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Not Too Little, Not Too Much and Shortcut: A Review on the Effectualness of Per Capita Pollutant Discharge Indicators

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Abstract

In the fields of wastewater treatment planning, institutional and governance aspects are sometimes emphasised in developing and middle-developed countries. This paper summarises some important technical issues for the stakeholders of municipal wastewater treatment and water environment management. Pollutant removal efficiencies at wastewater treatment plants (WWTPs) are important but effluent water quality is sometimes emphasised. To achieve high pollutant removal efficiencies, maintaining a certain level of pollutant concentrations in the influent, or "Not Too Little" pollutant, is necessary. The second point is pollutant discharge from the river catchment should be "Not Too Much". Excess and rapid pollutant discharge increase in the catchment results in high costs and lengthy time periods for the river water environment to recover the original water environment conditions. The third point is that developing and middle-developed countries can use a "shortcut" or technological bypass by use of existing hard and soft measures to facilitate environmental improvements. This can be done with appropriate financial mechanisms. Pollutant discharge per capita (PDC) and pollutant load per capita flowing into water body (PLC_{wb}) are effective and efficient indicators that can be used to address these three concepts.

Keywords: Pollutant removal efficiency; Influent concentration; Monod-type equation; Pollutant discharge per capita; Inverted-U shaped curve relationship; Environmental Kuznets curve (EKC); Wastewater treatment planning

Introduction

In the fields of wastewater treatment planning in urban and peri-urban areas of economically developing and middle-developed countries, many researchers have conducted academic and practical purpose research over several decades [1]. Wastewater treatment management and planning is usually conducted with a primary requirement of effluent quality [2] and systematic considerations on the wastewater treatment systems have been conducted in developed countries [3]. Other aspects including economic, institutional and political, climatic, environmental, land availability-properties, socio-cultural and other-local aspects are secondary considerations, and lastly cost effectiveness is pursued. On the contrary, in developing countries, economic, institutional, political, and other-local aspects are usually the primary considerations. Normal pollutant concentration in the influent and effluent of wastewater treatment plant (WWTP) are typical by countries [4,5]. From the technological perspective, pollutant removal efficiencies are also important, as well as the requirement of effluent water quality [6,7].

From engineering perspectives, designing facilities with too small a capacity results in overflow of untreated wastewater to ambient water [2], and designing facilities with too large a capacity results in lower pollutant removal efficiencies [6,7]. Both centralised and decentralised municipal wastewater treatment systems have been developed based on socio-cultural conditions and available technologies [8]. Major decentralised treatment methods are Facultative Lagoons (FL) and Aerated Lagoons (AL), Anaerobic Lagoons (AnL), Aerobic Lagoons (AoL), Suspended Growth (SG), Sequencing Batch Reactor (SBR), Attached Growth (AG), Constructed Wetlands (CW) and simple and combined johkasou (SJ and CJ) [9,10]. Ecological wastewater treatment is a widely used term, and some of these technologies that apply biological and natural processes might be categorised as ecological wastewater treatment methods [6,11-14].

Technological, economic and institutional aspects of these ecological wastewater treatment methods have been studied many years. For example, technical and institutional aspects of constructed wetlands have been developed especially in developing countries [15-19]. A large percentage of municipal wastewater is still discharged without treatment especially in East and Southern Asia, Caspian Sea, Central and East Europe, West and Central Africa and Caribbean Regions [20]. From the sustainable engineering design concepts, sustainable design processes (SDPs) have advanced to integrated sustainable engineering design processes (ISEDP) [21]. When designing centralised and on-site WWTPs, the aim should be to attain high pollutant removal efficiencies in order to address "the needs of the present" and "their (future generations) own needs" World Commission on Environment and Development (WCED) [22]. When the design is not appropriate, it will take much time and cost to repair the damage to the environment [23].

A selection of wastewater treatment methods was systematically analysed in a case study in peri-urban and rural areas of South Africa and sustainability indicators were found to address all the sustainability dimensions [24], i.e., environmental, economic and socio-cultural, while other indicators and analysis methods such as energy analysis, Material Flow Analysis (MFA), economic analysis and Life Cycle Assessment (LCA), addressed limited aspects of the sustainability of wastewater treatment systems. Based on the results of their study, sustainability indicators are considered to be the most comprehensive tool to assess the sustainability of engineering systems. New paradigms

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have been developed for sustainable wastewater treatment in developing countries [25,26].

