# Influence of a circular jet arrangement in a rectangular tank on flow and suspended sediment release

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***Abstract:*** *With the objective of high sediment release out of a rectangular tank the performance of a circular jet arrangement has been investigated. Therefore, experiments with four jets arranged in a horizontal circle placed in water with quasi homogeneous sediment concentration were conducted. The induced circulation was analysed by measuring the flow field. The influence of the flow circulation on suspension and on sediment release through the water intake was studied and discussed. The off-bottom clearance of the jet arrangement, the water intake height as well as the discharge of the jets was varied. Thus, the optimal parameter combination regarding sediment release was identified. The results of this study allow giving recommendation on best installation and discharge practice of the jets resulting in high sediment release. This jet mixing method can be applied in real reservoirs when fighting against sedimentation.*

***Keywords:*** *water jet, flow pattern, suspended sediment, sediment release, reservoir sedimentation*

## 1. INTRODUCTION

The purpose of the present study is to release a sediment load as high as possible out of a rectangular tank having a quasi homogeneous sediment-water mixture as initial condition. Specific jet arrangements should provide the energy and generate the optimal circulation needed to maintain the sediment in suspension and enhance its entrainment into the intake. Therefore a circular jet arrangement was tested. Several off-bottom clearances, water intake heights and jet discharges were investigated.

The optimal jet arrangement was evaluated by physical experiments. Flow velocities were measured providing flow patterns. Turbidity measurements combined with flow velocity measurements gave information about the sediment release efficiency.

The optimized jet arrangement can be used for practical application in real reservoirs.

## 2. LITERATURE REVIEW

### 2.1. Jet mixing

Extensive research has been performed in the field of jet mixing. The following parameters and their influence on mixing time have been reported as follows:

- tank dimensions in cylindrical tanks (Grenville and Tilton 1997, Fox and Gex 1956, Lane and Rice 1982)
- jet characteristics like:
    - jet velocity (Fossett and Prosser 1949)
    - jet diameter (Coldrey 1978, Perona et al. 1998, Patwardhan and Gaikwad 2003)
    - and their product (Fossett and Prosser 1949, Fossett 1951, Lane and Rice 1982, Grenville and Tilton 1997, Stefan and Gu 1992, Ranade 1996)
    - jet Reynolds and Froude number (Okita and Oyama 1963, cited in Maruyama et al. 1982)
    - jet location (Mewes and Renz 1991 cited in Wasewar 2006, Perona et al. 1998,

    Maruyama et al. 1984, Zughbi 2006)
    - jet angle and jet length (Fox and Gex 1956, Patwardhan and Gaikwad 2003, Revill 1992, Zughbi and Rakib 2004)
- and multiple jets (Perona et al. 1998, Revill 1992).

Some authors studied the influence of the residence time (Stefan and Gu 1992) and circulation time (Maruyama et al. 1982) on mixing time; others investigated the flow patterns regarding mixing time.

There are, however, some important differences between the goals, conditions and requirements of the cited investigations and the present study:

1. A homogenisation of mixtures in the whole container is usually aimed, whereas in the present study high concentration is required locally in front of the water intake.
2. The main focus is usually set on the minimization of mixing time, where complete mixing is accomplished as soon as homogenisation of the physical properties is achieved. In the present study, the already established suspension (initial condition) has to be maintained over a long time.
3. In chemistry normally closed circuits are used. In the present study the water-sediment mixture evacuated by the water intake is replaced by clear water, and hence, the sediment amount is continuously reduced.

None of the studies reports about a jet arrangement similar to the one investigated in the present study. Nevertheless, the importance of the jet position, the jet diameter and velocity as well as the residence time seems evident for every jet mixing case.

### 2.2. Solid suspension in impeller stirred vessels

Since the pioneering work of Zwietering (1958) in the late 1950s, numerous empirical and semi-empirical investigations on solid suspension in stirred vessels have been reported in literature. Sharma and Shaikh (2003) also carried out suspension experiments with particulate solids in stirred tanks employing Pitched Blade Turbines (PBT) as the impellers in cylindrical glass vessels having flat bottoms with round corners.

The most critical place for the suspension is the tank bottom, and the ease or difficulty of suspension from it, depends on the type of flow pattern that the agitator generates. Sharma and Shaikh (2003) confirmed from the results of Armenante and Nagamine (1998) showing that the flow pattern from an axial flow impeller is more favourable for suspension in comparison to the flow pattern produced by a radial flow impeller (Figure 1). Moreover, they demonstrated that a typical axial impeller changes its flow pattern with increasing off-bottom clearance $C$ to radial.

