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Estimation of the effects of chemically-enhanced treatment of urban sewage system based on life-cycle management

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ABSTRACT

Effluent requirements have frequently been established that are more stringent than those traditionally considered possible using biological secondary treatment. We evaluated aeration energy and CO_2 emissions using an inorganic polymer coagulant of polysilicato-iron (PSI) as a pre-treatment alternative to an aluminium coagulant. Use of the PSI coagulant for CO_2 reduction was evaluated in terms of the effects on the quality of the treated water and overall cost effectiveness using a simplified life-cycle assessment (LCA) technique for a wastewater treatment system in an urban catchment. The water quality improvement effects of the wastewater treatment were evaluated by calculating the flux change according to the water quality characteristics in an urban catchment using a catchment simulator. The system evaluated, in an integrated manner, the quality of the treated water and the CO_2 emissions from a wastewater treatment system. The effects of wastewater treatment management measures were assessed by evaluating their CO_2 emissions and cost, in addition to the water quality improvement. A flocculating agent was used at a concentration close to the water quality standard, and a major effect was seen in terms of reduced aeration energy costs and CO_2 emissions. Model calculations of the cost of using flocculating agents, such as polyaluminium chloride (PAC), PSI, ferric chloride, and a polymer coagulant, indicated that the most economical agent was PSI with a polymer. For a cost burden of about 200 million JPY per year, including the cost of the flocculant and of sludge disposal, the CO_2 emissions could be reduced by approximately 30%. Thus, a reduced energy technology was established to optimally manage catchment wastewater.

1. Introduction

Raw wastewater frequently undergoes chemical treatment, either as the only direct precipitation treatment or as a pre-precipitation treatment before biological treatment. Because most wastewater contaminants are associated with organic matter particles, suspended matter, organic micropollutants, bacteria, heavy metals, and other pollutants may also be precipitated (e.g., phosphates and metals), and chemical treatment alone can result in substantial removal of these contaminants (Aguilar, Martinez-Guerra, & Poznyak, 2002; Ji, Qiu, Wai, Wong, & Li, 2010; Odegaard, 1995). Physical–chemical treatment of wastewater has been widely practiced, introducing biodegradation and chemical advanced oxidation for biological treatment (Liu, Kanjo, & Mizutani, 2009). Physical–chemical treatment has been revived and continues to the present day, particularly in treatment plants that are overloaded during peak flow events and in regions where bypassed discharges of excess wastewater during storm events are no longer permitted (Berlamont & Torfs, 1996; Geiger, 1987; Parker, Kaufman, & Jenkins, 1971; Soonthornnonda & Christensen, 2008). The impact of treating all flows up to and including peak storm water flows is illustrated by the following example. For a contributing population of 0.1–1.0 million served by a separate sewerage system, the hydraulic capacity needed for sedimentation tanks is approximately twice the average dry-weather flow if diversion of excess storm flows is allowed. If the whole flow is treated at all times, the hydraulic capacity may need to be four-fold or more the average dry-weather flow, which markedly increases the capital cost of treatment (Bratby & Marais, 1977; Khalil, 2012). An alternative to treatment of the whole flow is to provide physical–chemical treatment of the excess bypass flow.

Abbreviations: APT, advanced primary treatment; ASM, activated sludge model; BOD, biochemical oxygen demand; CEPT, chemically-enhanced primary treatment/sedimentation; CSO, combined sewer overflows; DOC, dissolved organic carbon; DT, detention tank; FT, flocculant treatment; GHG, greenhouse gas; LCA, life-cycle assessment; PAC, polyaluminium chloride; PS, present status; PSI, polysilicato-iron; RIA, reduction of the impervious area; SC, small-scale domestic wastewater control; SS, suspended sediment; SRT, solids retention time; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus; TSS, total suspended sediment; WWTP, waste water treatment plant.

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The addition of coagulant chemicals to primary clarifiers or to other dedicated physical separation processes is effective in reducing the load to downstream biological processes, or in some cases may be used for direct discharge. Chemically-enhanced primary treatment (CEPT) or advanced primary treatment (APT) employs chemicals to enhance coagulation and flocculation, thus more effectively removing pollutants from raw wastewater (Haydar & Aziz, 2009; Wang, Li, Keller, & Xu, 2009; Yan, Wang, You, Qu, & Tang, 2006). CEPT possesses some advantages in wastewater treatment, such as a savings footprint (Aiyuk, Amoako, Raskin, Van Haandel, & Verstraete, 2004). Harleman and Murcott (2001) promoted CEPT as an effective first step of pollution control, particularly in large urban areas that have evolved with sewage systems, but without centralised wastewater treatment and that have limited financial resources for more complete but capital-intensive biological treatment options such as activated sludge systems. Urban areas may also not have the area available for appropriate technology options, such as stabilisation pond processes. Harleman and Murcott (2001) concluded that CEPT, while not a complete treatment, is far better than no treatment. After implementing chemical treatment as an initial stage, biological polishing of some sort can be added later for soluble biochemical oxygen demand (BOD) removal and nitrogen conversion, if required, as funds become available. One issue in the chemical treatment of wastewater, including CEPT, is coagulant dosage control. Leentvaar, Werumeus Buning, and Koppers (1978) investigated the dependence of coagulation on a number of raw wastewater parameters to optimise total organic carbon (TOC) removal. The parameters included TSS, TOC, dissolved organic carbon (DOC), total P, and total Kjeldahl nitrogen (TKN).