A concept for planning of on-site and centralised wastewater systems has been developed from the aspects of pollutant discharge indicators, pollutant removal efficiency functions, and scenario-based pollutant load analysis [7,27]. Pollutant load, pollutant discharge and water quality should be quantitatively managed and planned from the planning phase of Wastewater Treatment Plants (WWTPs) especially in low- and middle-income countries because huge public investments have been directed into centralised WWTPs. These parameters should be the most basic and fundamental markers for the framework of planning of WWTPs. It should be noted that there are some WWTPs which miss the mark and are not efficiently operated and managed, e.g. smaller pollutant removal ratios because of smaller influent concentration.

The purpose of this paper is to describe some fundamental issues in wastewater treatment management and planning issues based on recent research and to discuss importance of these issues in the institutional and governance fields of wastewater treatment planning. In this paper, critical points on the planning are described based on these existing papers from the perspective of sustainability. Sustainability indicators include multiple aspects such as technology, economy and institutional [24,28]. This paper focuses on technological issues related to sustainability and discusses the meaning of results from several recent publications [5-7,26,27,29]. The research topics of these papers have been the necessity of maintaining a certain pollutant concentration or load in the influent of WWTPs [6,7], and a problem of a rapid and excess pollutant discharge increase in a catchment [30]. For a technological shortcut for municipal wastewater treatment systems, on-site treatment systems are considered to be cost effective in areas with smaller population density. A simple simulation on payment for the on-site WWTP under the conditions of moderate economic development with purchase-power parity based gross domestic product (PPP-GDP) in 2014 as US$ 2,000 was conducted in this paper to think about shortcuts or early development stages from an economics perspective.

For the three concepts presented in this paper, Not Too Much refers to restricting pollutant discharge into the catchment and corresponds to general directions for environmental preservation; however, Not Too Little suggests that WWTP influent should be maintained with a certain level of pollutants. Biological technologies which are applied in many centralised WWTPs need a certain level of pollutants for their operation. Development of a WWTP, especially a centralised system, needs a long-term and huge investment [31]. Shortcuts sometimes may need to utilise financial mechanisms to support the early stages of development. PDC and PLC_{wb} are efficient and effective indicators to address these three concepts. Biological (or biochemical) oxygen demand (BOD) is commonly applied in the three topics of this paper. BOD is considered to be an appropriate indicator for biological treatment processes and also for evaluating organic consumption capacity of ambient water. Regarding biological treatment processes, there are still problems with a mixture of non-biodegradable or toxic materials in the influent in some countries, however, such problems are beyond the scope of this paper.

Not Too Little: The Necessity to Maintain a Certain Pollutant Concentration or Load in Wastewater Treatment Plant (WWTP) Influent

The relationships between pollutant removal efficiency and influent concentration can be expressed using the Monod-type equation 1. (Figure 1) [6,7,32]. The Monod-type equation has been originally developed for the growth rate of bacteria, and is applicable to pollutant removal efficiency at WWTPs. Organic carbon concentrations such as BOD and chemical oxygen demand (COD) are most applicable for the pollutants in this context [6]. Figure 1 shows that a certain pollutant concentration is necessary in WWTP influent to maintain large pollutant removal efficiency. Pollutant removal efficiency increases with an increase of pollutant concentration in the influent [6]. If the pollutant concentration is too small, pollutant removal efficiency decreases and sometimes becomes a negative value, i.e. effluent concentration is larger than influent concentration [7,25]. Small pollutant removal efficiencies can be found at some WWTPs, and these are mostly because of planning problems, i.e. the actual influent pollutant concentration and load is smaller than the planned pollutant load. There are several existing technological solutions for this problem [7]. In Figure 2, the relationship between pollutant influent concentration (C_{in}) and effluent concentration (C_{ef}) is illustrated more simply based on the following Eqs. 2 and 3 [6].

$$R_{BOD} = \frac{R_{BOD-MAX} \times C_{BOD,in}}{K_s + C_{BOD,in}} \tag{1}$$

Where R_{BOD} is the removal efficiency of BOD at a WWTP (%); $R_{BOD-MAX}$ is the maximum value of the removal efficiency of BOD (%); $C_{BOD,in}$ is the BOD influent concentration at a WWTP (mg/l); and Ks is the half saturation coefficient (mg/l).

