Solution to Secondary Sedimentation Problem by Spreadsheet and VBA

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Abstract

The sedimentation process is one of the most commonly used processes in environmental engineering. Modelling and simulation of secondary sedimentation units usually requires writing mass balance equations for each layer of the settler. Then, the set of ordinary differential equations (ODEs) is solved to obtain solids concentration in each layer of the sedimentation tank. This paper presents implementation of an MS Excel add-in for solving the secondary settling problem. The add-in contains a number of Visual Basic for Applications (VBA) functions, which can be used directly on the worksheet. It is capable of calculating steady-state solution by the multivariate Newton-Raphson method. Also, the add-in is equipped with a VBA function that integrates the set of ODEs until a certain time specified by the user, providing an option for dynamic simulation of the sedimentation tank. The author uses the add-in for teaching settling models in an environmental modelling course. Both students and teachers can benefit from the tool.

Keywords: Wastewater treatment, settling, secondary clarification, simulation, Takacs model

1. Introduction

The field of environmental engineering deals with a wide variety of environmental protection activities including air pollution control, and treatment of water and wastewater. One of the main steps in water and wastewater treatment is sedimentation and it is one of the most commonly employed physical processes in environmental engineering field, which involves removal of solid particles by gravitational forces. Four types of settling processes are usually identified including discrete settling, flocculent settling, zone or hindered settling, and compression settling. These classes of settling processes can be observed under various conditions.

A discrete settling mechanism is usually dominant at low solids concentrations (usually under 800 mg/L) under which conditions the particles are extremely dispersed in the liquid phase and each particle settles at its own terminal settling velocity. This type of settling is usually observed in primary sedimentation units (primary settling tanks, PSTs) in wastewater treatment systems. If particles show flocculating properties, on the other hand, such as in the case of long-chain polymer addition prior to the sedimentation unit, they tend to flocculate and grow in size. Flocculated, larger particles attend larger terminal velocities, however, they still settle as individual particles. This type of settling mechanism is called flocculent settling and is usually observed in water treatment systems and other chemically-enhanced sedimentation units.

A zone or hindered settling mechanism is observed at high solids concentrations (usually above 800 mg/L) when the distance between the particles is so small that inter-

particle interaction forces are sufficiently strong, and particles do not settle as individuals. In this case, particles settle collectively as a zone, forming an obvious interface between the supernatant and the settling zone of particles called the sludge blanket. This mechanism is usually observed in secondary sedimentation units (secondary settling tanks, SSTs) in biological wastewater treatment systems. When the solids concentration increases further (up to at least 3,000 mg/L), the particles usually come into physical contact affecting their settling behaviour further by compressive stress, which is also called compression settling mechanism and is usually observed at the bottom parts of SSTs.

Secondary settling tanks are the units in which biological sludge is removed from the mixed liquor in activated sludge systems. They are usually referred to as the backbone of the process in that they reduce the solids concentration in the effluent and keep the activated sludge within the biological treatment system. Besides, the underflow of the SSTs is a good choice for wasting activated sludge in a concentrated suspension.

Being the most important part of an activated sludge system, modelling of SSTs is also of vital importance. Although one-, two-, and three-dimensional models have been proposed for the simulation over the years, one-dimensional (1D) models have usually been employed in most activated sludge modelling works to save computational power. 1D models for SSTs are usually simple in theory and assume negligible gradients of horizontal velocity and solids concentration. Consequently, the settling process and concentration gradients take place in vertical direction. Therefore, the SST is divided into layers which are considered to be completely mixed [1]. It is the general assumption that solids in each layer move with the bulk flow of wastewater and settle under the effect of gravity at the same time.

Takacs' model [2] of 1D settling models is based on the well-known Vesilind model and updates the settling velocity of particles by a second exponential function, a so-called double exponential model. By the inclusion of a second exponential term, Takacs' model describes the settling behaviour of particles as unsettleable fraction, slowly settling fraction, and rapidly settling fraction [1]. Although a number of other settling models have been proposed [3-7], Takacs' double exponential model remains the most widely used one to date.

