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Overview of Historical Reservoir Flushing Events and Screening Guidance

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) provides an overview of the current state-of-the-practice screening criteria for reservoir sediment management actions, as well as a listing of historical reservoir flushing events and programs. This document also outlines the next steps in the Reservoir Flushing Research and Development Work Unit.

INTRODUCTION: Reservoirs are an important component of water resource systems around the world. Sediment trapped in reservoirs threatens their usefulness while also having the potential to cause problems upstream and downstream of the reservoir itself (Kondolf et al. 2014). The U.S. Army Corps of Engineers (USACE) maintains and operates more than 350 reservoirs within the United States, and many of those reservoirs are experiencing decreased project benefits due to sediment deposition (Pinson et al. 2016; USACE 2016). Existing and continued sediment deposition will result in a reduction of reservoir storage available for project uses such as flood control, water supply, hydropower, recreation, and environmental purposes (e.g., minimum flows). To achieve long-term sustainable performance of reservoirs, it is necessary to find and understand sediment management techniques that could be effective for each reservoir.

Flushing is one simple technique for managing sediment in reservoirs. In general, reservoir flushing involves opening low-level gates in a dam and allowing the water to remove sediment from the reservoir. There are two general cases of this technique. Pressure flushes are conducted for a short time, thereby limiting the drawdown of water in the reservoir while also restricting the affected area to a relatively small area immediately upstream from the gate. Drawdown flushes lower the water level in the reservoir, using both the increased flow of water and the increased water surface slope to erode large quantities of sediment throughout the reservoir. When a drawdown flush is timed to coincide with a large, sediment-laden inflow, it may be referred to as sluicing or drawdown routing (ICOLD 1999).

This CHETN provides a listing of reservoirs that have implemented reservoir flushing programs, describes the current state-of-the-practice screening criteria for successful reservoir flushes, and discusses the next steps required to improve guidance for reservoir flushing.

HISTORICAL RESERVOIR FLUSHING EVENTS: Flushing sediment through a reservoir is not a new technique. According to a review of the literature, there have been reports of sediment flushing as early as 1939 in the Zemo-Afchar Reservoir in the Former USSR (Chaudhry 2012). A full-drawdown flushing program apparently took place until 1955 removing approximately 1 million cubic meters of sediment per year.

A review of current literature identified 31 reservoirs around the world that have attempted sediment flushing (Table 1). At least nine of these reservoirs (Gmund, Hengshan, Honglingjin,

Naodehai, Baira, Mangahao, Gebidem, Palagneda, and Santo Domingo) were capable of maintaining more than 50% of their original capacity through flushing, the criteria considered successful based on the screening guidance provided by Atkinson (1996).

Table 1. Reservoirs where flushing has been attempted.

Reservoir	Location	Dam Completed	Source
Gmund	Austria	1945	Rienossl and Schnelle 1982; Atkinson 1996
Gaunting	China	1953	Atkinson 1996
Heisonglin	China	1959	Atkinson 1996
Hengshan	China	1966	IRTCS 1985; Atkinson 1996
Honglingjin	China		IRTCS 1985; Atkinson 1996
Nanqin	China	1974	Chen and Zhao 1992
Naodehai	China	1942	IRTCS 1985; Atkinson 1996
Sanmenxia	China	1960	Atkinson 1996
Shuicaozi	China	1958	Atkinson 1996
Cachí	Costa Rica	1966	Jansson and Rodriguez (eds) 1992; Brandt and Swenning 1999; Jansson and Erlingsson 2000
Ouchi-Kurgan	Former USSR	1961	IRTCS 1985; Atkinson 1996
Zemo-Afchar	Former USSR	1927	Atkinson 1996
Genissiat	France	1948	Sumi 2008
Baira	India	1981	Jaggi and Kashyap 1984; Atkinson 1996
Ichari	India	1975	Atkinson 1996
Sefid-Rud	Iran	1962	Amini and Fouladi 1985; Parhami 1986; Mahmood and Mundial 1987; Atkinson 1996
Dashidaira	Japan	1985	Sumi 2008
Unazuki	Japan	2001	Sumi 2008
Mangahao	New Zealand	1924	Jowett 1984; Atkinson, 1996
Warsak	Pakistan	1960	Mahmood and Mundial 1987
Barenburg	Switzerland	1960	Sumi 2008
Gebidem	Switzerland	1968	Dawans et al 1982; Atkinson, 1996
Innerferrera	Switzerland	1961	Sumi 2008
Palagneda	Switzerland	1952	Swiss Nat. Committee on Large Dams 1982; Atkinson, 1996
Verbois	Switzerland	1943	Sumi 2008
Khashm-el-Gibra	Sudan	1964	Chaudhry 2012
Jensanpei	Taiwan	1938	Sumi 2008
Fall Creek	USA		Gibson and Crain ¹
Guernsey	USA	1927	Mahmood and Mundial 1987
Spencer Dam	USA	1927	Boyd and Gibson, 2016
Santo Domingo Reservoir	Venezuela	1974	Krumdieck and Chamot, 1979; Atkinson, 1996

