Reservoir Sedimentation – Schleiss et al. (Eds)

Influence of geometry shape factor on trapping and flushing efficiencies

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ABSTRACT: The trap efficiency of a shallow reservoir depends on the characteristics of the inflowing sediments and the retention time of the water in the reservoir, which in turn are controlled by the reservoir geometry. With the purpose of controlling the trapped and flushed sediments in shallow reservoirs, the effects of the geometry on sediment deposition and removal were investigated with systematic physical experiments. The geometry shape factor is an important factor to predict the flow and sediment deposition in the reservoir. The evolution of trap efficiency has an increasing or decreasing effect according to the geometry shape factor and flow patterns. The channel formed during flushing attracts the jet and stabilizes the flow structures over the entire reservoir. Empirical formulas to describe the relationship between the geometry shape factor and sediment trap efficiency as well as flushing efficiency were developed.

1 INTRODUCTION

1.1 *Problematic of sedimentation in shallow reservoirs*

Suspended sediment deposition is a complex phenomenon in deep and shallow reservoirs. The sediment deposition in shallow reservoirs of run-of-river power plants reduces the storage capacity and generates a risk of blockage of intake structures as well as sediment entrainment in hydropower schemes. The planning and design of shallow reservoir require the accurate prediction of sediment trapping and release efficiencies. Reservoir sedimentation is the principal cause preventing sustainable use of storage reservoirs (Annandale, 2013). Many flows in nature can be considered as shallow as for examples flows in wide rivers, lakes, bays and coastal regions. For such flows, the horizontal dimensions are much larger than the vertical depth and turbulence is of a special nature, as was discussed already by Yuce and Chen (2003). Reservoir sedimentation has been methodically studied since 1930s (Eakin, 1939), but dam engineering has focused on structural issues, giving relatively little attention to the problem of sediment accumulation (De Cesare and Lafitte, 2007). The problem confronting the designer is to estimate the rate of deposition and the period of time before the sediment will interfere with the useful functioning of a reservoir. Several concepts of reservoir life may be defined as its useful, economic, useable, design and full life as adapted from (Murthy, 1977), (Sloff, 1991). The rapid reservoir sedimentation not only decreases the storage capacity, but also increases the probability of flood inundation in the upstream reaches due to heightening of the bed elevations at the upstream end of the reservoir and the confluences of the tributaries (Liu et al., 2004). In order to remove and reduce reservoir sedimentation, many approaches such as flushing, sluicing, dredging and water and soil conservation are developed (ICOLD, 1989). Among these approaches, flushing is considered the only economic approach to swiftly restore the storage capacity of

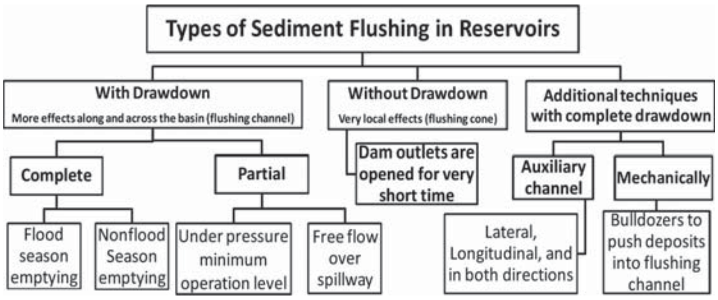


Figure 1. Classification of sediment flushing techniques.

the reservoir with severe deposition. Basically, there are two types of flushing operations with, and without drawdown, and optional techniques can be used with the complete drawn flushing as shown in Figure 1.

