ORIGINAL ARTICLE

Modeling for Prediction of Sludge Accumulation in Septic Tanks

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Abstract. Sludge accumulation in septic tanks usually affects the tank performance and is essential for planning of the sludge emptying frequency and treatment. Based on the laboratory-scale experimental results, material balance analysis of TS and TVS concentrations in the septic tank influent, effluent and accumulation was used to calculate the first-order rate constant of sludge reduction, which was found to be 0.004 d-1. To deal with complex mechanisms in the septic tanks, a dynamic model for sludge accumulation using STELLA software was developed by integrating key factors/equations that represented the septic tank performance. The model was validated by using data from the laboratory-scale septic tank and 8 units of actual-scale septic tanks of peri-urban households, resulting in the R^2 values of 0.70 - 0.80 which suggested the applicability of the model in predicting the sludge accumulation in septic tanks. The technical feasibility of applying the developed dynamic model in predicting the desludging frequency of septic tanks. Due to insufficient desludging, usually resulting in poor treatment performance of septic tanks, this model should be useful for the septic tank users and municipal officers in planning for emptying the accumulated sludge and creating a modelling platform for describing TS and TVS accumulation in the septic tanks.

Keywords: Dynamic modelling; Sludge accumulation, Septic tank; Treatment performance.

1. Introduction

The WHO/UNICEF Joint Monitoring Program (JMP) for Water Supply, Sanitation and Hygiene reported that 4.5 billion people, mostly in developing countries, still lack access to basic sanitation facilities[11]. As a result of poor sanitation, more than 1 million people, especially children, die from infection and diarrhea everyday[10]. Currently, human wastes or wastes generating from human activities and containing high level of organic pollutants and pathogens, are discharged into nearby vicinities which can cause environmental pollution and health risks[4]. It is a well-established fact that septic tanks are a prevalent on-site treatment system to treat/collect toilet wastewater in most developing countries. Due to fluctuations of organic loading rates (OLRs) and short hydraulic retention times (HRTs), septic tank effluents still contain high concentrations of organic matters and pathogens. After operation for a certain period, there will be high accumulation of septic tank sludge or septage which requires frequent desludging and consequently treatment. Most developing countries including Thailand, Vietnam, the Philippines, etc., still lack septage treatment facilities, thus, the common practice of septage management is direct disposal into paddy fields or canals without any treatment[5,9]. Because insufficient desludging usually results in poor treatment performance of septic tanks, development of sludge accumulation model should be useful to determine performance of the septic tanks and planning for desludging frequency. The main objective of this study was to develop a dynamic model for prediction of sludge accumulation in the septic tanks using laboratory-scale data and testing the model applicability with data of 8 units of actual-scale septic tanks.

2. Materials and Methods

2.1 Laboratory-Scale and Actual-Scale Septic Tanks

A laboratory- scale septic tank with a volume of 40 L and a dimension of 64x25x40 cm (LxWxH) was constructed at the Asian Institute of technology (AIT) campus, Pathumthani, Thailand. Temperature in the laboratory-scale septic tank was controlled at 30 °C using heated water circulating around the tank (Figure 1). To start up the experiment, septage collected from a household community was mixed at a ratio of 50:50 with anaerobic inoculums collected from a septage treatment plant and added into the laboratory-scale septic tank, and nitrogen gas was fed to purge out the oxygen gas. The laboratory-scale septic tank was allowed to acclimatize until steady-state conditions, based on stable biogas production rate of about 2 weeks, were reached. During the steady-state period, the laboratory-scale septic tank was operated at a hydraulic retention time (HRT) of 24 h for about 6 months by continuous feeding with a septage collected from household communities in central Thailand. To adjust the operating conditions to be similar to actual septic tanks, the septage was diluted with tap water to maintain the TS and TVS concentrations of 900-2,000 and 600-1,700 mg/L, respectively, or the TS and TVS loading rates of 1.7±0.8 and 1.4±0.7 kg/m^3.d, respectively. The influent and effluent samples were collected twice weekly for analyses of total solid (TS) and total volatile solid (TVS) concentrations and the accumulated sludge in the septic tanks was determined monthly by thoroughly mixing the septic tank contents with N_2 gas and collecting the mixed liquor samples or mixed of accumulated sludge samples. These samples were analyzed according to the methods described in “Standard Methods for the Examination of Water and Wastewater” (APHA, AWWA and WEF, 2005). A total of 8 actual-scale septic tanks, each treating toilet wastewater of a household, were analyzed for sludge accumulation and the data used for model validation. These septic tanks are located in 4 provinces in central and northern Thailand and their details are presented in Table 2.