The main disadvantages of a wholly physical–chemical solution to wastewater treatment are problems associated with the highly putrescible sludge produced and the high operating costs of using the chemical additives. However, much of the current interest in physical–chemical treatment stems from its suitability for use in emergency conditions: seasonal applications, avoidance of excess wastewater discharges during storm events, and primary treatment before biological treatment, where the above disadvantages are less important. Moreover, in the past, physical–chemical treatment has been well established in tertiary wastewater treatment.

Much energy is required for wastewater treatment by an activated sludge method. A previous study in Australia holistically investigated the operational energy consumption and/or GHG emissions associated with all urban water system components, including water supplies, water filtration plants, water distribution, sewage systems, and wastewater treatment systems (Lundie, Peters, & Beavis, 2004; Machado et al., 2007; Pasqualino, Meneses, Abella, & Castells, 2009). The proportions of the environmental indicator scores resulting from the construction of the infrastructure alone were small (i.e., 4% or less of each impact category) relative to the proportions attributable to the operation of wastewater systems (i.e., 8% or less of each impact category). This result is consistent with the conclusions of the present study of systems optimisation. Thus, this study focused on strategies for managing the environmental impact of operating system components for enhanced chemical treatment.

It is possible to reduce the CO_2 emissions from urban activities by applying the life-cycle assessment (LCA) technique. This technique has been used to evaluate energy consumption, CO_2 emissions, and the cost of space heating and hot water supply through the initial and operational stages of a district heating system that derives its heat from sewage (Ichinose, Hanaki, Ito, Matsuo, & Kawahara, 1997). Tillman, Svingby, and Lundström (1998) conducted a similar type of study on small-scale sewage treatment processes to evaluate the consequences of changing a district's heating system for wastewater treatment systems. That study included analysis of the environmental impacts of the investment in both production of the system components and their operation. Other studies have investigated the energy consumption and/or greenhouse gas (GHG) emissions associated with a single component or multiple components of an urban water system (Lundie et al., 2004). Other LCAs of wastewater treatment systems have focused on the environmental impacts of component production in a system (Schuurmans-Stehmann, Van Selbst, & Bijen, 1996).

2. Objective

In this study, we evaluated the feasibility of chemically-enhanced treatment based on life-cycle assessment (LCA), with the aim of improving water quality, reducing CO_2 emissions, and improving cost effectiveness compared with traditional and innovative urban sewage management. We compared the effects of different management scenarios, including traditional methods, such as the installation of a water detention tank (DT), the optimisation of the solids retention time (SRT), the optimisation of household effluents (SC), and the reduction of the impervious area (RIA), and including methods based on innovative technology, such as use of a flocculant (FT), for an entire year (2004) using a catchment simulator (Mouri & Oki, 2010a, 2010b; Mouri, Shinoda, & Oki, 2010; Mouri, Shiiba, Hori, & Oki, 2011a,b; Mouri, Shinoda, & Oki, 2012; Mouri, Golosov, Chalov, Vladimir, et al., 2013; Mouri, Minoshima, et al., 2013; Mouri, Golosov, Chalov, Takizawa, et al., 2013). Paying attention to the wastewater treatment technology, we considered the possibility of high utilisation of the system. The wastewater treatment management scenario at the time of applying each technology was set up and examined by an integrative approach from a viewpoint of optimising the quality of the treated water, the effects on CO_2 emissions, and the overall cost. We particularly focused on the effects of chemically-enhanced treatment using a flocculating agent to reduce the aeration energy requirements and CO_2 emissions.

3. Methods

In the model, the effects of floods, low water, flow rate changes, and water quality were calculated for sub-catchments (unit grids), and a synthetic evaluation was performed to determine the effect of wastewater treatment on water quality. Subsequently, the results for the entire grid were unified, and the catchment-scale effects were evaluated. In addition, one object of the evaluation was to determine the amount of CO_2 emitted in the process of handling the wastewater, a parameter that represents an important measure of environmental impact and that has not been easy to evaluate until now. We proposed optimal management methods that maximise water quality improvements and minimise energy consumption (CO_2 emissions) in a wastewater treatment system.

3.1. Study site description

The Shigenobu River basin (445 km^2) is located on the western border of the Dogo Plain on Shikoku Island, Japan. The urban catchment area (approximately 41.9 km^2) is drained by a separate sewer system. The combined sewer system, including the retention facilities, has a total storage volume of approximately 46,000 m^3. The life cycle of each facility is set at 50 years. Wastewater is treated using a standard activated sludge system; this can become extremely overloaded during heavy rainstorm events, resulting in serious water pollution due to combined sewer overflow (CSO) approximately 20 times per year. Approximately 56% of the population (287,000 individuals) is served by the sewer system, accounting for approximately 20% of the total combined sewer system length (1244.7 km).

Within the basin, a surface area of approximately 41 km^2 is impervious (Mouri, Takizawa, & Oki, 2011; Mouri, Kanae, & Oki, 2011).

