



# TECHNICAL PAPER

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# Analysis and Design of Sediment Basins

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**Abstract:** Sediment basins are typically designed based on ideal settling theory, with a factor to account for turbulence. The advantage of this approach is that it is simple to use, and will often yield a reasonable approximation to actual sediment removal efficiency. However, ideal settling theory does not quantify turbulence, and various empirical and analytical methods have previously been proposed to estimate basin performance. A numerical model for computing efficiency of sediment basins is presented and is compared to these methods. The model is solved using a spreadsheet and yields similar results to Camp's (1946) detailed analytical approach. The comparison indicates that when basins are sized using ideal settling theory with typical turbulence factors, up to 15% of the target sediment particles may not be removed.

**Keywords:** Sediment basins, settling efficiency, turbulence, numerical simulation.

## 1. INTRODUCTION

Water engineering comprises facilities to collect, divert, convey, store, or discharge water in a controlled manner. The presence of sediment can hinder the performance of the water management facilities (Janssen, 2003), and can have a detrimental impact on downstream receiving water bodies. Sediment management should therefore always be considered in water engineering, and may include preventing the intake of sediment; removing sediment from water; transporting sediment through water conveyances; and discharging sediment in a controlled manner. Sediment basins are one of the most commonly used structures for sediment management, reducing the through-flow velocity to allow settling. For removal of a target sediment particle size with a fall velocity of  $w_s$ , the required surface area of a sediment basin,  $A$ , is typically given by the following relationship:

$$A = \frac{KQ}{w_s} \quad (1)$$

where  $Q$  is the design flow rate and  $K$  is a coefficient to account for turbulence. (1) is based on ideal settling theory described in the Appendix, and  $K$  is typically set to 1.2 (Goldman et al, 1986, as adopted by IEAUS, 1996). This equation is simple to use, but care should be taken since it does not explicitly quantify the impact of turbulence on sediment settling. Increased turbulence in a sediment basin can be expected to reduce sediment removal efficiency.

The assessment of sediment removal efficiency over a range of sediment sizes is important not only to ensure that the design criteria are being met, but also to be able to plan maintenance and cleaning activities. Ideal settling theory is also applied to estimate basin removal efficiency for sediment other than the target size. Although the factor  $K$  can be adjusted to account for turbulence, it is not based on any physical hydraulic parameters. BHRA (1989), Camp (1946), Haan et al (1994) and others present analytical and empirical approaches to quantifying turbulence in sediment basins. The objective of this paper is to compare these approaches and their impact on predicted sediment removal efficiency over a range of sediment sizes. A numerical model for sediment settling in basins has been developed to provide a reference for this comparison.

Janssen (2003) presents other factors that impact sediment settling, including:

- Short-circuiting, where the active flow area does not cover the available basin surface area
- Hindered settling due to high sediment concentrations, requiring adjustment to the fall velocity
- Scour and re-suspension of deposited sediment due to excessive through flow velocity
- Variability in flow rate over time

Quantifying the impact of these factors on settling is beyond the scope of this paper, but these are addressed by others such as BHRA (1989) and Haan et al (1994).

## 2. PERFORMANCE OF SEDIMENT BASINS

(1) is used to size sediment basins for removal of a target sediment size. Performance of a sediment basin is the removal efficiency over a range of sediment sizes. Removal efficiency can be estimated based on ideal settling theory, or on empirical and analytical relationships.

### 2.1 Ideal settling efficiency

For the linear ideal settling behaviour (see Appendix), the efficiency of removal,  $\eta$ , for a sediment size with a fall velocity,  $w$ , is given by the following relationship:

$$\begin{aligned} \eta &= \frac{w}{KV_o} & w < KV_o \\ \eta &= 1 & w \geq KV_o \end{aligned} \quad (2)$$

$V_o$  is the overflow rate based on the basin surface area and design flow rate, as defined in the Appendix. (2) yields the result that 100% of the target sediment particles ( $w=w_t$ ) will be removed for  $w \geq KV_o$ . Assessment of this result is provided later.