2.2 Model Development

Dynamic modelling was developed by using STELLA (version 10) software in which SPSS (version 20) was used in analysis of the experimental data. The STELLA software could translate mathematical equations to model structures for determination of TS and TVS concentrations of the accumulated sludge. The applicability of the developed dynamic model was validated with data of septic tanks.

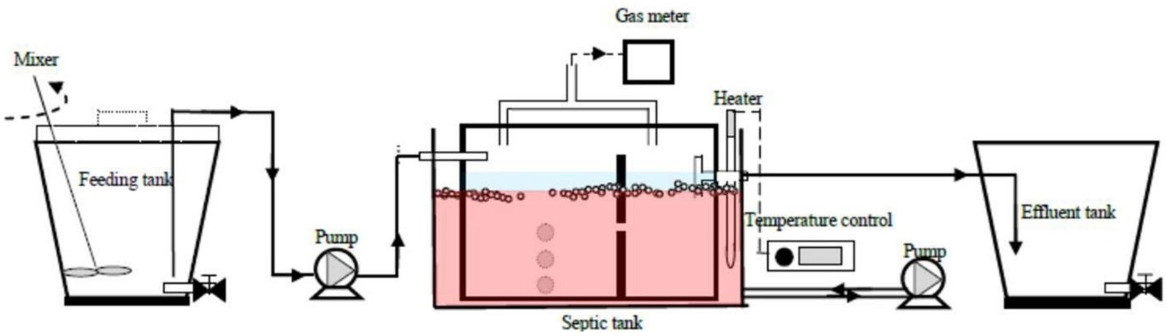


Figure 1. Laboratory-scale septic tank

3. Results

3.1 TS and TVS Removal and Accumulation of Laboratory-Scale Septic Tank

The average TS and TVS removal efficiencies of the laboratory-scale septic tank during steady-stage conditions, shown in Figures 2(a) and (b), were 63 and 67 %, respectively. A previous study by Pickford (1980)[8] reported that at the HRTs longer than 6 h, the percent removal efficiency of TS was about 60 %. Removal efficiencies of TS in septic tanks were dependent on the tank configuration (L: H or H: W) and the number of compartments (Pickford 1980)[8]. The TS and TVS concentrations in the accumulated sludge of the laboratory-scale septic tank were about 44,000 and 28,000 mg/L, respectively (Figure 3).

3.2 Sludge accumulation model

As shown in Figures 2 and 3, solid removal efficiencies in the septic tank likely depended on the solid accumulation over the operational period by which sedimentation and biodegradation of the organic solids would play key roles. To address role of biodegradation, analysis of TVS mass balance of the laboratory-scale septic tank was undertaken according to Equations 1 and 2 and Figure 4:

(1) $$TVS_{reduction} = TVS_{input} - TVS_{output} - TVS_{accumulation}$$

(2) $$TVS\ accumulation = \frac{\text{TVSinside} - TVSintitial}{\tau}$$

Where : TVS reduction = TVS settled- TVS accumulation (mg/L.d), TVS_{input} = TVS concentration contained in the influent (mg/L.d), TVS_{output} = TVS concentration contained in the effluent (mg/L.d) τ =reaction times (d), TVS_{inside} = TVS concentration inside septic tank (mg/L), $TVS_{initial}$ = initial TVS concentration (mg/L), t= operation period, (d) and n= no. of operational periods (d)

The TVS accumulation in the laboratory-scale septic tank (divided by reaction times) during the operation periods of 105 days were found to decrease from 980 to 220 mg/L, as shown in Table 1.

