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Research article

Management of turbidity current venting in reservoirs under different bed slopes

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ABSTRACT

The lifetime and efficiency of dams is endangered by the process of sedimentation. To ensure the sustainable use of reservoirs, many sediment management techniques exist, among which venting of turbidity currents. Nevertheless, a number of practical questions remain unanswered due to a lack of systematic investigations. The present research introduces venting and evaluates its performance using an experimental model. In the latter, turbidity currents travel on a smooth bed towards the dam and venting is applied through a rectangular bottom outlet. The combined effect of outflow discharge and bed slopes on the sediment release efficiency of venting is studied based on different criteria. Several outflow discharges are tested using three different bed slopes (i.e., 0%, 2.4% and 5.0%). Steeper slopes yield higher venting efficiency. Additionally, the optimal outflow discharge leading to the largest venting efficiency with the lowest water loss increases when moving from the horizontal bed to the inclined positions.

1. Introduction

Reservoir operations must fulfill several requirements. On one hand, the long-term use of reservoirs should be ensured while meeting its purposes such as electricity generation, water supply for irrigation and households, flood protection, flow regulation and navigation. On the other hand, reservoirs cause the obstruction of rivers and should be operated in a way to minimize the environmental impacts downstream. Sedimentation of reservoirs is a process that affects the sustainability of reservoirs by reducing their storage capacity and simultaneously leads to downstream sediment impoverishment. For these reasons, managing reservoir sedimentation is of great importance. Many techniques to mitigate reservoir sediments are applied in reservoirs around the world (Annandale, 2005; Kantoush and Sumi, 2010; Schleiss, 2013; Schleiss et al., 2016). Different criteria exist for choosing the most efficient sediment management strategy for a specific reservoir (Palmieri et al., 2001). For instance, flushing of the reservoir can be performed if enough storage is available as large amounts of water are flushed downstream in a relatively short period of time (Lai and Shen, 1996). Also, high suspended sediment concentrations (Espa et al., 2016) and ecological problems (Chung et al., 2008) might occur in the downstream river during flushing.

Nevertheless, fine and coarse sediments are mostly transported from the watershed into reservoirs during flood events. The coarse sediments settle at the entrance of the reservoirs forming a delta and the fine sediments can be transported along the reservoir down to the dam, mainly due to the formation of turbidity currents (Fan and Morris, 1992). The latter are sediment-laden density currents formed during flood events (Meiburg and Kneller, 2010). Once turbidity currents enter the reservoir, they plunge below the clear water surface due to their higher density. If the density difference between the clear water and the turbidity current is sufficiently high, the current can travel long distances (e.g., 80 km in Sanmenxia reservoir (Fan, 1986) and 129 km in Lake Mead (Morris and Fan, 1997)) until reaching the dam where a muddy lake is formed. If no low-level outlet or intake is opened to evacuate the sediments at the right time, the suspended sediments in the muddy lake settle and may consolidate. Apart from filling up the reservoir, sediment deposits can block water release structures and lead to the abrasion of hydro-mechanical equipment. Many researchers have studied the dynamics of turbidity currents. For instance, Lee and Yu (1997) have experimentally studied turbidity currents in reservoirs, particularly the plunge point characteristics as well as velocity and concentration profiles. Lamb et al. (2004) described the deposits induced by surging and continuous turbidity currents in intraslope

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minibasins, inspired by the minibasins found in the Gulf of Mexico while Lowe (1982) presented depositional models of different types of turbidity currents based on their grain population. Other researchers also highlighted different aspects of turbidity currents (Alavian et al., 1992; Garcia and Parker, 1993; Kneller and Buckee, 2000; Simpson and Britter, 1979).

In the particular case of sedimentation due to turbidity currents, venting through bottom outlets or intakes is highly recommended (Chamoun et al., 2016a). This technique has both economic and environmental advantages because outflow discharges used during venting and the resulting sediment concentrations are relatively low. By directly transiting the suspended sediments contained in turbidity currents, the eco-morphological continuity in terms of fine sediments is preserved.

Venting of turbidity currents is documented in numerous reservoirs worldwide (Chamoun et al., 2016a). Lee et al. (2014) investigated venting operations in the Tsengwen reservoir in Taiwan through a hybrid numerical, theoretical and experimental approach leading to a formula used to predict sediment concentrations and venting efficiencies. Fan (1986) proposed a methodology to estimate the characteristics of turbidity currents progressing in a reservoir and verified the method by applying venting in his model and successfully comparing the efficiency of venting with efficiency data observed in Guanting and Lake Mead reservoirs. Morris and Fan (1997) studied the influence of the reservoir's length and outflow discharge on the efficiency of venting operations based on data from Sanmenxia, Guanting, Heisongling and Lake Mead reservoirs. In Switzerland, at Mapragg reservoir, venting was economically optimized by implementing alarm systems that are triggered only when a turbidity current is reaching the dam with a minimum concentration of 2 g/l. In these cases, venting is considered to be a more profitable technique to mitigate the sediments than a future dredging (Müller and De Cesare, 2009). Many other field experiences provide crucial information on the operation of venting and its efficiency. Examples include the Dez Dam in Iran (Schleiss et al., 2010), the Iril Emda reservoir in Algeria (Raud, 1958), the Elephant Butte reservoir in the USA (Lara, 1960), and the Großsölk reservoir in Austria (Schneider et al., 2007) among others. However, systematic research on venting turbidity currents is still lacking and very few experimental studies (Chamoun et al., 2017; Fan, 1986; Lee et al., 2014; Yu et al., 2004) were carried out and published. Dam operators still miss the required knowledge needed for an optimal performance of venting operations. The main parameters affecting the efficiency of venting operations are well known from field experiences. Such parameters include the outlet discharge, the timing of venting (Chen and Zhao, 1992), the reservoir bed slope, and the position and size of the low-level outlet among others (Morris and Fan, 1997).