The selection of the number of vertical layers in 1D settling models is also of concern. This selection is based on the compression settling behaviour. Vlasschaert [8] stated that simulating the SST with 100 vertical layers gives a good prediction of the sludge blanket while the prediction capability in this case worsens in the compression stage. Although Takacs [9] reported an optimum number of vertical layers as 9, it is common to assume 10 vertical layers in most simulation works.

Considering the importance of secondary settling in activated sludge systems, the author believes that teaching the SST simulation to young environmental engineers must be of great concern. The motivation of this study comes from the need for a reliable open-source tool for SST simulation. This paper presents implementation of an MS Excel add-in for simulating SSTs. The add-in is developed in Visual Basic for Applications 7.1 and is capable of calculating solids concentrations in layers of the settler under both steady-state and unsteady-state conditions.

2. Materials and methods

2.1. Takacs' settling model

Takacs' settling model divides the settler into five distinct regions of different characteristics. These regions are shown in Fig. 1. The top layer of settling tank receives bulk flux of solids from the layer below and bulk flow leaves this layer from the top as the effluent wastewater. At the same time, the concentration of particles in this layer changes due to the settling flux. The second region of the settler is the up-flow region, where part of influent wastewater moves upward, carrying solids toward the upper layers. The layers in this region also receives settling flux from the upper layer and conducts it to the lower layer. The same upward and downward settling fluxes apply to the feed layer, in which a source term is also included. The distinction is that this layer includes bulk fluxes of solids both upward and downward direction which is proportional to the over- and under-flowrate of the settler. The layers in down-flow region show similar behaviour to those in up-flow region with the difference that the bulk flow of liquid and the bulk flux of solids are downward. Takacs' model assumes no settling flux in the bottom layer. This layer only receives settling flux from the layer above.
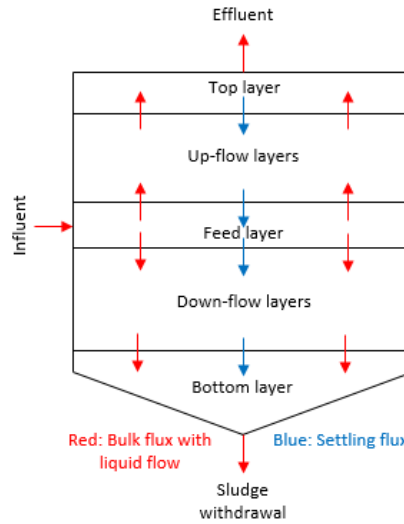

Figure 1: Regions in a sedimentation tank

The mass balance equations for all layers form a set of ordinary differential equations for an N-layered settling tank to which influent wastewater enters through the mth layer. The mass balance equation in each layer is given as follows:

$$\frac{dX_1}{dt} = \frac{1}{h}\left[\frac{q_o}{A}(X_2 - X_1) - v_1 X_1\right] \tag{1.a}$$

$$\frac{dX_i}{dt} = \frac{1}{h}\left[\frac{q_o}{A}(X_{i+1} - X_i) + v_{i-1}X_{i-1} - v_i X_i\right] \qquad i = 2, 3, \dots m\text{-}1 \tag{1.b}$$

$$\frac{dX_m}{dt} = \frac{1}{h}\left[\frac{q_o+q_u}{A}(X_0 - X_m) + v_{m-1}X_{m-1} - v_m X_m\right] \tag{1.c}$$

$$\frac{dX_i}{dt} = \frac{1}{h}\left[\frac{q_u}{A}(X_{i-1} - X_i) + v_{i-1}X_{i-1} - v_i X_i\right] \qquad i = m\text{+}1, m\text{+}2, \dots N\text{-}1 \tag{1.d}$$

$$\frac{dX_N}{dt} = \frac{1}{h}\left[\frac{q_u}{A}(X_{N-1} - X_N) - v_{N-1}X_{N-1}\right] \tag{1.e}$$

