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GEOMETRY EFFECT ON FLOW AND SEDIMENT DEPOSITION PATTERNS IN SHALLOW BASINS

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The design of stilling basin geometry of flood mitigation dams in view of clear water flow may differ when considering of the water-sediment and deposition effects. To ensure effectiveness of energy dissipation, appropriate design of stilling basin leading to optimal geometry is required. The present study investigates the influence of the shallow basin geometry on flow and sediment deposition patterns. The effect of the geometry was investigated using systematic physical experiments, numerical simulation, and field data. This allowed to identify the optimal stilling basin shape of the flood mitigation dam that dissipates more energy, minimizes the deposition and reduces the number of horizontal recirculation cells. The results help to understand the influence of geometry on the flow stability, sediment deposition and flushing process in order to choose the appropriate stilling basin geometry. The prediction of sediment profile depends on the prediction of flow pattern and, in turn, sediment deposits were able to change the flow structure.

Key Words: *Influence of geometry, flood retention dam, flow pattern, sedimentation pattern, stilling basin*

1. INTRODUCTION

Flow separation and reattachment due to sudden changes in geometry in internal flow occur in many engineering applications such as in open channels, shallow reservoirs, groin fields and stilling basins. The occurrence of large-scale instabilities and consequent vortex formation in planar jets in various geometries has been studied[1)]. In shallow flow both the limited depth and the bottom friction influence the development of the mixing layer[2)]. The limited depth restricts the large structures in the mixing layer to basically 2D horizontal motions.

A model was developed for obtaining the optimal dimensions of stilling basin and its appurtenances[3)]. In symmetrical geometries of stilling basins for a fixed and horizontal channel bed, and various expansions and aspect ratios, the hydraulic jumps have been classified[4)]. The hydraulic jump moves upstream and its front gradually become normal (R-jump) as the tailwater level is increased[4)]. Several ratios of the stilling basin width to the inlet channel width were analyzed, which affect flow stability, necessary tailwater depth, and length for the hydraulic jump[5)]. A more detailed analysis of hydraulic jumps in abruptly expanding channels was provided[6)]. Many experimenters have observed that the flow in symmetric expansions is asymmetric. The asymmetric flow in sudden expanding stilling basins may cause asymmetric scour downstream the basin.

Numerical and theoretical stability analysis of shallow flows in a series of rectangular reservoirs compared with experimental data has been discussed[7)]. A series of numerical simulations and compared with scaled laboratory experiments, to investigate the sensitivity of flow and sediment parameters were presented[8)].

2. OBJECTIVES AND TARGET PROJECT

Design of stilling basin of flood mitigation dams

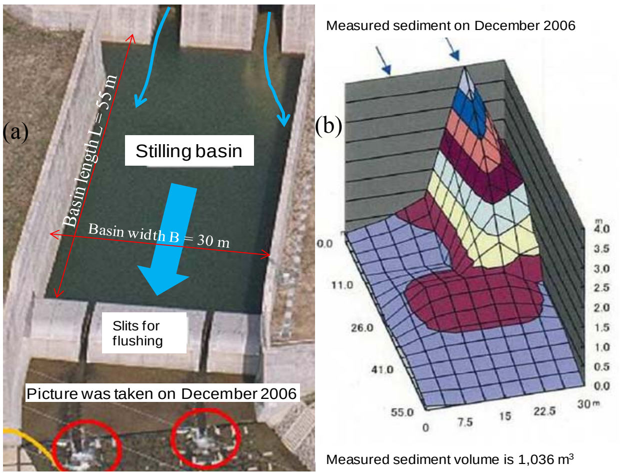

Fig.1 Stilling basin of Masudagwa dam (a) schematic picture of flow and deposition; (b) measured sediment profile and volume

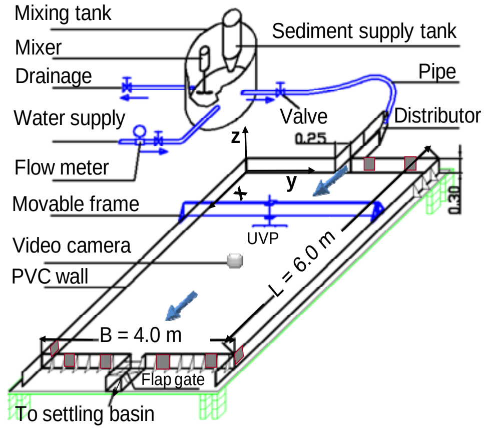

Fig.2 Schematic view of experimental facility installation.

such as Masudagawa dam in Shimane Prefecture is governed by several parameters such as: number of bottom outlets, approach Froude number, basin geometry, and tailwater level. Flood mitigation dam is a gateless outlet dam designed only for the purpose of flood control which provides long-term and efficient protection against floods and is called dry dam in USA.

