Investigation of the propagation of multi-inflow turbid density currents in a deep narrow reservoir using three-dimensional modeling: Maroon Reservoir, Iran

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Abstract

In reservoirs with narrow morphologies, a dense turbidity current, originated from a riverine flood, moves downstream along the thalweg and its influence of the euphotic zone depends on mixing behaviors near the plunge point. However where low-to-moderate density currents form overflows or interflows, the euphotic zone through a reservoir can be affected with increasing turbidity, which alters light penetration, the thermal evolution of stratification, and hence the overall aquatic ecosystem. Numerical modeling of the reservoir hydrodynamics with density currents can provide insight into fate of different types of turbid inflows and help develop proper reservoir management strategies.

In this study a three-dimensional (3D) numerical hydrodynamic model coupled with a particle dynamics model has been used to simulate turbid density currents developed from multiple stream inflows in a large stratified reservoir. The Maroon reservoir, in southwest Iran, has a deep and narrow morphology formed by the connection of two main impoundments and a narrow canyon. Turbid inflows with multiple suspended sediment sizes, determined by means of a grain-size analysis of the river-suspended sediments, have been simulated. Model forcing conditions for the main stem Maroon river were developed from available measured flows and sediment, whereas inflows and sediment for two minor streams were calculated by using a rainfall-runoff model and site-specific flow-sediments relationships. The numerical model shows illustrates different fates and turbidity effects of different sediment size classes.

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1. Introduction

Turbidity introduced by river inflows during storm events can directly affect the entire ecosystem in reservoirs by changing the light penetration in the vertical water column. If the turbidity persists over an extended period, this, in turn, can alter adversely the primary production and the distribution of fish and biotic organisms (Kim et al. 2001; Chung, 2004; Chung et al. 2009). When a storm flood with entrained suspended solids enters a stratified reservoir, it forms a turbid density current as an underflow, interflow or overflow depending on the inflow density and reservoir stratification (Ford and Johnson, 1983). Turbid inflows propagate through reservoirs as density currents due to the density difference between inflows and the impounded water. Because of the complicated and dendritic morphometry of the reservoirs (especially for dammed narrow canyons), cross-channel wind forcing is often small and the density currents have a low lateral mixing, leading to low dilution rates. A turbidity current eventually dissipates through settling of coarse grains, dilution of fine grains, and/or release at the dam outlets. Since the reservoirs typically have a larger watershed than that of natural lakes, they often entrain a larger amount of fine sediment and nutrient loads (Ji, 2008), which can remain in the euphotic zone and affect the reservoir water quality (Gray and Ward, 1982). In large reservoirs collecting inflows from a large basin (e.g. the study herein), critical issue for reservoir management is predicting behavior of inflowing turbidity currents such as the travel time throughout the reservoir, thickness of the current, dilution rates, suspended sediment concentration and the consequent turbidity (Chung et al. 2009), which all are affected by the reservoir stratification. Reservoir management strategies (e.g. selective withdrawal) can be used to minimize effects of turbid density currents by controlling the flow patterns within a reservoir and altering stratification. Numerical modeling of the density-current hydrodynamics can provide insight into how different sediment classes within a turbidity current interact with the stratification of a reservoir. In this study, the propagation of a turbidity current due to a flood event into Maroon reservoir (Iran) is studied. A three-dimensional hydrodynamic model (ELCOM, Hodges et al 2000) was coupled with an aquatic ecosystem dynamics model (CAEDYM, Hipsey et al 2006), which was used to simulate the particle dynamics.

