

# Comparing the flow dynamics and particle settling in full-scale sedimentation tanks of different lengths

S. Arendze and M. S. Sibiyi

## ABSTRACT

The efficiency of sedimentation is dependent on settling tank design and operation, where the streamlined solid–liquid separation results in water of safe potable quality. It is therefore important that the tank design and operation are sufficiently optimised. Sedimentation tanks are commonly overdesigned, leading to unwarranted capital expenditure, and overloading. This study used computational fluid dynamics to model the current conditions of two full-scale sedimentation tanks of different lengths at a large drinking water treatment plant in South Africa, using the shear stress transport turbulence model. The flow dynamics and the polyelectrolyte flocculated particle settling efficiency between the short tank and the long tank were compared. Recirculation zones near the inlet were pronounced in the short tank, which resulted in particles being drawn towards the outlets. The flow in the long tank isolated the inlet and outlet, with low particle volume fractions and particle velocities at the weirs. The particle removal in both tanks was greater than 99%; however, removal was higher in the long tank (99.86%), hence it was more efficient despite greater infrastructure cost. Computational fluid dynamics modelling is a tremendous operational tool which can review the performance of alternative tank designs and provide valuable input into future design.

**Key words** | computational fluid dynamics, operational application, particle settling, rectangular sedimentation tank, sedimentation, water treatment

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## INTRODUCTION

The multi-barrier approach in water treatment ensures that the failure of one barrier can be compensated by effective operation of the remaining barriers, thus minimising the likelihood of contaminants passing through the treatment system (LeChevallier & Au 2004). To ensure that a water treatment plant (WTP) delivers safe, high quality drinking water that adheres to water quality regulations in a cost-effective manner, it needs to ensure that all barriers needed for treatment are adequately optimised. The sedimentation process is a crucial and important step in water treatment (Corbitt 1998), as this is where the bulk of suspended matter is removed. Sedimentation is a physical solid–liquid separation process that involves the removal of particulate matter, chemical floc, and precipitates produced during the

coagulation process from suspension through gravity settling (Hammer 1975). The efficiency of sedimentation is dependent on the tank design and operation. The correct operation allows for undisturbed efficient sedimentation which results in water of a safe potable quality that protects public health, while poor operation can result in contaminants passing through to the water delivered to the community; hence it is important that the process is sufficiently optimised and cost-effective (AWWA 1990; US EPA 1998).

Sedimentation tanks are commonly overdesigned, leading to unwarranted capital expenditure, sludge production, and overloading of subsequent treatment processes like filtration and disinfection (Lemmer & Du Toit 2004). Good sedimentation tank design involves a good

understanding of the hydrodynamics which occurs during the process (Al-Sammaraee *et al.* 2009). The performance of sedimentation is governed by operational factors which fall into one of two categories, i.e. particle characteristics and hydraulic factors (Schutte 2006). Particle characteristics are dependent on the efficiency of the coagulation/flocculation process and include particle concentration, size, nature, density and strength of the flocculated particles, all of which have a direct effect on the particle settling velocity during sedimentation (Schutte 2006). Hydraulic factors include flow rate, residence time, geometry of the tank, inlet and outlet conditions, sludge concentration and the sludge removal mechanism (Schutte 2006).

There is a large body of research on tanks in waste-WTPs. Larsen (1977) was one of the first to apply computational fluid dynamics (CFD) modelling to several secondary clarifiers. Shamber & Larock (1981) used a finite volume method to solve the Navier-Stokes equations, the  $k - \epsilon$  model equations and to model solid concentration settling in a secondary clarifier. Imam *et al.* (1983) applied average particle velocity and fixed settling velocities to a primary sedimentation tank. McCorquodale *et al.* (1991) used a combination of finite element and finite difference methods to develop a model for clarifier performance. McCorquodale & Zhou (1993) developed a two-dimensional model for a circular clarifier which included hydraulic and solid particle models.

In terms of modelling of sedimentation in drinking water treatment, Van der Walt (1998) was one of the first to develop a three-dimensional model in FLO++ that simulated the sedimentation process and used it to model an existing sedimentation tank at the Vaalkop purification plant. Van der Walt (2002) also demonstrated how CFD modelling can be used as a design tool to optimise several aspects of process tanks in a South African context. Lemmer & Du Toit (2004) followed a similar approach and developed a CFD model using FLO++ for a sedimentation tank at the Midvaal purification works.

