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Channel formation during flushing of large shallow reservoirs with different geometries

Sameh A. Kantoush [ab]; Anton J. Schleiss [c]
[a] Kyoto University, Department of Civil Engineering, Kyoto City, Kyoto 615-8540, Japan [b] Swiss National Fund for Scientific Research (SNSF), Bern, Switzerland [c] Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), CH-1015 Lausanne, Switzerland

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Channel formation during flushing of large shallow reservoirs with different geometries

Sameh A. Kantoush[a,c]* and Anton J. Schleiss[b]

[a]*Kyoto University, Department of Civil Engineering, Kyoto City, Kyoto 615–8540, Japan;* [b]*Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), Station 18, CH-1015 Lausanne, Switzerland;* [c]*Swiss National Fund for Scientific Research (SNSF), Bern, Switzerland*

Depositional and flow patterns are first described to gain an understanding of the erosion patterns during hydraulic flushing in a reservoir. Considering the importance of this issue, two modes of flushing operation for control of sedimentation were performed in several experiments with different reservoir geometries. In order to investigate the effect of flushing and the effectiveness during free and drawdown flows, ten experiments have been conducted. The final bed morphology formed previously was used as the initial bed topography for the two modes of flushing. The entire experiments lasted for two days. Investigations of the flow pattern and the associated bed topography for free flow with normal water depth and drawdown flushing in various shallow reservoir geometries are presented. To effectively apply the flushing processes for the removal of sediment deposits, the location, depth and width of the flushing channel can be changed by modifications to the reservoir geometry. The channel formed during flushing attracts the jet and stabilizes the flow structures over the entire surface. Empirical formulae to describe the relationship between the reservoir geometry and flushing efficiency for the two modes of flushing were developed. Flushing at normal water level allows only a relatively small part of the deposited sediment to be evacuated. As deposits could be flushed out of the basin.

Keywords: flushing channel; drawdown flushing; deposits removal; sediment management strategy; shallow reservoir geometry

Introduction

Run-of-river reservoirs for hydropower, storage or flood control are subject to sediment deposition in which deposition patterns are non-uniformly distributed over the reservoir surface. Today's worldwide annual mean loss of storage capacity due to sedimentation is already higher than the increase in the capacity by construction of new reservoirs [1]. Thus, sustainable use of the reservoirs is not guaranteed in the long-term. Particular attention has to be paid to minimize accumulation of sediment in reservoirs to ensure sustainable use. Many measures for reservoir sedimentation control can be utilized to ensure the sustainable development of water resources.

In general, reduction of incoming sediment yields from watersheds is often employed in conjunction with hydraulic methods such as flushing or density current venting, but it requires long-term efforts to achieve the desired goal. Mechanical removal by dredging or dry excavation can immediately regain the storage capacity, but it is usually considered as the last measure because of its higher cost and disposal problems. Hydraulic methods have been applied successfully and have been found to be efficient and inexpensive in many cases [2–3].

In order to control reservoir sedimentation, different approaches such as bypassing, dredging, flushing, sluicing and upstream sediment trapping have been developed. Although combinations of these sediment control measures are usually adopted to gain the maximum effect, the flushing and sluicing methods play an important role in the sediment removal. Depending on reservoir geometry, flushing can be an efficient hydraulic sediment removal technique to restore the reservoir storage capacity. The first time a flushing is done, a channel will form in the deposited material, and on subsequent flushings this channel will be maintained by the flushing flows [4]. A phenomenon in reservoirs that is not well investigated is the formation of incisive (flushing) channels in the depositional area of the reservoir. It is most pronounced in reservoirs with a seasonal fluctuating water level (as in most hydropower, flood-control and water-supply reservoirs) or in reservoirs that are operated with regular water level drawdown to flush sediments from the delta (e.g. [5]). During flushing, erosion of deposited material from the reservoir will lead to a significantly different time-wise pattern of sediment, released to the reaches below the dam, compared with the sediment inflow [4].

*Corresponding author. Email: kantoush@yahoo.com

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Current sediment management practice focuses almost exclusively on erosion control in the catchment area. While this is an essential sediment management activity, alone it cannot establish a sediment balance across the impounded reach and preserve long-term capacity [5]. An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs [5]. Integrated sediment management includes analysis of the complete sediment problem and application of a range of sediment strategies appropriate to the site. It implies that the dam and the impoundment are operated in a manner consistent with the preservation of sustainable long-term benefits, rather than the present strategy of developing and operating a reservoir as a non-sustainable source of water supply [6]. A sustainable sediment strategy should also include the downstream reaches; so monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir [4].