3.2. Materials: PSI coagulant

The long-term performance effects of PSI compared with PAC on coagulation, phytoplankton sedimentation and filtration, turbidity, and DOC in raw water from a eutrophic reservoir were evaluated at a pilot plant. PSI was found to be more effective than PAC at coagulation and removal. Because the flocs formed by PSI settle more quickly than those of PAC, the size of sedimentation facilities could be reduced by using PSI in high-rate chemically-enhanced primary treatment (CEPT), which also produced filtered water with low turbidity and colour. Wang et al. (2002) evaluated an inorganic polymer coagulant of PSI as an alternative to aluminium and ferric chloride coagulants. PSI reduced the number of phytoplankton cells in filtered water over that of PAC. Most residual flocs in settled water were trapped in the coarse layer of anthracite, suggesting that a higher filtration rate could be achieved with PSI by increasing the particle size of the filter media. Phytoplankton in raw water is a precursor of the need for disinfection and interferes with coagulation and filtration processes (Bernhardt, Schell, Hoyer, & Lusse, 1991). However, the removal of phytoplankton by aluminium coagulants, such as aluminium sulphate and polyaluminium chloride (PAC), is not always optimal (Dolejs, 1993). Large quantities of aluminium coagulant are frequently used to prevent coagulation interference by phytoplankton. However, many reports on the genetic determinants of Alzheimer's disease suggest that because of its neurotoxicity aluminium may be an important factor in this disease (Martyn, Barker, & Osmond, 1989; McLachlan, Bergeron, & Smith, 1996).

In Japan, aluminium coagulants, such as aluminium sulphate and PAC, are commonly used as major coagulants in drinking water treatment. PSI was developed to provide a substitute for aluminium coagulants. Investigations of its coagulation characteristics (Hasegawa, Hashimoto, Onitsuka, Goto, & Tambo, 1991; Hashimoto, Hasegawa, Wang, & Tambo, 1994) have shown that PSI has a strong bridging property, derived from polysilicic acid, which plays an important role in coagulation and separation. PSI can produce substantial flocs at a given stirring speed, and flocs formed by PSI are stronger than those formed by alum (Ohno, Uchiyama, Saito, Kamei, & Magara, 2004). Due to its combined charge neutralisation and bridging, PSI performs better in the coagulation and separation of turbid and organic matter (Hasegawa, Wang, Kurokawa, & Hashimoto, 1999). PSI has also been applied to the pre-coagulation of municipal wastewater in a jet-mixed separator (JMS). Pre-coagulated sludge produced by PSI from municipal wastewater has shown promise as an excellent phosphate fertiliser (Wang et al., 2002). In practice, removals may be lower or higher than those in the example. In warm climates with larger collection systems and relatively flat sewers, a higher degree of hydrolysis of particulate matter, resulting in higher soluble fractions, is expected, resulting in lower overall CEPT removal. On the other hand, if the collection system is relatively small, the climate is cold, and the wastewater is relatively fresh, a higher proportion of particulate material may be present, and CEPT removals could be higher. In physicochemical pre-treatment, flocculation with screened flocculants showed around 50% chemical oxygen demand (COD) elimination (Aiyuk et al., 2004; Gray, Yao, & OMelia, 1995; Michael et al., 2005; Peters & Lundie, 2001; Stumm, 1977; Yu et al., 2009). In this research, the extraction ratio of total nitrogen and organic matter was assumed to be 50%, and the amount of flocculating agent was examined.

An expression for the concentration of non-adsorbing electrolyte required to destabilise dispersion can be derived by assuming a potential energy curve. The electrolyte solution contains electrically charged ions, atoms, or molecules and is electrically conductive. Typically, a great deal of stimulation is required to overcome the electrostatic attraction (Gray et al., 1995; Peters & Lundie, 2001; Stumm, 1977). The molar concentration of electrolyte solution C_0 required to destabilise dispersion is given by:

$$C_0 = \frac{9.75 \times 10^3 B^2 \varepsilon^3 (kT)^5 \gamma^4}{(Ae)^2 N z^6} = \frac{\text{constant}}{z^6} \tag{1}$$

where B is a constant equal to $4.36 \times 10^{20}/\text{A}^2\text{S}^2$ and A is Hamaker's constant, which ignores the influence of an intervening medium between the two particles of interaction, and

$$S = \frac{R}{a}, \tag{2}$$

where R is the distance between centres of spheres, a is the radius of assumed spherically shaped particles, ε is the permittivity (7.08×10^{-12} coulombs/V/cm), and kT is the Boltzmann constant multiplied by the absolute temperature (0.41×10^{-20} V coulombs at 20 °C), which is a physical constant relating energy at the individual particle level with temperature.

$$\gamma = \frac{\exp(ze\psi_\delta/2kT) - 1}{\exp(ze\psi_\delta/2kT) + 1}, \tag{3}$$

where z is the valency of counterions, $1/K$ is the thickness of diffuse part of double layer, and N is the shortest distance between spheres.