Goula *et al.* (2008) applied CFD simulations to evaluate the effect of adding a feed flow control baffle to a full-scale circular tank for potable water treatment. Al-Sammaraee *et al.* (2009) studied a full-scale longitudinal sedimentation tank using CFD large-eddy simulation modelling to determine the particle settling performance. Tarpagkou & Pantokratoras (2013) studied the three-dimensional

hydrodynamics and flow behaviour of an experimental sedimentation tank by modelling the momentum exchange between the water and solid particles using a Lagrangian method with two-way coupled calculations.

In terms of drinking water treatment, CFD modelling for full-scale WTP applications has been limited. Most research in CFD modelling has focused on the theory behind the models and less on the operational application of the models, to WTPs. The CFD modelling of horizontal sedimentation tanks studied in the research listed was either at an experimental scale, or of a smaller scale than the sedimentation tanks that are described in this paper.

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## STUDY AIMS

The main aim of this investigation was to model the current conditions in two full-scale sedimentation tanks of different lengths at a large drinking-WTP in South Africa, using the shear stress transport (SST)  $k - \omega$  two-equation turbulence model in ANSYS FLUENT to compare the flow efficiency between the two tanks. An additional aim was to add a secondary phase to the model to account for the addition of flocculated particles, and to use the results to advise on operational optimisation and design specifications for future expansions.

This research investigated whether, under the same design conditions, the length had a major impact on the sedimentation efficiency. The short-length sedimentation tank has the benefit of having a lower infrastructure cost, while the longer-length sedimentation tank has the benefit of having a greater length for particles to settle out. It might be argued that a longer tank is always the better option; however, this could mean that a design is overly conservative and that excessive costs are incurred (Van Der Walt 2002), especially if the performance of the shorter tank in terms of settled water quality meets acceptance criteria.

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## METHODS

### CFD model

The computerised analysis of the flow in the sedimentation tanks was undertaken using ANSYS FLUENT version 12.1,

which is commercially available CFD software. The flow through the sedimentation tanks was assessed using the average flow magnitude and performance. This was achieved by averaging the basic Navier-Stokes equations to separate out the numerous scales of the turbulent flow, which results in the Reynolds Average Navier-Stokes (RANS) equations. The RANS equations are not closed and include the Reynolds stress tensor term, which is modelled separately using a turbulence model of the mean flow, in order to solve the equations (El-Beherly & Hamed 2009).

There are various turbulence models for the computation of the Reynolds stress tensor term including the  $k - \epsilon$  model, which assumes that the flow is fully turbulent and that viscosity is insignificant, and the  $k - \omega$  model, which takes into account the turbulent kinetic energy and the specific dissipation (El-Beherly & Hamed 2009). This study used the two-equation SST  $k - \omega$  turbulence model. The SST  $k - \omega$  model was developed by Menter (1993) and combines the independence of the  $k - \epsilon$  model in the free-stream with the sensitivity of the  $k - \omega$  model near the boundary region. The SST  $k - \omega$  model is used to effectively depict low Reynolds numbers flow (Goula *et al.* 2008), which is applicable to the two sedimentation tanks modelled in this study.

The model which was developed was calibrated using full-scale data. Calibration was done under steady-state conditions using online flow velocities, turbidity measurements, and sludge levels. Velocity, turbidity and sludge profiles were gathered for various points along the tank, i.e. at the inlets and outlets. These experimental points were compared with the simulated conditions. There was an acceptable level of agreement achieved between the simulated data and the experimental data.

### Operational hydraulic aspects

The efficiency of sedimentation depends not only on the design of the tank, but also on operational hydraulic aspects, including the following:

- Surface loading rate – The surface loading rate is defined as the degree at which the water surface of a treatment tank receives the incoming flow of water, and relates to

the settling velocity of the particles, as particles with settling velocities higher than the surface loading rate will be removed (Symons *et al.* 2000). The surface loading is calculated using Equation (1), where  $v_s$  is the upflow velocity,  $Q$  is the inflow rate and  $A$  the surface area:

$$v_s(\text{ms}^{-1}) = \frac{Q(\text{m}^3\text{s}^{-1})}{A(\text{m}^2)} \quad (1)$$