If designers neglect or underestimate the problem of siltation, they may fail to adopt appropriate measures for the eventual release of sediment, such as the installation of adequately sized deep bottom sluices for sediment flushing [5]. The dramatic and costly measures required to balance sediment inflows and outflows across the impounded reach of a river have been implemented at only a few reservoirs to date; however, these measures will become increasingly commonplace worldwide as reservoirs age and sediments accumulate to the point where reservoir performance becomes unacceptably impaired [5].

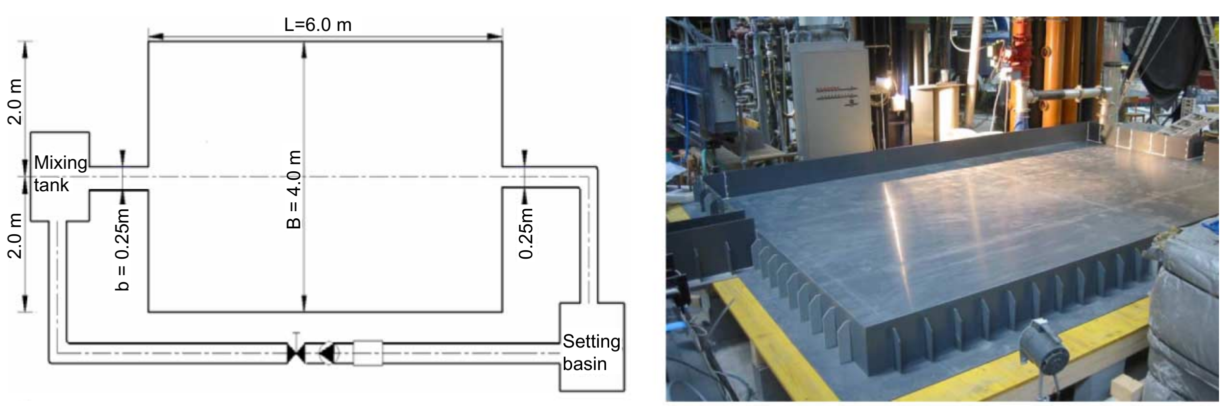
The aim of this research work was to study the effect of reservoir geometry on flow, sedimentation, and trap efficiency in shallow basins. This should allow the definition of the optimal shape of the geometry and the management rules of such shallow reservoirs. In this paper the emphasis is on desiltation by hydraulic flushing through a shallow reservoir. Flushing removes accumulated sediments after they have been deposited. The main objective of the present paper is to contribute to the understanding of the active processes and formation of flushing channels in reservoirs with different geometry.

Experimental set-up

The experimental tests were conducted in a rectangular shallow basin with inner maximum dimensions of 6.0 m in length and 4 m in width, as shown in Figure 1. The inlet and outlet rectangular channels are both 0.25 m wide and 1.0 ml ong. The bottom of the basin is flat and consists of hydraulically smooth PVC plates. The walls, also in PVC, can be moved to modify the geometry of the basin. Adjacent to the reservoir, a mixing tank was used to prepare the water–sediments mixture. The water–sediments mixture was supplied by gravity into the water-filled rectangular basin. Along the basin side walls, a movable frame, 4.0 m long, was mounted to carry the measuring instruments.

The sediments were added to the mixing tank during the tests. To model the suspended sediment currents in the laboratory, crushed walnut shells with a median grain size d_{50} of 50 μm and a density of 1500 kg/m^3 were used in all experiments. This is a non-cohesive, light-weight and homogeneous grain material. The grain size distribution of the sediment material was determined with a Maven Mastersizer (laser refraction method). The material had a wide grain-size range, and the frequency histogram was skewed towards large grain sizes, which is typical for ground particles.

The main measurement techniques employed included ultrasonic probes for measuring water levels, an Ultrasonic Velocity Profiler device (UVP) for measuring 3D velocity components as well as a Large Scale Particle Image Velocimetry technique (LSPIV)



a) b)

Figure 1. (a) Plan of the experimental setup, (b) photograph of the experimental setup, looking downstream.

