Modeling Full-scale Granular Sludge Sequencing Tank Performance

Peter Dold[1], Bill Alexander[2], Gillian Burger[1], Mark Fairlamb[1], Daniela Conidi[1], Chris Bye[1], Weiwei Du[1]

[1]EnviroSim Associates Ltd., Ontario, Canada
[2]Royal HaskoningDHV B.V., Amersfoort, The Netherlands

ABSTRACT

This paper presents the calibration of a BioWin model to the performance of a full-scale Nereda® nutrient removal plant at Garmerwolde, Netherlands. The approach to modeling granular sludge sequencing tanks (GSST) is discussed. A one-dimensional dynamic biofilm model is merged with a general Activated Sludge/Anaerobic Digestion model (ASDM) and a one-dimensional layered solids flux model in a variable volume unit. The GSST model has been developed to balance pragmatic design with mechanistic modeling rigour. A dynamic solver generates fast solutions and allows interactive design and analysis.
The calibrated GSST model accurately predicts key aspects of the observed full-scale Garmerwolde Nereda® plant over the period from March to December, 2014: sludge production; total system mass, and fraction of the total mass in the granular phase; dynamic biological removal of carbon, nitrogen and phosphorous within the Nereda® tank; aeration requirements; and effluent concentrations.

KEYWORDS: Innovative technology, modeling, nutrient removal, granular sludge sequencing tanks, biofilm.

INTRODUCTION

A granular sludge sequencing tank (GSST) plant model was set up and calibrated to the performance of a full-scale Nereda® nutrient removal municipal wastewater treatment plant at Garmerwolde, Netherlands. The paper includes background information on the modeling approach, and comments on extending the approach for modeling GSST systems beyond what is considered for the Garmerwolde case.

The Garmerwolde plant is comprised of a conventional AB-process and a Nereda® plant that was started up in 2013 (Pronk *et al.*, 2015). The AB-process treats 59% of the total influent flow and the remaining 41% is treated by two parallel Nereda® reactors fed from a common buffer tank. The Nereda® reactors achieve biological nitrogen and excess phosphorus removal, and remove 86% of the influent total nitrogen and 87% of the influent total phosphorous.

The model calibration provides insights on a range of performance characteristics:

- The amounts of granular sludge mass and granular sludge surface area required to achieve a specific process objective.
- The average diameter of the granules (in mm) depending on substrate loading, solids exchange between the granules and the bulk liquid, EPS strength coefficients and the effect of gas (N_2, CH_4, CO_2) generation inside the granules.
- The distribution of soluble and particulate components inside the granules.
- The amount of active biomass within the granular sludge and the distribution of biomass types [Ordinary heterotrophic organisms (OHO), phosphorus accumulating organisms (PAO), ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), *etc.*].
- The development of different growth regimes (*e.g.* aerobic, anoxic, anaerobic) over the granular radius.
- The distribution of the reaction rates for the biological processes (growth and decay of heterotrophic and autotrophic biomass, fermentation, *etc*.) within the granules.
- The effects of pH within the granules on reaction rates and the potential for precipitation.

BACKGROUND

Before presenting the model calibration of the Garmerwolde Nereda® plant, the approach for modeling GSSTs is first discussed. Figure 1 shows the four distinct phases in GSST operation which are simulated in BioWin:

- The cycle starts at the beginning of the mixed phase. Typically, the reactor is full or nearly full at this point. During the mixed phase granular sludge and non-granular mixed liquor are well-mixed. The reactor may be continuously aerated during the mixed phase or may involve unaerated and aerated periods (based on either DO setpoint or air flowrate).
- The settling phase commences when mixing stops. Granules are assumed to immediately form a settled bed on the base of the reactor (with a void volume) and non-granular mixed liquor solids settle on top of the granular sludge bed. Typically waste activated sludge (WAS) is withdrawn from the bottom of the settled non-granular solids prior to commencing feed, resulting in a high concentration of WAS solids (and small volume). The model assumes that granules are never removed directly during wasting; only non-granular solids are wasted from above the settled granular sludge bed. However, there is turnover of granular mass *via* attachment and detachment from the granule surface.
- Influent feed typically commences well into the unmixed settling period. At this point the upper section of the reactor should be well-clarified liquid. Influent is distributed across the base of the reactor (into the granular sludge voidage) and moves in plug-flow mode up through the reactor. At the top level, liquid overflows into launders and is displaced as effluent.

- At the end of the settle/feed phase, prior to commencing the next cycle's mixed phase, there may be a small decant of clarified liquid near the top of the reactor to drop the liquid level below the launders. This prevents spillage of mixed reactor contents when the next cycle starts.