Eq. (1) illustrates an interesting point: The optimum concentrations of indifferent electrolytes yielding counterions with valency $z = 1$, 2, and 3, for example, should be in the ratio $1/1^6{:}1/2^6{:}1/3^6$, or approximately 800:12:1. In fact, this corresponds reasonably well with experimental evidence on the coagulation of hydrophobic colloids by nonadsorbable ions.

3.3. LCA methodology

We examined the environmental impacts associated with construction and operation of a sewage treatment system using the LCA technique. Life-cycle methods are an effective means of examining site remediation activities in a broader context and considering several options in a consistent framework. A life-cycle approach allows for systematic review of potential impacts beyond those immediately associated with the contaminated site and therefore enables consideration of potentially wider impacts. LCA has been applied primarily for evaluating system component production (Mouri & Oki, 2010a; Schuurmans-Stehmann et al., 1996). Other LCAs of wastewater treatment systems have examined the burdens associated with a product or process over its lifetime, with the intent of minimising them. LCM, which evolved from LCA, is a streamlined approach to structuring and conceptualising environmental activities (Friedrich, 2002; Page & Diamond, 1998). LCA and LCM are typically used for product-based systems in the manufacturing and processing sectors. For example, Peters and Lundie (2001) used LCA to examine options for processing biosolids (i.e., sewage sludge) into separate reusable organic materials. Some studies have investigated energy consumption and/or GHG emissions associated with a single component of an urban water system, while others have taken a wider view and investigated multiple components (Lundie et al., 2004; Machado et al., 2007; Pasqualino et al., 2009). The synthesis of distributed wastewater treatment plants (WWTPs) has focused on cost reduction, but never on the reduction of environmental impacts. The environmental and economic feasibility of a total wastewater treatment network system including distributed and terminal WWTPs was estimated using LCA and life-cycle costing (LCC) methods (Lim, Park, & Park, 2008).

These approaches can be extended to new sectors where systematic assessment of CO_2 emissions and water quality is required as an integrated approach to analyzing the life cycle of an urban sewer system. In this study, CO_2 emissions were presumed for an entire wastewater treatment system using the LCA technique. LCA was used to evaluate CO_2 emissions associated with WWTP products and processes over the lifetime of the sewage treatment system, with the intent of minimising those emissions.

Water quality and CO_2 emission flow in the whole sewage system were also evaluated in an integrated manner using the LCA technique, while considering cost effectiveness. The LCA procedure was in accordance with the ISO 14040 series of standards (ISO, 1997). In calculating flux change, the water quality characteristics of an urban catchment were included using a catchment simulator (Mouri & Oki, 2010a, 2010b; Mouri et al., 2010, 2012a; Mouri, Golosov, Chalov, Vladimir, et al., 2013; Mouri, Minoshima, et al., 2013). The construction-phase data were based on accumulating the energy-consumption basic unit from annual sewer statistics (JSWA, 2004). The annual energy consumption in an operation phase was computed using data on the annual consumption of electric power and fuel of a sewage treatment plant. CO_2 emissions calculations were based on the fuel-use rate. About 30% of the CO_2 generated by building a plant was associated with pipe construction, and about 60% of the pipe was basic pipe with a diameter of less than 600 mm (Mouri & Oki, 2010a).

3.4. Urban sewage system sub-model

The matrix format for the presentation of biokinetic models was explained with a simple model and expanded for the Activated Sludge Model No. 1 (ASM1) of the International Association on Water Pollution Research and Control (IAWPRC) Task Group for Mathematical Modelling for Design and Operation of Biological Wastewater Treatment (Gujer & Henze, 1991). With the aid of a simulation programme, a complex activated sludge model that included two organic substrates and nitrification was developed stepwise and compared with experimental results. In addition, ASM1 was applied to improve the effluent water quality at the WWTP, as proposed by the IAWQ (Cheng & Ribarova, 1999). An optimisation technique was used to calibrate the ASM (Wanner, Kappeler, & Gujer, 1992), with model parameters to be estimated including the maximum specific growth rate of heterotrophic organisms, the substrate half-saturation constant of the heterotrophic organisms, the hydrolysis rate constant, the yield coefficient of the heterotrophic organisms, and so forth. The wastewater and effluent for modelling the activated sludge process were expressed as COD and nitrogen (Henze, 1992). Acute water pollution in urban areas was evaluated based on oxygen and ammonia concentrations, key parameters of acute water pollution in urban rivers; these two abiotic parameters were analysed in a historical rain series (Rauch & Harremoes, 1997).

In this study, we calculated the effect of wastewater treatment with rain and wastewater as natural and artificial external forces, respectively. Variation over time in the amount of influent and water quality was calculated by performing dynamic simulation of wastewater treatment using the ASM. We examined the response of a natural system to input conditions, i.e., the amount of water, flood flow, and rate of drainage, the temporal response of water quality, and the water quality model. We confirmed that it was possible to reproduce wastewater treatment process results under dry-weather conditions and that the estimates were in general agreement with past observations (Mouri & Oki, 2010a, 2010b; Mouri et al., 2010; Mouri, Takizawa, et al., 2011; Mouri, Shinoda, Golosov, et al., 2012b). Influent quality was based on survey data provided by the city of Matsuyama, Japan. Data on suspended solids (SS), total nitrogen (TN), and chemical oxygen demand (COD) of WWTP inflow/outflow were available from the city of Matsuyama from September to October 2004 and were used in model calibration and validation. Removal of an organic substance by a heterotrophic microbe is defined as being proportional to the microbe's multiplication rate. Therefore, if a multiplication rate is determined in principle, organic substance removal velocity can be determined. Thus, the aerator residence time is set to maximise organic substance removal. Therefore, the main COD components in the final treated water reflect the presence of substances that are difficult to biodegrade.