**Figure 1 a) Axial and b) radial impeller type and their typical flow pattern**

## 3. EXPERIMENTAL SET-UP

### 3.1. Description of the experimental facility

The physical experiments were carried out in a prismatic tank with vertical walls. The tank had an elongated rectangular shape with a total inner basin length of 4 *m*, an inner width of $B$ = 1.97 *m* and a total basin height of 1.50 *m* (Figure 2a). In the middle of the front wall there is a vertical stripe made of PVC, where the water intake is insertable at three different levels: 0.25, 0.50 and 0.75 *m* above the basin bottom (Figure 2a). This allows varying the level of the intake.

A pipe guides the outflowing water into a small energy dissipating basin. The flow rate is controlled by a valve and monitored with a V-notched weir plate at the basin outlet.

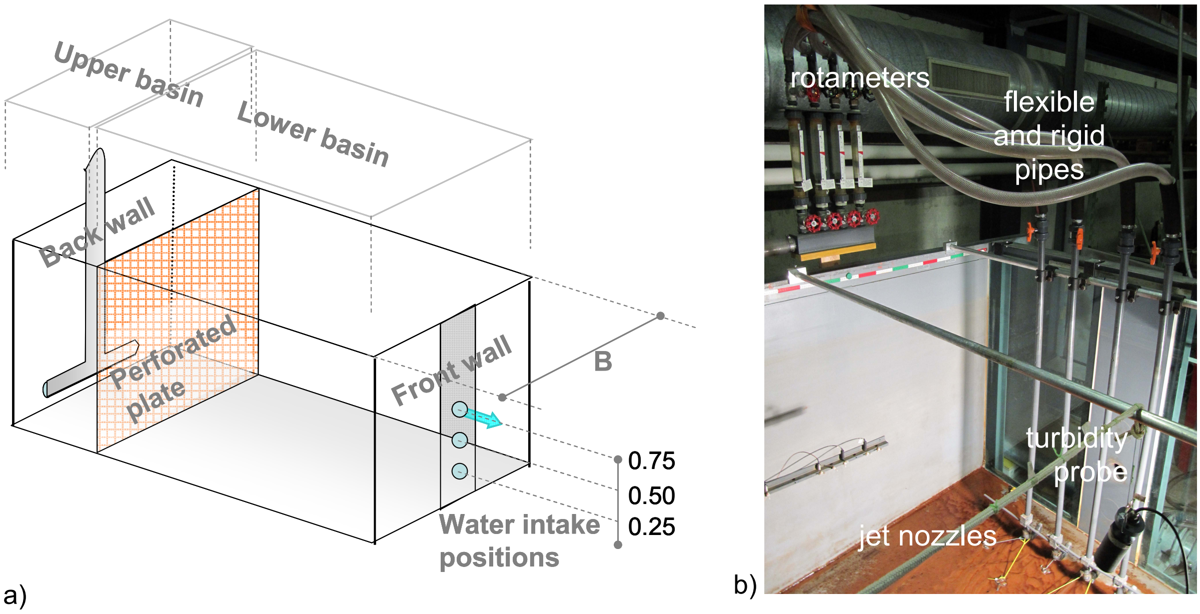


**Figure 2 a) schematic drawing of the experimental installation; b) picture of the tank with the four rotameters leading the water into flexible pipes and to the rigid pipes and down to the nozzles (linear jet configuration). The turbidity probe is suspended on a rope.**

A 50.8 *mm* diameter pipe, supplied by the laboratory pump, leads clear water to a level 150 *mm* above the upper tank edge, where it is distributed from a horizontal chamber into four rotameters (Figure 2b). The use of the rotameters allows an equal distribution of the total flow rate into the four nozzles. Each rotameter feeds a flexible pipe which leads the water into rigid pipes leading the water downward to the nozzles. The nozzle position as well as its diameter $d_j$ can be varied (3, 6 and 8 *mm*).