### 2.2 Empirical and analytical approaches for basin efficiency

Turbulent velocity fluctuations, especially those in the vertical, will result in mixing and a reduced effective average settling rate. Turbulence will tend to keep sediment suspended, and hence reduce the basin efficiency. Several approaches to providing a more realistic estimate of sediment basin efficiency have been proposed. BHRA (1989) presents the Hazen equation:

$$\eta = 1 - \left[ 1 + m \left( \frac{w}{V_o} \right) \right]^{-\frac{1}{m}} \quad (3)$$

The parameter,  $m$  is used to quantify performance of the settling basin, where  $m=0$  represents best performance, and  $m=1$  represents very poor performance.  $m$  is therefore used to represent all of the non-linear effects, but in itself is not based on any physical characteristics.

The Vetter equation, as presented by Haan et al (1994), is based on high turbulence in the basin, and is given by:

$$\eta = 1 - \exp\left(-\frac{w}{V_o}\right) \quad (4)$$

Neither of these methods quantifies the degree of turbulence based on hydrodynamic criteria.

Camp (1946) discusses in detail the effects of turbulence on settling, and proposes a solution to the turbulence closure equations. Camp uses this to develop an analytical relationship for sediment removal efficiency that incorporates a turbulence term. Since there is no analytical solution to Camp's relationship, this has been solved by trial and error and plotted as settling efficiency curves (Camp, 1946, also shown in BHRA, 1989, and Haan et al, 1994). These curves have been redrawn by BHRA (1989), in which efficiency is dependent on two parameters:

$$\eta = f\left(\frac{w}{V_o}, \frac{w}{U^*}\right) \quad (5)$$

The shear velocity  $U^*$  is a measure of turbulence intensity, and is given by:

$$U^* = \sqrt{gRS_f} \quad (6)$$

where  $g$  is acceleration due to gravity,  $R$  is the basin cross section hydraulic radius, and  $S_f$  is the friction slope, which can be computed from relationships such as Manning's equation.

## 3. NUMERICAL MODEL OF SEDIMENT SETTLING

Valioulis and List (1984), Haan et al (1994), Olsen and Kjellesvig (1999), and others have applied detailed hydrodynamic models to sediment settling. The model presented here is a simplified numerical approach that quantifies turbulence based on Prandtl's mixing length theory applied to flow in open channels. Within this model, suspended sediment transport is solved in a two dimensional vertical plan along the length of the basin.

### 3.1 Velocity profiles

Two-dimensional, uniform, steady state flow conditions are simulated, so that the velocity profile through the sediment basin is constant. The following standard logarithmic profiles (e.g. Simons and Sentürk, 1976) are used to compute the velocity,  $u$ , at a depth,  $y$ , above the bed:

Turbulent Smooth Velocity Profile:

$$\frac{u}{U^*} = 5.75 \log\left(\frac{U^* y}{\nu}\right) + 5.5 \quad (7)$$

Turbulent Rough Velocity Profile:

$$\frac{u}{U^*} = 5.75 \log\left(\frac{y}{k_s}\right) + 8.5 \quad (8)$$

Two cases of sediment settling have been analysed, one with low turbulence (smooth velocity profile) and one with high turbulence (rough velocity profile). The impact of the viscous sublayer on overall settling within the basin is considered to be negligible, and has not been included. In the cases analysed, velocity profile and settling velocity were considered to be independent of sediment concentration, though this is worth further investigation.

### 3.2 Suspended sediment transport equations

Simulation of suspended sediment transport through the basin includes terms for horizontal transport by advection, settling due to gravity, and vertical turbulent mixing. Note that lateral mixing, bed load transport, and flocculation were not included in this sediment transport simulation. The transport velocities given below are mass transport rates per unit cross-section area ( $[\text{kg/s/m}^2]$ ), at a distance  $y$  above the bed, where the concentration is  $C$  ([% by weight]).

$$\text{Horizontal transport velocity} = \rho u C \quad (9)$$

$$\text{Vertical transport velocity due to settling} = -\rho w C \quad (10)$$

$$\text{Vertical transport velocity due to mixing} = -\rho \varepsilon_s \frac{dC}{dy} \quad (11)$$

