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Review

Managing reservoir sedimentation by venting turbidity currents: A review

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ABSTRACT

Reservoir sedimentation is an issue that dam operators are increasingly facing as dams are aging. Not only does it reduce a reservoir's capacity but it also affects its outlet structures such as bottom outlets and powerhouse intakes. Sedimentation may also impoverish downstream ecosystems. For these reasons, several strategies for sediment management are being investigated and applied worldwide. Among these methods, venting of turbidity currents reaching the dam can be very beneficial and economical. This measure helps in preserving a certain continuity of sediment transport in rivers obstructed by dams. However, several practical but also theoretical challenges hamper this technique, rendering its use less common and its aspects relatively unknown. The present paper aims to gather the actual state-of-the-art concerning turbidity currents venting and to present an outlook for future development and research in this field.

1. Introduction

Reservoir sedimentation is a worldwide problem causing the loss of reservoir capacity of existing dams. The global annual reservoir capacity is decreasing due to sedimentation, and the construction of new reservoirs is not sufficient to compensate this loss (Oehy & Schleiss, 2007). However, the loss of storage capacity is not the only consequence of sedimentation. Other problems are faced, among which the obstruction of intakes and the abrasion of hydraulic machinery (e.g., Mauvoisin dam in Switzerland (Boillat et al., 2000b)), disturbance of navigation, downstream starvation for sediments (termed *hungry water* by Kondolf (1997)), loss of flood control, aggregation of backwater region (e.g., Sanmenxia and Guanting reservoirs in China (Fan & Morris, 1992a)) and chocking of bottom outlets (e.g., Rempen dam in Switzerland (Boillat & Pougatsch, 2000)).

Even reservoirs located in regions with moderate surface erosion, like part of the Alps, face sedimentation (Schleiss et al., 2008). Nevertheless, the rate of sedimentation in the Alpine region is relatively low (Schleiss & Oehy, 2002). In Switzerland, for instance, the average annual loss in reservoir capacity is 0.2% only (Beyer Portner & Schleiss, 1998). While in China, the mean annual loss rate in storage capacity is of 2.3% (Wang & Hu, 2009). A record sedimentation occurred in China when the Laoying Reservoir of Shanxi province was completely filled up with sediments during a flood before the completion of its construction (Ren & Ning, 1985). Japan's reservoirs also face severe sedimentation: 100 million m^3 of sediments out of the 200 million m^3 produced from mountain areas per year are deposited in reservoirs (Kantoush & Sumi, 2010).

To face this problem, balancing sediment inflow and outflow in reservoirs is a key challenge for sustainable reservoir management. In order to ensure the sustainability of reservoir capacity, different techniques are applied and optimized in reservoirs worldwide (e.g., Althaus, 2011; Basson & Rooseboom, 1997, 1999; Boillat et al., 2000a; Brandt, 2000; Chang et al., 2003; De Cesare & Lafitte, 2007; De Cesare et al., 2009; Fan & Morris, 1992a, 1992b; Kantoush & Sumi, 2010; Khan & Tingsanchali, 2009; Li et al., 2005; Lowe & Fox, 1995; Wang & Hu, 2009). Fig. 1 illustrates the most common operations for sediment removal. Selecting the appropriate method not only depends on the reservoir size and mode of operation, but also on the region where it is located, which highly impacts the quantity and size of sediments transported. Each method has its limitations and impacts regarding ecological, economic, and practical issues.

Among these measures, turbidity current venting can be, in many cases, very effective and economical (Wan et al., 2010), especially since suspended sediments often count for the major source of sediments in reservoirs. It is generally preferred to other sediment mitigation techniques such as airlift and hydrosuction, mainly because it is less harmful for the downstream environment but also for economic reasons. Nonetheless, most research studies that mentioned venting turbidity currents are rather qualitative.

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Venting of turbidity currents was scarcely discussed compared to other sediment removal techniques (e.g., flushing, dredging). Systematic experimental, numerical as well as prototype investigations are still lacking.

The present paper reviews previous research related to turbidity currents venting and points out potential fields of future investigation. The purpose is to firstly provide a definition and application conditions for venting of turbidity currents. Afterwards, a description of the main parameters that affect the efficiency of venting is given, followed by an overview of the main venting applications worldwide. Furthermore, difficulties and challenges encountered while performing or planning for venting are discussed. Finally, conclusions and gaps for future development are presented.

