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REMOVAL OF FINE NON-COHESIVE SEDIMENT BY SWIRL/VORTEX SETTLING BASIN AT SMALL RIVER ABSTRACTION WORKS

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A vortex settling basin (VSB) offers a promising alternative to conventional sediment settling structures, such as sand traps, for the removal of fine non-cohesive sediment for potable water use at small river abstraction works of less than 100 l/s pump capacity (7.2 Ml/d at 20 h/d). The hydraulic design of a suitable VSB was carried out by numerical CFD model. The design was optimized and validated against two physical VSB models: 0.48 m diameter and 0.7 m high, as well as 0.68 m diameter and 1.0 m high, in order to optimize the hydraulic design. The simulation results indicate that a design with the following characteristics works well: inlet velocity = 0.26 m/s, $\frac{position\ of\ inlet(H_i)}{cylinder\ height(H_t)} = 0.50 - 0.88$, $\frac{Underflow(Q_u)}{Inflow(Q_i)} = 0.05 - 0.10$, $\frac{Cylinder\ height\ (H_t)}{cylinder\ diameter\ (D)} > 0.5$, $\frac{Cylinder\ diameter(D)}{Inlet\ diameter\ (D_i)} = 8.2$ and deflectors. It was also established that sediment size and concentration, play important roles in controlling the sediment trapping efficiency. The cone angle and the angle of the inlet effects are minimal. Two VSBs designs for removal of 75µm sediment particles at maximum inflow sediment concentration of 10,000 mg/l are proposed: (a) inflow of 5 l/s with 5% water loss at a 99% trap efficiency and (b) inflow of 10 l/s with 8% water loss at 91% trap efficiency.

KEY WORDS: Vortex Settling Basin; Swirl separator; Sediment removal; Settling; River abstraction

1. INTRODUCTION

A Vortex settling basin (VSB) is a cylindrical fluidic device with a conical base where sediment-laden flow enters tangentially to the flow domain, utilizing gravity and weak centrifugal forces, more concentrated flow (underflow) exits at the bottom outlet and clear water as overflow (Chrysostomou, 1983; Paul et al. 1991). VSB's have small footprints, no moving parts, no chemical dosing, high sediment removal rates and continuous flushing of sediment back to the river, which makes them attractive for selection (Mashauri, 1986). VSB's have been applied widely in grit removal in wastewater treatment and stormwater systems for the removal of coarse sediments, but have not often been implemented at river abstraction works (Andoh and Saul, 2003; Field and O'Connor, 1996). It is the objective of this study to give a better understanding of VSB separation mechanism for the removal of non-cohesive sediment particles in the order of >75 µm for utilization in small river

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abstraction works for African rivers. Numerical modelling was utilized to design and test various VSB layouts and validation was undertaken on two physical models.

2. PHYSICAL MODELLING

Figure 1 shows a schematic of the physical model used in this study with the range of model parameters summarised in Table 1. The inflow was supplied from an overhead tank regulated by a valve and monitored at a flow meter with all the flow recycled back to the tank to have a closed system. For each run, the flow was injected in the VSB domain and allowed to stabilise and sediment particles were injected into the stream at a constant rate to achieve a predetermined concentration. Both overflow and underflow particles were captured on a filter, oven dried, the mass determined and the trapping efficiency calculated as follows:

$$\eta_{\text{trap}} = \frac{sediment\ mass\ of size \geq\ x\ \ in\ underflow}{mass\ of\ inflow\ sediment}$$