- Retention time – The retention time is the amount of time the water resides in the tank. It is dependent on depth and gives an indication of the sludge concentration (Schutte 2006). It can be calculated using Equation (2), where  $\tau$  is the residence time,  $V$  is the volume of the tank and  $Q$  is the inflow rate:

$$\tau(\text{s}) = \frac{V(\text{m}^3)}{Q(\text{m}^3\text{s}^{-1})} \quad (2)$$

- Weir overflow rate – The weir overflow rate, also known as the weir loading rate, is the rate at which settled water flows over the outlet weirs, and gives insight into whether the weirs are overloaded, which would lead to inadequate settling conditions in the tank (Symons *et al.* 2000). It is calculated using Equation (3), where  $v_w$  is the weir overflow rate,  $Q$  is the inflow rate, and  $l$  is the length of the weir. The number of weirs is also needed:

$$v_w(\text{m}^2\text{s}^{-1}) = \frac{Q(\text{m}^3\text{s}^{-1})}{l(\text{m}) \times \text{Number of weirs}} \quad (3)$$

### Boundary conditions

The two sedimentation tanks which were modelled were full-scale tanks which are in operation at a large WTP in South Africa. The WTP will be expanding in the near future to cater for the growing population and demand in the area. Source water from the Vaal Dam is treated using the following unit processes: coagulation, flocculation, sedimentation, filtration, and disinfection using chlorine.

The short tank has a capacity of 200,000 m<sup>3</sup> per day while the long tank has a capacity of 250,000 m<sup>3</sup> per day;

the design of the two tanks was the same, with the only differences being the length of the tanks and the inlet baffle configuration. The capacity was the maximum flow that the tank could handle without compromising the water quality. The boundary conditions for the two tanks are shown in Table 1. The fluid properties that were used are shown in Table 2.

### Particle properties

The sedimentation process has two phases; the inflowing water and the flocculated particles. A secondary phase was added to the flow model, to account for the flocculated particles. Only discrete particles are considered in this model, i.e. particles are considered as single units with no significant interactions with other particles. A cationic polyelectrolyte, a diallyldimethyl ammonium chloride (DADMAC) and polyamine and polyaluminium chloride (PACl) blended product

**Table 1** | The characteristics of the two tanks

	Units	Short tank	Long tank
Length	m	200	250
Width	m	50	50
Apparent depth	m	3.30	3.30
Total depth	m	3.80	3.80
Weir length	m	115	140
Number of weirs	–	6	6
Inflow rate	m <sup>3</sup> s <sup>-1</sup>	2.31	2.89
Retention time	hrs	4.56	4.56
Surface loading rate	m d <sup>-1</sup>	20	25
Weir overflow rate	m <sup>2</sup> d <sup>-1</sup>	144.92	148.81
Weir discharge	m <sup>3</sup> s <sup>-1</sup>	1.05 × 10 <sup>-3</sup>	1.05 × 10 <sup>-3</sup>
Weir channel depth	m	805	920
Weir crest height	m	0.055	0.055
Weir height above floor channel	m	3.75	3.75
Sludge extraction velocity	m s <sup>-1</sup>	5.00 × 10 <sup>-6</sup>	5.00 × 10 <sup>-6</sup>

**Table 2** | Properties of the fluid phase in the sedimentation tank

	Units	Water
Density	kg m <sup>-3</sup>	998.20
Viscosity	kg m·s <sup>-1</sup>	1.00 × 10 <sup>-3</sup>

was used to model the flocculated volume fractions within each tank.

Table 3 shows the flocculated particle properties that were input into the CFD models. The settling rate was determined experimentally using settling cylinder tests. The flocculated particles were introduced as a granular fluid with the same viscosity as water, but with a higher density, as the sludge is extracted when the sludge concentration is 40,000 mg L<sup>-1</sup> (4% mass over volume). The particles were simulated in a two-dimensional scale. The particle extraction rate was assumed to be the same across the entire bottom surface of the tanks.

