Water Pollutant Discharge Indicator Estimation and Water Quality Prediction in Pak Kret District, Bangkok, Thailand

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ABSTRACT

After several decades of water and sanitation sector development in developing countries, ambient water pollution is still one of the major environmental problems. Safe and convenient sanitation, toilet use, public health issues, hygiene behavior and ambient water quality improvement are purposes and benefits of sanitation. The sanitation indicator of Millennium Development Goals (MDGs) showed that the proportion of population with access to improved sanitation in Thailand was 99 % in 2004, however, ambient water quality deterioration is still a major environmental problem. Therefore, pollutant discharge and affordability should be discussed in a quantitative manner. In this paper, municipal wastewater pollutant discharge contribution to ambient water pollutant loads was given attention. The pollutant load per capita flowing into water body (PLC_{wb}) were estimated as 7.2 g-BOD person⁻¹day⁻¹, 9.2 g-TN person⁻¹ day⁻¹ and 1.2 g-TP person⁻¹ day⁻¹, in Pak Kret Municipality, a peri-urban area of Bangkok, Thailand. PLC_{wb} can evaluate both anthropogenic pollutant removal effects of wastewater treatment systems and natural purification effects in ambient water. Scenario-based analysis showed water quality improvement in the Chao Phraya River to be 0.12-0.26 mg-BOD l⁻¹, 0.19-0.33 mg-TN l⁻¹ and 0.03-0.05 mg-TP l⁻¹ compared to the current annual average water quality of 1.94 mg-BOD l⁻¹, 1.19 mg-TN l⁻¹, and 0.22 mg-TP l⁻¹. Pollutant discharges per capita (PDCs) estimation results and cost-benefit comparison results showed the effectiveness of PDCs to evaluate various municipal wastewater treatment systems.

Keywords: municipal wastewater; pollutant discharge per capita (PDC); pollutant load per capita flowing into water body (PLC_{wb}); water and wastewater management

ABBREVIATIONS

BMA: Bangkok Metropolitan Area;

BOD: biological oxygen demand;

CJ: combined *johkasou* (an on-site treatment system in Japan);

COD: chemical oxygen demand;

COD_{Mn}: chemical oxygen demand measured with manganese dioxide;

CP: community plant;

EKC: environmental Kuznets curve;

IGES: Institute of Global Environmental Strategies, Japan;

IWRM: integrated water resource management;

LCA: life cycle assessment;

MDGs: Millennium Development Goals;

MFA: material flux analysis or material flow analysis;

NST: night soil treatment system (an old-type on-site treatment system in Japan);

ODA: overseas development assistance;

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PCD: Pollution Control Department, Thailand
PDC: pollutant discharge per capita;
PDC_BOD: BOD discharge per capita;
PDL: pollutant discharge per land area
PGC: pollutant generation per capita;
PLC_{wb}: pollutant load per capita flowing into water body;
PLC_{wb}_BOD: BOD load per capita flowing into water body;
PLC_{wb}_TN: TN load per capita flowing into water body;
PLC_{wb}_TP: TP load per capita flowing into water body;
SJ: simple *johkasou* (an old-type on-site treatment system in Japan);
TN: total nitrogen;
TP: total phosphorus;
TSP: total suspended particle (air quality);
WEPA: Water Environment Partnership in Asia;
WWAP: United Nations (World) Water Assessment Program; and
WWTPs: wastewater treatment plants;

INTRODUCTION

Pollutant discharge and pollutant load indicators are effective to clarify the relationship between municipal wastewater pollutant discharge and ambient water quality (Tsuzuki, 2007; 2008; 2009b; Tsuzuki et al., 2008a,b; 2009). The indicators may be applicable for comparison of cost-effectiveness of wastewater treatment systems. This kind of quantitative analyses and comparisons will enhance understanding of the situations of sanitation system to assess the sustainability of sanitation systems in developing and developed countries. Ujang and Buckley (2002) summarized the distance between desirable development in developing countries and development scheme by developed country experts in water and wastewater planning and management. Thus, detailed or quantitative investigations and analyses on the actual conditions of the whole planning and management in developing countries are truly necessary.

In the Millennium Development Goals (MDGs), sanitation target is a central topic in the world water and sanitation sectors. We should consider from the historical aspects of sanitation from the International Drinking Water and Sanitation Decade to the water and sanitation goals of MDGs to find desirable directions of sanitation system development in developing countries (Table 1). Decreasing proportion of population without access to safe drinking water and appropriate municipal wastewater treatment facilities are very urgent tasks of the world community. These goals have been determined based on the discussions and considerations for a few decades starting from the United Nations Conference on Human Environment in Stockholm in 1972 (UNESCO-WWAP, 2003).

This paper focuses on municipal wastewater discharge reduction as a purpose or a benefit of sanitation. In the first edition of the World Water Report (UNESCO-WWAP, 2003), sanitation provisions were summarized as (1) safe and convenient sanitation, (2) toilet use, (3) public health issues and (4) hygiene behavior. One more step to achieve a good level of sanitation is to reduce pollutant discharges. Pollutant discharge reduction has been targeted to improve water quality in ambient water especially in developed countries. After the achievement of sanitation goal of the MDGs or even on the way to

achieve the goal, reducing pollutant discharge should be also considered even in developing countries.

Table 1 - Discussions and considerations for a few decades in the sanitation sector (based on Choguill et al., 1993, UNESCO-WWAP, 2003, and United Nations Secretary-General's Advisory Board on Water and Sanitation, 2006)