$\varepsilon_s$  is the mass transfer coefficient, assumed to be equal to the momentum transfer coefficient,  $\varepsilon$ , given by Camp (1946) to be:

$$\varepsilon_s = \varepsilon = 0.075 D U^* \quad (12)$$

For steady state conditions being considered, there is a balance between the three transport terms, which yields the following advection-diffusion equation for sediment continuity in differential form:

$$u \frac{\partial C}{\partial x} - w \frac{\partial C}{\partial y} - \varepsilon_s \frac{\partial^2 C}{\partial y^2} = 0 \quad (13)$$

### 3.3 Computational solution

The sediment continuity equation (13) was discretised into an implicit finite difference form, and solved by iteration on a spreadsheet. For the cases presented here, a uniform rectangular grid size of 1m horizontal by 0.1m vertical was used. The sediment deposited in the basin was computed by summing all the sediment falling vertically from the lower computational layer, using (10). Once the equations had been set up, this proved to be a simple approach to implement, with no programming required.

In developing the above relationships for suspended sediment behaviour, the following assumptions were made:

- Flow velocity is constant across the width of the sediment basin
- Horizontal turbulent diffusion is negligible compared to the horizontal advection, and hence can be ignored
- Sediment is completely mixed at the inlet to the sediment basin, and the sediment concentration at the inlet is constant with depth.

## 4. COMPARISON OF ANALYSIS METHODS

### 4.1 Description of cases analysed

The numerical analysis was conducted for two cases, one with low turbulence (smooth velocity profile) and one with high turbulence (rough velocity profile). The key parameters for each case analysed are summarised in Table 1. Mannings n values for sediment basins will generally be between 0.02 and 0.03, and hence the two cases analysed are considered to be the low and high turbulence extremes of typical sediment basins.

	Low Turbulence Case	High Turbulence Case
Flow Rate, $Q$ [ $m^3/s$ ]	1	2
Target sediment size [ $\mu m$ ]	50	75
Overflow velocity, $V_o$ [m/s]	0.002	0.004
Manning n	0.02	0.03
Shear velocity, $U^*$ [m/s]	0.0014	0.0052

Table 1: Summary of parameters for low and high turbulence cases analysed

The numerical model was used to compute settling efficiency for a range of sediment sizes. In addition, the two parameters in (5) were evaluated and the basin efficiency was read off curves shown in Camp (1946). The sediment basin efficiencies are plotted against the  $w/V_o$  in Figures 1 and 2, for low and high turbulence, respectively. Also plotted is the commonly used case with a turbulence factor of 1.2, and the two extreme cases of quiescent settling ( $K=1.0$ ) and high turbulence Vetter equation.

Figure 1: Plot comparing the sediment removal efficiency for a range of sediment particle sizes, for low turbulence