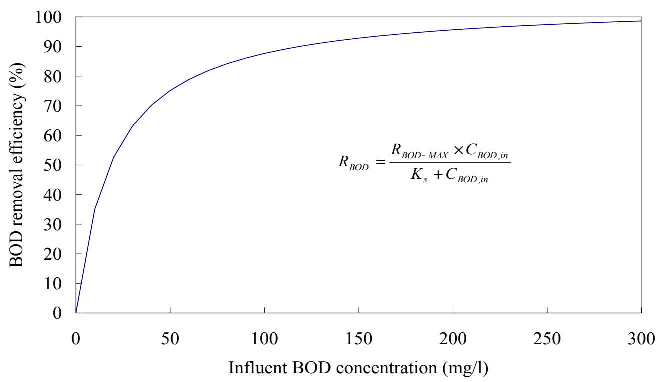

Figure 1: The Monod-type equation of BOD removal efficiency and influent BOD concentration which is obtained from management data from several ecological wastewater treatment plants (WWTPs) in Bangkok, Thailand (Modified from [6]).

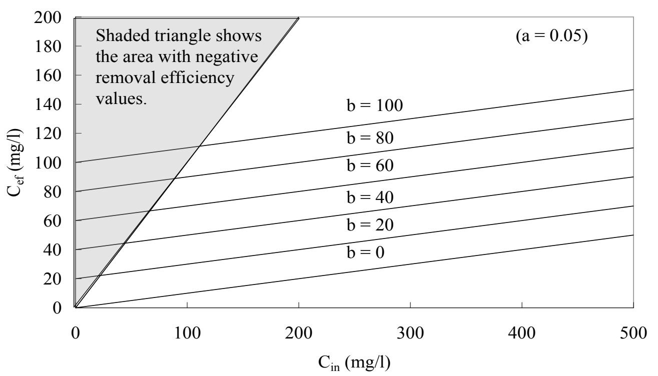

Figure 2: Relationship between influent and effluent concentrations of pollutant in wastewater treatment plants (Modified from [6]).

$$C_{ef} = a \times C_{in} + b \quad (2)$$

where C_{ef} is the effluent pollutant concentration/load (g m^{-3} or g day^{-1}); Cin is the influent pollutant concentration/load (g m^{-3} or g day^{-1}); a is a coefficient (dimensionless); and b is a coefficient (g m^{-3} or g day^{-1}).

$$\text{Removal Efficiency (\%)} = (1-\frac{C_{ef}}{C_{in}})\times 100 = (1-a-\frac{b}{C_{in}})\times 100 \quad (3)$$

The values of $R_{BOD\text{-}MAX}$ and Ks in Eq. 1 and a and b in Eqs. 2 and 3 can be obtained empirically based on management data of WWTPs or experimental data. Figure 2 shows effluent pollutant concentration increase with an increase of pollutant concentration in the influent. The shaded area shows negative removal efficiency, i.e. pollutant concentration in the effluent is larger than that in the influent.

These relationships will lead to one of the common understandings among wastewater professionals: it may be possible that total pollutant discharge to ambient water will decrease when more wastewater is collected and treated at WWTPs. Pollutant removal efficiency would increase under such conditions. This common understanding can be supported from the following contents in this paper, however, it may be also possible that some types of pollutants in the influent cannot be removed efficiently because of a design mismatch or design failure between the treatment plant itself and the piped collection system. Some methods to address design failures should be developed to address such cases [23].

The scenario-based analysis results show a decrease in total pollutant discharge per capita (PDC) with an increase in the percentage of wastewater treated at centralised WWTPs for Scenario 1 or for the percentage of population served with centralised WWTPs (%) for Scenario 2 (Figure 3) [27]. This analysis has been conducted in urban and peri-urban areas of Bangkok, Thailand, where both on-site and centralised wastewater treatment systems are applied. The scenario-based analysis results shown in Figure 3 have been derived from a set of PDC values which have been based on the material flow analysis (MFA) [7]. The x-axes or percentage values are different in the two scenarios because existing mixture conditions of centralised and on-site treatment systems are considered to be maintained in Scenario 1 and centralised WWTPs areas and on-site WWTPs areas are considered to be divided in Scenario 2.

