A concept for planning and management of on-site and centralised municipal wastewater treatment systems, a case study in Bangkok, Thailand. I: Pollutant discharge indicators and pollutant removal efficiency functions

Yoshiaki Tsuzuki, Thammarat Koottatep, Thitiphon Sinsupan, Supattra Jiawkok, Chira Wongburana, Suraphong Wattanachira and Yuttachai Sarathai

ABSTRACT

The concept of pollution load indicators for planning and management of the mixture conditions of centralised and on-site wastewater treatment systems has not been discussed in detail so far. In this paper, pollutant discharge (load) indicators and pollutant removal efficiencies were quantitatively analysed to develop a part of a strategy for planning and management of municipal wastewater treatment systems (WWTSs) under the mixture conditions in Bangkok, Thailand, as a case study. Pollutant discharge indicators of on-site WWTSs were estimated based on the relevant literature. Three kinds of pollutant removal efficiency function at centralised wastewater treatment plants (CWWTPs) were empirically developed for biological oxygen demand, chemical oxygen demand, total nitrogen, total phosphorus, total coliforms and faecal coliforms based on the existing CWWTP management data. These results will be integrated into the scenario-based analysis in the second paper in the series. The results will be base datasets, and the concept and estimation methods can be applied for wastewater treatment planning and management in other areas.

Key words | centralised and on-site wastewater treatment systems (WWTSs), pollutant discharge per capita (PDC), pollutant load per capita (PLC), pollutant removal efficiency function, seepage and septage from on-site treatment systems and leachate from composting (SSL)

INTRODUCTION

There are several kinds of methods for on-site and centralised municipal wastewater treatment systems (WWTSs) applicable in urban and peri-urban areas. Since the end of the nineteenth century, several kinds of technologies of WWTSs and other measures to improve ambient water quality have been developed, as well as their concepts. For example, eco-sanitation (Otterpohl et al. 1997; Zeeman & Lettinga 1999) and the life support system (LSS) (Hammes et al. 2000) should decrease total pollutant discharge per capita (PDC\textsubscript{total}) of municipal wastewater.
A decrease of PDC$_{total}$ leads to ambient water quality improvement. Measurements against leakage from influent collection systems of centralised wastewater treatment plants (CWWTPs) and grey water reuse technologies for toilet flush, sprinkling and other purposes (Yamagata et al. 2003) should also decrease PDC$_{total}$. Technologies of combined jokhasou, a typical Japanese on-site treatment system which treats both black and grey water, have been developed since the 1980s including nutrient removals especially for advanced systems (Gaulke 2006; Tsuzuki 2006). Constructed wetland, recirculated duckweed pond system (Benjawon & Koottatep 2007) and tertiary treatment system using Chlorella vulgaris (Steesai & Pakpain 2007) were developed to treat grey water and on-site treatment system effluent to decrease PDC$_{total}$, especially for those of infectious bacteria and nutrients. Membrane biological reactors enhanced technologies in wastewater reuse and desalination (Yamamoto et al. 1989; Melin et al. 2006). Packaged on-site wastewater treatment plants (WWTPs) for both black and grey water have recently been introduced in Thailand (Tsuzuki et al. 2009). The effects of the soft measures in households to reduce pollutant discharges (Tsuzuki et al. 2010) and hard interventions including WWTs and river water purification facilities (Tsuzuki et al. 2012) were quantitatively evaluated. Libralato et al. (2012) qualitatively summarised social, economic and environmental aspects of municipal WWTs. The effects of WWTP effluent on water quality in the coastal areas were analysed with a simulation model in Western Australia (Machado & Imberger 2012). Summaries of drivers of and technologies for on-site wastewater treatment were conducted at local scale in Seattle, USA (Seattle Public Utilities 2008), and South East Queensland, Australia (Tjandraatmadja et al. 2009).

