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Research article

Cost comparison of centralized and decentralized wastewater management systems using optimization model

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A B S T R A C T

There is a growing interest in decentralized wastewater management (DWWM) as a potential alternative to centralized wastewater management (CWWM) in developing countries. However, the comparative cost of CWWM and DWWM is not well understood. In this study, the cost of cluster-type DWWM is simulated and compared to the cost of CWWM in Alibag, India. A three-step model is built to simulate a broad range of potential DWWM configurations with varying number and layout of cluster subsystems. The considered DWWM scheme consists of cluster subsystems, that each uses simplified sewer and DEWATS (Decentralized Wastewater Treatment Systems). We consider CWWM that uses conventional sewer and an activated sludge plant. The results show that the cost of DWWM can vary significantly with the number and layout of the comprising cluster subsystems. The cost of DWWM increased nonlinearly with increasing number of comprising clusters, mainly due to the loss in the economies of scale for DEWATS. For configurations with the same number of comprising cluster subsystems, the cost of DWWM varied by ±5% around the mean, depending on the layout of the cluster subsystems. In comparison to CWWM, DWWM was of lower cost than CWWM when configured with fewer than 16 clusters in Alibag, with significantly less operation and maintenance requirement, but with higher capital and land requirement for construction. The study demonstrates that cluster-type DWWM using simplified sewer and DEWATS may be a cost-competitive alternative to CWWM, when carefully configured to lower the cost.

1. Introduction

Adequate management of wastewater remains an important challenge in developing countries (UNICEF and World Health Organization, 2015). In industrialized countries, the standard solution is centralized wastewater management (CWWM) (Andersson et al., 2016; Libralato et al., 2012; Wilderer et al., 2000), in which wastewater is collected by sewer from a defined, typically large geographic area and treated at a central wastewater treatment plant (WWTP) (Libralato et al., 2012; U.S. Environmental Protection Agency, 1994). In parts of developing countries, decentralized wastewater management (DWWM) is increasingly recognized as an appropriate alternative to CWWM (Andersson et al., 2016; Libralato et al., 2012; Massoud et al., 2009; Wilderer et al., 2000). In DWWM, wastewater is treated closer to the source using independent modular subsystems for individual households, or collection of buildings (Libralato et al., 2012; U.S. Environmental Protection Agency, 1994). Such use of modular subsystems in DWWM provides increased flexibility and resilience and can be more favorable in rapidly developing regions that lack resources and reliable infrastructure (Bakir, 2001; Brown et al., 2012; Tchobanoglous et al., 2004).

The modular subsystems in DWWM may be configured in different ways, varying in the degree of decentralization (e.g., numerous small on-site systems to a few larger cluster subsystems) and layout (e.g., size and location of cluster subsystems); consequently, the cost of DWWM can vary significantly. In practice, DWWM configurations are rarely optimized to minimize the cost, but are shaped by the interests of local shareholders and other context-specific factors, such as land availability, social and administrative boundaries, and regulations (Government of Karnataka, 1974; Parten, 2008). Therefore, understanding the cost implication of using DWWM requires a comprehensive assessment of the potential DWWM configurations that can arise in the local

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context. Despite growing interest in DWWM, however, the cost implication of potential DWWM configurations, and the comparative cost of DWWM and CWWM are not well understood (Eggimann et al., 2015).

Relevant studies have focused on finding the minimum-cost configuration of wastewater management infrastructure, instead of comprehensively assessing the cost distribution of potential configurations. A number of studies identified the optimum configuration of wastewater infrastructure for a region with several communities while minimizing the cost (Brand and Ostfeld, 2011; Leitao et al., 2006) or environmental impact (Cunha et al., 2009; Leitao et al., 2006; Lim et al., 2008; Zeferino et al., 2017). For instance, Cunha et al. used an optimization model to identify the optimum sewer layout, and the number and location of WWTPs for a region with 38 communities (Cunha et al., 2009). While relevant, the studies did not apply the model to analyse the cost distribution for potential configurations, and focused exclusively on regional wastewater management systems.

Eggimann et al. (2015) is the only study to our knowledge that used a wastewater infrastructure optimization model to analyse the cost trend of community wastewater management systems across the degree of decentralization (Eggimann et al., 2015). The authors developed a model that uses shortest path-finding and clustering algorithms to form minimum-cost household clusters for DWWM. The model was applied at discrete intervals across the degree of decentralization, finding the optimum cluster layout at each interval. When applied to a Swiss town of 1500 people, the model found that the optimally decentralized wastewater management scheme was 40% cheaper than centralized scheme. While the study analysed the cost trend across the degree of decentralization, the cost distribution across the potential layout of clusters at each interval of the degree of decentralization was not examined. Furthermore, the study solely focused on conventional sewer and wastewater treatment plant, and did not consider alternative wastewater management technologies that are of practical interest for decentralized schemes.