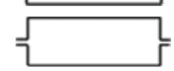
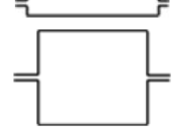
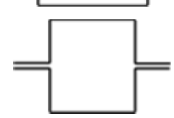
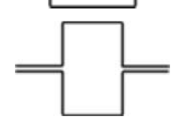
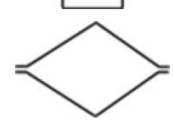
for measuring surface velocity fields. A more detailed description of the experimental set-up and measurement equipment is given in [7,8]. The evolution of the bed level was measured with a Miniature echo sounder (UWS). The sounder was mounted on a movable frame which allowed whole basin area to be scanned. The sediment concentrations of the suspensions material using the crushed walnut shells were measured. Two SOLITAX sc sensors were installed at the inlet and outlet channels for online suspended sediment measurements. A more detailed description of the experimental set-up and measurement equipment is provided by [9,10].

The hydraulic and sediment conditions were chosen to fulfil the sediment transport requirements. Furthermore, for all tests, the Froude number ($0.05 \leq Fr \leq 0.43$) was small enough and the Reynolds number ($14{,}000 \leq Re \leq 28{,}000$) high enough to ensure subcritical, fully developed turbulent flow conditions. The following parameters remained constant for all configurations with suspended sediment transport: discharge (Q = 7.0 L/s), suspended sediment concentration (C = 3.0 g/L), water depth (h = 0.2 m).

Test configurations

Ten axi-symmetric basins with different forms were tested to study the geometry shape effect on the flow and deposition pattern (see Table 1). In order to gain insight into the physical processes behind the sedimentation of shallow reservoirs governed by suspended sediment; a reference basin geometry with width B = 4.0 m and length L = 6.0 m was used. The reference geometry was used for the first six tests, from Test 1 (T1) to Test 6 (T6), to examine different test procedures and find the optimal one to continue with future test configurations. As a reference case, the rectangular basin geometry was analysed in detail [7–10]. To investigate the effect of the

Table 1. Configurations of different test series and their geometrical characteristics: L and B are length and width, A is the total surface area of the basin, *ER* and *AR* are the expansion and aspect ratios, *P* is the wetted perimeter of the length of the side walls, and *SK* is the shape factor $SK = (P/\sqrt{A})*AR*D_{exp}$.

Test	B [m]	L [m]	P [m]	A [m^2]	AR = L/B [-]	ER = B/b [-]	$SK = (P/\sqrt{A})*AR*D_{\mathrm{exp}}$ [-]	Form
T1, T2, T3, T4	4.0	6.0	19.5	16	1.5	16	5.97	
T7	3.0	6.0	17.5	12	2.0	12	8.25	
T8	2.0	6.0	15.5	8	3.0	8	13.42	
T9	1.0	6.0	13.5	4	6.0	4	33.07	
T11	4.0	5.0	17.5	16	1.25	16	4.89	
T12	4.0	4.0	15.5	16	1.0	16	3.88	
T13	4.0	3.0	13.5	16	0.75	16	2.92	
T14	4	6	14.1	8	1.5	8	11.2	
T15	4	6		16	1.5	16	11.08	
T16	4	6		12	1.5	12	4.65	

basin width on the flow and sedimentation processes in the reservoir, the experiments focused on the width achieved in a rectangular reservoir 6.0 m long and 3.0, 2.0, 1.0 or 0.5 m wide (from T7 to T10, respectively). In a second set of tests, to examine the effect of the basin length, experimental tests were conducted in a rectangular shallow basin 4.0 m wide and 5.0, 4.0, or 3.0 m long (from T11 to T13, respectively). Finally, geometries with three expansion angles were tested (from T14 to T16). In the present paper the results of flushing for experiments T1, T8, T14 and T16 are presented hereafter.

Geometrical parameters

The definition of the geometrical parameters is shown in Figure 2 and the configurations of the different test series and their geometrical characteristics are summarized in Table 1. In order to represent all geometrical characteristic parameters with flow and deposition results, a geometry shape factor *SK* was developed. In the present study several reservoir geometries with different shapes were conducted. Thus, there is a need for a dimensionless coefficient representative of different geometry shapes which can be correlated with flushing efficiency. The following definitions are used (see Figure 2 and Table 1):

- length and width of the upstream and downstream channels which remained constant for all configurations: L = 1.0 m, b = 0.25 m and L = 4 b
- length and the width of the basin: L and B;
- depth of lateral expansion, ΔB;
- distance from the edge of channel to the edge of the basin, R;
- total surface area of the basin, A;
- lateral expansion ratio: ER = B/b;
- aspect ratio as AR = L/B;
- jet expansion density can be defined as $D_{exp} = R/\Delta B$;
- geometry shape factor can be defined as $SK = (P/\sqrt{A}) * AR * D_{exp}$.