Year	Topic	Description
1972	United Nations Conference on Human Environment in Stockholm	For "the discharge of toxic substances or of other substances and the release of heat", "the just struggle of the peoples of all countries against pollution should be supported."
1981-1990	International Drinking Water and Sanitation Decade	'The goal of the Decade was that, by the end of 1990, all people should possess adequate water supply and satisfactory means of excreta and sullage disposal...it would have involved the provision of water and sanitation services to over 650,000 people per day for the entire ten year period'.
1990	New Delhi Statement in the Global Consultation on Safe Water and Sanitation for the 1990s	'Some for all rather than more for some' was included and it was stated that 'safe water and proper means of waste disposal.....must be at the center of integrated water resources management'.
1994	Action Programme of the Ministerial Conference on Drinking Water Supply and Environmental Sanitation in Noordwijk	It was declared that 'to assign high priority to programmes designed to provide basic sanitation and excreta disposal systems to urban and rural areas'.
1995	Copenhagen Declaration on Social Development	'Safe drinking water and sanitation' was included in the efforts to be addressed considering the root causes of poverty.
1997	Marrakech Declaration in the First World Water Forum	Accessing to clean water and sanitation was recognized as the basic human needs.
1998	Paris Declaration on Water and Sustainable Development	The importance was emphasized 'to ensure the achievement of sustainable development, management and protection, and equitable use of freshwater resources'.
2000	World Water Vision in the Second Water Forum in Hague	Stakeholders involvement and funding were emphasized.
2002	Implementation plan of the Johannesburg Declaration on Sustainable Development	An agreement was made to halve the proportion of people who are unable to reach or to afford safe drinking water and the proportion of people who do not have access to basic sanitation by the year 2015.
2003	First edition of the World Water Report	Sanitation provisions were summarized as (1) safe and convenient sanitation, (2) toilet use, (3) public health issues and (4) hygiene behavior.
2006	Sanitation objective of Hashimoto Action Plan	Accelerated research on alternative models and technologies to improve sanitation such as eco-sanitation, the vacuum car and treatment plant system, and urine separation from sewage was targeted in the academic and scientific communities.

Further improvement of sanitation facilities should be considered especially on their pollutant discharge reduction function as a benefit of wastewater treatment facilities. The proportion of people with improved sanitation was 80 % in 1990 and 99 % in 2004 in Thailand (United Nations, 2007; UNDP, 2006). These figures show that Thailand is well equipped with appropriate sanitation. However, water quality deterioration in the rivers and canals is still one of the important environmental problems to be solved especially in the central area of Thailand including Bangkok (World Bank, 2001; Pollution Control Department (PCD), 2006a).

In the academic sector, various studies have been conducted to clarify the relationships between anthropogenic and natural pollutant discharges and water quality in ambient water. Land-based pollutant load analyses have been conducted to clarify the relationships between pollutant discharges and pollutant loads in rivers (Kunimatsu and Muraoka, 1989; Hosoi et al., 1996; Friedler and Butler, 1996; Ichiki et al., 1996; Sarikaya et al., 1999; Schreiber et al., 2001; Takeda and Fukushima, 2004; 2006; Wakida and Lerner, 2005; Donohue et al., 2006; Stutter et al., 2007). Researches on integrated water resource management (IWRM) (e.g. Butler & Parkinson, 1997; Harremoës, 1997; Larsen and Gujer, 1997) have also been conducted.

Effectiveness and efficiency of wastewater treatment technological options should be assessed using some appropriate indices. Many researches to improve municipal wastewater treatment efficiencies have also been conducted on centralized and on-site treatment systems in developing countries since the end of the last century (e.g. Yu et al.,

1997; Jetten et al., 1997; Fittschen & Niemczynowicz, 1997; Hanæus et al., 1997; Henze, 1997; Chen and Beck, 1997; Koottatep et al., 2001). Low-cost and decentralized natural treatment systems were recommended for the municipal wastewater treatment systems because of low-organic concentrations in the influent sewage and high organic compound degradability in tropical climate (Giri et al., 2006). The same types of systems were also recommended based on the results of life cycle assessment (LCA) of wastewater treatment system in Bangkok City (Koottatep and Chaosakul, 2005). Suharyanto and Matsushita (2009) discussed similarities and differences between sanitation systems in Japan and Thailand. When appropriateness and effectiveness of overseas development assistance (ODA) projects in sanitation sector are considered, several technological options should be included in the preliminary project design phase as described by Jarusombat and Wajjwalku (2003).

Tsuzuki (2006a) conducted pollutant load analyses on municipal wastewater and proposed pollutant discharge per capita (PDC) and pollutant load per capita flowing into water body (PLC_{wb}) as effective and efficient indicators of the municipal wastewater contribution to water pollution in the receiving water body. PDC is estimated with pollutant generation per capita (PGC) and pollutant removal efficiency of municipal wastewater treatment methods (Eqs. 1 and 2). The first one is for a specific wastewater treatment method:

$$(PDC_POL_j)_i = PGC_j \times \frac{(100 - WTE_{i,j})}{100} \quad (1)$$

where $(PDC_POL_j)_i$ is PDC of pollutant j with municipal wastewater treatment method i ($g\ person^{-1}\ day^{-1}$); PGC_j is PGC of pollutant j ($g\ person^{-1}\ day^{-1}$); and $WTE_{i,j}$ is wastewater treatment efficiency of pollutant j with municipal wastewater treatment method i (%). The second one is for an area with mixed treatment methods:

$$PDC_POL_j = \frac{\sum \{ (PDC_POL_j)_i \times POP_i \}}{\sum POP_i} \quad (2)$$

where PDC_POL_j is population averaged PDC of pollutant j in an area ($g\ person^{-1}\ day^{-1}$); POP_i is population served with municipal wastewater treatment method i in the area (person).

PLC_{wb} is estimated with PDC and reaching ratio of a pollutant in receiving water (Eq. 3). Pollutant reaching ratio is estimated based on the overall pollutant load analyses in the drainage areas or the river basins. The indicator, PLC_{wb} , reflects both treatment efficiencies of anthropogenic municipal wastewater treatment systems and natural water purification effects in ambient water. The equation is given as

$$(PLC_{wb_POL_j})_i = (PDC_POL_j)_i \times \frac{RR_j}{100} \quad (3)$$

where $(PLC_{wb_POL_j})_i$ is PLC_{wb} of pollutant j with municipal wastewater treatment method i ($g\ person^{-1}\ day^{-1}$); and RR_j is reaching ratio of the pollutant j (%). Reaching ratio is estimated with total pollutant discharge of a pollutant in an area and

pollutant load of the pollutant in ambient water including rivers (Eq. 4) and given as

$$RR_j = \frac{PL_j}{\sum (PD_{j,k})} \quad (4)$$

where PL_j is pollutant load of pollutant j in the receiving water body including rivers (t day^{-1}); and $PD_{j,k}$ is pollutant discharge of pollutant j from pollutant source k (t day^{-1}).

