A Mathematical Model to Plan for Long-Term Effects of Water Conservation Choices on Dry Weather Wastewater Flows and Concentrations

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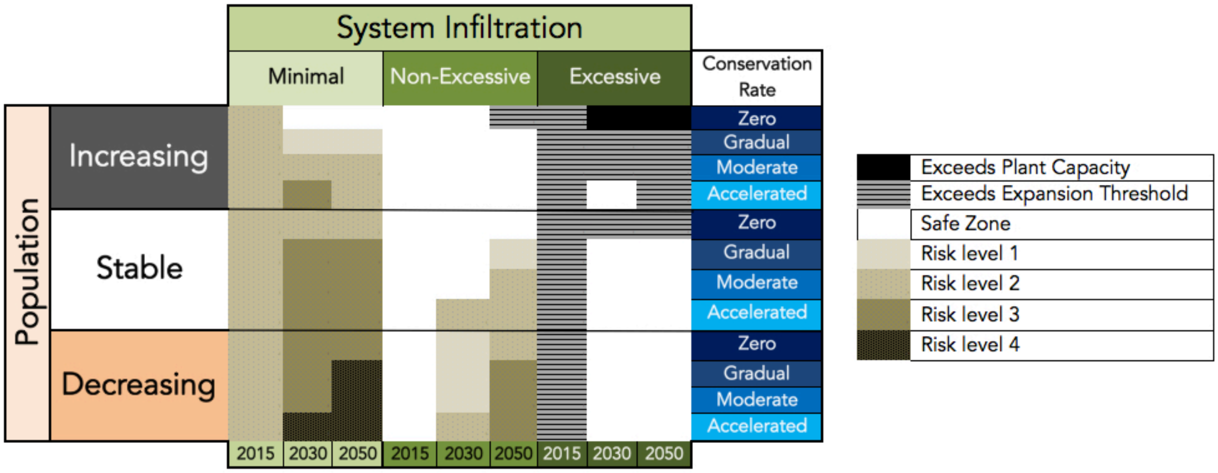
Abstract. In many cities, sewer systems are experiencing conditions that are significantly different from those for which they were designed. Factors such as water conservation efforts, changes in population, and efforts to reduce infiltration are altering the quantity and quality of sewage. These changes may affect the ability of sewers to maintain self-cleansing velocities, which are crucial to avoid 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 the 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.

Graphical Abstract:



Keywords: water conservation; planning models; wastewater flow; plant expansion; sedimentation

Highlights:

- A wastewater model that incorporates rate of conservation can aid utility planning
- Conservation is most beneficial to systems with high dry weather infiltration
- Conservation is most detrimental to systems with low dry weather infiltration
- Results are most sensitive to infiltration, population rate, then conservation pace

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 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; Beans 2016; Rhoads et al. 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 & Consulting 2003). Woltemade and Fuellhart (2012) 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 toilets and there is additional potential to reduce water use for dish and clothes washing (DeOreo et al. 2016). With 100% adoption of high efficiency fixtures and appliances and customer leak repair programs, indoor use is projected to drop 35% or more from 2016 levels, to below 36.7 gallons per capita per day (gpcd) or 139 liters per capita per day (Lpcd) (DeOreo et al. 2016; Mayer 2016). This level is slightly higher than the 2011 level for indoor use in the Netherlands, which is 34 gpcd (129 Lpcd)(Graveland and Baas 2013).

Declining water use is expected to lead to declining wastewater production and sewer flows. For example, during a period of drought in California in the 1970's, mandatory water restrictions led to significant reductions in wastewater flow (Koyasako 1980). From 1976 to 1977, per capita wastewater flow decreased by 24% on average, from 98 to 75 gpcd (371 to 284 Lpcd). Total wastewater inflow at 13 wastewater treatment plants was observed to decline in the range of 15% to 60% in California in the same time period (DeZellar and Maier 1980; Koyasako 1980). Cook et al. (2010) estimated that flow reductions to the sewer by more than 20% would result in velocities lower than those needed for self-cleansing conditions, which are critical to ensure solids move through the sewers and reach the treatment plant rather than settling in the sewer pipes. DeZellar and Maier (1980) calculated that sanitary sewers designed according to standard practice (maintaining flow velocities above 0.60 m/s or 2 ft/s when flowing full) would not maintain self-cleaning velocities at 40% of full pipe flow, leading to settling and corrosion. Seven of the 14 treatment plants did not observe a change in mass-load of Biological Oxygen Demand (measured as BOD_5) and Total Suspended Solids (TSS); however, five plants reported a decline of over 10%. The load decline was attributed to reduction in garbage disposal use, and possibly to solids settling in the collection system and therefore not reaching the treatment facilities. Despite the load reduction, BOD_5 concentrations increased by an average of 34% (ranging from 6 to 82%) (DeZellar and Maier 1980) due to the significant flow reductions.

