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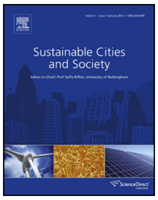

Estimation of the effects of chemically-enhanced treatment of urban sewage system based on life-cycle management

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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).