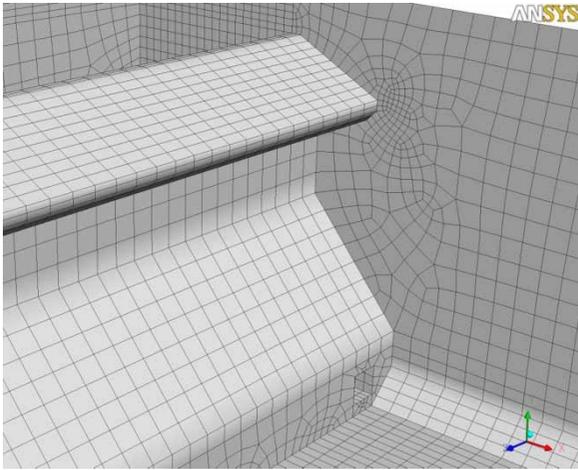
### The grid

The modelled geometry of the two tanks was identical, with the exception of the difference in length. The inlets consisted of small holes at the bottom of the tank, where water enters vertically upward; and the water then flows over a baffle into the sedimentation channels. Sludge is removed through a sludge removal bridge, which pumps sludge out of each channel, once the sludge has a concentration of 4% mass over volume. The clean water flows out through the overflow weirs located at the end of the tanks on the surface.

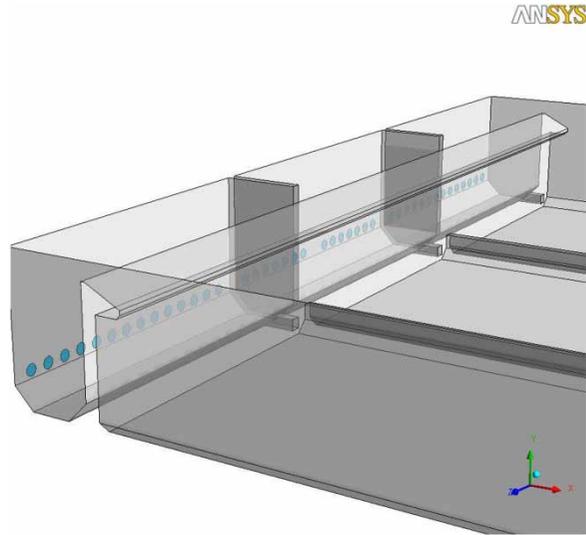
From design drawings of the two sedimentation tanks, a 3D model of the geometry and mesh was created electronically using ANSYS GAMBIT v2.4, such that the exact conditions were represented in the model. The ANSYS GAMBIT software generates a mesh, based on the input variables, to approximate the geometry. A section of the mesh at the inlet is shown in Figure 1. Figure 2 shows an

**Table 3** | Property of the flocculated particles using lime-ferric and polyelectrolyte as coagulants

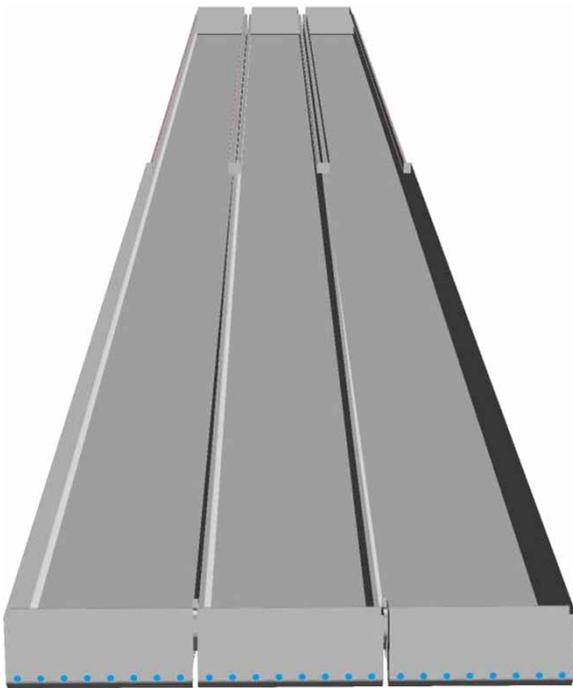
	Units	Polyelectrolyte flocculate particles
Viscosity	kg m·s <sup>-1</sup>	1.00 × 10 <sup>-3</sup>
Particle diameter	m	4.45 × 10 <sup>-3</sup>
Settling rate	m h <sup>-1</sup>	9.29
Sludge density at 4%	kg m <sup>-3</sup>	1,025
Volume fraction at the inlet	–	9.76 × 10 <sup>-5</sup>