2. Study site

The Maroon dam is a large rockfill dam with a clay core and is located at the 10 km northeast of Behbahan City in southwest Iran (30°40´N, 50°21´E). The impounded reservoir volume, established in 1998, is $1200 \times 10^6$ m$^3$; the surface area is 24.6 km$^2$; the maximum depth is 105 m; and the length is 25 km. Maroon Reservoir collects the surface water of a $3824$ km$^2$ basin (Fig. 1). The Maroon reservoir is warm-monomictic, according to the limnological categorization by Hutchinson and Löffler (1956), with one major summer stratification and one major overturn in winter. The thermal state of the reservoir determines the density stratification and consequent buoyancy forces which are essential factors in the assessment of turbidity currents in reservoirs. The main inflow into the Maroon reservoir is from the Maroon river, supplemented by several minor streams whose inflows are typically seasonal. These minor streams are ungauged and are often neglected in the hydrological analyzes of Maroon reservoir as not being significant in the overall water balance. However, large storm events in these smaller catchments can somehow affect the propagation patterns of turbidity currents. Two of the largest ones (Figure 1) are selected to simulate in this study.
The Maroon reservoir consists of two large impoundments which draw water from two basins that are separated by a narrow canyon. The upstream basin was a long narrow lake before construction of Maroon dam. The upstream basin, with a length of 18 km, includes a long riverine and transition zone with a lacustrine zone that ends at the narrow canyon connecting to the downstream basin. The main stem of the Maroon river and two smaller streams (modeled herein) debouch into the upstream basin. The narrow canyon connecting the basins plays the role of a riverine zone for the downstream basin. Because of the mentioned canyon, the two basins have different hydrodynamic behaviors affecting sedimentation patterns and the propagation of density currents.

3. Model description

3.1. Hydrodynamic model

ELCOM is a 3D hydrodynamic flow and transport model for simulating temporal variations of flow temperatures and densities in thermally (density) stratified lakes and reservoirs with environmental forcing (inflows, winds, radiation) including advection and dispersion processes by numerically solving the Reynolds-averaged Navier-Stokes (RANS) equations for flow, as well as a scalar transport equation for temperature (or solutes) under the Boussinesq approximation and neglecting non-hydrostatic pressure terms. The numerical solution approach uses a semi-implicit solution technique with a conservative finite-difference scheme that incorporates hexahedral cells in an Arakawa-C grid stencil (Cassuli and Cheng, 1992; Hodges et al, 2000, Hodges and Dallimore, 2010).

3.2. Particle dynamics model

To simulate the suspended non-cohesive sediment dynamics, the CAEDYM model was coupled to ELCOM model. CAEDYM is a complex aquatic ecological model including comprehensive process representation of several size classes of inorganic suspended solids, including settling and resuspension of nutrient cycles and phytoplankton dynamics with numerous optional biological and other state variables configurations that can resolve species or group specific ecological interactions (Hipsey et al., 2006). Herein, only the sediment processes from CAEDYM were used.
4. Input data and model setup

4.1. Input data

All of the hydrodynamic, sediment, and meteorological data used herein was from year 2006. The water temperature and suspended solids data were collected on a monthly basis (Ghorbani, 2006) at 4 stations shown in Fig. 1: the reservoir main river inlet (ST1), in upstream basin (ST2), in downstream basin (ST3) and at outflow of the dam (ST4). Hourly meteorological data were obtained from the Iranian Meteorological Organization station at Behbahan city 10 km southwest of the dam-site. Hydrological data includes daily river flow. The average annual flow is 53 m$^3$s$^{-1}$, but is seasonal and highly variable. A flood event with a 194 m$^3$s$^{-1}$ peak flow occurred on 30 March 2006. This flood and the subsequent sediment load entrained by into the reservoir are reflected in the early April peak inflow and sediment discharge shown in Fig 2.

Measured sediment data includes monthly suspended sediment (SS) concentration and turbidity at the four sampling stations, as well as daily measured inflow sediment concentration during the flood event mentioned above. The total suspended sediment data were divided into class fractions of clay, silt, and sand, in the suspended sediment grain size analysis of Maroon river (Fakhri and Ghomeshi, 2007). The coarse-grain sand class was omitted from the present analysis since it occupies only less than 7 percent of the total suspended sediments and settles far upstream in the reservoir. Table 1 shows the suspended sediment specifications of Maroon reservoir used in this study, as well as the parameters adjusted for the particle dynamics model.

The inflows from the two small tributaries were estimated as area-proportional flows based on the ratio of these smaller catchment areas and the main Maroon river catchment. The suspended sediment loads for the smaller catchments were estimated from site-specific flow rate-sediment relationships of Emamgholizadeh and Torabi (2009).