## 3.2. Measurement devices

### 3.2.1. Flow velocity measurements

An L-shaped rack was built with two wings hosting five equally distanced UVP-transducers, each. This rack was fixed at the lower end of a vertical rod (Figure 3c). The lateral distance from one sensor to another was 200 *mm*; the distance between the sensors and the wall was 230 *mm*. Flow velocities were measured on two vertical planes: on the transversal axis at 1.05 *m* from the front wall corresponding to the jet arrangement centre (Figure 3a), and the longitudinal mid-width axis of the tank corresponding to the water intake axis (Figure 3b).

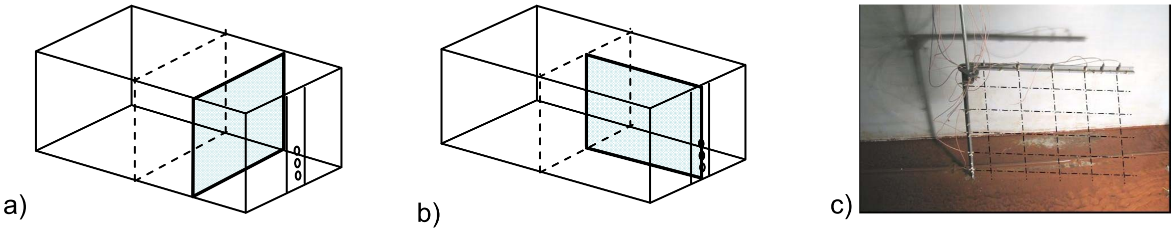


**Figure 3 Schematic view of the position of the UVP-sensor-frame for a) transversal 2D-flow pattern; b) longitudinal 2D-flow pattern and c) rack of 5 x 5 UVP-transducers fixed at the lower end of a vertical rod. The sensor emitting axes are schematically indicated.**

### 3.2.2. Turbidity measurements

Two SOLITAX sc sensors (brand Hach) were employed for measuring turbidity by infrared absorption scattered light technique. The relationship between the suspended sediment concentration and the turbidity signal was derived in the laboratory by placing the probe in suspensions of known crushed walnut shells concentrations. The obtained calibration relationship is linear. One of the turbidity sensors is installed in the dissipation basin right below the exit of the headrace tunnel and measures suspended sediment concentration continuously. The other one is used to measure sporadically (5 to 8 times per experiment) suspended sediment concentration at different positions within the experimental tank.

## 3.3. Properties of the sediment materials

For the present study ground walnut shell powder was used. This material has been tested in former studies of sedimentation in shallow reservoirs (Kantoush 2008 among others) and has been found to perform very well. It is easy to mix, almost cohesionless and lightweight ($\rho_s$ = 1500 $kg/m^3$). The particle size distribution is relatively narrow and the mean settling velocity is small (according to Stokes' theory: $w_s \approx 0.8$ *mm/s* in water at 15°*C*). The particles have a median diameter of $d_m = d_{60} = 0.06$ *mm*. With a standard deviation $\sigma_g = 2.4$ some grain sorting effects can be expected to occur. The particles are not spherical, but have slightly angular shapes, like natural sediments.

## 3.4. Circular jet arrangement

The circular jet experiments are arranged as follows: The jet configuration consists of four water jets with equal nozzle diameter $d_j$ and jet velocity $v_j$, arranged in a circle in a horizontal plane. Each jet is pointing in a 90°-angle to the axis of the neighbouring jet (Figure 4). This jet arrangement is installed in the front part of the tank. The parameters influencing the effectiveness of the jets are the jet velocity, jet diameter, and the geometry of their arrangement.

a) b)

**Figure 4 a) schematic top view of the circular jet configuration. Each jet points on the transition zone of its neighboring jet; b) circular jet arrangement with the water intake in the front wall.**

# 4. RESULTS AND DISCUSSION

## 4.1. Sediment evacuation efficiency

In order to compare and evaluate the different experiments and to identify the most efficient jet configuration composed by the optimal parameter combination, the evacuated sediment ratio was determined. This ratio is defined as the evacuated sediment weight $P_{out}$ divided by the sediment weight initially supplied to the tank $P_{in}$ (3 *kg* dry sediment, Equation (1)). It represents the normalized temporal integral of the released sediment amount.

$$ESR = \frac{P_{out}}{P_{in}} = \frac{\sum c_{s,i}\left[g/l\right]\cdot Q_{out}\left[l/s\right]\cdot \Delta t\left[s\right]}{P_{s,in}\left[g\right]} \tag{1}$$

where $\Sigma c_{s,i}$ is the integrated suspended sediment concentration measured in intervals of $\Delta t$ (mostly equal to 5 seconds). $Q_{out}$ is the discharge released through the water intake.