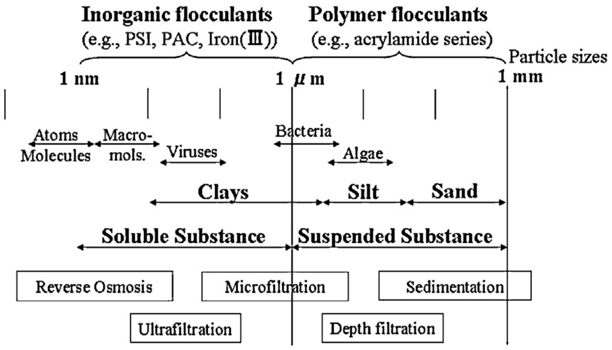

Fig. 1. Flocculation range for inorganic and polymer flocculants of waterborne particles consisting of soluble and suspended substances such as sand, silt, and clays. Data are from Stumm (1977) and Gray et al. (1995).

4. Results and discussion

The effects of drainage system management were evaluated using an integrated approach, with the aims of improving water quality, reducing CO_2 emissions, and maximising cost effectiveness. We compared the effects of different management scenarios for an entire year (2004). The above method was applied using the catchment simulator with the LCA method to the Shigenobu River Basin, located on the western border of the Dogo Plain over Holocene sediments on Shikoku Island, Japan. Table 1 provides an improved sewage system management scenario, based on that of Mouri and Oki (2010a). Paying attention to operation energy reduction at WWTPs, we modelled the effects of each wastewater treatment management measure for dry- and wet-weather periods, with the goal of reducing CO_2 emissions. We considered the present situation (PS), as well as traditional methods such as CSO, DT, SRT, SC, and RIA, and innovative methods such as the use of a flocculant (FT), especially inorganic flocculants of PSI with polymer flocculants (Fig. 1). A catchment simulator and a numerical model were developed and applied to a real catchment. The performance of the model was validated, including assessments during a heavy rainfall event and a low-water period. The matrix format for the presentation of biokinetic models was explained with a simple model and expanded to the Activated Sludge Model No. 1 (ASM1) of the International Association on Water Pollution Research and Control (IAWPRC) Task Group for Mathematical Modelling for Design and Operation of Biological Wastewater Treatment (Gujer & Henze, 1991). With the aid of a simulation programme, a complex activated sludge model including two organic substrates and nitrification was developed in a stepwise fashion and compared with experimental results. In addition, ASM1 was applied to improve the effluent water quality at the WWTP, as proposed by the IAWQ (Cheng & Ribarova, 1999). An optimisation technique was used to calibrate the ASM (Wanner et al., 1992). We applied the model to data obtained in the main sewer trunk. After the validation, we were able to predict the effluent concentration profiles within the main sewer trunk, which differs from the upper trunk in that it receives both wet- and dry-weather flows from the urban sewage system (Fig. 2). Most previously developed urban storm water quality models were

Table 1
Management strategies for sewer system optimisation based on Mouri and Oki (2010a).

		Scenario	Sub system	Control device	Objective of control
1	PS	–	–	–	–
2	CSO	Combined sewer system	Overflow structure, gate	• CSO reduction (water quantity, pollution load) • Peak-cut of flood	Reduce the peak by using an overflow structure for flow rates in excess of 2.1 (m^3/s)
3	DT-1	Detention tank at the end of the drainage pipe system	Detention tank	• Peak control of flood	Peak control using a detention tank for flow rates in excess of 2.1 (m^3/s). Post-flood, intake of water from tank at a rate of 1.5 (m^3/s)
	DT-2	Detention tank in each household	Detention tank	• CSO reduction (water quantity, pollution load) • Peak control of flood	30% of the annual influent is stored during rain events and treated later in WWTP
4	SRT	Wastewater treatment plant	Aeration	• Improvement of effluent quality • Organic removal, nitrification efficiency	Extend the solids retention time by about 9.5 h under unusual conditions
5	SC	Home unit	Household effluent	• Reduction of influent water quantity and pollution load	Reduce domestic water use by 20% during rain events
6	RIA	Soil infiltration	Infiltration well	• Reduction of water quantity to sewer system	Improve soil infiltration by using an infiltration well for 10% of rainfall
7	FT_1	Chemically enhanced treatment	Pre-treatment	• Reduction of aeration energy	Flocculating agent was used by the Schulze–Hardy rule
8	FT_2	Chemically enhanced treatment	Pre-treatment	• Reduction of aeration energy	Flocculating agent was used close to the water quality standard
9	SC+DT_1	Home unit, detention tank	Household effluent, detention tank	• Reduction of influent water quantity and pollution load • Peak control of flood	Reduce domestic water use by 20%, together with peak control using a detention tank for flow rates in excess of 2.1 (m^3/s). Post-flood, intake of water from tank at a rate of 1.5 (m^3/s)
10	RIA+DT_1	Soil infiltration, detention tank	Infiltration well, detention tank	• Reduction of water quantity to sewer system • Peak control of flood	Improve soil infiltration by using an infiltration well for 10% of rainfall, together with peak control using a detention tank for flow rates in excess of 2.1 (m^3/s). Post-flood, intake of water from tank at a rate of 1.5 (m^3/s)
11	FT_2+DT_1	Chemically enhanced treatment, detention tank	Pre-treatment, detention tank	• Reduction of aeration energy • Peak control of flood	Flocculating agent was used close to the water quality standard, together with peak control using a detention tank for flow rates in excess of 2.1 (m^3/s). Post-flood, intake of water from tank at a rate of 1.5 (m^3/s)