The study focuses on the use of the findings of the fundamental research study about influence of geometry to define the stilling basin in flood mitigation dam. Case of study for stilling basin of Masudagawa dam, newly completed flood mitigation dam in Japan is shown in Fig. 1. The stilling basin of Masudagawa dam dissipates the energy by hydraulic jump type equipped with an endsill and slits for flushing sediment and allowing fish passage. The flow width from the bottom outlet shows a narrow flow width comparing with the width of the downstream river (Fig.1(a)).

Horizontal recirculation cells are formed at the sides of the inflow jet. These recirculation cells combined with sediment transport are harmful. During the first and last stages of a flood when the reservoir water level is reduced, a huge sediment outflow occurs. While increasing the basins water level, the velocity is increased and large sediment volumes are deposited in the basin as shown in Fig.1(b). Therefore, it is possible to minimize the damage by stopping the horizontal recirculation cells in the stilling basin during the high water level conditions. An asymmetric flow pattern with a low number of circulation cells is favorable to reduce the exchange processes between flow, bed deposition and the damage of basin slits. Flow pattern with large stagnant zones allows only a portion of flow to pass the basin in a time period less than the settling time. Beside the purpose of controlling the number of recirculation cells and deposition, the objective is also to gain deeper insight into the physical processes of sedimentation in shallow basins. The findings will help designers of stilling basins of new flood mitigation dams to predict the flow and sediment deposition and to choose an appropriate geometry. To obtain an optimum design and operation of bottom outlets and stilling basin, 3D numerical modeling will be carried out for different scenarios. The main criterion for the different simulation is to find out which geometry dissipates more energy and transports the maximum volume of sediment over time.

3. METHODOLOGY

The complexities associated with predicting the flow and sedimentation pattern in various basin geometries emphasis the need of combination of the numerical results with the physical experiments. This helped to deeply understand the physics and the process of the sedimentation in the shallow basins.

Sixteen experiments with clear water and water-sediment mixture were performed in a facility (Fig.2) at the Laboratory of Hydraulic Constructions (LCH) of the Swiss Federal Institute of Technology (EPFL). The experiments have been conducted in a rectangular shallow basin shown in Fig. 1(b), with inner maximum dimensions of 6 m in length and 4 m in width. The inlet and outlet rectangular channels are both 0.25 m wide and 1 m long. The influence of different shallow reservoir geometries, with variable widths and lengths has been achieved experimentally. To investigate the effect of basin width on the flow and sedimentation processes, first the 6 m long basin was performed (Fig. 1(a)).

The width was then reduced successively from 4 to 3 to 2, to 1, and to 0.50 m. In a second step the effect of basin length was examined by reducing the length of the rectangular shallow basin from 6 m to 5, to 4, and to 3 m successively.

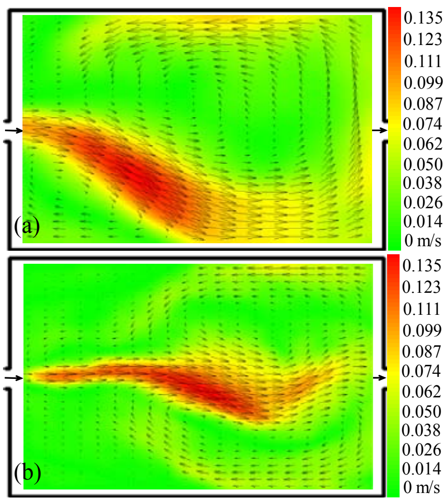

Fig.3 Time averaged flow pattern and velocity magnitude (a) clear water; (b) sediment entrainment flow.

