Journal of Environmental Management 206 (2018) 684–697

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

A mathematical model to plan for long-term effects of water conservation choices on dry weather wastewater flows and concentrations

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ARTICLE INFO

Article history:
Received 20 June 2017
Received in revised form
6 October 2017
Accepted 7 October 2017

Keywords:
Water conservation
Planning models
Wastewater flow
Plant expansion
Sedimentation

ABSTRACT

In many cities, sewer systems are experiencing conditions that are significantly different from those for which they were designed. Factors such as water conservation efforts, changes in population, and efforts to reduce infiltration are altering the quantity and quality of sewage. These changes may affect the ability of sewers to maintain self-cleansing velocities, which are crucial to avoiding solids settling and corrosion issues. Further, such changes may alter the timeline for expected wastewater plant expansion. The present work proposes a method for predicting average annual dry weather wastewater flow, as well as pollutant load and concentration over time. The method takes into account potential declines in per person wastewater production due to water conservation and reuse practices, as well as other potential changes such as shifts in population, transformations in industrial wastewater production, and variations in dry weather infiltration. Results show that the amount of dry weather infiltration will play a large role in whether or not conservation will affect self-cleansing velocities or plant expansions. Conservation is most beneficial to systems with high levels of dry weather infiltration since plant expansion could be avoided; and most detrimental to systems with low levels of infiltration since low flow conditions could lead to settling and corrosion in the sewer. Furthermore, the rate of implementation of conservation efforts influences when impacts to the system would occur. Utility planners will be able to use this method to predict treatment plant upgrade and expansion needs more accurately as well as to assess the relative value of utility-based maintenance activities and conservation practices.

1. Introduction

Water conservation and urban water management practices have been expanding over the past several decades in response to water scarcity from drought, increasing population, and public education initiatives (Christie et al., 2003; Corral-Verdugo and Frías-Armenta, 2006; Fielding et al., 2012; Licata and Kenniff, 2013; Salvaggio et al., 2014; Heberger et al., 2014; DeOreo et al., 2016; Irwin, 2016). With the potential for energy and economic savings and alignment with public preference (Kenney, 2014; Stokes et al., 2014; Sokolow et al., 2016), various levels of government are introducing water saving practices, even in water-rich regions (Woltemade and Fuellhart, 2013). These measures include: leak reduction; conservation marketing or water pricing campaigns; mandates or incentives for the installation of high-efficiency appliances (e.g., 1992 and 2005 Energy Policy Acts (102d Congress, 1992; 109th Congress, 2005)); labeling programs (e.g. EPA Water Sense (U.S. EPA, 2017)); and reuse or recycling of rainwater or greywater (Kavvada et al., 2016; Marleni and Nyoman, 2016; Campisano et al., 2017).

Due to these factors, per person water use in the United States has declined considerably over the past several decades. A typical single-family household in 2008 used 44,206 fewer liters of water annually (i.e., 121 fewer liters per day or 32 fewer gallons per day) than a similar household did in 1978 (Rockaway et al., 2011), and per capita indoor water use decreased 15% from 1999 to 2016 (Mayer et al., 1999; DeOreo et al., 2016; Mayer, 2016). Declining industrial and commercial use has also been occurring (Frost et al., 2016); data from the United States Geological Survey (USGS) indicates industrial water withdrawals in the U.S. fell by 27% between 1995 and 2010 (Solley et al., 1998; Maupin et al., 2014).

These water use reductions have been considered a success in

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https://doi.org/10.1016/j.jenvman.2017.10.013

terms of reduced energy needs to treat and transport water and reduced or deferred cost associated with water supply expansions necessitated by population increases (Licata and Kenniff, 2013). Recently, increased attention has focused on effects of conservation on water quality in drinking water distribution systems. Conservation and efficiency measures can increase the amount of time water is stored in the distribution system (Rhoads et al., 2015), resulting in increased microbial growth (including pathogens such as *Legionella*), increased corrosion leading to elevated lead levels, and taste and odor issues (Nguyen et al., 2009; Rhoads et al., 2014). High efficiency buildings with lower than typical water use are especially at risk for these effects (Rhoads et al., 2015, 2016; Beans, 2016). However, less consideration has been given to how these practices will affect the wastewater collection system, which may also experience problems due to lower flows. Declines in total wastewater flow can lead to increases in pollutant concentrations (Cook et al., 2010; Penn et al., 2013; Marleni et al., 2015a); reductions in flow velocity (DeZellar and Maier, 1980; Parkinson et al., 2005); and increased sedimentation, odor, and corrosion in sewers (DeZellar and Maier, 1980; Koyasako, 1980; Parkinson et al., 2005; Marleni et al., 2015b, a; Sun et al., 2015; Abdikheibari et al., 2016).