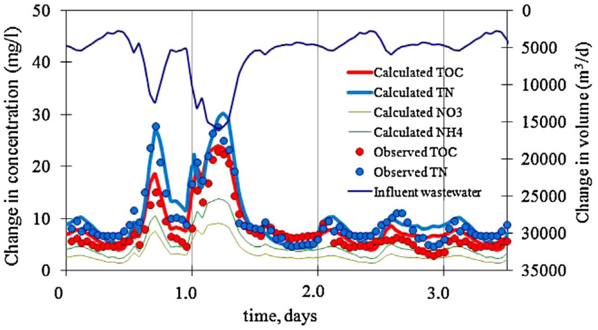

Fig. 2. Validation of concentration profiles of effluent wastewater quality. The red line shows the calculated total organic carbon concentration. Data are from the city of Matsuyama.

developed as sets of equations, with each equation or subset of equations treated as a description of a part of the whole process and analysed as a chain of successive steps or sub-processes (Mouri & Oki, 2010b; Rauch et al., 2002).

Applying a model based on the LCA technique to a wastewater treatment system, Mouri and Oki (2010a) derived CO_2 emissions data associated with construction and operation of WWTPs and pumping stations. The construction-phase data were based on accumulating the energy-consumption basic unit from annual sewer statistics (JSWA, 2004). The annual energy consumption in an operation phase was computed using data on the annual consumption of electric power and fuel of a sewage treatment plant. CO_2 emissions calculations were based on the fuel-use rate. About 30% of the CO_2 generated by building a WWST plant was associated with pipe construction, and about 60% of the pipe was basic pipe with a diameter of less than 600 mm (Mouri & Oki, 2010a).

Fig. 3 shows the water quality and CO_2 emission flow per year from the whole sewage system in the present situation (PS) scenario. Reducing the amount of influent to the WWTP greatly affected the energy consumed and CO_2 emissions. A large portion of the energy used for water quality improvement is consumed by aeration in the reaction vessel of a WWTP system; thus, the energy consumption is proportional to the amount of WWTP influent. During dry and wet weather, the predominant particles in suspension are approximately 40 μm in diameter and can be primarily attributed to sanitary solids (e.g., Ashley & Crabtree, 1992; Verbanck, 1993). Most of the suspended particle load in combined sewer flows is organic (90%) and has a high specific surface area (i.e., biochemically active particles with a significant capacity to adsorb various micropollutants). When integrated over the flow cross-section, the relative volume of water conveying suspended particles is such that lower concentrations (250 mg/L), compared with near-bed material (3500 mg/L), still cause greater overall total mass fluxes. Typically, about 12% of all solids, by mass, are conveyed in material moving near the bed (Ashley, Arthur, Coghlan, & McGregor, 1994). In this integrated approach, verification of the model was performed first. Calculations for a natural catchment area and a WWTP in an urban area were performed independently, and the outflow quantity and quality of water from a catchment were sequentially input into the WWTP water quality model as input data. The WWTP water quality model considered four aspects: ammonia generated by hydrolysis and the organic substances from microbe multiplication, autolysis, and organic

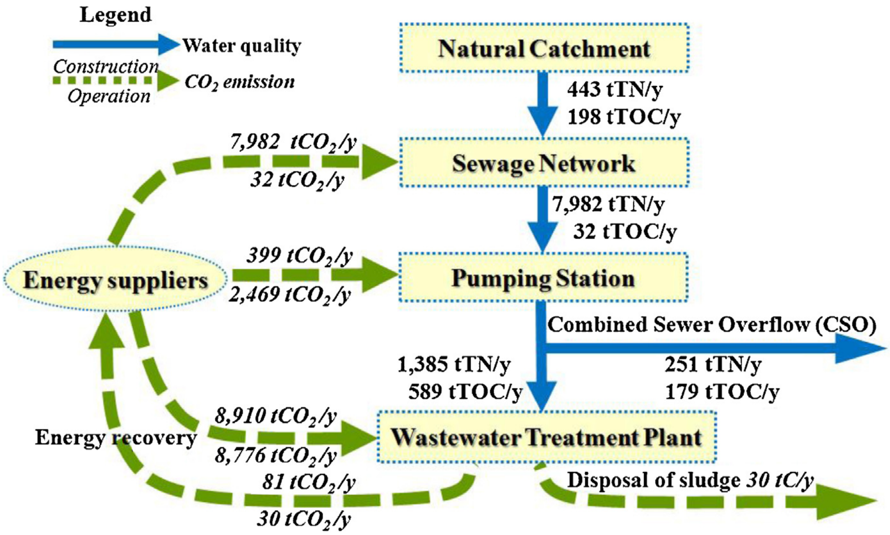

Fig. 3. Integrated flow diagram of water quality and CO_2 emissions within the defined system boundaries for the current sewage system. Data are from the Japan Sewage Works Association (JSWA) (2004) and the city of Matsuyama.