The present paper aims to experimentally investigate the operation of venting turbidity currents. The combined effect of bed slope and outflow discharge on the release efficiency of venting is studied. Due to the high measurement frequency, the effect of the duration of venting was also assessed. The experimental set-up, measuring instruments, testing procedure and analysis concept are firstly presented. The turbidity currents generated are then characterized, followed by the evaluation and discussion of the venting efficiency obtained under different bed slopes and outflow discharges. Finally, conclusions and an outlook are presented.

2. Experimental set-up

The tests are performed in a narrow flume of 8.55 m length, 0.27 m width, and 0.9 m height. The flume is divided into three parts i.e., a head tank, a main flume simulating the reservoir, and a downstream compartment (Fig. 2). It can be tilted from a horizontal position to a 5% slope. The water-sediment mixture is prepared in a mixing tank. The latter is equipped with a submerged pump that internally recirculates the mixture, ensuring good mixing by avoiding the settling of the sediments before and during the tests. The mixing tank is connected to the head tank by two pipes; a pumping pipe is used to pump the mixture from the mixing tank to the head tank and a restitution pipe used to spill the mixture back into the mixing tank. A rectangular inlet (Fig. 3(b)) is placed on the whole width of the flume, between the head tank and the main flume. A sliding gate (red slab in Fig. 1) serves to open and close the inlet. The sliding gate is kept closed (lower position) before the beginning of the test and is opened (higher position) to trigger the turbidity current and start the test. The main flume simulates the reservoir receiving the turbidity current. At a distance of 6.7 m from the inlet, a wall is positioned representing the dam with a bottom outlet (12×9 cm^2) centered on the width of the flume (Fig. 2(b)). The wall also serves as a weir spilling the clear water from the main flume during the turbidity current flow in order to maintain the clear water level. When venting begins, a venting pipe evacuates the flow into a downstream tank where concentration measurements are taken. Furthermore, a recirculation pipe is placed between the downstream compartment and the main flume. It serves for pumping clear water from the downstream compartment back into the main flume (through a diffusor shown in Fig. 3) in the cases where the outflow discharge is higher than the turbidity current's discharge, in order to avoid the lowering of the clear water level of the flume.

The sediment material used consists of a polyurethane powder that has a particle density of $\rho_s = 1160$ kg/m^3, characteristic diameters of $d_{10} = 66.5$ µm, $d_{50} = 140$ µm and $d_{90} = 214$ µm, where d_x represents the grain size diameter for which x% of the sediments have smaller diameters. The settling velocity of the d_{50} diameter is $v_s = 1.5$ mm/s and is considered to be the representative settling velocity of the material.

2.1. Experimental measurements

Several parameters are measured throughout the experiments:

- Discharges are measured using three electromagnetic flowmeters. One is placed at the pumping pipe (Fig. 1) to measure the inflow discharge Q_{TC} of the turbidity current. A second one is placed at the venting pipe (Fig. 1) to measure the outflow discharge Q_{VENT} used for venting. Finally, a third flowmeter is placed at the recirculation pipe (Figs. 1 and 3). The latter measures the discharge of clear water pumped from the downstream compartment to the main flume Q_{RES}. In the range of the discharge values used, the accuracy of the flowmeters is estimated at ±0.6% (Endress+Hauser, Switzerland).
- Concentrations are measured using two SOLITAX sc turbidity probes. One is placed at the head tank and the other one at the exit of the venting pipe. These probes measure turbidity values in FNU. Through a calibration procedure, turbidity is converted into concentration values in g/l. Concentrations of the turbidity current inflow C_{TC} and the vented current C_{VENT} are measured with an accuracy of around 1%.
- Water levels are measured using two ultrasonic level probes placed in the head tank and in the main flume. Levels are kept constant and equal in order to ensure that there are no fluxes between the clear water of the main flume and the mixture of the head tank, which could dilute the latter, reduce its concentration, and affect the inflow discharge. The accuracy of this instrument is around ±0.5 mm (Baumer, Switzerland).
- Velocity profiles are measured at different locations (i.e., 2.8 m, 4.1 m, 5.5 m, 5.8 m, 6.0 m, and 6.2 m from the inlet) in the main