Original Article

Water Volume- and BOD- based Flow Analysis for Domestic Wastewater Treatment Using Wastewater Inventories of Bangkok, Thailand

Tomohiro Okadera ^a, Kazuaki Syutsubo ^a, Wilasinee Yoochatchaval ^b, Yoshitaka Ebie ^c, Rieko Kubota ^c

^a Center for Regional Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan

^b Department of Environmental Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand

^c Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Tsukuba, Japan

ABSTRACT

Urban population, it is predicted that, will reach at 5 billion by 2030 and 95% of urban expansion in the next decades will take place in developing countries. In addition, it is indicated that rapid urbanization brings pressures on freshwater supply and sewage treatment. Then sustainable development goal 6 shows 8 targets to ensure availability and sustainable management of water and sanitation for all, and intends to increase proportion of population using safely managed sanitation services, wastewater safely treated and bodies of water with good ambient water quality. Bangkok, which is the capital of Thailand, has 8 centralized sewage treatment plants (CSTP) designed to treat domestic wastewater of approximately a half of residents. However, water quality of some canals in the area provided with sewage works (APSW) has not been improved well, and the cause is not found out due to uncertainty of flows of domestic wastewater. Thus, this study has identified flows of domestic wastewater by an inventory approach to estimate volume of wastewater and biochemical oxygen demand (BOD) discharge based on population distribution in Bangkok. As the results, it is estimated that 75% of BOD discharged in APSW does not reach CSTP.

Keywords: wastewater inventory, material flow analysis, domestic wastewater treatment, urban, Bangkok

INTRODUCTION

Half of global population, it is estimated that, as of 2016, live in urban areas and it is predicted that urban population will reach at 5 billion by 2030 with 95% of urban expansion of developing countries in the next decades [1]. Meanwhile it is indicated that such rapid urbanization brings pressures on freshwater supply and sewage treatment. Then eight targets to ensure availability and sustainable management of water and sanitation for all have been decided, as the sixth sustainable development goal (SDG), and intends to increase proportion of population using safely managed sanitation services, wastewater safely treated and bodies of water with

good ambient water quality by 2030 [2].

Eastern and South-Eastern Asia has the most urban population, 32% of the 2015 world urban population, and it is predicted that the share will have been almost kept until 2030 [3]. Eastern Asia including China is dominant in the urban population of Eastern and South-Eastern Asia, but it is projected that its growth ratio will decrease and finally fall into the negative between 2045 and 2050. In addition, South-Eastern Asia shows higher growth ratio than Eastern Asia after 2015 and the differences will widen. Since these results imply that future urbanization in South-Eastern Asian may be more serious than Eastern Asia for SDG, we focus on South-Eastern Asia in this study.

Corresponding author: Tomohiro Okadera, E-mail: okadera@nies.go.jp

Received: June 27, 2019, Accepted: November 11, 2019, Published online: April 10, 2020

Open Access This is an open-access article distributed under the terms of the Creative Commons Attribution Non-Commercial No Derivatives (CC BY-NC-ND) 4.0 License. <http://creativecommons.org/licenses/by-nc-nd/4.0/>

In 2015, averagely 88% of residents in urban areas of South-Eastern Asia use at least basic sanitation facilities (ALBSF), designed to hygienically separate excreta from human contact, which are not shared with other households [4]. Singapore has already provided safely managed sanitation facilities (SMSF) to all residents and almost all urban residents use ALBSF in Malaysia. More than 90% of urban residents in Brunei, Thailand, Laos and Vietnam can access to ALBSF as well [4]. Though the other countries, such as Philippines, Indonesia, Myanmar and so on, show lower percentage than the average of South-Eastern Asia, it is estimated that ALBSF of urban areas is used by at least 73% of residents [4].

Bangkok, which is one of the most representative city in the Southeast Asia and the capital of Thailand, has eight centralized sewage treatment plants (STP), designed to treat domestic wastewater of approximately a half of residents, for safely managing sanitation. However, water quality of some canals in the area provided with sewage works (APSW) has not been improved well, while the other canals show good water quality. The fact throws a basic issue why water quality of water bodies could not be improved well even if SMSF have been installed, but the cause has not been traced so far. To elucidate the issue, this study has quantitatively identified flows of domestic wastewater by an inventory approach to estimate volume of wastewater and biochemical oxygen demand (BOD) discharge based on population distribution in Bangkok.