Over the past several decades, utilities have observed declining wastewater flows and some have begun to incorporate these observations into future planning. For example, the Washington, D.C. Water and Sewer Authority (DC-WASA) reported a decline in potable water demand of 20% from 1986 to 2005. They anticipated a decline in wastewater of 19.4 MGD (73,430 m^3/day) by 2010 due to pipe repair projects, as well as a reduction of 6 MGD (22,700 m^3/day) by 2015 due to water conservation practices (DC-WASA 2008). This equates to a total decline in per capita flow of approximately 41 gpcd (155 Lpcd) by 2015. The Metropolitan North Georgia Water Planning District (Metro), which uses the "Demand Side

Management Least Cost Planning Decision Support System" (DSS) to predict indoor and outdoor per capita water demand, expected a decline in total per capita demand from 151 gpcd (572 Lpcd) in 2009 to 135 gpcd (511 Lpcd) by 2035 (AECOM et al. 2009). These predictions were used to forecast Maximum Monthly Flow (MMF) by multiplying indoor per capita demand by population and employment forecasts, assuming an additional 20% of flow from I&I, and using a peaking factor of 1.25 (AECOM 2009). Peaking factors represent the ratio between Annual Average Daily Flow (AAD) (the total annual flow divided by 365 days) and the Maximum Monthly Flow (the average daily flow for the highest month that year). Despite declining per capita demand, wastewater flow for Metro was expected to increase by approximately 166% from 2006 to 2035 due to significantly increasing population.

Some utilities, like the City of Boulder, CO, have not yet begun to incorporate declining flows into expansion planning. The wastewater utility observed a 20% reduction in average annual wastewater flows from 1995 to 2005, which they attributed to household conservation and system rehabilitation to reduce infiltration and inflow (I&I). Due to expected growth in population, Boulder does not anticipate the decrease in total flow to continue in the future, even though per person wastewater generation may continue to decline as households replace appliances and fixtures with more water conserving models. The utility assumes per capita use is 102 gpcd (386 Lpcd) and commercial use is 50 gallons per employee per day (190 L/employee/day), and thus they anticipate a plant upgrade will be needed to accommodate an additional 1.1 MGD (4,160 m^3/day) by 2025 (Brown and Cadwell 2007). However, current indoor per capita use in the region was approximately 85 gpcd (322 Lpcd) in 2015 and has been declining rapidly since 2002 (Rozaklis & Associates 2016), suggesting that the plant upgrade might not be needed until later.

While planning documents may or may not focus on the beneficial effect of reduced flow in delaying plant expansion needs, several studies have raised operational concerns. A case study for Melbourne, Australia estimated that flow reductions to the sewer by more than 20% would result in velocities lower than those needed for self-cleaning conditions (Cook et al. 2010). Parkinson et al. (2005) modeled the effects of high-efficiency toilets on dry and wet weather flows in a combined sewer system and found an increase of solids deposition during dry flows and a *decrease* in the number of self-cleansing flushes of sediment. The combination of these two effects can lead to an increase in the concentration of contaminants in the first overflow event after a dry period. Changes in the biogeochemistry in sewer pipes associated with solids retention that lead to increases in odors and corrosive gases have also been reported due to declining flows (DeZellar and Maier 1980; Ashley et al. 2002; Marleni et al. 2012, 2015a; Sun et al. 2015). Additional corrosion control chemicals may have to be deployed if flows decrease significantly (DeZellar and Maier 1980; Koyasako 1980; Sun et al. 2015). Furthermore, laboratory studies have analyzed the effect of lower flows on sulfide and methane emissions and found that lower wastewater flows resulted in a longer hydraulic retention time, which led to higher dissolved sulfide concentrations, increased methane emissions, and lower pH (Sun et al. 2015; Marleni and Nyoman 2016). These factors may result in higher gas phase hydrogen sulfide concentrations at manholes, pumping stations, or treatment plant inlets, which will require changes in the frequency and concentration of chemical additions for control of this toxic gas. In addition, methane is a hazard to workers in the sewer as well as a potent greenhouse gas (Sun et al. 2015).