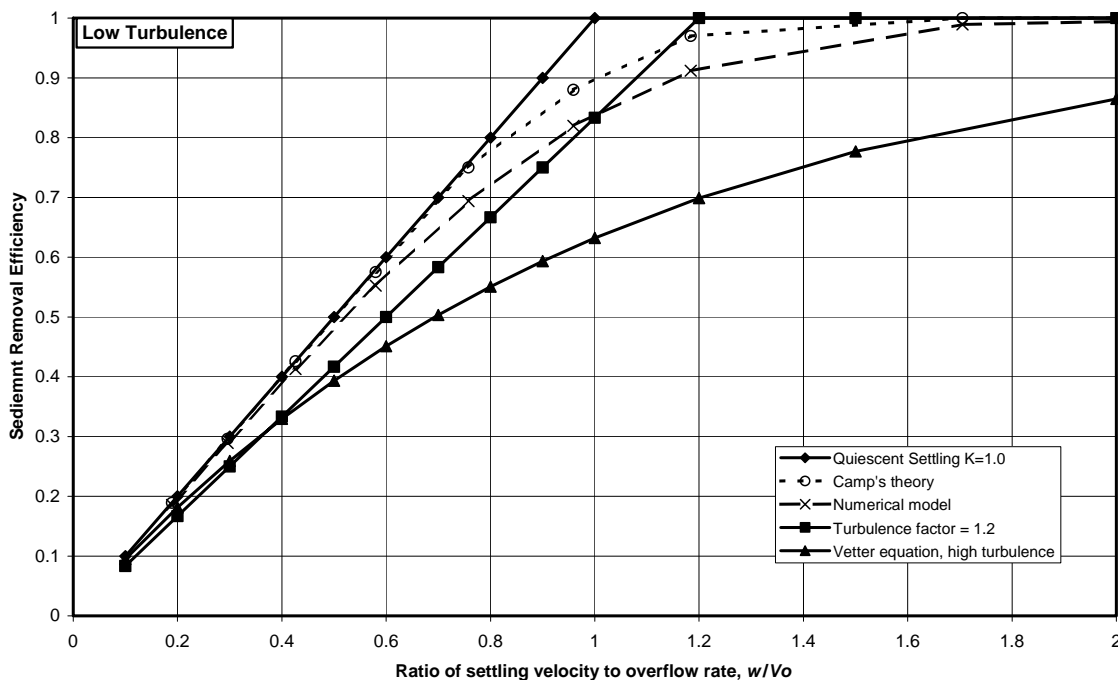
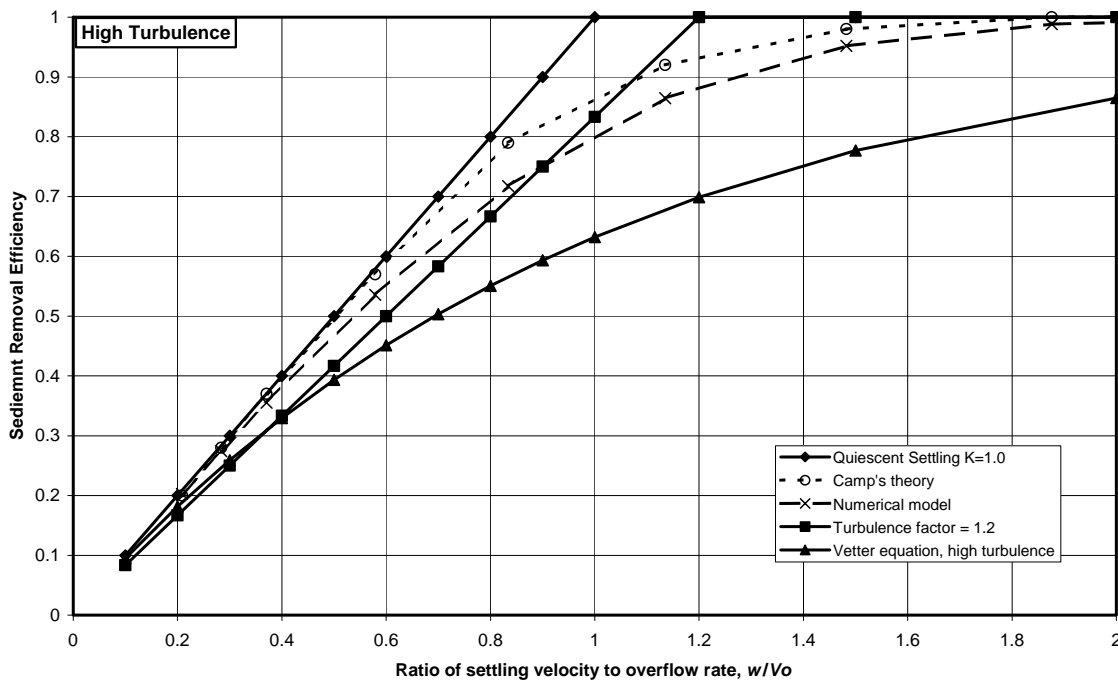


Figure 2: Plot comparing the sediment removal efficiency for a range of sediment particle sizes, for high turbulence



## 4.2 Discussion of results

Plots of the removal efficiencies for the numerical model and Camp's plots have similar shapes, and lie between the quiescent and high turbulence extremes. Settling efficiency predicted by Vetter's equation appears to be for high turbulence not normally expected in sediment basins. The linear plot for a turbulence factor of 1.2 is a reasonable linear approximation to the non-linear plots. In general, use of a turbulence factor of 1.2 tends to under-predict basin efficiency for low values of  $w/V_o$  (smaller than the target sediment size), but over-predicts efficiency for higher values of  $w/V_o$  (approximately the same as the target sediment size and larger). Although under-prediction of basin efficiency may appear to be conservative, this may not be the case when trying to assess sediment storage volumes and maintenance requirements. The example in Section 5 illustrates this impact.