The rate of TVS reduction in the laboratory-scale septic tank could be expressed as a first-order reaction (Equation 3):

(3) $$In\frac{C_{TVS_\tau}}{C_{TVS_0}} = -k_T\tau$$

(4) $$k_T = k_{20}\theta^{(T-20)}$$

In which $C_{TVS\,\tau}$ = TVS concentration at reaction times (mg/L), C_{TVS0} = settled TVS concentrations (mg/L), k_T = first-order rate constant at temperature T (d^{-1}), k_{20} = first order rate constant at temperature 20 ºC (d^{-1}) and θ = temperature coefficient which is 1.11 (Haandel and Lettinga 1994)[2].

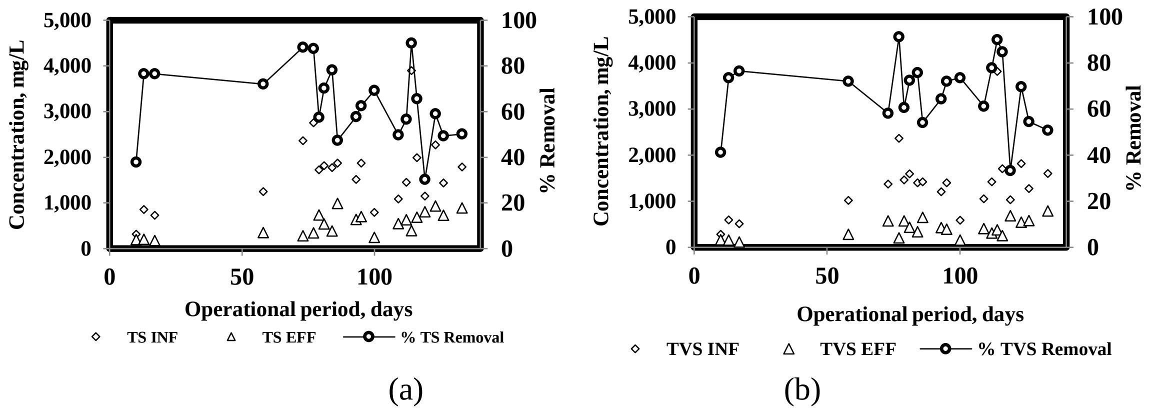


Figure 2. (a) TS and (b) TVS removal efficiencies of the laboratory-scale septic tank

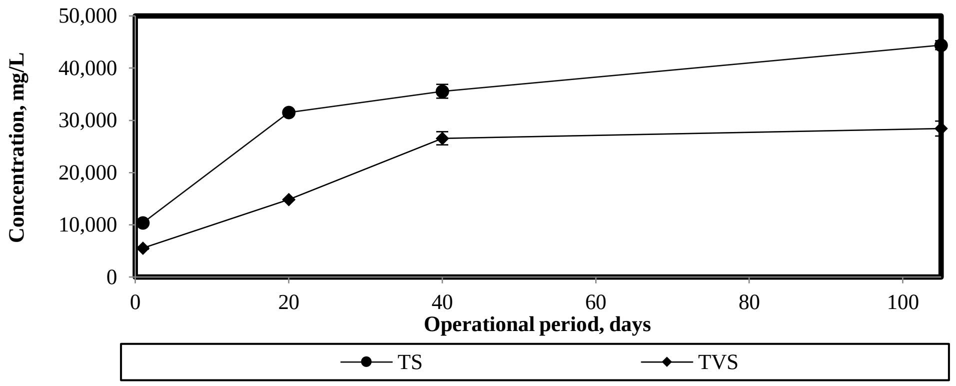


Figure 3. Accumulated TS and TVS concentrations (mg/L) in the laboratory-scale septic tank