Scientific aspects and values of these municipal wastewater pollutant indicators have not been well discussed in scientific papers especially in sanitation policy and wastewater management in developing countries. The symbol $(PDC_POL_j)_i$ is known as pollutant discharge unit load or *haisyutsu gentan'i* in Japanese. Unit loads are usually applied per capita for municipal wastewater, per area for nonpoint sources, and per production amount for industrial sources. One of the merits of PDC is that it is applicable as an indicator in an area with mixed wastewater treatment systems. PDC and PLC_{wb} are fundamental indicators in wastewater treatment planning and river basin-based pollutant load analyses (e.g. Kunimatsu and Muraoka, 1989; Japanese Sewage Works Association, 1997).

Guo and Yang (2003) conducted regression analysis between water pollution and economic level in the Lower Mekong Basin in 1985 to 2000 and found little evidence to support the environmental Kuznets curve (EKC) hypothesis. However, they found out that water pollution including total phosphorus (TP) and chemical oxygen demand (COD) had been significantly related to income level, and Thailand had the least water pollution in the LMB. Moreover, water pollution is a major environmental problem in the Central Thailand area (World Bank, 2001; PCD, 2006a). PDCs were considered to be more reasonable water quality indices to be analyzed against income level (Tsuzuki, 2007; 2008; 2009b). Relationships between PDCs and water, sanitation and economic parameters were statistically analyzed and EKC like inverted U-shaped curve relationships were found in some cases (Tsuzuki, 2006a,b; 2007; 2008; 2009b). Water management in the Southeast Asian countries was discussed focusing on urban water-related environments (Marcotullio, 2007). The comprehensive approach by Marcotullio (2007) encompassed the MDGs indicator, economic development, ambient water quality, coastal environment, pollutant flux in the ambient water, flooding, and cost for improving the situations, and summarized the water-related challenges in local, city-wide, and regional and global scales. In addition to the macro-scale approach by Marcotullio (2007), our micro-scale approach is necessary to clarify some relationships among these phenomena. This is because municipal pollutant discharge per capita is handled only briefly in the actual wastewater treatment planning project, and some complicated features have been found in recent studies (Ii and Fujita, 2005; Ebise and Kawamura, 2008; Sugimoto et al., 2008).

Both costs and benefits of sanitation systems should be considered to improve ambient water quality. Affordability has been emphasized in urban sanitation (e.g. Mara, 1996; Tsuzuki, 2006a; Tsuzuki et al., 2008b). When affordability in sanitation sector is large, water quality improvement can be achieved more easily. There are also conceptional problems in municipal sewerage/excreta management in Thailand (Ludwig and Mohit,

2000).

A previous study of PDCs estimation in Pak Kret Municipality, a peri-urban area of Bangkok, Thailand, showed larger contribution of *seepage and septage from septic tanks and leachate from composting* (hereafter refers to SSL unless otherwise described) to pollutant loads in ambient water (Tsuzuki et al., 2008a). Estimated PDCs in Thailand were generally found to be larger than those in Japan. The estimation results quantitatively showed possibility of ambient water quality improvement by pollutant discharge reduction with larger treatment efficiency of the treatment methods in a country with larger MDG sanitation indicator.

In this paper, we first reviewed papers and documents focusing on the water quality profiles in ambient water and municipal wastewater pollutant discharges in Bangkok area, Thailand. Second, pollutant loads in the Chao Phraya River were estimated based on the existing water quality and flow rate data to update the estimation results of pollutant indicators obtained by Tsuzuki et al. (2008a,b). Third, scenario-based water quality predictions were conducted for the corresponding section of the research area in the Chao Phraya River. Fourth, relationship between pollutant discharge reduction function of on-site treatment systems and their construction costs were compared based on the existing literatures and database. The pollutant discharge reduction function was indicated by PDC.

METHODS

Description of the research area

Pak Kret District (*Amphoe*) is located northeast of Notanburi Province, north of Bangkok (Figure 1). The urban sub-district or Pak Kret Municipality is situated on the left bank of the Chao Phraya River and consisted of five communities (*Tambon*) among the twelve communities in the Pak Kret District. Total area of Pak Kret Municipality area is 36.04 km² and the total population was 242,800 including 80,000 non-registered inhabitants, which were rather normal in social systems in Thailand. The population density was 6,728 persons km⁻² at the end of 2003 (Sinsupan, 2004).

In Bangkok Metropolitan Area (BMA), 4.65 million m³ day⁻¹ or 91 % of total water supply source is withdrawn from the Chao Phraya and Mae Klong Rivers and the rest, 9 %, from deep wells (Jarusombat and Wajjwalku, 2003). Therefore, water quality in the rivers receiving wastewater discharges is important.

Characteristics of the Chao Phraya River

The Chao Phraya River flows in the central area of Thailand. The basin area is 159,283 km², annual precipitation is 1,179 mm year⁻¹, annual potential evapotranspiration is 1,538 mm year⁻¹, and annual average discharge is 196 m³ s⁻¹ (Working Group of ONWRC of Thailand, 2003). Major dams in the river basin are Bhumiphol Dam completed in 1963 and filled for the first time in 1970, and Sirikit Dam completed in 1972. Effective storage capacities of these dams are 9.7 and 6.7 billion m³, respectively. These two dams control the runoff from 22 % of the entire drainage area of the river. Among a number of barrages developed in the Lower Chao Phraya River basin, larger barrages are the Rama VI barrage completed in 1924, and the Chao Phraya (Chainat)

diversion dam completed in 1957. The central government policy of water quality was established based on the National Economic and Social Development Plan, and the National Policy and Plan for Natural Resources and Environment Management. The national goal of water quality was determined to maintain the surface water quality at the 1996 level. Priorities in the Chao Phraya River basin was determined as health, cities, water sharing, governance and risk management as one of the United Nations Water Assessment Program (WWAP)'s eleven predetermined challenge areas (UNESCO-WWAP, 2003).

Figure 1 - Research area for this study in the lower section of the Chao Phraya River (Distance from the river mouth is shown in parentheses).