The values of pollutant discharge or pollutant load are expressed as pollutant discharge per capita (PDC) in Figure 3. When these percentages increase, pollutant load in WWTP influent increases and pollutant load in direct discharge to ambient water decreases. These parameters are measured using PDC. Pollutant discharge and pollutant load can be assessed as per capita values by using PDC. Pollutant discharge and pollutant load values have been converted to WWTP influent concentrations in the simulation analysis [27]. The alteration of WWTP effluent is not simple because pollutant removal functions are included in the analysis especially for Cases 2a and 2b. The increase or decrease of PDC for WWTP effluent depends on the explanatory variables. The increase in PDC for WWTP effluent is smaller compared to the other PDCs, and the total PDC decreases with an increase in the explanatory variables on the x-axes in both scenarios and all cases. In these investigations, costs were not taken into account. Inclusion of economic parameters and life cycle analysis (LCA) will lead to more comprehensive understanding of wastewater treatment planning [33]. These parameters are more sensitive to local natural and socio-economic conditions.

Equations 1–3 are based on normal operations of biological WWTPs for municipal wastewater. Inclusion of other wastewater in WWTP influent should be carefully considered and its dilution effects are beyond the scope of this paper. Note that dilution often does not decrease pollutant loads. Other aspects which should be further considered in the practical planning would be centralised and on-site wastewater treatment [7,27], treatment of black water and gray water [34] and source-separation [35].

Not Too Much: Excess Pollutant Discharge into the Catchment Causes Excessive Water Pollution

Natural conditions generally change in the long term and

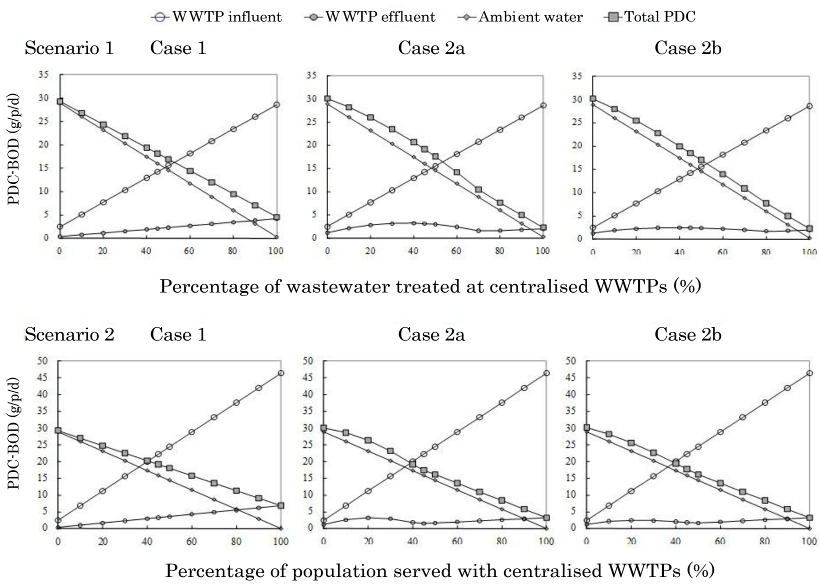

Figure 3: Estimation of pollutant discharge per capita (PDC) of BOD for two scenarios (Modified from [27]).

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anthropogenic conditions change in the short term. In a natural water environment with no or minimum human effects, a certain relationship between pollutant discharge and ambient water quality should maintain some equilibrium conditions. The relationship between pollutant discharge and water quality in a natural water environment may be originally in the linear or first-order relationship, and perturbation or dynamic equilibrium change of stable conditions for the relationship have been observed under the rapid increase and excess pollutant discharge conditions in the Yamato-gawa River Catchment, Japan (Figure 4) [30]. Water quality stationarity alongside changes of pollutant discharge from the catchments has sometimes found [36,37]. Over a longer timeframe than anthropogenic condition changes, morphological or sea level changes also occur.

Many developed countries including Japan have experienced severe ambient water pollution especially from the 1960s to the 1980s during rapid economic growth (Figure 4) [30]. Because of such growth, urban development and industrialisation, BOD discharge in the Yamato-gawa River Catchment has increased rapidly in the late 1960s. National level environmental regulations including those protecting against water pollution have established in 1970, however, BOD discharge into the river basin has continued to increase until the late 1970s and BOD concentration in the river has deteriorated rapidly and became worse until the mid-1970s (Phase 1). In the late 1970s and 1980s, BOD discharge into the river basin has been still substantial, but BOD concentration has improved a little (Phase 2). In the 1990s, BOD discharge has decreased because of several measures to improve water quality (Phase 3). In the late 1990s, the relationship between BOD discharge and BOD concentration returned to that of the late 1960s. After that, BOD concentration improved with decreases in BOD discharge (Phase 4).