MATERIALS AND METHODS

Description of the study area

Bangkok, located on the low flat plain of Chao Phraya River which extends to the Gulf of Thailand, consists of 50 districts, whose total area is 1,568.737 km² [5]. It is accounted that 5.6 to 8.3 million people live there [6,7]. Eight centralized STP, whose design capacity is 1.1 million m³ per day to cover 3.4 million residents in total. In addition, 11 community-scale STP, whose design capacity is 18,000 m³ per day, are installed in some residential areas by national housing authority. Sewage is collected by combined sewerage systems which gather rain water as well. Water quality, however, of some canals in APSW has not been improved well since their annual mean BOD shows more than 20 mg/L which is effluent standard of centralized STP (Fig. 1).

Inventory approaches for wastewater and this study

Inventory approaches for wastewater are categorized into two groups: life cycle inventory and emission inventory. The life cycle inventory is a tool to analyze various material requirements and environmental impacts to construct and operate a wastewater treatment plant or resource recovery technology in life cycle perspectives [8–11]. On the other hand, the emission inventory, which this study adopts, is a method to estimate amount of wastewater and water pollutants discharged from socio-economic activities, such as agriculture, industry and households [12,13]. These emission inventories are calculated using regional input-output tables (IOT).

In Thailand, there is no regional IOT, though national IOT are published every five years [14]. Thus, we develop a bottom-up model to estimate amounts of domestic wastewater and water pollutants discharge based on population. In addition, spatial boundaries are different between districts and APSW, as shown as Fig. 1, so 1-km grid-based population data [15], which are available to compile according to spatial boundary, are utilized.

Model

Amount of domestic wastewater (w_w) of a grid is estimated by

$$w_{w(g)} = \omega_{w(r)} p_{(g)} \quad g \in r \quad (1)$$

where ω_w is per capita wastewater discharge, p is population, and r and g denote region and grid codes, respectively. Furthermore, with BOD concentration in wastewater (c_{bod}), amount of BOD discharge (w_{bod}) by grid is calculated by

$$w_{bod(g)} = c_{bod(r)} w_{w(g)} \quad g \in r \quad (2)$$

The amount of wastewater and BOD discharge of APSW ($w_{*(s)}$) is aggregated by

$$w_{*(s)} = \sum_g^s w_{*(g)} \quad (3)$$

where w_* denotes w_w or w_{bod} and s means APSW. The amount of wastewater and BOD discharge in out of APSA is estimated by subtracting $w_{*(s)}$ from the total value of the study area.

The model was operated by a GIS software, ArcGIS Pro 10.5.1 (ESRI Japan Corp, Tokyo, Japan) to finally aggregate the grid-based results by APSW and out of APSW in the study area.

Fig. 1 Central sewage treatment plants and annual mean BOD concentration of canals in Bangkok.

Notes: Original data are provided by Department of Drainage and Sewerage, Bangkok Metropolitan Administration.

Parameter setting and data

First, we selected 2015 as a target year, which is the latest year that has the most available data for calculation. ω_w is estimated based on data of tap water supplied for residences and conversion ratio to wastewater (CRW) from tap water in Bangkok, which are produced by Metropolitan Waterworks Authority (MWA), Bangkok, Thailand, and collected by personal communication with a local specialist [16]. MWA supplies tap water to not only Bangkok but also three neighboring provinces (Samut Prakan, Nonthaburi and Nakhon Pathom). The service area consists of 18 water supply districts (WSD), 14 WSD of which cover the whole of Bangkok. Thus, per capita tap water supplied for residences by WSD is set dividing its volume of the supplied water by served population aggregated with LandScan dataset [15]. At the same time, CRW is finally assumed as 88%, because it is estimated that a resident of Bangkok discharge 150 L of wastewater from toilet, kitchen, washing and bathing every day based on a domestic manual of wastewater management for household [17] while averagely 170 L of tap water is supplied to the

resident per day [16].

