DYNAMIC ANALYSIS APPROACH FOR DECISION MAKING AROUND EXPANSION OF WASTEWATER TREATMENT FACILITIES

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ABSTRACT

Phosphorous Total Maximum Daily Loads (TMDL) to Lake Mead is limited for City of Las Vegas Water Pollution Control Facility (LVWPCF) under any operating conditions. However, the plant is required to treat more volumes of wastewater due to expansion of Las Vegas metropolitan. Struvite ($MgNH_4PO_4.6H_2O$) is a scale that causes operational problems in wastewater treatment plants (WWTPs). It is well known for fouling pumps, aerators, screens and clogging the pipes and the connections. Although, the stoichiometry of scale formation is well-known, there has been no attempt to approach the scale formation problem through dynamic modeling concept. Decision makers need the results of such simulations to decide which technology would be the option for future expansion of the plant. This study presents a structural model for development of future dynamic modeling on struvite formation. The model has been developed based on available data from LVWPCF. Simulations show that in the current operating situation at LVWPCF, struvite formation is determined by the input phosphorus daily loading into the plant, as well as, influent flow distribution between different treatment lines. The results revealed that the occurrence of struvite at LVWPCF is phosphorus limited, and scale formation is very sensitive to the percentage of the influent allocated to the line employing enhanced biological phosphorus removal (EBPR) system. It is the decision makers' choice to use either EBPR system or conventional precipitation system. In the case of EBPR system, the capital expense (CapEx) is low but the risk of scale formation and operational expenses (OpEx) is higher, however using conventional precipitation requires higher CapEx but the OpEx is low.

INTRODUCTION

Phosphorous is a nutrient that exists in wastewater streams and is responsible for most of the algal bloom incidents in water reservoirs around the world. In the United Sates, phosphorous daily loads form wastewater treatment plants to water bodies is regulated to protect the conditions of water bodies. Phosphorus is a common element found in many different forms in wastewater. Orthophosphate (OP) or reactive phosphorous; condensed phosphorus (i.e. pyro, metal or other polyphosphates); and organically bound phosphate are different types of phosphorus in the aqueous environment. Orthophosphate (PO_4^{-3}), which is the simplest form of phosphorous, is bioavailable. The other forms of the phosphorus can be converted into the bioavailable form after some microbial activities.

Chemical precipitation process and biological methods are the common methods of removing phosphorus form wastewater. In chemical process, ferric chloride ($FeCl_3$) as flocculation agent is added to wastewater, and as a result phosphorus precipitates as $FePO_4$. Comparatively high operation cost is the disadvantage of this method. However, the phosphorus strong molecular bound with iron allows the operators to handle the sludge, centrifuge, and finally dispose it.

Struvite ($MgNH_4PO_4.6H_2O$) is a scale that causes operational problems in wastewater treatment facilities. It is well known for fouling pumps, aerators, screens and other equipment. On pipe walls and different equipment surfaces during and after anaerobic digestion and post-digestion processes struvite scale formation always can be a potential problem. Scale removal is usually not practical and very costly. Many problems regarding struvite scale formation have been reported at treatment facilities [1] [2]. Equation (1) shows the struvite precipitation:

$$Mg^{2+} + NH_4^+ + H_nPO_4^{3-n} + 6H_2O \rightarrow MgNH_4PO_4.6H_2O + nH^+ \quad (1)$$

Analytical methods have been developed to determine struvite precipitation potential in anaerobic digestion and post-digestion processes. These models consider the effects of ionic strength on the activities of the struvite component ions [3]. To the best of current knowledge, there are no studies reported on system dynamics approach to model decision making of operation of wastewater treatment plants.

Enhanced biological phosphorus removal (EBPR) systems have a good efficiency with lower cost to remove phosphorus from the aqueous environment. In EBPR systems, first specific bacteria are exposed to anaerobic conditions. They are then exposed to aerobic environment, in which they oxidize the up taken VFA, gain energy and grow. In addition, because they have been excited to be in the favorable condition after being in an anaerobic environment, they accumulate energy via poly-phosphate accumulation in their bodies through phosphorous removal from the aqueous environment. Hence, the bacteria remove a considerable amount of phosphate from the water. Therefore, by wasting the biomass from the system, phosphorus is removed from the water. Handling of this biomass in the digester is difficult, because it is very sensitive to the level of oxygen and as soon as it reaches to the anoxic zone, it starts releasing the orthophosphate back to the water, which may result in struvite formation in the digester [1].