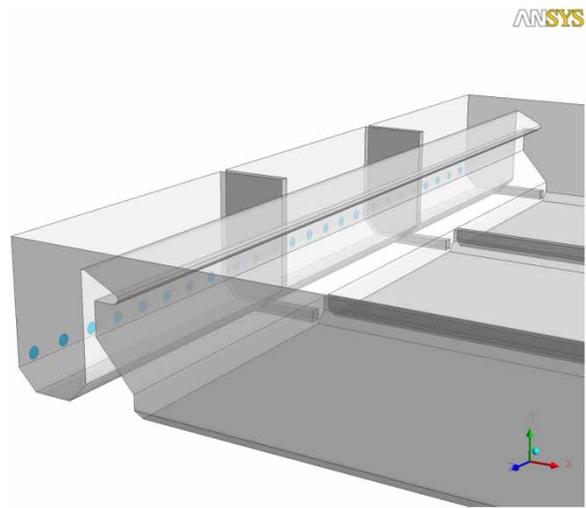
**Figure 1** | A section of the mesh generated by GAMBIT to recreate the geometry of the sedimentation tank.



**Figure 3** | Close-up of the inlet for the short tank showing the P-shaped baffle.



**Figure 2** | The modelled geometry of the long sedimentation tank.



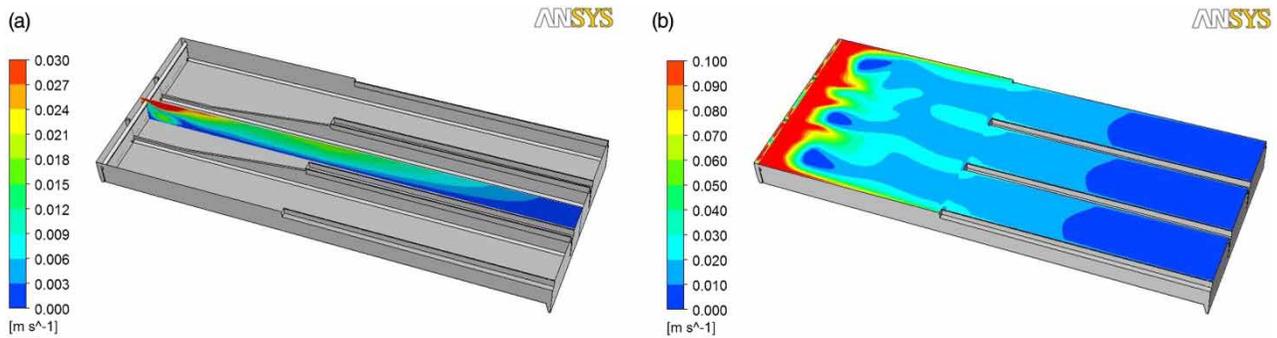
**Figure 4** | Close-up of the inlet for the long tank showing the R-shaped baffle.

overview of the modelled geometry of the long sedimentation tank. Figures 3 and 4 show close-ups of the inlets for the short and long sedimentation tanks respectively. The short tank has a P-shaped baffle while the long tank has an R-shaped baffle at the inlet channels.

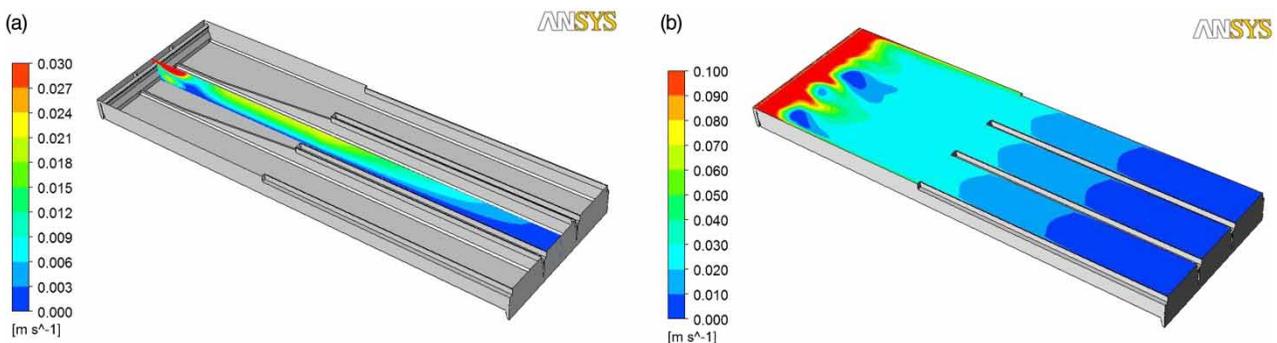
## RESULTS

### Flow dynamics

Figure 5 shows the flow pattern contours and velocity magnitude within the short sedimentation tank; Figure 5(a) shows the velocity magnitude through a vertical cross-section along the length of the short sedimentation tank and Figure 5(b) shows the velocity magnitude on the free surface of the short sedimentation tank. Figure 6 shows