In addition to effects in the collection system, water conservation has also caused changes at the wastewater treatment plant. Based largely on observations reported in DeZellar and Maier (1980) and Koyasako (1980), at the treatment plant, there is the potential for changes in: mass loadings (from increased sedimentation in sewers), treatment plant removal efficiency, energy costs for pumping, and chemicals required for disinfection and dechlorination. Treatment plants could also see an increase in pollutant concentrations, odor, grit loads after heavy rains, or bulking problems from increased growth of filamentous bacteria in secondary clarifiers (Koyasako 1980).

The long-term effects of water conservation on wastewater collection and treatment systems are unknown. Modeling and prediction for wastewater collection and treatment systems is generally focused on real-time predictions for process control (e.g., Butler and Graham 1995; Carstensen et al. 1998; El-Din and Smith 2002) or on short-term forecasting based on weather patterns (e.g., Jacobs and Haarhoff 2004a, b; Parkinson et al. 2005; Cook et al. 2010; Penn et al. 2013; Marleni et al. 2015a), rather than on long-term projections associated with changing use patterns. Due to the focus on short-term forecasts, these prior models do not consider changes in water usage rates or system-level controls (such as I&I reductions). However, as time horizons increase, demand management strategies, population changes, and utility controls may play a role in decision-making for utilities. The present work develops a mathematical model that incorporates potential changes in per capita wastewater generation over time, as well as changes in population and external flows (infiltration and industrial flow), to improve long-term planning for wastewater utilities and associated stakeholders.

3. METHODS

3.1 Conceptual model

Figure 1 shows the relevant flows in wastewater collection systems and the drivers of those flows. Residential, commercial and industrial flows originate from the potable water supply or source water. Increasing industrialization or population affect the size of these flows, and conservation can reduce them. Inflow to the system from stormwater during wet weather is significant in combined sewer systems. Infiltration of groundwater occurs in both combined and separate systems during dry or wet weather, but is often negligible compared to infiltration and inflow (I&I) during wet weather. Utility interventions to repair pipes to reduce I&I and to manage stormwater (e.g., using Best Management Practices (BMPs)) can all change the flow conditions in sewer pipes. Exogenous changes such as decreasing population and decreasing water use affect base sanitary flows, increasing capacity in the pipe for wet weather flows, thereby reducing the likelihood of overflow events. Flows and loads to the plant may be affected by these changes, resulting in altered performance in the treatment processes and possible changes to timelines for plant expansion.

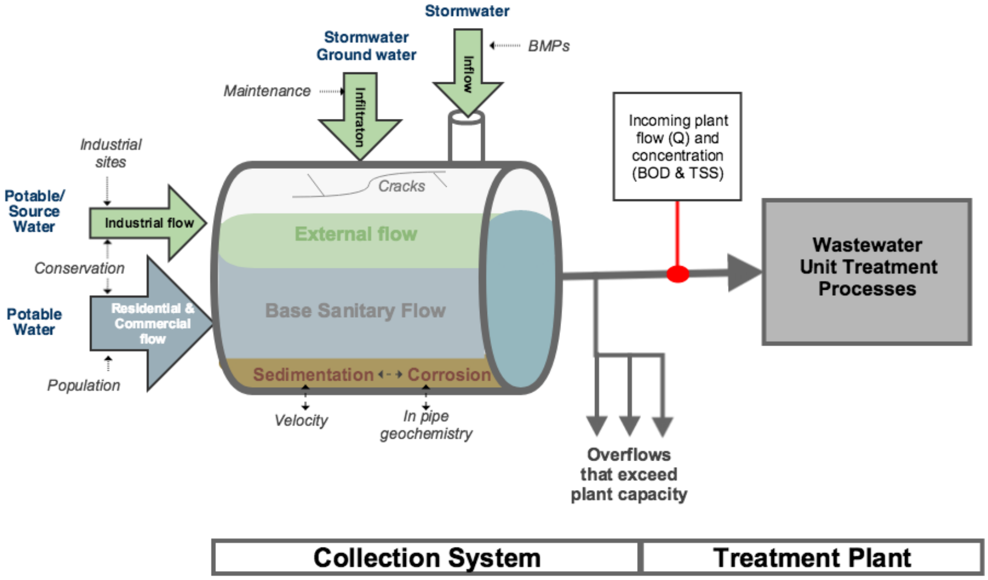


Figure 1. Conceptual approach to modeling urban wastewater flows.