According to the permit, Las Vegas Water Pollution Control Facility (LVWPCF) is required to remove about 95% of the phosphorus entering the plant. Considering the planned plant expansion and to meet the plant’s Total Maximum Daily Loads (TMDL), LVWPCF will need to lower its phosphorus concentration in the effluent, which is entering to the Las Vegas wash and finally Lake Mead. In the planned expansion of the plant, LVWPCF should be very careful for phosphorus removal. On the other hand, the plant is evaluating to use EBPR system for phosphorus removal of the one-third (30 MGD) of total current flow of 90 MGD. The other 60 MGD is treated using the conventional chemical precipitation method. The hardness of influent water is relatively high, and Mg is always available in the digesters’ environment. Ammonium is also accessible in large amounts from degradation of nitrogenous material from primary sedimentation tanks. Therefore, theoretically, it is likely that the struvite formation in the anaerobic digesters is phosphorus limited.

The objectives of this study are: (a) to predict the formation of struvite in sludge digesters, in presence of both conventional chemical precipitation system and EBPR systems for phosphorus removal, based on available real-world input data; and (b) to forecast and make appropriate decisions based on the future condition of the digesters and struvite formation potential based on different future scenarios of influent wastewater (i.e. flow rate, magnesium, phosphorus and ammonium concentrations) and the technology used for phosphorous removal.

METHODOLOGY

Study Area

Three wastewater treatment plants are located in Las Vegas, NV, and because of the high population growth rate, plant operators are planning to expand the capacity of treatment in the valley. For this study, LVWPCF has been selected. The data for this project is provided by LVWPCF. Also, some input data from the previous study [4] were used to develop the model and for model calibration purposes.

Dynamic Model Development Hypotheses

The model platform is STELLA (ver. 7.0.2). Based on the objectives, the overall approach can be defined as:

a) Using system dynamics, the entire treatment plant and its different processes were modeled in STELLA. The stock flow diagram in Stella is the flow diagram in the plant. Relationship between different sections (treatment processes) was defined based on the mass balance concept of the critical parameters of struvite formation. Finally in the digesters using the available concentration of the major species (i.e. magnesium, ammonium, and phosphorous) the struvite formation is determined.
b) For the second objective it has been assumed that the removal efficiency of each component in each treatment process in the plant is independent and they cannot affect each other. Also, it has been assumed that always the minimum required nutrient for microbial growth in the reactor is available and the concentration of the nutrient components cannot be less than the required amounts.

The proposed plan approach included the following sequential tasks:

- Identification of all flow streams in the plant associated with current and future phosphorus removal;
- Determination of critical parameters associated with the potential of struvite formation; and
- Determination of the struvite formation potential (SFP).

The nature of the model has caused it to be affected by the recycle stream flows, heavily. This is one of the hypotheses that the model should be affected by the recycle stream lines. Recycle lines bring the information from the end of the stock and flow network to the beginning ones and they change the results. Also, they may increase the time to reach to the steady state. Since, the concentration of the contaminations in the recycle stream lines is typically high; the effect of these lines cannot be neglected.

The model similar the real treatment facilities consists of three different treatment lines. Basically, all of the units and reactors of the plant from bar screen to effluent discharge have been defined similar to the real plant. The top treatment line uses the EBPR technology and the other two lines use traditional chemical precipitation for phosphorus removal. Model consists of two major sectors. The main sector is shown in Figure 1. It consists of 23 stocks and many flow connections. The blue, red and green lines show the water flow, sludge flow and recycle water flows respectively. The brown lines represent decay or product of different components which have been selected for the simulation.

The EBPR treatment section consists of primary sedimentation to remove the major part of suspended solids and the biological nutrient removal (BNR) to remove BOD, ammonia and dissolved phosphorous. The sludge from the sedimentation tank flows to gravity thickener. After the BNR, water flows to final clarifier and then filtration and disinfection units. The other two treatment lines consist of primary sedimentation tanks, gravity thickener, trickling filters to remove the organic carbon compounds at the beginning. In order to remove ammonia, water goes through the aerobic nitrification basins. In these basins, ammonia is converted to nitrate. Then, water flows to secondary clarifier tanks, filtration units and disinfection. Finally, treated water from this process combines to the finished water from the EBPR treatment line and merges to the Las Vegas Wash. The primary sludge after gravity thickener flows is pumped to the digesters. Also, the sludge from the secondary clarifiers after storage in storage tanks and centrifuge units is pumped to the digesters.