EXISTING SCREENING GUIDANCE: To achieve long-term sustainable sediment management in a reservoir, at least as much sediment needs to be removed from the reservoir on an annual basis as is deposited. Kondolf et al. (2014) suggest that at least 300 years be considered

¹ Gibson, S., and J. Crain. In review. Modeling Sediment Concentrations during a Drawdown Reservoir Flush: Simulating the Fall Creek Operations with HEC-RAS. ERDC RSM Technical Note. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

for long-term sustainability, meaning that even small differences in the reservoir sediment balance can allow significant accumulation. Reservoir flushing can be a cost-effective means of removing that sediment, but it is not always practical. Flushing can seldom maintain all of the original reservoir capacity in perpetuity. In some cases, a drawdown flush may only move sediment from the upstream delta farther into the reservoir rather than routing it all the way past the dam. Atkinson (1996) defines a successful reservoir flushing program as one that maintains a long-term capacity ratio (LTCR) (sustainable capacity/original capacity) greater than 0.5. There may be situations where a smaller LTCR is acceptable because flushing will extend the useful life of the reservoir or maintain sediment continuity with the downstream river system.

The primary screening criteria for successful flushing of reservoirs in current guidance are based on three factors: the total capacity of the reservoir (CAP), the mean annual runoff to the reservoir (MAR), and the mean annual inflow of sediment to the reservoir (MAS). The lower the ratios of CAP/MAR and CAP/MAS, the more likely it is that flushing can be a successful method for maintaining reservoir capacity (Atkinson 1996; ICOLD 1999; Kondolf et al. 2014; Sumi 2008). ICOLD (1999) recommends using $CAP/MAR < 0.1$ and $CAP/MAS < 30$ as screening criteria for conditions favorable to sediment flushing and sluicing.

While these broad screening criteria provide an initial assessment of the feasibility of flushing, they do not guarantee success. One of the most important additional constraints is the presence of suitable, low-level outlet gates for use in flushing the reservoir. If these are not present, they would need to be retrofit, usually at significant expense. The typical grain size of sediments in the reservoir and the amount of time the sediment has been allowed to consolidate (i.e., the time between flushing events) will influence the effectiveness of a drawdown flush. Incomplete drawdowns, where the flow depth during the flush is not significantly less than the normal level of the impoundment, will limit the success of the flush. Atkinson (1996) recommends at least a 70% reduction in water level during the flush. Other factors that can significantly impact the viability of reservoir flushing include downstream environmental concerns, reliability of water supply and forecasts, operational rules, reservoir geometry, and frequency of flushing events.

The reservoir volume that can be maintained over the long-term through flushing can be estimated based on the slope of the former river channel, the size and elevation of the flushing gates, and an estimate of the side-slope stability of the drawn-down reservoir (Atkinson 1996). Given sufficient time with a free-flowing river condition in the reservoir, the drawdown flush should create a channel through the reservoir that is equal to the width of the gate openings and at the slope of the former river bed. The volume of this open channel can be estimated by treating it as a trapezoidal channel with the side slopes based on the properties of the sediment (e.g., grain size and consolidation time).

FUTURE WORK: More refined criteria would be beneficial to reservoir operators to determine whether drawdown flushes or sluicing can be a useful technique for reducing sedimentation at individual projects. USACE researchers are working to codify the impacts of sediment size and type, as well as reservoir geometry characteristics such as the length, width, depth, and slope. The researchers will also look for patterns and differences between reservoirs in arid environments and those with more reliable rainfall.

Improvements in the ability of numerical models to simulate reservoir flushes will also be undertaken. This will include the ability to use operational rules for gate openings in the Adaptive Hydraulics (AdH) model, an adaptive finite-element model for one-, two- and three-dimensional flow and transport (ERDC CHL 2017). A significant factor in the effectiveness of reservoir flushing is the erosion and failure of side slopes in the drawn-down reservoir. Future work will need to look at how side slope erosion and failure occur and how to implement these processes in numerical models. The required algorithms and approaches include the parameters for failing the slopes and how to adjust the bank stations in one-dimensional models or the mesh in a multi-dimensional model.

It is likely that reservoir flushing efficiency can be improved through changes to operational rules. This includes determining how frequently to flush a given reservoir. In some cases, a sequence of drawdown and refill events may be more effective at mobilizing sediment. Mechanical disturbance of the reservoir sediment has been used to improve reservoir flushing in some locations. This could be done using heavy machinery or water-injection dredging. If the reservoir has not been flushed for several decades, initial dredging may be necessary before starting a routine of regular drawdown flushes. These management procedures will be explored during future phases of the Reservoir Flushing Research and Development Work Unit.

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