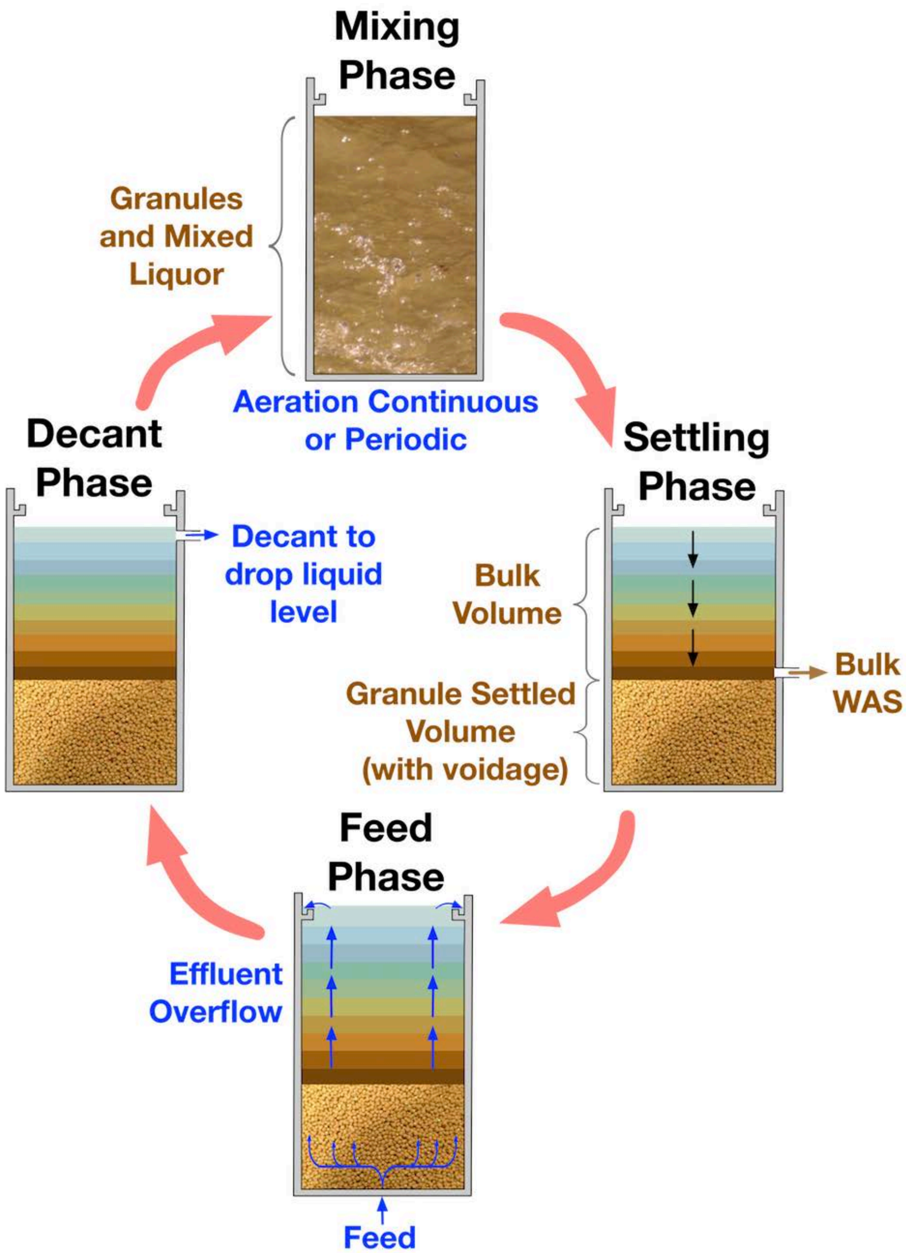

Figure 1. Operational cycle of the GSST.

The GSST modeling approach applies the full BioWin Activated Sludge/Anaerobic Digestion (ASDM) model throughout the variable volume unit. Detailed physical-chemical modeling (pH, chemical precipitation, gas/liquid mass transfer, *etc.*) is included.

BioWin's one-dimensional biofilm model is used to mimic the granular sludge; biofilm thickness is equivalent to granule radius. Settling of mixed liquor (non-granule) solids is based on a one-dimensional solids flux model. The bulk liquid above the bed of settled granules is divided into ***n*** equal-depth layers during settling as shown in Figure 2.

The granular sludge mass is represented by a biofilm with a calculated area and film thickness. The biofilm thickness is assumed to be equivalent to the "average" granule radius. The model does not predict new granule formation or consider a granule size distribution, but the average diameter and composition of granules can change dynamically depending on substrate loading, as well as physical aspects such as solids impingement/erosion.

