Optimisation of sand trap and settler designs for efficient deposition of suspended sediment

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Introduction
What is a settler and sand trap?

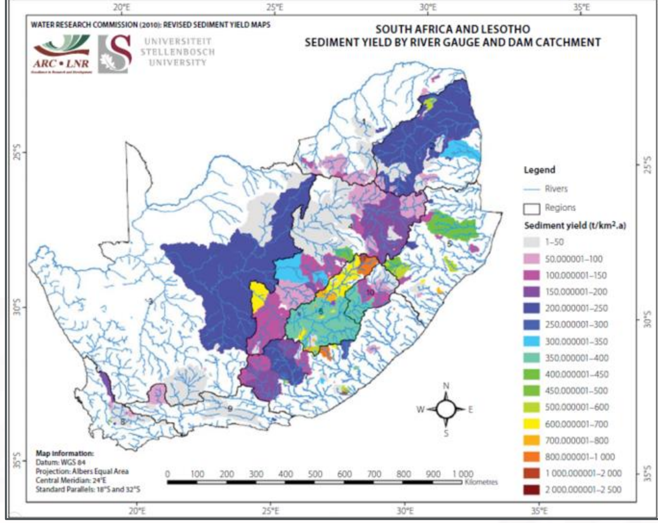
- Large concrete canal type sediment traps
- Used at river abstraction/diversion works - control of sediment loads
    - potable
    - irrigation
    - hydropower usage
- Performance judged: capability to sufficiently deposit suspended sediment particles and its flushing capability of bed load sediment
- The design properties that determine its hydraulic efficiency:
    - depth of flow
    - total length
    - cross-section
    - slope
    - inlet position

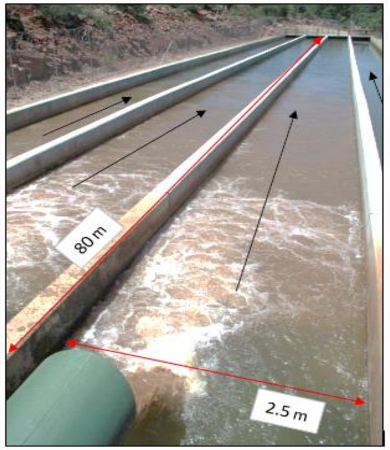
Introduction
Why does the designs need to be optimized?

Need for Hydraulic design guidelines for sand traps and settlers:

- Insufficient design guidelines available in South Africa
- contribute towards alleviation of sedimentation problems experienced by large intakes on rivers
- safeguarding essential infrastructure, including pumps, pipelines, and turbines utilised in hydropower plants
- combat sediment deposition in d/s conveyance systems, enhancing reliability of water supply for potable, irrigation & hydropower purposes

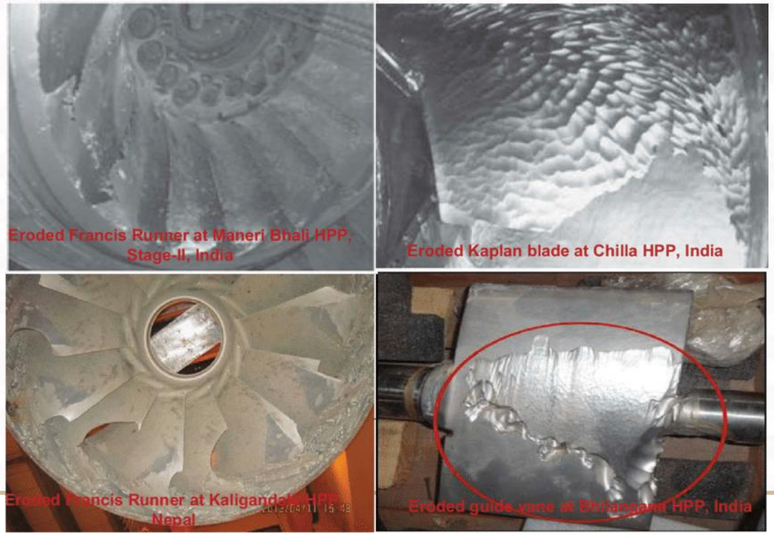
High sediment yield in SA rivers





Too much turbulence = insufficient settling length

Abrasion to turbines due to sediment



Fails to flush sediment = insufficient design

Main Objective 1

Conduct research and formulate hydraulic design guidelines for sand traps and settlers

→ Numerical investigations on design aspects:

- structural design parameters: dimensions, slope, cross-section type, intake types and sediment intake concentrations

- different inlet designs: assess impact on velocity & turbulence distribution

→ Evaluation of existing sand trap and settler performance:

- Conduct field measurements: analysis of sediment deposition patterns, and velocity assessments, sediment sampling
- Numerical simulations to identify potential areas for design enhancements aimed at improving trap efficiency

Main Objective 2

Investigate the Split-and-Settle sand trap concept proposed by Støle in 1993 through physical model experiments

&

develop a calibrated numerical model for the Split-and-Settle sand trap that can be used to explore further design modifications.

- Physical model experiments:
  - Performed to investigate concept of "split-and-settle" approach
  - Measurements of velocity & Suspended Sediment concentration around split-plate collected for further calibration and validation in numerical model
- Numerical model calibration and validation:
  - Existing 3D model was used & further calibrated to fit experimental data of 1 test condition of Split-and-Settle sand trap model
  - Calibrated numerical model validated by comparing model-generated results with experimental data obtained from other test conditions in physical model study
- Additional refinement of split-plate design and placement by numerical modelling
  - aim to visually investigate distribution of flow velocity and SSC in order to enhance efficiency and performance

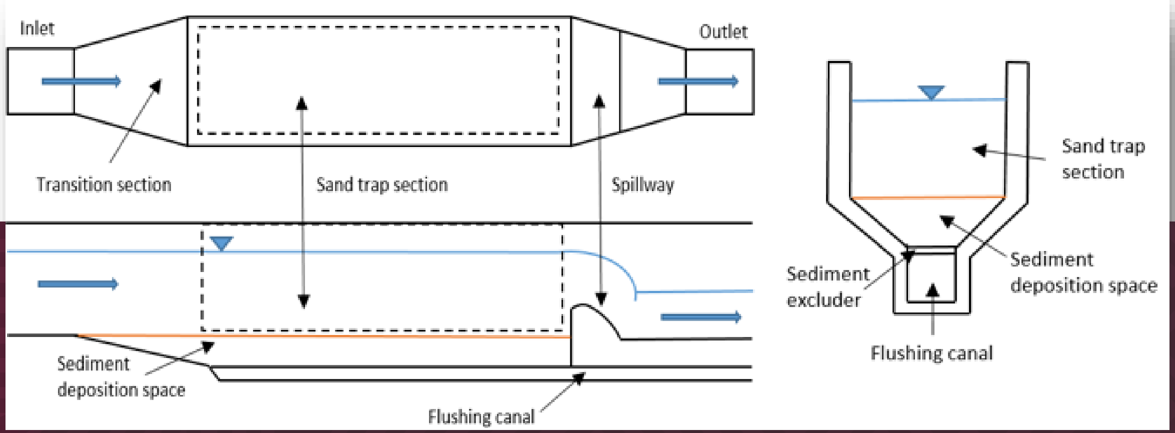
Settlers vs Sand Traps

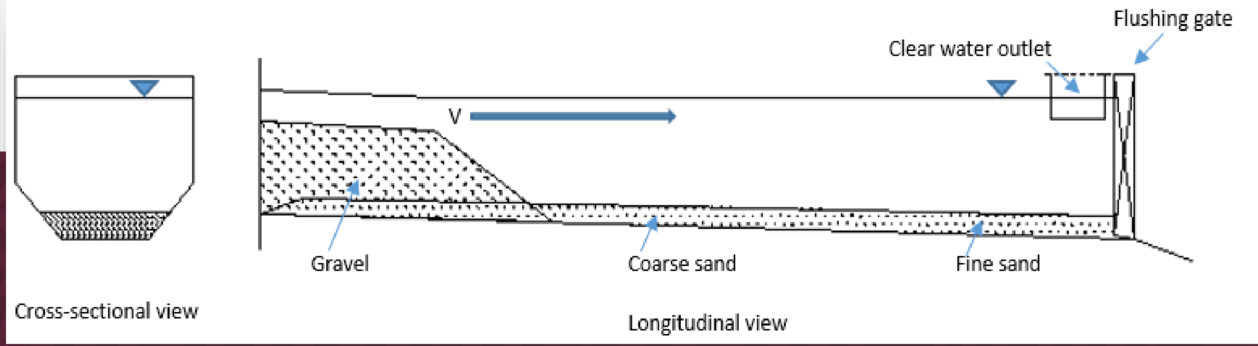
Long concrete structures used to deposit suspended sediment load entering via river abstraction/diversion works & removed by gravitational flushing

2 canal type sediment traps investigated: sand-traps & settlers

Main differences = Design, operating conditions & flushing method

Sand traps	Settlers
• **Operating velocities: 0.3 - 0.5 m/s (Q > 15 m³/s)**	• **Operating velocities: 0.1 - 0.2 m/s (Q: 4 to 5 m³/s)**
• rectangular cross-section for the settling zone & trapezoidal lower section for the scouring system	• Consist of a rectangular or trapezoidal cross-section
• Sediment removal efficiency --> based on the flushing system designed	• Sediment removal efficiency is based on the slope
• **Continuous downstream flushing system or distributed scour outlet system**	• **Flushing takes placed intermittently at a downstream controlled gate**
• Up to 20% of the water abstracted is used for continuous flushing	• No water is wasted in between flushing periods
• More prone to clogging of the distributed scour outlets	• Less likely to clogging of the outlet
• Able to deal with a set amount of sediment load	• Able to deal with significant variations in sediment load
• **Typically designed to remove particles ≥ 0.3 mm**	• **Designed to remove particles ≥ 0.1 mm, but can remove some silt as well if the trap is long enough**
• More complex design due to scouring system	• Simpler design as it is a straight canal with no scouring system
• Generally larger than settlers, especially in terms of the width	• Generally smaller than sand-traps



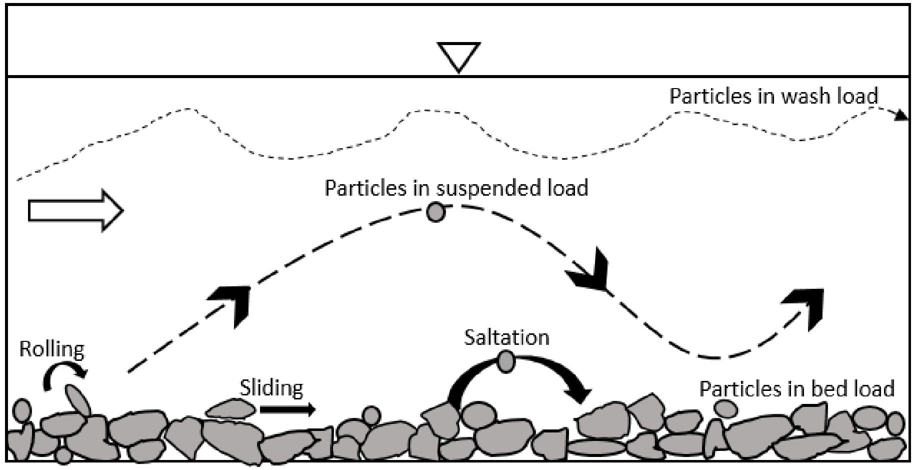


Overview of sediment properties and transport

How does sediment deposit in settlers and sand traps?

Need to understand:

1. Flow dynamics - Open channel flow
2. Sediment transport - Suspended sediment transport

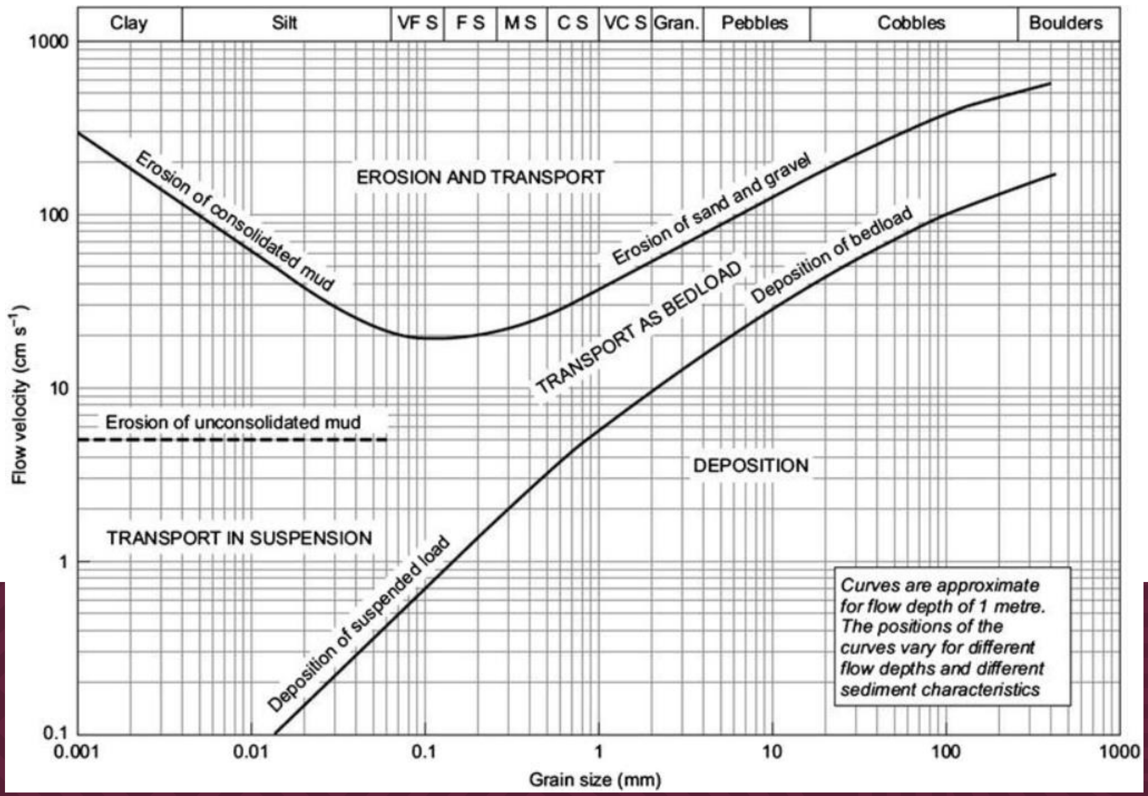


Sediment transport in a Nutshell:

- hydraulics of trap: water depth, velocity…
- Sediment characteristics
- Suspended load transport, deposit, erosion, bedload transport

… many other factors involved!!

Bed shear stress, stream power, particle Reynolds number, critical shear velocity, critical flow velocity,



Overview of sediment properties and transport

Suspended Sediment transport

Van Rijn (1993) stated: initiation of sediment suspension could be approximated once the value of the bed shear velocity becomes comparable to the particle's settling velocity.
To determine shear velocity and local bed shear stress, proposed to use the wall function:

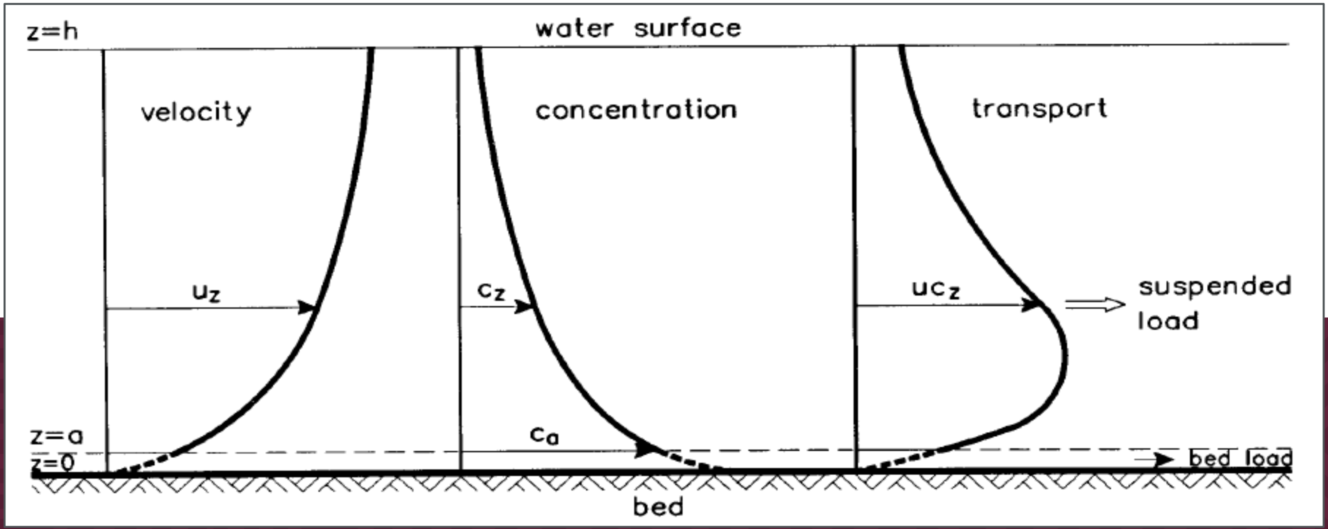
Suspended sediment transport will occur $u_{*,cr} > w$

$$\frac{v}{u_*} = \frac{1}{\kappa} ln\left(\frac{z}{z_0}\right),$$

Where u_* shear velocity, κ is Von Karman's constant, z is height above bed and z_0 is reference level near bed = $k_s/30$.

$$u_* = \sqrt{\frac{gRS}{n}} \qquad \tau_0 = \rho u_*^2.$$

Fully developed flow velocity profile



particle's settling velocity (w)

Particle diameter	Author of formula
$d \leq 0.1$ mm	Stokes' law for spherical particles
0.1 mm $< d <$ 1.0 mm	Zanke (1977)
$d \geq$ 1.0 mm	Van Rijn (1987)

$$w = \frac{1}{18v}\left(\frac{\rho_s}{\rho} - 1\right) gd^2$$

$$w = \frac{10v}{d}\left[\left(1 + 0.01D_*^{\,3}\right)^{0.5} - 1\right]$$

$$w = C_D\left(\left(\frac{\rho_s}{\rho} - 1\right) gd\right)^{0.5}$$

Suspended sediment concentration decreases with distance from bed at a rate dependent on the ratio of the settling velocity and bed-shear velocity.

Depth-integrated suspended load transport = integration of velocity x concentration from edge of bed layer to water surface:

$$q_{s,c} = \int_a^h vc\, dz$$

where $q_{s,c}$ is the volumetric suspended load transport (in m2/s), v is the velocity of the fluid at height z above the bed (in m/s), c is the sediment concentration at height z above bed (in kg/m3) and h is the water depth (in meters).

The suspended load transport also = as the product of mean volumetric concentration and flow discharge per unit width as:

$$q_{s,c} = c_{mean}\, q.$$

The mean concentration is approximately the same as the depth-averaged concentration for fine sediments

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Overview of sediment properties and transport

Suspended Sediment concentration

Steady & uniform turbulent flow: sediment concentration distribution over water depth described ito diffusion model.
Diffusion model: vertical sediment transport by turbulence is proportional to vertical concentration gradient with a proportionality coefficient, known as the diffusion coefficient

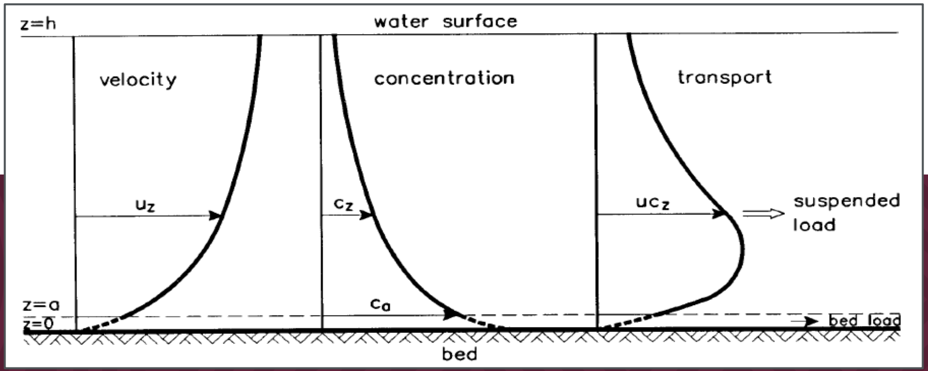
Convection-diffusion equation $$cw + \varepsilon_s \frac{dc}{dz} = 0,$$

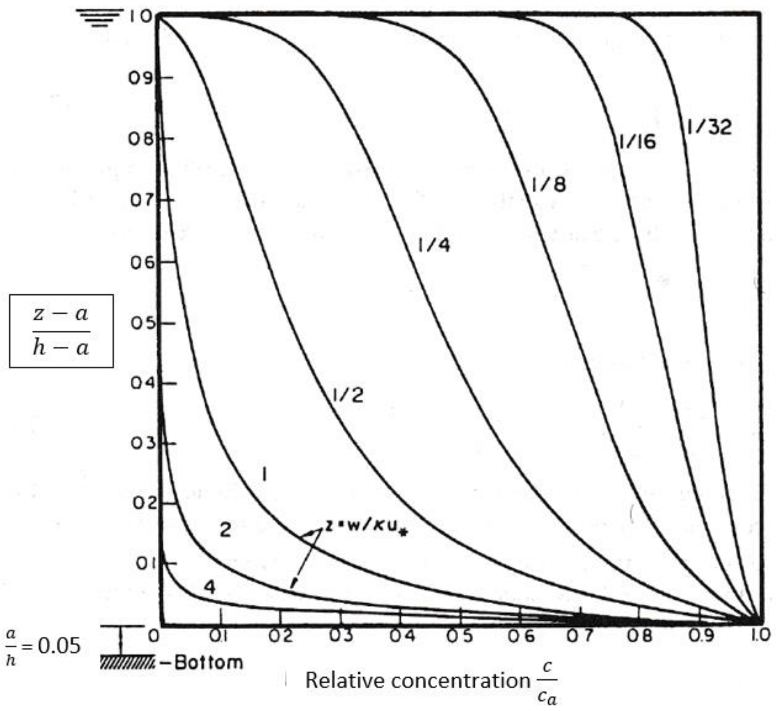
Where c is sediment concentration, ε_s is diffusion coefficient of sediment particles at height z above bed

Rouse (1936) proposed expression sediment concentration profile for low concentrations by integrating convection-diffusion equation:

$$\frac{c}{c_a} = \left(\frac{a(h-z)}{z\,(h-a)}\right)^Z, \qquad Z = \frac{w}{\beta\kappa\, u_*},$$

Z is Rouse number and β – factor is difference in diffusion of a fluid particle and a sediment particle and denotes the effect of stratification, u_* is shear velocity and w is particle settling velocity





Small Rouse number

- a uniform distribution of sediment throughout flow depth.
- Case for fine sediment with small settling velocity and given shear velocity

Large Rouse number:

- A considerable variation in concentration: for coarser sediment with higher settling velocity and same given shear velocity.

Numerical Modelling of suspended sediment in traps

Fully 3D coupled hydrodynamic and suspended sediment transport model - Developed by Sawadogo (2015)

Computational Fluid Dynamic (CFD) models: used to solve hydrodynamic & convection-diffusion equations to determine sediment transport and settling in sand traps and settlers

ANSYS Fluent: CFD simulation software uses:

- Finite Volume Method to model fluid flow in complex geometries
- User Defined Function (UDF) to modify material properties & boundary conditions through inputting customized code

Sawadogo (2015) developed a coupled fully 3D hydrodynamic and suspended sediment transport model to be used for simulating suspended sediment transport

This model was validated for one net-deposition case (as what occurs in sand traps and settlers) with 2D data from experimental results of one study and by prescribing an inlet concentration and fully developed velocity profile at the inlet.

- Interest to: investigate if model could predict flow velocity & suspended sediment concentration distribution in 3D for two real-world scenarios.
- Model was further used for 2 case studies and compared to /validated with field measurements
- Model was used to numerically investigate design considerations of settlers
- Model was further calibrated & validated with experimental results for Split-and-Settler sand trap case

Numerical Modelling of suspended sediment in traps

Hydrodynamic modelling

Summary of fully three-dimensional coupled hydrodynamic and suspended sediment transport model (Developed by Sawadogo (2015))

Flow field in hydrodynamic model obtained by solving:

Reynolds-averaged Navier-Stokes equations

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial}{\partial x_j}\left[-\delta_{ij}\left(P + \frac{2}{3}k\right) + \upsilon_T \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right],$$

where U is component of local time-averaged flow velocities, P is dynamic pressure, k is turbulent kinetic energy, δij is the Kronecker delta function and υ_T is eddy viscosity

Turbulence model:

- Standard **k-epsilon (k -Ɛ) turbulence model** is used.
- Described by turbulent kinetic energy and rate of its dissipation (Ɛ)

$$\upsilon_T = C_\mu \frac{k}{\varepsilon^2},$$

where C_μ is turbulence model coefficient value = 0.09.