The results in Figures 1 and 2 show that Camp's method predicts higher sediment basin efficiency compared to the numerical model. Since the same mass transfer coefficient given in (12) was used for each method, the difference is likely due to different assumptions regarding velocity distribution and numerical discretisation. However, it is encouraging that the two curves are similar enough to provide a degree of validation.

It is interesting to note that for a basin sized using a turbulence factor of 1.2, a portion of the target sediment size ( $w/V_o=1.2$ ) will not be retained within the basin. Should 100% removal of the target sediment be required, then the factor  $K$  should be increased to between 1.5 and 2 (depending on the level of turbulence), which obviously results in much larger sediment basins. Designers should always consult the performance specifications of the sediment management system that they are designing, to check whether some discharge of the target sediment size is allowable.

## 5. EXAMPLE APPLICATION

The importance of correctly analysing the efficiency of a sediment basin for the full range of expected sediment ranges is illustrated here for the seawater supply to a processing plant in the Gulf of Mexico. Following tropical storm events, the seawater used for cooling was found to contain extremely high suspended sediment concentrations. This high sediment concentration led to abrasion and corrosion of the cooling water pipework and pump impellers, reduction in hydraulic capacity of intake pipelines, blockage of strainers, and deposition of

sediment in the pump sumps. After monitoring the performance of the existing cooling water system, Bechtel engineers presented the owner with a series of capital and operational improvements to the cooling water intake to limit future impacts and extend the life of the existing infrastructure.

Figure 3: Example Application - Suspended sediment concentration in seawater intake

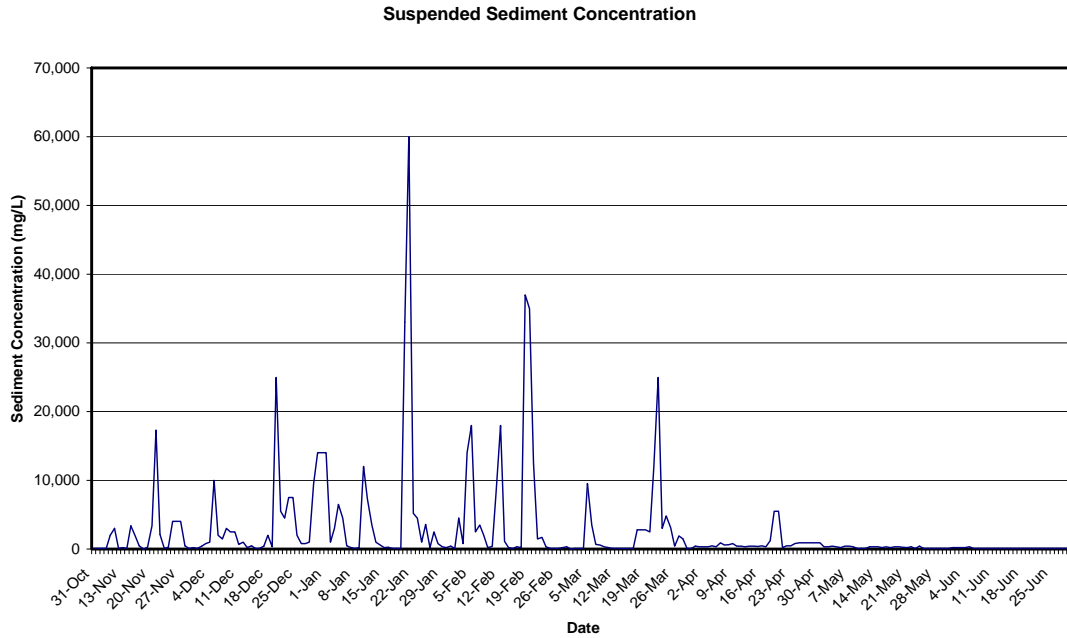
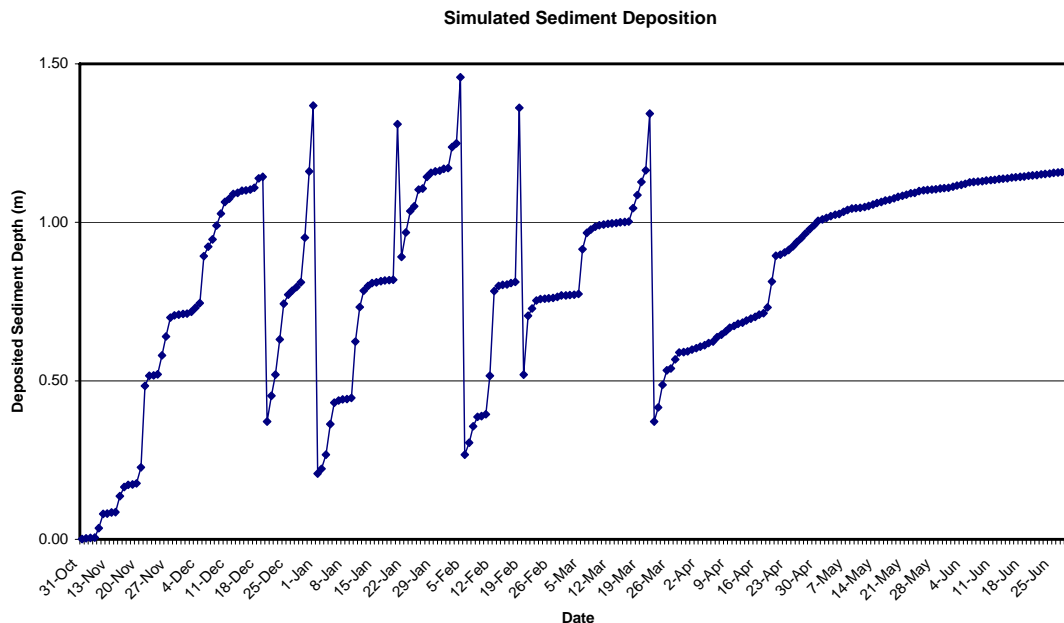