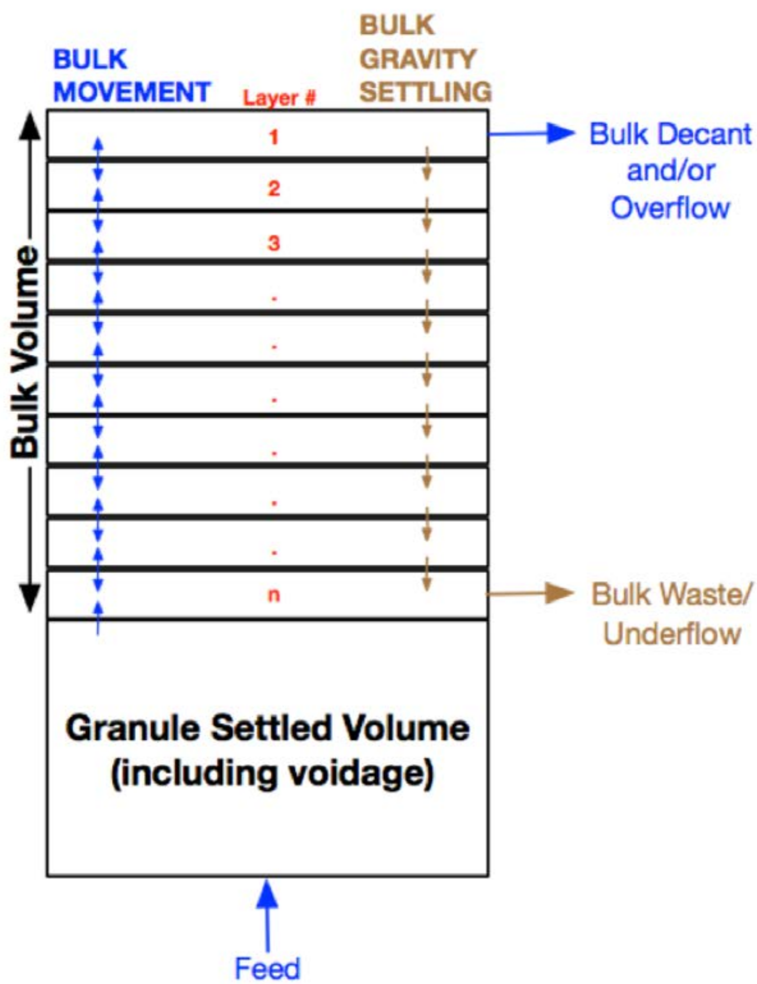

Figure 2. Schematic of the GSST model in settle mode.

METHODOLOGY

A GSST plant was set up in BioWin to represent the Nereda® plant at Garmerwolde, Netherlands, as shown in Figure 3 below. The reported operational and physical plant data was input to the BioWin model (Pronk *et al.*, 2015). The plant has two parallel GSSTs with a total volume of 19,200 m^3 (9,600 m^3 each). The average dry weather influent flow to the Nereda® portion of the Garmerwolde plant is 28,600 m^3/d. The plant was represented in BioWin using a single GSST element with a volume of 19,200 m^3 and depth of 7.5 m.

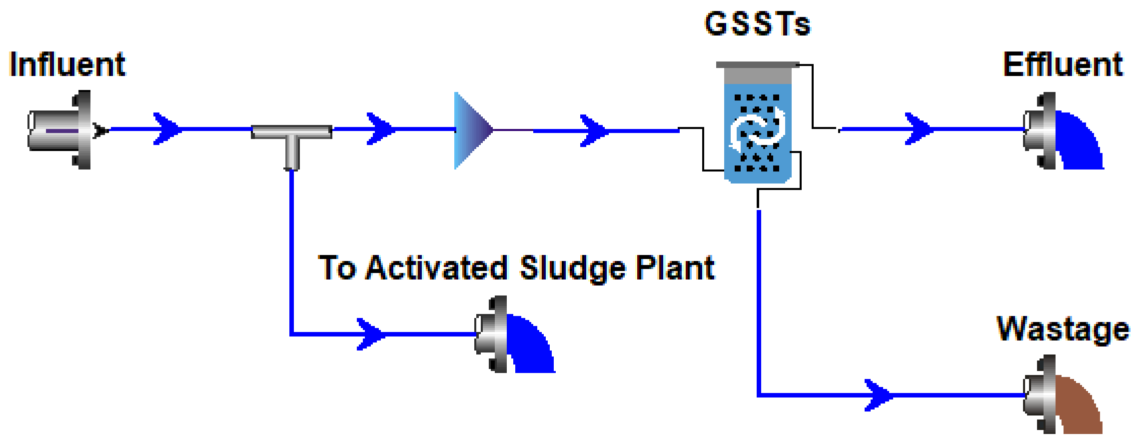

Figure 3. BioWin flowsheet of the Garmerwolde Nereda® plant.

The user specifies initial estimates for the granule diameter (*D*), the granular sludge settled volume fraction (*FG*), and a voidage fraction (*E*) for settled granules, as follows:

- Estimated granule diameter (*D*) [mm]: This sets the initial diameter of the granules at the beginning of a simulation started from seed conditions. The actual diameter is a simulated output and will change from the initial estimate over the duration of a simulation.
- Estimated granule settled volume fraction (*FG*): This sets the initial estimate of the reactor volume (*Vt*) occupied by granules when granules are settled on the bottom of the reactor; this includes the intergranular voidage. This value is applied at the beginning of a simulation from seed conditions. The actual settled volume is a simulated output and will change from the original estimate over the duration of a simulation.
- Voidage (of settled granules) (*E*): This sets the percentage of the granule settled volume occupied by voidage. Although the granule diameter and settled volume are simulated and may change over the course of a simulation, the voidage percent is assumed to remain constant over the duration of a simulation.