For bacterial pollution, total coliform (TC) is an indicator of a bacteria group consisting of several genera that belong to the family Enterobacteriaceae, including both faecal origin species and those found in unpolluted environments (Pedley et al. 2006). Faecal coliform (FC) is equivalent to thermotolerant coliforms and is used as an indicator of faecal contamination and pathogen presence (Jiménez 2005). TC and FC concentrations were reported in a wide range, from 56 to $10^7$ and from $1.0 \times 10^8$ to $8.03 \times 10^8$ cell 100-mL$^{-1}$ in mixed grey water, respectively (Li et al. 2009). Those in bathroom grey water were from 103 to $2.4 \times 10^3$ and from 70 to 3,500 cell/100 mL, and those in laundry grey water were 8.9 to $56 \times 10^3$ and 1.6 to $9 \times 10^4$ cell 100-mL$^{-1}$. Evaluation of microbial pollution was conducted based on travel time, attenuation potential and microbe survivals (Howard et al. 2006). Periodical monitoring of groundwater and soil samples with simulation model analysis was applied for the evaluation. In Thailand, health-related Millennium Development Goal indicators including the mortality rate under 5 years of age have been improving (World Bank 2012); however, diarrhoeal diseases have still remained a problem both for residents (Jiraphongs et al. 2005) and travellers (Trible et al. 2007).

Groundwater is important in quantity and quality for water and wastewater planning and management. A large volume of groundwater abstraction has been conducted for many years, which has caused lowering of groundwater levels and land subsidence in Bangkok, Thailand (Jag-on et al. 2009). Seepage fluxes of radon and nutrients from groundwater to the Chao Phraya River were found to be large compared to those in other areas (Burnett et al. 2009). Pollutant discharge per capita (PDC) of seepage and septage of on-site WWTPs and leachate from composting (SSL) were found to occupy a large portion of pollutant discharge amounts from municipal wastewater and wastes (Tsuzuki et al. 2009; IWA Waterwiki 2011).

Pollutant removal efficiencies of CWWTPs are expressed as functions of influent pollutant concentrations, especially when water temperature is considered to be constant (Tsuzuki 2012). Pollutant removal rates and efficiencies of CWWTPs were expressed as functions of miscellaneous parameters including temperature, hydraulic retention time, sludge retention time and influent concentration (e.g. Grady & Williams 1975; Toprak 1995; Sperling 1999; Banda et al. 2005; Itayama et al. 2006; Tsuzuki 2012). For the activated sludge process, the International Water Association (IWA) models were developed (Gujer et al. 1995; Mino et al. 1997; Vanrolleghem et al. 1999).

Typical methods of WWTPs in Thailand are septic tanks, cesspools and anaerobic filters for on-site WWTPs, and aerated lagoons, oxidation ditches, stabilisation ponds and activated sludge processes for CWWTPs (Koottatep & Jiawkok 2008; Tsuzuki et al. 2009, 2010; Tsuzuki & Koottatep 2010; Honda et al. 2010). On-site WWTPs are mandatorily installed in most houses, even in the areas served with CWWTPs (Tsuzuki et al. 2009). Smaller organic carbon concentrations are found at some CWWTP influents in Thailand, which sometimes cause smaller pollutant removal efficiencies at the CWWTPs (Giri et al. 2006; Tsuzuki et al. 2009). Influent of CWWTPs consists of grey water direct discharge, flush-toilet wastewater and effluent of on-site WWTPs (Giri et al. 2005). Reasons for the smaller organic carbon concentrations in the CWWTP influent were explained as leaching from septic tanks, traditional usage of water after defecation, and organic material
degradation in the collection pipes/canals under the tropical climate (Giri et al. 2006).