4.2. Model preparation

The bathymetry of the Maroon reservoir model was defined in the form of a $\Delta x = \Delta y = 200$ m in horizontal and $\Delta z = 2$ m in vertical direction for 37,586 computational grid cells. The 200 m cell size was selected as a compromise between minimizing computational time and capturing the complicated bathymetry of Maroon Reservoir. A time step of 20 seconds was defined to satisfy the Courant-Friedrichs-Lewy (CFL) condition for high velocities in the narrow canyon. The model was run on a desktop PC with a 3.40 GHz processor to simulate two months of the reservoir operation. The results focus on the processes of propagation, dilution and settling of the turbid density current during and after the flood inflowing the reservoir.

Boundary conditions of the hydrodynamic model include inflow data of the Maroon river and two small tributaries, outflow data of two outlets and the spillway of Maroon dam. The other boundary conditions are meteorological data, and inflow water characteristics including water temperature, salinity and suspended sediment groups. The measured water temperature and suspended sediment profiles at ST2 were used as the model initial conditions. The turbulence model was the wind-mixed-layer closure scheme with energy transport (Hodges et al. 2000), which applies the turbulence kinetic energy from wind stirring, convective overturns, and
Soil class & Percentage & Average density (kg/m$^3$) & D50 (mm) \\
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Clay & 0.35 & 2650 & 2.00E-03 \\
Silt & 0.58 & 2650 & 8.00E-03 \\
Sand & 0.07 & 2650 & 12.00E-02 \\

wind shear to compute vertical mixing.

Coefficients for the CAEDYM particles dynamic model were taken the site-specific sediment data of Fakhri and Ghomeshi (2007) for clay and silt suspended sediment classes. For simplicity, it was assumed that both classes are non-cohesive particles, whose settling velocities follow Stokes law. The settling velocities are modelled by stoke’s law in CAEDYM model according to the user-defined particle size and density.

5. Results

5.1. Reservoir hydrodynamics

Fig. 3 shows time-evolving temperature and density profiles from the simulation at ST2 and ST3 (the two main basins of Maroon reservoir). The stratification period begins from the middle of February and indicates formation and progressive deepening of the thermocline. The effect of the wind-induced turbulence in creating the mixed layer and temporarily deepening the thermocline is clearly seen on the profiles. The dispersion due to the wind-induced turbulence can have a negative effect on decreasing the concentration of the turbidity current as the inflowing current moves toward the dam (Ford and Johnson, 1983). This is of critical importance since the fine particles can remain in water and cause turbidity even for months.

The most challenging area to model in the Maroon reservoir is the connection of two basins, where velocities can be quite high and cause model instability unless the time step is set sufficiently small. Figure 4 shows surface water temperatures and the velocity vectors at the start of the flood event and a few weeks after the flood. The area is mainly affected by wind and the inflows (primarily by the main inflow and secondarily by the sub-basin B). The epilimnion (especially water surface) is more affected by the wind than that of the layers beneath. However, depending on the intensity of each; the mentioned factors (wind and inflow) impact the advection and dispersion processes as well as turbulent mixing with different intensities. Figure 4(a) indicates that before the flood event has affected the main stem of the Maroon river, the flow between the reservoir basins dominated by flow from Stream B (see Fig. 1). During and after flood event (Fig. 4b, c) there appears to be a sharp velocity interface within the upstream basin that separates the inflows from Stream B from the flooding flows from the main stem. A surface recirculation appears to indicate that this water might be trapped due to surface density differences. By 25 May, 2006, storms with winds up to 20 ms$^{-1}$ from the northeast appear to dominate the surface flows (Fig. 4d).

The results show that the water density was mostly dominated by water temperature than that of the SS. Of the factors affecting the former, the inflow water temperature was significantly the dominant factor of the water density variations during the flooding period because the density stratification was not formed yet. After the forming of the thermal stratification, it overcame the effects of the inflow on the water density variations. During the simulation period, the maximum water temperature difference within observed between 16 to 27°C. The consequent water density change was in the range of 0.15 to 2.56 kg m$^{-3}$.