These user-defined parameters are used to calculate the base granular surface area (A) [in metric units]:

$$A\ (m^2) = \frac{[FG \times Vt \times (1 - E)]}{\frac{D}{2000}}$$

The base granular surface area and the user-specified voidage fraction are held constant throughout a dynamic simulation. The GSST model dynamically calculates the granular diameter depending on a number of factors such as substrate loading, reactions within the granules, and solids exchange between the granules and the bulk liquid. The granular settled volume fraction of the reactor volume changes proportionally to the model-calculated granular diameter, according to the rearranged base granular surface area equation:

$$FG = \frac{[A \times D]}{Vt \times (1 - E) \times 2000}$$

For the Garmerwolde Nereda® plant, the specifications are: Vt = 19,200 m^3; D = 1.2 mm; FG = 31%; and E = 25%. This results in a base granular surface area of 3,720,000 m^2, and the granular surface area to tank volume ratio is 388 m^2/m^3.

The biofilm thickness in the GSST model is assumed to be equivalent to the "average" granule radius. Although the "average" granule radius was not reported, once the granule bed stabilized, the granular sludge consisted of more than 80% of granules larger than 0.2 mm and more than 60% larger than 1 mm (Pronk *et. al*, 2015). The initial estimate for the granule diameter was therefore selected to be 1.2 mm.

The major operational setting for the GSST is the cycle information. The user specifies the cycle length, when settling starts, when wasting occurs, when influent feed starts, and when the small decant occurs. The Garmerwolde GSST plant was simulated according to the dry weather operational cycle for the full-scale plant, as shown in Figure 4. Thickened mixed liquor is removed from the bottom settling layer of the GSST partway into the settling period, just before the GSST starts feed. Granules are never wasted from the GSST, only non-granular solids. Influent is fed to the GSST from 330 min (5:30) until 390 min (6:30) during each 6.5-hour cycle. A small decant to drop the liquid level to 96.5% of full was included prior to starting the mix/react phase; this prevents spillage of mixed liquor when mixing and aeration commences.

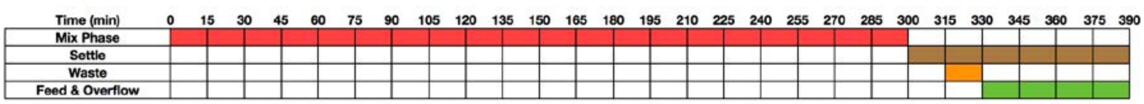

Figure 4. One dry weather cycle of the Garmerwolde Nereda® plant (after Pronk *et al.*, 2015).

At the start of each mixing period, the GSST was aerated at a high DO concentration to nitrify the influent ammonia fed during the previous settle period. Once the ammonia concentration in the GSST fell below a certain level, the DO concentration was reduced to promote simultaneous nitrification/denitrification for the remainder of the mixing period. The react/mix phase in the GSST element sets the maximum time span for aeration; BioWin shuts off aeration in the GSST during the settling period.
Oxygen modelling was applied throughout the simulation.

The "volume exchange ratio" is defined as the volume fed per cycle divided by the liquid volume in the GSST. The average dry weather influent flow to the Garmerwolde Nereda® plant is 28,600 m^3/d and hence the flow to each GSST is half this flow, *i.e.* 14,300 m^3/d. The volume of each GSST is 9,600 m^3. One dry weather cycle lasts 6.5 hours hence there are 3.69 cycles per day. The volume of influent fed to each GSST per cycle is calculated as follows:

$$= \frac{14{,}300 \frac{m^3}{d}}{3.69\ cycles/d} = 3{,}873\ m^3$$

Because each GSST is always operated full or nearly full, it overflows shortly after feeding commences. The volume exchange ratio is therefore calculated as 3,873 m^3 / 9,600 m^3, which is 40%.

The initial bulk mixed liquor concentrations in the GSST were set at the BioWin default values. The initial liquid hold-up was specified as 96.5% of full. Parameter values specific to the GSST element were applied (*i.e.* biofilm, kinetic, diffuser and settling parameters). These values differ from BioWin's global defaults.

The influent parameter concentrations (*e.g.* TCOD, TSS, VSS, TP, TN, ammonia, *etc.*) in the model were set to match the averages for the calibration period, March to December, 2014, reported by Pronk *et al*. (2015). The influent wastewater COD fractions were estimated based on the provided effluent TCOD data and ash content of the sludge.

Operational parameters for the BioWin GSST model of the Garmerwolde Nereda® plant are summarized in Table 1.