Figure 4: Example Application - Plot of results of simulation of sediment deposition depths in a settling basin



The design flow rate for the water intake was  $1.2 \text{ m}^3/\text{s}$ , and sediment concentrations reached 60,000 mg/L for several days during storm events. Sediment basins were designed for removal of sediment particles  $50\mu\text{m}$  and larger. A fall velocity of  $1.96\text{mm/s}$  was calculated for  $50\mu\text{m}$  particles, taking into account the effects of hindered

settling given the 60,000 mg/L suspended sediment concentration. Using (1) with a turbulence factor,  $K$ , of 1.2, the required settling surface area was determined to be 735 m<sup>2</sup>. Allowing approximately 5% for inactive settling areas, two parallel basins, 77m long by 10 m wide each, were designed. Two basins were used to ensure that water supply would be uninterrupted while one of the basins was being cleaned.

An 8-month record of measured daily sediment concentrations in the water is shown in Figure 3. A sediment basin model based on Camp's (1946) relationship was used to simulate daily sediment deposition over this period of record. A plot of sediment depths in the basin is shown in Figure 4. In generating this plot, it was assumed that the basin would be cleaned when the deposited sediment depth reached 1.5m, and operation would switch to the adjacent basin. The results showed that very rapid filling of the basin during storms, which led to the recommendation that both basins should be cleaned in advance of expected storms.

## 6. CONCLUSIONS

A numerical model for computing efficiency of sediment basins is presented. This model is solved using a spreadsheet and is simple to implement. The numerical model yields similar results to Camp's (1946) detailed analytical approach, which provides a degree of validation. The results of the numerical model and Camp's approach show that Vetter's equation significantly under-predicts efficiency. Further work is required to address the differences between the two sets of results, and sensitivity of the results to the assumptions made. In particular, re-suspension of sediment from the bed is expected to influence efficiency for small sediment sizes (relative to the target size), and hindered settling due to increasing sediment concentration with depth is expected to reduce settling velocity. Both of these impacts can be incorporated into the numerical model in the future.

Sediment basins are typically designed based on ideal settling using (1) with a turbulence factor of 1.2. The advantage of this approach is that it is simple to use, and will often yield a reasonable approximation of actual sediment removal efficiency. However, it is important for designers to be aware of the following:

- Up to 15% of the target sediment particles will not be removed by sediment basin. This fact is often overlooked, and 100% removal of the target sediment size is assumed. 100% removal would require use of a turbulence factor of 1.5 to 2.0.
- Sediment removal of smaller sediment sizes tends to be under-estimated, and larger sediment sizes tends to be over-estimated. This could have a significant impact on overall basin efficiency, depending on the particle size distribution.

