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Multi-objective evolutionary optimization for greywater reuse in municipal sewer systems

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ABSTRACT

Sustainable design and implementation of greywater reuse (GWR) has to achieve an optimum compromise between costs and potable water demand reduction. Studies show that GWR is an efficient tool for reducing potable water demand. This study presents a multi-objective optimization model for estimating the optimal distribution of different types of GWR homes in an existing municipal sewer system. Six types of GWR homes were examined. The model constrains the momentary wastewater (WW) velocity in the sewer pipes (which is responsible for solids movement). The objective functions in the optimization model are the total WW flow at the outlet of the neighborhoods sewer system and the cost of the on-site GWR treatment system. The optimization routing was achieved by an evolutionary multi-objective optimization coupled with hydrodynamic simulations of a representative sewer system of a neighborhood located at the coast of Israel. The two non-dominated best solutions selected were the ones having either the smallest WW flow discharged at the outlet of the neighborhood sewer system or the lowest daily cost. In both solutions most of the GWR types chosen were the types resulting with the smallest water usage. This lead to only a small difference between the two best solutions, regarding the diurnal patterns of the WW flows at the outlet of the neighborhood sewer system. However, in the upstream link a substantial difference was depicted between the diurnal patterns. This difference occurred since to the upstream links only few homes, implementing the same type of GWR, discharge their WW, and in each solution a different type of GWR was implemented in these upstream homes. To the best of our knowledge this is the first multi-objective optimization model aimed at quantitatively trading off the cost of local/onsite GW spatially distributed reuse treatments, and the total amount of WW flow discharged into the municipal sewer system under unsteady flow conditions.

1. Introduction

In many countries, the urban sector is the largest consumer of potable water. In Israel it consumes some 700–800 × 10^6 m^3/year (for agriculture irrigation mostly treated WW effluents are used). Domestic/residential consumers consume about 70% of the municipal water demand, while the rest is consumed for uses such as: tourism, offices, education, commerce, health services, recreation and sporting activities, and firefighting. Therefore, reducing domestic water demand by on-site water reuse has the potential to play a significant role in alleviating the stress from existing water sources, in reducing the urgent need for exploring new (and usually costly) water resources, and to increase the sustainability of urban water usage.

The use of evolutionary optimization techniques for multi – objective optimization is not new in the field of urban

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drainage/sewer systems. In a comprehensive review of state of the art for genetic algorithms (GA) methods and their application in the field of water resources planning and management (including sewer systems) carried out by Nicklow et al. (2010) it was shown that evolutionary computation can be a flexible and powerful tool when used appropriately in this field. They further stated that it will continue to evolve in the future due to several challenges. The efficiency in using GA for multi-objective optimization of integrated sewer systems (integrating some of the following: the sewer system, the wastewater treatment plant (WWTP), the receiving water bodies, pollution – load and water quality model) was shown by Boomgaard et al. (2004), Fu et al., 2008, Muschalla 2008, Rathnayake and Tanyimboh 2011, Rauch and Harremoës 1999 and others. The optimization of sewer networks in terms of speed and reliability was found to be more efficient by using an adaptive GA, in which the constrain handling method was adapted (Haghighi and Bakhshipour, 2012). Pan and Kao 2009 optimized sewer system design by developing a GA based approach combined with a nonlinear cost optimization model that was approximated and transformed into a quadratic programing. Atef et al., 2012 presented an algorithm to allocate budgetary resources for condition assessment of water and sewer networks. Ward and Savic 2012 applied a multi-objective GA optimization model, coupled with an enhanced critical risk of failure methodology for sewer rehabilitation. 1D2D coupled model (1D subsurface and 2D surface flow models) was linked with NSGA-II (an evolutionary algorithm) for multi-objective optimization of cost-benefit of urban flood management (Delelegn at al., 2011). The computational efficiency of this method was proved to be acceptable for optimization. As shown above, optimization of urban sewer systems by GA multi-objective optimization, is broadly found in the literature. However modeling greywater reuse (GWR) together with evolutionary optimization as a tool for evaluating the optimum distribution of GWR homes, has not been found in the literature.