India's sanitation and wastewater management challenges are well-documented (Central Pollution Control Board India, 2015; Ministry of Health and Family Welfare, 2015; UNICEF, 2017). Approximately 51% of the Indian population lack access to improved sanitation (Ministry of Health and Family Welfare, 2015), and the installed wastewater treatment capacity is 51% of generated sewage in metropolitan cities and 8% of that in semi-urban city centres (Central Pollution Control Board India, 2009). Of the existing centralized WWTP, 11% was reported to be nonoperational due to the lack of skilled manpower, irregular maintenance, and interruptions in power supply (Central Pollution Control Board India, 2015, 2013). In light of these challenges, the Government of India issued the National Urban Sanitation Policy (NUSP) to engage urban municipalities to locally implement wastewater management solutions, and to encourage integration of low energy intensive, decentralized wastewater treatment technologies (Ministry of Urban Development, 2008). The recommended technologies included simplified sewer, pond system variants, and DEWATS (Decentralized Wastewater Treatment Systems), which is a wastewater treatment approach comprising a sequence of low-maintenance treatment subprocesses (BORDA, 2009; Ministry of Urban Development, 2008; The World Bank and Minitry of Urban Development Goverment of India, 2008). Better suited for small-scale application, the aforementioned technologies have been shown to deliver similar functionalities and performance as conventional wastewater management technologies (BORDA, 2009; Ministry of Urban Development, 2008; The World Bank and Minitry of Urban Development Goverment of India, 2008).

In this study, we conduct a comparative cost analysis of CWWM and cluster-type DWWM schemes in our case study site, Alibag, in Maharashtra, India. The potential DWWM schemes of various configurations are simulated using an optimization model. We evaluate CWWM comprised of conventional sewer and activated sludge plant, the most commonly used technologies in India (Central Pollution Control Board India, 2015). DWWM comprised of simplified sewer and DEWATS technologies is chosen for this study, based on NUSP recommendations for their adaptability to urban settings (Ministry of Urban Development, 2008).

2. Method

2.1. Analysis and case study site overview

The costs of CWWM and DWWM in Alibag were compared. The cost of a CWWM plan that has been proposed by local consultants for the Alibag Municipal Council was assessed. For comparison, we simulated DWWM schemes in a wide range of configurations, and determined the cost distribution.

Alibag is a Class II urban town with a population of 20,743 as of the 2011 Census (Office of the Registrar General & Census Commissioner India, 2011). Located south of Mumbai in Maharashtra, India, Alibag spans 1.98 km^2 of flat land on the bank of the Arabian Sea, with altitude ranging between 2 and 4.5 m. The town currently lacks a wastewater management system; untreated sewage is either collected by open drainage and discharged to the Arabian Sea, or released directly to the immediate environment. Wastewater generated in Alibag has average biological oxygen demand (BOD) of 164 mg/L and chemical oxygen demand (COD) of 279 mg/L, typical of municipal wastewater. Alibag's projected population and wastewater generation in 2025 and 2040 are shown in Table 1.

The proposed CWWM scheme for Alibag consists of a central activated sludge WWTP that is connected to all buildings in the town by conventional gravity sewers and pumping stations (Fig. 1, Table 2). The simulated DWWM schemes incorporate multiple cluster subsystems covering Alibag; each cluster subsystem is composed of a collection of buildings served by a single DEWATS and a simplified sewer network without pumping stations (Fig. 1, Table 2). The configuration of the simulated schemes is varied by the number of comprising cluster subsystems (N_c) and the layout of the comprising cluster subsystems.

The proposed treatment process for CWWM involves the following: primary treatment consisting of a settling chamber and a clarifier in which solid particles settling occurs; an activated sludge bioreactor for secondary treatment; secondary settling chamber for settling and recirculating the treated effluent; and chlorination for tertiary treatment. The DEWATS treatment process involves primary settling chamber, anaerobic baffled reactor and anaerobic

Table 1
Population projection and wastewater generation.

	2025	2040
Fixed population[a]	28,400	35,900
Floating population[a,b]	3200	4500
Wastewater generation[c]	3182 m^3/d	4039 m^3/d

[a] Projected by Alibag municipality, using the average of geometrical and incremental increase estimation methods (Cental Public Health and Environmental Engineering Organization, 2012).

[b] Floating population consists of people visiting the town for tourism or for seasonal work.

[c] Assuming wastewater generation of 0.108 m^3/d for fixed population and 0.036 m^3/d for floating population (Cental Public Health and Environmental Engineering Organization, 2012). Excludes groundwater infiltration (560 m^3/d) and design flow peak factor (2.5) (see Supplementary Information).