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## 8. APPENDIX - IDEAL SETTLING THEORY

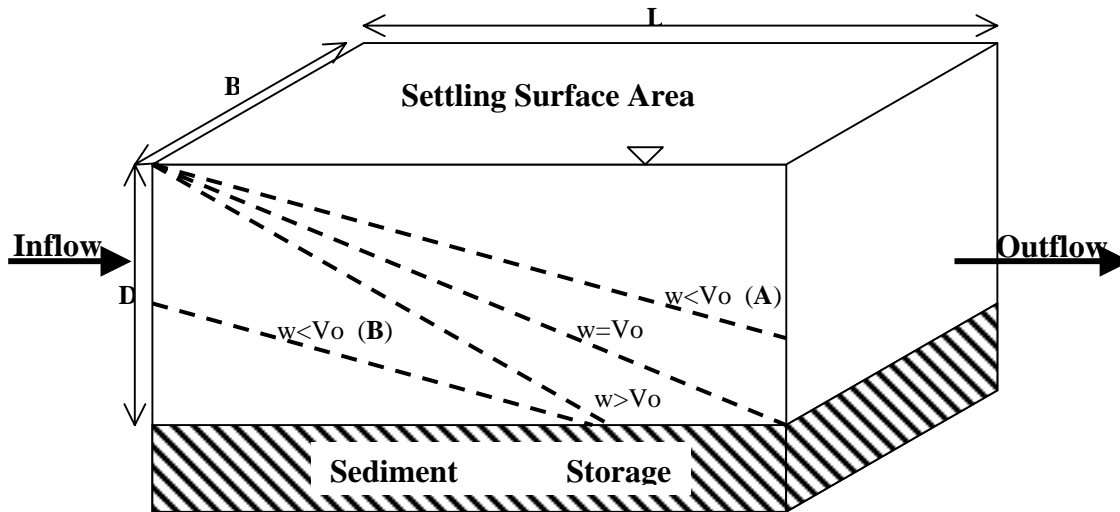
The theory of ideal settling in quiescent conditions is based on the following assumptions:

- There is no scouring or re-suspension of deposited material
- The through-flow velocity is steady and uniform
- Sediment particles settle at a constant fall velocity throughout the basin

For illustrative purposes, the theory of ideal settling will be applied to a rectangular basin, as shown in Figure 5, with a basin width  $B$ , length  $L$ , and depth of the settling region,  $D$ . The cross section average flow velocity (left to right in Figure 5) is assumed to be constant and uniform within the settling region, and is given by:

$$V = \frac{Q}{BD} \quad (14)$$

Figure 5: Schematic section of an ideal settling basin, illustrating linear settling paths of various different sized particles under ideal conditions



The target sediment, with a fall velocity  $w_t$ , is the size for which all particles will just settle in the basin. Equating the time taken for a sediment particle to fall to the bed to the time to be conveyed along the length of the basin, yields:

$$\frac{D}{w_t} = \frac{L}{V} \quad (15)$$

Combining (14) and (15), we obtain:

$$w_t = \frac{Q}{BL} = \frac{Q}{A} = V_o \quad (16)$$

Note that  $A=BL$  is the surface area required for settling under ideal conditions. (1) is obtained by including the factor  $K (>1)$  to adjust the fall velocity for non-quiescent conditions.  $V_o$  is referred to here as the *overflow rate* (not to be confused with the through flow velocity,  $V$ ), also know as the "surface loading" or "surface overflow rate". Settling of various particles under ideal conditions, with fall velocities equal to, greater than, and less than  $V_o$ , is shown schematically in Figure 5. Where the fall velocity is equal to the overflow rate ( $w=V_o$ ), a particle at the water surface at the entrance to the basin will have settled down to the deposition zone by the time it reaches the basin outlet, and hence this particle will be deposited in the basin. Hence, all particles will be removed whose fall velocity is equal to or greater than the overflow rate. Although some particles with fall velocities less than the overflow rate will not be deposited and will exit the basin ( $w < V_o$  (path A) ), there are some particles of the same size that will reach the deposition zone ( $w < V_o$  (path B) ), and hence a certain portion will be removed.