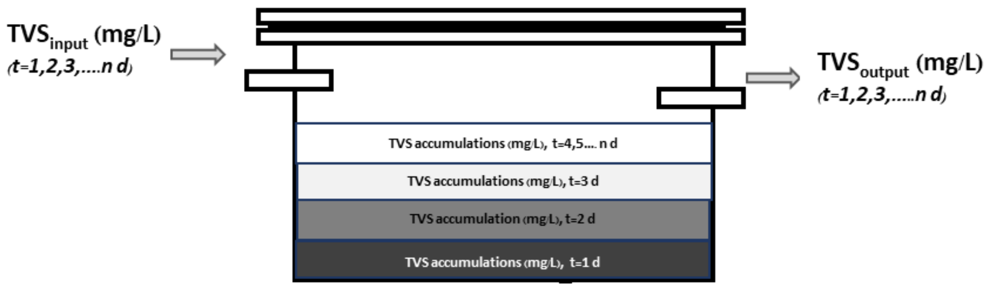


Figure 4. Mass balances analysis of sludge accumulation

Table 1. TVS Reduction per day

Operation period (t), d	TVS input	TVS output	TVS settled*	TVS accumulation**	TVS reduction
	mg/L	mg/L	mg/L	mg/L	mg/L
0	1,380	400	980	980	0
20				460	510
40				530	450
105				220	760

** TVS settled = TVS_{input}-TVS_{output}*
*** Divided by reaction times (Equation 2)*

A relationship between C_{TVSt}/ C_{TVS0} and reaction times, as in Figure 5, exhibited a linear relationship between the k_{20} value of 0.004 d^{-1} and R^2 value of 0.96. Probably resulted from the less amount of active microorganisms and characteristics of the septage which had been partly digested in the septic tanks, the k_{20} value of 0.004 d^{-1} was found to be relatively low when compared with the literature data. However, it should be noted that the k_{20} value was calculated from the laboratory-scale septic tank fed with the diluted septage to maintain the concentrations of TS and TVS within the range of actual condition. To make the k_{20} value more applicable in various condition, further validation and reliability testing of this value with factions of biologically inert material and slowly biodegradable organic matter contained in actual black water is recommended. Chatsanguthai (1986) [1] reported the kinetic values of organic reduction in anaerobic waste stabilization ponds to be about 0.08-0.20 d^{-1}, while Nwabanne *et al.* [7] (2010) found the kinetic values of anaerobic digestion of municipal waste to be about 0.14 d^{-1}. Up to present, there have been very few researches about TVS reduction in septic tanks.

Based on the experimental data in Table 1 and Equation 3, a model of sludge accumulation in septic tanks was developed as shown in Equation 5.

$$(5)\quad \frac{dC_{sludge}}{dt} = \frac{Q}{V}\left\{\left(C_{TS\,settled}\right) - \left(\partial C_{TS\,settled}\left(1-e^{-k_T\tau}\right)\right)\right\}$$

Where: C_{sludge} = accumulated sludge con-centration (mg/L), $C_{TS\ settled}$ = *concentration of* TS_{input}- TS_{output} (mg/L) and ∂ = average TVS/TS ratio which was equal to 0.8 (based on results obtained from the analysis).

Because the degradation rate and the solubilization of organic matters in septic tanks theoretically increase with increasing temperatures, a temperature correction factor (β), from trial and error, developed from the operating temperature at 30 °C was incorporated in the model (Equations 6 and 7).

$$(6)\quad \frac{dC_{sludge}}{dt} = \frac{Q}{V}\left\{\left(C_{TS\,settled}\right) - \left(\partial C_{TS\,settled}\left(1-e^{-k_T\tau}\right)^{\beta}\right)\right\}$$

$$(7)\quad \beta = \frac{30}{T}$$

A dynamic modeling for prediction of sludge accumulation in septic tanks was subsequently developed to simulate the TS and TVS concentrations, as shown in Figure 6.

