Modeling a Plunging Underflow

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Abstract: A coupled three-dimensional hydrodynamics and two-dimensional underflow model is adapted to provide simulation of plunging inflows in reservoirs. The new approach accounts for the effect of the barotropic term prior to the plunge point of the inflow. Simulations of plunging flows in constant width and constant slope channels are conducted and the resulting plunge depths are in agreement with prior empirical models. Simulation of a previously measured underflow in Wellington Reservoir (Australia) demonstrates the model application to a plunging inflow in a natural water body and good agreement between field and model results.

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Introduction

Rivers may introduce nutrients, suspended sediments, and contaminants into a lake or reservoir. A dense river inflow that penetrates to the hypolimnion of a lake will have different ecological consequences than a less-dense inflow that inserts into the metalimnion or a light inflow that remains on the lake surface. It follows that predicting mixing the fate of a river inflow is a concern for water quality management. River inflows may have different temperatures, salinities, and/or turbidities than the ambient lake water, leading to baroclinic forces affecting the flow structure. A less-dense inflow will form a buoyant overflow whose mixing with the ambient is strongly affected by wind forces. However, momentum of a heavier inflow pushes the ambient water ahead until a "plunge point" is reached, where the inflow forms a negatively buoyant underflow. A dense underflow may be isolated from wind-driven mixing and can remain a cohesive water body with unique temperatures, nutrient concentrations, oxygen levels, and turbidity as it flows down the bottom boundary to either its level of neutral buoyancy or the bottom of the lake. This paper focuses on dense underflows, which have previously been studied in the laboratory (Ellison and Turner 1959; Britter and Simpson 1978; Akiyama and Stephan 1984; Alavian et al. 1992; Hallworth et al. 1996), in field surveys (Elder and Wunderlich 1972; Hebbert et al. 1979; Dallimore et al. 2001), and with numerical models (Chung and Gu 1998; Bournet et al. 1999). Due to the complexity of plunging underflows through the convoluted bathymetry of real lakes and reservoirs, empirical models devised for understanding gravity flows in laboratory and simple geometry may provide only limited predictive ability and cannot be readily linked to effects of internal waves and wind-driven mixing. Thus, numerical modeling of underflows is necessary for predicting the spatial and temporal distributions of temperature, nutrients, pollutants, and turbidity that rivers provide to lakes and reservoirs.

Following Akiyama and Stefan (1984), three flow regions can be identified for a dense inflow to a reservoir (Fig. 1). In the "homogenous region," the inflow momentum is large enough to displace the ambient water horizontally over the entire depth of the lake. At the "plunge point," the baroclinic force resulting from the inflow/ambient density difference balances the inflow momentum, so the inflow plunges beneath the ambient water. In the "plunge region" close to the plunge point, both the flow momentum and baroclinic forces affect the flow dynamics. In the "underflow region" the flow is entirely baroclinic and is therefore independent of inflow momentum. Ellison and Turner (1959) showed that after plunging the underflow quickly reaches a normal state where the bulk Richardson number is constant. The "plunge depth" is therefore the depth where the inflow moves from momentum-dominated to buoyancy-dominated and marks the transition of an inflow to an underflow. Failure to accurately predict the plunge depth will result in an inaccurate representation of the initial underflow layer thickness and therefore causes a distortion of the underflow dynamics beyond the plunge point.

A number of models (Table 1) have been proposed for prediction of plunge depth. These models are generally valid only for channels of constant slope and width. The Singh and Shah (1971) model was developed from laboratory experiments that provided an empirical relationship between plunge depth and the initial densimetric Froude number of the inflow. The initial Froude number is given by

$$\mathsf{F}_0 = \frac{U_0}{\sqrt{g' H_0}}; \;\; g' = g\frac{\rho_0 - \rho_{\text{amb}}}{\rho_{\text{amb}}}$$

where U_0=inflow velocity; H_0=initial height of the inflow; and g'=reduced gravity of the low. Hebbert et al. (1979) used the typical triangular cross section of a drowned river channel in a reservoir to derive a plunge depth equation based on the underflow Froude number and the half angle of the river cross section. Their approach used a simple two-layer approximation and Elli-

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