## 4.2. Experiments without jets

In the experiments without jets carried out as reference configuration the sediment load evacuated through the water intake was examined while the outflowing water was continuously replaced by clear water through the back wall. These experiments showed an almost linear relation between the sediment release *ESR* and the discharge $Q_{out}$ within the tested range: the higher the discharge, the higher the evacuated sediment ratio. For the tested discharge range the sediment release *ESR* was between 0.09 and 0.37 after four hours (Figure 5).

## 4.3. Influence of the discharge on sediment release

Jet experiments and experiments without jets were performed within the following discharge range: $\Sigma Q_j$ = 570 to 4050 *l/h*. After four hours of experiment duration and within the range of the experimentally tested discharges Figure 5 reveals an almost linear relationship between the measured evacuated sediment ratio and the discharge. It has to be mentioned that in the jet experiments the jet discharge $\Sigma Q_j$ and the released discharge through water intake $Q_{out}$ were identical. Jets are effectively mixing: after roughly half an hour the standard deviation of the suspended sediment concentration was approximately 5 %, what in chemistry is considered as homogeneous. Consequently, less sediment was settled and, hence, the sediment release was higher than without jets and reached for the highest tested discharge ($\Sigma Q_j$ = 4050 *l/h*) *ESR* = 0.73. Moreover, contrary to the experiments without jets, with jets resuspension of settled sediment was observed. Resuspension started once steady state conditions for the circulation were reached. It has been detected for discharges higher than an experimentally determined threshold ($\Sigma Q_j$ = 2030 *l/h*). The observed evolution of the resuspension rate suggests that for a final stage all of the initially supplied sediment can be evacuated.

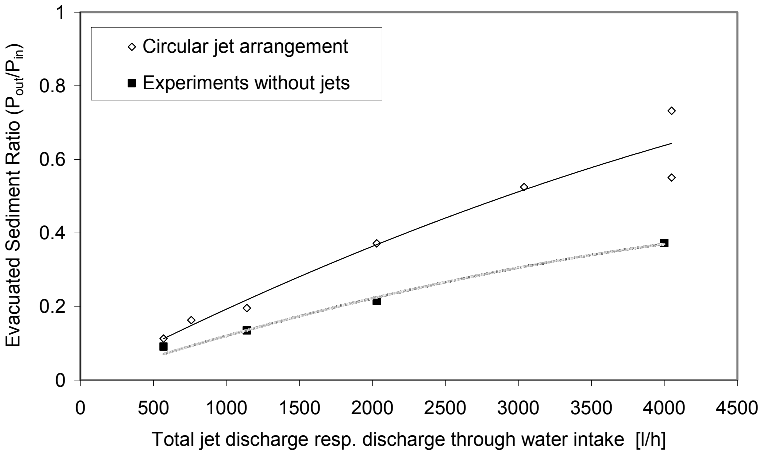
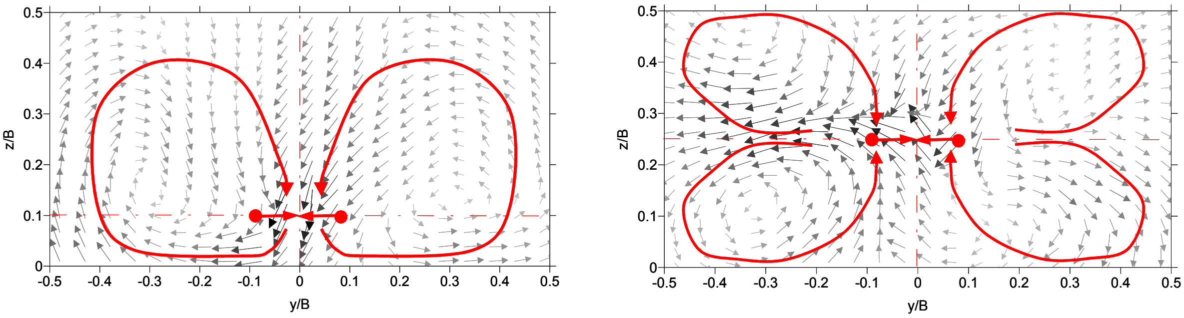