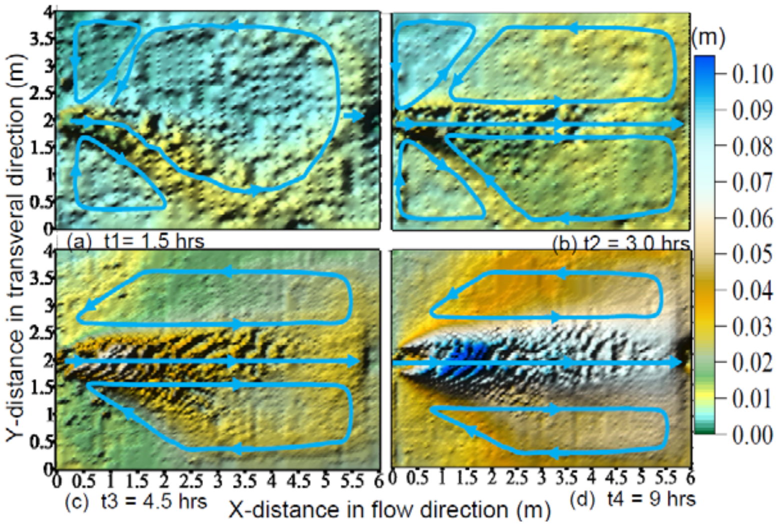

Fig.4 Long-term morphological evolution of deposition at 4 runs with Q =7.0 *l/s*, *h* = 0.2 m and sediment concentration *C* = 3.0 *g/l*.

To model suspended sediment flow in the laboratory model, crushed walnut shells with a median grain size d_{50}=50 μm, and a density of 1500 kg/m^3 were used in all tests. Several parameters were measured during every test, namely: 2D surface velocities, thickness of the deposited sediments, as well as concentration.

Two dimensional depth-averaged flow and sediment transport simulations representing the experimental set-up have been performed with the numerical model CCHE2D[9)], developed by NCCHE (National Center for Computational Hydroscience and Engineering) based on a variant of the finite element method. The model was used to predict river flow patterns and related bed and bank erosion for both uniform and non-uniform sediment transport. Both depth-averaged *k–ε* and eddy viscosity turbulence closures are available. CCHE2D was used for its capabilities to simulate suspended sediment transport.

4. RESULTS AND DISCUSSIONS

(1) Flow pattern with and without sediment

The flow features and large–scale structures were investigated by using LSPIV measurement technique. Fig. 3(a) shows an overview of the velocity field and behavior of large-scale coherent structures in clear water. A plane jet issues from the narrow leading channel and enters straight ahead in the first half meter of the wider basin. Then, the main flow tends to develop in a curved way towards the right hand side over the next two meters until it touches and follows the right wall. When separating from the right wall, the main flow induces a recirculation zone. A main large stable circulation cell is generated in the centre of the basin rotating anticlockwise. Two small triangular cells are formed rotating clockwise in the upstream corners of the basin. The two corner cells are dependent from each other and alternatively change. Both are controlling the size of the main gyre. The jet preference for the right side is weak, since a stable mirror image of the flow pattern can easily be established by slightly disturbing the initial conditions.

The stable asymmetric pattern, with a larger and smaller recirculation zone at the right and left corners, can be explained by a Coanda effect by which any perturbation of the flow field, pushing the main flow to one side of the basin, gives rise to larger velocities at the left side along the jet. The entrainment of mass into the jet creates a mass flux bigger than the discharge, which contributes to the recirculation. When the distance between the inflow and outflow section is big enough, the two are decoupled and the recirculation has room to push the jet aside, which is helped by the Coanda effect.

Fig.3(b) shows the second flow feature developed with sediment entrainment. The addition of sediment decreases the mixing length or increasing the eddy size of the right corner gyre with time. The flow becomes more stable and symmetric as shown in Fig. 3(b). As a result of ripple formation (see Figs. 4(a), (b)) and suspended sediment concentrations, the flow field is completely changed as shown in Fig. 3(b). The gyres in the upstream corners disappeared and a pattern emerges rather symmetric with respect to the center line (see flow pattern schema in Fig. 4). The two remaining gyres interact with the jet which shows tendency to meander. The changes in the bed forms or effective roughness resulting from the sediment deposition can completely modify the overall flow pattern.