**Figure 5** | Contours of the velocity magnitude within the short sedimentation tank, for (a) a vertical cross-section along the length of the tank, and (b) on the water free surface.



**Figure 6** | Contours of the velocity magnitude within the long sedimentation tank, for (a) a vertical cross-section along the length of the tank, and (b) on the water free surface.

contours of the flow patterns in the long sedimentation tank, along the vertical in [Figure 6\(a\)](#) and on the free surface in [Figure 6\(b\)](#) of the long sedimentation tank.

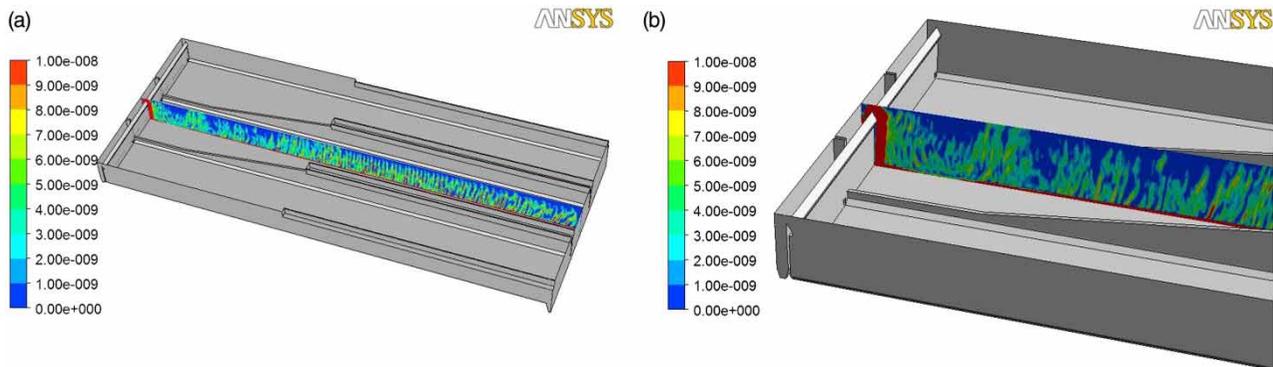
In general the flow velocity gradually decreases along the length of each sedimentation tank, as indicated by the change in colour from ‘warm’ colours at the inlet of the tank to ‘cool’ colours at the outlets of the tank. The incoming flow velocity in both tanks was high, with velocities of  $0.1 \text{ m s}^{-1}$  in [Figures 5\(b\)](#) and [6\(b\)](#). The inlet baffle dampens the incoming velocity, and deflects the flow downward, and forms a slight density waterfall at the bottom of the tank near the inlet. The flow splits soon after the inlet, which results in a recirculation region.

The recirculation zone was highly pronounced in the short tank, as the recirculation had an effect on the surface flows and the flow at the outlet weirs as shown in [Figure 5\(b\)](#). The flow pattern in the short tank indicates that the flocculated particles will likely be dragged towards the outlet weirs. The flow patterns in the long tank were more uniform and the recirculation zones were less pronounced as shown