1.2 *Reservoir trap efficiency*

Brune's curve is used by dam engineers to predict the trap efficiency which is the proportion of deposited to flowing sediments into a reservoir (Brune, 1953). This curve provides an estimate of the relative amounts of sediment that will be retained by reservoirs of various sizes. The size of a reservoir is quantified by using the same measure we defined before. Recall that we indicated that a good way of determining the relative size of a reservoir is to divide its storage volume by the mean annual river flow (Annandale, 2013). Churchill (1948) based his empirical relationship on the concept of sediment releasing, whereas Brune (1953) used the concept of sediment trapping which has come into more common use. Several approaches have been undertaken to quantify sediment trap efficiency. Churchill (1948) presented a curve relating the trap efficiency to the ratio between the water retention time and mean velocity in the reservoir. As a result of the complexity of the phenomenon involved in sediment deposition in lakes and reservoirs, focused research efforts on numerical and laboratory modeling also have been published. The Trap Efficiency (*TE*) of reservoirs depends on several parameters (an overview of the processes taking place in a reservoir is given by (Heinemann, 1984). Since *TE* is dependent on the amount of sediment, parameters controlling the sedimentation process are shown in Figure 2.

Therefore, the particle-size distribution of the incoming sediment controls TE in relation to retention time. Coarser material will have a higher settling velocity, and less time is required for its deposition. Very fine material, on the other hand, will need long retention times to deposit. The retention time of a reservoir is related to: 1. The characteristics of the inflow hydrograph and; 2. The geometry of the reservoir, including storage capacity, shape and outlet typology. The reservoir geometry can also govern the retention time.

1.3 *Empirical and theoretical models for predicting TE*

Simple models relating TE to a single reservoir parameter are, on the other hand, easy to implement but are far less accurate. One has to distinguish between the TE of a reservoir on a mid to long-term basis and its TE for one single event. Heinemann (1984) gave an overview of the many empirical models that could be used for predicting TE. An overview of the theoretically based TE models is provided by Haan et al. (1994). Verstraeten and Poesen (2000) provided an overview of the different methods available to estimate the trap efficiency of reservoirs and ponds. As already mentioned the empirical models predict trap efficiency, mostly of normally ponded large reservoirs using data on a mid to long-term basis. These models relate trap efficiency to a capacity/catchment ratio, a capacity/annual inflow ratio or a sedimentation index. Today, these empirical models are the most widely used models to predict trap efficiency, even for reservoirs or ponds that have totally different characteristics from the

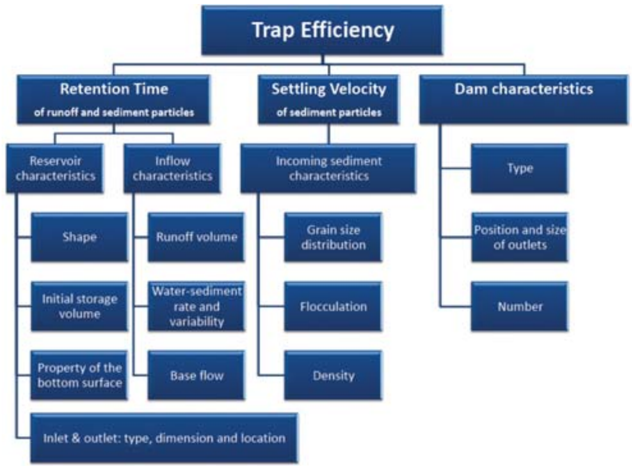


Figure 2. Factors influencing the trap efficiency of reservoirs.

reservoirs used in these models. For small ponds, these models seem to be less appropriate. Furthermore, they also cannot be used for predicting trap efficiency for a single event.

At present only limited research has been done on establishing mid-term trap efficiency models based on theoretical principles. This is probably the most important gap in trap efficiency research that the present study is presenting. The study aims at investigating the evolution of the sediment trap efficiency based on ten laboratory test with various reservoir geometries, and proposes measures to control and predict the channel characteristics. Therefore this study is focusing mainly on influence of the reservoir geometrical parameters as Aspect Ratio AR, Expansion Ratio ER, Expansion area ratio σ, Expansion density ratio and geometry shape factor SK, on trap and flushing efficiencies. Finally, several empirical formulas that describe the relationship between the reservoir geometry and sediment trap efficiency as well as flushing efficiency for two modes of flushing were developed. An empirical formula for drawdown flushing describes the function between the geometry shape factor and flushing efficiency is presented.