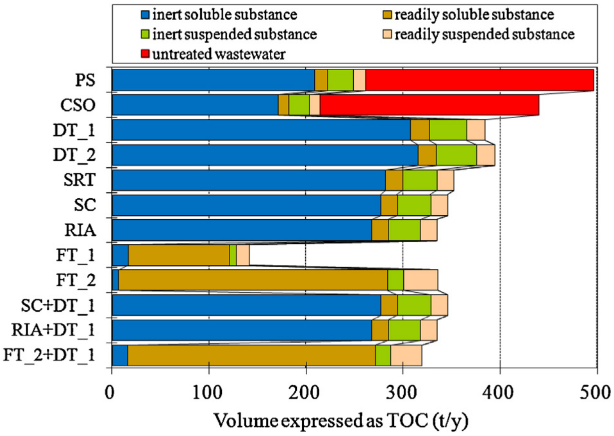

Fig. 4. TOC results of an additional case study that examined the feasibility of chemically-enhanced treatment using flocculants. See Table 1 for details on the management strategies.

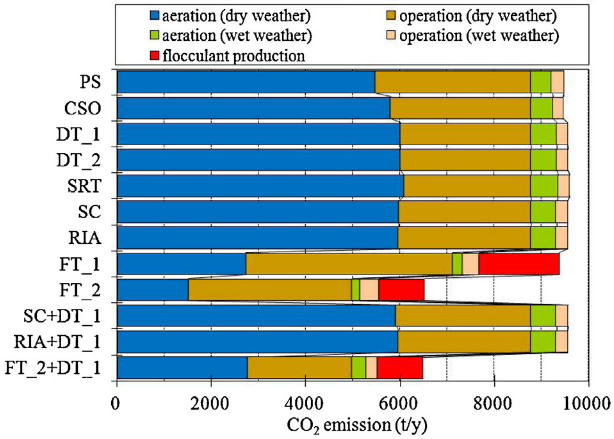

Fig. 5. CO_2 results of an additional case study that examined the feasibility of chemically-enhanced treatment using flocculants. See Table 1 for details of the management strategies.

nitrogen. In addition, as a result of calibration of the parameters relevant to reaction kinetics and stoichiometry, the growth rate (μ_A) of autotrophic microorganisms (nitrifying bacteria) was determined to be an important parameter in the WWTP water quality model and was most concerned with removal of ammonia nitrogen. We show this effect, focusing on the removal effect of organic matter, in Fig. 4. The graph shows 11 scenario results; however, little spread of data was observed with the traditional management of an urban sewage system, such as the DT_1, DT_2, SRT, SC, and RIA methods, and their use in an integrated scenario.

FT_1 was more effective than the traditional scenario. In FT_1, a flocculating agent was added until TOC showed a 50% water quality improvement. Thus, the water quality was greatly improved. However, not only was the operating cost large (Table 2), but also much CO_2 was emitted in this case (Fig. 5). The CO_2 emissions in the traditional scenarios DT_1, DT_2, SRT, SC, and RIA were nearly the same. In the FT_2 scenario, the flocculant was used to achieve the water quality standard, and major effects were seen in the aeration energy and CO_2 emissions; they were reduced by approximately 30%. In the FT_2 scenario, the treatment of 1 m^3 of raw wastewater

Table 2
Additional dosage and cost of the flocculant. Data are from the city of Matsuyama.

	Scenario	Flocculants	Dosage (mg/l)	Dosage per year (t/year)	Additional cost (million JPY/year)	Present cost (million JPY/year)	Applied cost (JPY/m^3)
1	FT_1	PSI	214	10,397	311.9	65.1	6.4
2		$FeCl_3$	288	13,992	419.8		8.6
3		PAC	189	9182	459.1		9.5
4		Polymer	4	194	174.9		3.6
5		PSI + Polymer	182	8856	291.2		6.0
6	FT_2	PSI + Polymer	64	3118	105.8		2.2

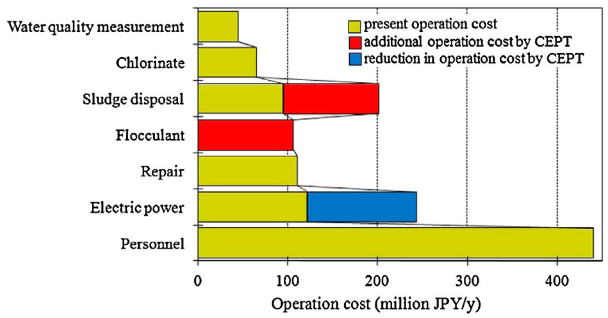

Fig. 6. Cost of using an inorganic polymer flocculant of polysilicato-iron (PSI). The yellowish brown bar shows the current operation cost for each segment of the WWTP. The blue bar shows the additional operation cost associated with chemically-enhanced primary treatment. The red bar shows the reduction in operation cost associated with chemically-enhanced primary treatment.