5.2. Dynamics of density currents

Overall, the model results indicate water density is affected more by water temperature than by concentrations of suspended solids. The inflowing water temperature from the catchment was a dominant control on the water
density variations during the flooding period because the seasonal thermocline was only weakly developed by the end of March (see Fig. 3). Thus, the warm inflows acted as overflows, despite the suspended sediment loads, and further enhanced the thermocline. During the simulation period, the maximum water temperature difference was between 16 to 27°C. The consequent water density change was in the range of 0.15 to 2.56 kg m$^{-3}$.

The results of the simulation for the SS1 and SS2 suspended sediment classes are shown in Fig. 5. The fine SS1 portion remained suspended in the density overflow layer and traveled the length of the reservoir in the epilimnion with the warm flood waters. A SS1-turbidity-maximum developed in the metalimnion, where it remained for two months with low dilution due to the development and deepening of the stratification during this period. Dilution was principally due to wind-induced turbulence that breaks the formed neutral buoyancy zone and brings some metalimnetic SS1 back to the epilimnion during periodic erosion/deepening cycles of the thermocline development. The main portion of the SS1 turbid current remained entrapped in the metalimnion of the lacustrine zone of the upstream basin. The portion of diluted SS1 passing through the narrow canyon into the downstream basin had a lag time of 10 days. As the two outlets of Maroon Dam are installed on the bottom of the dam wall (at the elevations 420 and 435 m asl$^*$) only a small portion of the SS1 class could be released to the downstream during the two simulated months.

The coarser SS2 sediments tended to settle out in the upstream portion of the reservoir and developed a turbidity maximum in the metalimnion. The coarse class SS2 plunged into the reservoir as an interflow. Unlike the SS1 class, the SS2 travelled a shorter distance along the thalweg within the metalimnion. The SS2 remained suspended within the transition zone of upstream basin and entrapped before the canyon without reaching the outlets to be released. The major part of the coarse sediments settled during a 20-days period after plunging into the reservoir.

5.3. Effect of the inflows from tributaries

According to the very high amount of inflowing current by the main stream, i.e. the Maroon river, the inflowing stormwater from the two major tributaries did not have any significant effect on the reservoir density currents propagation. However, as it was discussed in the section 5.1, during the seasonal inflows from the tributary B, the lacustrine zone of the upstream impoundment is mostly affected by incidence of two inflowing currents (mainly by the main current from Maroon river and the tributary B). This incidence of the flows, in addition to having the narrow canyon as the only possible outflow and the complex morphometry of the facing zone, causes a subsequent area affected by turbulent mixing due to the vortices (Ford and Johnson, 1986) which consequently causes more dilution of the turbidity before passing into the downstream lake.

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$^*$ Above sea level
6. Conclusion

In this study a three-dimensional hydrodynamic model coupled with a dynamic particles model was used to simulate the propagation of turbid overflow and interflow density currents caused by a flood event into the Maroon reservoir (Iran). The narrow canyon connecting the two upstream and downstream reservoir basins plays an important role in separating the hydrodynamic behavior of the basins. The model results indicate that fine suspended sediments propagate along the length of the reservoir as an overflow in the epilimnion, but with peak concentrations in the metalimnion. The fine suspended sediment turbidity reached the downstream basin with a 10-days lag and at a lower turbidity due to upstream dilution. Wind-induced turbulence was the most significant factor affecting the dilution in the epilimnion and metalimnion. The coarse suspended sediments were dominated by settling behavior and remained in the upstream basin (initially in the metalimnion) and were not seen at significant concentrations in the downstream basin. The long suspension time of the fine sediments within the water column affects the light penetration which particularly would affect the entire lake ecosystem (Reynolds, 2004; Ji, 2008). Consequently, the different hydrodynamic behavior beside the subsequent difference in turbidity propagation in two impoundments of Maroon reservoir may cause different responses at the ecosystems of two impoundments.
Fig 5. Longitudinal cross section of the Maroon reservoir during the propagation of the turbidity current: left: SS1 (fine sediment) and right: SS2 (coarse sediment)
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