where X_i is the solids concentration in the ith layer of the settler, h is the depth of ith layer, X_0 is the inlet solids concentration to the settler, q_o and q_u are over- and under-flowrate, respectively, A is the surface area of the settler, m is the inlet layer, N is the number of layers, and v_i is the settling velocity of solids in the ith layer, which is calculated by Takacs' double exponential model [2] as follows:

$$v_i = MAX\left\{0;\ MIN\{v_0';\ v_0[\exp(-r_h(X_i - X_{min})) - \exp(-r_f(X_i - X_{min}))]\}\right\} \qquad (2)$$

where r_h and r_f are hindered and flocculent zone settling parameters, respectively, v_0 and v_0' are maximum theoretical and practical settling velocities, respectively, and X_{min} is the minimum attainable suspended solids concentration in the effluent which is calculated as the product of fraction of non-settleable solids (f_{ns}) and influent solids concentration as follows:

$$X_{min} = f_{ns}X_0 \qquad (3)$$

The default values of Takacs' settling parameters are given in Table 1 and the change of settling velocity with solids concentration is shown in Fig. 2.

Table 1: Default values of Takacs' settling parameters

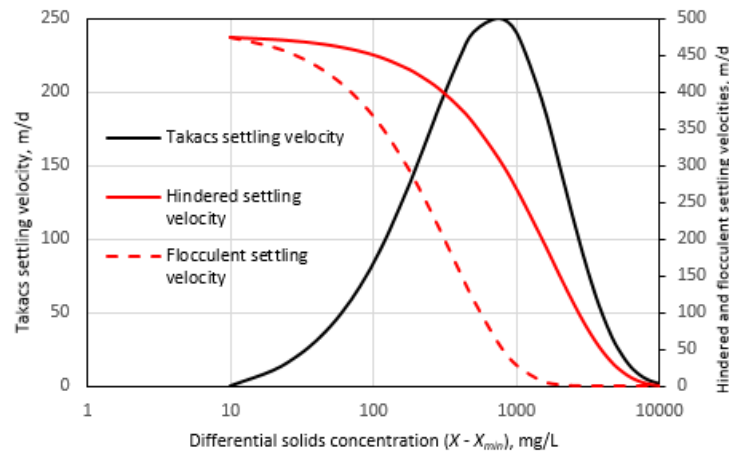| Symbol	Description	Unit	Value
r_h	Hindered settling parameter	m³/kg	0.576
r_f	Flocculent settling parameter	m³/kg	2.86
v_0	Maximum theoretical settling velocity	m/d[1]	474
v_0'	Maximum practical settling velocity	m/d	250
f_{ns}	Fraction of non-settleable particles	–	0.002

Figure 2: Takacs' settling velocity calculated by default values of parameters

2.2. Steady-state solution

The mass balance equations in Eqn. (1) suggest that, starting from random initial values, solids concentration in each layer slowly converges to a unique solution vector

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[1] Metres per day.

([X]) of solids concentrations at which the rate of change of solids concentration in each layer becomes zero as follows:

$$[f] = 0 \qquad (4)$$

where [f] is the vector of the mass balance equations given in Eqn. (1). Theoretically, the settling tank reaches steady-state as the time goes to infinity. Thus, a steady-state solution by integrating the mass balance equations is practically impossible. For this purpose, multivariate Newton-Raphson method (as applied to another environmental engineering problem in [10]), which aims to find out the roots of the set of equations as given in Eqn. (4), can be employed as

$$[X]_{new} = [X]_{old} - rJ^{-1}[f] \qquad (5)$$

where $[X]_{new}$ and $[X]_{old}$ are vectors of the successive estimates of the solids concentrations in each layer, r is a relaxation factor, and J is the Jacobian matrix, which is defined as follows:

$$J = \begin{bmatrix} \dfrac{\partial f_1}{\partial X_1} & \dfrac{\partial f_1}{\partial X_2} & \cdots & \dfrac{\partial f_1}{\partial X_N} \\ \dfrac{\partial f_2}{\partial X_1} & \dfrac{\partial f_2}{\partial X_2} & \cdots & \dfrac{\partial f_2}{\partial X_N} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{\partial f_N}{\partial X_1} & \dfrac{\partial f_N}{\partial X_2} & \cdots & \dfrac{\partial f_N}{\partial X_N} \end{bmatrix} \qquad (6)$$