2 PHYSICAL EXPERIMENTS

2.1 *Experimental facility*

The experimental tests have been conducted in a rectangular shallow basin with inner maximum dimensions of 6.0 m in length and 4 m in width, as sketched in Figure 3(a). The inlet and outlet rectangular channels are both 0.25 m wide and 1.0 m long. The bottom of the basin is flat and consists in 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 is used to prepare the water-sediments mixture. The water-sediments mixture is supplied by gravity into the water-filled rectangular basin. Along the basin side walls, a 4.0 m long, movable frame is mounted to carry the measuring instruments. The sediments were added to the mixing tank during the tests. To model suspended sediment currents in the laboratory model, walnut crushed shells with a median grain size d_{50} = 50 μm, density 1500 kg/m^3 was used in all experiments. These are non-cohesive, light weight and homogeneous grain material. The bed level evolution was measured with a Miniature echo sounder (UWS). The sounder was mounted on a movable frame which allowing to scan the whole basin area. The sediment concentrations of the suspensions material using the crushed walnut shells were measured. The hydraulic and sediment conditions were chosen to fulfill the sediment transport requirements. Furthermore, for all tests, Froude number ($0.05 \le Fr \le 0.43$) was small enough and Reynolds

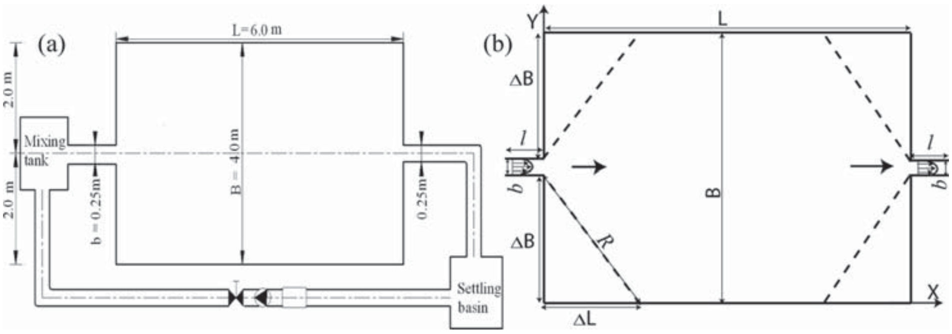
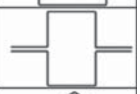


Figure 3. (a) Plan view of the laboratory setup; (b) Geometrical parameters of the test configurations.

Table 1. Configurations of different test series and their geometrical characteristics: L and B are length and width, A 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* [-]	$SK = (P/\sqrt{A})*AR*D_{exp}$ [-]	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	25	4.65	

number (14000 ≤ Re ≤ 28000) high enough to ensure subcritical, fully developed turbulent flow conditions.

2.2 *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 process behind the sedimentation of shallow reservoirs governed by suspended sediment; a reference basin geometry with width of B = 4.0 m and length of 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 analyzed in detail (Kantoush, 2008, Kantoush and Schleiss, 2010). To investigate the effect of the basin width effect on the flow and sedimentation processes in the reservoir the experiments focused on the width achieved in rectangular reservoir 6.0 m long and 3.0, 2.0, 1.0, 0.5 m wide (from T7 to T10), respectively. With a second set of tests the effect of the basin length experimental tests have been conducted in a rectangular shallow basin 4.0 m wide and 5.0, 4.0, and 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.

2.3 *Geometrical parameters*

The geometrical parameters are defined in Figure 3(b) and all tests are summarized at Table 1. In order to represent all geometrical characteristics parameters with flow and deposition results, a geometry shape factor *SK* was developed. In the present study several reservoir geometries with different shapes have been 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 3(b) & Table 1):

- Length and the 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 $SK = (P/\sqrt{A})*AR*D_{exp}$.

2.4 *Test procedure*

After filling the basin and having reached a stable state with the clear water. First LSPIV recording (Large Scale Particle Image Velocimetry) has been performed during 3 minutes. Then 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 90 minute's period. The flap gate was then closed to permit for the suspended sediment to deposit and then start bed level profile measurements by using UWS. Every 1.5 hrs, the bed morphology was measured at different cross sections. After each time step the pump was interrupted to allow bed morphology recording. 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. Normal water depth of h = 0.20 m was used without lowering of reservoir during free flow flushing. With lowering the water depth in the reservoir to half of the normal water depth (h = 0.10 m), the drawdown flushing was conducted. Each mode of flushing lasted for two days with flow field and final bed morphology measurements.