In this paper, firstly, several kinds of pollutant discharge indicators, PDCs of on-site WWTPs, were estimated based on the relevant literature, in peri-urban areas of Bangkok, Thailand (Figure 1). These are PDCs of black water (PDC_b), PDCs of grey water (PDC_g), PDCs of septage in on-site WWTPs (PDC_sep), PDCs of seepage in on-site WWTPs (PDC_see), PDCs of on-site WWTP effluent (PDC_eff), and PDCs of discharge to ambient water through soil and groundwater, which is derived from septage and seepage of septic tank (PDC_a) (see Figure 2). Chemical oxygen demand (COD), TC and FC are newly investigated water quality parameters in this paper after Tsuzuki et al. (2009). Secondly, pollutant removal efficiency functions were empirically developed using CWWTP management data in Bangkok, Thailand, and the Monod-type and first-order equations with several kinds of explanatory variables. The term pollutant load per capita (PLC) is applied instead of PDC only for CWWTP influent because this is not pollutant discharge but influent.

Figure 1 | Schematic diagram of analysis conducted in this paper.

Figure 2 | Estimation results of pollutant discharge per capita (PDC) of on-site treatment systems in peri-urban areas of Bangkok, Thailand (estimated based on Sinsupan & Koottatep (2004), Jiawkok & Koottatep (2006), and Tsuzuki et al. (2009)).
METHODS

Pollutant discharge indicator

An analysis of pollutant discharges from on-site treatment systems was conducted to present a more complete PDC dataset after Tsuzuki et al. (2009) and Tsuzuki & Koottatep (2010). The analysis was mostly based on the material flux analysis results (Sinsupan & Koottatep 2004) and the field survey results (Jiawkok & Koottatep 2006) (Figure 1). These results were more carefully considered in this paper. The mixture conditions of septic tanks and cesspools in a peri-urban area of Bangkok, Thailand, were assumed. Major relationships between PDC indicators are:

\[
PDC_{bg} = PDC_b + PDC_g
\]

\[
PDC_b = PDC_{sep} + PDC_{see} + PDC_{eff}
\]

\[
PDC_a = f(PDC_{sep}, PDC_{see})
\]

where \(PDC_{bg}\) is PDC of black and grey water (g person\(^{-1}\) day\(^{-1}\)).

Pollutant removal efficiency function

Pollutant removal efficiency functions at CWWTs were developed with the Monod-type and first-order equations. Influent and effluent pollutant concentration data of several CWWTs in Bangkok, consisting of stabilisation ponds, oxidation ditches and aerated lagoons (Tsuzuki et al. 2009), were applied for the regression analyses. The Monod-type equation was applied only for biological oxygen demand (BOD). For the six pollutant parameters, BOD, COD, total nitrogen (TN), total phosphorus (TP), TC and FC, pollutant removal efficiencies were expressed as first-order equations of influent pollutant concentrations and reciprocals and logarithms of influent pollutant concentrations. For nutrients, TN and TP, several kinds of equations with influent BOD concentrations were also investigated because it might be possible that nutrient removal efficiencies were dependent on BOD removal in biological removal processes.

RESULTS

Pollutant discharge indicator

PDCs of on-site WWTSs in peri-urban areas of Bangkok, Thailand, were estimated as shown in Table 1 and Figure 2. From the estimation results, PDC\(_a\), PDC of on-site WWTPs seepage flowing into ambient water, was found to be comparable to PDC\(_{eff}\), PDC of on-site WWTP effluent, for almost all the water quality parameters, especially for COD and TN. The result shows the importance of seepage and septage from on-site WWTPs in pollutant discharge from on-site WWTPs and PDC\(_a\) cannot be ignored, which supports the results of Tsuzuki et al. (2009), which showed the importance of SSL. For nutrients, a larger portion of phosphorus was found in on-site WWTP effluent (PDC-TP\(_{eff}\) > PDC-TP\(_a\)) while a larger portion of nitrogen was found to be discharged through soil and groundwater to ambient water (PDC-TN\(_{eff}\) < PDC-TN\(_a\)). The ratios of PDC\(_{eff}\) to PDC\(_{bg}\) were estimated to be 3.0% for BOD, 5.0% for COD, 6.8% for TN, 24.7% for TP, 0.11% for TC and 0.66% for FC. The ratios of PDC\(_a\) to PDC\(_{bg}\) were estimated to be 0.65% for BOD, 4.2% for COD, 13.9% for TN, 2.2% for TP, 0.023% for TC and 0.012% for FC (Table 1).