Multivariate Newton-Raphson method was used to find the roots of mass balance equations in Eqn. (1). Pseudocode of the computational algorithm is given in Fig. 3.
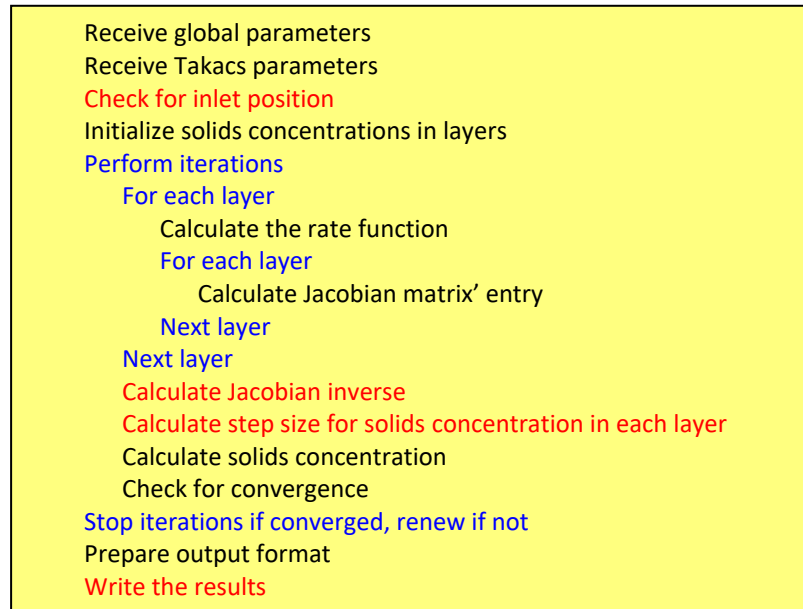


```
Receive global parameters
Receive Takacs parameters
Check for inlet position
Initialize solids concentrations in layers
Perform iterations
    For each layer
        Calculate the rate function
        For each layer
            Calculate Jacobian matrix' entry
        Next layer
    Next layer
    Calculate Jacobian inverse
    Calculate step size for solids concentration in each layer
    Calculate solids concentration
    Check for convergence
Stop iterations if converged, renew if not
Prepare output format
Write the results
```

Figure 3: Steps of computational algorithm for steady-state solution

2.3. Time-dependent solution

Time-dependent solution of the set of ODEs requires simultaneous integration over time step. Although Euler algorithm is the simplest method for accomplishing numerical integration and is used widely [11], this application requires speed and

fourth-order Runge-Kutta (RK4) algorithm was employed for dynamic simulation, by which integration can be achieved faster with larger time steps [12]. The RK4 algorithm can be employed for the current problem as follows:

$$X_i(t + \Delta t) = X_i(t) + \frac{1}{6}(k_{1i} + 2k_{2i} + 2k_{3i} + k_{4i}) \qquad i = 1, 2, \ldots N \qquad (7.a)$$

$$[k_1] = \left[\frac{dX}{dt}\right]\Big|_{[X]=[X(t)]} \Delta t \qquad (7.b)$$

$$[k_2] = \left[\frac{dX}{dt}\right]\Big|_{[X]=[X(t)]+0.5[k_1]} \Delta t \qquad (7.c)$$

$$[k_3] = \left[\frac{dX}{dt}\right]\Big|_{[X]=[X(t)]+0.5[k_2]} \Delta t \qquad (7.d)$$