Elevation of river bed and water surface, width of river bed, and cross sectional area of the Chao Phraya River were summarized by Apichatvullop (1976) and Lohani et al. (1980). The research area of this paper was along 67-80 km section in the Chao Phraya River from the river mouth, and cross sectional area of the river was estimated as around $5,000 \text{ m}^2$ near the river mouth and $2,000\text{-}3,000 \text{ m}^2$ at 60-104 km from the river mouth. Flow rate was smaller from December to July, and larger from August to November, when monthly average flow rate exceeded $500 \text{ m}^3 \text{ s}^{-1}$. The annual average flow rate was estimated as $479 \text{ m}^3 \text{ s}^{-1}$ (Apichatvullop, 1976). According to Apichatvullop (1976), in the lower section of the Chao Phraya River, well-mixed condition existed at low and moderate river flow up to $200 \text{ m}^3 \text{ s}^{-1}$, and partially-mixed condition that existed at larger river flow rate exceeded $200 \text{ m}^3 \text{ s}^{-1}$. The fluctuation of salinity was found to be a trigonometrical function curve that coincides with the tidal fluctuation. Horizontal flow rate distribution by the distance from the river mouth at a time in a year was estimated by Lohani et al. (1980).

Typical boundaries between salt and fresh water, remittent and unidirectional flow, and water level variability with tidal level fluctuation were summarized in relation to distance from the river mouth and river discharge (Chay, 1973). Major biological oxygen demand (BOD) pollutant sources in the Chao Phraya estuary were summarized as (1) canals (klongs) serving as outfalls during ebb tide and storing the waste during high tide, (2) direct discharge of wastes into the river by people living on boats or properties contiguous to the river, (3) industrial wastes discharged by a number of small industrial plants located along the river banks, and (4) refuse and garbage dumped directly into the river (Pescod and Ratasuk, 1968). Among the BOD pollutant sources, pollutant contributions from the canals were estimated as largest at that time. BOD pollutant load from the twelve major canals in Bangkok were also summarized (Kasesman, 1970; Chay, 1973). Kasesman (1970) estimated BOD discharge per capita (PDC_BOD) of domestic and industrial wastewater as $57 \text{ g person}^{-1} \text{ day}^{-1}$, which was estimated from the data of Camp, Dresser and McKee (1968) with PDC_BOD of municipal wastewater as $55 \text{ g person}^{-1} \text{ day}^{-1}$. BOD discharges by sewer, households on river bank, factories and canals were also summarized by Lohani et al. (1980). Water quality evaluated with BOD and DO in the lower Chao Phraya River was mostly deteriorated among surface water in the Central Thailand area (World Bank, 2001; PCD, 2006a).

Pollutant load profiles in the Chao Phraya River

Horizontal water quality profiles in the Chao Phraya River in 1999-2000 were summarized based on the administrative data (PCD, 2006c; Tsuzuki et al., 2007a,b; 2008a,b). Annual average flow rate at each point of the river was estimated based on the flow rate profile by Lohani et al. (1980) and annual average discharge at the river mouth estimated by Working Group of ONWRC of Thailand (2003), $196 \text{ m}^3 \text{ s}^{-1}$. Horizontal profiles of annual average pollutant loads of BOD, the sum of the inorganic nitrogen parameters, ΣN ($= \text{NO}_2\text{-N} + \text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) and TP in the river were estimated from the annual average horizontal river water quality profiles (PCD, 2006c; Tsuzuki et al., 2007a,b; 2008a,b) and the flow rate profile.

Municipal wastewater and nonpoint pollutant discharge analysis

Municipal wastewater pollutant load analysis in Pak Kret Municipality was conducted in urban and peri-urban area of Bangkok, Thailand, in the previous studies (Tsuzuki et al., 2007a; 2008a). In this study, pollutant load analysis in the Chao Phraya River was updated from Tsuzuki et al. (2008a,b) based on the existing literatures, i.e. pollutant discharges from Pak Kret District on both sides of the river were estimated, and PLC_{wb} estimation was also conducted. PDC values applied in this study were PDCs with SSL, i.e. $48.4 \text{ g-BOD person}^{-1} \text{ day}^{-1}$, $12.4 \text{ g-TN person}^{-1} \text{ day}^{-1}$, and $2.38 \text{ g-TP person}^{-1} \text{ day}^{-1}$, which were estimated based on the material flux analysis (MFA) results (Sinsupan, 2004; Tsuzuki and Thammarat, 2008; Tsuzuki et al., 2008a,b). Because of the geographic flatness of the lands around Bangkok, the groundwater level is rather high. Therefore, pollutant discharge estimation results with SSL should be rather reliable to evaluate municipal wastewater contributions to ambient water pollution.

Land use data were obtained from the International Steering Committee for Global Mapping (2008). The values of pollutant discharges per land area (PDLs) for BOD, total nitrogen (TN) and TP from build-up area, agriculture area, forest and mixed area in

Japan were mostly applied from Kunimatsu and Muraoka (1989) because of data availability. There have been many researches in the fields of point and nonpoint sources in Thailand (Thapinta et al., 2008). However, comprehensive summary of land unit loads or pollutant discharges per land area by land uses are not available in Thailand.

Pollutant loads in the Chao Phraya River corresponding to Pak Kret District including municipal area, Pak Kret Municipality, and non municipal area were estimated. Pollutant load increases were estimated between the corresponding monitoring points for Pak Kret District, i.e. pollutant load increases between 80 and 67 km from the river mouth (Figure 1). The sum of inorganic nitrogen, ΣN , is actually different from TN which includes both organic and inorganic nitrogen. However, in the estimation, ΣN was applied as TN because of data availability. The estimation method of PLC_{wb} applied in the analyses in Japan (Tsuzuki, 2004; 2005; 2006a) was with targeted water body as the river mouth. The same method was considered unreasonable to evaluate contributions of land-based pollutants to ambient water pollutant loads. The reasons for the unreasonableness are that most concerned section of water quality should be along BMA, i.e. 20-80 km from the river mouth (Figure 2), and there is the existence of larger tidal flow in the lower section of the river because of riverbed flatness (Apichatvullop, 1976). Therefore, the pollutant load increases at 67 km from the river mouth were regarded as the point for estimation of PLC_{wb} in this study.