The distribution of k and ε are determined via model transport equations as:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{v_T}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + P_k - \varepsilon, \text{ and}$$

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{v_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\frac{\varepsilon}{k}\varepsilon, \text{ and}$$

$$P_k = \upsilon_T \frac{\partial U_j}{\partial x_i}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right),$$

where P_k is production of turbulent kinematic energy and $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k, and σ_ε are empirical constants.

Discretization: Finite Volume Method in ANSYS Fluent used to discretise equations

5 boundary conditions defined for hydrodynamic model:
- inlet-velocity
- pressure-outlet
- water surface: symmetry condition is applied at water surface as it includes zero gradients and zero fluxes perpendicular to boundary
- bed & flume walls: a wall boundary condition is used for bed and flume walls, parameters are set as defaults

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Numerical Modelling of suspended sediment in traps

Suspended sediment modelling

Summary of fully three-dimensional coupled hydrodynamic and suspended sediment transport model (Developed by Sawadogo (2015))

Suspended sediment concentration is determined by **solving convection-diffusion equation** in which particle settling velocity is introduced

Convection-Diffusion equation

$$\frac{\partial c}{\partial t} + U_j \frac{\partial c}{\partial x_j} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_T}{\sigma_C}\frac{\partial c}{\partial x_j}\right),$$

- $\frac{\partial c}{\partial t}$: Change in concentration in time
- $U_j \frac{\partial c}{\partial x_j}$: Convection of sediment: change in concentration over distance at certain velocity
- $w \frac{\partial c}{\partial z}$: Convection term: change in concentration over vertical distance at certain settling velocity
- $\frac{\partial}{\partial x_j}\left(\frac{\upsilon_T}{\sigma_C}\frac{\partial c}{\partial x_j}\right)$: Diffusion term: due to the mixing by turbulence in the water

The Schmidt number is calculated from settling velocity and shear velocity by:

$$\sigma_C = \frac{1}{1 + \left(\frac{2w}{u_*}\right)^2}$$

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Numerical Modelling of suspended sediment in traps

Suspended sediment modelling

Summary of fully three-dimensional coupled hydrodynamic and suspended sediment transport model (Developed by Sawadogo (2015))

To solve convection-diffusion equation: a **near-bed reference concentration** is needed

When sediment transport reaches equilibrium state: entrainment rate (e) = deposition rate (d_r)
Celik and Rodi (1988) developed equations for entrainment model for fixed bed with an upstream supply of sediment (used in transport model)

$e = wc_{bmax}$ for loose beds

$e = \min(wc_b, wc_{bmax})$ for fixed beds with an upstream sediment supply

For use of model in case of settlers and sand traps: net deposition on a fixed bed approach followed. For initial conditions: (C_{bmax}) = 0 & Ps = 1

Net-deposition rate to the bed within model defined as:

$$d_r - e = P_s w c_b,$$

where P_s is defined as settling probability that a particle reaching bed is deposited.

$P_s = 0$ for $c_b < c_{bmax}$,

$P_s = 1 - c_{bmax}/c_b$ for $c_b > c_{bmax}$

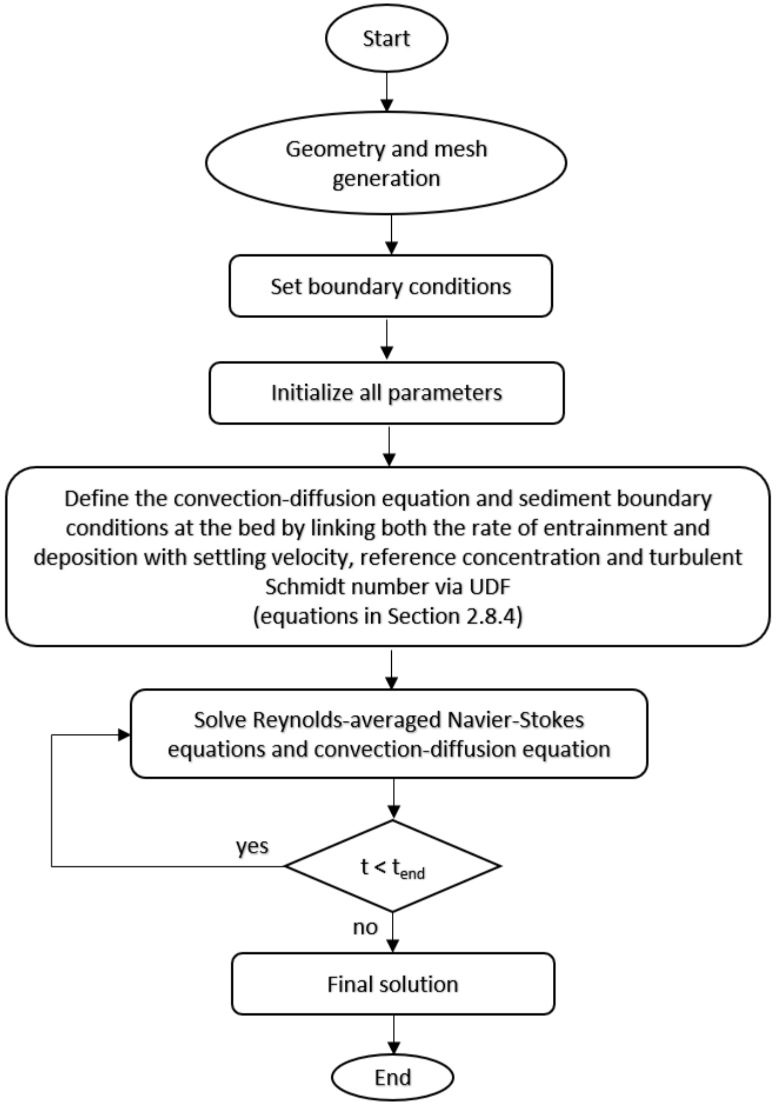
UDF in ANSYS fluent used to define sediment transport equation & sediment boundary conditions at bed

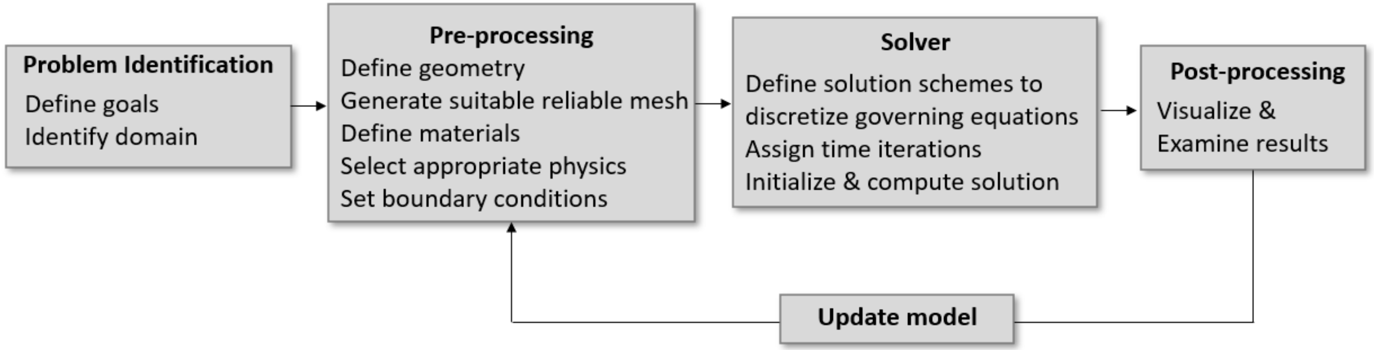
Model Susp sed / deposition:

- does not simulate alterations in bottom level resulting from sediment deposition
- dedicated to monitoring distribution of suspended sediment concentration throughout trap
- Sediment deposition is assumed based on reduction of sediment concentration in water depth and an increase in sediment concentration near bed or other areas within sediment traps.

In this approach, rather than default Fluent multi-phase model, solids transport is calculated as a passive scalar or volume of sediment concentration.

ANSYS Fluent - CFD modelling Procedure





Solving procedure: Different numerical schemes assigned to discretize governing equations including number of time steps & iterations to control convergence until accuracy is achieved

The default solution methods suggested by ANSYS Fluent were selected to ensure computational stability for transient pressure-based solver for incompressible flows:

- **SIMPLE scheme** for pressure-velocity coupling
- **1st Order Implicit transient scheme**
- **2nd Order Upwind spatial discretization schemes**

(estimates concentration at wall based on linear extrapolation from two elements upstream of the wall)

Main Objective 1

Conduct research and formulate hydraulic design guidelines for sand traps and settlers

→ Numerical investigations on design aspects:

- structural design parameters: dimensions, slope, cross-section type, intake types and sediment intake concentrations
- different inlet designs: assess their impact on velocity & turbulence distribution

→ Evaluation of existing sand trap and settler performance:

- Conduct field measurements: analysis of sediment deposition patterns, and velocity assessments, sediment sampling
- Numerical simulations to identify potential areas for design enhancements aimed at improving trap efficiency

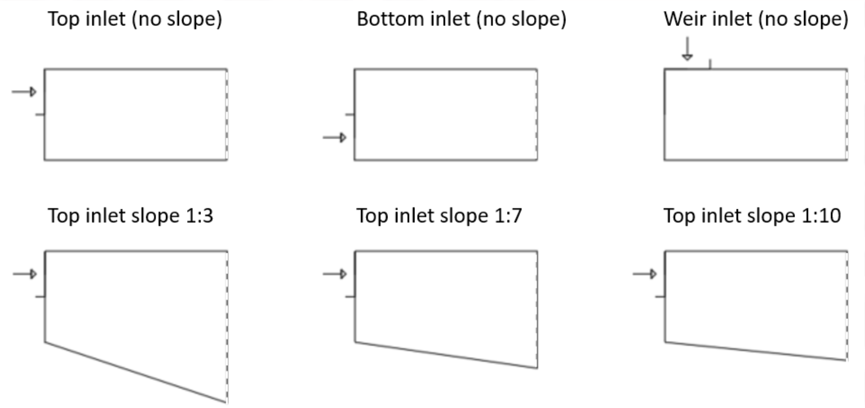
Numerical investigation of sensitivity of sediment trap design elements

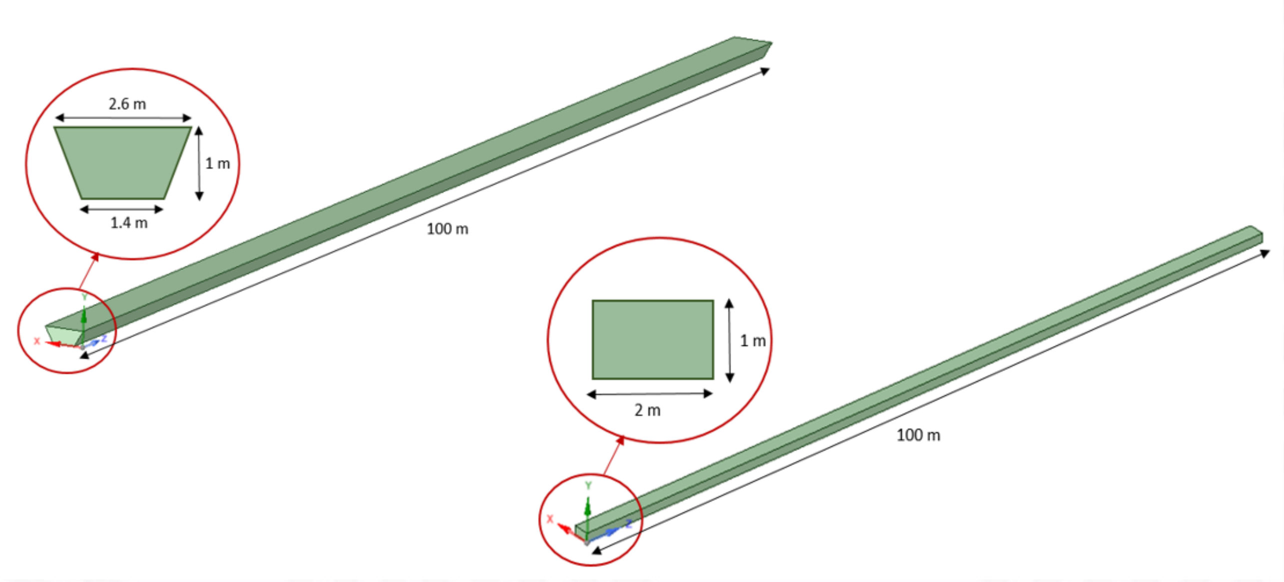
Investigated numerical settling length vs. Analytical settling length of sediment particles, velocity & sediment concentration distribution for:

- Cross-section type (Rectangular vs Trapezoidal)
- Influence of sediment intake concentration
- Influence of +3% and -3% slope on num. settling length
- Intake types - velocity and turbulence distribution

For sediment particles: 0.1 mm, 0.2 mm, 0.3 mm
For inlet flow velocities: 0.1 m/s, 0.2 m/s

- Cross-section
  - Rectangular
  - Trapezoidal
- Sediment diameter
  - 0.1 mm
  - 0.2 mm
  - 0.3 mm
- Inlet velocity
  - 0.1 m/s
  - 0.2 m/s
- Sediment concentration
  - 1000 mg/L
  - 10 000 mg/L
- Height of sediment entering
  - Whole depth on inlet
  - Top 1/3 of depth





Current Design elements of sediment traps

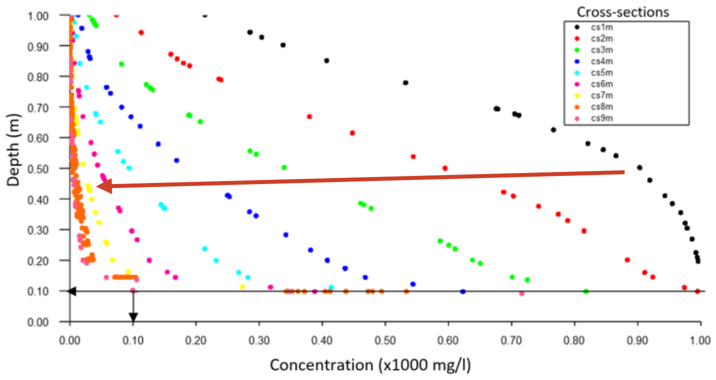
For settlers and sand traps:
Particles will be carried in suspension: when mean velocity in channel is higher than critical velocity $(v > v_{cr})$.
Particles tend to deposit: when critical velocity is higher than mean velocity $(v < v_{cr})$.

Bouvard (1992) recommended calculating v_{cr} ito sediment particle's w and R of channel as:

$$v_{cr} = 10\, w\, R^{\frac{1}{6}}.$$

v_{cr} defines transition between particles in suspension and settling.

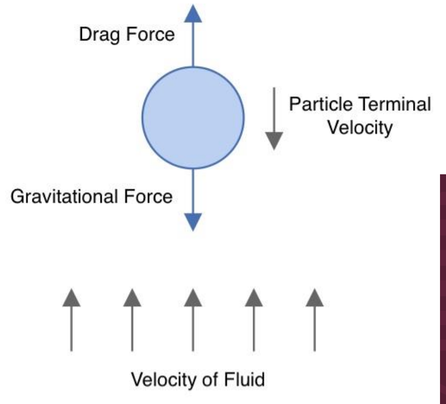
Settling of sediment particles



Analytical settling length: horizontal distance a sediment particle travels within trap as it settles
→ depends on height or water depth at which particle enters trap
→ velocity variations experienced in progress of settling

In designing a trap: consider whole length of trap to deposit all sediment down to a specific diameter or size

$$L\_analytical = \frac{vh}{w - u_*}, \qquad u_* = \frac{4.2v}{100R^{1/6}}.$$



Numerical Settling lengths

Rectangular vs. Trapezoidal

Results:

- Analytical vs. Numerical settling length:
  For d > 0.2 mm – 33% difference
  For d < 0.2 mm – 70% difference

Recommendations for calculating Total Length of settlers with no slope:

For d> 0.2 mm: Total Length = **1.5 L_analytical + 20%L_analytical** (turbulence effect depending intake type)
For d< 0.2 mm: Total Length = **3.3 L_analytical + 20%L_analytical** (turbulence effect depending intake type)

- Concentration inlet amount & position of inlet:

(1000 mg/L & 10 000 mg/L) Does not have an effect on the num. settling lengths

- Inlet velocity vs. numerical settling length:

Proportional Increases with increase in velocity (Lengths double from 0.1 m/s to 0.2 m/s)

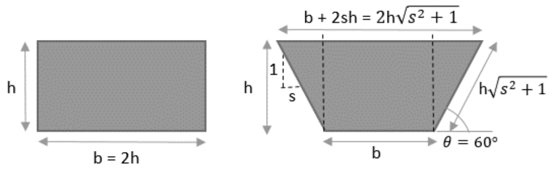
Rectangular Settler

			v = 0.1 m/s			v = 0.2 m/s		
Inlet height	Sediment diam.(d_{50})	(mm)	0.1	0.2	0.3	0.1	0.2	0.3
	Settling velocity (w)	(m/s)	0.009	0.026	0.044	0.009	0.026	0.044
	Analytical set. (L)	(m)	23.4	4.8	2.6	-	12.3	5.8
			Numerical settling lengths					
Whole depth	c = 1000 mg/L		75	7.4	3.8	-	*17	*8.5
	c = 10 000 mg/L		75	7.5	3.8	-	17	8.5
Top only	c = 1000 mg/L		75	7.4	3.8	-	17	8.5
	c = 10 000 mg/L		75	7.5	3.8	-	17	8.5

Trapezoidal Settler

			v = 0.1 m/s			v = 0.2 m/s		
Inlet height	Sediment diam.(d_{50})	(mm)	0.1	0.2	0.3	0.1	0.2	0.3
	Settling velocity (w)	(m/s)	0.009	0.026	0.044	0.009	0.026	0.044
	Analytical set. (L)	(m)	23.1	4.7	2.6	-	12.2	5.8
			Numerical settling lengths					
Whole depth	c = 1000 mg/L		80	8	4.2	-	*18	*9
	c = 10 000 mg/L		80	8	4.2	-	18	9
Top only	c = 1000 mg/L		80	8	4.2	-	18	9
	c = 10 000 mg/L		80	8	4.2	-	18	9

Cross-sectional designs
Rectangular vs. Trapezoidal



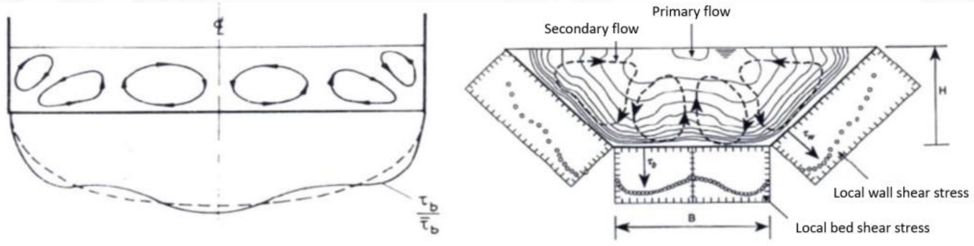
Rectangular

Trapezoidal

Results show distinctive sediment concentration patterns in rect. & trap. settlers

- **Concentration distribution:**
  - For rectangular CS: sediment tends to accumulate uniformly at centre
  - For trapezoidal CS: higher concentrations along its sloped sides and corners
- Reason: **Velocity distribution & boundary shear stress**
  - **Velocity distribution** within the CS' contributes to sediment concentration disparities
  - For trapezoidal CS: sediment concentration aligns with parabolic shape mirroring velocity distribution.
  - **boundary shear stress along the wetted perimeter**: shape of cross-section affects incipient deposition shear stress. Due to change in wall-normal component of g forces from which friction force stems
- Settling length (Rect. Vs Trap): occurs at different locations within the settler → difference are not significant (< 5 m)

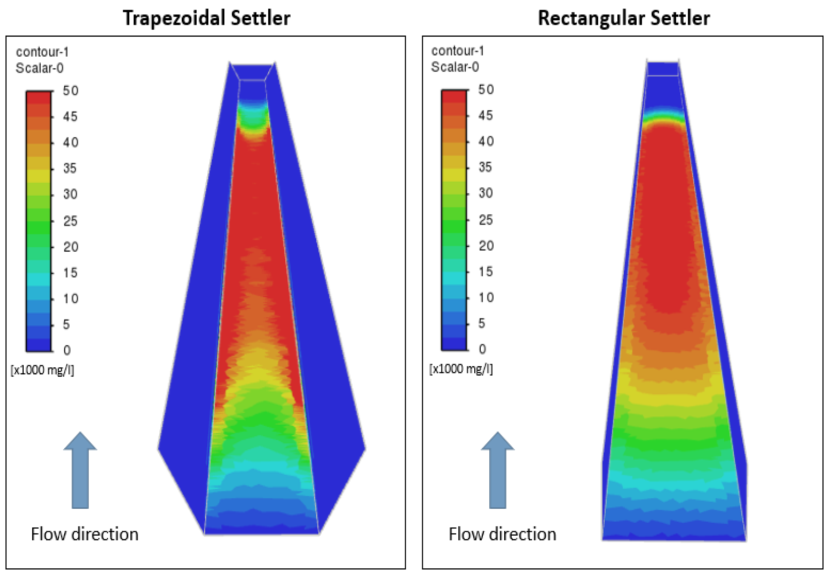
boundary shear stress along the wetted perimeter

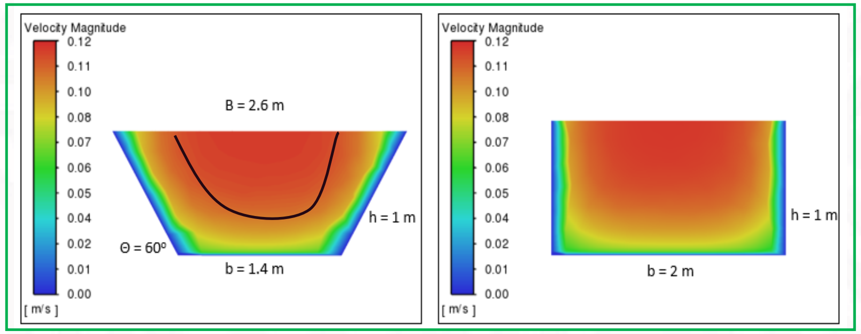


(a) Rectangular Cross-section (Knight et al., 1983)

(b) Trapezoidal Cross-section (Knight et al., 1994)

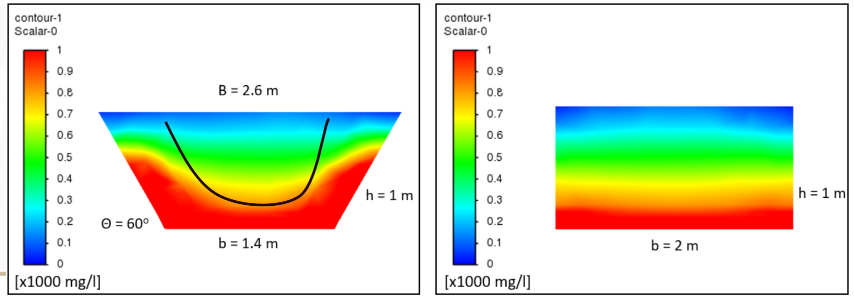
Concentration distribution





Velocity distribution

Concentration distribution



Cross-sectional designs

Slope vs. %3 positive slope vs. 3% negative slope

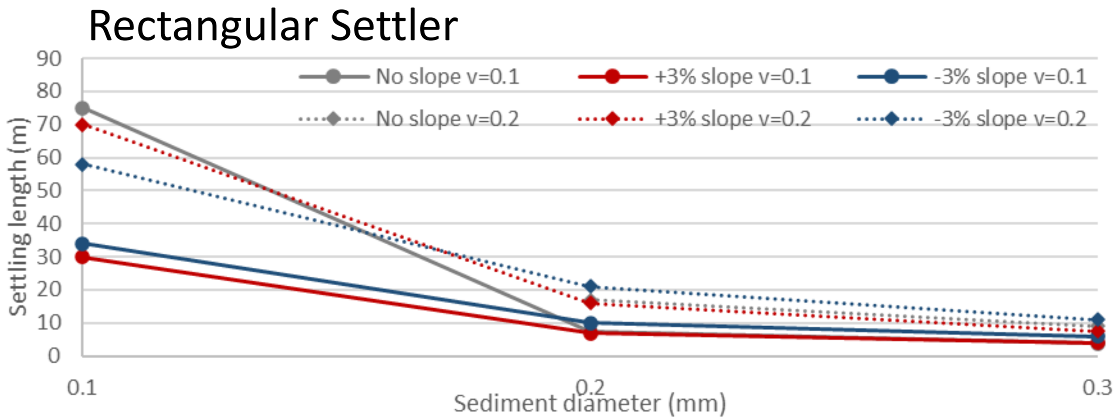
Results

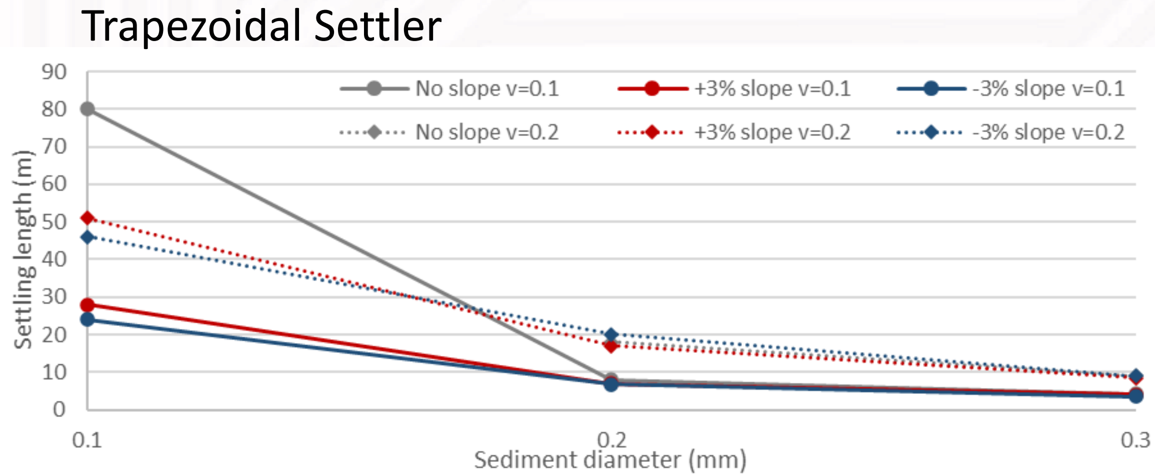
- **Slope in settler** → <u>reduces</u> settling lengths compared to no slope
  → changes in: vertical h, cross-sectional A, average v & bed shear stress