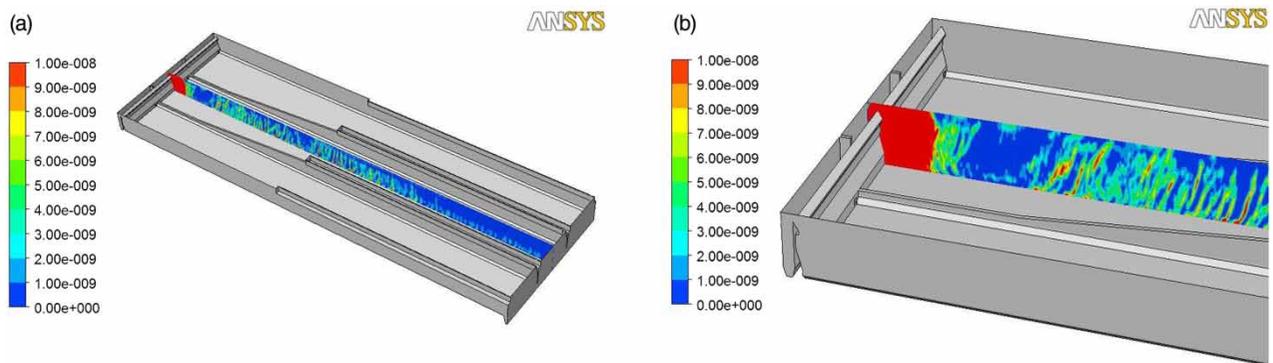
in [Figure 6\(b\)](#). The long tank’s R-shaped baffle and length provided better isolation between the inlet and outlet, which allowed for enhanced sedimentation. The velocity along the bottom of the long tank was low, which indicated that the settling was highly efficient.

### Particles

[Figure 7\(a\)](#) and [7\(b\)](#) show the contours of the volume fraction of polyelectrolyte flocculated particles, through a vertical cross-section and at the inlet of the short sedimentation tank. [Figure 8\(a\)](#) and [8\(b\)](#) show the volume fraction through a vertical cross-section and at the inlet of the long tank. The volume fraction in both tanks was highest at the inlets. The volume fraction then decreased along the length of the sedimentation tanks as the particles settled to the bottom. The recirculation zones observed in the flow patterns seem to be caused by the sudden settling of particles just as the water enters the tanks at the inlets.



**Figure 7** | Contours of the volume fraction of polyelectrolyte flocculated particles (a) through a cross-section along the length of the short sedimentation tank and (b) a close-up of the volume fraction of flocculated particles at the inlet.



**Figure 8** | Contours of the volume fraction of polyelectrolyte flocculated particles (a) through a cross-section along the length of the long sedimentation tank and (b) a close-up of the volume fraction of flocculated particles at the inlet.

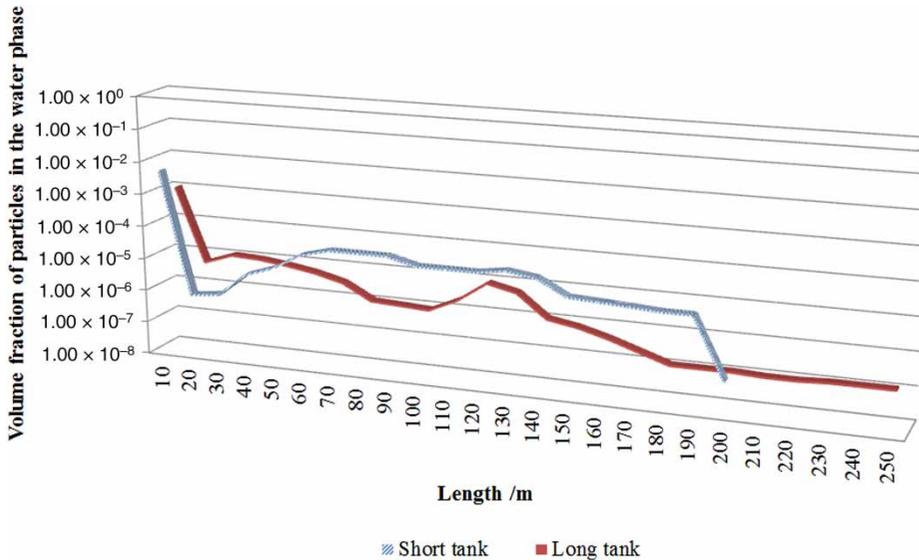
On comparing the two tanks, the particle concentration in the long sedimentation tank remained high for a longer distance as compared with the shorter tank, hence the particles remained in suspension for an extended period of time and particle settling at the inlet was not as rapid. Further, the particles were less concentrated at the outlet of the long tank, as compared with the shorter tank; hence the environment for settling was more stable in the long tank, which suggested better turbidity values at the outlet weirs. The volume fraction contours in the short tank indicated that it was probable that flocculated particles could end up flowing through the outlet weirs, hence the inlet P-shaped baffle and the tank length were less favourable than that of the long tank.