Pollutant removal efficiency function

The analysis results of pollutant removal efficiency functions are shown in Table 2. For the Monod-type equation, maximum BOD removal efficiency and half-saturation constant were estimated as 105.2% and 20.0 g m\(^{-3}\), respectively, with 99% confidence level (Table 2, Figure 3). Some first-order equations were more correlated than the Monod-type equation for BOD (Table 2, Figure 4). Figure 4(a) shows correlations of influent BOD and BOD removal efficiency in both linear and logarithmic relationships with 95% confidence intervals. The graphs may show a different relationship in smaller and larger influent BOD concentration. Therefore, Figures 4(c) and (d) were prepared to show the results for 0–40 mg L\(^{-1}\) and 40–220 mg L\(^{-1}\) of influent BOD concentration ranges, respectively. Figure 4(b) shows the results of the reciprocal of influent BOD concentration as an explanatory valuable. These figures show that the larger the influent BOD concentration, the larger and more stable is the BOD removal efficiency. For COD and TC, significances were larger for equations with influent BOD concentration than for equations with influent concentrations of the pollutant parameters themselves (Table 2). The square of adjusted regression coefficients, adjusted \(R^2\), of first-order coefficients of COD and TC against these influent pollutant concentrations were 0.017, −0.046 and −0.064, which were smaller than those against influent BOD concentration, 0.265, 0.094 and 0.026, respectively. Based on the results for the five water quality...
parameters other than TP, the first-order equations of influent BOD concentration and the first-order equations of logarithm of influent BOD concentration were considered to be applicable for the pollutant removal efficiency functions in Tsuzuki et al. (2009) (Table 2).

For TP, adjusted $R^2$ was smaller, less than 0.13, and all the analysed cases were not significant at 5% significance level (Table 2, Figure 5). Therefore, TP removal efficiency which will be applied in the scenario-based analysis should be constant values: upper 30% values of influent TP concentration at the CWWTPs, which were 83.8% for large removal efficiency group, and 60% for average of large and small efficiency groups (Figure 5).

The authors concluded from the analysis results that three kinds of pollutant removal efficiency functions were empirically developed: two kinds of pollutant removal efficiency functions for the five water quality parameters other than TP, and constant values for TP.

DISCUSSION

Pollutant discharge indicator

The PDC estimation results of typical on-site municipal WWTSs in the peri-urban areas of Bangkok, Thailand, for
Table 2  First-order regression analysis results of pollutant removal efficiency and influent pollutant concentration of CWWTPs