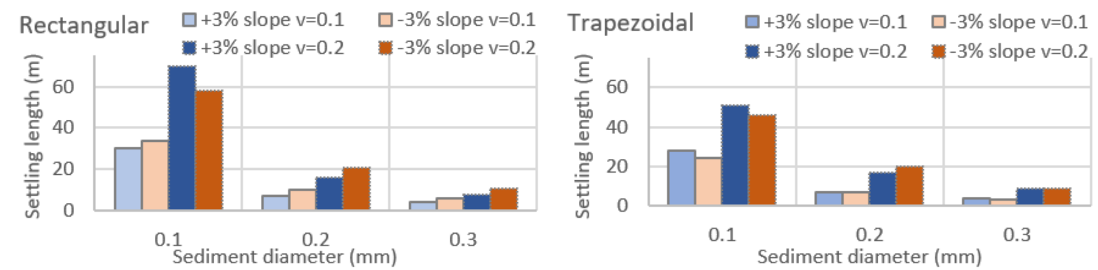
- **Positively sloped settlers:**
  - Increased: vertical fall h, cross-sectional A, and bed shear stress,
  - Decrease: average v decreases along settler length

- **Negatively sloped settlers:**
  - Decrease: vertical fall h, cross-sectional A, & bed shear stress
  - Increase: average v along length

- **Comparing positively and negatively sloped settlers:**
  - Trapezoidal sloped settler <u>shorter</u> than in Rectangular sloped settler for various sediment particle sizes and flow velocities.
  - Attributed: <u>difference in wetted perimeter</u> of settler cross-section + slope, which changes cross-sectional A and influence mean V
  - Mean velocity changes was the largest influence for the test conditions in this study.
  - (Vinlet and h in both cross-sections remained similar)







Inlet designs

Velocity & Turbulent Intensity distribution

Results

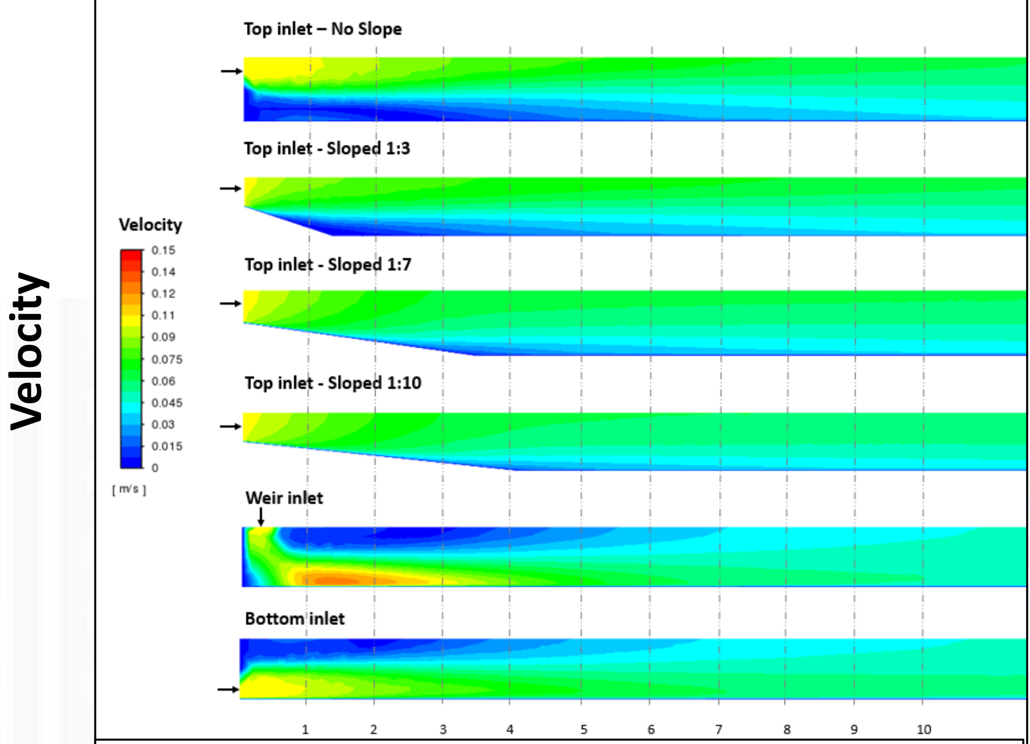
From the numerical investigation on the different types of inlets:

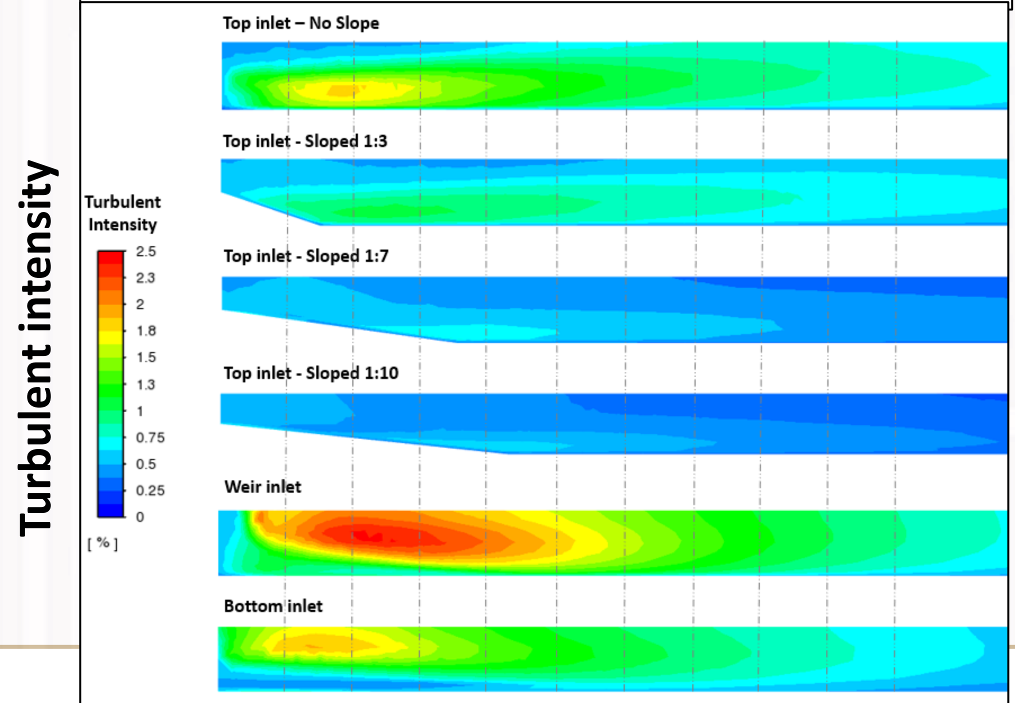
- **1:10 sloped** top inlet had most gradual change in V
    - where V at surface decreases in a shorter length
    - inlet caused least amount of turbulence at surface and bottom
- **Slopes:**
    - gentler slope at inlet leads to improved flow distribution & reduced turbulence compared to a steeper slope.
    - Of options considered, a sloped 1:10 inlet is recommended for settling a sediment particle of 0.2 mm with an inlet V of 0.1 m/s.
    - Gentler slopes (example 1:20) - could possibly be better based on results
- **A weir and bottom inlet:**
    - high V and turbulence at bottom
    - advantageous to use in sand traps with bottom outlet scour
    - not recommended for settler as high V and turbulence at inlet

        → leads to a longer inlet transition zone

        → could prevent sediment from settling

        → Must increase total length to compensate for longer turbulent inlet zones





Evaluation of hydraulic performance of 2 existing sediment traps

Field Investigations conducted to observe turbulence in traps & collect velocity and sediment samples

- ADCP → Measure flow velocities & depth of flow (sediment bed level in trap)
- Bed grab sampling → sieve analysis & hydrometer tests
- Suspended sediment sampling → concentration & Lazer scatter PSD

When conducting a field investigation, it is of utmost importance to calibrate equipment used in investigation, verify accuracy of results, taking into account accuracy of equipment


Bed - Grab bucket

TIENFONTEIN SETTLER

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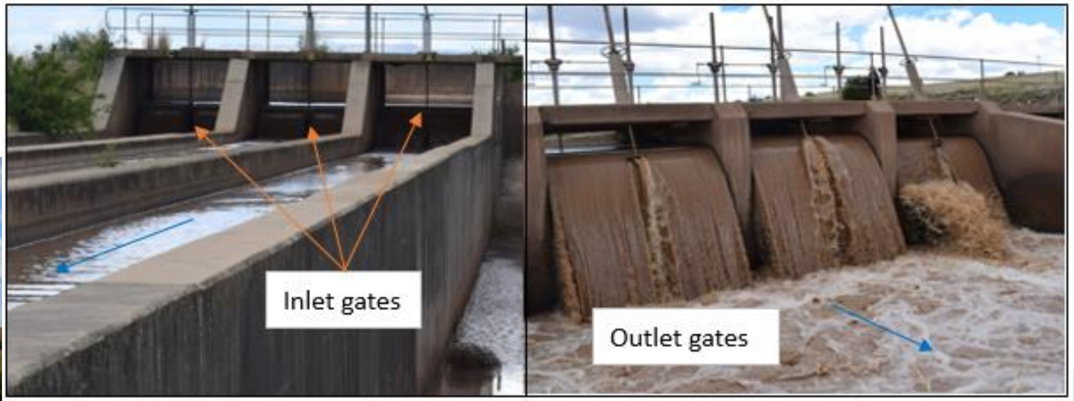
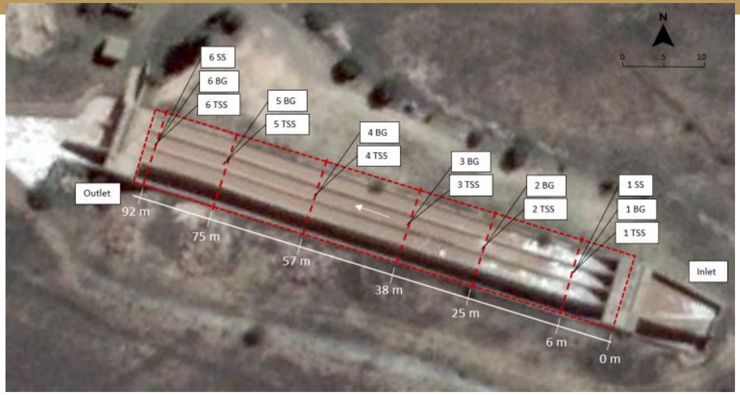
- 92 m long, 2.5 m wide, inlet h = 2.5 m; positive slope = 0.9%
- Designed to settle suspended particles > 0.3 mm
- Design flow of 0.6 m^3/s

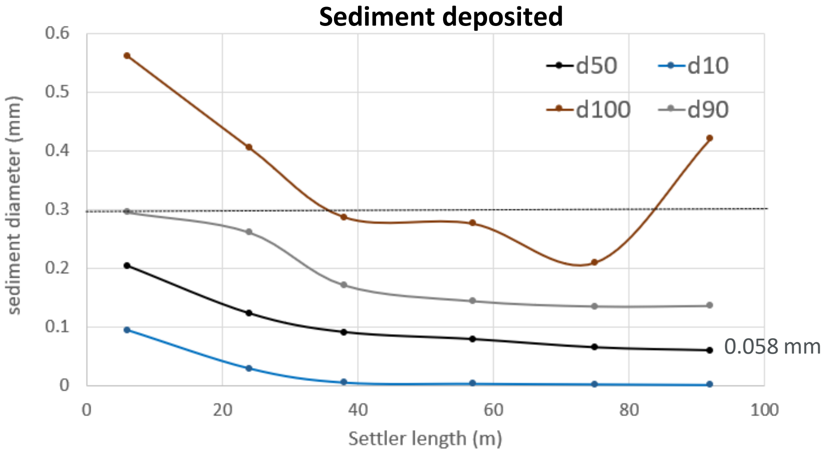


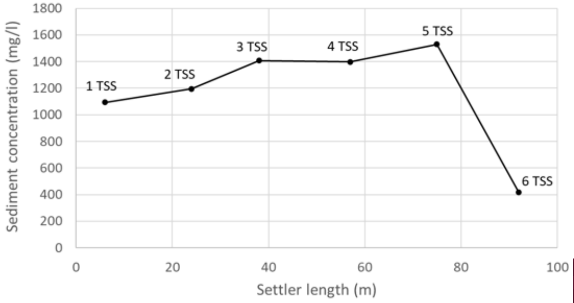
- inlet & outlet controlled by gates operated manually
- At inlet, water spills over gates acting as a weir
- Outlet gates are used to control water level within settler

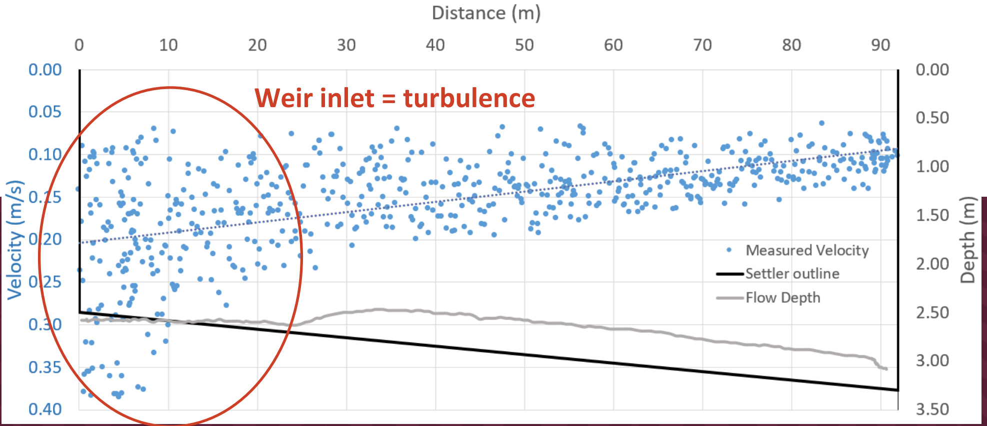
Field investigation results

- **Measured discharge:** 0.8 m^3/s (> design 0.6 m^3/s)
- **Sediment size removal:**
  - successfully deposits & removes sediment particles > 0.3 mm (as designed)
  - deposits sediment particles as fine as 0.058 mm near outlet
    can deposit → due to adequate length and low velocities measured near outlet
- **Sediment characteristics:**
  - samples' taken > 10% silt & clay (d < 0.075 mm)
  - Indicates sediments are cohesive
  - Risk: can compact if not frequently flushed
- **Flushing:**
  - flushed all sediments within 10 minutes:
  - Success due to positive slope of 0.9% + scour velocity due to draw-down flushing
- **Weir inlet:**
  - Caused high fluctuation in flow velocities at the inlet
  - Settler could benefit from sloped top inlet
  - to reduce turbulence at inlet
  - Due to adequate length, turbulent zone was compensated for.









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Numerical modelling

- assess velocity and sediment concentration distribution throughout the settler
- compared to the field measurement data

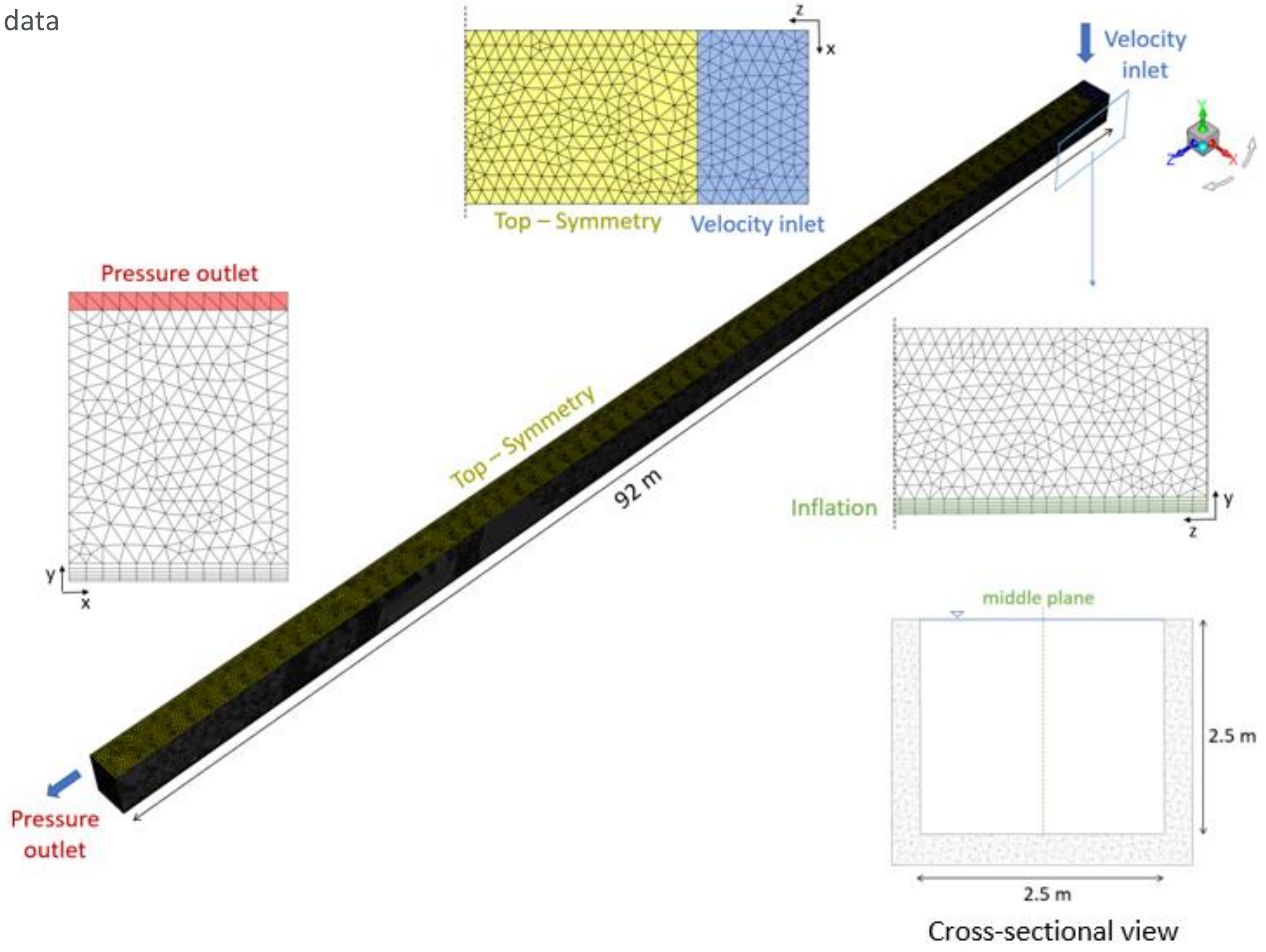
- 2 cases investigated:

As Measured during field investigation

- $Q = 0.8\ m^3/s$.
- Particle size = 0.058 mm, w = 0.003 m/s
- C_inlet = 1000 mg/L

As Designed - not discussed in PPT (time)

- $Q = 0.6\ m^3/s$
- Particle size = 0.3 mm, w = 0.044 m/s
- C_inlet = 1000 mg/L

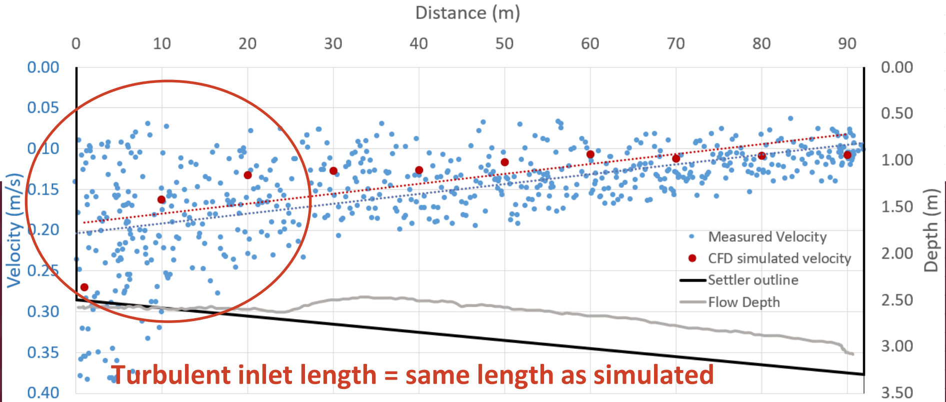


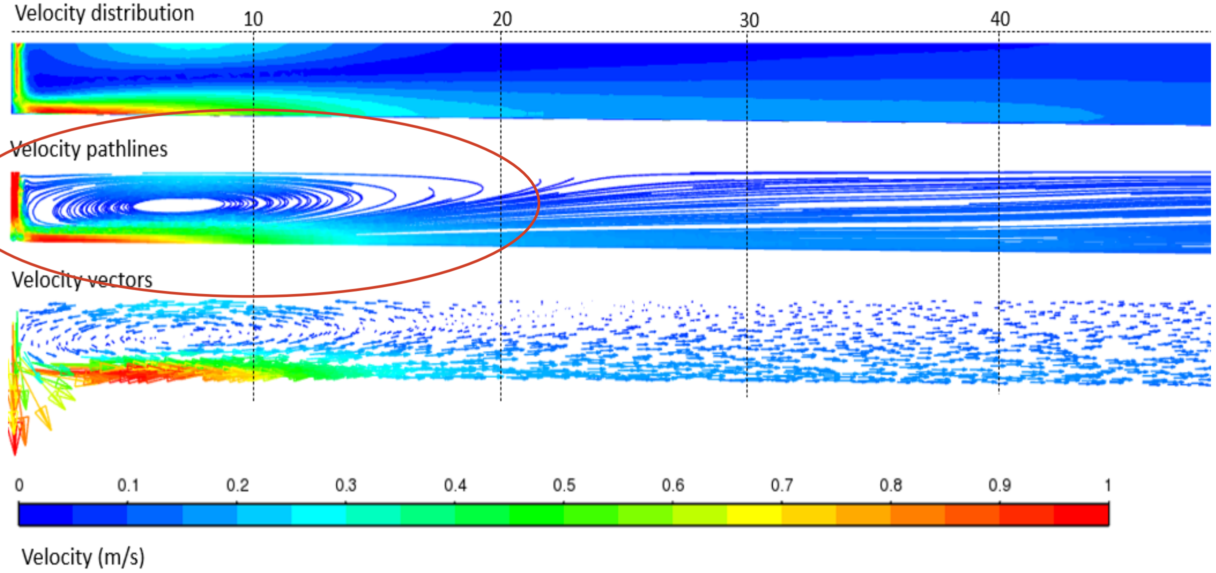
Numerical Modelling Results

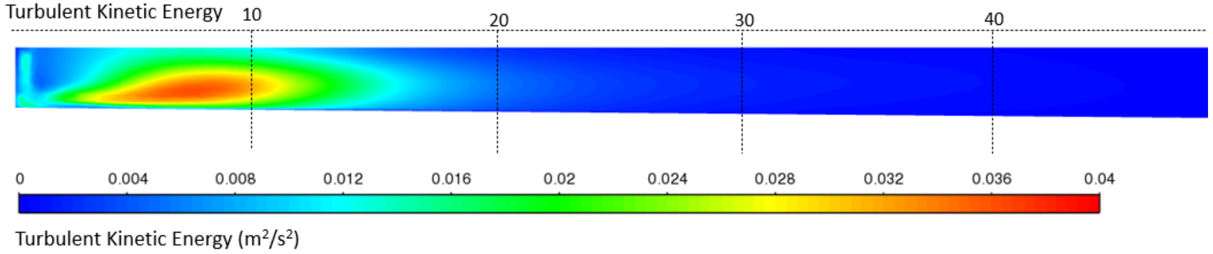
Numerical analysis based on the measured design discharge during fieldwork

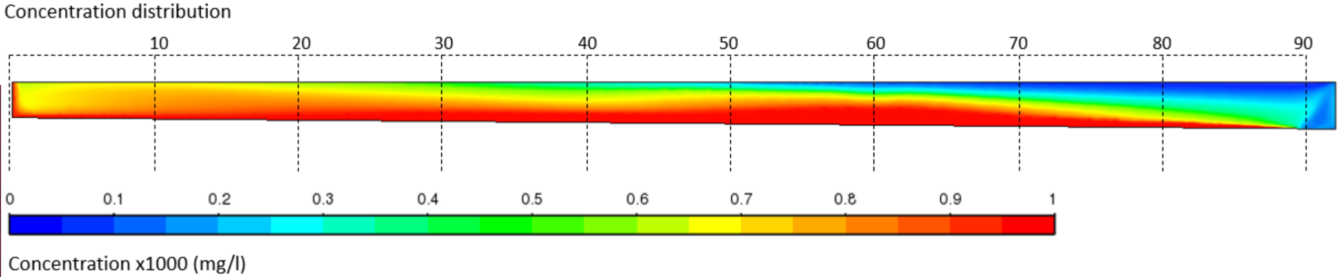
- **weir inlet:**
  - forces flow to base of canal, causing high turbulent zone
  - spiral flow within first 20 m of inlet
- **Velocity:**
  - mean flow velocities simulated slightly < measured velocities
  - follows same trend
  - measured field velocities are higher due to deposited sediment in settler
  - can also be due to boat's speed to which ADCP was attached being inconsistent
  - Spiral flow identified at inlet in numerical simulation → likely contributes to extensive variation observed in measured velocity data in field
- **Sediment deposition:**
  - Boundary of circulating current /spiral flow simulated in numerical model corresponds closely to length of inlet area, after which sediment deposition starts occurring as measured by ADCP in field.
  - Concentration distribution of 0.058 mm sediment decreases throughout length of canal, which indicates that particle deposits (from 60 – 90 m)
  - Most sediment particles deposit within settler at 90 m as with in field measurements

Conclusion: CFD model predicts flow velocities and settling length of 0.058 mm particle reasonably well, can be used for future simulations to predict sediment deposition of specific particle size.



