simplification of the equation of continuity.
- Shallow water assumption: the vertical accelerations are small enough to be ignored, which results in the hydrostatic pressure distribution for the z-momentum equation. This is reasonable when the characteristic length in the vertical direction is two to three orders of magnitude smaller than the horizontal direction.
- Boussinesq approximation: the variation of water density is taken into account only in the gravity term. This is reasonable where the density variations are of the order 10^{-3}.

Turbulence closure within the IDOR3D model is provided by the eddy viscosity-diffusivity approach. In this approach the turbulent transport terms are written in terms of eddy viscosity and diffusivity coefficients (ν_h,ν_v), (K_h,K_v), and (M_h,M_v) representing the turbulent viscosity and diffusivities for velocity, temperature and concentration, respectively. The governing equations using the approximations and turbulence closure scheme outlined above are given by Eqs. (1)–(6) (Shen et al., 1995).

Continuity of mass:

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

Momentum in the x-, y-, and z-directions:

$$\frac{\partial u}{\partial t}+\frac{\partial (uu)}{\partial x}+\frac{\partial (vu)}{\partial y}+\frac{\partial (wu)}{\partial z} = fv-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+\nu_h\frac{\partial^2 u}{\partial x^2}+\nu_h\frac{\partial^2 u}{\partial y^2}+\frac{\partial}{\partial z}\left(\nu_v\frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial (uv)}{\partial x}+\frac{\partial (vv)}{\partial y}+\frac{\partial (wv)}{\partial z} = -fu-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+\nu_h\frac{\partial^2 v}{\partial x^2}+\nu_h\frac{\partial^2 v}{\partial y^2}+\frac{\partial}{\partial z}\left(\nu_v\frac{\partial v}{\partial z}\right) \tag{3}$$

$$0=-g\frac{1}{\rho}-\frac{\partial p}{\partial z} \tag{4}$$

$$\frac{\partial T}{\partial t}+\frac{\partial (uT)}{\partial x}+\frac{\partial (vT)}{\partial y}+\frac{\partial (wT)}{\partial z} = S_T+K_h\frac{\partial^2 T}{\partial x^2}+K_h\frac{\partial^2 T}{\partial y^2}+\frac{\partial}{\partial z}\left(K_v\frac{\partial T}{\partial z}\right) \tag{5}$$

$$\frac{\partial C}{\partial t}+\frac{\partial (uC)}{\partial x}+\frac{\partial (vC)}{\partial y}+\frac{\partial (wC)}{\partial z} = S_C+M_h\frac{\partial^2 C}{\partial x^2}+M_h\frac{\partial^2 C}{\partial y^2}+\frac{\partial}{\partial z}\left(M_v\frac{\partial C}{\partial z}\right) \tag{6}$$

where u, v and w are the velocity components in the x, y and z directions, with x positive eastward, y positive northward and z positive upward; f is the Coriolis parameter; p is the water pressure; ν_h and ν_v are the eddy viscosity coefficients in the horizontal and vertical directions, respectively; g is the acceleration due to gravity and ρ is the water density; ρ_0 is the reference water density (at 4 °C); T is the water temperature; S_T is the source term for the water temperature; K_h and K_v are the eddy diffusivity coefficients for water temperature in the horizontal and vertical directions, respectively; C is the concentration; S_C is the source for concentration. Finally M_h and M_v are the eddy diffusivity coefficients for concentration in the horizontal and vertical directions, respectively (Shen et al., 1995).

The eddy viscosity and diffusivity for momentum, temperature and concentration are reduced and evaluated by the following formulas, respectively (Leendertse and Liu, 1975),

$$\nu_v=\nu_{v0}\,e^{-1.5Ri} \tag{7}$$

$$K_v=K_{v0}\,e^{-3.0Ri} \tag{8}$$

$$M_v=M_{v0}\,e^{-3.0Ri} \tag{9}$$

where ν_{v0}, K_{v0} and M_{v0} are the eddy viscosity and diffusivities in the neutral state (isothermal state) respectively, Ri is the local Richardson number and is defined as

$$Ri=-\frac{g\partial T/\partial z}{\rho_0(\partial\overline{u}/\partial z)^2} \tag{10}$$

where $\overline{u}$ is the average velocity in the horizontal plane.