Figure 9 shows the average volume fraction of flocculated particles in the water phase at different lengths of the two tanks. Table 4 is a summary of the volume fractions,

flow rates and percentage removal of particles for the use of polyelectrolyte as coagulant in the tanks.

The particle concentration at the inlets was high, then decreased considerably soon after the inlet at a length of 10 m into each tank. The volume fraction at 10 m was lower in the short tank compared to the long tank. At a length of 40 m, the concentration of particles in the water phase of the short tank increased again, and remained elevated along the length of the tank all the way to the outlet weirs. The sudden decrease and increase in the particle concentration near the inlet was likely due to the inlet baffle P-shaped configuration and the density waterfalls which were more prevalent in the short tank, and which caused pronounced recirculation zones.

The volume fraction in the long tank decreased more uniformly towards the outlet weirs; the long tank provides better separation of the influent and effluent. The particle



**Figure 9** | The average volume fraction of flocculated particles in the water phase along the length of the two sedimentation tanks.

**Table 4** | Volume fractions, flow rates and percentage particle removal at the outlet weirs for the short and long sedimentation tanks

	Length m	Volume fraction -	Particle flow rate $\text{m}^3 \text{s}^{-1}$	Particle removal %
Short	200	$5.03 \times 10^{-7}$	$5.71 \times 10^{-11}$	99.48
Long	250	$1.32 \times 10^{-7}$	$1.87 \times 10^{-11}$	99.86

concentration and the particle flow rate at the outlet were lower for the long tank. Further, the percentage particle removal from the long tank was 99.86%, as compared with 99.48% in the short tank. Hence the long tank was more efficient in terms of solid-liquid separation during the sedimentation process. The key parameters in this study were the inlet baffle conditions and tank length, which also consequently related to the distance from the inlet to the overflow weirs. The inlet baffle configuration was a vital aspect in the uniform settling of particles; the R-shaped baffle was more efficient than that of the P-shaped baffle as the recirculation zones were less prominent. The tank length is an important aspect in the designing of sedimentation tanks, as this study showed that the longer the length of the tank, the more efficient the particle removal was and also the less the likelihood of particles breaking through at the outlet weirs, to affect subsequent processes. However, as particle removal through both tanks was above 99%, it is up to the water treatment facility

to decide if the additional cost of the long tank warrants the minor improvement in particle removal. However, the long tank could prove to be more robust, if there were any operational issues or change in raw water quality, to produce superior final water quality.

## CONCLUSIONS

This study highlighted that the efficiency of sedimentation is dependant on many factors, including hydraulic and particle characteristics. CFD allows for the modelling of these factors and enables process optimisation and operational improvements to be tested practically using a computer. CFD models give visual insight into the flow patterns and the settling of flocculated particles within the sedimentation process, and valuable insight into how the tanks are working. This study highlighted that CFD modelling is an excellent operational tool to review tank design and to assess the expected performance. Further decisions regarding future design specifications can be made based on these models.

A comparative assessment of two full-scale sedimentation tanks with identical dimensions, except for a difference in length and the inlet baffle configuration, highlighted the following:

- The flow patterns indicated that the efficiency of sedimentation was excellent in both tanks with a particle removal efficiency of greater than 99% in both tanks.
- The inlet conditions and the flocculated particle concentration allowed for recirculation zones due to density waterfalls, which were more pronounced in the short tank. These zones could cause flocculated particles to be drawn towards the outlets, which could affect the final potable water quality.
- The long tank provided isolation between the inlet and outlets, which allowed for enhanced sedimentation. Further, the effects of density waterfalls and the recirculation zones were minimal on the flow conditions and particle settling in the long tank. The particle volume fraction and velocity were lower at the outlets of the long tanks. The particle removal was slightly higher for the long tank. Hence even though they may cost slightly more in terms of infrastructure, the longer tanks were more efficient at settling particles.
- The inlet baffle configuration was also crucial to uniform settling as the R-shaped baffle was more efficient than the P-shaped baffle as recirculation zones were less prominent, which allowed for improved sedimentation.
- The tank length was emphasised as an important design consideration for a sedimentation tank design. This study found that the longer the length of the tank, the more efficient the particle settling was. Further, the likelihood of particles being drawn through the outlet weirs and being carried over to affect processes that follow was lower when the tank length was longer.

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