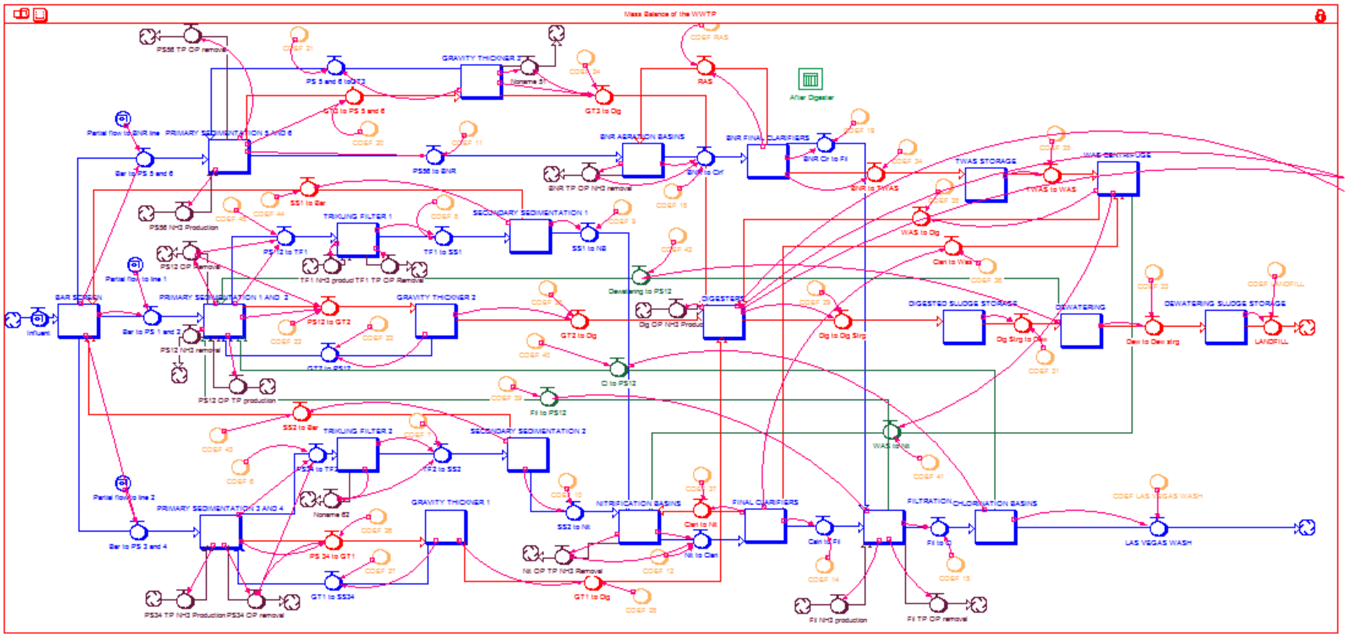

Figure 1. The stock and flow diagram in details in the main sector

Second sector is struvite formation calculation sector. This sector gets its input data from the digester stock in the main sector. The amounts of simulated orthophosphate, and ammonium in the digester and also the amount of magnesium loading (lb/day) are used to calculate the maximum amount of struvite that can be formed per day (lb/day). Some stoichiometric coefficients are used to relate these three components together. Struvite formation calculation sector is also able to determine the limiting component that is very important to know in different runs.

The model consists of a one dimensional array with 4 levels for four different parameters. Flow rate of wastewater (Q), total phosphorus (TP) daily loading, orthophosphate (OP) daily loading, and ammonium (NH3) daily loading are four different parameters that can be found in all of the stocks in the model.
The unit consistency has been kept during the simulations.

The simulation time horizon in the model is 365 days (1 year). However, it takes 130 days to reach the steady state. Initial value for all the stocks is zero. The shortest time constant in the model is 1 day Euler's method is selected as the integration method. Special function that has been used is IF ELSE function.

RESULTS AND DISCUSSION

To compare the results of the model to the real world, a set of input real data [4] has been used to verify the model's accuracy. The results of the accuracy test of the model are shown in Table 1. As it is shown, for Q, OP, TP, and HN_3 we have 14.8%, 3.4%, 1.2%, and 2.6% error, respectively. As it mentioned before, struvite formation calculations are based on the loading of the components per day. Hence, the largest error is 3.4% from OP.

