Coupling an Underflow Model to a Three-Dimensional Hydrodynamic Model

Chris J. Dallimore[1]; Ben R. Hodges, A.M.ASCE[2]; and Jörg Imberger, M.ASCE[3]

Abstract: A separate underflow model is coupled to the three-dimensional (3D) estuary and lake computer model. The underflow equations are solved on a two-dimensional (2D) grid underlying the 3D model grid. The underflow model entrains ambient water whose properties are given by the fluid properties of the bottom boundary cells in the 3D model. This new approach allows improved representation of underflow effects in *z*-coordinate models by reducing numerical convective entrainment. An idealized case is used to illustrate the benefits of the underflow model. Comparisons of model results and field data for a saline underflow event in Lake Ogawara and a cold-water underflow in Lake Kinneret demonstrate improved model capability in representing underflow events that are thin compared to the vertical grid scale.

DOI: 10.1061/(ASCE)0733-9429(2003)129:10(748)

CE Database subject headings: Currents; Inflow; Reservoirs; Hydraulic models; Two-dimensional models; Australia; Lakes; Three-dimensional models.

Introduction

When a river enters a lake or reservoir there is usually a density difference between the inflowing water and the ambient water body. The density difference may be caused by differences in turbidity (Parker et al. 1986), salinity (Hebbert et al. 1979) or temperature (Serruya 1974; Fischer et al. 1979). If the inflow is less dense than the surface water it forms a surface buoyant overflow. Conversely, when the inflow is heavier than the surface water the inflow plunges to form an underflow along the bottom boundary. In a stratified water body, an underflow may reach a level of neutral buoyancy where it separates from the bottom and intrudes horizontally. This paper focuses on modeling underflows in the presence of ambient stratification.

River inflows are a principle source of nutrients, suspended sediments, and contaminants in many lakes and estuaries. The density differences between the inflows and ambient water provide baroclinic forcing, distributing inflowing water far from the river entry. In particular, a dense underflow can retain its identity as a cohesive water mass with its own temperature, nutrient concentration, oxygen level, and turbidity. Gravity causes this water mass to flow down the benthic boundary, seeking either its level of neutral buoyancy or the lowest point in the lake. Consequently, underflow propagation may be a critical factor determining spatial and temporal distributions of water properties. For water quality management, accurate prediction of underflow behavior is essential to understanding nutrient dynamics and oxygen replenishment in the hypolimnion.

The importance of underflows in oceanography and atmospheric science as well as limnology has led to a large body of research into their behavior. Ellison and Turner (1959) provided a substantial contribution through a series of laboratory experiments coupled with an analytical study of plume dynamics. These experiments were followed by other work in both field and laboratory settings (e.g. Lofquist 1960; Elder and Wunderlich 1972; Britter and Simpson 1978; Hebbert et al. 1979; Alavian et al. 1992; Hallworth et al. 1996). More recently, Dallimore et al. (2001) provided detailed measurements of the mean flow and turbulent properties of a saline underflow entering Lake Ogawara, Japan. The importance of underflow dynamics is recognized in one-dimensional (1D) lake and reservoir modeling (e.g., DYRESM—Imberger and Patterson, 1981) where underflow entrainment and intrusion is approximated through parametrizations based on reservoir length, ambient stratification, and boundary slope. Recently, Bradford and Katopodes (1999), modeled unsteady dynamics of a turbid underflow into a homogeneous water body using a two-dimensional (2D) depth-averaged approach. Additionally, 2D laterally averaged models have been used to simulate underflows in long narrow reservoirs (Chung and Gu 1998; Bournet et al. 1999).

Oceanic modeling has shown the *z*-coordinate numerical approach has difficulty modeling an underflow due to the step-like representation of bottom topography (Hirst and McDougall 1996). As dense water flows down these steps, ambient water is artificially mixed into the plume through a process called ‘‘numerical convective entrainment’’ (Winton et al. 1998). Dense water on a step flows horizontally outward over lighter ambient fluid on the step below. In a hydrostatic model, the ambient water on the lower step and underflow water from the upper step are mixed to remove the numerical instability. As a result, the entrainment rate is a function of the step size (i.e., the slope of the bottom and the grid size relative to the plume thickness) rather than the physics of the underflow. This numerical convective en-

---

[1] Research assistant, Centre for Water Research, Univ. of Western Australia, Perth 6009, Western Australia.

[2] Assistant Professor, Environmental and Water Resources Engineering, Dept. of Civil Engineering, Univ. of Texas at Austin, Austin, TX (corresponding author). E-mail: hodges@mail.utexas.edu

[3] Professor and Chair, Centre for Water Research, Univ. of Western Australia, Perth 6009, Western Australia.

Note. Discussion open until March 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 11, 2001; approved on April 23, 2003. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 129, No. 10, October 1, 2003. ©ASCE, ISSN 0733-9429/2003/10-748–757/$18.00.