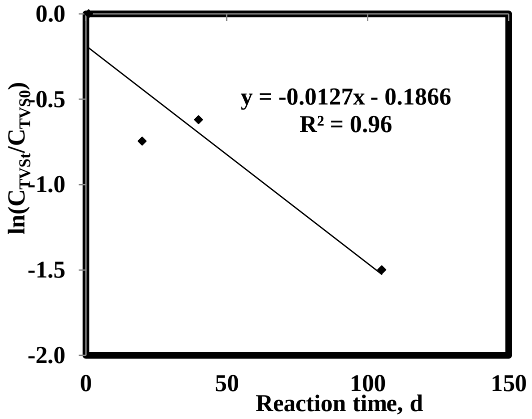
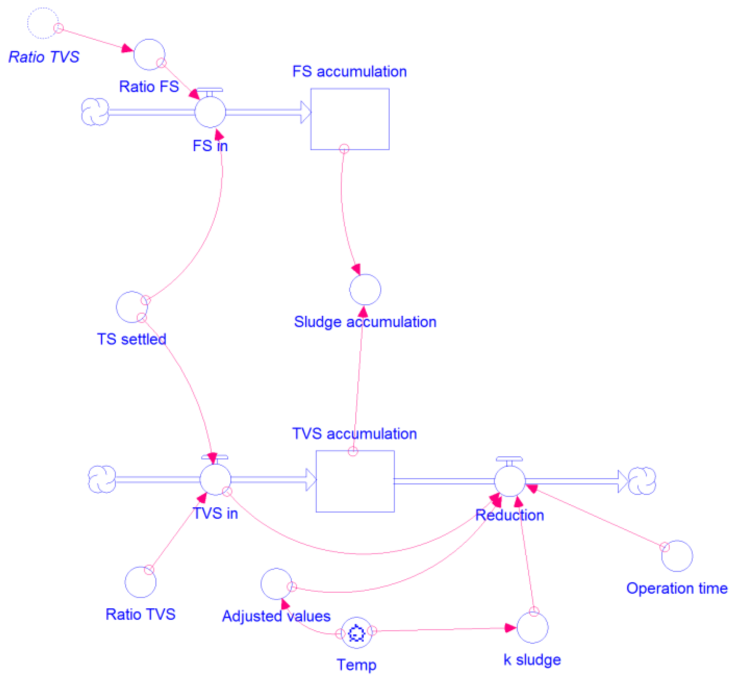


Figure 5. TVS reduction in laboratory-scale septic tank fitted with first-order model



Where: Ratio TVS = ratio of total volatile solid/total solid and Ratio FS = ratio of fixed solid/ total solid

Figure 6. Dynamic modeling of sludge accumulation in septic tanks based on STELLA software

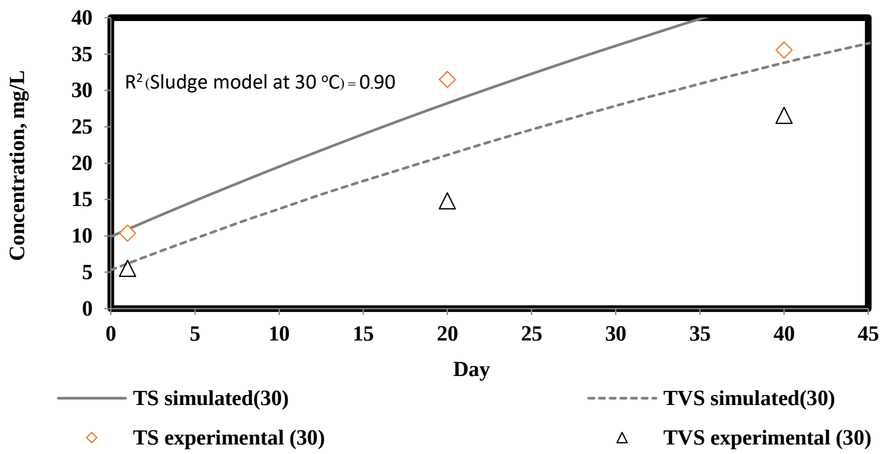


Figure 7. Comparison of simulated and experimental data of sludge accumulation in laboratory-scale septic tank