3 RESULTS AND DISCUSSIONS

3.1 *Influence of Aspect Ratio of reservoir (AR) on Trap Efficiency (TE)*

Various geometrical configurations with different aspect ratio $AR = L/B$, where *L* and *B* is length and width of the reservoir, respectively, hydraulic and sediment conditions have been analyzed. By knowing the actual deposited sediment (V_{dep}) and the sediment volume flowing into a reservoir (V_{in}), it is possible to calculated the V_{dep}/V_{in} ratio and determine the percentage of sediment flowing into a reservoir that will be trapped *TE*. Figure 4(a) shows the trap efficiency *TE* as a function of the reservoir aspect ratio, AR, at six measurement periods (from t_1 to t_6). The trap efficiency is ranging from 98% at t_6 of 1080 minutes ($AR = 1.5$) to 38% at t_1 of 90 minutes ($AR = 0.75$). The TE has a rising tendency while *AR* increasing until reaches a critical *AR* value. Then *TE* starts to decrease for a higher *AR*. The *TE* curves at $t_2 = 180$ min and $t_3 = 270$ min have approximately the same trend as for t_1. That means the reservoirs did not reach to equilibrium state and flow patterns were changing during these three periods. The reservoir reached to a quasi-equilibrium state during the longest test duration of $t_6 = 1080$ min, since the observed *TE* reached to 100%. Equilibrium is associated with vanishing the cumulative net of sediment concentration but this does not imply that the instantaneous sediment flux vanishes. It can be concluded that *TE* increases with increasing reservoir aspect ratio until it reached the highest *TE* and then it decreases with increasing aspect ratio as shown in Figure 4. Lesser amounts of sediment may be retained by reduced aspect ratio of reservoir.

3.2 *Influence of Expansion Ratio (ER) of reservoir on Trap Efficiency (TE)*

The influence of the Expansion Ratio (ER) on the trap efficiency TE is illustrated in Figure 4(b). It can be seen that the increase of the efficiency between ER of 8 and 12 is the same order of magnitude as the increase between 16 and 26 (about 40%–45%). Therefore, the changes from an asymmetric flow pattern to a symmetric flow pattern for ER of 16 are responsible for a break in the efficiency curve of the reservoir. The evolution of the trap efficiency is compared for six different runs at 90, 180, 270, 450, 540, and 1080 minutes. Several data points are located at ER = 16 which indicated that expansion ratio is not representative for geometries with a fixed width and variable length. Trap efficiency increases with increasing ER till it reaches ER = 12 where TE is almost 100%. The minimum TE was obtained for a