$$[k_4] = \left[\frac{dX}{dt}\right]\Big|_{[X]=[X(t)]+[k_3]} \Delta t \qquad (7.e)$$

where $X_i(t)$ is the solids concentration in the ith layer at time t, Δt is time step, $[k_1]$, $[k_2]$, $[k_3]$, and $[k_4]$ are vectors for RK4 integration parameters calculated separately for each layer at each time step. Pseudocode of the computational algorithm is given in Fig. 4.
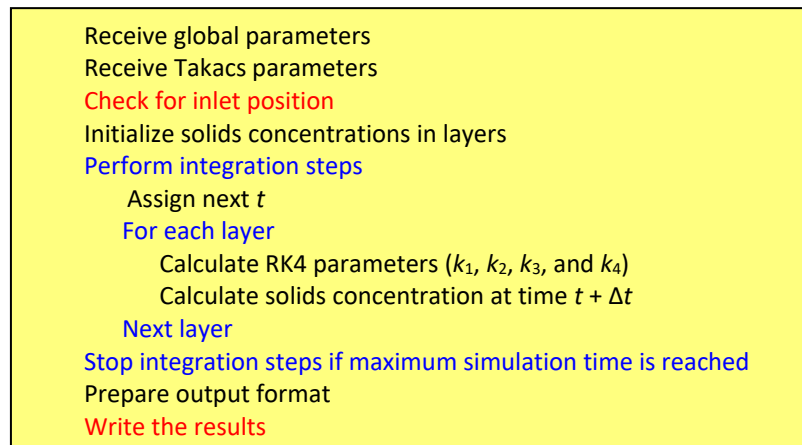

Receive global parameters
Receive Takacs parameters
Check for inlet position
Initialize solids concentrations in layers
Perform integration steps
   Assign next *t*
   For each layer
      Calculate RK4 parameters (k_1, k_2, k_3, and k_4)
      Calculate solids concentration at time $t + \Delta t$
   Next layer
   Stop integration steps if maximum simulation time is reached
Prepare output format
Write the results

Figure 4: Steps of computational algorithm for time-dependent solution

3. Application

The tool was implemented in MS Excel Visual Basic for Applications v7.1 (VBA7.1) and was saved as an MS Excel add-in. An XML part was also added to the add-in to create a custom ribbon for the tool. The XML part is available for MS Excel 2010 or higher. The tool is used together with the third party IntelliSense add-in (available free of charge at https://github.com/Excel-DNA/IntelliSense). The IntelliSense add-in helps create in-sheet tips for user-defined VBA functions, which unfortunately not supported in MS Excel. For installing the add-in the user needs to apply following steps:

- Start MS Excel

- Under the "File" ribbon, click "Options" button

- Click on the "Add-Ins" tab on the pop-up menu and click "Go…"

- Browse for the files xlSST.xlam and ExcelDna.Intellisense.xll. Please note that if the 64-bit version of MS Excel is installed on the computer, the 64-bit version of the add-in, "ExcelDna.Intellisense64.xll" must be used.

- Close all windows by clicking "OK" button. The add-in is ready for use if the xlSST ribbon tab (above the Excel formula bar) is created.

A user form was added to the tool, which can be activated through the custom ribbon tab. The user form can be used to set global parameters and Takacs settling parameters for both steady-state and time-dependent solutions. The user form is shown in Fig. 5. There are five parameters in both pages named "Global" and "Takacs". The number of layers in the settler, the differentiation factor (percent of the value to calculate the differential by central finite difference method), relaxation factor and maximum error for Newton-Raphson iterations, and time step for RK4 integration can be set through the "Global" page. The hindered and flocculent settling parameters, maximum theoretical and practical settling velocities, and the fraction of non-settleable solids can be set through "Takacs" page. The add-in tool receives the model parameters and saves them on a hidden worksheet.