Table 2. Sludge Accumulation in Actual-Scale Septic Tanks of Thailand

Septic tank no.	Number of people	Volume (L)	HRT (d)	TS loading (kg/m^3.d)	Desludging frequency (year)	TS accumulation (mg/L)[a]
1	4	1,181	10	0.2	1	3,668
2	3	975	11	0.2	1	3,288
3	6	777	4	0.4	1	14,820
4	3	6,256	70	0.02	1	10,153
5	9	810	3	0.6	1	80,010
6	2	235	4	0.4	1	20,868
7	2	1,200	20	0.1	1	8,864
8	6	1,153	6	0.3	0.25	5,200

Source: Koottatep et al. (2012)[6]
[a] *Mixed liquid samples in septic tank sludge*

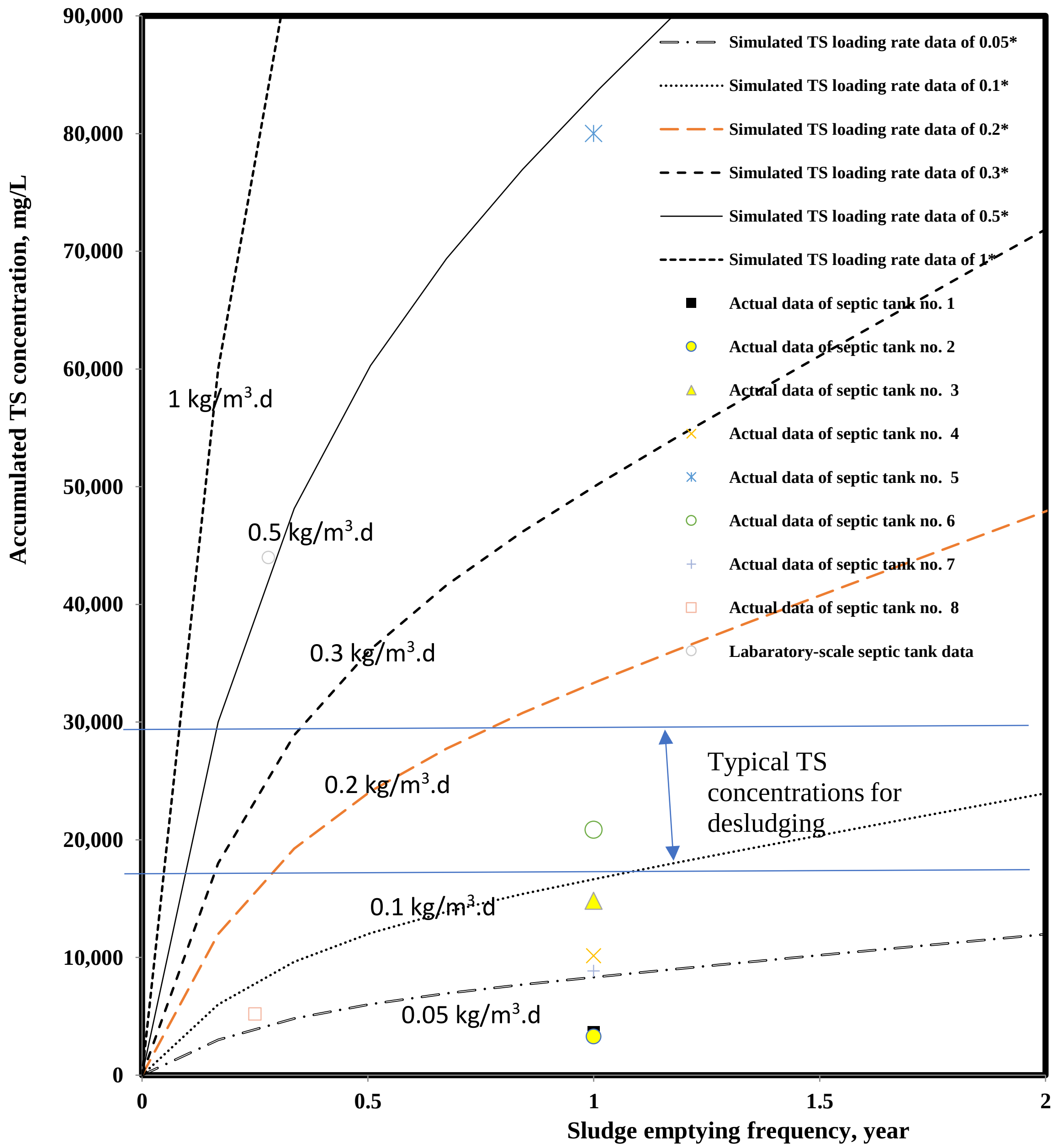


Figure 8. Sludge accumulation data of actual-scale and laboratory-scale septic tank and simulated results various at TS loading rates *($kg/m^3.d$)

Equations 6 and 7 were tested with the experimental data of sludge accumulation obtained from the laboratory-scale septic tank experiments, shown in Figure 7, with the R^2 value of 0.90.

Equations 6 and 7 were further validated with data of the 8 actual-scale septic tanks with sizes ranging from 200-6,000 L, TS loading rates of 0.02-06 $kg/m^3.d$ and TS accumulation of 3,000-80,000 mg/L (Table 2)

Figure 8 represents the simulated data of TS accumulation at various TS loading rate which compare satisfactorily with the TS accumulation data obtained from the actual-scale septic tanks and the laboratory-scale septic tanks, with the R^2 values of 0.7.

Model application and example

The results from this study suggested the technical feasibility of applying the developed dynamic model in predicting the desludging frequency of septic tanks. Generally, septic tanks should be desludged when the accumulated TS concentrations are 18,000-30,000 mg/L[3], Form Figure 8, the simulated TS concentrations in the septic tanks operating at the TS loading rate of 0.1 $kg/m^3.d$ (about 2-3 users per household) were found to be about 18,000 mg/L, after the operation period of about 2 years, suggesting the frequency of septage desludging