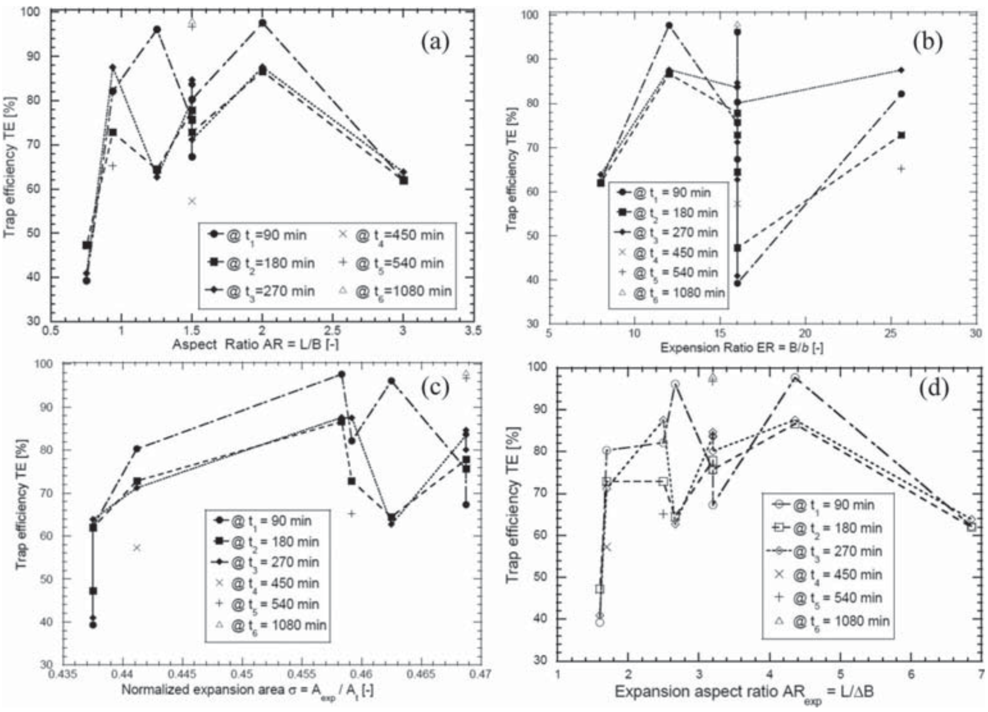


Figure 4. Influence of (a) Aspect Ratio (*AR*), (b) Expansion Ratio (*ER*) (c) normalized expansion ratio, (d) Expansion Aspect Ratio AR_{exp}, on trap efficiency of reservoir $TE = V_{dep}/V_{in}$.

basin with ER = 16. For higher ER, the trap efficiency decreases again. There is no significant changes of TE evolution for narrow reservoirs with low of ER = 8.

3.3 *Influence of normalized expansion area* $\sigma = A_{exp}/A_t$ *of reservoir on Trap Efficiency (TE)*

The effect of expansion area ratio is defined as ratio of expansion to total surface areas. Figure 4(c) shows the influence of σ on the *TE*. In beginning after first period $t_1 = 90$ min, the trap efficiency increases with rising expansion area ratio σ until a maximum TE value is reached. Then, it decreases again for higher expansion area ratio. Almost the same trend was found at t_2 and t_3.

3.4 *Influence of normalized expansion aspect ratio* $AR_{exp} = L/\Delta B$ *of reservoir on TE*

The evolution of trap efficiency as a function of expansion aspect ratio $AR_{exp} = L/\Delta B$ was investigated as shown in Figure 4(d). Trap efficiency is rising for higher expansion aspect ratio, which can be defined as the ratio of expansion length to the expansion width. It reaches a maximum *TE* at $AR_{exp} = 3.2$ before it decreases again with for higher AR_{exp}. The trap efficiency after $t_1 = 90$ min reached to the peak; afterwards it declined by almost 15%. Finally *TE* increased again to asymptotically reaching 100% before decreasing again with further increase of AR_{exp}.

3.5 *Influence of geometry shape factor SK on trap efficiency TE*

There are several non-dimensional geometrical parameters as (AR, ER, σ, and A_{exp}) that have no clear influence on trap efficiency by considering each parameter separately. Therefore, a set of several combinations of these parameters were used and analyzed versus trap efficiency. It was found that geometry shape factor *SK* affects the trap efficiency. The geometry shape factor SK is defined as the $SK = (P/\sqrt{A})*AR*D_{exp}$. The evolution of trap efficiency and relationship with geometry shape factor was depicted in Figure 5(a). It is clearly visible in that *TE* decreases with increasing geometry shape factor (*SK*). The evolution of trap efficiency is increased with time and it reached quasi equilibrium during the last period of last run. An empirical relationship between trap efficiency *TE* in percentage and geometry shape factor *SK* was developed from all experiments in Eq. (1) with application range of $2.92 < SK < 13.42$.