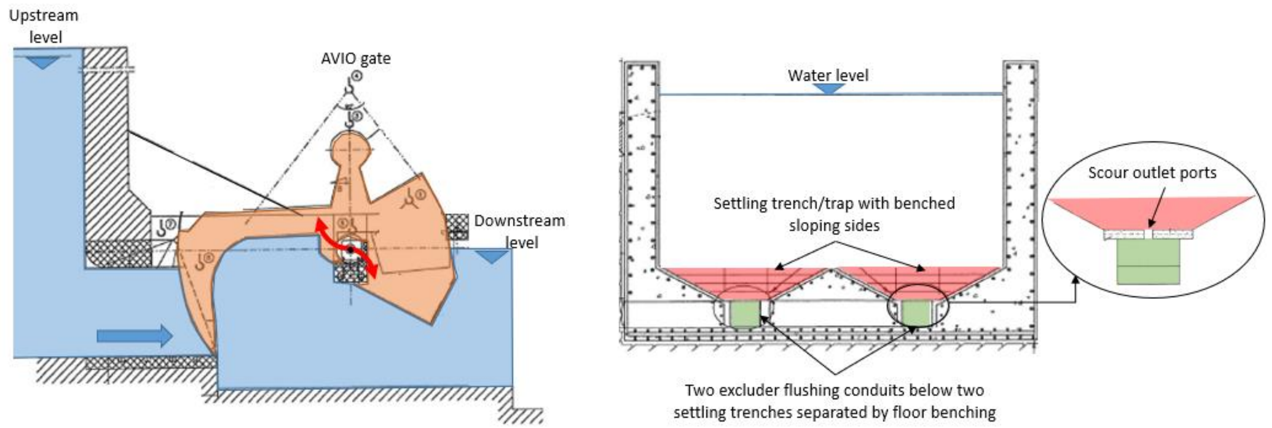






LUSIP SAND TRAP

- Design based on Dufour type 2 (Dufour, 1940)
- 65 m long, 8 m wide
- Designed to settle particles > 1 mm
- Max flow of 15.5 m^3/s
- Distributed scour outlet holes (d=100 mm) with sediment excluder canals (1:175 slope)
- Scour flow = 2 m^3/s



AVIO gate cross-section

Trap cross-section

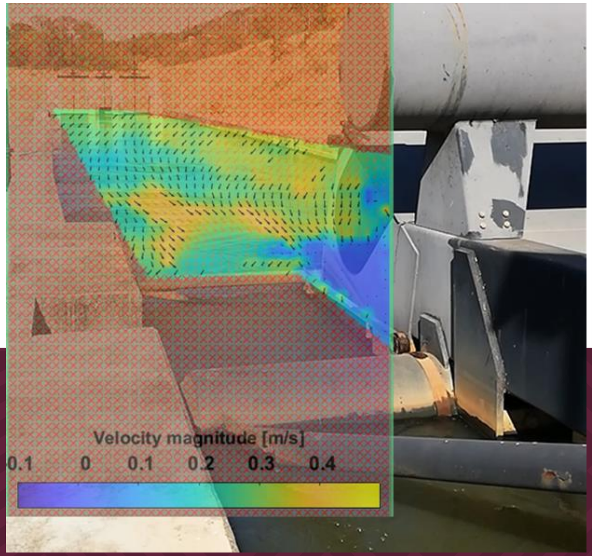
- Avio gate controls water level depending on inlet discharge
- Water flows under pressure into sand trap
- Outlet gates are used to control water level within settler

Field investigation results

- **Measured discharge:** 5 m³/s low flow conditions (< max design 15.5 m³/s)
- **Avio Gate at inlet:**
    - Causes a great deal of turbulence
    - Reverse flow back to inlet
    - Reduces effective settling length of trap from 35m to 30m
    - PIVlab used for processing video resulted in velocities of 0.3 – 0.5 m/s at surface around Avio gate
- **After drainage of trap:**
    - Inadequate flushing of sediment from trap
    - Sediment build-up in trap (approx. 2 m height)
    - Scour holes clogged by debris
    - Sediment flushing canal silted

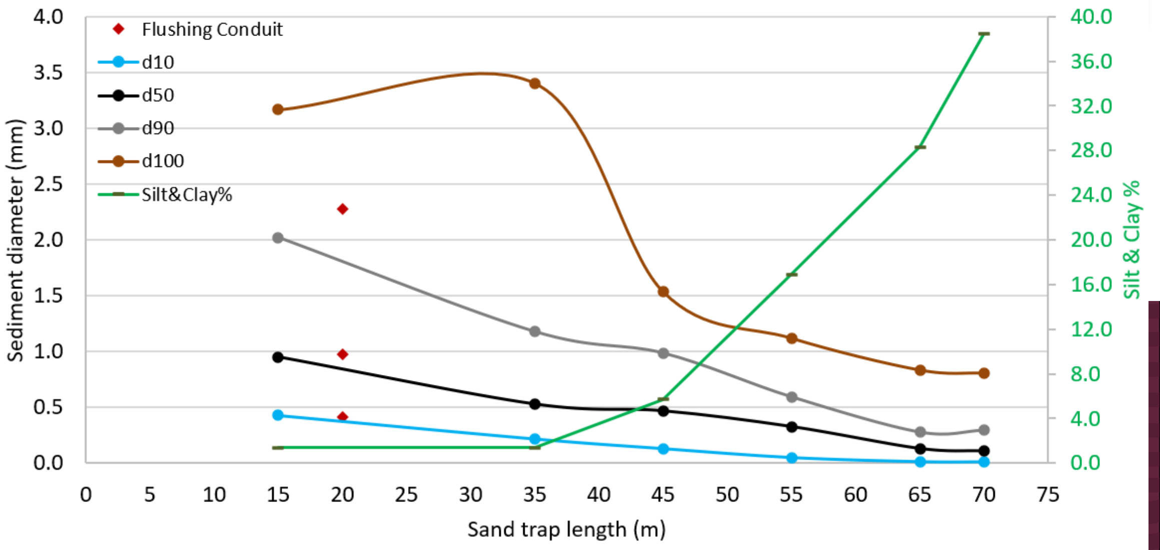






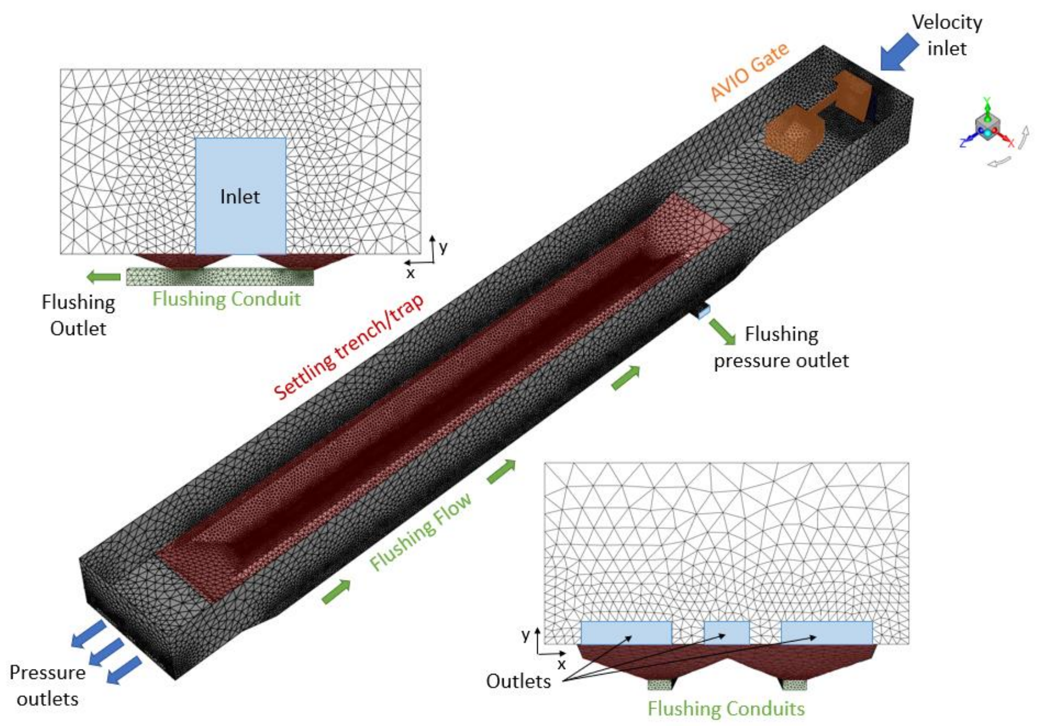
Field investigation results

- **Sediment size removal during low flow conditions:**
  - Successfully deposits sediment particles d100 =0.83 – 3.17 mm & d50 =0.32 – 0.95 mm in deposition area (for Q = 5 m^3/s, low flow conditions)
  - However, particles with a d100 = 0.8 mm found in d/s feeder canal outside trap during low flow conditions, which is close to the design limit of 1 mm for high flow conditions
  - BUT: struggles to flush sediment from trap's distributed scour holes
    - Scour holes clogged due to debris entering sand trap
    - Fine cohesive sediment (> 10% silt &clay at d/s side of trap) becomes consolidated and difficult to flush from clogged scour holes
  - **Inability to flush sediment from trap** causes a sediment build-up (even more significant in high flow season)
    - Reduces cross-sectional area,
    - increases velocity
    - impedes settling of sediment
    - causes resuspension of sediment which then escapes sand trap at d/s gates.
  - Also reported by operation manager that particles > 1 mm escapes trap in high flow season
    - sand trap experiences shutdown for manual cleaning
    - as often 2 x a month to prevent sediment particles coarser than 1 mm from escaping trap



Numerical modelling

- assess velocity and sediment concentration distribution throughout the settler
- compared to the field measurement data
- model used to investigate design modifications to improve performance/efficiency of sediment deposition and flushing



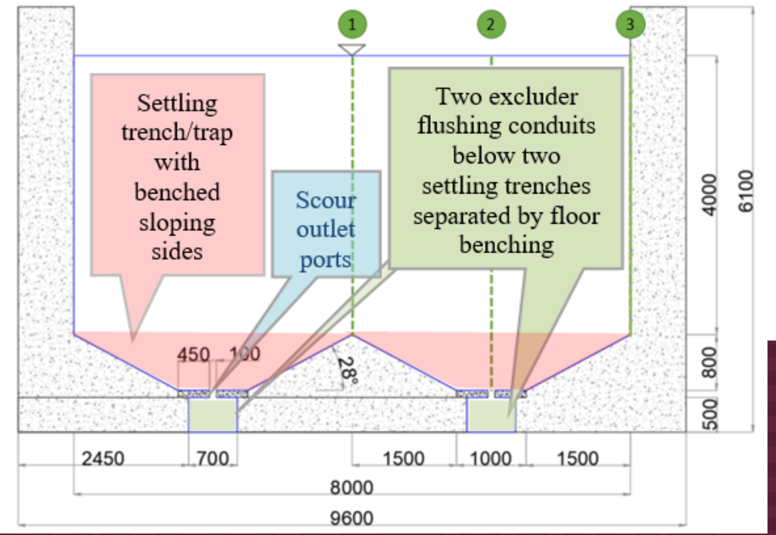
- 2 cases investigated + 1 improved design:

As Measured during field investigation

- Inflow Q = 5 m^3/s, scour flow Q = 2 m^3/s
- Particle size = 1 mm, w = 0.14 m/s
- C_inlet = 1000 mg/L

As Designed - not discussed in PPT (time)

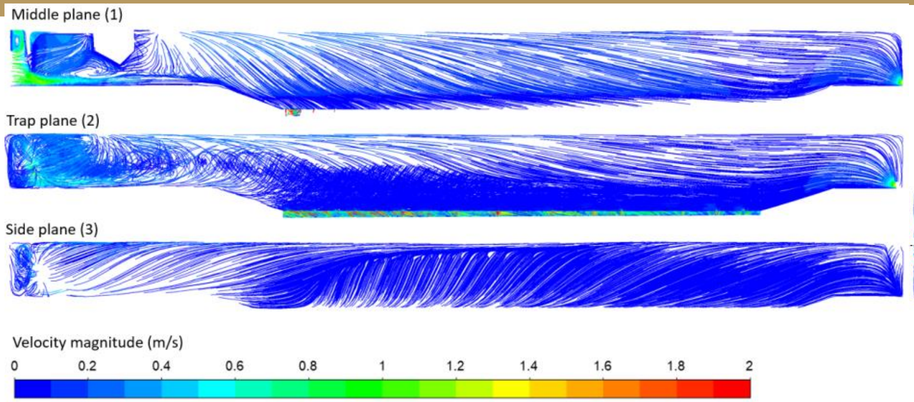
- Q = 15.5 m^3/s, scour flow Q = 2 m^3/s
- Particle size = 1 mm, w = 0.14 m/s
- C_inlet = 1000 mg/L

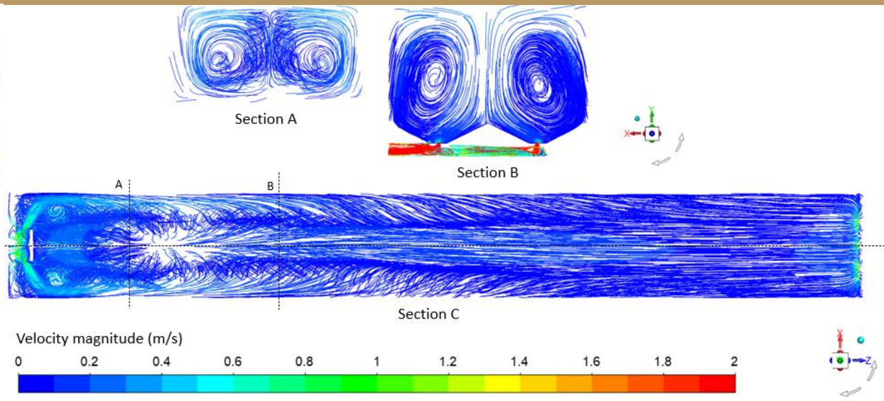


Numerical Modelling Results

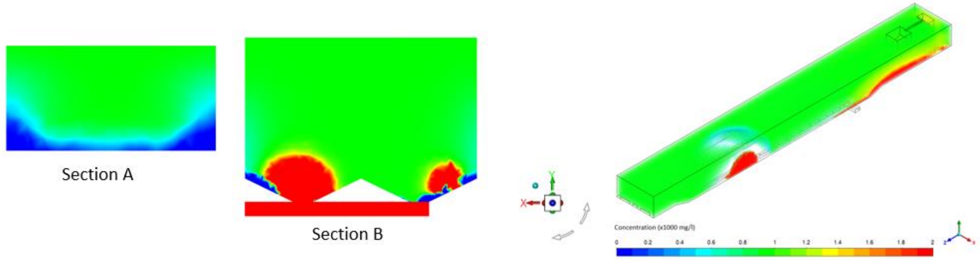
As Measured during field investigation

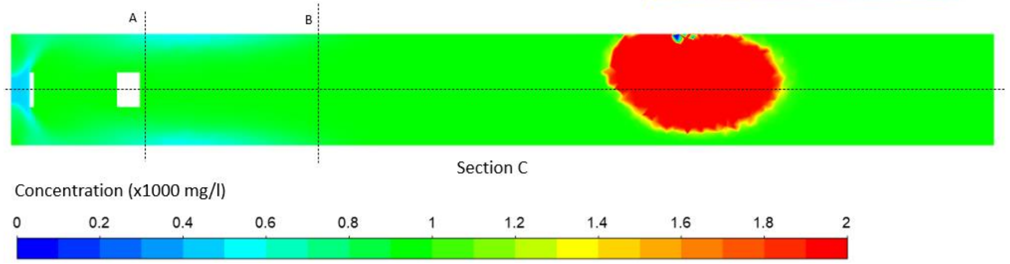
- Inflow Q = 5 m^3/s, scour flow Q = 2 m^3/s
- Particle size = 1 mm, w = 0.14 m/s
- C_inlet = 1000 mg/L



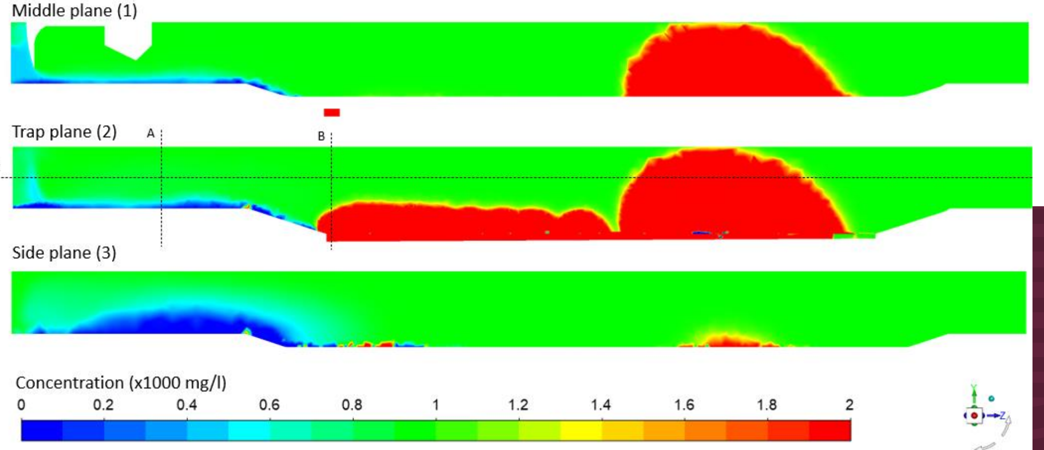


- **Velocity**
  - velocity around Avio gate is relatively high (at top varies from 0.3 – 0.5 m/s – same as PIVlab results)
  - Avio gate causes spiral flow (upward flow at wall and downward in middle of trap) extending to halfway through deposition zone
  - Spiral flow also observed during field investigation
  - Velocities decrease throughout trap & increases again at outlet gates
  - Average velocity of 0.2 m/s through settling trap length
  - velocity in the flushing conduit is higher near upstream side where flushing gate is located





- **Sediment concentration distribution (focus on left trap plane)**
  - Sediment entering trap deposits within settling trap length
  - Concentration increases within the flushing conduits, becoming too high to flush out sufficiently
  - Numerical results align with field observation and indicate sediment build-up at same location
  - Sediment particles of 1 mm escapes sand trap at d/s gates



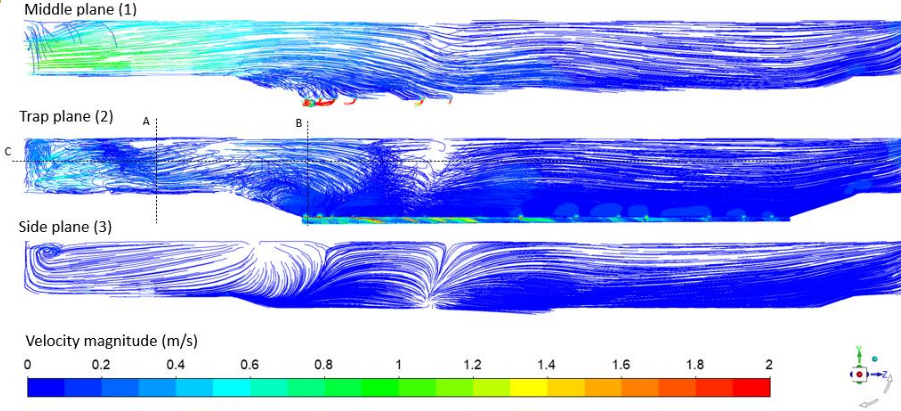
Conclusion:

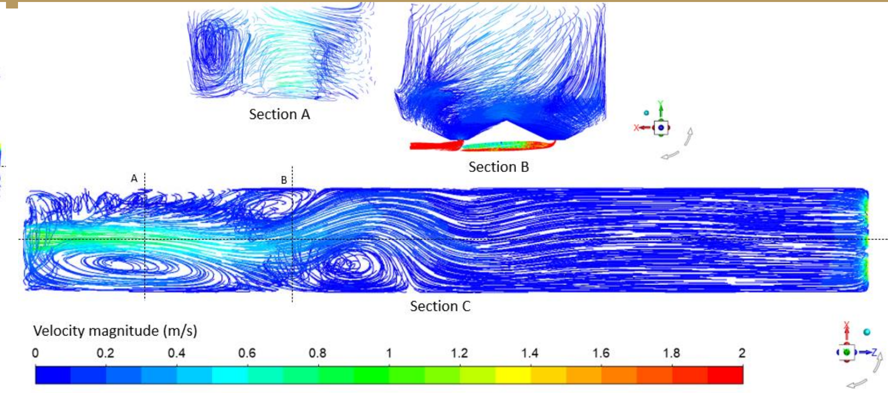
- Avio gate's floatation chamber, causing turbulence prevents settling of sediment at inlet
- Trap's low flow velocity during low discharge flow (Q = 5 m^3/s), is favorable for sediment deposition, becomes problematic for flushing of sediment.
- Accumulation of high sediment concentrations within flushing conduits prevents efficient removal of sediment from trap
- Flushing velocity through scour holes and into conduits are too low, influenced also by spiral flow caused by Avio gate

Numerical Modelling Results

Design upgrades for low flow

- Inflow Q = 5 m^3/s, scour flow Q = 2 m^3/s
- Particle size = 1 mm, w = 0.14 m/s
- C_inlet = 1000 mg/L





- **Velocity**
  - Removing Avio gate at inlet reduces spiral flow - concentrating high velocity in middle
  - Velocity decreases through inlet area and becomes more uniformly distributed in deposition area
  - Turbulence still high at inlet, but effects less of the effective deposition area (compared to Avio gate effects)
  - Flow is more directed to trap plane and scour holes
  - Local velocities above scour holes increases and velocities within flushing conduits is sufficiently high for efficient sediments flushing
  - Addition of baffle plates at inlet area could potentially improve further enhancement of velocity distribution

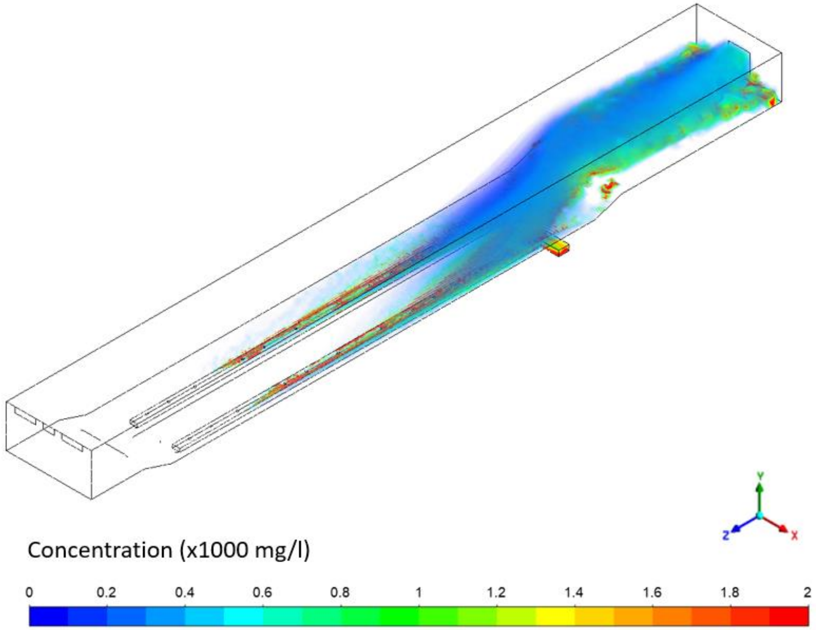
- **Sediment concentration distribution**
  - Simulated concentration distribution of 1 mm particles decreases along length trap indicating sediment settle in deposition area
  - Higher sediment concentration occurs at deposition area of trap and in flushing conduits, showing efficient flushing
  - Minimal sediment concentration at outlet section, suggesting sediment has scoured out via scouring holes
  - The flushing conduits maintain a high velocity to efficiently transport the sediment load towards the upstream flushing gate.
  - However, possibility of scour holes getting blocked by debris, advisable to install fine screens at river diversion works.