Table 1. Operational parameters for the Garmerwolde GSST plant model, for the period from March to December, 2014 (after Pronk *et al.*, 2015)

Parameter	**Units**	**Garmerwolde BioWin model**
Granule diameter	mm	1.2
Granule settled volume of total volume	%	31
Voidage between granules	%	25
Granular surface area in each GSST	m^2	3,720,000
Volume of each GSST	m^3	9,600
Granule surface area to GSST tank volume ratio	m^2/m^3	387.5
Average influent flowrate to GSST plant	m^3/d	28,600

Number of GSSTs		2
Average influent flow to each GSST	m^3/d	14,300
Cycle length in GSST	hours	6.5
Influent volume to each GSST per cycle	m^3	3,873
Volume exchange ratio	%	40
Average influent TCOD concentration	mgCOD/L	506
Average influent TKN concentration	mgN/L	49.4
Average influent TP concentration	mgP/L	6.7

RESULTS

The Garmerwolde GSST plant was dynamically simulated from seed values for an extended period (*e.g.* 4 SRTs) until a quasi-steady-state was reached. Figure 5 below shows how the total solids mass in the system achieves a stable condition.

The Garmerwolde GSST plant model was calibrated against average data reported for the period from March to December 2014. The predicted waste solids mass rate was 4,050 kg/d compared to the reported value of 3,900 kg/d (Pronk *et al*., 2015). This is reasonable given the uncertainty over influent wastewater characteristics. Once the calibrated Garmerwolde GSST plant model reached quasi-steady-state, the predicted SRT was 37 days which is within the reported range of 20 to 38 days (Pronk *et al.*, 2015). The total mass of granules and bulk mixed liquor divided by the GSST tank volume (referred to as the "net TSS concentration") was 9.7 kg/m^3 in the calibrated plant model. This is in line with the reported net TSS concentration of greater than 8 kg/m^3 for the stabilized granule bed (Pronk *et al.*, 2015). The predicted percentage of sludge present as granules in the calibrated plant model was 86% which corresponds to the reported value of greater than 80% (Pronk *et al.*, 2015). The average granule diameter calculated by the calibrated model was 1.2 mm which corresponds with the measured data reported by Pronk *et al.* (2015).

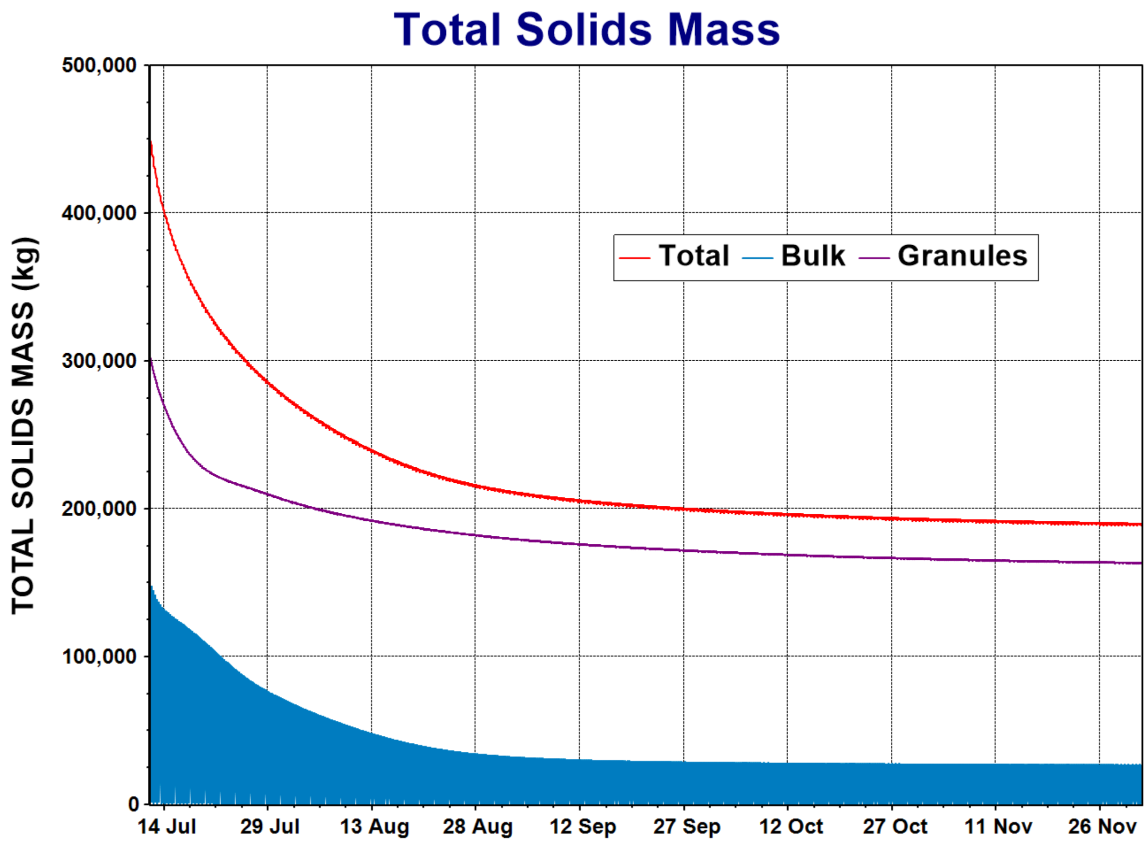

Figure 5. Total solids mass in the Garmerwolde GSST plant simulated for 4 SRTs from seed values.