Table 1 shows the estimated value of ω_w by WSD for this study. In addition, the values have a large difference between 25.7 and 85.8 m³ per year by district. First, it is assumed that local characteristics, such as bias of income and family structure by district, may cause this differences. In the technical aspect, it is found that areas whose per capita wastewater indicates low value, such as WSD-4 and 5 located in the central area of Bangkok, show low percentage in total water supply for household (30% or less) [16] though they have big population (700–800 thousand residents). Meanwhile these areas supply more water to shops and restaurants (approximately 50 to 60%) [16]. On the other hand, in areas whose per capita wastewater shows high value, such as WSD-9 and 14, approximately 60% or more water is supplied for household while they have small population (less than 500 thousand residents). It is assumed that the differences may be caused by local competition between residents and commercial service sectors (i.e. shopping centers and restaurants) for water supply in central areas.

Table 1 Estimated per capita wastewater (ω_w) by water supply district in Bangkok, Thailand (2015).

	Name of WSD	Per capita wastewater (m ³ /year)
WSD-1	Sukhumvit	43.6
WSD-2	Phra Khanong	67.4
WSD-3	Phayathai	38.7
WSD-4	Thungmahamek	28.0
WSD-5	Mansri	25.7
WSD-6	Ladprao	57.4
WSD-7	Prachachuen	71.0
WSD-8	Bangkheng	58.8
WSD-9	Minburi	85.8
WSD-10	Suvarnabhumi	69.1
WSD-11	Bangkok Noi	50.0
WSD-12	Taksin	52.8
WSD-13	Phasi Charoen	47.0
WSD-14	Suksawat	71.1

c_{bod} is set based on data of BOD concentration of influent (BOD-IN) flowing into centralized and community-based STP and the situation to installing septic tanks. We have collected data on BOD-IN compiled by the Department of Drainage and Sewerage (DDS), Bangkok Metropolitan Administration (BMA) with monthly reports from every STP in Bangkok. First we calculated annual mean BOD concentration of centralized STP in dry season, namely excluding data from May to August (rainy season), to avoid influence of rainwater inflow, and the results showed 38 mg/L. However, the value is much lower than an estimated BOD concentration in domestic wastewater in Thailand [17] and annual mean BOD-IN into STP of Tokyo [18], which is a city utilizing centralized STP with combined sewerage systems. Therefore, we assumed that BOD is removed in the process among households (e.g. septic tank), sewerage systems and STP for some reasons.

In the process between households and sewerage systems, septic tanks have a possibility to remove some amounts of BOD. A septic tank is an on-site sanitation facility for night soil treatment and generally installed to a household to treat black water in Thailand while the other wastewater (grey water) is not treated. Septic tanks in Thailand is categorized into 4 groups: one cesspool, two-cesspool in series, concrete septic tank and commercial septic tank, and 69% of residents of urban areas in a province of Thailand use one cesspool while 23% by two-cesspool in series and 6% by commercial septic tank [17]. At the same time, it is reported that removal ratio for BOD by one cesspool, two cesspool in series and commercial septic tank are 59%, 43% and 52% respectively.

Referring to these results, we assume that 55% of BOD in black water is removed by septic tanks in Thailand in this study.

The past study indicates that BOD loading by black water is accounted at 12% of the total [17], but the results of total BOD loading may be overestimate because it uses BOD concentration in wastewater from kitchen without screen (1,800 mg/L) in 1987. Since it is presumed that a kitchen has been updated currently, we considered that the BOD concentration should be replaced to the value for a kitchen with screen (540 mg/L) [19]. As the result, it is accounted that 24% of total BOD loading caused by black water. Thus finally it is considered that septic tanks remove 13% of BOD loading from total domestic wastewater before flowing into sewerage systems in Bangkok.

It is presumed that BOD is removed in the sewerage systems as well before flowing into centralized STP, because some parts of the sewerage systems consist of open ditch. Therefore we have compared BOD-IN of centralized STP with that of community-based STP connecting with households by culvert drain pipes. Then we selected Din Daeng centralized STP and two community-based STP (Huaykwang and Bonkai) located in Din Daeng APSW. With the data of BOD-IN during 2011 and 2015, BOD-IN of Din Daeng centralized STP is accounted as 38 mg/L whereas that of two community-based STP is 154 mg/L, thus we assume that approximately 76% of BOD is lost in the sewerage systems before flowing into centralized STP in Bangkok.