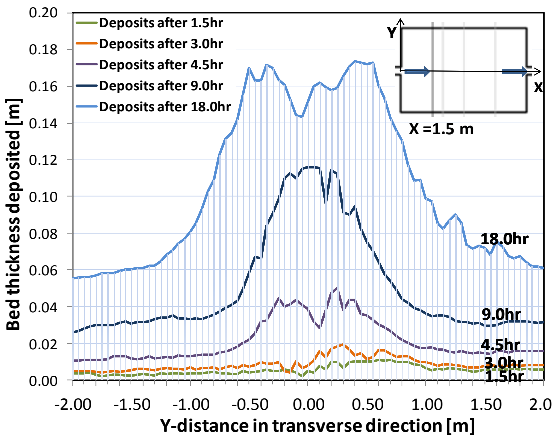

Fig.5 Cross section bed profiles for reference geometry

As a conclusion, a strong interaction between flow field and bottom topography occurred in the basins inlet region with a quasi equilibrium state. There, most of the bed form features disappeared, as the deposition was increased fairly fast. Numbers of recirculation cells that exist in the basin have a strong influence on the flow and sediment deposition behavior. By increasing the numbers of cells, the deposited volume of sediments in the basin increased. The bed morphology and the corresponding schematic flow field for the reference geometry are shown in Fig.4 for four different runs (1.5, 3, 4.5, 9 hrs) allow a comparison of the long-term bed evolution in the rectangular basin.

For all runs, two sedimentation behaviors were observed. First is the development of the sediment deposition developed with ripples formation concentrated on the right hand side till bed thickness deposition reaches up to 15% of the water depth as shown in Fig.4 (a). Then the sediment deposition concentrated along the centerline with relatively steep gradients near the inlet channel and the first part of the jet (Fig.4 (b)). Deposits configurations in Fig. 3 shows how the mixture of water and sediment is diffused throughout the basin following the general flow patterns. The footprint of the flow patterns was clearly visible in the morphology. However, the increased roughness height associated with mobile sediment may contribute to increase in shear velocity. A symmetric ripples pattern forming in the middle of the basin is clearly visible after 4.5 hrs (Fig. 4(c)). After 9.0 hrs (Fig. 4 (d)), the deposition on the center gradually increased generating a wider bed elevation underneath the jet centerline.

Fig. 5 illustrates the depositions in transversal direction of the basin at a distance of 1.5 m from the inlet, for the 5 runs. After 1.5 hrs, almost uniform depositions over the basin with average thickness of 0.015 m are observed. Due to the complete change of the flow pattern after 3.0 hrs, sediment deposition

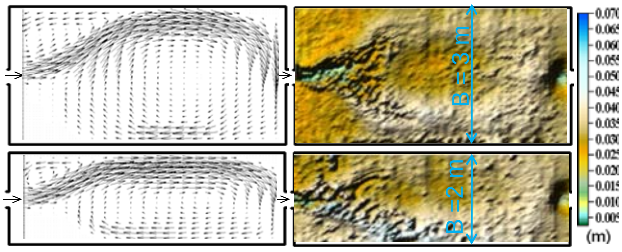

Fig.6 Flow patterns, (left) and evolution of deposition, (right) for reservoir width (a) B = 3.0 m, (b) B = 2 m, at 4.5 hrs

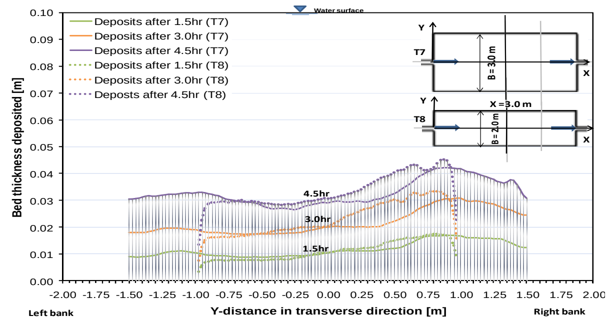

Fig.7 Bed thickness evolution of the reduced widths of B = 3.0, 2.0 m at 1.5, 3.0 and 4.5 hrs for cross section at X =3.0 m

rate is slightly increased by 0.005 m. Fig. 5 shows almost constant sediment deposits within the first hours for run 2, run 3, and run 4 but the deposits rate is increased for runs 4 and 5. It may be concluded that a stable morphology has been reached after 18.0 hours and almost morphological equilibrium in the basin has been reached for. Bed forms are almost uniform after 1.5 and 3.0 hours but 4.5 hr deposits show wavy bed forms (Fig.5). The bed thickness observed after 9.0 hrs is almost three times higher than for 4.5 hrs. Almost 50% of the basin volume was filled by the deposits after 18 hrs.