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Influent pollutant concentration</th>
<th>The number of data</th>
<th>First-order coefficient</th>
<th>T-value</th>
<th>Constant</th>
<th>T-value</th>
<th>Adjusted $R^2$</th>
<th>X intercept</th>
<th>Concentration</th>
<th>Adopted for estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>BOD</td>
<td>334</td>
<td>0.471</td>
<td>14.412</td>
<td>**</td>
<td>46.373</td>
<td>25.732</td>
<td>0.385</td>
<td>0.383</td>
<td>−98.477</td>
</tr>
<tr>
<td>1/BOD</td>
<td>−447.572</td>
<td>144.12</td>
<td>**</td>
<td>87.895</td>
<td>48.764</td>
<td>**</td>
<td>0.408</td>
<td>0.406</td>
<td>0.196</td>
<td>5.1</td>
</tr>
<tr>
<td>log(BOD)</td>
<td>46.177</td>
<td>16.330</td>
<td>**</td>
<td>43.289</td>
<td>−0.382</td>
<td>0.445</td>
<td>0.444</td>
<td>−0.937</td>
<td>0.1</td>
<td>108.554</td>
</tr>
<tr>
<td>BOD (0–40 g m$^{-3}$)</td>
<td>180</td>
<td>−1.789</td>
<td>43.689</td>
<td>10.458</td>
<td>**</td>
<td>0.018</td>
<td>0.012</td>
<td>−108.554</td>
<td>518.288</td>
<td>NA$^d$</td>
</tr>
<tr>
<td>BOD (&gt;40 g m$^{-3}$)</td>
<td>152</td>
<td>8.170</td>
<td>**</td>
<td>74.946</td>
<td>53.500</td>
<td>**</td>
<td>0.308</td>
<td>0.303</td>
<td>−518.288</td>
<td>3769.7</td>
</tr>
<tr>
<td>1/BOD</td>
<td>0.190</td>
<td>4.268</td>
<td>**</td>
<td>0.010</td>
<td>3.503</td>
<td>**</td>
<td>0.052</td>
<td>0.049</td>
<td>−0.050</td>
<td>−20.0</td>
</tr>
<tr>
<td>(Monod Eq.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>COD</td>
<td>365</td>
<td>0.069</td>
<td>2.704</td>
<td>**</td>
<td>38.279</td>
<td>14.550</td>
<td>0.020</td>
<td>0.017</td>
<td>−557.558</td>
</tr>
<tr>
<td>1/COD</td>
<td>312.400</td>
<td>2.605</td>
<td>**</td>
<td>39.084</td>
<td>15.999</td>
<td>**</td>
<td>0.018</td>
<td>0.016</td>
<td>−0.125</td>
<td>−8.0</td>
</tr>
<tr>
<td>log(COD)</td>
<td>−1.227</td>
<td>−0.257</td>
<td>46.674</td>
<td>5.180</td>
<td>**</td>
<td>0.000</td>
<td>−0.003</td>
<td>38.051</td>
<td>1.12 $\times 10^3$</td>
<td></td>
</tr>
<tr>
<td>COD (0–120 g m$^{-3}$)</td>
<td>266</td>
<td>−0.489</td>
<td>−9.135</td>
<td>68.478</td>
<td>19.257</td>
<td>**</td>
<td>0.240</td>
<td>0.237</td>
<td>139.936</td>
<td>139.9</td>
</tr>
<tr>
<td>COD (&gt;120 g m$^{-3}$)</td>
<td>100</td>
<td>0.332</td>
<td>5.437</td>
<td>4.519</td>
<td></td>
<td></td>
<td>0.023</td>
<td>0.224</td>
<td>−13.631</td>
<td>−13.6</td>
</tr>
<tr>
<td>BOD</td>
<td>122</td>
<td>0.636</td>
<td>6.679</td>
<td>14.896</td>
<td></td>
<td></td>
<td>0.271</td>
<td>0.265</td>
<td>−25.413</td>
<td>−23.4</td>
</tr>
<tr>
<td>log(BOD)</td>
<td>65.609</td>
<td>7.766</td>
<td>−61.175</td>
<td>−4.167</td>
<td>**</td>
<td>0.355</td>
<td>0.329</td>
<td>0.932</td>
<td>8.6</td>
<td>1.12 $\times 10^3$</td>
</tr>
<tr>
<td>TN</td>
<td>TN</td>
<td>21</td>
<td>5.286</td>
<td>2.473</td>
<td></td>
<td></td>
<td>0.243</td>
<td>0.204</td>
<td>8.123</td>
<td>8.1</td>
</tr>
<tr>
<td>1/TN</td>
<td>−140.986</td>
<td>−3.307</td>
<td>50.029</td>
<td>2.698</td>
<td></td>
<td></td>
<td>0.365</td>
<td>0.332</td>
<td>0.355</td>
<td>2.8</td>
</tr>
<tr>
<td>BOD</td>
<td>21</td>
<td>0.657</td>
<td>1.116</td>
<td>−10.328</td>
<td>−0.334</td>
<td></td>
<td>0.062</td>
<td>0.012</td>
<td>15.708</td>
<td>15.7</td>
</tr>
<tr>
<td>1/BOD</td>
<td>−273.102</td>
<td>−0.841</td>
<td>31.200</td>
<td>1.217</td>
<td></td>
<td></td>
<td>0.036</td>
<td>−0.015</td>
<td>0.114</td>
<td>8.8</td>
</tr>
<tr>
<td>log(BOD)</td>
<td>21</td>
<td>60.518</td>
<td>1.240</td>
<td>−71.937</td>
<td>−0.970</td>
<td></td>
<td>0.075</td>
<td>0.026</td>
<td>1.189</td>
<td>15.4</td>
</tr>
<tr>
<td>TN/BOD ratio</td>
<td>21</td>
<td>136.599</td>
<td>1.751</td>
<td>−31.262</td>
<td>−0.947</td>
<td></td>
<td>0.139</td>
<td>0.094</td>
<td>0.229</td>
<td>NA$^d$</td>
</tr>
<tr>
<td>TP</td>
<td>TP</td>
<td>21</td>
<td>0.695</td>
<td>0.449</td>
<td>57.405</td>
<td>7.071</td>
<td>0.011</td>
<td>−0.042</td>
<td>−82.595</td>
<td>−82.6</td>
</tr>
<tr>
<td>1/TP</td>
<td>21</td>
<td>4.096</td>
<td>0.510</td>
<td>56.776</td>
<td>6.668</td>
<td></td>
<td>0.014</td>
<td>−0.038</td>
<td>−13.860</td>
<td>−13.860</td>
</tr>
<tr>
<td>BOD</td>
<td>21</td>
<td>−0.226</td>
<td>−1.195</td>
<td>69.107</td>
<td>6.938</td>
<td>**</td>
<td>0.070</td>
<td>0.021</td>
<td>305.127</td>
<td>305.127</td>
</tr>
<tr>
<td>1/BOD</td>
<td>21</td>
<td>185.952</td>
<td>1.897</td>
<td>50.016</td>
<td>6.467</td>
<td>**</td>
<td>0.159</td>
<td>0.115</td>
<td>−0.269</td>
<td>−3.7</td>
</tr>
<tr>
<td>log(BOD)</td>
<td>21</td>
<td>−28.333</td>
<td>−1.882</td>
<td>101.328</td>
<td>4.430</td>
<td>**</td>
<td>0.157</td>
<td>0.113</td>
<td>3.576</td>
<td>3769.7</td>
</tr>
<tr>
<td>TP/BOD ratio</td>
<td>21</td>
<td>236.560</td>
<td>1.961</td>
<td>39.202</td>
<td>3.281</td>
<td>**</td>
<td>0.168</td>
<td>0.125</td>
<td>−0.166</td>
<td>NA$^d$</td>
</tr>
</tbody>
</table>