Conclusion:

- With design changes efficiency of trap increases and is able to function at lower discharge of 5 m^3/s
- CFD Numerical model shows applicability to improve designs of troublesome sediment traps
- Reliable tool that can be used for enhancing performance of sediment management structures

Design upgrades to enhance efficiency of trap:

- Removal of Avio gate → get rid of spiral flow
- Larger scour holes 100mm to 200mm → increased local velocities above holes & better flushing
- Downstream gates as weir outlets (not bottom outlets) → prevents sediment reaching d/s from escaping



Main Objective 1 Conclusions & Contribution to Engineering Science

- **Formulated Design Guidelines for Settlers and Sand traps (published WRC report)**
  - Provided valuable insights into hydraulic design of settlers, and their efficiency on settling lengths:
    - cross-section type (rectangular vs. trapezoidal)
    - influence of sediment intake concentration on settling length
    - intake types (weir type, bottom inlet, sloped inlets) – velocity and turbulence distribution caused
    - influence of slope on settling length of sediment – sloped settlers decrease settling lengths
  - Revealed distinct sediment concentration patterns in rectangular and trapezoidal settlers
    - valuable information for designing settlers for flushing
  - Recommendations for calculating Total Length of settlers with no slope
    - For d> 0.2 mm: Total Length = 1.5 L_analytical + 20%L_analytical (turbulence effect depending intake type)
    - For d< 0.2 mm: Total Length = 3.3 L_analytical + 20%L_analytical (turbulence effect depending intake type)
- **Field & Analytical investigation of 2 Case studies design:**
  - Evaluated performance through field measurements & compared to the design criteria
  - Post construction evaluation add to the improvement of design criteria for future designs
- **Numerical investigation of 2 Case studies design**:
  - Validated existing numerical model coupled in terms of hydrodynamics and sediment transport developed by Sawadogo (2015) with real-world field results
  - Proposed design upgrades for the sand trap to improve efficiency based on design changes made and evaluated through numerical modelling - Further contributed to design guidelines for sand traps
- **Demonstrated the capability of the numerical model developed by Sawadogo (2015) in accurately simulating sediment concentration and flow velocities in real-world hydraulic conditions:**
  - Model stands as a reliable tool that can be used for assessing and enhancing the performance of sediment management structures.


DESIGN GUIDELINES OF RIVER ABSTRACTIONS/DIVERSION WORKS FOR POTABLE WATER USE, IRRIGATION AND HYDROPOWER GENERATION IN SOUTH AFRICA

Design Guidelines and typical Hydraulic Designs of small to large River Abstractions/Diversion works

WRC project K5/2750

VOLUME 1

March 2020

Stellenbosch UNIVERSITY IYUNIVESITHI UNIVERSITEIT

Main Objective 2

Investigate the Split-and-Settle sand trap concept proposed by Støle in 1993 through physical model experiments

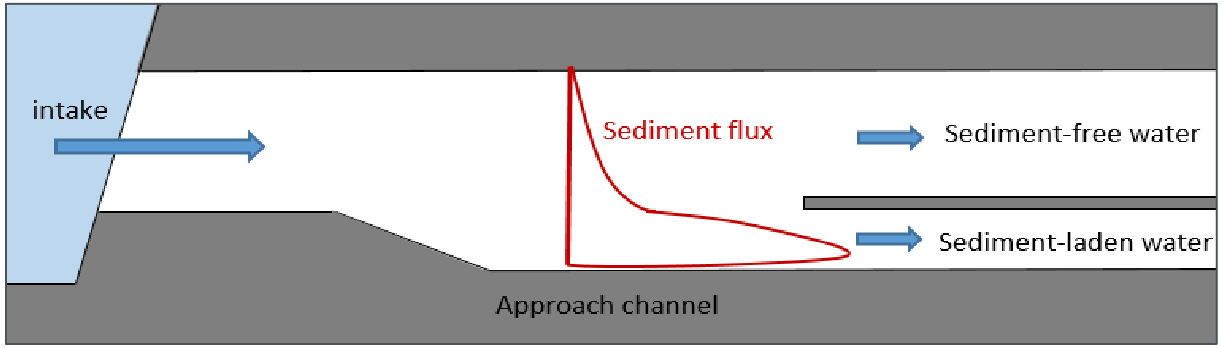
&

develop a calibrated numerical model for the Split-and-Settle sand trap that can be used to explore further design modifications.

- Physical model experiments:
  - Performed to investigate the concept of the "split-and-settle" approach
  - Measurements of velocity & Suspended Sediment concentration around split-plate collected for further calibration and validation in numerical model
- Numerical model calibration and validation:
  - An existing 3D model was used & further calibrated to fit experimental data of 1 test condition of the Split-and-Settle sand trap model.
  - The calibrated numerical model was validated by comparing the model-generated results with experimental data obtained from the other test conditions in the physical model study
- Additional refinement of the split-plate design and placement by numerical modelling
  - aim to visually investigate distribution of flow velocity and SSC in order to enhance the efficiency and performance of the Split-and-Settle sand trap.

Split-and-Settle sand trap concept

Concept developed at NTNU by Dr. Støle (1993)



Different in design concept compared to regular Sand traps:

Rather than attempting to settling all targeted sizes of particles in one operation, this concept provides for separate settling of upper and lower part of flow separately in two or more basins

- Concept takes advantage of variation in sediment conc. over depth of flow
- As sediment-laden water flows in canal, suspended sediment conc. increases near bottom as it tends to deposit
- Flow divided: upper and lower part making use of a "split" (plate)
- Sediment-free water conveyed above plate & sediment-laden water below plate
- This process can be repeated in 2 or more basins until water is of acceptable quality (each split for different sediment target size)

Aims to:

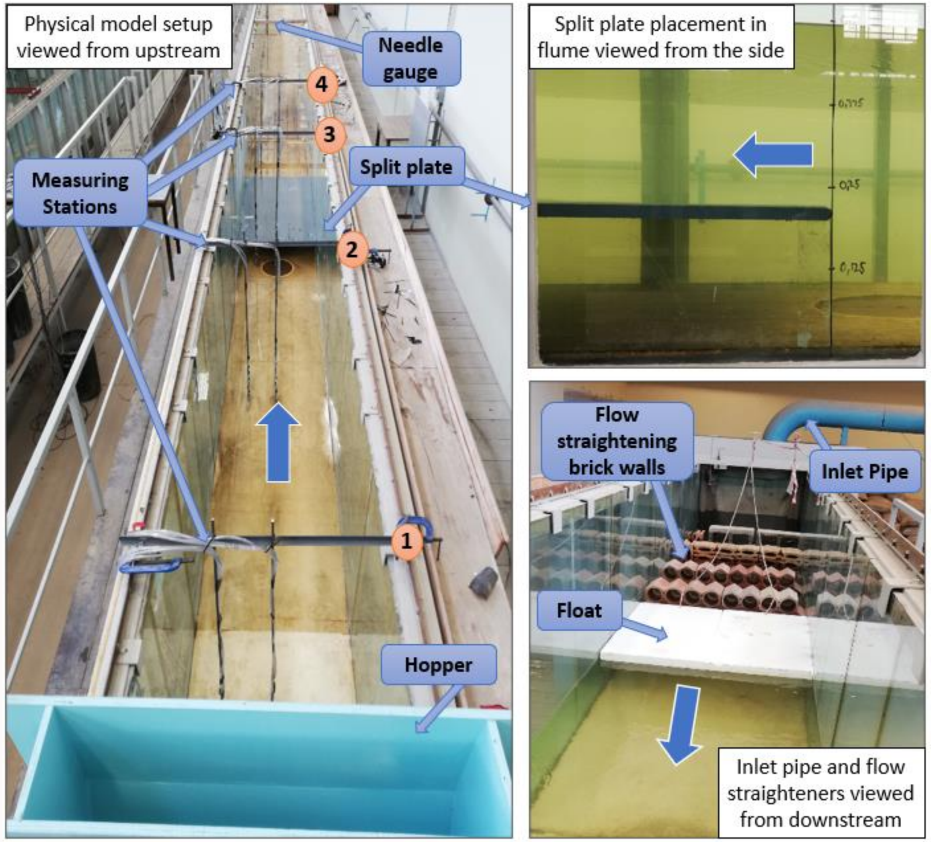
- ✓ Shorten total sand trap length & more economical
- ✓ Improve sediment removal efficiency
- ✓ To be used for both pressurized & gravitational flow conditions
- ✓ Can potentially be used to upgrade existing inefficient sediment traps

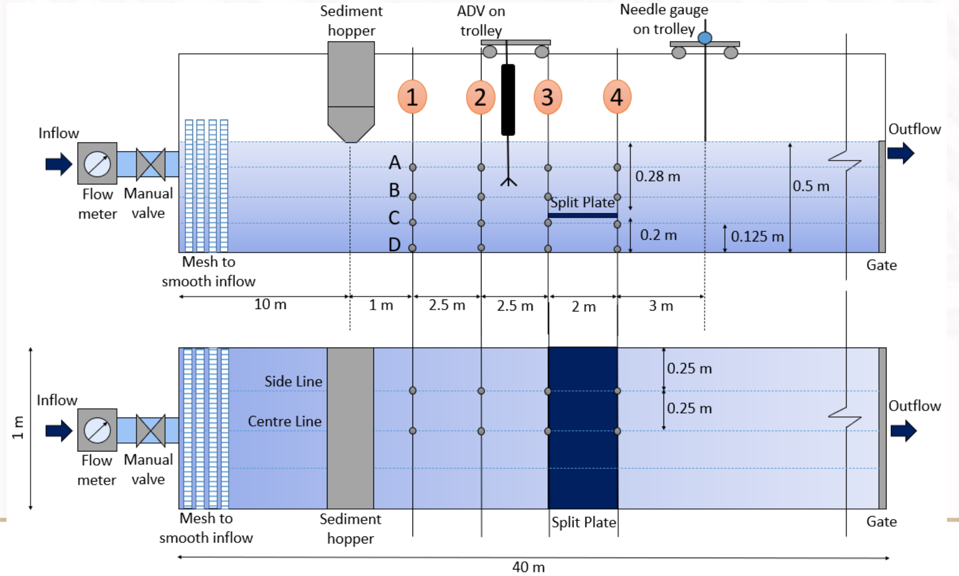
Physical model Investigation of the Split-and-Settle sand trap

Sediment was released from u/s end of flume through a hopper with a specific concentration. Suspended sediment samples were taken at different water depths at 4 CS's (measuring stations) distributed through length and width of flume. Velocities measurements at various points to visualize flow field

Setup:

- Rectangular glass flume used in SU hydraulics lab & Concrete floor bed
- Full-scale model (no scaling effects of sediment)
- Flow straightening walls and float to reduce turbulence at water surface
- Flowmeter used to measure flow
- ADV measure velocities at different depths & cross-section (CL & SL)
- Split plate:
  - 2m long, 20 mm thick PVC, rounded at edges
  - Placement in flow depth: in flume at 60/40 split (overflow/underflow) - Recommended by Agrawal (2005)
  - Placement in length: according to analytical settling length of particle L = 5 – 7m
- Hopper to discharge sediment of known concentration into water
- Syphoning tubes at different water depths to collect suspended sediment concentration
  - 32 SSC measuring points
  - Measurements at 4 CS's in CL and SL

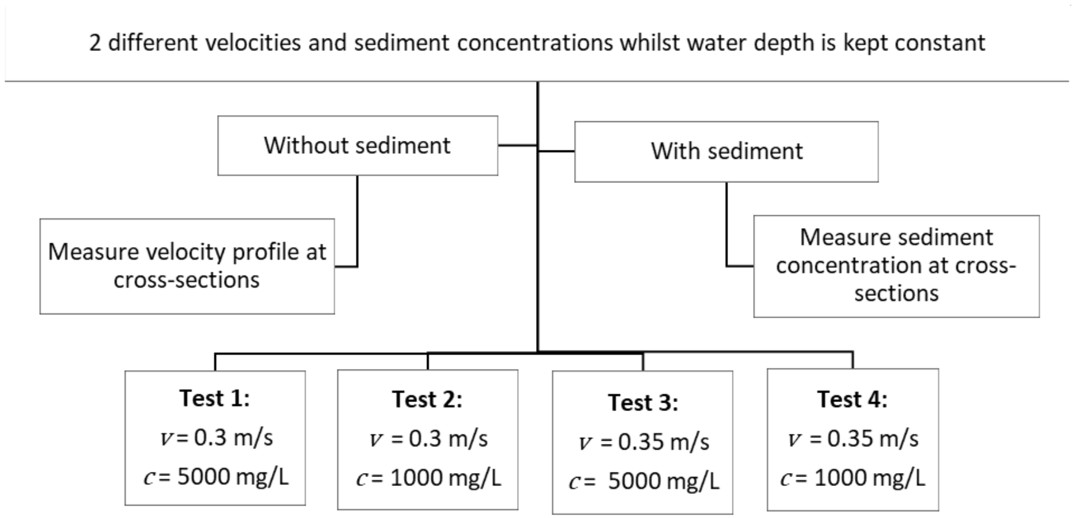




Physical model setup

Hydraulic parameters:

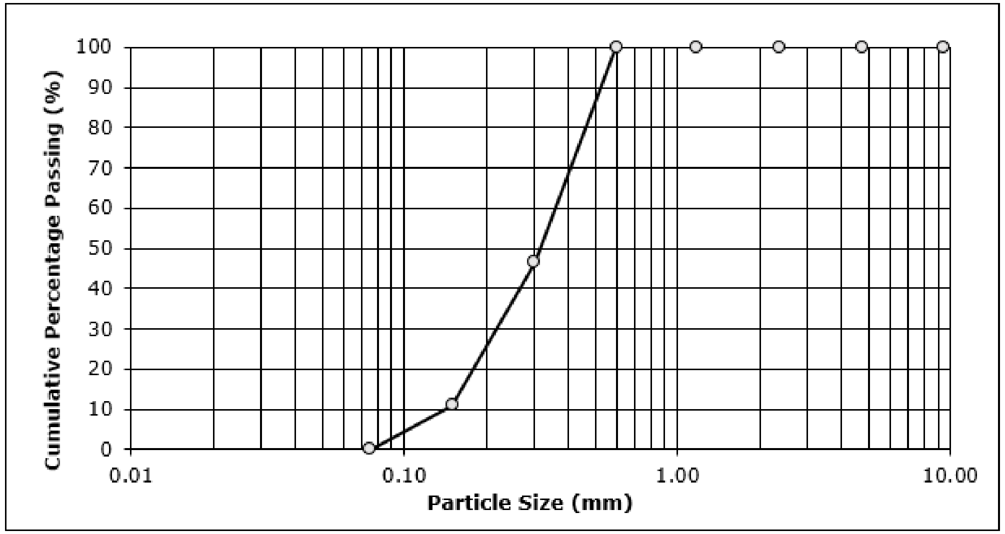
- 1 m wide, 0.5 m water depth (hydraulic efficient rectangular cross-section)
- Turbulent flow (Re > 5000) for turbulent suspended sediment transport
- The critical velocity (Vcr) for deposition of a 0.32 mm: Vcr = 0.35 m/s.
- For the particles to settle: Vcr > V flume
- Four Test conditions: Vcr > V flume & Vcr = V flume
- Sediment concentrations: 1000 mg/L & 5000 mg/L representing non-cohesive sediment concentrations during normal operation and flood events



Sediment properties:

- Foundry grade silica sand (AFS 45)
- Sediment particle size d50 = 0.32 mm

Properties	d_{10} (mm)	d_{50} (mm)	d_{90} (mm)	d_{100} (mm)	σ_g	w_{50} (m/s)	SG	φ
Sediment	0.14	0.32	0.54	0.60	0.23	0.047	2.63	30°



Flow & velocity measurements

Flow
flow meter & a manual valve on 200 mm inlet pipe used to control flow

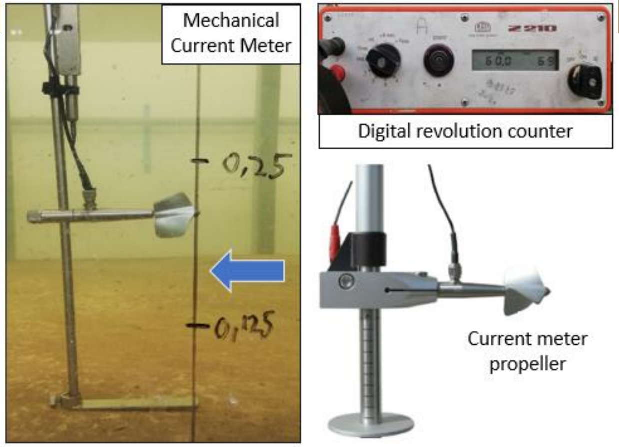
Water depth
D/s gate used to control water depth & needle gauge (accuracy of 0.1 mm) to measure & monitor

Streamline observations
Rod with dye bags (filled with potassium permanganate) placed in centre of flume, 0.5 m u/s of split plate used to observe streamlines. A video camera used to record streamlines. PIVLab used for postprocessing

Depth-averaged velocities
- MCM used to measure depth-averaged velocities at CS's before placement of split-plate
- Mean velocity measured at single point 0.6xwater depth from surface = 0.2 m from bed - Nalluri and Featherstone (2016)
- To ensure fully developed flow
- Compared to ADV to confirm accurate calibration, measurement settings & despiking of data during statistical analyses

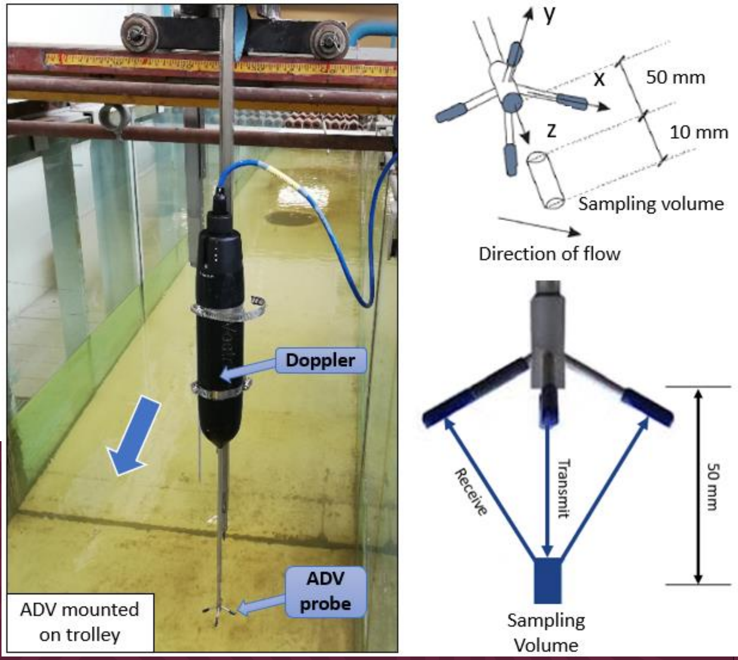
Time-averaged Point velocities
- ADV used to measure time-averaged velocities at several points (with & without placement of split-plate).
- Mounted on a movable trolley such that velocity field can be measured at different water depths (0.0625 m, 0.125 m, 0.1625 m, 0.25 m, 0.3125 m & 0.4 m) on CL and SL at each of 4 CS's.
- Take into account needed submergence (> 0.05 m) and minimum distance (> 0.025 m) from boundaries to prevent unreliable measurements
- Sampling at a rate of 50 Hz (measuring every 0.02 sec) for 2 minutes to cancel out noise average out random velocity vectors caused by turbulent flows
- Statistical analysis performed to clean and despike data (get rid of outliers)

Flowmetrix SAFMAG electromagnetic flowmeter used to measure flow (accuracy of ±0.5%)

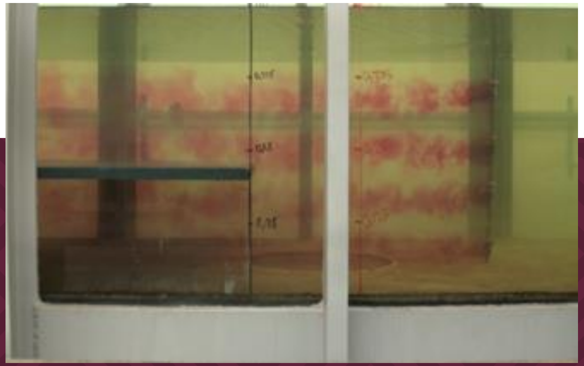


Mechanical current meter (MCM) to measure depth-averaged velocities (accuracy of ±2%)

Acoustic Doppler Velocimeter (ADV) used to measure instantaneous velocities at several points (accuracy of ±1%)



Rod with dye bags (filled with potassium permanganate) used for streamline observations

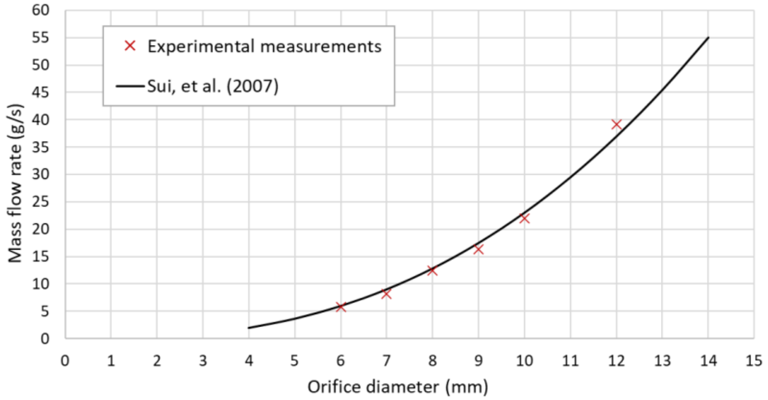


Sediment concentration inlet

- Designed to introduce non-cohesive dry sediment into flow for a constant concentration inlet
- Sloped side with a 60' angle (steeper than angle of repose of sediment) for mass flow to occur by making use of gravity flow
- Bottom - 4 steel plates were designed with distributed orifices spaced equally over length to control outflow of sediment

- Mass flow rate of granular solids through horizontal orifice - Beverloo et al. (1961) equation
- Tested in lab: 0.32 mm sand particle flow through orifice - compared well to eqn and emperical values of Beverloo et al. (1961) & Sui et al. (2017)

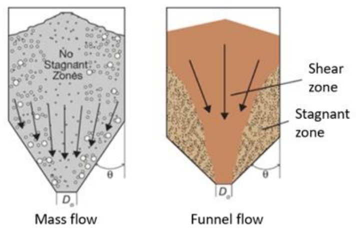
- Based on results – diameters and amount determined for each tests for specific concentration inlet
- The set flow rate in flume and required suspended sediment concentration in flow used to determine sediment flux from hopper
- Sediment flux inlet from distributed orifices (g/s) = flow of water in flume (m3/s) x inlet concentration (mg/L)
- Tested in lab: Total sediment flux from hopper with different plates 0.5% diff. between analytical & measured results

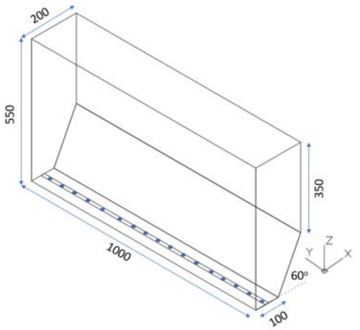


$$W = C_0 \rho_b \sqrt{g} (D_0 - k_0 d_{50})^{5/2}$$

Beverloo et al. (1961)

where W is average mass discharge through the orifice (in g/s), Co is empirical discharge coefficient, ρb is bulk density of material (in kg/m3), Do is diameter of outlet orifice (in m) and ko is empirical shape coefficient.
Sui et al. (2017) - empirical values of Co=0.5 and ko=1.26 for sand grain size 0.1 - 0.5 mm.