There should be a capacity in regards to pollutant discharge into the river basins. When pollutant discharge exceeds the capacity and increases rapidly, water quality deteriorates and a lot of time and expense would be necessary to recover to the original relationship of pollutant discharge and water quality. The grey line of Figure 4 supposes the original linear relationship between BOD discharge and BOD concentration. Rapid increase and excess BOD discharge has caused the relationship to drift away from the original linear relationship, and

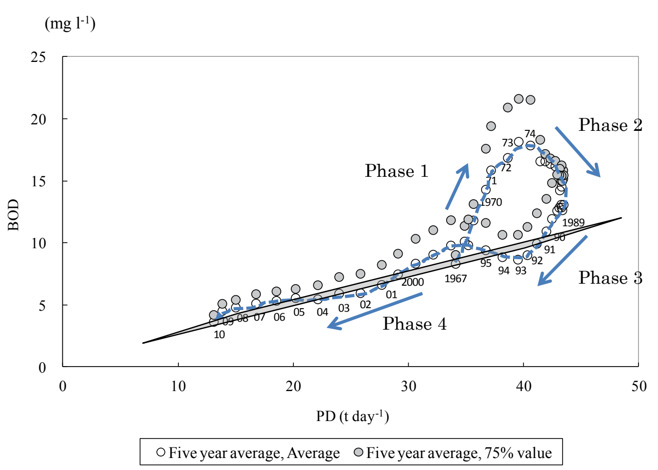

Figure 4: Relationship between BOD discharge and BOD concentration, five-year average of average and 75% value, in the Yamato-gawa River, Japan, during 1967–2010. The grey line indicates the original linear relationship between BOD discharge and BOD concentration (Modified from [30]).

the BOD concentration in Phase 1 has deteriorated to increase above the original relationship.

Shortcuts: Economic Development with Smaller Environmental Burden

In developing and middle-developed countries, many people are working to develop their technologies and economies. During rapid economic development periods, developed countries have experienced environmental pollution including water pollution, e.g. in the 1960s and 1970s in Japan. At that time, there were not effective and efficient measures to decrease environmental pollution, which cause severe water pollution (Figure 4). During the history of development of environmental friendly technologies in developed countries, appropriate technologies and methods have been developed to mitigate environmental pollution. Advanced technologies suitable for developing and middle-developed countries have also been developed [38-40].

For developing and middle-developed countries, shortcuts or bypasses of technology development should be theoretically possible (Figure 5). Many kinds of environmental friendly technologies and methods to improve river water quality have been developed over several decades, e.g. the soft measures to improve river water quality [41]. There would be institutional, governance, cost and application problems to actually introduce these technologies and methods into these countries [2], however, these countries are benefitting from the situations that socio-economic tools including cost estimation methods of centralised treatment system have been developed [42].

In the fields of water pollution, pollutant discharge per capita (PDC) would be one of the important indicators used to describe the magnitude of pollutant discharge from municipal wastewater in certain areas [5,7,43]. PDC is found to have an inverted-U shaped curve relationship with the economic development indicator, namely Environmental Kuznets Curve (EKC) relationship (Figure 5) [42]. The indicator, pollutant discharge per capita flowing into the water body (PLC_{wb}), is also applicable to assess the effect of pollutant discharge on ambient water quality [5]. "Shortcut" planning can be introduced for municipal wastewater treatment by applying PDC and PLC_{wb} Figure 5. PDC and PLC_{wb} address pollutant loading aspects and would be a part of a set of sustainable indicators together with indicators that address socio-economic aspects.

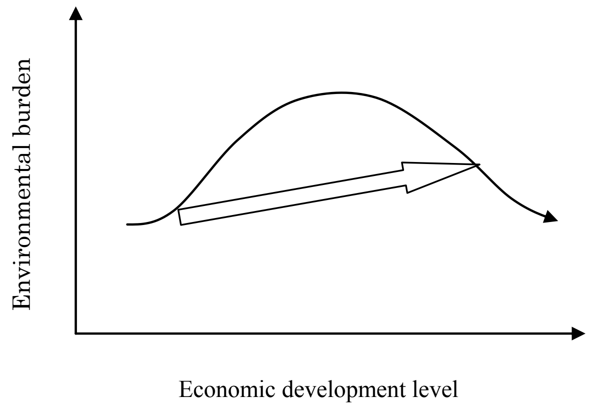

Figure 5: Relationship between economic development level and environmental burden. Inverted U-shaped curve is supposed. The white arrow shows the shortcut (Modified from [10]).