(2) Influence of the basin width

Flow patterns and associated bed depositions after 4.5 hrs for reduced width basins of 3 and 2 m, are shown in Fig. 6. The bed morphology for a reduced width of B = 3.0 m and 2.0 m have a uniform deposition rate over entire reservoir surface and symmetric ripple patterns as shown in Fig. 5. During the first hour of the tests, the observed flow pattern was deviated to the right side. But, after two hours the asymmetric jet was flipped from the right side to the left one as shown in Fig.6. The footprints of previous stages of the flow patterns are clearly visible in Fig. 6(a). As a result of the asymmetry flip flop from one side to the other, bed forms persisted throughout the alternately deflected jet. An asymmetric flow pattern has been observed for all reduced width basins. Hence, the reservoir width did not affect the asymmetric separation of the deflected jet. However, the size of the center and the upstream corner eddies were in accordance with the width.

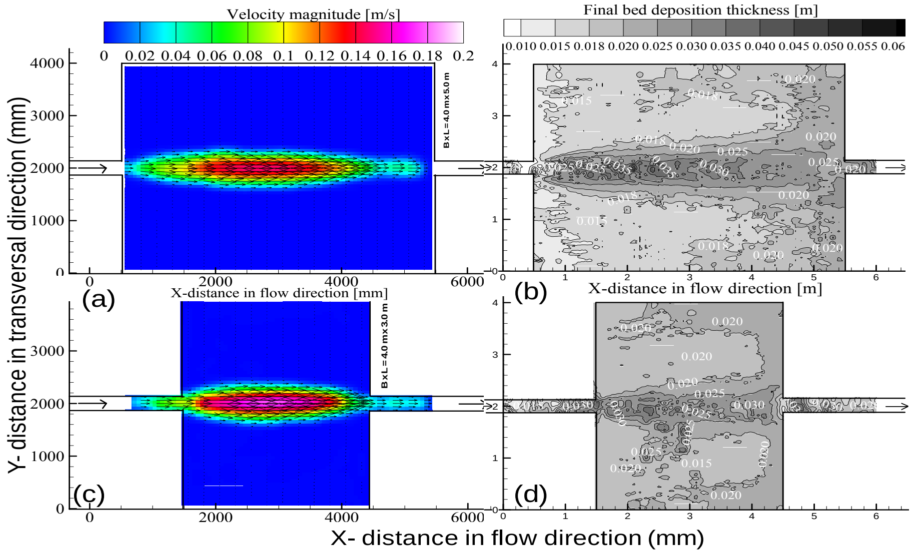

Fig.8 Flow pattern with vectors and sediment deposition at 4.5 hrs of the reduced basin lengths L (a, b) 5.0 m, (c, d) 3.0 m.

By reducing the reservoir width, the decelerating of the deviated jet is reduced. Final deposition patterns were affected by the reservoir width, with more symmetric and uniform distributions on the entire surface, and concentrated deposits on both sides. The evolution of bed at 1.5, 3.0, and 4.5 hrs at the middle cross section of X = 3.0 m, for the reduced widths of 3.0 and 2.0 m, are shown in Fig.7. The depositions are progressively increased in the downstream direction. The evolution process is increasingly fast with speed of 0.66 cm/hrs, for both widths. In fact, the velocity magnitude is increased by reducing reservoir width. As a result, a fairly deep scour hole develops in the bed profile near the inlet as shown in Fig. 7. Proceeding with time, this variation becomes slow due to the counteracting effect of the jet flow and the formation of a submerged channel under the centerline.

(3) Influence of the basin length

Influence of sediment transport

The average flow field and the corresponding bed morphology contours after 4.5 hrs for the reduced reservoir length are shown in Fig.8. In the first ten minutes for a reduced basin length with sediment entrainment, the flow is symmetric with one circulation cell on each side. The reduction of horizontal cells occurs with sediment transport. As sediment is added to the flow, the turbulence is reduced together with increasing roughness, which causes an increase in velocity gradient when compared to clear-water flow. The turbulence was generated locally by the horizontal entrainment of a mixture into the basin with stagnant water. The jet pulse created a region of 3D turbulent flow, characterized by mixing and entrainment. Then the size of the turbulence increased rapidly. During the subsequent stage of sediment settled down, the horizontal motions are suppressed and the mixed region becomes flat and the motion becomes quasi vertical.