Figure 5: The user form to set model parameters

A total of six VBA functions were created. Five of these are public functions and are accessible through worksheets in the Excel application, while one is defined to be private and is not accessible by the user. Two of the public functions, named GET_GPARAM and GET_TPARAM, were created to view the model parameter. Neither function needs any arguments and each can be used to view the global and Takacs parameters, respectively, on a worksheet by typing "=GET_GPARAM()" and "=GET_TPARAM()", respectively, in any empty cells. Please note that the parentheses cannot be omitted when using functions on spreadsheet. Then, the formulae must be extended to a cell range of 5 by 2. The extension of a formula in MS Excel can be accomplished by the following procedure:

- Select the cell range to extend the formula. The original cell that contains the formula must be on top left of the selected range.

- Open the formula for editing by pressing "F2" key while selection is still active.
- Press "CTRL+SHIFT+ENTER" to extend the formula over the selected range of cells.

The use and the outputs of the functions are shown in Fig. 6.

Figure 6: Model parameter functions. a) The use of functions, b) The outputs of the functions

A public VBA function named TAKACSV was also created for calculating settling velocity. One can use this function by typing its name and arguments. The syntax is as follows:

"=TAKACSV(X; X_min)"

where X is the TSS concentration and X_min is the minimum attainable suspended solids concentration calculated by Eqn. (3). One can prepare a calculation table as shown in Fig. 7 to draw a settling velocity profile as shown in Fig. 2 using Takacs double exponential model in Eqn. (2). The multiplier 86,400 is for converting settling velocity unit into meters per day.

Figure 7: The use of TAKACSV function

A public VBA function named STEADY_SOLVE was created for steady-state solution of the mass balance equations in Eqn. (1). The function employs multivariate Newton-Raphson method to calculate steady-state concentrations of suspended solids in all layers of the secondary sedimentation tank. Similar to the previous functions, the user can employ this function by writing its name and arguments into an empty cell. The syntax is as follows:

"=STEADY_SOLVE($InletTSS$; $OverFlowrate$; $UnderFlowrate$; $SurfaceArea$; $SidewallDepth$; $InletLayer$; [$LayersInRows$])"

where $InletTSS$ is the suspended solids concentration in the influent (mg/L), $OverFlowrate$ is the flow rate of effluent stream (m³/s), $UnderFlowrate$ is the flow rate of

sludge withdrawn from the bottom of the settler (m³/s), *SurfaceArea* is the surface area of the setter (m²), *SidewallDepth* is total depth of the settler (m), and *InletLayer* is the order of the feed layer from top. The argument *LayersInRows* is of Boolean type and optional. It can be used to format the return values of the function. If omitted, the function returns suspended solids concentrations in rows. In order to receive the results in columns, the argument value must be given as "False" or "0". One can prepare a calculation table as shown in Fig. 8 to predict steady-state suspended solids concentrations in all layers. The cell formula for "D2" is

"=STEADY_SOLVE(B1; B2 / 3600; B3 / 3600; B4; B5; B6;)"

and this formula must be extended to the cell range "D2:D11". Note that the dimension of the formula array after the extension must be *N* by 1. After extending the formula and the calculation table is complete, the user can change the value of any arguments in the cell range "B1:B6" to see the effect of that argument on the solids concentrations in layers. The solution is automatically updated whenever a cell value is changed.

Figure 8: The use of STEADY_SOLVE function

For dynamic simulations, one can use the public VBA function named UNSTEADY_SOLVE to calculate suspended solids concentration in each layer at a given time *t*. The syntax is as follows:

"=UNSTEADY_SOLVE(*InletTSS*; *OverFlowrate*; *UnderFlowrate*; *SurfaceArea*; *SidewallDepth*; *InletLayer*; *TheHour*; [*LayersInRows*])"

where *TheHour* is the hour of simulation until which the suspended solids concentrations in all layers are to be integrated, and all other parameters are as defined before. At the start of simulation UNSTEADY_SOLVE function assumes concentrations in all layers as equal to 1% of the influent solids concentration.