**Figure 5 Evacuated sediment ratio *ESR* after four hours as a function of the total jet discharge $\Sigma Q_j$ (resp. discharge through water intake) shown for the jet experiments with circular jet arrangement with off-bottom clearance *C/B* = 0.175, water intake height $h_i/B$ = 0.25, as well as for the experiments without jets.**

## 4.4. Influence of off-bottom clearances of jets and water intake height

### 4.4.1. Influence of off-bottom clearance of jets on flow pattern and sediment release

A strong influence of the off-bottom clearance of jets (*C/B*) on the flow patterns was observed. When keeping the water intake height $h_i$/B constant for lower off-bottom clearances of the jet arrangement on one hand, the flow pattern was in the transversal plane similar to the one of an axial mixer (Figure 6a). On the other hand, if the off-bottom clearance was high (*C/B* = 0.25) radial mixer-like flow patterns were detected in the same plane (Figure 6b). The same observation was made in the longitudinal plane. These results confirm the findings of Sharma and Shaikh (2003).



a) b)

**Figure 6 Flow patterns in the transversal plane for water intake height $h_i/B$ = 0.25 and total discharge $\Sigma Q_j = Q_{out}$ = 760 *l/h*. a) off-bottom clearance *C/B* = 0.1; b) off-bottom clearance *C/B* = 0.25.**

As reported by Sharma and Shaikh (2003) radial mixers are not as favourable as axial mixers regarding particle suspension. This is indirectly confirmed by the present study since the sediment release was less significant if radial mixer-like (for *C/B* > 0.175) instead of axial mixer-like flow patterns (for *C/B* ≤ 0.175) were detected in the transversal plane. Nevertheless, contrary to what would be expected for classical impeller mixing problems from the literature, the lowest off-bottom clearance (*C/B* = 0.1) was not the most efficient one regarding sediment release. The off-bottom clearance *C/B* = 0.175 provided an optimal circulation and highest sediment release (Figure 7). This different finding is due to different set-up conditions (sediment laden water being extracted and replaced by clear water instead of closed circuit).

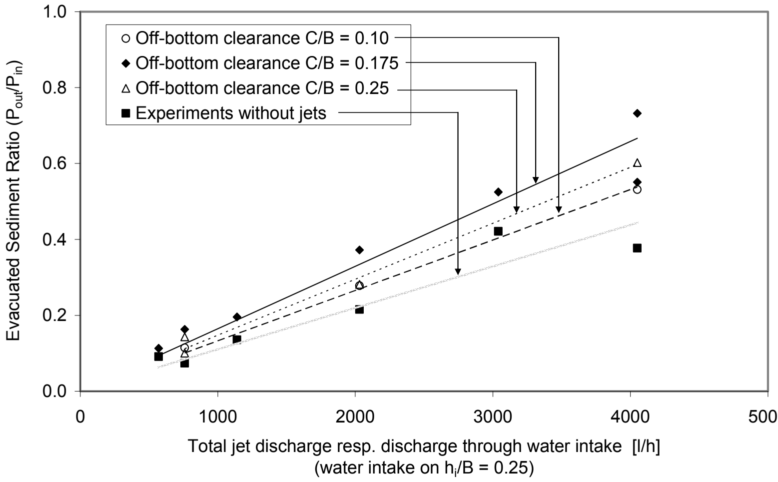
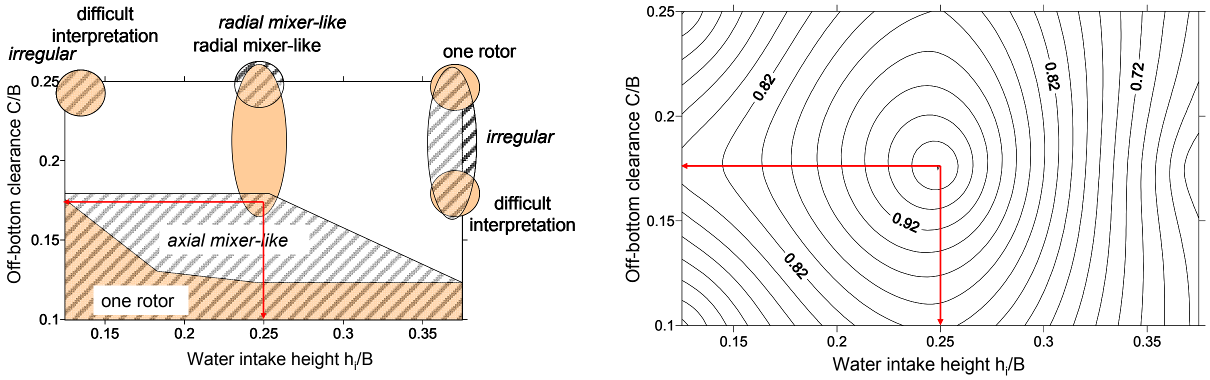