In the general air quality monitoring stations, annual average value of total suspended particle (TSP) was 0.09 mg m^{-3} and nitrogen dioxide was 21.1 ppb (PCD, 2006a) in Bangkok in 2004, whereas in Japan in 1999, TSP was 0.028 mg m^{-3} and nitrogen dioxide was 16 ppb (Japanese Ministry of the Environment, 2001). In roadside monitoring stations, annual average value of TSP was 0.18 mg m^{-3} and nitrogen dioxide was 34.7 ppb in Bangkok in 2004, whereas in Japan in 1999, TSP was 0.037 mg m^{-3} and nitrogen dioxide was 30 ppb. Average annual precipitation in Pak Kret Municipality is $1,650 \text{ mm year}^{-1}$ (Polprasert, 2007), which is almost the same as the average annual precipitation in Japan. The air quality data comparisons do not necessarily show the similarity of the air quality between Bangkok and Japan, and precipitation frequency and pattern in Pak Kret Municipality are not necessarily similar to Japan. However, PDL values in Japan were applied because of data availability.

Scenario-based water quality estimation

Water quality predictions were conducted based on PDCs and PLC_{wb} estimated in this paper (Table 2). Wastewater treatment efficiency of BOD with packaged wastewater treatment systems was defined based on the wastewater discharge regulations for buildings and housings (PCD, 2006b) as 80%, and those of nutrient parameters were defined as 20% for both TN and TP based on average values of combined *johkasou* (CJ) in Japan because of data availability. Treatment efficiencies of pollutants at existing centralized domestic wastewater treatment plants (WWTPs) in Thailand differed much based on the influent organic pollutant concentrations and wastewater treatment methods (Tsuzuki et al., 2009). Therefore, treatment efficiencies at WWTPs were arbitrarily defined in two cases of Scenario 2, 2a and 2b (Table 2). Predictions of pollutant discharges and water quality in the Chao Phraya River were conducted for the three scenarios, i.e. Scenario 1, 2a and 2b.

Table 2 - Conditions of scenario-based estimations

Scenario	Conditions
Scenario 1	Current on-site treatment systems with SSL are to be converted to the packaged on-site wastewater treatment systems without SSL (Tsuzuki et al., 2009).
Senario 2	Centralized WWTPs and piped collection systems of both black and gray water are to be constructed in Pak Kret Municipality.
Scenario 2a	Smaller concentration of influent BOD was supposed and removal ratios were assumed to be 50% for BOD, TN and TP.
Scenario 2b	Larger concentration of influent BOD and introduction of nutrient removal system were supposed and removal ratios were assumed to be 80% for BOD, TN and TP.

When the river flow is remittent and most of the river water does not flow into the Gulf of Thailand, the impact of pollutant discharge should be limited to certain specific areas near the discharge points of pollutant sources. Chay (1973) estimated using a water quality simulation model and found that most influenced area from polluted canals were around 20 km length in the Chao Phraya River. Cross sectional area of the river width near Pak Kret Municipality is 2,000-3,000 m² (Apichatvullop, 1976; and Lohani et al., 1980). Contributions of pollutant discharge in Pak Kret District to the river water quality increases were estimated as

$$\begin{aligned}
 POL_{i,cont.} &= \frac{POL_{i,disch.}}{L \times CSA} \times \frac{L \times CSA}{Q} \times \frac{RR_i}{100} \\
 &= \frac{POL_{i,disch.}}{Q} \times \frac{RR_i}{100}
 \end{aligned} \quad (5)$$

where $POL_{i,cont.}$ is contribution of pollutant discharge to water quality increase of pollutant i (g m⁻³), $POL_{i,disch.}$ is pollutant discharge of pollutant i (g day⁻¹), L is length of the specific river section (m), CSA is cross sectional area of the specific river section (m²), Q is flow rate of the river (m³ day⁻¹), and RR_i is reaching ratio of pollutant i (%).

Scenario-based water quality predictions were conducted based on estimated water quality at 67 km from the river mouth using interpolation method with the current annual average water quality of the Nonthaburi Bridge monitoring point (CH15), 83 km from the river mouth, and Rama 6 Bridge (CH12), 58 km from the river mouth, as 1.93 g-BOD m⁻³, 1.28 g-TN m⁻³ and 0.234 g-TP m⁻³.

Cost-benefit comparison and additional PDC estimations

Pollutant discharge reduction is considered to be a benefit of sanitation in this paper and evaluation of the benefit is conducted by the use of PDCs. In order to address affordability of municipal wastewater treatment methods, the relationship between construction cost and PDCs was summarized based on the existing database (Water Environment Partnership in Asia (WEPA), 2007). The WEPA database has been developed by the Institute for Global Environmental Strategies (IGES), Japan. PDCs were estimated using the current wastewater treatment technology data of effluent water quality and construction cost in some Asian countries including Cambodia, Lao PDR, Malaysia, Myanmar, Thailand, Vietnam and Japan.

PDC of CJ and community plants (CP) in Japan were summarized in relation to the

equivalent population for wastewater treatment based on the existing literatures (Nishimura et al., 2004; Ogawa, 2006). CP is medium-sized on-site treatment plants for both black and gray water. Moreover, PDCs of CJ and CP were also summarized based on the existing literatures (Nishimura et al., 2004; Ogawa, 2006) to reassure PDC estimations in Japan by Tsuzuki (2006a).

RESULTS

Pollutant load in the river

Annual average pollutant loads of BOD, ΣN and TP in the Chao Phraya River were estimated from annual average river water quality (PCD, 2006c; Tsuzuki et al., 2007a,b; 2008a,b) and flow rate (Lohani et al., 1980; and Working Group of ONWRC of Thailand, 2003) as shown in Figure 2. Pollutant loads in the river were found to increase in the river sections corresponding to the BMA.

Figure 2 - Annual average pollutant loads in the Chao Phraya River (estimated from the horizontal flow rate profile developed by Lohani et al. (1980) and Working Group of ONWRC of Thailand (2003); and water quality data of PCD (2006c) and Tsuzuki et al. (2007a,b; 2008a,b)).