	Test 1	Test 2	Test 3	Test 4
	Plate 1	Plate 2	Plate 3	Plate 4
Velocity (m/s)	0.3	0.3	0.35	0.35
Flow (m^3/s)	0.15	0.15	0.175	0.175
Inlet concentration (mg/L)	5000	1000	5000	1000
Sediment flux required (g/s)	750	150	875	175
Diameter of orifices on plate (mm)	12	7	12	7
Flux through one orifice (g/s)	39.7	8.2	39.7	8.2
Number of orifices	19	18	22	21
Total sediment flux from hopper measured (g/s)	754	148	873	173


Four Plates with distributed outlet holes

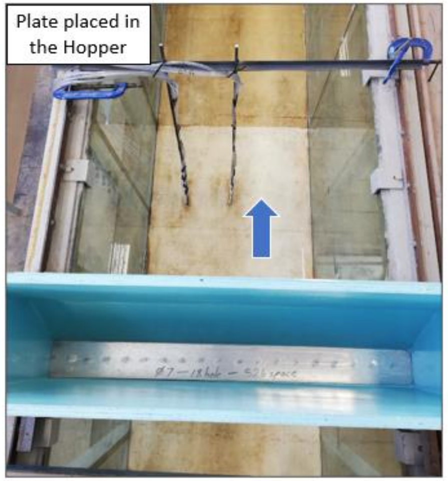
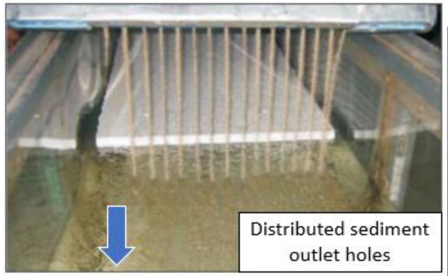
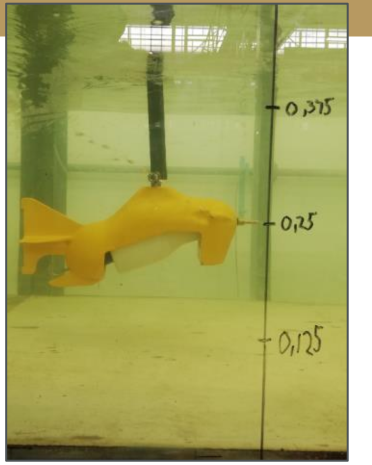


Plate placed in the Hopper


Distributed sediment outlet holes

Suspended sediment concentration sampling

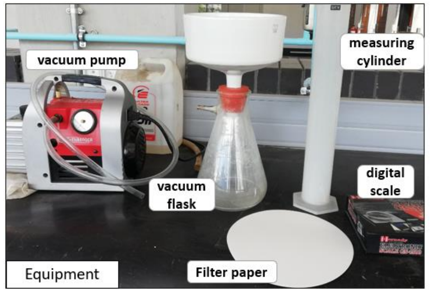
USGS sampler, with 6 mm intake nozzle used to determine flow rate into a bottle at different water depths for different test velocities (0.3 m/s & 0.35 m/s)

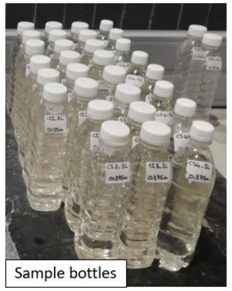


- Similar systems as the Transverse Suction System (TSS) developed by Bosman et al. (1987)
- adapted (no vacuum pumps available) and used for measuring time-averaged suspended sediment concentration

- 32 Syphon tubes inner diam. = 6 mm were placed at each measuring point to extract samples in direction of flow.
- Tubes secured to steel support structure – intakes extruded 20 mm from structure

Post-processing of samples to determine concentration



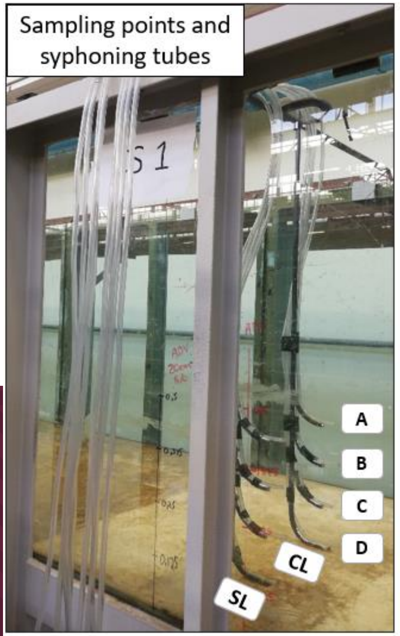


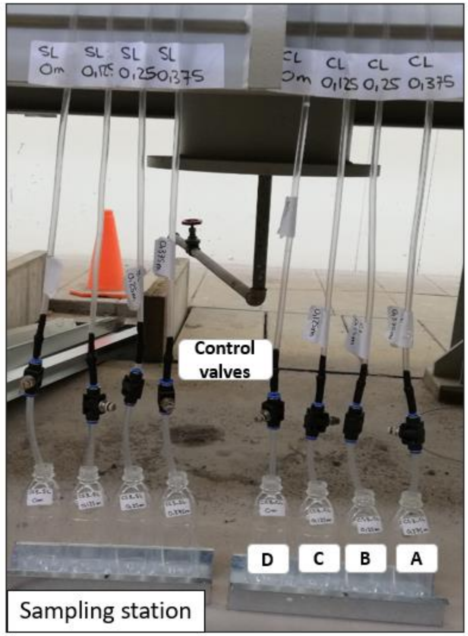
<u>Flow velocity into syphon pipes:</u>

- USGS sampler with 6 mm intake nozzle was used to determine flow rate into bottle at different water depths for the 2 tested flows
- Ball valves attached to syphon tubes to set the correct flow rate through the pipes at each water depth based on results from USGS sampler
- For accuracy of measurement: Velocity in tubes = velocity in flow at respective depth
- Trapping efficiency of syphon tubes calculated.

- Samples were taken simultaneously for each test at each measuring point.
- The suspended sediment samples were collected in 500 mL bottles.

Ball valves attached to syphon tubes to set correct flow rate based on results obtained from USGS sampler to ensure same velocity in pipes as in sampling water depth in flume





The mean concentration is approximately the same as the depth-averaged concentration for fine sediments - Rooseboom (2005)

At each cross-section: 8 measuring points = 4 measuring at CL + 4 at SL
Water depth: 0.375 m (Point A), 0.25 m (Point B), 0.125 m (Point C), 0.025 m (point D) from flume bed

Validation of sediment concentration inlet and sampling

When conducting a physical model investigation, it is of utmost importance to calibrate equipment used in the investigation, verify the accuracy of the model, measurements and generated data and to validate the data collected with analytical or empirical solutions.

Sediment flux from hopper:

The mean sediment concentration entering the water below the hopper was assumed to be equal to the flux of the sediment entering over the width divided by the flow discharge per unit width of water

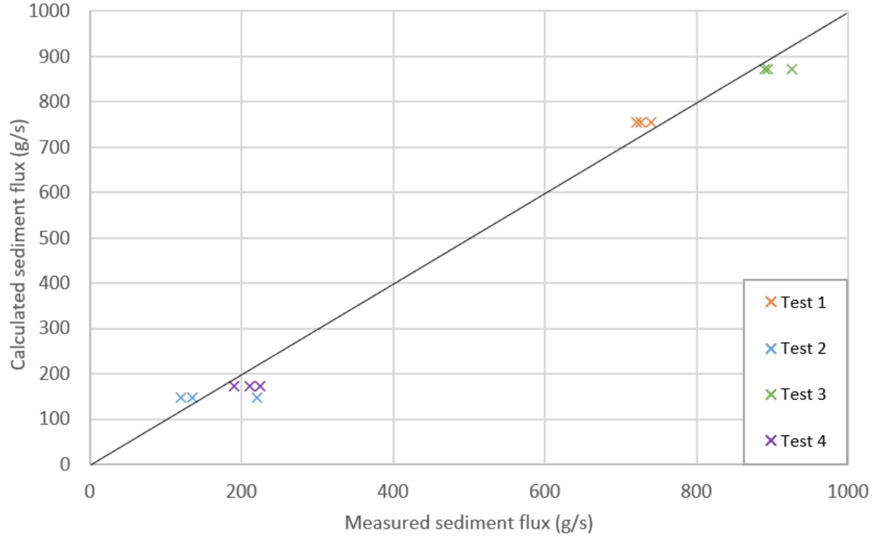
Sediment flux at CS1:

- Concentration & velocities measured over depth of water at centre line and at CS1, which is located 1 m away from the hopper inlet.
- The depth-integrated suspended load was calculated by integrating the velocity multiplied by the concentration at each point in depth from the edge of the bed layer to the water surface.
- The results of the measured sediment flux at CS 1 in the centre line was used as most sediment was transported as a suspended sediment load at this CS and the velocity profile is fully developed.

suspended sediment concentration sampling accuracy determines the calibration of the suction

	Test 1	Test 2	Test 3	Test 4
Flow in flume (m³/s)	0.15	0.15	0.175	0.175
Concentration inlet (mg/L)	5000	1000	5000	1000
Flux inlet from hopper calculated (g/s)	754	148	873	173
Actual Concentration inlet (mg/L)	5027	987	4989	989
Centre line (avg C in mg/L measured in depth)	4601	973	3463	738
trapping coeff of syphon tubes	*0.92*	*0.99*	*0.69*	*0.75*
Flux measured	741	135	926	191
% error from hopper	*2*	*9*	*6*	*10*

Comparison of measured sediment flux from experiments at CS1 compared to calculated sediment flux from hopper

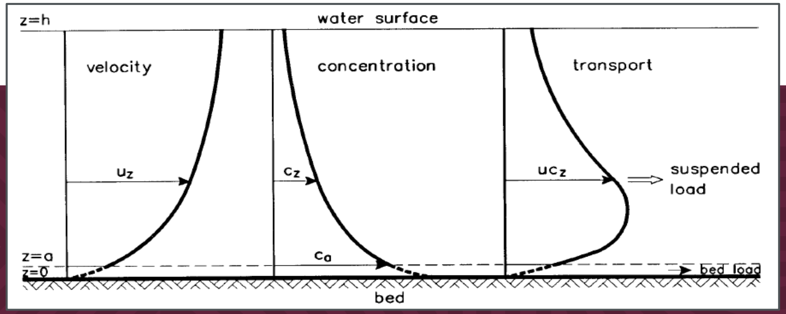


$$q_{s,c} = \int_a^h vc\, dz$$

$$q_{s,c} = c_{mean}\, q.$$

Van Rijn (1993)

The mean concentration is approximately the same as the depth-averaged concentration for fine sediments.



Physical model Results

Velocity measurements - ADV

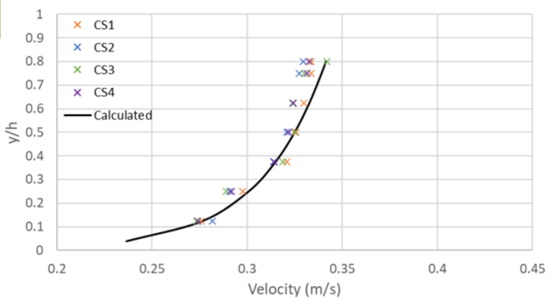
With Split-plate added:

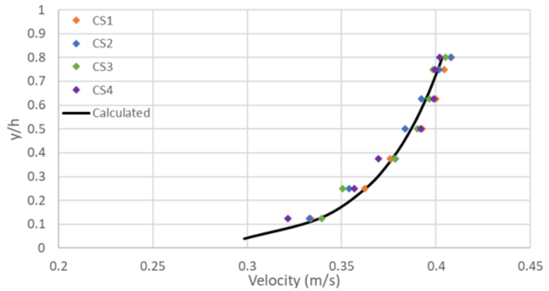
- Validated results at CS 1 and CS 2 against Fully developed flow analytical equation of Van Rijn (1993)- compared well with analytical profile
- The shape of velocity profiles measured at CS3 & CS4 at CL for each exhibit comparable shapes. The same is true at SL.
- Results show velocity profiles at SL measured lower velocities at upstream side of plate at CS3 compared to the measurements on CL. (differ with approx. 0.1 m/s)
- This difference due to interference of flow caused u/s of split-plate creating a turbulent area where secondary flow can occur.
- The velocity measurements around the split-plate revealed a notable difference, with velocity below plate approximately 20% lower than above it.
- This discrepancy is attributed to the split-plate's placement in the depth of flow, causing a 60/40% split in flow and a reduction in the cross-sectional area.
- When analysing the velocity profiles at CS4 in CL - Above split plate, velocity profile mirrors free surface flow, while below, it follows a parabolic distribution resembling pipe or pressurized flow with max. velocity at centre of flow below plate at y/h = 0.1

Without split-plate:
velocity profiles compared to velocity profile of fully developed flow conditions as calculated by Van Rijn (1993) for the experimental flume and flow conditions

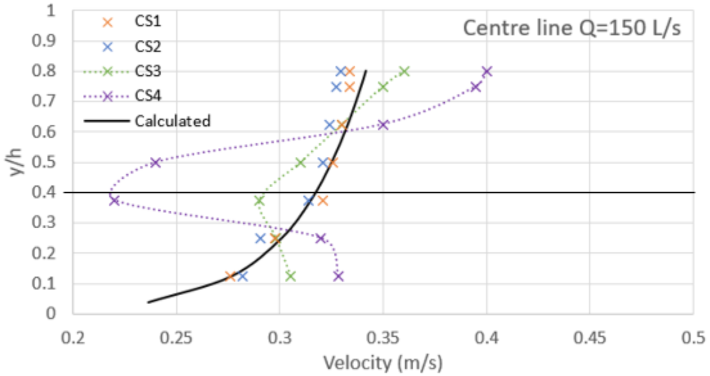
$$\frac{v}{u_*} = \frac{1}{\kappa} ln\left(\frac{z}{z_0}\right), \qquad \text{Van Rijn (1993)}$$

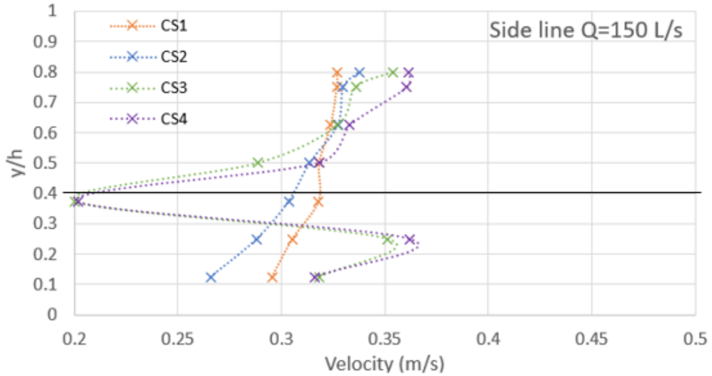
ADV velocities average difference of 1% in the intermediate layer & 3% in free surface layer - difference is due effect of the free surface & secondary flows - the velocity-dip phenomenon.

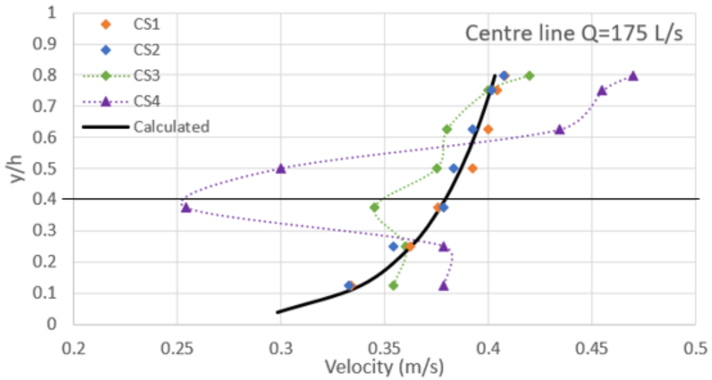


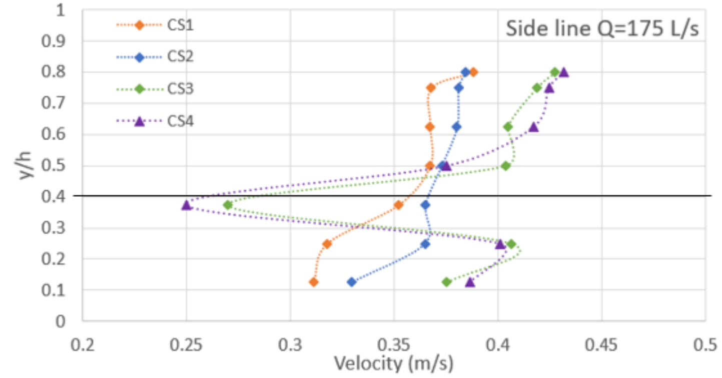


With split-plate







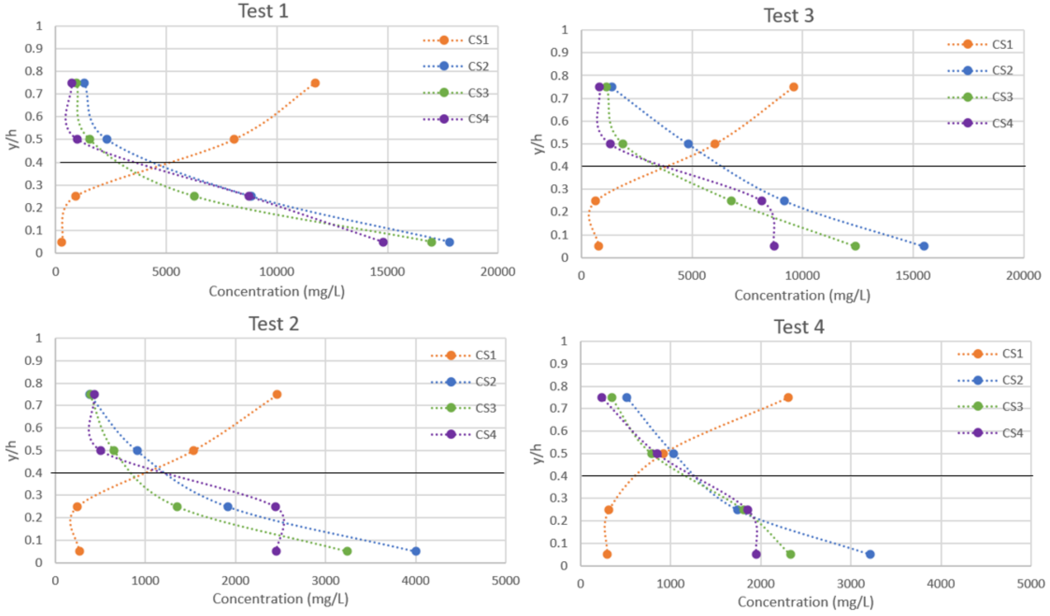


Physical model Results - suspended sediment concentrations

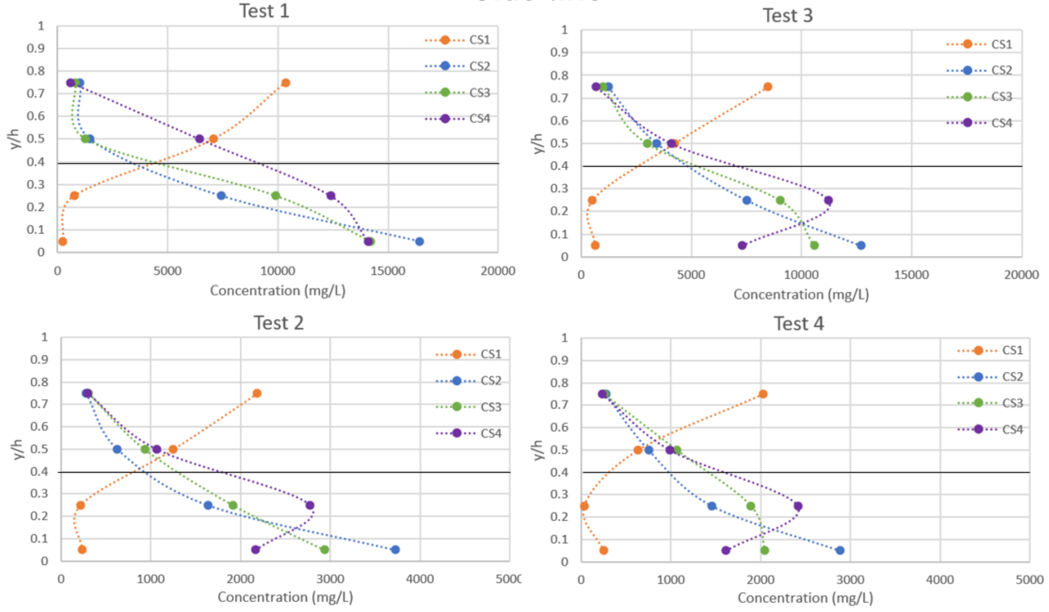
- Across all tests, CS2 exhibits highest sediment concentration near flume bed
- significant outcome is heightened suspended sediment concentration between CS3 & CS4 below split plate
- The sediment concentration measurements conducted around the split-plate indicated that, under all test conditions at CS3, concentration of suspended sediment below plate is 80% higher than above it in depth of flow
- The concentration measurements at y//h=0.25 at CS4 increases from measurement at CS3 in all tests, indicating that sediment particles are resuspended underneath split-plate
- Occurrence of higher concentrations being transported at centre of flow distribution could be due to factors associated with pressurized flow, such as pressure gradient flow
- The "split-and-settle" approach, dividing flow into sediment-free and sediment-laden streams, was proven with results obtained from physical model tests.
- As sediment-laden water moves through flume canal, suspended sediment concentration increases near bottom as sediment tend to deposit.
- The split-plate divides flow into upper and lower parts, transit velocity is reduced below plate and increased above plate, allowing relatively sediment-free water (containing 20% of suspended sediment in the depth of flow) to flow over while diverting sediment-laden water. The suspended sediments continue to accumulate in lower region of flow.

In all tests except Test 1, it is apparent that concentration measurement at bed level at CS4 either failed to accurately capture sediment concentration or may be influenced by higher concentrations being transported at centre of flow distribution due to factors associated with pressurized flow, such as pressure gradient flow.