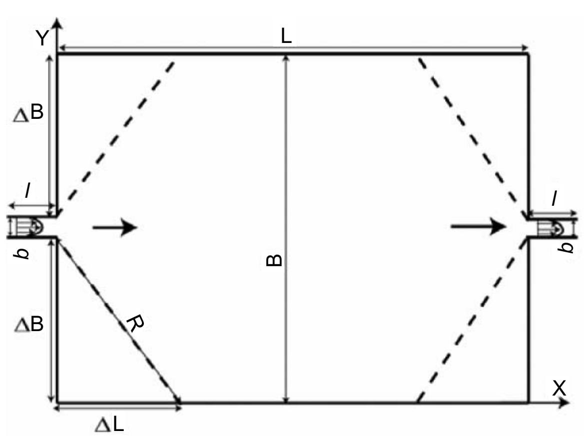


Figure 2. Definition of the geometrical parameters of the test configurations.

Test procedure

After filling the basin and having reached a stable state with the clear water, first LSPIV recording was performed for three minutes. Then, in a second phase, the water–sediment mixture was drained by gravity into the water-filled rectangular basin. The flow circulation pattern with suspended sediment inflow was examined every 30 minutes using LSPIV over a 90 minute period. The flap gate was then closed to permit the suspended sediment to deposit and then bed-level profile measurements were started using UWS. Every 1.5 h, the bed morphology was measured at different cross sections. After each time step the pump was interrupted to allow recording of the bed morphology.

The final bed morphology was used as the initial topography for two modes of flushing (free flow and drawdown flushing). Clear water without sediment was introduced into the basin to investigate the effect of free flow and drawdown flushing. A normal water depth of 0.20 m was used without lowering of the reservoir during free-flow flushing. After lowering the water depth in the reservoir to half the normal water depth (0.10 m), the drawdown flushing was conducted. Each mode of flushing lasted for two days with flow field and final bed morphology measurements.

Results and discussions

Free-flow flushing and bed morphology

A detailed description of two representative experiments (T1 and T16) provides a general view of the asymmetric and symmetric jet flow experiments of free-flow flushing without lowering of the reservoir. The final bed morphology obtained from both experiments was used as the initial topography for the clear-water test. Here, clear water without sediment was introduced into the basin to investigate the further bed evolution under those circumstances. Figure 3 shows the flow velocity with vectors and the bed topography contours after two days of free-flow flushing. In the free-flow flushing the amount of the flushed sediments depends on many parameters such as water depth, discharge released, the size of the outlets, the geometry of the reservoir, the size and the kind of the deposited sediments in the reservoir. The hydraulic conditions were kept constant during free-flow flushing (Q = 7.0 L/s and h = 0.20 m).

Laboratory experiments were carried out to investigate the flushing processes during free-flow flushing. Figures 3a and 3c present the flow patterns for two