(continued)
the mixture conditions of cesspools and septic tanks, would be a base dataset for pollutant load analysis in consideration with the effects of SSL (Figure 2, Table 1). Proliferation of the packaged on-site WWTPs would greatly change this dataset.

Pollutant removal efficiency function

For BOD and COD, larger correlations were found than for the other water quality parameters of TN, TP and TC (Table 2). The results show that these pollutant removal efficiencies at CWWTPs should depend largely on influent BOD concentration. The results in this paper on aerated lagoons, oxidation ditches and stabilisation ponds are consistent with the existing literature on biological WWTPs: COD loading rate was one of the factors to determine COD removal efficiency in anaerobic stabilisation ponds (Toprak 1995), COD removal efficiency was a function of COD influent concentration in two-step up-flow anaerobic sludge bed systems (Miron (1997), cited in Zeeman & Lettinga (1999)), and organic carbon removal efficiencies of ecological WWTPs were expressed as first-order equations of influent pollutant concentrations, especially when water temperature is considered to be constant (Tsuzuki 2012).

The pollutant removal efficiency function found in this paper can be used to quantitatively control and manage CWWTP operation. Larger influent BOD concentration is necessary to obtain larger pollutant removal efficiency, which may lead to smaller pollutant concentration in the effluent and efficient removal of pollutant from wastewater.