Figs. 8(b, d) show a high sediment deposition in the center under the jet and low deposition near the walls under the reversed jet. In both the experiments ripples formed after about 3.0 hrs. By reducing the basin length the flow is stabilized with a stable symmetrical pattern. Four cells exist in the basin length L = 5 m[9]. The four gyres interact with the jet, which has some tendency to meander. By reducing the basin length for L = 4, the number of gyres remains constant and the flow pattern becomes rather symmetric with respect to the centerline[10]. The predominant change in the flow pattern is an evolution from a four cells flow to a distinct two cells flow. The length of the reservoir plays a critical role in determining the jet flow type and the associated bed deposition pattern. By reducing the reservoir length as shown in Figs. 8 (a, c) the flow is stabilized with a stable symmetrical pattern. Asymmetric and switching flow behavior continues towards the downstream end, where the jet is forced to pass through the outlet channel.

(4) Drawdown flushing

The experiments in drawdown flushing were started by opening the outlet gate and the water depth reached to 0.1 m in the basin of the initial water depth. Fig. 9 shows the flow structure and bed thickness contours after two days of flushing in the reduced basin width of 2.0 m. If the water surface can be draw down significantly the flow starts to erode a wide zone. At that stage, significant amounts of sediments deposits were flushed through

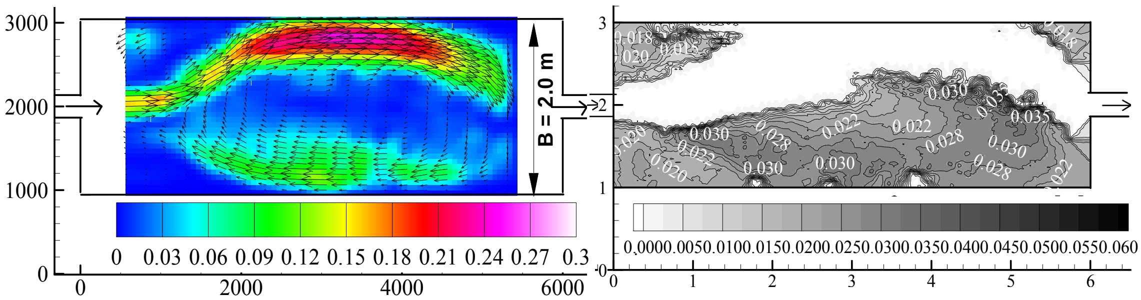

Fig.9 Flow field and contours after two days flushing with lowering basin level to 50% (Q = 7.0 *l/s* and h = 0.1m)

the basin, and the initial flushing channel deepened and widened as a result of the strong jet flow and erosion. The flushing channel is defined as self forming channel in the deposited material in the basin and that will be maintained by the flushing jet flow. Initially all deposited sediment resuspended with the high velocity jet. The flushing channel location was clearly visible by the re-suspended sediment, which was rapidly released during 30 minutes. This 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 the channel widening, the flushing channel continues to widen at a more gradual rate.

The larger basin volume will induce higher bed shear stress, and hence produces more effective removal of sediments on the bed. A significant amount of sediment deposits was flushed through the basin. To effectively apply the flushing processes for removing deposits, the location, depth, and width of the flushing channel can be changed by modifications of the geometry or installation of islands or a movable wall near the inlet jet. The channel attracts the jet and stabilizes the flow structures over the entire surface.

5. CONCLUSIONS

Although the geometry of a rectangular basin is symmetric, the flow pattern is asymmetric under certain conditions. The basin geometry influences the behavior of the large turbulence structures, and the flow is quite sensitive to the geometry shape. When suspended sediment is added to the turbulent flow over a plane bed the following was observed: (a) the large coherent structures disappear compared to clear water flow with similar flow properties and (b) depositions and flow structure remains asymmetric with reduced width of the reservoir and disappears when reducing the length of the reservoir. The findings can be used to define the optimal shape of the stilling.

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