With the above assumptions of septic tanks and sewerage systems and BOD-IN of centralized STP, we have estimated

BOD concentration in domestic wastewater in 8 AWPS, and computed centralized-STP-based average value by administrative district by setting the data in geographic information systems (GIS). At the same time, we have estimated BOD concentration in domestic wastewater based on 11 community-based STP and the assumption of BOD removal by septic tanks, and set as GIS data. Then a district which has centralized and community-scale STP adopts their average value as BOD concentration in domestic wastewater. In other districts which has no STP, total average value is used as BOD concentration in domestic wastewater.

Table 2 shows estimated value of $c_{\text{bod}(r)}$. With **Table 2**, it is presumed that 160 ± 33 mg/L of BOD is discharged from household in Bangkok. By an interview to person in charge of DDS, BMA, 200 mg/L of BOD is design criteria of influent into some central STP in Bangkok. Furthermore, the mean value of 27 samples of influent into Bonkai community-based STP, by our composite sampling from 27 Oct. 2016 to 15 Feb. 2017, is 106 ± 35 mg/L of BOD. Therefore, it is considered that our estimated values are in the reasonable range (106–200 mg/L) averagely, though some districts are out of these range. The districts whose BOD indicates more than 200 mg/L refer to centralized STP whose BOD concentration in influent is in the range of 43–50 mg/L. Because the value reported by centralized STP is relatively reliable and representative, BOD reduction in sewerage pipeline may be less than our estimation for these area. In addition, by two time sampling of municipal wastewater in a sewerage system in Phetchaburi Province, Thailand, BOD reduction in the pipelines is calculated as 15–30% approximately [20]. However, if the reduction ratio would be used, BOD concentration would be underestimated (less than 70 mg/L of BOD). Meanwhile, because recently it seems that dietary habit has been rapidly changing due to popularization of foreign food and convenience stores in Bangkok, the possibility that more than 200 mg/L of BOD includes in domestic wastewater in some districts is assumable as well. On the other hand, districts whose BOD is under 100 mg/L, such as Lat Krabang and Saphan Sung, refer to data reported by community-based STP, thus these parameters may include bias. Finally we directly utilize, however, the parameters for some districts, since the limitation of local data accessibility for the bias correction.

RESULTS AND DISCUSSION

Water volume-based flow of domestic wastewater in Bangkok

With the calculated results and practical data on influent and effluent through the STP provided by DDS, BMA, we have identified water volume-based flow of domestic wastewater in Bangkok as **Fig. 2**. 434 million m³ of domestic wastewater, it is estimated, is discharged annually in Bangkok, and 331 million m³ (76%) is discharged out of APSW. 103 million m³ of domestic wastewater is discharged into combined sewerage systems while 283 million m³ of combined sewage flows into STP in Bangkok. We found 180 million m³ of differences between them, but it is considered that this is because of wastewater from other sectors (offices, department stores, restaurants, schools etc.) and rainwater which are out of the target of this study. In addition, combined sewage overflow is not accounted in this study as well.

BOD-based flow of domestic wastewater in Bangkok

BOD-based flow of domestic wastewater in Bangkok is identified as **Fig. 3** in the same way as the water volume-based flow. The results show that 69 thousand tons of BOD (t-BOD) are generated and 60 thousand t-BOD are discharged with domestic wastewater after septic tanks, 44 thousand t-BOD (73%) of which is discharged out of APSW. Though 16 thousand t-BOD is discharged from households in APSW, it is accounted as the only four thousand t-BOD flows into STP while the rest of that does not reach STP in Bangkok. As the same as the results based on water amount, there is a gap between calculated BOD inflow and actual value due to lack of terms of the other sectors. With the reported value of DDS, BMA, more than 80% of BOD flowing into STP is removed.

Assumable reasons for BOD unreached to STP

Although the results show that 75% of BOD discharged with domestic wastewater in APSW does not reach to STP, the reasons are unclear. However, we presume five reasons: self-degradation of BOD in sewerage systems, dilution by much rainwater inflow, overflow with combined sewage from sewerage systems, accidental or chronical leakage or dilution by groundwater from the damaged sewage pipes and directly discharging out of sewerage systems. First, sewage may easily stay in sewer pipes of Bangkok, located on the low flat plain of Chao Phraya River, because sewerage systems have almost no differences of elevation. It is implied that BOD could be removed in the sewage pipes if the conditions,

Table 2 Estimated BOD concentration in domestic wastewater (c_{bod}) by district in Bangkok (2015).