Water conservation also has the potential to affect wastewater system operations (e.g., reducing treatment costs), and planning (e.g., altering the timing of plant expansions associated with population increase or system consolidation). The New York City Department of Environmental Protection (NYC DEP) found that each 5% reduction in water use and wastewater flows to the system would result in avoided variable wastewater collection and treatment costs of approximately $6.3 million (in 2011 dollars) (Licata and Kenniff, 2013). San Antonio avoided an estimated $1 billion dollars in plant expansion costs as a result of significant water conservation programs (BBC Research and Consulting, 2003). Woltemade and Fuellhart (2013) estimated the potential cost savings that would result from delaying treatment plant expansion due to installation of low flow devices for a utility with 14,000 residents. They defined conservation scenarios as savings of water (in liters per day) that would accrue from low to high adoption of water saving devices. Results indicate that expansion could be delayed from one month to one year as a result of conservation, and a maximum of 12% reduction in wastewater could be obtained with high participation. However, high participation was not found to be cost effective and only 50% of scenarios were cost effective under very low conservation (Woltemade and Fuellhart, 2013).

These prior studies suggest the *potential* for declining water use to affect wastewater collection and treatment system operation and planning. However, regionally-specific climatic and population conditions, and utility-specific structural characteristics play a significant role. For example, changes may be affected by: (i) how fast the conservation and efficiency measures are implemented; (ii) the rate of population growth; (iii) the amount of non-sewage flow entering the system during dry weather through cracks or direct connections as infiltration and inflow (I&I); and (iv) stormwater flows entering the system during wet weather. Challenges associated with sediment accumulation and corrosion might be more important in separate systems with low I&I or during long periods of dry weather. In some areas, rapid population growth may outpace declines in per person wastewater production, leading to small changes in the collection system but significant increases in wastewater concentration (and therefore load) at the plant. Additionally, conservation-induced flow reductions may enable delays in capital expenditures associated with plant expansions.

The present work considers the effects of different rates of water use declines to develop a model for projecting average daily dry weather wastewater flow, pollutant load, and pollutant concentration over time. The model incorporates different rates of population change and different levels of existing infiltration into the projected flows in sewer systems and loads to sewage treatment plants. Scenario-based simulations allow an exploration of trade-offs. The model and underlying methods can be used as tools to project the timing of plant upgrade and expansion needs, as well as to assess potential risk of solids settling under low flow conditions. The methods could be used to assess the relative value of utility-based maintenance activities (e.g. controlling infiltration and inflow) and rate of implementation of conservation measures.

2. Background

Water demand has been modeled extensively, often using regression techniques (Wentz and Gober, 2007; House-Peters and Chang, 2011; Ashoori et al., 2016) and artificial neural networks (e.g. (Jain et al., 2001)). Population, water price, conservation methods (Maggioni, 2015), climatic variables (Balling et al., 2008), household demographics, and household occupancy (Fielding et al., 2012) influence water demand, and their relative effects can vary and are often interrelated (Hornberger et al., 2015). Furthermore, some households are more likely to use less water than others. For example, regions recently exposed to drought use less water than those that did not experience drought, and households that value conservation also used less water than those without a preference to conserve (Fielding et al., 2012). Population and price had the highest effect on demand across all usage categories in Los Angeles, and specifically for residential use, price and conservation measures stabilized water demand despite population growth (Ashoori et al., 2016).

Demand management strategies, including water conservation, incorporate engineering and policy changes that alter water needs or wants. These strategies are generally introduced to reduce the amount of source water required for a region (Cook et al., 2010; Marleni et al., 2012). Water conservation refers to any policies, practices, or programs that promote reduction of water consumption through behavioral changes such as taking shorter showers, or by changing the frequency of a water-intensive activity, like clothes washing. Water efficiency refers to minimizing water use while achieving the same level of service (e.g., through installation of low flow toilets or fixtures). Conservation and efficiency practices reduce the amount of water used per person, per household, or per commercial site. In comparison, alternative water sourcing reduces demand by offering a substitute for potable water for some applications, like rain water or greywater (Marleni et al., 2012; Penn et al., 2013). Greywater reuse reduces per capita source water withdrawal, since a portion of the withdrawn water is now recycled. Per capita wastewater is also reduced, since water that would have been sent to the sewer (for example, from the shower) is diverted and used elsewhere in the household (for example, in the toilet) prior to entering the sewer. Rainwater use may affect per capita use of piped supply water by substituting collected rainfall for some uses (e.g., using rainwater for toilets); however, per person wastewater would not change even if rainwater is substituted for source water. Wet weather infiltration would, however, change, since the rainfall is now diverted to the household instead of directly entering the sewer.

As a result of demand management and attention to leak repair in water distribution systems, many U.S. cities have seen declines in water use and are setting goals for future reductions. Residential customers in Los Angeles used 30% less water in 2015 compared to 2006, and the city aims for a further reduction of 25% in per capita use by 2035 (compared to 2013) (LA DWP, 2015). According to a 2016 study by the Water Research Foundation, future decreases in per household and per capita water use are expected nationally, since only half of U.S. households have installed high efficiency