Once the simulated plant reached quasi-steady-state, the 24-hour flow weighted average effluent concentrations of ammonia, NO_X, TP, sPO_4-P, TSS, *etc.*, were compared to the respective reported values, as shown in Table 2. The Garmerwolde GSST plant model accurately predicted the average effluent concentrations over the calibration period from March to December, 2014. The data show that the plant was achieving biological nitrogen and phosphorous removal. The influent and effluent average TN concentrations are 49.4 mgN/L and 6.9 mgN/L, respectively, which is a removal of 86%. The influent and effluent average TP concentrations are 6.7 mgP/L and 0.9 mgP/L, respectively, which is a removal of 87%.

Table 2. Effluent Concentrations from the Garmerwolde Nereda® Plant, for the period from March to December, 2014 (after Pronk *et al.*, 2015)

Effluent Concentration (24-h flow weighted average)	**Units**	**Garmerwolde (simulated)**	**Garmerwolde (Pronk *et al.*, 2015)**
TSS	mgTSS/L	18	20
TCOD	mgCOD/L	68	64
BOD5	mg/L	4.2	9.7
Ammonia	mgN/L	0.8	1.1
NO_X	mgN/L	4.6	Not reported
TN	mgN/L	7.1	6.9
TP	mgP/L	0.9	0.9
sPO4-P	mgP/L	0.4	0.4

The dynamic behavior in the GSST is quite complex. Figure 6 presents the model-predicted response starting with the 60 minute feed period (during settling) followed by 5 hours of the mixed and aerated period. Aeration commences at the start of the mixed period, initially at a high rate so that DO increased to approximately 1.8 mg/L after one hour. After this aeration was decreased and the DO settled to approximately 0.5 mg/L for the remainder of the mixed period. Figure 6 shows the DO response and the concentrations of ammonia, nitrate and soluble phosphate associated with the biological nutrient removal behavior. Over the first hour influent percolates upwards through the settled granule bed (unaerated), and substantial phosphate release by PAOs is evident. The plotted phosphate line during the feed period of 1 hour tracks phosphate concentration in the voidage of the granular sludge bed. After feed terminates and mixing commences, the plotted phosphate line tracks the concentration in the bulk liquid throughout the reactor. During the feed period, even though the concentration of phosphate in the voidage becomes quite high, it would take significant time for the phosphate to propagate up through the reactor towards the discharge. Aeration commences when influent flow terminates in the cycle, and there essentially is complete uptake of P. Concomitantly ammonia concentration decreases through nitrification, but there is a significant amount of denitrification occurring mainly within the granules.