**Figure 7 Evacuated sediment ratio *ESR* as a function of the total jet discharge $\Sigma Q_j$ (resp. discharge through water intake) varying the off-bottom clearance while holding the others geometrical parameters constant.**

### 4.4.2. Influence of water intake height on flow pattern and sediment release

The height of the water intake had its influence mainly on the flow pattern in the longitudinal plane. Depending on the water intake position in relation to the off-bottom clearance, the current issued horizontally out of the jets circle was more or less deflected. A straight horizontal current pointing almost directly towards the water intake resulted in very effective sediment release. This kind of current induces a radial mixer-like flow pattern.
Figure 8a summarizes the apparent characteristic flow patterns resulting from the tested combinations of off-bottom clearance of jets *C/B* and water intake heights $h_i/B$. Figure 8b provides an overview on the respective sediment release for a discharge $\Sigma Q_j = Q_{out} = 760$ *l/h* after four hours. The maximum sediment release is obtained when combining *C/B* = 0.175 and $h_i/B = 0.25$ and indicated as unity. The sediment release *ESR* for other combinations is indicated in isolines of parts of the maximum.
Consequently, the combination of an axial mixer-like flow pattern in the transversal plane and a radial mixer-like flow pattern in the longitudinal plane revealed to be optimal regarding sediment release.



a) b)

**Figure 8 For $\Sigma Q_j$ = 760 *l/h,* a) superposition of the characteristic flow pattern in the transversal (hatched areas and italic caption font) and in the longitudinal (grey areas with normal caption font) planes resulting from different combinations of off-bottom clearance and water intake height; b) optimal off-bottom clearance of jets and water intake height above bottom.**

## 5. CONCLUSION AND RECOMMENDATION

Physical experiments in a rectangular tank were performed to investigate the influence of a circular jet arrangement on the circulation, sediment behavior and sediment release. For the tested circular jet arrangement a quasi linear relationship between the jet discharge and the sediment release was found: the higher the discharge the more sediment is evacuated.
A sensitivity study regarding off-bottom clearance of the jet arrangement and water intake height showed that the combination generating an axial mixer-like flow pattern in the transversal plane and a radial mixer-like flow pattern in the longitudinal plane is most effective when aiming for high sediment release. Optimal off-bottom clearance of jets has been found to be *C/B* = 0.175 and optimal water intake height $h_i/B = 0.25$. For this combination and for discharges exceeding an experimentally determined threshold ($\Sigma Q_j$ = 2030 *l/h*) even resuspension was observed. This leads to the assumption that at a final stage all initially supplied sediment can be released. Nevertheless, the results show that even with small jet discharges at least 1.7 times more sediment is evacuated than without jets (depending on time and discharge).
This jet mixing method is very promising. It is thought to be applied in real reservoirs as mitigation measure against reservoir sedimentation. Scale effects need to be considered. It presents a low cost and efficient installation transferring a high amount of fine sediment out of the reservoir.

## 6. ACKNOWLEDGEMENTS

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## NOTATION

| | |
|---|---|
| $B$ | inner tank width |
| $C$ | off-bottom clearance of jet arrangement |
| $\Sigma c_{s,i}$ | sum of suspended sediment concentration measurements recorded in time intervals of $\Delta t$ |
| $d_j$ | nozzle opening diameter |
| $d_m = d_{60}$ | median sediment particle diameter |
| $\Delta t$ | time step duration |
| $ESR$ | evacuated sediment ratio ($ESR = P_{out}/P_{in}$) |
| $h_i$ | height of water intake |
| $P_{in}$ | sediment weight initially added to the basin |
| $P_{out}$ | evacuated sediment weight |
| $Q_{out}$ | discharge released through the water intake |
| $Q_j$ | jet discharge at one nozzle |
| $v_j$ | jet velocity at nozzle |
| $w_s$ | settling velocity (particle fall velocity in a clear fluid) |
| $\rho_s$ | sediment density |
| $\sigma_g$ | standard deviation of grain size distribution |

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