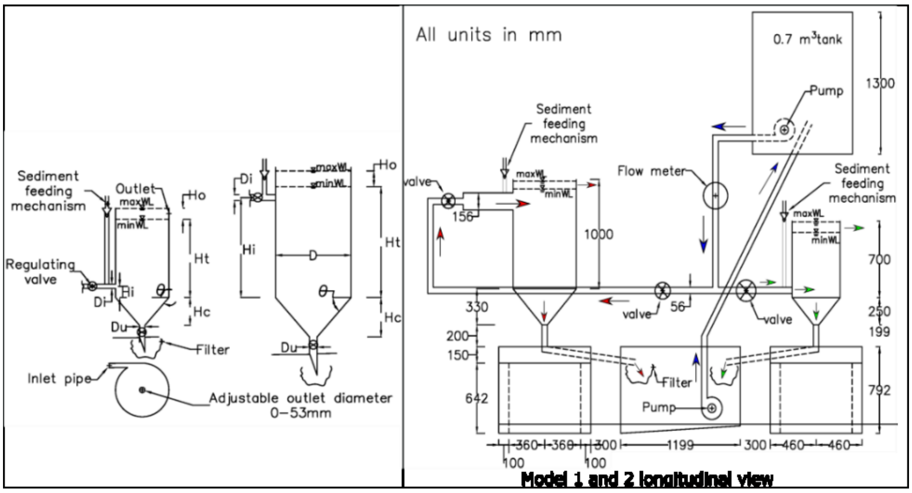

Figure 1. Schematic diagram of the vortex settling basin

Table 1

Vortex settling basin dimensions

Parameter	Symbol and unit	Model 1	Model 2
Inlet flow	Qi (l/s)	1-3	3-5
Cone height	Hc (mm)	250-1570	330
Cylinder diameter	D (mm)	480-1500	634
Cylinder height	Ht (mm)	240-1530	700-1000
Inlet diameter	Di (mm)	30-100	90-156
Inlet height	Hi (mm)	11.5-525	11.5-800
Outlet height	Ho (mm)	80	80
Inflow sediment concentration	C (mg/l)	10,000-50,000	10,000-50,000
Sediment particle diameter	d50 (μm)	75-112	75-112
Underflow diameter	Du (mm)	0-53	0-53

3. NUMERICAL MODELLING

Modelling of the VSB was undertaken with commercial CFD software FLUENT ANSYS version19.1. The structured mesh was used with in-compressible continuity, momentum and energy Navier-Stokes equations, discretized by Finite Volume Method. Flow in the VSB domain is of moderate turbulent nature and ANSYS, (2013) have recommended the use of realizable k- ε turbulence model but Griffiths and Boysan, (1996); Cullivan et al., (2004) noted the results can have a deviation of 12% with the physical model. Slack et al., (2000); Gimbun et al., (2005) recommended the use of Reynolds Stress Model (RSM) models which was adopted for this study with standard wall function. To simulate fluid-particle interaction, Volume of Fluid (VOF) simulated the interaction between air-water phases and Discrete Phase Model (DPM) between water-sand particles as by volume the particle fraction were less than 12% (ANSYS, 2003). To investigate the effects of concentration Euler granular model was utilized allowing full interaction between all phases. Grid sensitivity analysis was conducted and validated by corresponding physical model ensuring grid independent results.

4. RESULTS AND DISCUSSION

4.1 INFLUENCE OF UNDERFLOW

From literature, no apparent trend could be observed from data undertaken by previous studies as shown in Figure 2a. Curi et al. (1979); Mashauri, (1986); Paul, (1988) underflow(Qu)/inflow(Qi) ratios were between 4% to 16%. This was investigated on model 1 summarized in Table 1 with only the underflow being varied. Figure 2b summarizes physical and numerical model results with different sediment particles: 75 μm, 100 μm and d_{50} = 112 μm. Having a ratio greater than 10% leads to air core formation decreasing trapping efficiency thus a ratio 5% to 10% is recommended as to achieve maximum trapping efficiency with minimum water loss.

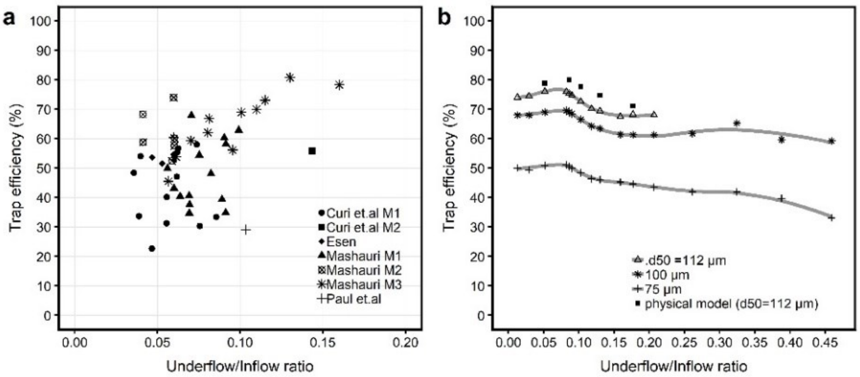

Figure 2. Influence of underflow on sediment trapping efficiency: a) investigation by various authors b) model 1 numerical and physical model results

4.2 INFLUENCE OF INLET VELOCITY AND FLOW

Richardson et al. (2002) and Veerapen, (2003) established VSB is mainly gravity driven and weak centrifugal forces aid in keeping the sediment particles in suspension near the wall. Having high inlet velocities increase the centrifugal forces and secondary currents which are detrimental to removal efficiency. This was investigated by varying the model 1 inflow and the influence of velocity and inflow was investigated for d_{50}=112 µm, 100 µm and 75 µm sediment particles. The numerical and physical model trap efficiencies results are shown in Figure 3. Flow velocity and inflow are directly proportional and an inflow velocity of 0.26 m/s is recommended. A dip in efficiency was experienced at a velocity of 0.20 m/s and it is due to destructive secondary currents/turbulence.