Using the UNSTEADY_SOLVE function, one can prepare a calculation table to predict evolution of the sludge blanket with time. For this purpose, the calculation table as shown in Fig. 9 is prepared. The cell range "E2:N2" is filled with the formula in the cell "E2", which is "=0.01*$B2". The UNSTEADY_SOLVE function is used in the cell "E3" as

"=UNSTEADY_SOLVE(B$1; B$2/3600; B$3/3600; B$4; B$5; B$6; D3; FALSE)"

and extended to the cell range "E3:N3". The function calculates solids concentrations in all layers at 0.5 hours of simulation, which is given in the cell "D3". Then, the same procedure is followed to calculate the solids concentrations at 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0 hours of simulation.

Hour of simulation (h)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
0.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	
0.5	=UNSTEADY_SOLVE(B$1;B$2/3600;B$3/3600;B$4;B$5;B$6;D3;FALSE										
1.0											
1.5											
2.0											
3.0											
4.0											
5.0											

UNSTEADY_SOLVE(InletTSS; OverFlowrate; UnderFlowrate; SurfaceArea; SidewallDepth; InletLayer; TheHour; **[LayersInRows]**)
Calculates unsteady-state TSS concentrations in all layers at a given time
[LayersInRows]: *TRUE for layer results in rows*
FALSE for layer results in columns

Figure 9: The use of UNSTEADY_SOLVE function

The results of the simulation in Fig. 9 are shown in Fig. 10. It is clear that solids quickly accumulate in the bottom layer of the settler starting from the beginning. At the end of 0.5 hours, solids concentrations in almost all layers stabilized. In the bottom layer, steady-state conditions reached after 4 hours. In simulations, the sludge blanket quickly evolves just above the fifth layer, which is the feed layer.

Hour of simulation (h)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9	Layer 10	
0.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	
0.5	21.1	33.3	57.6	140.4	698.3	698.3	698.3	698.3	698.3	7503.1	
1.0	21.1	33.3	57.6	140.4	698.3	698.3	698.3	698.3	698.3	7503.1	
1.5	21.0	33.2	57.5	140.4	698.3	698.3	698.3	698.3	698.3	7886.7	
2.0	21.0	33.2	57.5	140.4	698.3	698.3	698.3	698.3	698.3	7886.7	
3.0	21.0	33.2	57.5	140.4	698.3	698.3	698.3	698.3	698.3	7899.7	
4.0	21.0	33.2	57.5	140.4	698.3	698.3	698.3	698.3	698.3	7900.2	
5.0	21.0	33.2	57.5	140.4	698.3	698.3	698.3	698.3	698.3	7900.2	

Figure 10: Time-dependent concentrations of suspended solids in all layers at various simulation times

4. Student Tasks

The simulation results for a settling model are very difficult to foresee prior to simulation due to the complicated nature of the process as well as the mathematical complexity of the equations for Takacs' settling model. Therefore, a steady-state or time-dependent solution to the model equations must be performed in order to see the effects of a changing parameter. Unfortunately, both steady-state and time-dependent solution to the Takacs' settling model requires a great deal of calculations including thousands of integration time steps or several iterations with multivariate Newton-Raphson method. It is impossible to complete even a single simulation as an example during the class hours. This is where the software becomes a great educational tool that help students comprehend the effects of parameters on the separation efficiency of the settler and the formation of sludge blanket with time.

In a classroom setting, the instructor gives an example with the default values of settling parameters and a randomly-set physical design parameters such as influent, effluent, and sludge flowrates as well as influent solids concentrations. After calculating a few time steps for time-dependent solution, or a single iteration for steady-state solution, the instructor makes use of the software to show the simulation results, i.e. the solids concentrations in each layer with time (formation of a sludge blanket) as well as the steady-state concentrations in each layer. The students are then

given the tasks of performing random-trials by setting various physical design parameters and settling parameters and comparing simulation results to comprehend the effects of several parameters on the output of the Takacs' model. The instructor sets the ruling to perform one or two steps of integration by hand calculations.