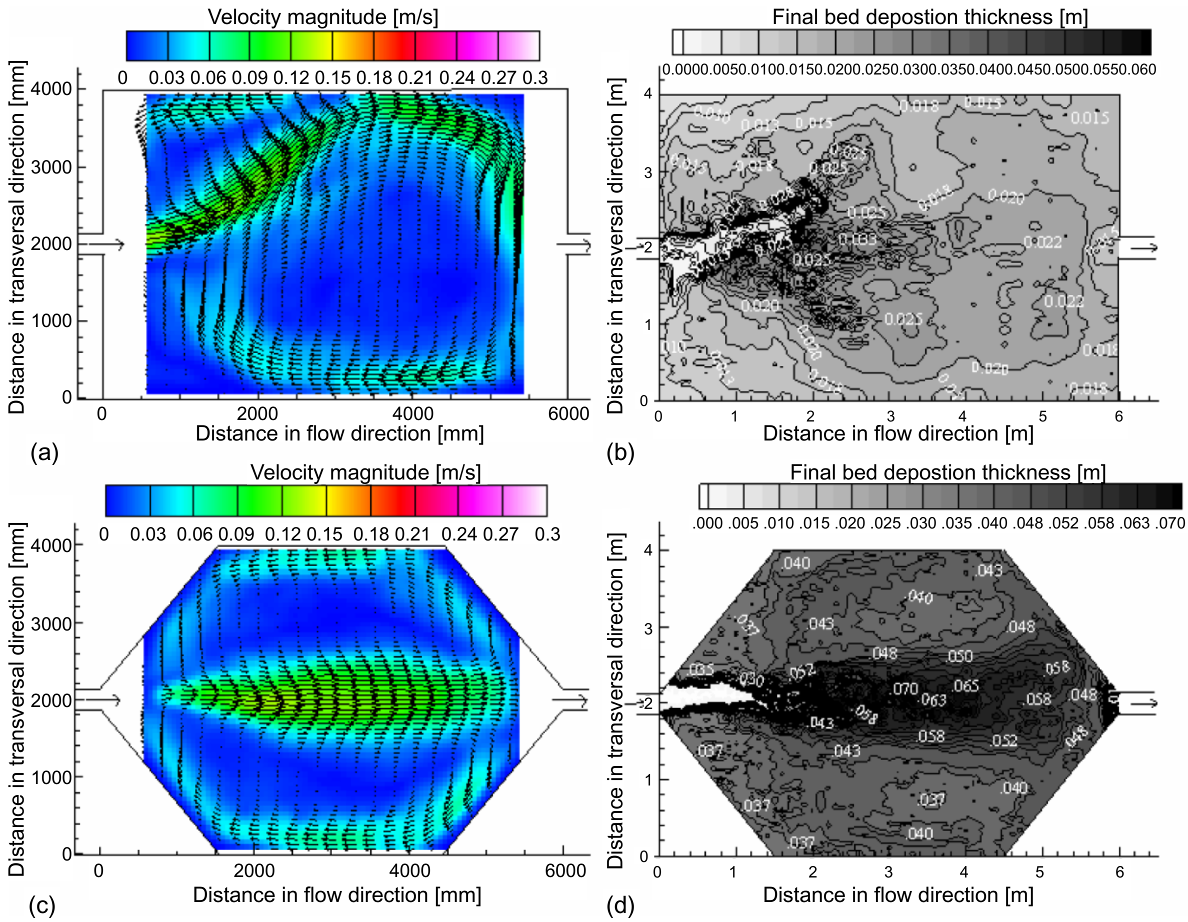


Figure 3. Flow velocity with vectors and bed topography contours after two days of free flow flushing without lowering of reservoir level (Q = 7.0 L/s and h = 0.2 m) of experiments: (a, b) T1, and (c, d) T16.

different geometries. After stopping the flow, clear water (without sediment) was injected into the basin to investigate the further evolution of the bed for free-flow flushing. The flow pattern in Figure 3a was asymmetric with a deviated jet and three circulation cells. After restarting the flow it chooses the easiest path from the inflow to the outflow gate along the left side wall. The sedimentation from the previous period had apparently become too much of an obstacle to result in a symmetric flow pattern. If flushing takes place under a sustained water level, only a very limited area in the reservoir was cleared as shown by the bed topography contours in Figure 3b. The sediment deposit was scoured in the vicinity of the inlet and the deflected jet within a very short period of time (eight hours). After that the experiments lasted 40 hours with the same flow structures and bed topography. During the test the released suspended sediment concentration (SSC) was measured at the outlet. In about 10 minutes after the flow was started, the SSC was high, and afterwards the outlet discharge was almost clear. A tongue-shaped crater, called a flushing channel, was formed by the flushing flow.

Once the flushing channel was formed and there was no sediment moving into the channel, the water flowing through the outlet was clear, that is the formation of the channel was fairly stable and no sediment will be removed from the flushing channel afterwards. A symmetric flow pattern was observed in the hexagonal geometry experiment (T16), as shown in Figure 3c. The flow patterns that are brought about by the entrance jet, bed topography and the reservoir geometry control the location and the size of the scoured channel. The circulation cells in the initial clear water with a flat bed were rotating faster than in the pressure flushing case.