Data are from the Japan Sewage Works Association (JSWA) (2004) and the city of Matsuyama.

consumed about 64 g of PSI with a polymer flocculant, for a cost of 105.8 million JPY (Table 2).

Trial calculations were made of the cost of using various flocculants: PAC, PSI, chlorination iron(III), and a polymer coagulant. Using the PSI coagulant increased the cost by about 200 million JPY per year, including the cost of the flocculant itself, sludge disposal, and the reduced CO_2 emissions (of approximately 30%). On the other hand, the electrical power requirements were very large, and the operating costs were significant. In the innovative scenario, FT_2, the requirement for electrical power was reduced by approximately 50% (Fig. 6). However, the flocculant requirements cost approximately 200 million JPY per year and there was a significant sludge disposal cost. The total additional cost was 100 million JPY per year.

The LCA model was used to evaluate the impact of the amount of water from a natural drainage basin and the water quality accompanying a flood event. Moreover, it is possible by optimising the existing wastewater treatment system to assess management strategies with technologies, such as using CEPT. Although the addition of chemicals in the primary plant would increase the annual costs by about 3.7 million JPY, it can provide the additional operational flexibility and reliability needed for such a large politically visible facility (Chaudhary et al., 1991).

Regarding coagulant cost, in relation to TOC removal, the use of iron-III-chloride as a coagulant should be favourable in comparison to ferric chloride, hydrated lime, and alum. This study indicates that for an overloaded conventional mechanical–biological sewage treatment plant, chemical treatment as the first step in municipal wastewater treatment can be favourable, although the percentage removal is not high (Leentvaar et al., 1978).

Management strategies for environmental improvement based on the LCA model will be improved by increasing its accuracy. Numerical simulations and conditions for acquiring new data are under examination. When a flocculant is used among the 11 proposed scenarios as a technique for controlling the amount of water in a wastewater treatment system at times of dry and flood conditions, and the characteristics of water quality and CO_2 emissions are assessed, improved cost effectiveness can result.

5. Conclusions

From the integrated catchment management perspective, individual management approaches have been deployed for several decades to utilise individual components of sewage systems. This study summarises the status of integrated sewage management with respect to both ecological and economic perspectives. For the implementation of integrated management strategies, numerical dynamic modelling and LCA have been used to predict the behaviour of the complete system under both historical and future environmental contexts.

In this study, the effects of drainage system management were evaluated using an integrated approach, with the aim of improving water quality and reducing CO_2 emissions. The following technology was developed to aid in the management of an urban wastewater treatment system:

(1) Technology to predict the amount of water and the water quality of a water-cycle system in an urban sewage system. The WWTP water quality model considered four aspects: ammonia generated by hydrolysis and the organic substances from microbe multiplication, autolysis, and organic nitrogen. In addition, as a result of calibration of the parameters relevant to reaction kinetics and stoichiometry, the growth rate (μ_A) of autotrophic microorganisms (nitrifying bacteria) was determined to be an important parameter in the WWTP water quality model and was most concerned with removal of ammonia nitrogen.

(2) Technology to perform LCA evaluations of water quality and CO_2 emission flow in the whole sewage system. A large portion of the energy used for water quality improvement is consumed by aeration in the reaction vessel of a WWTP system. Hence, energy consumption is proportional to the amount of WWTP influent. Approximately 30% of the energy consumed and CO_2 emitted were from the operation phase of the WWTP. Reducing the amount of influent to the WWTP greatly affected the energy consumed and CO_2 emissions in the PS scenario.

Using a PSI coagulant increased the cost by about 200 million JPY per year, including the cost of the flocculant itself and sludge disposal. CO_2 emissions were reduced by approximately 30%. Electric power costs were reduced in wet- and dry-weather periods using PSI with polymer flocculants by approximately 50%.

In terms of concrete applications of the system, experiments using flocculants to examine the effects on reduced energy use and CO_2 emissions in times of wet and dry weather would be useful. Although the method of using a flocculating agent as a pre-treatment is technically possible, it is not always economically feasible. While pre-treatment with a flocculating agent does maintain or improve water quality, because a 30% reduction in CO_2 emissions is also possible, the extra cost burden may well be worth considering, given concerns about emissions and climate change. This work provides a comparative basis for assessing the results of climate change relief technology by reducing CO_2 emissions in the sewer management field while meeting water quality standards.

If the outlined technology is put into practical use, the effects on the reduction of greenhouse gases in Japan can be estimated as a crude oil equivalent: trial calculations suggest that the reduction for Japan would be on the order of 65×10^6 to 130×10^6 L/year crude oil equivalent. Establishing a technology to predict and control extreme sewage inflows to sewage disposal plants during flooding is also valuable for the optimal management of a catchment wastewater treatment system. If the technology outlined herein contributes to climate change relief measures by reducing CO_2 emissions and maintains or improves the quality of treated water, it will be of great value to global society.

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