Nutrient removals at biological WWTPs are generally targeted after achieving removals of organic carbons and

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**Table 2**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>The number of data</th>
<th>Influent pollutant concentration</th>
<th>First-order coefficient</th>
<th>First-order coefficient</th>
<th>Konstant</th>
<th>T2-value</th>
<th>R2a</th>
<th>Adjusted R2a</th>
<th>X intercept</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC</td>
<td>17</td>
<td>1099 × 10^18</td>
<td>0.091</td>
<td>2.58</td>
<td>96.695</td>
<td>1.031</td>
<td>0.0091</td>
<td>0.091</td>
<td>0.0091</td>
<td>0.091</td>
<td>0.091</td>
</tr>
<tr>
<td>BOD</td>
<td>17</td>
<td>265959.95</td>
<td>0.064</td>
<td>1.63</td>
<td>97.347</td>
<td>1.016</td>
<td>0.064</td>
<td>0.064</td>
<td>0.064</td>
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<td>0.064</td>
</tr>
<tr>
<td>COD</td>
<td>17</td>
<td>27952</td>
<td>0.049</td>
<td>1.05</td>
<td>98.572</td>
<td>0.954</td>
<td>0.056</td>
<td>0.056</td>
<td>0.056</td>
<td>0.056</td>
<td>0.056</td>
</tr>
<tr>
<td>TN</td>
<td>17</td>
<td>16587</td>
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**Figure 3** Monod equation approximation of BOD removal efficiency and influent BOD concentration. $R_{BOD}$: BOD removal efficiency; $R_{BOD-MAX}$: maximum BOD removal efficiency; $C_{BOD, IN}$: influent BOD concentration; $K_s$: half-saturation coefficient.

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Square of regression coefficient.

Concentration corresponds to x-intercept.

Scenario-based analysis in Tsuzuki et al. (2013).

Not available.

*: 1% confident; **: 5% confident.
**Figure 4** | BOD removal efficiency (%) as functions of (a) influent BOD concentration, (b) reciprocal of influent BOD concentration, (c) influent BOD concentration in a range of 0–40 g-BOD m$^{-3}$, and (d) influent BOD concentration in a range of >40 g-BOD m$^{-3}$.

**Figure 5** | Relationship between influent TP concentration and TP removal efficiency. Note: Data of the same WWTPs in dry and rainy seasons are connected with dotted lines. While large removal efficiency group with four WWTPs and small removal efficiency group with two WWTPs are identified on the graph, larger TP removal efficiency in the dry season and smaller TP removal efficiency in rainy seasons are found at another three WWTPs in the four WWTPs not included in the two groups.
infectious bacteria. In this paper, TN removal efficiencies are considered to be expressed as functions of influent BOD concentration; however, nutrient removal efficiencies are not necessarily simply explained by the C:N:P ratios in the biomass because typical nutrient removals are mostly specific biochemical reactions and are not related to simple growth of microorganisms, e.g. nitrification and denitrification for nitrogen and enhanced biological phosphorus removal for phosphorus. Therefore, theoretically and practically, modification of pollutant removal efficiency functions for nutrients will be necessary, especially when these specific nutrient removal processes are applied.

CONCLUSIONS

Estimation of pollutant discharge indicators, PDCs, was conducted for on-site wastewater treatment systems in Bangkok, Thailand, for six water quality parameters: BOD, COD, TN, TP, TC and FC.

Pollutant removal functions at CWWTPs are obtained for the six water quality parameters. These functions are developed for ecological WWTPs based on the existing WWTP management data. These functions constitute a new concept for WWTP management, which can lead to quantitative control and management of influent concentrations and removal efficiencies of pollutants at CWWTPs.

These results present a base dataset and a concept for wastewater treatment planning and management, especially for a mixture condition of on-site and centralised WWTSs. The methods used in this paper can be applied in planning and management of municipal wastewater treatment in other areas for both practical and scientific purposes.

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