Although it is possible to implement both steady-state and time-dependent solution on a spreadsheet without using VBA functions [13], the author experienced the difficulties pertaining to the application of this approach for teaching. The students usually have problems dealing with correct implementation of an integration or iteration algorithm on a spreadsheet, and usually make errors in the implementation if not supervised carefully (which is impossible for a homework task), resulting in erroneous simulation outputs and misinterpretation of the effects of parameters on the settling process.

The use of the software overcomes the difficulty of implementing a spreadsheet solution by providing correct simulation results to the students in a very short period of time and allows them to perform more simulations to better understand the process. The software provides the students with an opportunity to focus on the settling process and its simulation by Takacs' model rather than focusing on an implementation challenge.

5. Conclusions

Although a number of models for secondary sedimentation have been proposed over the years, the Takacs model has been the most widely used settling model to date. Due to its simplicity compared to others, it is also a part of environmental engineering curricula. Its implementation and use of an MS Excel add-in was presented in this paper. The add-in includes a number of VBA functions together with their respective in-sheet tips. It allows the user to set parameters. Also, the user can calculate settling velocity of particles depending on solids concentration. The two main functions of the tool, namely STEADY_SOLVE and UNSTEADY_SOLVE, can be used to calculate solids concentrations in layers of the secondary settling tank under both steady- and unsteady-state conditions. The open-source add-in is available for both students and teachers.

References

[1] Holenda, B., Pasztor, L., Karpati, A., and Redey, A. (2006). Comparison of one-dimensional secondary settling tank models. *E-Water*, 2006, 06.

[2] Takacs, I., Patry, G.G, and Nolasco, D. (1991). A dynamic model of the clarification-thickening process. *Water Research*, 25(10), 1263-1271.

[3] Otterpohl, R., and Freund, M. (1992). Dynamic models for clarifiers of activated sludge plants with dry and wet weather flows. *Water Science and Technology*, 26(5-6), 1391-1400.

[4] Hartel, L., and Pöpel, H.J. (1992). A dynamic secondary clarifier model including processes of sludge thickening. *Water Science and Technology*, 25(6), 267-284.

[5] Cho, S.H., Colin, F., Sardin, M., and Prost, C. (1993). Settling velocity model of activated sludge. *Water Research*, 27(7), 1237-1242.

[6] Dupont, R., and Dahl, C. (1995). A one-dimensional model for a secondary settling tank including density current and short-circuiting. *Water Science and Technology*, 31(2), 215-224.

[7] Bürger, R., Diehl, S., and Nopens, I. (2011). A consistent modelling methodology for secondary settling tanks in wastewater treatment. *Water Research*, 45(6), 2247-2260.

[8] Vlasschaert, P. (2013). *Calibration of a novel 1-D secondary settler model*, MSc Thesis, Ghent University, Belgium.

[9] Takacs, I. (2008). Experiments in activated sludge. PhD Thesis, Ghent Univeristy, Belgium.

[10] Demir, S., Duman, S., Manav Demir, N., Karadeniz, A., Lubura, E. (2018). An MS Excel add-in for teaching hydraulics of pipe flow in engineering curricula. *Computer Applications in Engineering Education*, 26, 449-459.

[11] Coto, B., and Suarez, I. (2018). Euler algorithm to solve reaction kinetic equations: Mathematical formulation, programing, and applications. *Computer applications in Engineering Education*, 26(1), 29-36.

[12] Manav Demir, N, Demir, S. (2017). An MS Excel tool for wastewater treatment modelling in undergraduate education: Activated sludge model No. 1. *Fresenius Environmental Bulletin*, 26 (12), 7008-7017.

[13] Tay, K.G., Kek, S.L., Abdul-Kahar, R. (2012). A spreadsheet solution of a system of ordinary differential equations using the fourth-order Runge-Kutta method. *Spreadsheets in Education*, 5(2), 5.