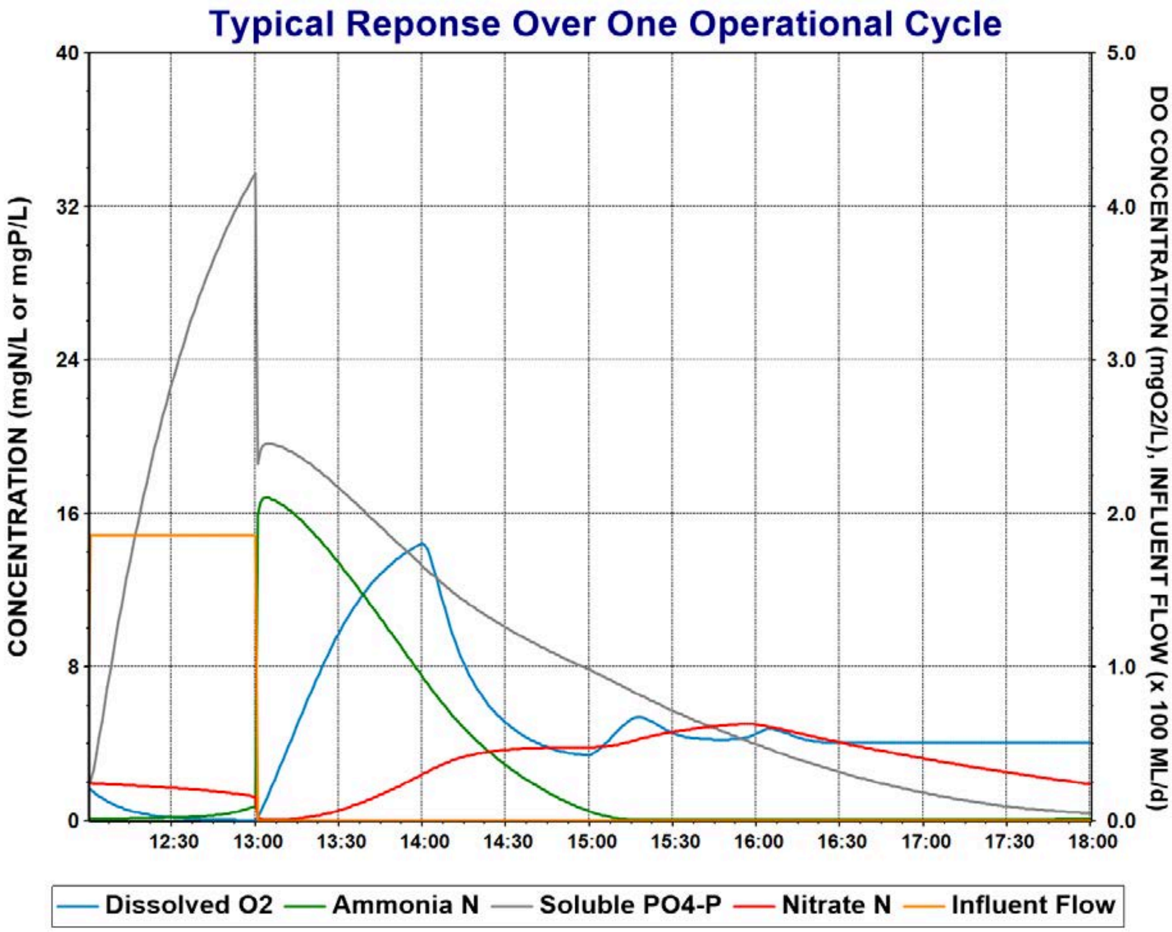

Figure 6. Model-predicted BNR response over one operational cycle in the Garmerwolde Nereda® reactor (*cf*. Figure 6 of Plonk *et al*.).

DISCUSSION

The paper has focussed on applying the GSST model to the Garmerwolde case. It is worthwhile mentioning a few of the ways in which modeling of GSST systems may be extended.

Aeration Control

BioWin Controller may be applied to improve nitrogen removal and optimize aeration in the simulated GSST. Although it is not possible to specify a different aeration pattern in the BioWin GSST element from one cycle to the next, BioWin Controller may be used to override the specified aeration pattern to deliver the air flow rate based on a defined control strategy. The aeration control strategy can monitor the model calculated concentrations of DO, ammonia and NO_X and adjust the delivered air flow rate to target certain set points or remain below defined limits. For example, a control strategy may be applied to extend the unaerated anoxic period to improve denitrification while ensuring adequate aeration to keep the effluent ammonia concentration below a specified value. BioWin Controller can also be used to apply a post-anoxic period in a mixing cycle when the conditions indicate potential for improved nitrogen removal. The GSST plant model may be used to assess the impacts of the selected aeration control strategy on other performance indicators such as biological phosphorous removal.

Simulating Parallel GSSTs with Upstream Buffer Tank

The GSST plant model may be expanded to include multiple GSSTs in parallel. A buffer tank may be used to store influent and regulate the flow of influent to parallel GSSTs, as shown in Figure 7 below. The influent flow and loading may follow a diurnal pattern.