Drawdown flushing flow and bed morphology

The experiments of drawdown flushing were started by opening the outlet gate until the water depth reached 10 cm. After that the pump was turned on with a normal discharge of Q= 7.0 L/s. In the drawdown flushing the discharge was kept constant and the water depth dropped by half. Figure 4 shows the flow structure and final bed thickness contours after two days of drawdown flushing in various reservoir geometries. If the water surface can be drawn down sufficiently to generate high flow velocity near the outlet, the flow starts to erode a wide channel. At that stage, a significant amount of sediment deposits were flushed through the reservoir, and the initial channel deepened and widened as a result of the strong jet flow and erosion. An extremely high suspended sediment concentration of around 10-20 g/L was measured. Eroded sediments were transported progressively downstream forming a flushing channel located either at the side wall or at the centreline. This location of the channel depended on the flow structure and basin geometry shape factor as will be shown in the following paragraphs. Figure 4a shows the flow pattern of the reduced reservoir width (T8) with asymmetric flow structure. Initially all deposited sediment was resuspended with the high velocity jet trajectory, which deviated to the left side wall. The flushing channel location was clearly visible by the resuspended sediment, which was rapidly released within 30 minutes. This was followed by a short period of very rapid widening of the flushing channel, forming a wide advancing front. Then, after a sudden change in the rate of widening, the flushing channel continued to widen at a more gradual rate.

The final channel form and bed morphology contours are shown in Figure 4b. The jet trajectory path was eroded and high deposition occurred under the circulation cell. Fine suspended sediments were carried and deposited on the right side and on the left upstream corner of the reservoir by the reverse eddies that are generated by the jet flow separation. The flow structure was stable and did not change during 48 hours, and the fixed bottom of the reservoir was exposed after erosion. The channel did not develop along the shortest path from inflow to outflow, but developed toward the left side. The channel location and size were varied by reducing the reservoir length rather than by reducing the reservoir width, as can be seen in Figures 4b and 4d. A straight flushing channel was formed during drawdown flushing for the reduced reservoir length (T13). For the shorter reservoir length experiments, the flushing channel width varied with the reservoir length. The channel width increased in the downstream direction, with a T-shape channel as shown in Figure 4d.

The channel width developed as time elapsed, increased smoothly with time and reached a dynamically stable state over the whole length (Figure 4d). The banks of the channel had a mild slope in the jet-shedding regions. The flow pattern shown in Figure 4c is symmetric with two circulation cells on both sides. The circulation velocity was able to erode two transverse channels on both sides of the outlet wall. The transverse eroded deposit was elevated with the reverse flow. Figures 4e and 4f present the flow field and bed morphology for the reduced entrance angle 32° (lozenge geometry). The flow pattern in Figure 4e shows a meandering jet along the centre line with two coupled eddies on both sides. The final bed deposition was able to change the flow pattern. Eroded sediments were transported progressively downstream forming a narrow advancing front over which the flow fanned out. Because of this fanning out, the flow loses its transporting capacity and causes the front to build up to form an underwater ridge before the outlet (see Figures 4f and 4h). If the water level is drawn down during flushing, the sediment removal can be divided into several phases. Flushing is most effective during the first hours after the stored water in the reservoir has been released. A stable narrow channel was created by the flushing flow in a short period. The footprint of the central meandering jet was clearly visible in the channel front, which deviated to the left side following the jet. The jet was straight and strong for 3 m from the inlet and after that it shifted left. The jet was meandering after the middle section over one metre in length before reattachment to the side wall. From the above results, it can be concluded that the outflow sediment discharge and the channel characteristics are influenced by the reservoir geometry as well as the discharge and water depth.

Prediction of the flushing efficiency

The efficiency of the flushing of suspended sediment through the reservoir is important to determine the feasibility of flushing operations according to the designed reservoir. In the present study, measured data for each run were recorded after one flushing with clear water was performed for two days. With the total cumulative deposited sediment at the end of each experiment and the volume of flushed sediments during this procedure, flushing efficiency,

FE, is defined as:

$$FE = V_{flushed} / V_{df} \tag{1}$$

where $V_{flushed}$ is the volume of flushed sediment after two days, and V_{df} is the total cumulative deposited volume after a specific period.

Free-flow flushing efficiency

Figure 5a shows the correlation between efficiency of free-flow flushing with normal flow depth and the geometry shape factor. As the geometry shape factor, *SK*, increases, the free-flow flushing efficiency increases. The flushing efficiency is fairly low with a maximum value of 10% for the narrowest reservoir with *SK* of 13.42. Qualitatively, it was found that almost all of the removed sediment from the final deposit was flushed out

