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Optimal Design of Sewerage Systems with On-site Grey Water Treatment and Recycling

Adwait Bharade[1], Timo, C. Dilly[2], Amin, E. Bakhshipour[2], Ligy Philip[1], Ulrich Dittmer[2], S. Murty Bhallmudi[1,*]
[1]Indian Institute of Technology Madras, Chennai - 600036, India
[2]Technical University of Kaiserslautern, 67663 Kaiserslautern, Germany
[*]bsm@iitm.ac.in
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EXTENDED ABSTRACT

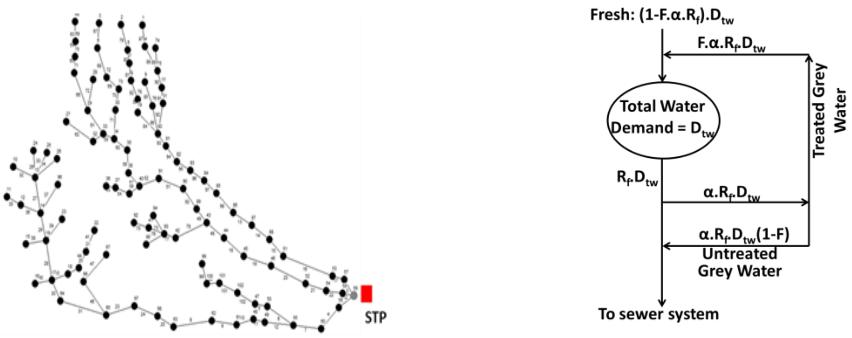
Introduction

Urban water supply in many countries with emerging economies is suffering from a large supply-demand gap due to increase in population, changing life styles, increased stress on water sources and failure to generate new sources [1]. For example, although the benchmark domestic per capita water supply in India is 135 lpcd, the actual supply ranges from 37 lpcd to 298 lpcd, and the water supply is intermittent [2]. One of the sustainable ways of reducing this supply-demand gap is by recycling the treated wastewater for non-potable uses and transitioning to a circular economy [3]. Several studies have been carried out earlier to understand the implications of introducing wastewater recycling on the functioning of existing sewerage systems and on the reduction in fresh water demand [4].

Recycling may not be an economically desirable option in all situations depending on the magnitude of demand-supply gap, unit costs of fresh water and treated water supplies, and operating constraints in the sewerage system. While Penn et al. [5] developed a multi objective optimization model for optimally introducing different grey water recycling options into existing sewerage systems, Zhang et al. [6] developed a multi objective optimization model for sustainable wastewater reuse and for water policy making in China. These studies did not consider the effect of wastewater reuse on the benefits that are accrued in terms of cost reduction in supply of fresh water. The optimization model developed by Newman et al. [7] focused on planning and designing green field water supply systems, which consider alternate water sources. Recently, Basupi [8] developed an integrated approach for the design of both water supply (WS) and sewerage systems (SS), which incorporates use of different water saving schemes (WSS) and considers the interaction between WS, WSS and SS. However, their model did not explicitly incorporate on-site grey water recycling in the formulation. In this study, we develop a simple optimal design model to design sewerage systems considering on-site grey water recycling. The decision variables are the diameters of sewer pipes and the percentage of grey water that should be treated and rec-cycled at each node in the sewerage system.

Methods and Materials

It is considered that a water supply system already exists in the study region and it is required to design a sewerage system which incorporates on-site grey water treatment and recycling for non-potable use at each node to achieve reduction in fresh water supply at that node. Referring to the schematic of a sewerage system shown in Fig. 1a;



(a) (b)

Figure 1. (a) Schematic of a sewer network and (b) Mass flow diagram at a node with grey water recycling

D_{tw} = total water demand at any node, R_f = fraction of water supplied at a node that comes out as wastewater and α = fraction of wastewater that is grey water. The grey water is the waste water coming from apartment blocks except that from toilets. α is taken as 0.6, based on the prevailing conditions in India. F = fraction of grey water that is treated and recycled to the node for non-potable use. Given the total water demand at each node and the network connectivity of the sewer network, the proposed model determines optimal values of F_j at each node j = 1 to N and diameters D_i for each link i =1 to M. It is assumed that the elevations of each node are fixed *a priori*. The objective function in the model is minimization of total cost, which comprises the operational cost of fresh water supply at all nodes, operational cost of treated water supply at all nodes, capital cost of grey water treatment plants, capital cost of sewerage system and operational cost of flushing the sewerage system if velocities are less than the self-cleansing value (V_i > 0.6 m/s).