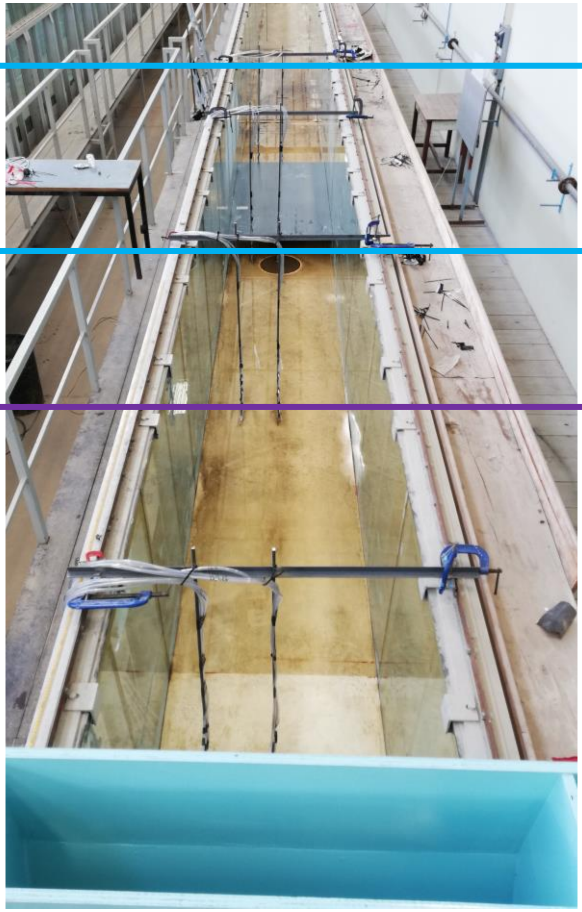
Centre line

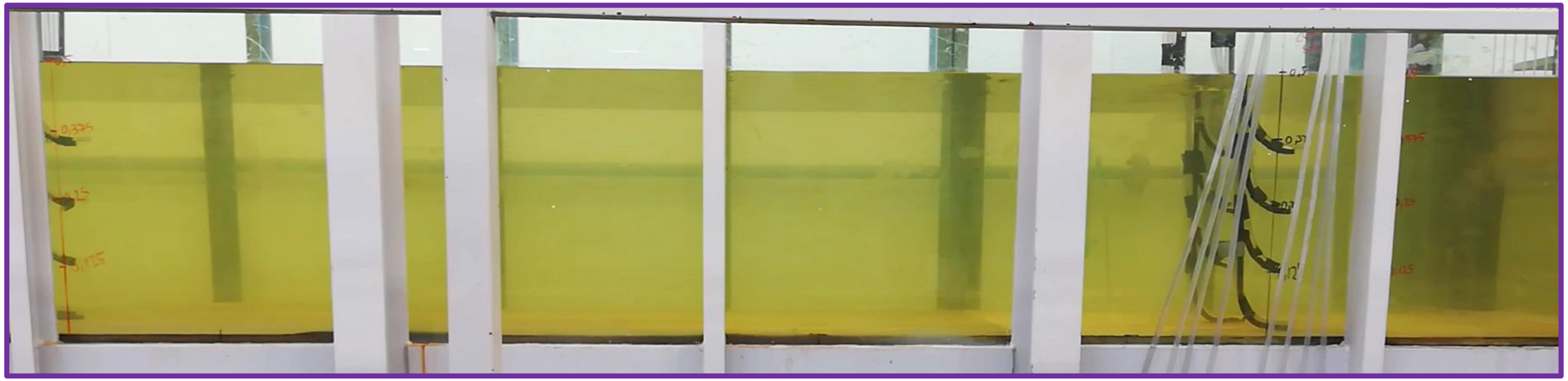


Side line



Physical model Results - videos



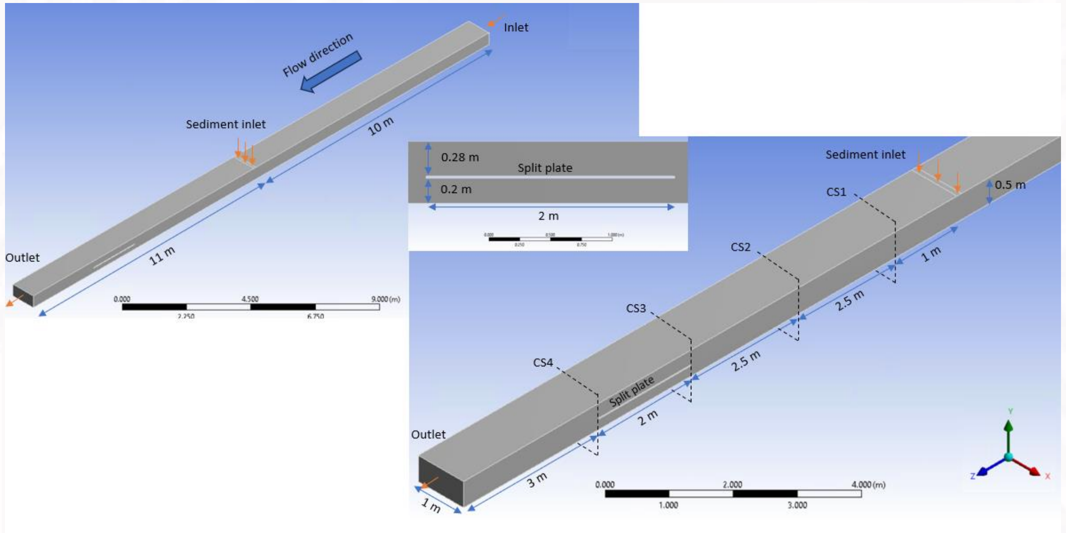


Numerical model setup of Split-and-Settle sand trap and calibration with physical model measurements

Stellenbosch UNIVERSITY IYUNIVESITHI UNIVERSITEIT

The numerical model used for the Split-and-Settle sand trap → precisely replicated the design dimensions used in the physical experimental model → full-scale representation.

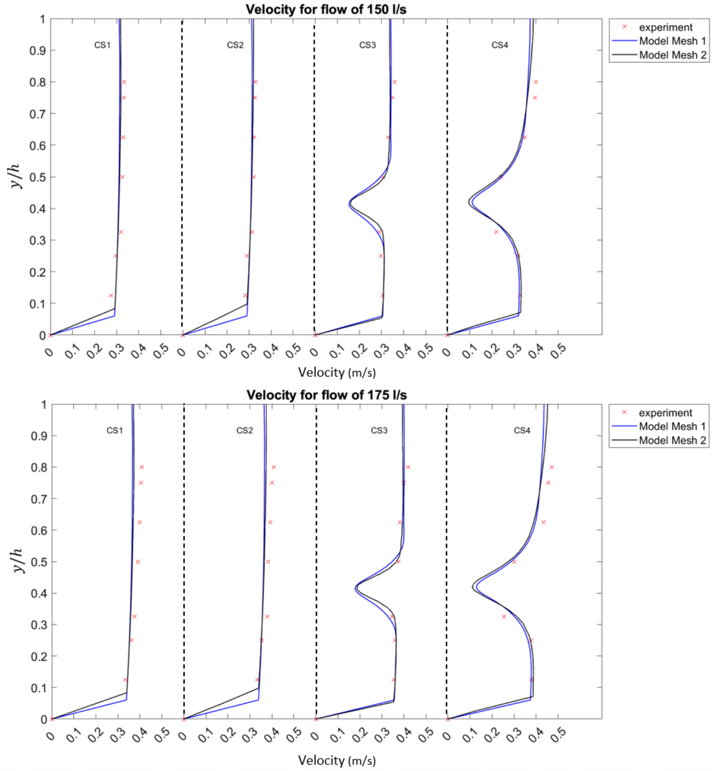
- **Further calibrated** to make numerical model fit SSC experimental data of 1 test condition (TEST 3) of S&S sand trap, meaning that it demonstrates capabilities of model of reproducing calibrated-against data.
- Parameters for Calibration: 4 mesh configurations, turbulence intensity (TI) and turbulent Schmidt number (σ_C).
- **Validated** by comparing model-generated results with experimental data obtained from other test conditions (TEST 1, 2 & 4), thereby establishing empirical validity.



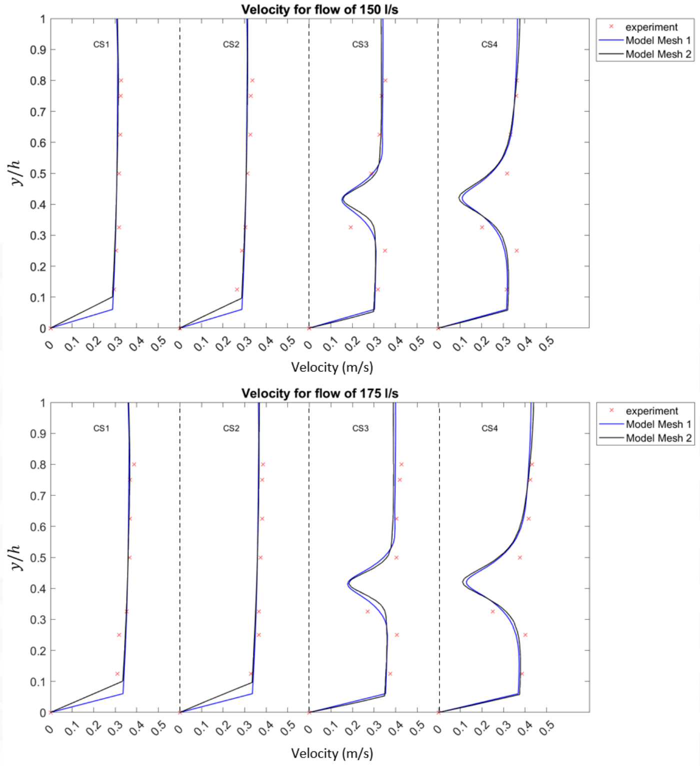
Hydrodynamic modelling

- Velocity profiles from numerical modelling exhibit smoother contours compared to measured, which appear rougher & more irregular
    - discrepancy attributed to coarser resolution of grid used in experimental data collection + interpolation & due to instrument measuring accuracy of ADV close to split-plate boundary where higher turbulence occurs
    - Computational grid in numerical model ranges from 2-32 mm, laboratory grid dimensions of 6.25 mm in depth and 250 mm in width
    - However, the predicted velocity profiles compare very well with experimental data.
- Numerical model produces a velocity profile that underestimates velocities near water surface, with maximum velocity simulated at a non-dimensional flow depth of 1.
    - attributed to numerical overestimation of fully developed profile due to boundary condition, which treats free surface as a shear-free rigid lid through symmetry boundary
- Profiles produced by Mesh 1 & Mesh 2 differ at CS1 & CS2 near bottom due to variations in grid sizes.
- Profiles CS3 & CS4 in CL compare well with numerical results - follows same trend & order of magnitude.
- Profiles CS3 & CS4 in SL higher than simulated velocities above & below split-plate, but still follows same trend.
    - Reason for higher velocities measured could be caused by split plate influence
- Hydrodynamic model performs reasonably well in replicating velocity profiles, at both CL & SL, as observed in laboratory.
    - Making inlet boundary of numerical model with prescribed velocity an accurate representation of conditions observed in physical model
- Overall, the numerical model with Mesh 2 provides more accurate results around the split-plate, due to the finer mesh cell size used.

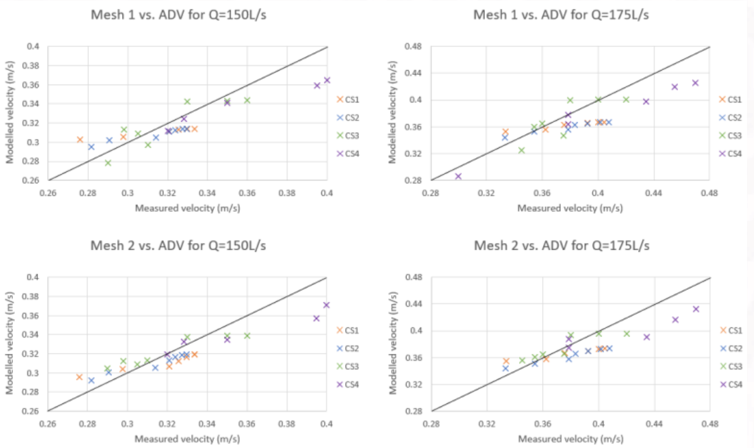
Centre line



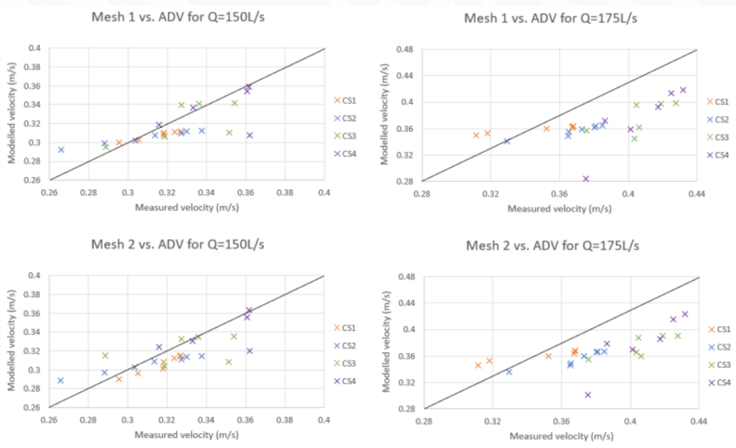
Side line



Comparison of modelled and measured velocities for CL



Comparison of modelled and measured velocities for SL



Hydrodynamic modelling

- Placement of split-plate within model and experimental setup –
  - velocities increases both above & below plate, producing higher velocities above than below - increase in V attributed to reduction in CS area & a division of flow discharge which leads to an overall velocity enhancement

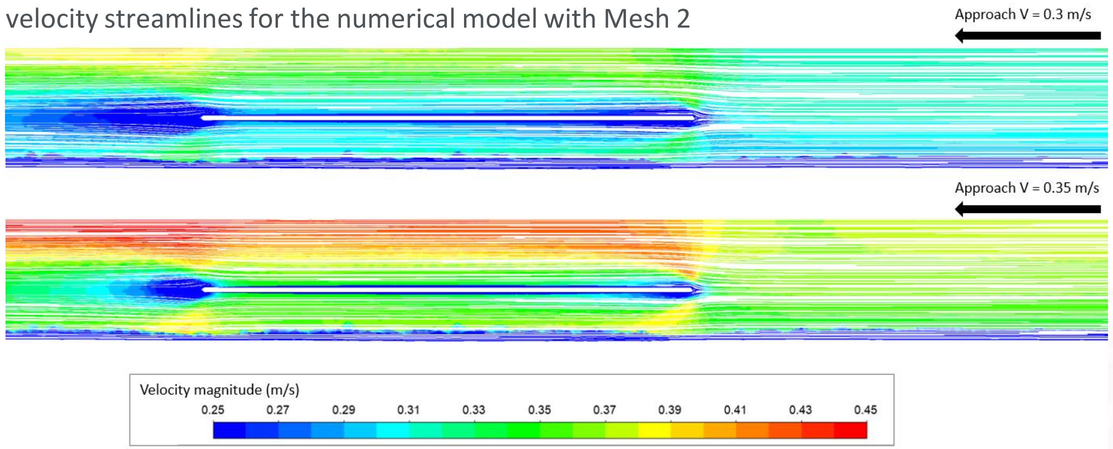
- Flow above plate characterised as free-surface flow – max. velocities at top
- Flow below plate represents developing profile experienced in closed conduits/pressurised flows – max. velocities at centre

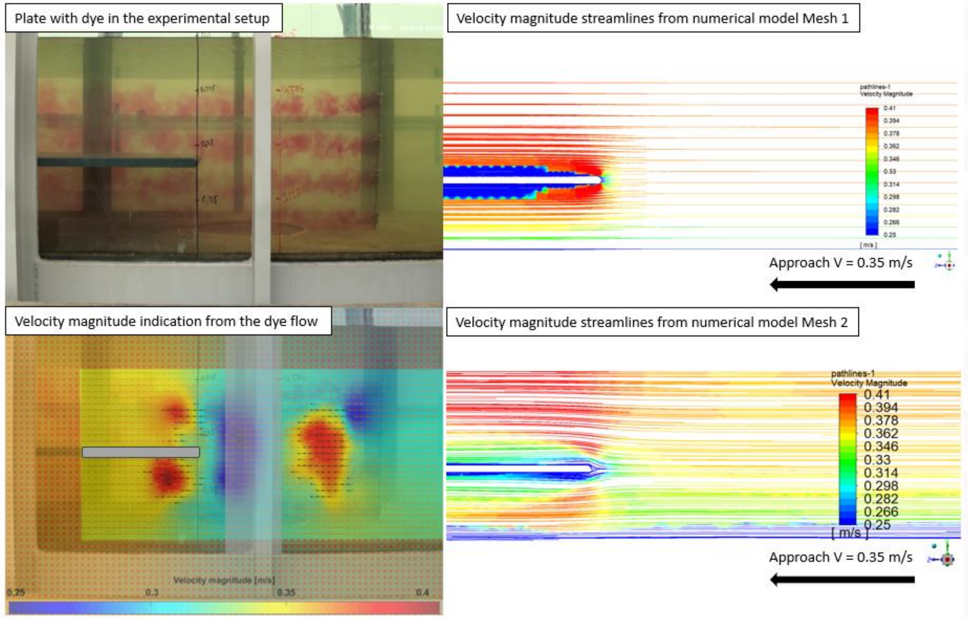
- Increased wetted perimeter below plate introduces more friction - reduces velocities

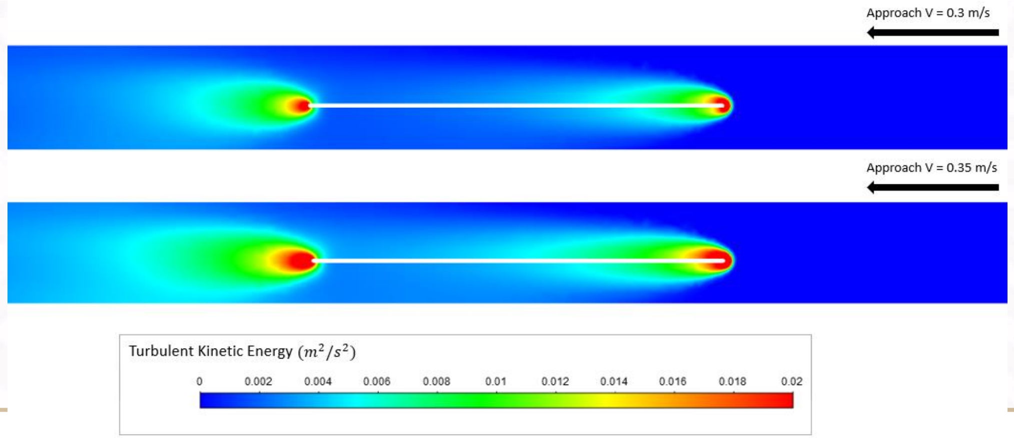
- Flow separation observed on u/s side of split-plate:
  - leading to circularity flow and formation of "separation bubble."
  - As extends d/s, flow reattachment takes place, seen by streamlines converging closer to plate boundary.
  - Flow separation occurs when fluid velocity decreases, leading to changes in flow pattern - caused by change in geometry of flow path due to split-plate.
  - u/s side: flow decelerates, causing boundary layer to separate from surface - results in formation of eddies and recirculation zones, disrupting smooth flow of water. Turbulence intensifies these effects, making flow separation more likely in turbulent water conditions.

- Turbulent wake observed on d/s side of split-plate:
  - turbulent regions influenced by velocity in fluid flow. In general, a turbulent wake tends to be smaller for higher flow velocities

velocity streamlines for the numerical model with Mesh 2







Turbulent kinetic energy higher both u/s & d/s sides of plate compared to area above & below:

- Increased kinetic energy at d/s side in higher velocity flow contributes to faster dissipation of turbulent eddies.
- Turbulence generated by object tends to break down & disperse more rapidly in a higher-speed flow.

Suspended Sediment modelling
Calibration – Mesh, Turbulent Schmidt number & TI

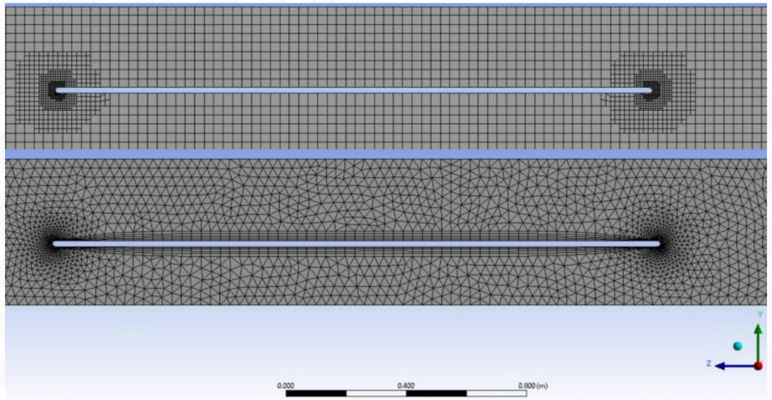
	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Assembly method	CutCell	Tetrahedrons	CutCell	Tetrahedrons
Number of cells	535 470	3 513 803	2 973 054	779 080
Number of nodes	605 108	663 493	3 146 085	146 017
Min cell size (m)	0.002	0.002	0.002	0.004
Max cell size (m)	0.032	0.032	0.016	0.064
Mean orthogonal quality	0.984	0.971	0.997	0.862
Min orthogonal quality	0.324	0.103	0.334	0.208
Inflation on plate	No	Yes	No	No

Mesh:
Large differences between 4 simulated meshes - show mesh is sensitive parameter for proposed numerical model.

- CutCell assembly mesh underpredicts suspended sediment concentration
- Tetrahedrons assembly mesh gives more accurate presentation of the measured data.
- Mesh 3 smaller mesh size than Mesh 1 and overestimates sediment concentration in suspension and at bottom
- Mesh 4 larger mesh size than Mesh 2 and shows very little variation in results

Mesh 2 was selected based on mesh refinement results.

The results Test 3, which featured an approach velocity of 0.35 m/s and sediment concentration inlet of 5000 mg/L, served as basis for calibrating model.



Turbulent Schmidt number:
Results somewhat contrary than expected - especially near the bottom surface.

- For increase Schmidt number - expected reduction in rate at which particles would settle
- Above split plate - increase in predicted settling of sediment for lower Schmidt number
- Slight increase in concentration at bottom of plate for higher Schmidt number

Results show predicted concentrations are relatively insensitive to a change in Schmidt number

Mesh 2 with a turbulent Schmidt number of 0.5 and turbulence intensity of 5% was used for calibrated numerical model

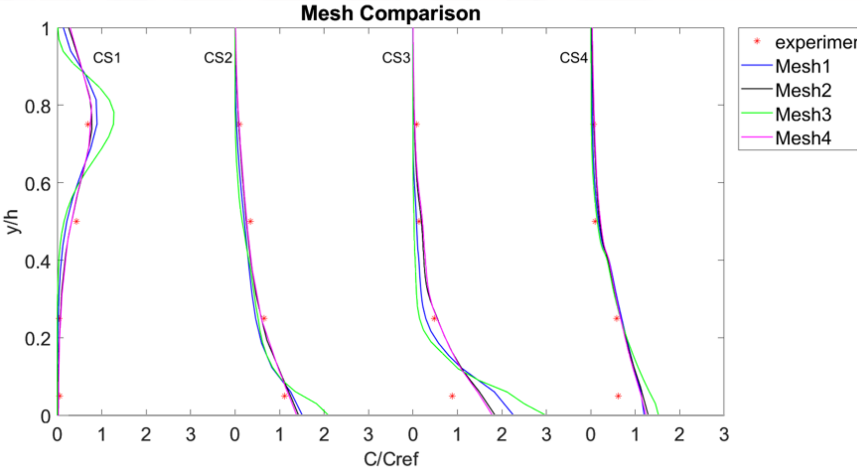
Turbulent intensity at Inlet:
TI settings have no effect on sediment concentrations distribution.

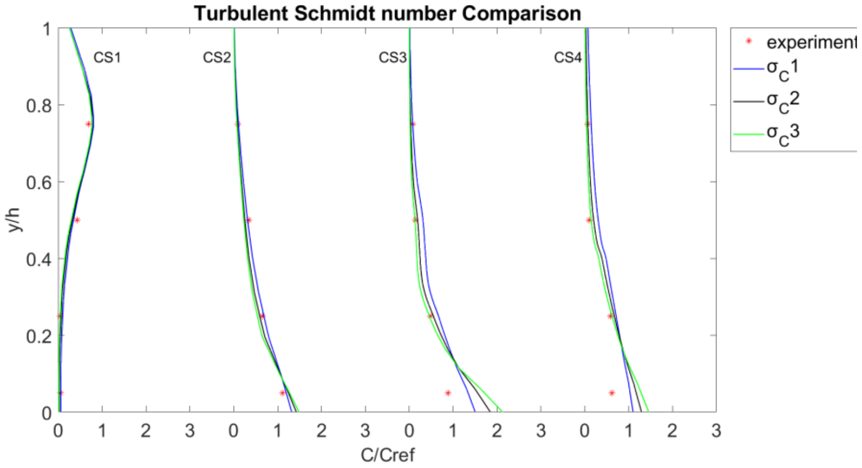
- some extent expected as flow approaching channel (at the measurement positions) was fully developed and steady
- Therefore inlet TI would have negligible effect on TI near split plate, for example.
- Another parameter that may be investigated: the effect of turbulence viscosity on magnitude of turbulence and consequently on sediment concentration.

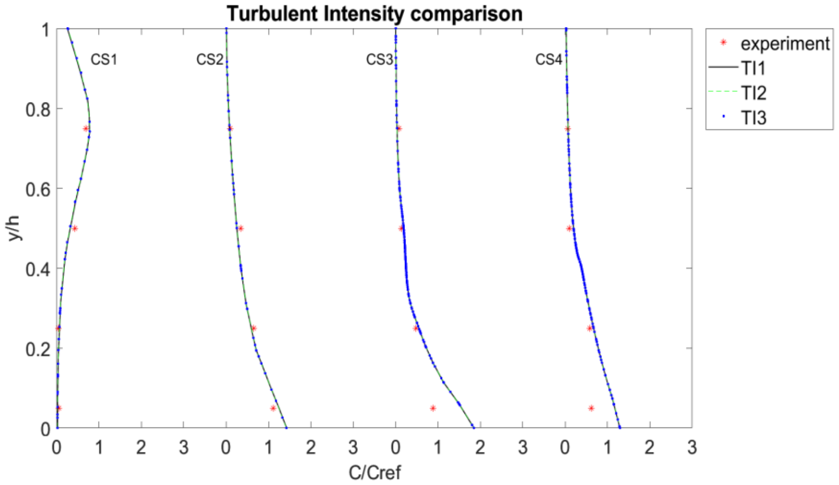
This was however deemed beyond the scope of this project.