	Name of districts	BOD (mg/L)
1	Bang Bon	160
2	Bang Kapi	125
3	Bang Khae	217
4	Bang Khen	114
5	Bang Kho Laem	137
6	Bang Khun Thian	127
7	Bang Na	101
8	Bang Phlat	160
9	Bang Rak	175
10	Bang Sue	168
11	Bangkok Noi	160
12	Bangkok Yai	217
13	Bueng Kum	160
14	Chatuchak	176
15	Chom Thong	127
16	Din Daeng	138
17	Don Mueang	160
18	Dusit	176
19	Huai Khwang	175
20	Khan Na Yao	160
21	Khlong Sam Wa	160
22	Khlong San	160
23	Khlong Toei	164
24	Lak Si	106
25	Lat Krabang	85
26	Lat Phrao	156
27	Min Buri	160
28	Nong Chok	160
29	Nong Khaem	217
30	Pathum Wan	191
31	Phasi Charoen	217
32	Phaya Thai	176
33	Phra Khanong	160
34	Phra Nakhon	236
35	Pom Prap Sattru Phai	222
36	Prawet	160
37	Rat Burana	127
38	Ratchathewi	194
39	Sai Mai	160
40	Samphanthawong	201
41	Saphan Sung	86
42	Sathon	165
43	Suan Luang	160
44	Taling Chan	160
45	Thawi Watthana	160
46	Thon Buri	127
47	Thung Khru	127
48	Wang Thonglang	156
49	Watthana	160
50	Yan Nawa	137

such as air, temperature and microbes in sewage, were satisfied. Next, severe rain storm brings much amount rainwater into sewerage systems, and may dilute BOD concentration in sewerage. Furthermore, combined sewerage systems of Bangkok are designed to release sewage more than its capacity, thus some organic matters, which determine BOD, may wash off from combined sewerage systems at the time of a heavy rainfall. In addition, sewage pipes damaged by severe land subsidence in Bangkok may make accidental or chronic sewage leakage or dilution by groundwater inflow when the groundwater level is high as the other reasons, some households, such as condominiums, can discharge treated domestic wastewater to canals, since they must install on-site wastewater treatment facilities, which satisfy the requirements of a local government in the design phase. However, a system of performance check has not been established enough, though the national government recommend them provide a performance report twice a year. Finally, it is considered that BOD unreached to STP should be caused by combination of these reasons.

Conceivable solutions for domestic wastewater treatment systems in Bangkok

Based on the results, we discuss conceivable solutions for domestic wastewater treatment in Bangkok. First, improvement to collect organic matters in domestic wastewater for the current centralized treatment systems, and mainly three options are presumable. As we summarized as above, the collection efficiency may be worsened due to a retention time of wastewater in sewage pipes, so shortening the retention time is considerable. In addition, it is expected to reduce loss of organic matters with combined sewage outflow (CSO) by heavy rain. As another option is increasing the number of households connecting to sewerage systems. However, since approximately 70% of the total capacity of STP has been already utilized, it is necessary to consider feasibility within the rest of the capacity. Separated sewerage systems is the other option. Although that might be effective if losses with CSO were the most, feasibility to replace the existing combined sewerage systems to separated systems would depend on budget constraint and social acceptances due to a large construction project.

Next, maintenance issues should be solved for decentralized treatment systems. Collection of septage accumulated in a septic tank is necessary to keep a performance to treat domestic wastewater, however, collecting frequency depends on a householder, and it seems that householders who do not collect septage with appropriate frequency are not

Domestic wastewater discharge

Fig. 2 Water volume-based flow of domestic wastewater in Bangkok (million m³; 2015).

Notes: * are actual data provided by Department of Drainage and Sewerage, Bangkok Metropolitan Administration.

a few, according to technical, socio-economic and cultural conditions. As one of the technical solutions, a replacement for a septic tank to low-maintenance technologies which hardly generate sludge [21,22] may be worth considering. At the same time, international standard on guidelines for the management of basic on-site domestic wastewater services, for appropriate collection of septage especially, should be an indicator for response to local socio-economic and cultural condition [23].