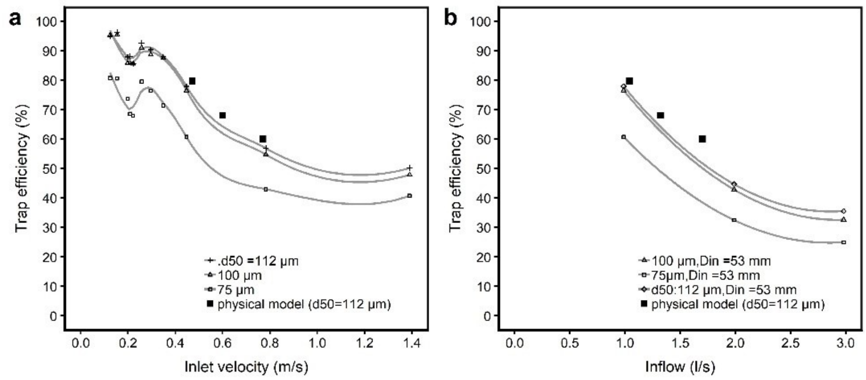

Figure 3. Simulated numerical and physical model impact of a) inlet velocity b) inflow on sediment trappingefficiency

4.3 INFLUENCE OF INLET POSITION

This was investigated by varying the position of the inlet location relative to the cylinder height while maintaining the Table 1 parameters constant. The resulting model 1 and 2 numerical and physical model results are shown in Figure 4. Trapping efficiency increased with the inlet closer to the outlet with a ratio of 0.50 to 0.88 recommended. This increase is counterintuitive and was experienced due to a higher percentage of secondary currents moving towards the underflow at the inlet location.

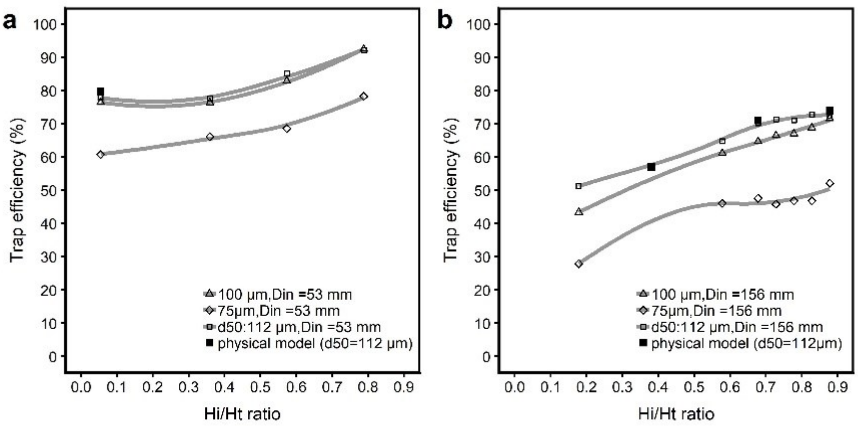

Figure 4. Numerical and physical model impact of inlet position relative to cylinder height on sediment trapping efficiency: a) model 1 b) model 2

4.4 INFLUENCE OF CYLINDER DIAMETER

Larger diameters of the VSB yield higher trapping efficiency however under a specific inflow rate and inlet velocity, there exists a specific small diameter where the system will act like a hydro cyclone or a large diameter where the system behaves like a sand trap. This was investigated and Figure 5 shows the influence of cylinder diameter on trap efficiency and residence time. It was concluded a ratio greater than 8.2 does not significantly increase the residence time and this ratio is thus recommended for removal of fine particles.

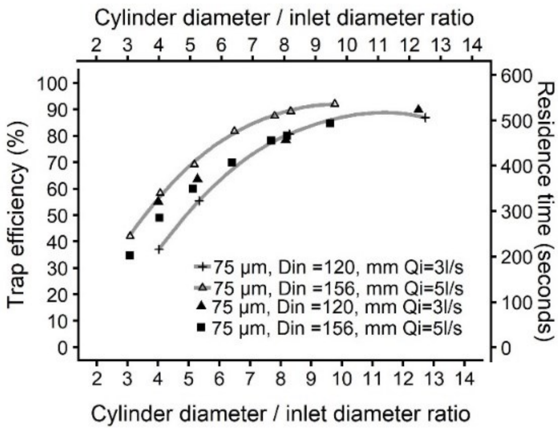

Figure 5. Influence of cylinder diameter/inlet diameter on sediment removal efficiency and residence time

4.5 INFLUENCE OF CYLINDER HEIGHT

Sullivan et al. (1974) and Chrysostomou, (1983) recommended Ht/D > 0.26 for removal of coarse sediment. This was investigated for fine sediment and concluded the influence of cylinder height is minor with a ratio Ht/D = 0.5 recommended.