Municipal wastewater and nonpoint pollutant discharge analysis

Pollutant discharges from nonpoint sources were estimated using land use data in Table 3 (International Steering Committee for Global Mapping, 2008) and PDLs in Japan as shown in Table 4. Total pollutant discharges from Pak Kret District were estimated as 663 kg-BOD day⁻¹, 648 kg-TN day⁻¹ and 25.8 kg-TP day⁻¹. Total anthropogenic pollutant discharges from households, markets and peri-agriculture were estimated in Pak Kret District and Pak Kret Municipality (Tsuzuki et al., 2008a,b) and population ratio of Pak Kret District to Pak Kret Municipality (Table 3) as shown in Table 5. Total anthropogenic pollutant discharges from Pak Kret District were estimated as 19.6 t-BOD day⁻¹, 5.54 t-TN day⁻¹ and 1.11 t-TP day⁻¹ (Table 5). Pollutant discharge contributions of the non-point sources to total pollutant discharges were estimated as 12% for TN and less than 10% for BOD and TP (Table 5, Figure 3). Municipal

wastewater pollutant discharges occupied most of the pollutant discharges from Pak Kret District. Nonpoint source contributions were only around or less than 12 % of the total pollutant discharges. Therefore, overall pollutant discharge estimation method with PDL values in Japan was considered to be acceptable.

Table 3 - Population, population density, land use of municipal and non-municipal areas of Pak Kret District.

Area	Population ^a	Population percentage	Population ^b	Land use ^c				Total area	Percentage of area	Population density
	person	%	person	Agricultural area km ²	Grassland/ shrub km ²	Built-up area km ²	Mixture km ²	km ²	%	person km ⁻²
Pak Kret District	177,282	100.0	302,693	72.1	13.2	2.7	0.9	89	100.0	3,401
Pak Kret Municipality	142,225	80.2	242,836	23.3	9.9	2.7	0.0	36	40.4	6,745
Non-municipal area	35,057	19.8	59,857	48.8	3.3	0.0	0.9	53	59.6	1,129

a: Census 2000; b: Including non-registered population in 2003 estimated from Sinsupan (2004) and population percentage of Census 2000; c: Landuse is estimated from grid data of Global Mapping (2008).

Table 4 - Estimated nonpoint pollutant discharges from Pak Kret District by land use (kg day⁻¹).

Pollutant and area	Agricultural area	Grassland/ shrub	Built-up area	Mixture	Total
PDL-BOD (kg km ⁻² day ⁻¹) ^a	5.5	0.5	90.4	13.7	
Pak Kret District	395	7	248	13	663
Pak Kret Municipality	128	5	248	0	381
Non municipal area	267	2	0	13	282
PDL-TN (kg km ⁻² day ⁻¹) ^a	8.2	0.8	13.6	8.2	
Pak Kret District	593	11	37	8	648
Pak Kret Municipality	192	8	37	0	237
Non municipal area	401	3	0	8	411
PDL-TP (kg km ⁻² day ⁻¹) ^a	0.27	0.03	1.81	0.82	
Pak Kret District	19.8	0.4	5.0	0.8	25.8
Pak Kret Municipality	6.4	0.3	5.0	0.0	11.6
Non municipal area	13.4	0.1	0.0	0.8	14.2

a: Pollutant discharges per land area (PDLs) were estimated by the authors based on Kunimatsu and Muraoka (1989).

Pollutant loads in the Chao Phraya River corresponding to Pak Kret District including municipal area, Pak Kret Municipality, and non-municipal area were estimated (Table 5). Increases of pollutant loads between the corresponding monitoring points for Pak Kret District, i.e. increases between 80 and 67 km from the river mouth, were estimated as 2.9 t-BOD day⁻¹, 4.1 t-N day⁻¹ and 0.56 t-P day⁻¹ (Tables 5 and 6). Reaching ratios to the point of 67 km from the river mouth were estimated as 15% for BOD, 74% for TN and 51% for TP (Table 5). PLC_{wb} at 67 km from the river mouth were estimated as 7.2 g-BOD person⁻¹day⁻¹, 9.2 g-TN person⁻¹day⁻¹ and 1.2 g-P person⁻¹ day⁻¹ (Table 7). Smaller PLC_{wb} of CJ for all the parameters and slightly smaller PLC_{wb} of night soil treatment systems (NST) for TN and TP were found by estimation result comparison with the results of a case study in Japan (Tsuzuki, 2006a). BOD load per capita flowing into water body (PLC_{wb}_BOD) in Pak Kret Municipality was found to be larger than that of CJ and smaller than that of simple *joukasou* (SJ) and NST. TN and TP loads per capita flowing into water body (PLC_{wb}_TN and PLC_{wb}_TP) in Pak Kret Municipality were found to be larger than those of CJ, SJ and NST.

Table 5 - Pollutant discharges from Pak Kret Municipality and District, pollutant load increases in the 67-80 km section of the Chao Phraya River and reaching ratios.

Pollutant	Total anthropogenic pollutant discharge with SSL in Pak Kret Municipality ^a	Total anthropogenic pollutant discharge with SSL in Pak Kret District ^{a,b}	Pollutant discharge based on land use	Total pollutant discharge	Pollutant load increase at 67-80 km	Reaching ratio
	(a)	(b)	(c)	(b)+(c)		
	t day ⁻¹	t day ⁻¹	t day ⁻¹	t day ⁻¹	t day ⁻¹	%
BOD	15.2	18.9	0.7	19.6	2.9	15
TN	3.92	4.89	0.65	5.54	4.1	74
TP	0.87	1.08	0.03	1.11	0.56	51

a: Pollutant discharge from households, market and peri-agriculture; b: Estimated from pollutant discharges from Pak Kret Municipality and the ratio of population of Pak Kret District and Municipality.

Figure 3 -Proportions of pollutant discharges by sources from Pak Kret District

In the estimations, ΣN was applied for ambient water quality. Pollutant load of ΣN is considered to be underestimated for TN pollutant load, reaching ratio of nitrogen is considered to be overestimated, and PLC_{wb} also overestimated. Larger nitrogen and phosphorus reaching ratios may show necessity of nutrient removal in wastewater treatment facilities especially because eutrophication in ambient water is expected in the tropical climate.

Table 6 - Annual average pollutant load in the section of 58-80 km from the river mouth of the Chao Phraya River.