Finally, it is considered that integrated approaches for domestic wastewater utilized both centralized and decentralized treatment systems. BMA has already instituted the similar countermeasure for wastewater treatment at condominiums in APSW of Bangkok and effluent standards are established by size of condominiums [24]. However, practical performance check remains a political issue, so establishment of a common method for performance test is considerable.

CONCLUSIONS

This is the first study to find that organic matters in domestic wastewater may not be collected to centralized STP

appropriately by identification of flows of domestic wastewater based on water volume and BOD in Bangkok, Thailand, and three options were discussed as centralized treatment systems, decentralized treatment systems and integrated approaches. For a conclusion, we note limitation of the results.

Limitation of the results

The calculated results are adequate, we consider, because practical local data for the same year are utilized as much as possible, though the results cannot be validated due to no other studies to compare with this study. However, **Figs. 2 and 3** show that 24 to 27% of total domestic wastewater is discharged in APSW, though centralized STP are designed to treat a half of total population in Bangkok. It is considered that the gaps are caused by differences of population data between this study and BMA. In this study, population data refer to a global dataset (LandScan 2015), which accounts 8.7 million people in Bangkok in 2015 [15] that almost equal population and housing census carried out every ten years for all residents [7]. On the other hand, BMA refers to population based on registration record, which is 5.7 million residents in Bangkok in 2015 [25], so the data may not

Fig. 3 BOD-based flow of domestic wastewater in Bangkok (thousand ton; 2015).

Notes: # are estimated using actual data provided by Department of Drainage and Sewerage, Bangkok Metropolitan Administration.

include a resident who registered in the other province and foreign residents. Furthermore, BMA has planned that 3.4 million residents use the current centralized STP while 2.8 million people lives in APSW with LandScan 2015. This fact infers that population distribution in Bangkok is uncertain, so more local analysis, such as districts or sub-districts, is probably limited. In addition, with the registration-record-based population data of BMA, our results also indicate that centralized STP cover a half of total residents in Bangkok.

ACKNOWLEDGEMENTS

A part of this research is financially supported by Environment Research and Technology Development Fund (1-1603) and Japan-ASEAN Integration Fund (JAIF). We show a great appreciation to Dr Pathan Banjongproo and Ms. Nisita Khongpaiboon at DDS, BMA and Dr Winai Chaowiwat at Hydro Informatic Institute (HII) for their cooperation to collect data for this study.

REFERENCES

- [1] United Nations: Goal 11: Make cities inclusive, safe, resilient and sustainable, United Nations, 2016. <https://www.un.org/sustainabledevelopment/cities/> [accessed in December, 2017]
- [2] United Nations: Goal 6: Ensure access to water and sanitation for all, United Nations, 2016. <https://www.un.org/sustainabledevelopment/water-and-sanitation/> [accessed in December, 2017]
- [3] United Nations DoEaSA, Population Division: World Urbanization Prospects: The 2018 Revision, Online Edition. United Nations, Department of Economic and Social Affairs, Population Division, New York, USA, 2018.
- [4] WHO and UNICEF: Household data, WHO and UNICEF, 2017. <https://washdata.org/data/household#/> [accessed in June, 2019]