4.6 INFLUENCE OF CONE AND INLET ANGLE

Due to the cohesive nature of washload in African rivers, a cone needs to be provided to avoid clogging of the underflow. In the design of hoppers, a cone of 2:1 (V: H) has extensively been used to ensure sustainability and is recommended. Varying the inlet angle has no significant influence on the trapping efficiency and thus a tangential inlet is recommended

4.7 PROPOSED LAYOUT

With the recommended parameters numerical model supervised optimization was undertaken to yield the final model configuration shown in

. Performance evaluation was undertaken over varying sediment sizes, underflows, inflow and sediment loading and to remove 75µm sediment particles at maximum inflow sediment concentration of 10,000 mg/l two models are proposed: (a) inflow of 5 l/s with 5% water loss at a 99% trap efficiency and (b) inflow of 10 l/s with 8% water loss at 91% trap efficiency.

5. CONCLUSIONS

The numerical and physical model research presented here has given a better understanding of the removal of fine sediment particles by VSB. The core findings can be summarized as follows:

- Gravity is the main driving removal mechanism assisted by weak centrifugal forces.
- Particles smaller than 75 µm cannot be effectively removed by a VSB due to long hydraulic retention time required for gravity-driven mechanism.
- An inlet velocity of 0.26 m/s should be maintained to provide adequate centrifugal forces.
- The Qu/Qi= 0.05-0.10 gives maximum trapping efficiency with minimal water loss.
- Having tall cylinders does not necessarily improve the trapping efficiency and a ratio of Ht/D>0.5 is recommended
- VSB's with large cylinder diameters will behave like settlers and small cylinders as Hydro cyclones operating under low pressure. A ratio of D/Di =8.2 is optimum for fine sediment removal
- The inlet should be placed closer to the outlet with a ratio Hi/H= 0.50-0.88 recommended. At this critical zone, strong secondary currents flowing towards the underflow assist in the removal of sediment particles.

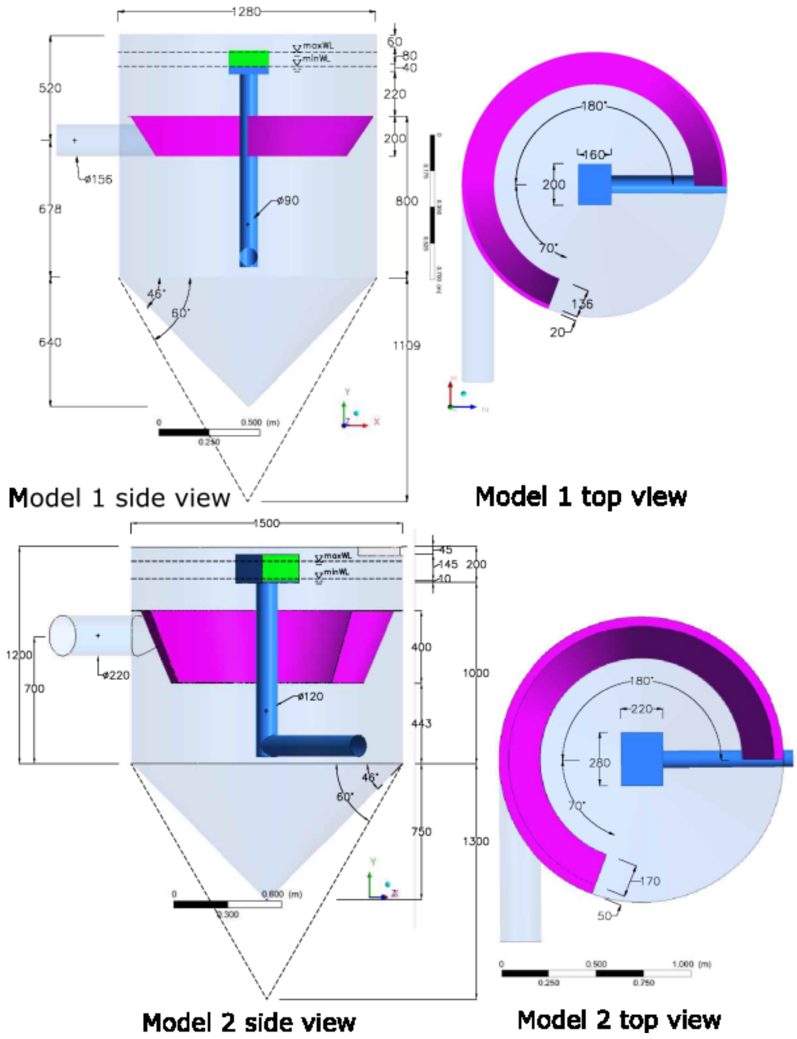

Figure 6. Proposed model dimensions

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