Measurement points in the Chao Phraya River	Distance from river mouth	Flow rate ^a	BOD ^b	ΣN ^b	TP ^b
	km	m ³ s ⁻¹	t day ⁻¹	t day ⁻¹	t day ⁻¹
A: Pibulsongkram Pier	58	110.6	18.4	14.5	2.45
B: Wat Tamnak Tai	67	97.4	16.3	10.0	1.89
C: Wat Photong Bon	80	79.8	13.4	5.9	1.34
B-C ^c	-13	17.6	2.9	4.1	0.56

a: based on Lohani et al., 1980, and Working Group of ONWRC of Thailand, 2003; b: based on the flow rate estimation and average water quality of PCD (2006); c: difference between B and C.

Table 7 - Pollutant load per capita flowing into water body (PLC_{wb}) in Pak Kret Municipality compared with PLC_{wb} in Japan.

Area; and domestic wastewater treatment method	PLC _{wb}		
	BOD	TN	TP
	g person ⁻¹ day ⁻¹	g person ⁻¹ day ⁻¹	g person ⁻¹ day ⁻¹
Pak Kret District; Averaged value	7.2	9.2	1.20
Chiba City; Combined <i>Johkasou</i>	1.1 ± 1.4 ^a	4.4 ± 2.1 ^a	0.41 ± 0.24 ^a
Chiba City; Simple <i>Johkasou</i>	13.5 ± 4.9 ^a	5.0 ± 2.2 ^a	0.39 ± 0.27 ^a
Chiba City; Night soil treatment system	11.2 ± 4.4 ^a	3.9 ± 0.4 ^a	0.32 ± 0.08 ^a

a: Average ± standard deviation in the small drainage areas (Source: Tsuzuki, 2006).

Scenario-based pollutant discharges and water quality prediction

Municipal wastewater pollutant discharge contributions from Pak Kret District to the river water quality increases were estimated through Eq. 5 as 0.34 mg-BOD l⁻¹ (18%), 0.48 mg-N l⁻¹ (38%) and 0.066 mg-P l⁻¹ (28%) in consideration with reaching ratios (Table 8).

Table 8 - Water quality increases estimated in the river section corresponding to Pak Kret District.

Pollutant	Pollutant discharge of municipal wastewater in Pak Kret District	Annual average flow rate of the Chao Phraya River at 67 km from the river mouth		Annual average water quality in the Chao Phraya River at 67 km from the river mouth	Contribution of pollutant discharge in Pak Kret District to the water quality in consideration with reaching ratio	
	t day ⁻¹	m ³ s ⁻¹	m ³ day ⁻¹	g m ⁻³	g m ⁻³	%
BOD	19.6	97.9	8,460,000	1.93	0.34	18
TN	5.54	97.9	8,460,000	1.28	0.48	38
TP	1.11	97.9	8,460,000	0.234	0.066	28

Based on the three scenarios, total pollutant discharges from Pak Kret District and water quality at 67 km from the river mouth were predicted (Figures 4 and 5). Percentages of pollutants discharge reductions were predicted as 23-64 % for BOD, 32-62 % for TN and 22-52 % for TP in all the scenarios (Figure 4). Due to the pollutant discharge

reductions, predicted water quality in the Chao Phraya River was 1.7-1.8 mg-BOD l⁻¹, 0.94-1.03 mg-TN l⁻¹ and 0.18-0.19 mg-TP l⁻¹ compared to the current annual average water quality of 1.93 mg-BOD l⁻¹, 1.28 mg-TN l⁻¹ and 0.234 mg-TP l⁻¹ (Figure 5). Percentages of water quality improvement were estimated as 6.4-14% for BOD, 15-26% for TN and 14-22% for TP.

Figure 4 - Pollutant discharges predicted with the scenarios in Pak Kret District.

Figure 5 - Water quality in the Chao Phraya River at 67 km from the river mouth predicted with the Scenario.

Cost-benefit comparison and additional PDCs estimations

Relationship between PDCs and construction cost per capita of the current wastewater treatment technologies in some Asian countries was summarized based on the database (WEPA, 2007) as shown in Figure 6. In the range of construction cost per capita of USD

4-2,942 person⁻¹, PDCs were estimated as 0.05-9.5 g-BOD person⁻¹ day⁻¹, 0.1-11.3 g-COD person⁻¹ day⁻¹, 0.4-5.7 g-TN person⁻¹ day⁻¹ and 0.02-0.82 g-TP person⁻¹ day⁻¹. There was no clear relationship between construction cost and PDCs (Figure 6a). Construction cost was USD 19-477 person⁻¹ in Thailand and USD 144-2,970 person⁻¹ in Japan, where it was found to be the most expensive (Figure 6b).

Figure 6 - Relationships between PDCs and construction cost per capita. (a): BOD, COD, TN and TP with centralized and de-centralized domestic wastewater treatment systems in Asian countries; and (b): PDC_BOD with centralized and de-centralized domestic wastewater treatment systems in Asian countries. Combined *johkasou* (CJ) is an on-site treatment system in Japan (based on WEPA, 2007).

PDCs of CJ and CP in Japan were summarized in relation to the equivalent population for wastewater treatment based on the studies of Nishimura et al. (2004) and Ogawa (2006) as shown in Figure 7. Designed PDC of combined *johkasou* were around 4 g-BOD person⁻¹ day⁻¹, 3 g-TN person⁻¹ day⁻¹ and 0.6 g-TP person⁻¹ day⁻¹ (Figure 7a). PDCs of community plants estimated from measured data were 0.5-6.7 g-BOD person⁻¹

day⁻¹, 1.2-4.4 g-COD_{Mn} person⁻¹ day⁻¹, 0.9-10.2 g-TN person⁻¹ day⁻¹ and 0.3-0.8 g-TP person⁻¹ day⁻¹ (Figure 7b). PDCs-BOD of CJ and CP estimated by Tsuzuki (2006a) were almost the same as those in Figure 7. However, PDCs-TN and PDCs-TP of CJ and CP estimated by Tsuzuki (2006a) were larger than those in Figure 7. These are because Tsuzuki (2006a) estimated PDCs based on the field survey data including older CJ and CP with lower nutrient removal efficiencies. PDCs in Figure 7 reflected recent development of nutrient removal function of CJ and CP. Stability and variance of effluent water quality of a treatment method is beyond the scope of this paper.