- [5] UNEP, Bangkok Metropolitan Administration: The Bangkok state of environment report 2003. Bangkok Metropolitan Administration, Bangkok, Thailand, 2003.
- [6] National Statistical Office: Statistical yearbook Thailand 2013. National Statistical Office, Ministry of Information and Communication Technology, Bangkok, Thailand, 2013.
- [7] National Statistical Office: The 2010 Population and Housing Census Bangkok. National Statistical Office, Bangkok, Thailand, 2012.
- [8] Foley J, de Haas D, Hartley K, Lant P: Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Res.*, **44**(5), 1654–1666, 2010. PMID:20022351 doi:10.1016/j.watres.2009.11.031
- [9] Li Y, Luo X, Huang X, Wang D, Zhang W: Life Cycle Assessment of a municipal wastewater treatment plant: a case study in Suzhou, China. *J. Clean. Prod.*, **57**, 221–227, 2013. doi:10.1016/j.jclepro.2013.05.035
- [10] Morera S, Corominas L, Rigola M, Poch M, Comas J: Using a detailed inventory of a large wastewater treatment plant to estimate the relative importance of construction to the overall environmental impacts. *Water Res.*, **122**, 614–623, 2017. PMID:28645067 doi:10.1016/j.watres.2017.05.069
- [11] Fang LL, Valverde-Pérez B, Damgaard A, Plósz BG, Rygaard M: Life cycle assessment as development and decision support tool for wastewater resource recovery technology. *Water Res.*, **88**, 538–549, 2016. PMID:26540509 doi:10.1016/j.watres.2015.10.016
- [12] Okadera T, Watanabe M, Xu K: Analysis of water demand and water pollutant discharge using a regional input–output table: An application to the City of Chongqing, upstream of the Three Gorges Dam in China. *Ecol. Econ.*, **58**(2), 221–237, 2006. doi:10.1016/j.ecolecon.2005.07.005
- [13] Ni JR, Zhong DS, Huang YF, Wang H: Total waste-load control and allocation based on input–output analysis for Shenzhen, South China. *J. Environ. Manage.*, **61**(1), 37–49, 2001. PMID:11381457 doi:10.1006/jema.2000.0398
- [14] Okadera T, Chontanawat J, Gheewala SH: Water footprint for energy production and supply in Thailand. *Energy*, **77**, 49–56, 2014. doi:10.1016/j.energy.2014.03.113
- [15] Oak Ridge National Laboratory (ORNL): LandScan 2015 Thailand. Pacific Vision Corp. Geospatial Div., Oak Ridge, USA, 2016.
- [16] Chaowiwat W: Volume data of water sales by area and users for FY2015. Metropolitan Waterworks Authority, Bangkok, Thailand, 2017. [in Thai]
- [17] Boontanon SK, Buathong T: On-site Management for Domestic Wastewater in Thailand. Water Environment Partnership in Asia (WEPA), Tokyo, Japan, 2013.
- [18] Japan Sewage Works Association: Statistics of sewage systems (FY2013). Japan Sewage Works Association, Tokyo, Japan, 2015. [in Japanese]
- [19] PCD: Waste Water Treatment System, Pollution Control Department (PCD), Bangkok, Thailand 2019. http://www.pcd.go.th/info_serv/water_wt.htm [accessed in February, 2019, in Thai]
- [20] Jinjaruk T, Chunkao K, Pohgput K, Choeihom C, Patamapitoot T, Wararam W, Thaipakdee S, Srichomphu M, Maskulrath P: HDPE pipeline length for conditioning anaerobic process to decrease BOD in municipal wastewater. *Environ. Asia*, **11**(1), 31–44, 2018.
- [21] Onodera T, Yoochatchaval W, Sumino H, Mizuochi M, Okadera T, Fujita T, Banjongproo P, Syutsubo K: Pilot-scale experiment of down-flow hanging sponge for direct treatment of low-strength municipal wastewater in Bangkok, Thailand. *Bioprocess Biosyst. Eng.*, **37**(11), 2281–2287, 2014. PMID:24817263 doi:10.1007/s00449-014-1206-5
- [22] Yoochatchaval W, Onodera T, Sumino H, Yamaguchi T, Mizuochi M, Okadera T, Syutsubo K: Development of a down-flow hanging sponge reactor for the treatment of low strength sewage. *Water Sci. Technol.*, **70**(4), 656–663, 2014. PMID:25116495 doi:10.2166/wst.2014.270
- [23] ISO: ISO/TC 224: ISO 24521:2016 Activities relating to drinking water and wastewater services—Guidelines for the management of basic on-site domestic wastewater services. International Organization for Standardization (ISO), Geneva, Switzerland, 2016.
- [24] WEPA: Building Effluent Standard in Thailand, Water Environmental Partnership in Asia (WEPA), 2019. http://www.wepa-db.net/policies/law/thailand/std_building.htm [accessed on 26 June, 2019]
- [25] National Statistical Office: Statistical yearbook Thailand 2016. National Statistical Office, Bangkok, Thailand, 2016.