OF: Minimize

$$Z = \sum_{j=1}^{N} C_f\left(1 - F_i.\alpha.R_f\right)D_{twi} + \sum_{j=1}^{N} C_r.F_i.\alpha.R_f.D_{twi} + \sum_{i=1}^{M} CF_i.\delta_i + AF.\left[\sum_{i=1}^{M} CP_i.L_i + \sum_{j=1}^{M} CT.X_j + C_{stp}.X_s\right]$$

where, C_f = unit cost of fresh water supply; C_r = unit cost of treated water supply and CF_i = cost of flushing for any pipe i, if velocity is less than 0.6 m/s (δ_i = 1). These unit costs are used to determine annual costs of supplies and flushing. CP_i = cost of sewer pipe i per unit length, which depends on chosen diameter D_i, CT = cost of grey water treatment plant per unit of treatment capacity, C_{stp} = cost of centralized sewage treatment plant (STP) per unit of treatment capacity, X_s = capacity of STP and X_j = grey water treatment plant capacity at node *j*. Capital costs are converted to annualized costs using factor AF, which depends on the interest rate and the life of the system. The constraints in the model are:

Constraints: (1) $F_{min} \le F_i \le F_{max}$; (2) $\left(\frac{d}{D}\right)_i \le 0.8$; (3) $v_i > 0.1\ m/s$

where d = depth of flow and v = velocity in the pipe. V in any pipe should not be less than a minimum value even though it is allowed to go below the self-cleansing value of 0.6 m/s. A simulation-optimization model which embeds the hydraulic simulator for sewer systems is developed for solving the optimization problem. The Standard Mixed-Integer Genetic Algorithm from the MATLAB© is used as the optimizer while the hydraulic simulator is based on solving the steady uniform flow equation to determine d and v in any pipe corresponding to the peak discharge. This is needed for evaluating the constraints. Diameters of pipes are chosen from a specified set of discrete sizes commercially available.

Results and Discussion

Proof-of-concept is demonstrated by applying the model to a hypothetical network of 102 nodes and 101 links. Based on the prevailing costs of water supply in IIT Madras, it is assumed that unit cost of fresh water supply, which includes the high transportation cost, is Rs. 80 /kilo litre. The unit cost of treated grey water supply is Rs. 18 / kilo litre. Grey water supply cost comes mostly from the cost of treatment by coagulation, flocculation, ultra-filtration and disinfection. For the case of no recycling, the total cost of the solution is Rs. 102.3 M annually (cost of fresh water = Rs. 90.7 M; other costs = Rs. 11.6 M). When optimal grey water recycling is considered, the total cost gets reduced by 20.8% to Rs. 81.0 M (cost of fresh water = Rs. 43.1 M; other costs = Rs. 37.9 M). There is a reduction in fresh water demand by 52.5 %. For the hypothetical network the model suggested 80 to 100% recycling of grey water at 86 nodes, while the percentage of recycling varied from 20% to 80% at remaining 15 nodes.

Conclusions

The proposed model can be used for optimal design of new sewerage systems which incorporate on-site grey water recycling to reduce the stress on existing fresh water utilization. The model can be used to determine the optimal scale of recycling at each node besides optimal diameters. In locations where cost of supplying fresh water from a central source is significantly high, on-site recycling of grey water for non-potable use can cut down the total cost significantly. This is besides substantial saving in the fresh water consumption.

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