$$TE = V_{dep}/V_{in} = 95 - 360\ (SK)^{-2} - 12\ (SK/10)^2 \tag{1}$$

It seems that smaller geometry Shape factor SK trapped less sediments and the evolution of trap efficiency can be approximated by a fitting decreasing curve as shown in Figure 5(a) for SK = 2.92. It can be conclude that the distance between inlet and outlet of the reservoir has a great influence of trap efficiency. By increasing SK to 3.41 trap efficiency increased by almost 35% and the evolution curve with decreasing tendency at the end of the experiment. With further increasing for *SK* still trap efficiency increases as shown in Figure 5(a). It is clearly visible in Figure 5(a) that the evolution tendency of *TE* decreases again from SK > 10, as the flow pattern was straight from inlet to outlet with no or one circulation cells inside the reservoirs. Therefore, the minimum deposited volume was obtained for higher geometry shape factor SK > 10. It can be concluded that flow pattern with no/odd number of cells are preferable to reduce depositions.

3.6 *Prediction of the drawdown flushing efficiency*

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

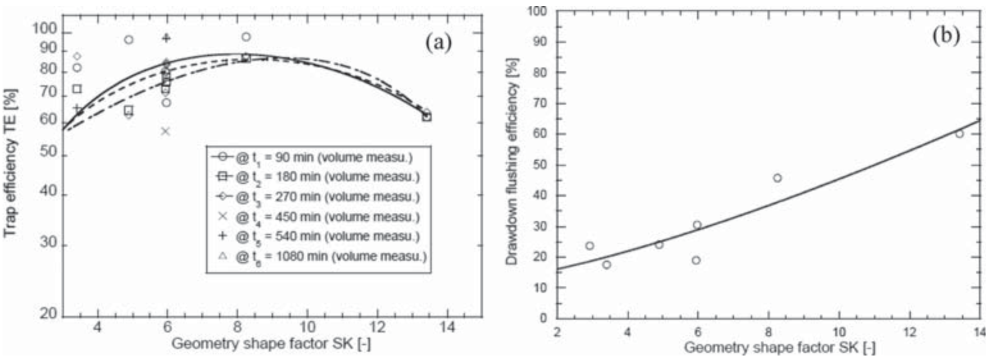


Figure 5. Influence of geometry shape factor SK on (a) trap efficiency; (b) flushing efficiency.

$$FE = V_{flushed}/V_{df} \tag{2}$$

where $V_{flushed}$ is the volume of flushed sediment with clear water after two days, V_{df} is the total cumulative deposited volume after a specific period. Figure 5(b) shows the influence of the geometry shape factor SK on drawdown flushing efficiency *FE*. Flushing efficiency FE is an index to describe the effectiveness of hydraulic flushing. With lowering the water depth in the reservoir to half of the normal water depth, the efficient drawdown flushing as a function of geometry shape factor were plotted in Figure 5(b). It was observed that the drawdown flushing efficiency increases with higher geometry shape factor. The drawdown flushing was higher compared to the free flow flushing. The minimum flushing efficiency was 20% for the smallest geometry shape factor. Additionally, the maximum drawdown flushing efficiency reached almost 65% for the highest geometry shape factor as shown in Figure 5(b). It was found qualitatively that almost fifty percent of the total volume removed sediments were flushed out in the one fourth of the flushing duration. Flushing efficiency was correlated with the geometry shape factor the empirical relationship formula in Eq. 3. The application range of Eq. 3 is $2.92 < SK < 13.42$ and the coefficient of determination $R^2 = 0.92$.

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

where *FE* is flushing efficiency ($FE = V_{flushed}/V_{df}$) and *SK* is the geometry shape factor ($SK = (P/\sqrt{A})*AR*D_{\text{exp}}$).

4 CONCLUSION

The trap efficiency reduces with time for the lozenge form (T14, SK = 11.2), but TE is high in the beginning. With the lozenge form the jet could expanded over all the basin geometry. According to the proposed empirical formula, trap efficiency can be estimated. The length of the reservoir plays a critical role in determining the jet flow type and the associated pattern of the bed deposition. The use of an elongated basin increases the retention of sediments as it is well known for sand trap basins. The maximum Aspect Ratio (Length to width ratio) of reservoir should be 1.5. 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 on 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 becomes better for increasing geometry shape factor SK as given by the empirical relationship in Eq. 3 within the application range of is $2.92 < SK < 13.42$.

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