Greywater (GW) is generally defined as domestic sewage excluding the wastewater (WW) stream generated by toilets. Kitchen (kitchen sink and dishwasher) wastewater is defined as dark GW; sometimes washing machine WW is included in this definition too. WW streams generated by the bath, shower and washbasin are defined as light GW, and WW generated from toilets (WC) is defined as blackwater.

To prevent hygienic and health risks, and to minimize negative aesthetic effects, treatment of GW is necessary prior to reuse (Diaper et al., 2001; Dixon et al., 1999). Friedler (2004) has shown that, as the demand for GW within the urban environment (i.e., for toilet flushing and garden irrigation) is significantly lower than its production, it is not necessary to recycle all GW streams, but rather to focus on the less polluted light GW, and to discharge the more polluted dark GW together with the blackwater stream to the urban sewer system.

Sustainable design and implementation of GW reuse (GWR) has to achieve an optimum compromise between costs and potable water demand reduction. Studies show that GW reuse (GWR) is an efficient tool for reducing potable water demand. Using onsite light GWR for toilet flushing can reduce daily household water consumption by 26%. Using the excess amount of the light GW for garden irrigation can further reduce the daily water demand to an overall reduction of 41% (Penn et al., 2012). Further, integrating residential wells, rainwater tanks and GW systems can result in significant water savings at the household scale (Hunt et al., 2011; Rozos et al., 2010; Rozos and Makropoulos, 2012). However, rainfall harvesting depends on stochastic phenomena (i.e., climatic conditions, including rainfall and temperature) whose variation introduces long-term uncertainties in the systems' performance (Rozos et al., 2010). In a research carried out by Rozos and Makropoulos (2012) the reliability of water-aware technologies (e.g., rainwater harvesting schemes and sustainable drainage systems) is proven to decrease with urban density. In this study the water saving tools focused on are low-flush toilets and different types of GWR. Friedler and Hadari (2006) demonstrated that under certain circumstances onsite GWR for toilet flushing can be economically worthy even to the consumer itself. It depends on the treatment technology chosen, on the size of the served population and on the price of water. With GWR it might be possible to postpone the enlargement of existing sewer systems, to construct new sewers with smaller pipe diameter, and lower energy consumption for sewage pumping (Friedler and Hadari, 2006; Penn et al., 2013).

Several studies dealing with multi-objective optimization between potable water demand reduction and costs can be found in the literature, however the water saving schemes usually include rainwater harvesting combined with GWR, whereas in Israel rainwater harvesting is not a feasible solution. Some of these studies are further briefly discussed. Oldford and Filion (2012) show, by multi-objective optimization, a trade-off between decreasing water demand and upgrading of operational cost. The decision variables in their model were the diameters of new water mains, the price of water, and the decision to offer rebates for various low-flow fixtures or appliances. This was demonstrated on a five-node network. Brock et al. (2010) used multiple objective optimization, by a genetic algorithm, to identify which of the following options, or combination of them, is the optimal solution for water saving: rainwater, stormwater and GWR systems. This was done by determining evaluation criteria that reflect the cost and environmental impacts and hence sustainability of these systems. Rozos et al. (2010) assessed sustainable design and implementation of two water saving schemes by multi-objective optimization between costs (including energy) and benefits (potable water demand reduction). The first scheme was rainwater harvesting. In this scheme harvested rainwater, stored in a local tank, was used for toilet flushing, washing mashing and outside uses. The reset of the appliances were supplied with potable water from water mains. The second scheme was a combination of rainwater harvesting and local GWR. In this scheme GW from the shower bath and wash basin was treated locally and stored together with the harvested rainwater. The influence of potential changes in climatic conditions (oceanic, Mediterranean, and desert) to the scheme's efficiency was also taken into account. Their results indicate that rainwater harvesting alone can achieve significant reduction in domestic potable water consumption. However, in this scheme the systems' performance can suffer from long term uncertainties since