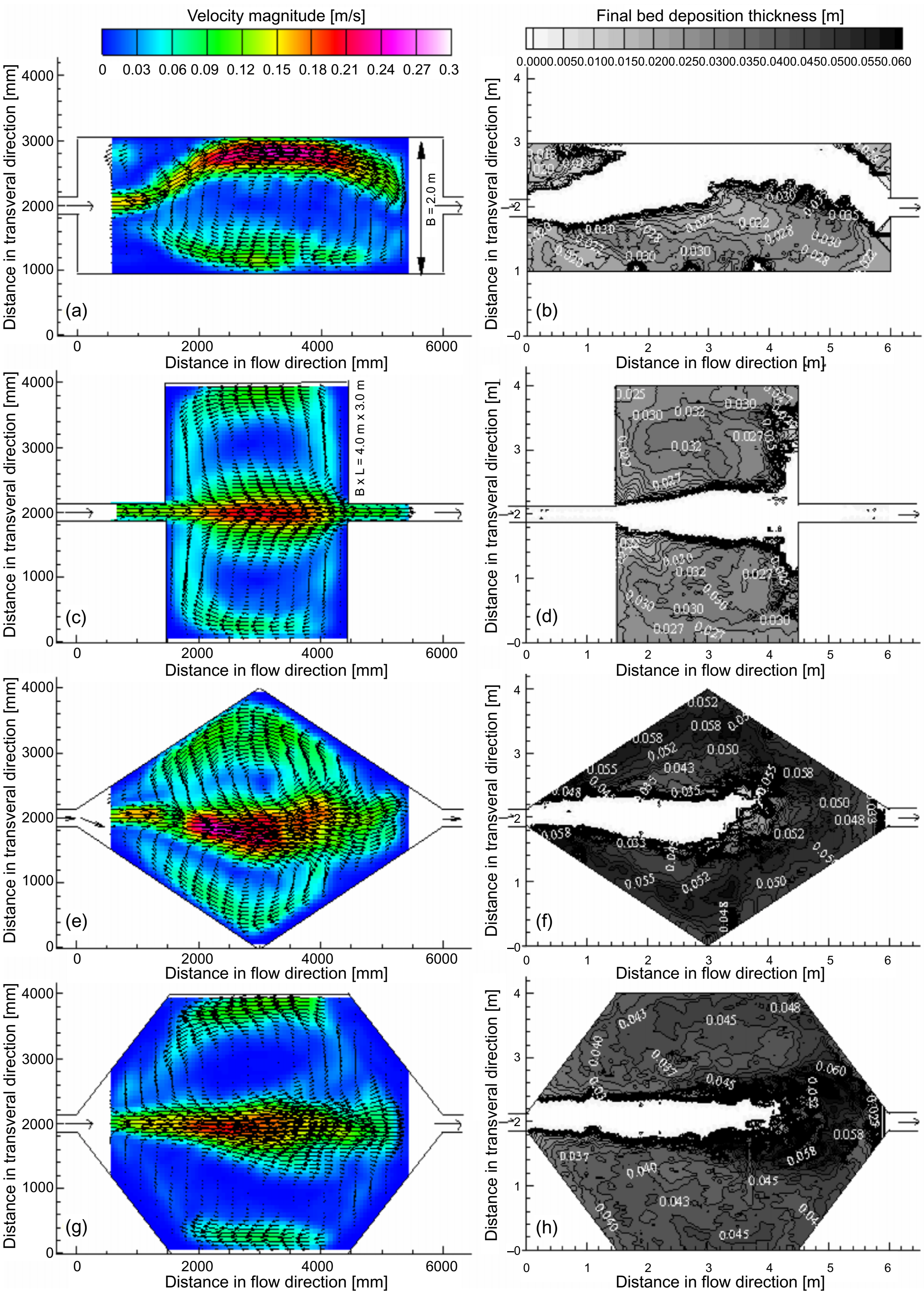


Figure 4. Flow velocity with vectors and bed topography contours after two days of drawdown flushing with lowering reservoir level to 50% (Q = 7.0 L/s and h = 0.1 m) of experiments: (a, b) T8, (c, d) T13, (e, f) T14, and (g, h) T16.

during the first third of the flushing period. The developed correlation from Figure 5a, between free-flow flushing efficiency and *SK*, can be given by Equation (2) and the application range is $2.92 < SK < 13.42$.

$$FE = 0.81 + 0.47 \cdot SK \tag{2}$$

Drawdown flushing efficiency

Flushing efficiency is an index to describe the effectiveness of hydraulic flushing. The efficiency of drawdown flushing as a function of geometry shape factor was plotted in Figure 5b. It was observed that the drawdown flushing efficiency increases with higher geometry shape factor. The drawdown flushing was higher compared with the free-flow flushing. The minimum flushing efficiency was 20% for the largest geometry shape factor. Additionally, the maximum drawdown flushing efficiency reached almost 65% for the highest geometry shape factor, as shown in Figure 5b. It was found qualitatively that almost 50% of the total volume of removed sediments was flushed out in the first quarter of the flushing duration. Drawdown flushing efficiency was correlated with the geometry shape factor in the empirical relationship shown in Equation (3). The application range of Equation (3) is $2.92 < SK < 13.42$.