Figure 7 - Designed PDC of combined *johkasou* (CJ) (a) and measured PDC of community plant (CP) (b) in Japan in relation to population equivalent for wastewater treatment (based on Nishimura et al., 2004, and Ogawa, 2006).

DISCUSSIONS

Pollutant discharge reduction benefit of sanitation

PLC_{wb}_BOD in Pak Kret Municipality estimated in this study was larger than PLC_{wb}_BOD of CJ in Chiba City, Japan (Table 7). Nutrient loads per capita flowing into water body, PLC_{wb}_TN and PLC_{wb}_TP in Pak Kret Municipality were larger than those of all on-site treatment systems in Japan. PDC values of CJ shown in Figures 6 and 7 are not the same and within some ranges. Nutrient removal of CJ has been one of the important targets in the development of on-site municipal wastewater treatment systems in Japan these days (e.g. Okumura et al., 2006).

Pollutant discharge and water quality improvement predictions

In the scenario-based estimation, water quality improvement was predicted as 6.4-14% for BOD, 15-26% for TN and 14-22% for TP (Figures 4 and 5). The prediction was based on pollutant discharge reductions only in Pak Kret Municipality. Water quality can be further improved when pollutant discharge reductions are also conducted with other upper and nearby areas.

For pollutant load analyses, the material flow analysis (MFA) has been applied recently by Schaffner (2007) and Schaffner et al. (2009). PDLs estimated in this study are in the same order as the estimated unit load values from Schaffner (2007) for nitrogen and phosphorus parameters. Schaffner (2007) classified agricultural land as rice, field crops, and fruits and vegetables. For the fruits and vegetables, the smaller values of pollutant discharge unit loads were applied. Therefore, more precise estimation with more minute categories of the agricultural land should be necessary in further research.

The pollutant load analysis result in this paper coincides with that of Noyboonya (2008) that phosphorus discharge contribution from households was found to be larger comparing to other point and non-point sources in the Mae Klong River drainage area, Thailand. Suharyanto and Matsushita (2009) recently presented a comparative study on sanitation systems in Japan and Thailand including pollutant load analysis. Problems of smaller influent concentration at centralized WWTPs may have to be addressed further, however, these kinds of systematic approach is necessary in urban water and wastewater management in Thailand

Wakida and Lerner (2005) conducted nitrogen source estimation in groundwater of the urban area in developed countries and found large contributions of wastewater disposal (on-site systems and leaky sewers) and solid waste disposal (landfills and waste tips). Dulaiova et al. (2006) analyzed groundwater inputs into the Chao Phraya River using radioactive tracer method and estimated groundwater inputs to the river as about 20 % of the river flow in January (dry season) and 4 % during high flow conditions. Quantitative investigation on groundwater pollution from on-site system and on relationship between groundwater and ambient water should be considered for further research.

Comparison of cost and a benefit of sanitation

PDCs in Thailand (Figure 6b) were estimated only with effluent water quality and quantity of the municipal wastewater treatment systems. Therefore, when SSL were included, PDCs in developing countries including Thailand would be larger than the

values shown in the figure. Construction cost of sanitation facilities per capita in Thailand was USD 19-477 person⁻¹, whereas that in Japan was USD 144-2,970 person⁻¹. It is reasonable for ordinary people to choose lower cost facilities with the same pollutant-removal performances. The difference of construction costs between developing and developed countries is one of the barriers to be overcome for introduction or export/import of on-site municipal wastewater treatment systems (Tsuzuki et al., 2008b).

Water quality improvement policies in Thailand

The estimation and prediction results shown in this paper would be ones of the aspects in the whole water and wastewater conditions and management in Thailand. The estimation results of pollutant discharges, pollutant loads, and water quality presented in this paper are partly based on the existing literature. These studies have been conducted mostly in 1970's and 1980's in Thailand. Integration of the research results is considered to be necessary to understand the conditions of whole water and wastewater conditions, which will be also useful for actual water and wastewater management development.

A framework of the research and administrative sectors to address water quality and management are well constructed in Thailand including periodical water quality monitoring in the rivers and canals, dissemination of information to ordinary people (PCD, 2006a,b), multi-functional water pollution control program (Simachaya, 2000; Tsuzuki et al., 2008a), integral water resource management (IWRM), and environmental education programs (Lekphet et al., 2004; Thongnoppakun, 2006). The results of this study showed the possibility of effectiveness of PDCs and PLC_{wb} estimations and the scenario-based approach in the existing framework in Thailand.

CONCLUSIONS

Pollutant discharge and pollutant load indicators were utilized to show the direction of ambient water quality improvement with quantitative analysis framework considering the economic aspect of on-site treatment facilities.

Pollutant discharges from municipal wastewater and pollutant loads in ambient water were estimated in Pak Kret District, peri-urban area of Bangkok, Thailand. Reaching ratios of pollutants from Pak Kret District to 67 km from river mouth were estimated as 15% for BOD, 74% for TN and 51% for TP. PLC_{wb} were estimated at 67 km from river mouth as the receiving water as 7.2 g-BOD person⁻¹day⁻¹, 9.2 g-TN person⁻¹day⁻¹ and 1.2 g-P person⁻¹ day⁻¹. PLC_{wb} estimation was considered to be more reliable when the nearest section of the river rather than river mouth was considered as receiving water because of the land and river bed flatness. Annual average pollutant contributions of municipal wastewater from Pak Kret District to the river water quality increases were estimated as 0.34 mg-BOD l⁻¹ day⁻¹, 0.48 mg-N l⁻¹ day⁻¹ and 0.066 mg-P l⁻¹ day⁻¹, assuming that discharged pollutants should spread over the 20-km section of the river.

The results of the scenario-based approach showed percentages of water quality improvement in the Chao Phraya River to be 6.4-16% for BOD, 15-26% for TN and 14-22% for TP in the three cases, i.e. by introducing packaged on-site wastewater

treatment systems without SSL or centralized WWTPs in Pak Kret District.

The PDCs estimation results and the cost benefit comparison results showed the effectiveness of PDCs to evaluate various wastewater treatment systems. PDCs estimation and scenario based approach will enhance sanitation sector activities in the frameworks of academia and administration in developing countries including Thailand to address water quality improvement.

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