	σ_c 1	σ_c 2	σ_c 3
Turbulent Schmidt number value	0.5	0.3	0.7

	TI 1	*TI* 2	*TI* 3
Turbulent Intensity value (%)	5	1	10







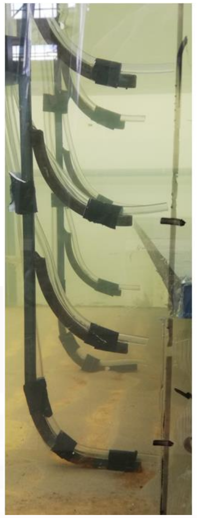
Validation: Sediment Concentration on CL

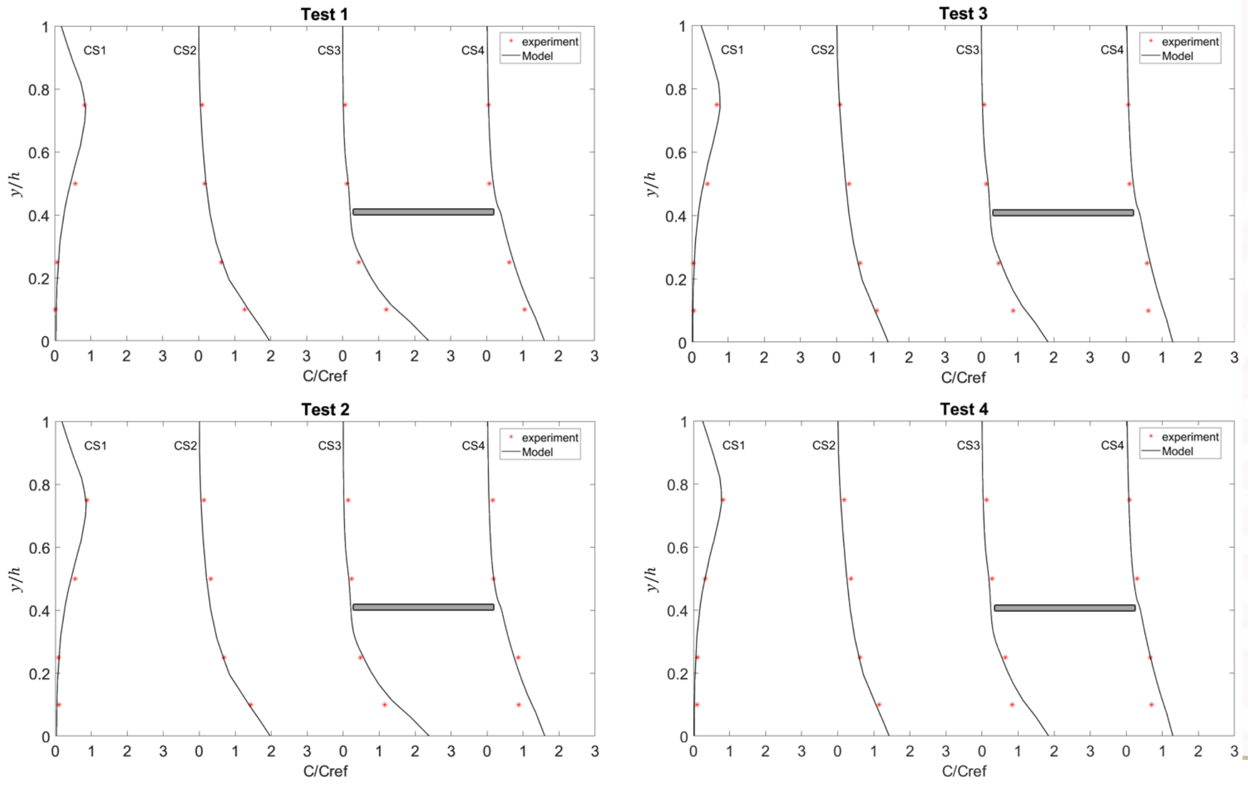
Results of measured suspended sediment concentrations in experimental tests (Test 1, Test 2, & Test 4) conditions with varied flow rates and inlet sediment concentrations are compared to the calibrated numerical model (using Test 3 results).

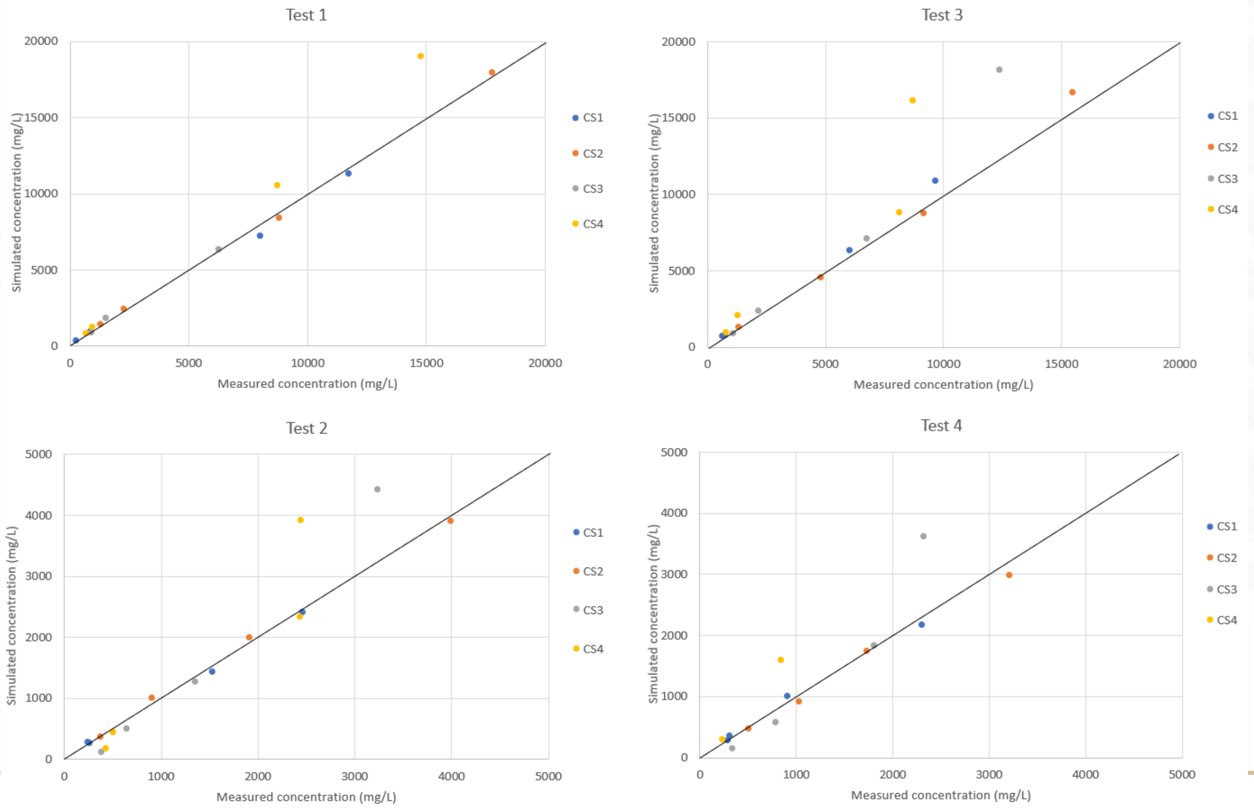
- Both simulated shape of profiles & modelled concentration values closely resemble those observed during laboratory experimental phase with less than 10% error for measurements taken at sampling points above y/h = 0.4 as well as for profiles at CS1 & CS2
- However, the measurements in proximity to bed at CS3 & CS4 yield results with a 20% and 30% margin of error

Experimental errors at bed at CS3 & CS4 below plate:

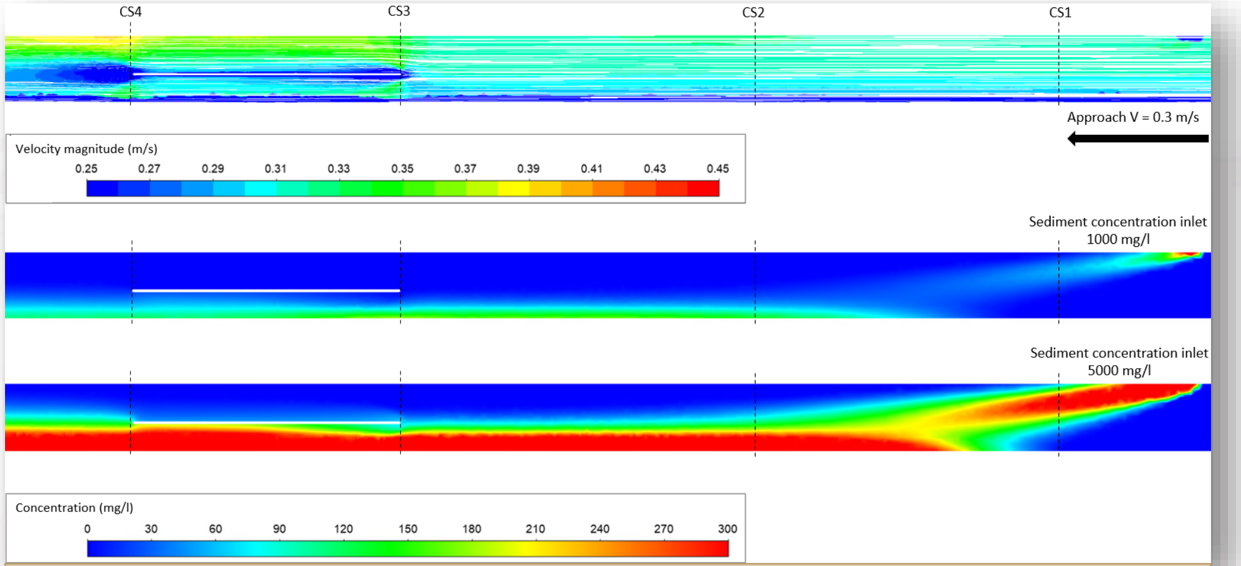
- laboratory measurements are susceptible to human errors during data collection
- variations in velocities & potential discrepancies in outlet flow settings regulated by ball valves through pipes
- sediment concentration samples collected in close proximity to flume bed may introduce a degree of variation in results obtained beneath plate
- presence of areas with high turbulence around u/s & d/s area of split-plate could introduce inaccuracies in measurements



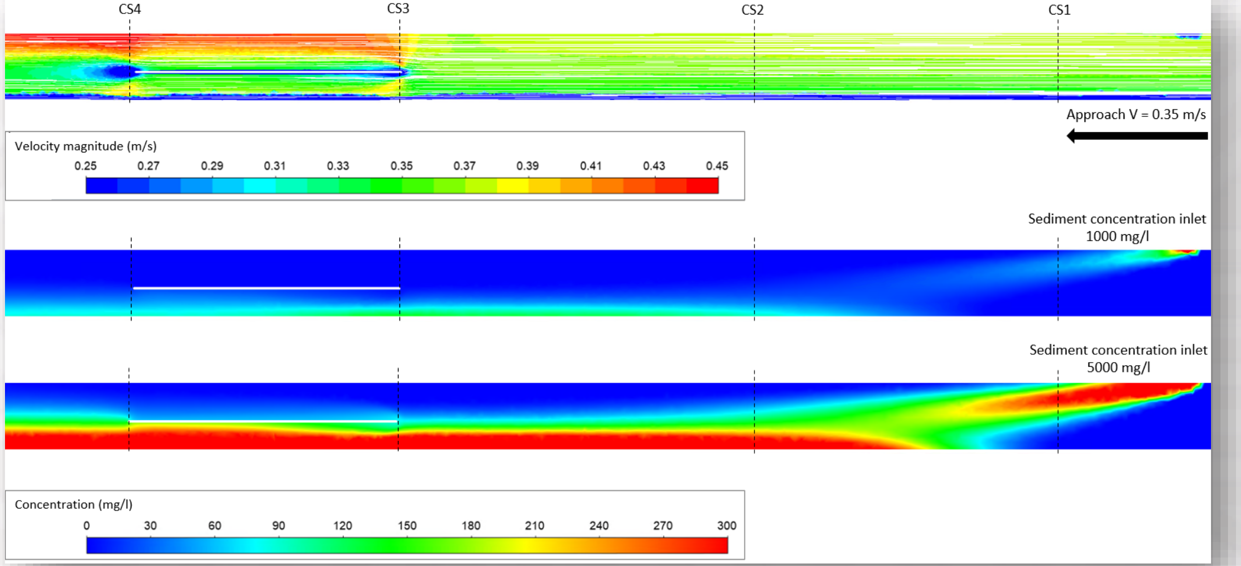




Sediment Concentration



scale chosen to showcase phenomena of suspended sediment transport in Split-and-Settle sand trap and actual maximum sediment concentration within model surpasses 300 mg/L



Test 1 – V = 0.3 m/s & C = 5000 mg/l

Test 2 – V = 0.3 m/s & C = 1000 mg/l

Test 3 – V = 0.35 m/s & C = 5000 mg/l

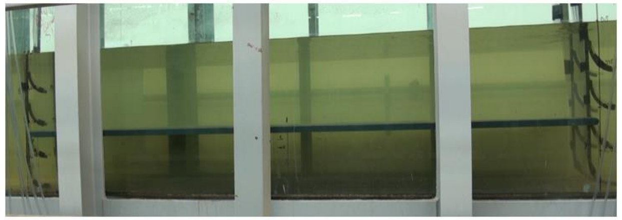
Test 4 – V = 0.35 m/s & C = 1000 mg/l

Test 1 – V = 0.3 m/s & C = 5000 mg/l

Test 2 – V = 0.3 m/s & C = 1000 mg/l

Test 3 – V = 0.35 m/s & C = 5000 mg/l

Test 4 – V = 0.35 m/s & C = 1000 mg/l

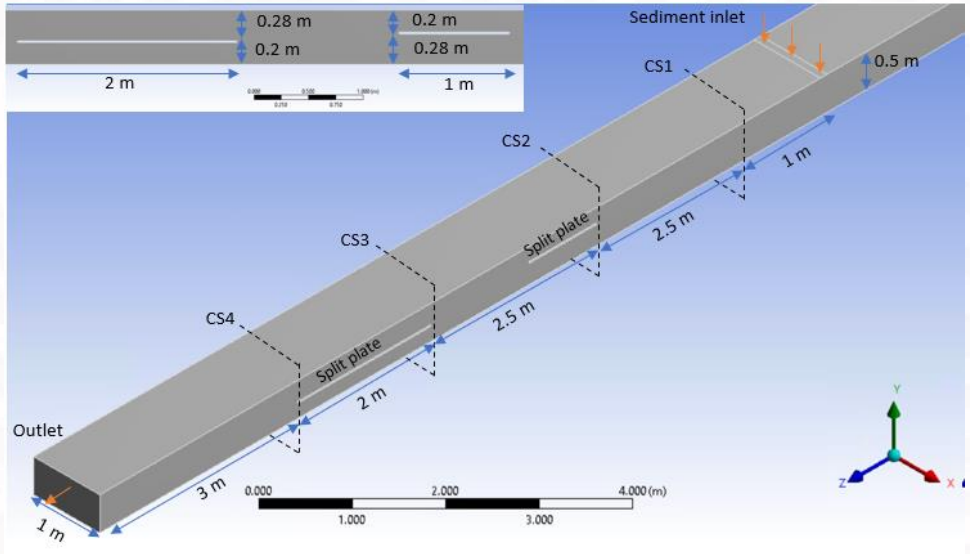


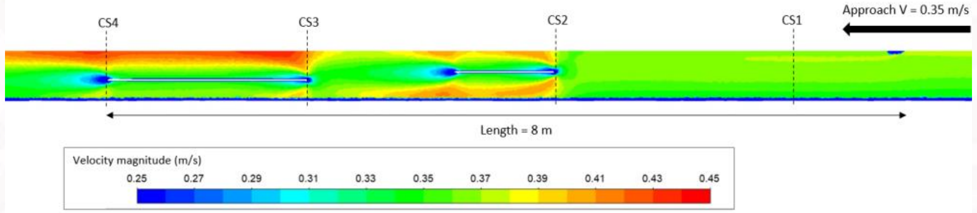
- Results shows majority of suspended sediment concentration passes underneath split plate in numerical model
- a low percentage of concentration passes over split-plate and majority of sediment in suspension passes underneath split-plate, difference in concentration is also visually seen in the bottom left side
- results of simulated sediment concentration coincide with results observed during experimental observations
- during critical flow conditions (in Test 3 where v=vcr=0.35 m/s and c=5000 mg/L), observations in physical model and numerical model consistently shows presence of sediment concentrations beneath split-plate
- This versatility makes the location of the split-plate applicable across a range of scenarios, spanning from flood conditions to drought conditions.

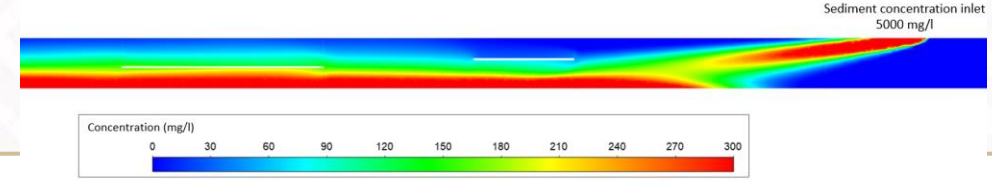
Refining Split-Plate Design

Additional refinement of split plate design & placement was **explored**
- aim to **visually investigate** distribution of flow velocity & suspended sediment concentration
- in an attempt to enhance efficiency and performance of Split-and-Settle sand trap

Consecutive plates







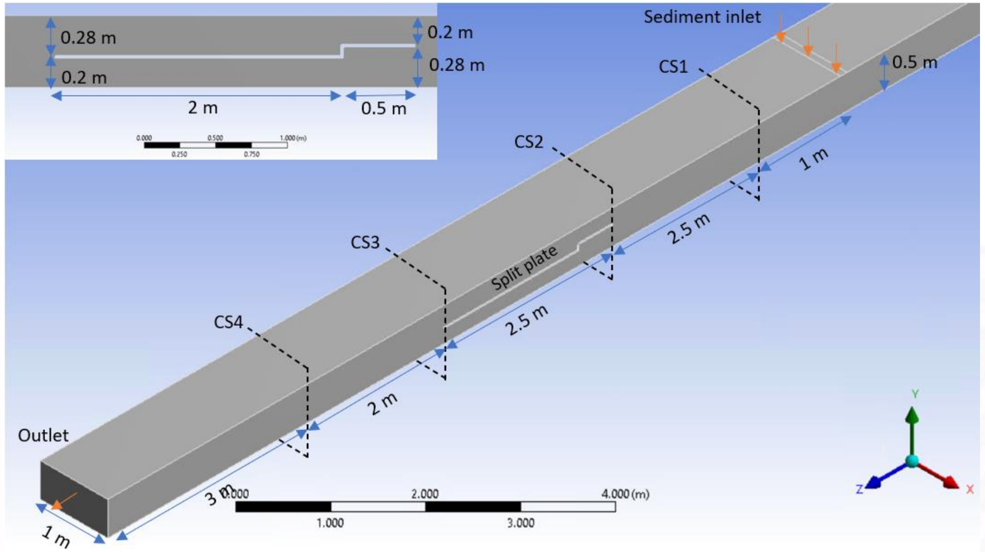
Consecutive plates:

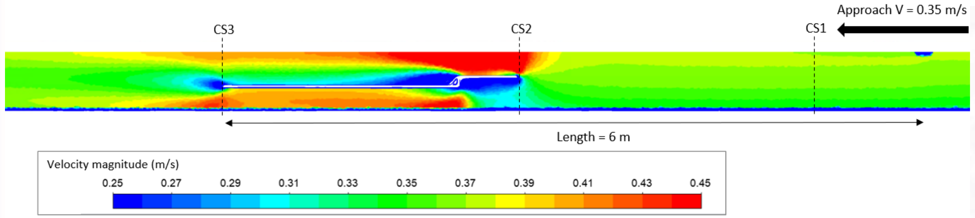
introducing a second plate did not effectively address sediment deposition concerns, due to occurrence of high velocities downstream of first plate, and elevated localised turbulence caused by end of first plate causing sediment resuspension. Nonetheless, it was observed that placement of first plate did enhance sediment concentrations beneath it.

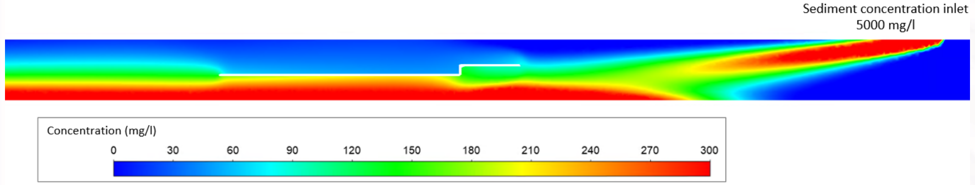
Conclusion

- Visual inspection of results took place should be quantitively analysed further
- Results should be validated by experimental results
- Effect of split placement at 40/60% or 20/80% should be further investigated

Optimised plate design to shorten total trap length







Optimised plate design to shorten total trap length:

The optimised split-plate design is successful in aiding the suspended sediment concentration from the upper plate towards the lower part of the split plate as seen in the suspended sediment concentration distribution BUT: drop in split-plate could have direct implications on 40/60% split in flow across top and bottom.

Main Objective 2 Conclusions & Contribution to Engineering Science

- **Physical Model investigation of Split-and-Settle Sand trap**
  - **The "split-and-settle" concept developed by Støle (1993) validated**
    - The concept was validated by the observations and measurement results from the physical model investigation. The results indicated that the placement of the split-plate for the test conditions, allowed for 80% of suspended sediment concentration to pass underneath the plate and 20% above the plate.
  - **Novel methods of Sediment concentration inlet and suspended sediment concentration measurement**
    - Demonstrated and validated a novel method to introduce specific sediment concentrations into a flume for physical model experiments through a hopper design with distributed outlet holes by applying gravity driven flow rate of granular materials equations derived by Beverloo et al. (1961) and Sui et al. (2017).
    - Demonstrated and validated a novel method to collect depth-integrated suspended sediment concentration samples in a flume study by adapting a design of Transverse Suction System developed by Bosman et al. (1987) by making use of ball-valves to control flow velocities in syphon tubes.
  - Generated a set of good experimental data of velocity and suspended sediment concentration around a split-plate that can be used for future studies.
- **Numerical Model investigation of Split-and-Settle Sand trap**
  - 3D model was used & further calibrated to fit experimental data of 1 test condition of the Split-and-Settle sand trap model. The model was then validated by other test conditions.
  - hydrodynamic model performs reasonably well in replicating the velocity profiles, at both the centre line and sideline, observed in the laboratory measurements
  - Sediment concentration profile simulated shape of the profiles and the calculated concentration values resemble those observed in the upstream side of the split-plate and above the split-plate **BUT** the sediment concentration values below the plate could not be accurately modelled.
  - Can be used for optimised design refinement, but needs to be validated by further experimental results
- **Additional refinement of the split-plate design and placement by numerical modelling**
  - Visually investigated the distribution of flow velocity and SSC in order to enhance the efficiency and performance of the Split-and-Settle sand trap – This was not validated by experimental results and should be quantitively analysed further.

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Recommendation for future studies

- **Further Settler design guidelines for flushing & volume**
  - Investigate numerical model's capacity for simulating high loads of sediment concentration flushing
  - Extend guidelines for seasonal flushing schedules with estimated inlet concentrations
  - Provide information on critical flow velocities required to effectively flush deposited sediment
  - More accurately determine required volume with estimated inlet concentrations
- **Use of Split-and-Settle Sand Trap numerical model for design refinements**
  - Recommended to further calibrate and validate the model with more experimental results to improve the results of the sediment concentration distribution below the split-plate.
  - The model would then be able to be used for optimised design refinement
    - precise placement of split plate: height and distance from inlet
    - for various sediment sizes (and mixtures) and flow conditions
    - Multiple plates, slope, design refinements
  - In current study: flow velocity and sediment concentration distribution was visually analysed for refined split-plate
  - Recommend: quantitative analysis conducted on the results
  - Investigate the effects of turbulence and vibrations generated by the split-plate
- **Extend capabilities of Numerical model**
  - explore sediment transport and deposition of multiple sediment fraction sizes
- **Case study for enhanced efficiency of sand trap:**
  - Recommend: Using Split-and-Settle plate to enhance existing ineffective sand traps
  - By making use of the numerical model

Thank you
Enkosi
Dankie

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Photo by Stefan Els