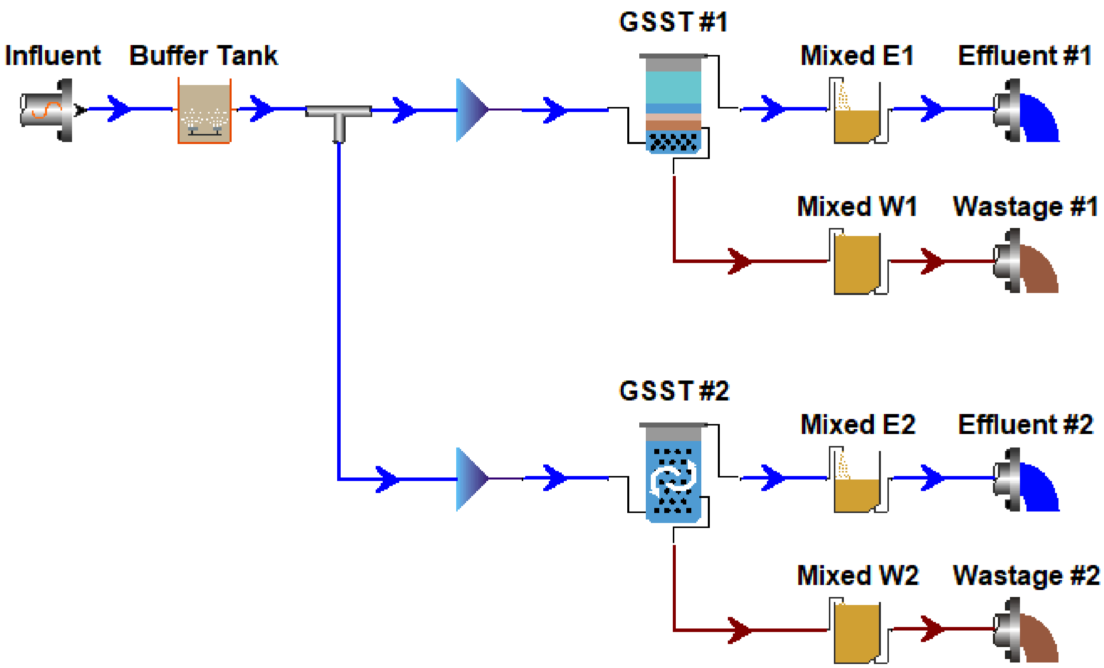

Figure 7. BioWin flowsheet of an example GSST plant

The total SRT of each GSST is calculated based on the total mass in the GSST divided by the total mass rate wasted in both the Effluent and Wastage elements. As a trick to smooth the calculated SRT [wasting is intermittent], a buffer tank has been added to each effluent and wastage pipe to mix each stream (labelled “Mixed E” and “Mixed W”). The outflow from each “Mixed E” and “Mixed W” buffer tank is set at a constant flow rate. Once the model is simulated for 3 or 4 SRTs and allowed to reach quasi steady-state, the dynamic SRT in each GSST stabilizes to a relatively constant value.

In the example plant presented in Figure 7 above, the volume of the buffer tank is 10,000 m^3. Flow is pumped out of the buffer tank at a rate of 64,000 m^3/d for 3 hours from 2:45 until 5:45 during each 6-hour cycle. For 1.5 hours of the 3 hours, outflow is directed to GSST #1, and then to GSST #2 for the remaining 1.5 hours. Over the 4 cycles in the day there is outflow from the buffer tank at a constant rate of 64,000 m^3/d for a total of 12 hours. This is equivalent to the average influent flow rate of 32,000 m^3/d to the buffer tank. A flow splitter downstream of the buffer tank routes the flow to GSST #2 from 2:45 until 4:15 and then to GSST #1 from 4:15 until 5:45 during each 6-hour cycle.

The cycle settings for GSST #1 and GSST #2 are shown in Figure 8 below. Each GSST has a cycle length of 6 hours. GSST #1 is the reference module and therefore has no cycle offset. GSST #2 operates with the same cycle as #1, but there is an offset relative to #1. We can think of the offset as “how far we are into the #2 cycle when the #1 cycle starts”. In this case, the cycle offset is 1.5 hours. Therefore, the simulation will start at time 0:00 in GSST #1 and at time 1:30 in GSST #2.

Due to the cycle offset of 1.5 hours in this example, at least one of the GSSTs will end partway through a cycle when running a dynamic simulation of any given duration.

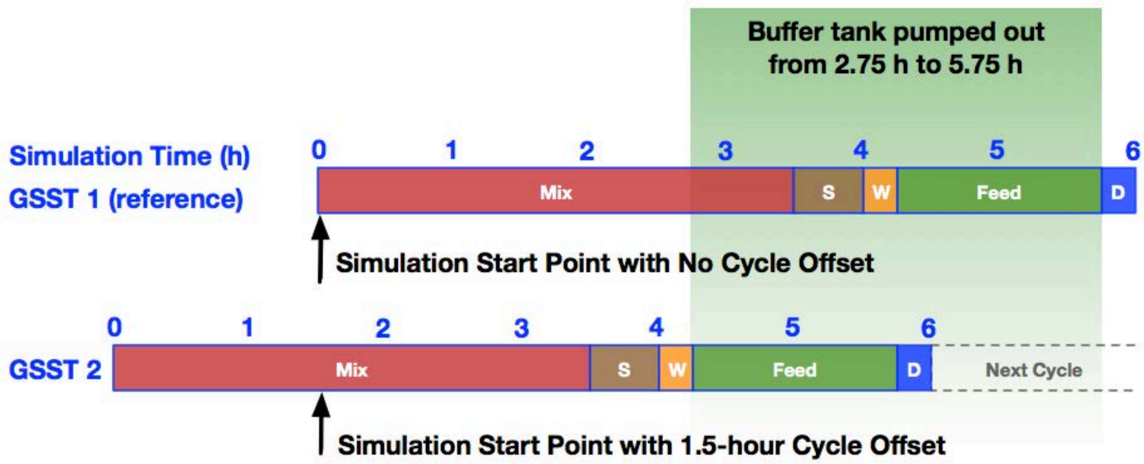

Figure 8. Operational cycle for two parallel GSSTs fed sequentially by upstream buffer tank.

CONCLUSIONS

The paper describes setting up a granular sludge sequencing tank (GSST) model in BioWin to represent the Nereda® plant at Garmerwolde, Netherlands. The modeling approach was outlined, and the empirical assumptions in developing the model were explained. In the BioWin GSST, a one-dimensional dynamic biofilm model is merged with a general Activated Sludge/Anaerobic Digestion model (ASDM) and a one-dimensional layered solids flux model in a variable volume unit. The GSST model has been developed to balance pragmatic design with mechanistic modeling rigour. A dynamic solver generates fast solutions and allows interactive design and analysis.

The GSST plant model was calibrated to the performance of the Garmerwolde Nereda® plant over the period from March to December, 2014. The calibrated GSST model accurately predicts key aspects of the observed full-scale plant over the calibration period: sludge production; total system mass and fraction of the total mass in the granular phase; dynamic biological removal of carbon, nitrogen and phosphorous within the Nereda® tank; aeration requirements; and effluent concentrations.

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