$$FE = 103 + 12.4 \cdot (SK/10)^{-2} - 65.75 \cdot (SK/10)^{-1} \tag{3}$$

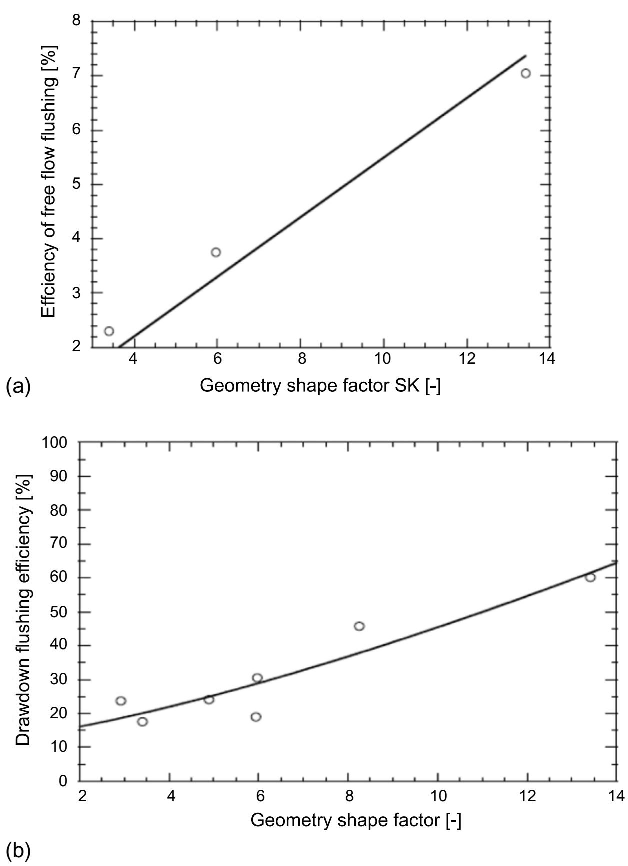


Figure 5. Influence of the geometry shape factor, *SK*, on flushing efficiency, *FE*, of the (a) free-flow flushing, (b) drawdown flushing.

Conclusion

Free-flow flushing without lowering of reservoir level

Free-flow flushing has only a very local effect. Experiments showed that under free-flow flushing an incisive channel can be formed in a very short time but only a relatively small amount of sediment was flushed out. This confirmed the observations by Lai and Shen [11]. Therefore it can only be applied to remove sediment deposited around the entrance of the inlet channel under the action of the main jet. The most important bed change occurred as a result of the erosion near the entrance. After the channel was formed, the location of the channel remained stable.

Experiments showed that under pressurized flow a flushing nose can be formed in a very short time but only a relatively small amount of sediment was flushed out. The free-flow flushing efficiency was fairly low with a maximum value of 10% for the most narrow reservoir with $SK = 13.42$. Qualitatively, it was found that almost all of the removed sediment from the final deposited one was flushed out in the first third of the flushing period. The developed correlation between free-flow flushing efficiency and geometry shape factor *SK* can be given by Equation (2) for the application range of $2.92 < SK < 13.42$.

Drawdown flushing with lowering of reservoir level

During drawdown flushing, three channel shapes (curved, straight and cone) were formed for the different reservoir geometries. The width of the channel depends on the inlet channel width, the flow pattern and the geometry shape factor. The flow structures and sediment deposition patterns of the drawdown flushing system were investigated in detail. A larger volume of sediments in the reservoir generally generates a higher flow depth and velocity in the flushing channel. To apply the flushing efficiently for removing deposits, the width, length and location of the flushing channel can be changed by modifications to the geometry shape factor.

For the experiments with drawdown flushing it is important to know the channel width and length in order to estimate the gain of the reservoir capacity. Due to the sensitivity of the flow pattern to the boundary conditions, initial conditions and the geometry (and changes in time), it is difficult to predicate the exact location of the flushing channel. Drawdown flushing efficiency could be correlated with the geometry shape factor by the empirical relationship given in Equation (3) within the application range of $2.92 < SK < 13.42$.

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