2. Overview of turbidity currents

Turbidity currents lie in a much wider category called density currents. The latter are driven by density differences in one single fluid or between two or more fluids. In the case of turbidity currents, the presence of suspended sediments is what causes the density difference with the ambient clear water of the reservoir, and triggers the plunging of the current. A turbidity current consists of three consecutive parts: the head, the body, and the tail (Kneller & Buckee, 2000). The head of the current is kept in movement by density differences (causing a pressure gradient) while the body and tail movements are due to gravitational forces. At this stage, it has to be noted that temperature differences between the water in the reservoir and the incoming sediment-laden flow affect the plunging position of the turbidity current. However, in the case of this paper, the considered currents are the most common ones, flowing at the bottom of the reservoir after their plunging due to their high densities imposed by the presence of suspended sediments (Fig. 2).

Note that the main focus of this work is on the venting process itself rather than on the dynamics of the turbidity currents. Numerous studies have addressed turbidity currents: Altinakar et al. (1990, 1996), De Cesare (1998), Fan (1986), Fan and Morris (1992a, 1992b), Garcia (1992), Georgoulas et al. (2010), Middleton (1993), Morris and Fan (1997), Meiburg and Kneller (2010), Nogueira et al. (2014), Oehy and Schleiss (2007), Simpson (1999), Wang and Hu (2009) among others, all described the formation, dynamics and evolution of turbidity currents. However, venting is an operation that requires not only a good knowledge of the dynamics of turbidity currents but also adequate and in-time bottom outlet operations.

3. Venting of turbidity currents

Venting of turbidity currents consists of opening bottom or low-level outlets as soon as the current reaches the dam in order to pass it downstream. Ideally, the goal is to vent all the sediments contained in the turbidity current if possible and feasible. Globally, venting of turbidity currents is not systematically applied, though the earliest data of releasing such currents from a reservoir were recorded already in 1919 at the Elephant Butte Reservoir in the United States (Lee et al., 2014). According to Batuca and Jordaan (2000), the first researcher that suggested that venting of turbidity currents can be an effective technique to avoid sediment deposition was Bell (1942).

During venting operations, the loss of water is minimized due to relatively small outflow discharges, which consequently limits ecological and economic impacts. Therefore, one major advantage of venting turbidity currents through bottom or low-level outlets is the possibility to reduce sediment accumulation without drawing down the reservoir level (Sahnaz & Aras, 2012). For this reason, venting is widely used in arid regions where water is in shortage (Brandt, 2000).

Before opting for venting operations, four main conditions must be fulfilled:

(a) The formation of turbidity currents: Forel (1885) was the first to report turbidity currents when observed during their plunging at Lake Constance and Lake Geneva in the 1880s. Many indicators of the presence of turbidity currents in a reservoir are commonly known (Morris & Fan, 1997) (e.g., emergence and disappearance of a muddy flow at the upstream part of the reservoir, sampling of highly concentrated water with sediments, velocity profiling of reservoir sections suggesting the advancing of a bottom flow). Field data from Shaver Lake (US) suggest that a turbidity current forms if the difference between its sediment concentration and that of the reservoir's clear water is around 1.28 kg/m^3 (Chien & Wan, 1999). Oehy et al. (2000) stated that favorable conditions for the formation of turbidity currents existed in narrow and deep Alpine reservoirs. However, this condition shall be completed by the following.

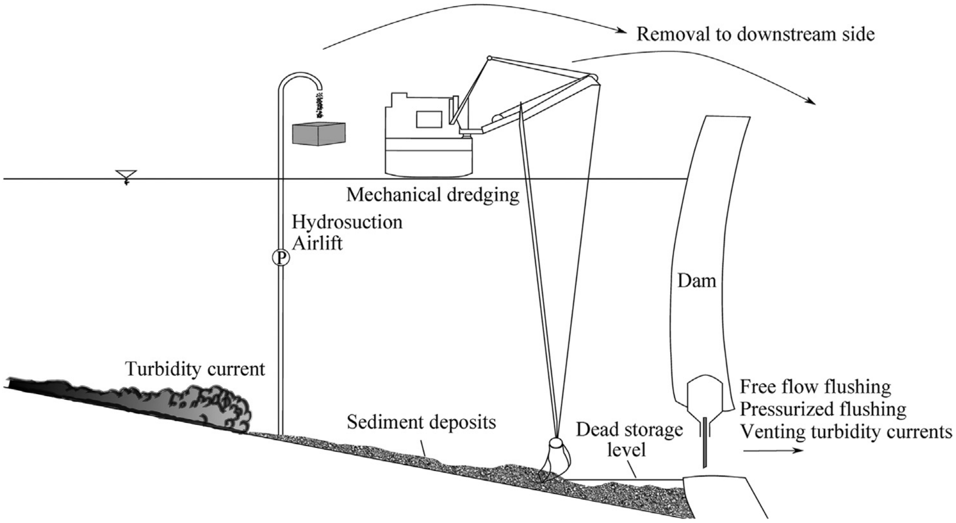

Fig. 1. Illustration of the most common sediment evacuation techniques (modified from Chamoun et al. (in press)).