Simple simulation of income and payment for the on-site WWTPs showed longer time lags for the investments and utilisation of on-site WWTP with the deposit-and-pay method, compared to loans and 50% subsidies plus loans (Figures 6 and 7). Simulation conditions were assumed for purchase-power parity based gross domestic product (PPP-GDP) per capita, price of on-site WWTP for a family, the number of paid persons in a family, and several annual change rates as shown in Table 1. For the deposit-and-pay method, it will take 25 years to install and start to use the on-site WWTP because of the nominal price increase of an on-site WWTP (Figure 7). If the nominal price was fixed at US$ 5,000 because of technology development effects, installation of the on-site WWTP would be possible in 14 years. For both loan cases, the full-cost loan and the half-subsidies in 2014, the on-site WWTP could be used from 2014 and payment would be finalised in 20 years and 11 years, respectively. The simulation results showed the effectiveness of loans and subsidies for early development of the on-site treatment systems or shortcuts.

Conclusions

Among the three concepts presented above, two concepts state the importance of moderate conditions, i.e. “Not Too Little”, suggesting that a certain pollutant inflow is necessary to maintain pollutant removal efficiency, and “Not Too Much”, suggesting that rapid increase and excess pollutant discharge in a catchment cause severe water pollution. Another important concept is “Shortcut” or bypass of technologies and measures for environment improvement, which will be important for developing and middle-developed countries and involves applying both the existing and newly developed technologies. For the “Shortcut”, financial mechanisms including subsidies and loans should be effectively utilised to introduce the measures to mitigate environmental pollution in the early stages of the development. In the municipal wastewater treatment and water environment fields, PDC and PLC_{wb} would be effective and efficient indicators to assess the magnitude of pollutant discharge and pollutant load.

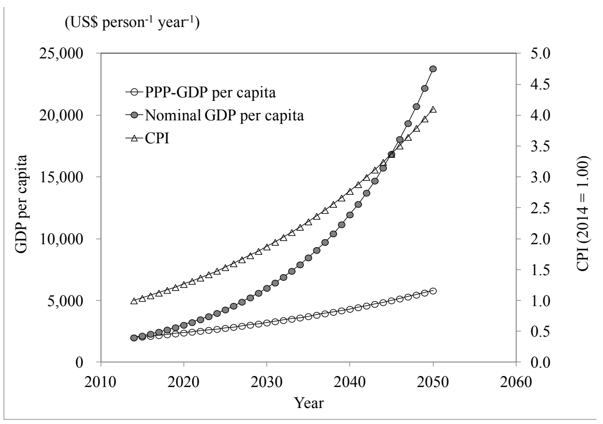

Figure 6: Chronological change of PPP-GDP per capita (2014 price), nominal GDP per capita, and consumer price index (PCI).

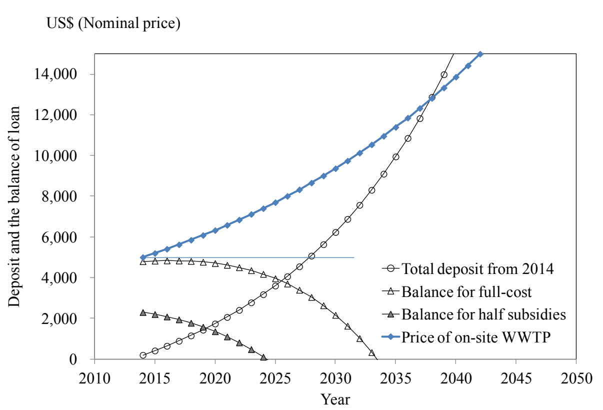

Figure 7: Total deposit from 2014, price of on-site WWTP, balances for loans of full-cost and half-subsides for on-site WWTP.

Parameter	Annual change rate (%)
PPP-GDP per capita	3
Consumer price index (CPI)	4
Percentage of income which is available for payment of on-site WWTP	5
Interest rate of loan for on-site WWTP construction	5
PPP-GDP per capita in 2014	US$ 2,000
Price of on-site WWTP for a family	US$ 5,000
The number of paid persons in a family	2 persons

Table 1: Simulation conditions on payment for on-site WWTPs.

Mutual and common understanding of scientific and technical issues is considered to enhance institutional and governance aspects of water environment preservation and improvement. The importance of maintaining moderate conditions for pollutant discharge and wastewater treatment and technological shortcut or bypass of environmental friendly technologies discussed in this paper would help enhance the mutual and common understanding among stakeholders of wastewater and water environment planning and management and sustainability in these fields.

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Conflicts of Interest

The authors declare no conflict of interest.

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