Table 1. Comparison of simulation results vs. observed data

Component	Simulation Result	Observed Data	Error
Q (MGD)	0.86	0.73	14.8%
OP (lb/day)	469	453	3.4%
TP (lb/day)	5035	5095	1.2%
NH_3 (lb/day)	4840	4713	2.6%

Policies Tested Using the Developed Dynamic Model

First scenario (base case scenario): The first scenario is to run the model and calculate the amount of struvite formation according to the available real-world input data. The real world input data is a set of data based on 90 MGD, and the amounts of input OP, TP, and NH3 are 2952, 5114, and 16004 lb/day, respectively. In case of magnesium, there is no available loading per day data. But according to the average concentration of the magnesium in the digesters that is available we calculated the loading of the magnesium as 293 lb/day. The results of the first scenario show that the amounts of OP and NH3 in the digesters are 469, and 4840 lb/day, respectively. Consequently, struvite that can be formed in the digesters is 1211 lb/day, and it is phosphate limited, as predicted.

Second scenario: The second scenario, which is the most critical scenario, is to change the distribution of influent wastewater between different treatment lines. Because of the different efficiencies of the treatment processes, the distribution approach is important to form struvite (Table 2).

Table 2. Changing influent wastewater between different treatment lines in various simulations

Run	Flow line 1 (%)	Flow in line 2 (%)	Flow in EBPR line (%)	Struvite formed (lb/day)
1	0	100	0	249
2	25	75	0	269
3	50	50	0	288
4	75	25	0	308
5	100	0	0	327
6 (current situation)	33	33	33	1211
7	0	0	100	3021

As results show that as long as the treatment plant uses conventional chemical precipitation method to remove the phosphate, the amount of struvite is low and the risk of scale formation in the facility is not serious. But, when the EBPR system comes into the line, the amount of struvite formation increases substantially. The results show that if the wastewater treatment plant uses only the EBPR system, the amount of struvite formation will increase more than ten times in comparison with the conventional treatment system.

Third scenario: The third policy tries to change the limiting component. To run the model for this scenario, two different decision-making situations were assumed:

a. First, the city administration decides to start a project to separate the urine from the rest of wastewater (grey water) in city and wants to see the effect of this project in struvite formation in the WWTP. Since about 70-80% of the ammonia in domestic wastewater is from urine [5], the models tried to evaluated the results of this decision.
All the components were kept the same as before, and only ammonium was decreased by 75%. Surprisingly, with deduction of 75% in the ammonium in the influent, still the limiting component for struvite formation is phosphorus and the amount of struvite that can be formed is the same as before, 1211 lb/day.

b. Second, it was assumed that the plant was located in another location with very low amounts of hardness. In the current situation, the loading amount of magnesium is calculated based on the concentration of magnesium in the digesters as 293 lb/day. The results show that as long as the amount of magnesium is higher than 118 lb/day, the limiting component for struvite formation is phosphorus and the struvite is 1211 lb/day, and as soon as it reaches 118 lb/day, suddenly the situation changes and the amount of struvite starts to decrease and the limited component will change to magnesium.

CONCLUSION

By law, Total Maximum Daily Loads (TMDL) of phosphorous to Lake Mead is limited for LVWPCF under any conditions. However, the plant is required to treat more volumes of wastewater due to population growth and expansion in Las Vegas. Struvite formation which causes several operational issues in the plant should be evaluated for future expansions of the plant. Decision makers need the results of such simulations to decide which technology would be the option for future expansion of the plant. The developed model helps to identify the risks of struvite formation in the plant. Small changes in the water distribution in the plant affect the struvite formation. Simulations show that increasing the amount of loading on the EBPR system increases the risk of struvite formation. The results show that 75% reduction of the influent ammonium cannot change the struvite formation situation. Finally, it has been estimated that deduction of approximately 60% (175 lb/day) of magnesium daily loading may change the struvite formation situation.

EBPR system is a new technology to remove nutrient with very low cost and high efficiency, however, using EBPR increases the risk of struvite formation. It is the decision makers' choice to use either EBPR system or conventional precipitation system. In the case of EBPR system, the capital expense (CapEx) is low but the risk of scale formation and operational expenses (OpEx) is higher, however using conventional precipitation requires higher CapEx but the OpEx is low.

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