of once in 2 years. On the other hand, for a septic tank operating at the TS loading rate of 0.3 $kg/m^3.d$ (e.g. a communal toilet), the accumulated TS concentration would become 30,000 mg/L after operation period of about 4 months (Figure 8), suggesting the frequency of septage desludging as approximately once in 4 months, while the TS loading rate of 0.3 $kg/m^3.d$ would require desludging about once in the 4 months However, for a public toilet having more than 10 users per day with the TS loading of about 0.5 $kg/m^3.d$, the frequency of sludge emptying should be once in 2 months. Therefore, Figure 8 can be applied to determine the TS concentration of the accumulated sludge and frequency of sludge emptying according to the TS loading rate of the septic tank.

4. Discussion

Based on the results obtained from this study, the following conclusions are made:

1. The removal efficiencies of TS and TVS of the laboratory-scale septic tank operating at the HRT of 24 h were found to be 63 and 67 %, respectively.
2. The mass balance analysis and relationship between TVS reduction rates and reaction times were used to determine the first order rate constant, which was about 0.004 d^{-1}. Subsequently, a dynamic modeling for prediction of sludge accumulation in septic tank was developed as shown below.

$$(6)\quad \frac{dC_{sludge}}{dt} = \frac{Q}{V}\left\{\left(C_{TS_{settled}}\right) - \left(\partial C_{TS_{settled}}\left(1-e^{-kT^{\tau}}\right)^{\beta}\right)\right\}$$

$$(7)\quad \beta = \frac{30}{T}$$

3. The developed dynamic model was able to simulate results of sludge accumulation in the septic tanks satisfactorily with R^2 value of 0.7-0.9. Application of the developed model to predict the amount of septage accumulation and planning for septage desludging frequency and transport was demonstrated.

Acknowledgements

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