3.2 Mathematical Model Development

3.2.1 Dry weather wastewater flows

Dry weather wastewater flow (DWF) is a function of the sanitary wastewater flow from residential, commercial and institutional sectors, specific industrial flows within the collection area, and unintended dry weather infiltration from groundwater or direct connections; exfiltration or removal of sewage out of the pipes (e.g., sewage mining) reduces this flow (see **Eq.1**) (U.S. EPA 2014). Base sanitary flow (BSF) is defined as the fraction of wastewater contributed by domestic, commercial and institutional sources[1].

$$DWF = BSF + Q^D + Q^I - Q^R \qquad [1]$$

where:

$DWF =$ *average annual daily dry weather flow [m³/day]*

$BSF =$ *average annual daily base sanitary flow (residential, commercial, institutional) [m³/day]*

$Q^D =$ *average annual daily industrial flow [m³/day]*

$Q^I =$ *average annual daily dry weather infiltration from groundwater or direct connections [m³/day]*

$Q^R =$ *average annual daily exfiltrated or removed wastewater [m³/day]*

Total base sanitary flow from residential, commercial and institutional sectors at a period in time (BSF_t) can be expressed as a function of the total population served and the amount of wastewater produced per person (converted to m^3/day) in time period t.

$$BSF_t = \frac{P_t K_t^q}{1000} \qquad [2]$$

where:

$P_t =$ *average total population served (residential, commercial, institutional) during time t [capita]*

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[1] The EPA defines BSF to also include wastewater from industrial sources (U.S. EPA 2014); however, we are excluding industrial flow from our definition, consistent with delineations in several wastewater utilities, e.g., Boulder, CO (Brown and Cadwell 2007).

$K_t^q =$ *average daily wastewater production per capita during time t [Lpcd]*

Population served, *P,* wastewater production per capita, *K*, industrial flows, *D*, and infiltration, *I,* all have the potential to change as a function of time. As a simplified approach, linear growth and decay functions are used to model population and per capita flow changes. These are structured as continuous functions with rate constants that can change at discrete points selected for the simulations (e.g., every five years). The model can assume a continuous rate of decline in water use (ever increasing efficiency) or it can be limited by an expected minimum wastewater generation level that, once reached, does not decline further.

Base sanitary flow for the time period *t+n* is presented in **Eq. 3.**

$$BSF_{t+n} = \frac{K_t^q P_t[(1-\epsilon_t)(1+\rho_t)]^n}{1000} \qquad [3]$$

where:

$BSF_{t+n} =$ *average annual base sanitary flow at end of time period t [m³/day]*

$\rho_t =$ *average rate of change of population from t to t+n*

$\epsilon_t =$ *average rate of decline of per capita wastewater production from t to t+n*

$n =$ *number of years in time period*

Industrial flows, infiltration and exfiltration may also change with respect to time; however, growth rates may be difficult to determine. Shown in **Eqs. 4a** and **b**, industrial flow and infiltration could increase or decrease from the previous time period at a constant annual rate, $\frac{dQ_t}{dt}$, given in m^3/day of expected annual change.

$$\alpha_t^q = 1 + \frac{(Q^D{}_t + n\frac{dQ^D{}_t}{dt})}{Q^D{}_t} \qquad [4a]$$

where:

$\alpha_t^q =$ *ratio of increase or decrease to average annual daily industrial flows in time t [%]*

Q_t^D *= average annual daily industrial flow in time t [m³/day]*

$\frac{dQ_t^D}{dt}$*= annual change in daily flow of industrial wastewater [m³/day/yr]*

$$\beta_t^q = 1 + \frac{(Q^I{}_t + n\frac{dQ^I{}_t}{dt})}{Q^I{}_t} \quad [4b]$$

where:

$\beta_t^q =$ *ratio of increase or decrease to average annual daily dry weather infiltration in time t [%]*

Q_t^I *= average annual daily dry weather infiltration in time t [m³/day]*

$\frac{dQ_t^I}{dt}$*= annual change in daily flow of infiltrated water [m³/day/yr]*

Future dry weather flow over time is the sum of BSF, industrial flow and dry weather infiltration, less any flows that leak out or are removed (e.g., via sewer mining).

$$DWF_{t+n} = \frac{K_t^q P_t[(1-\epsilon_t)(1+\rho_t)]^n}{1000} + \alpha_t^q Q^D{}_t + B_t^q Q_t^I - Q_t^R \qquad [5]$$

where:

DWF_{t+n} *= average annual daily dry weather flow at end of time t [m³/day]*

Q_t^R *=average annual daily removal of wastewater in time t [m³/day]*

3.2.2 Dry weather wastewater loads and concentration

Future dry weather loads of BOD_5 and TSS are modeled in a comparable manner to flow, as a function of per capita load, population served, industrial loads, and any additional loads that enter or remain in the pipe due to infiltration or sedimentation. The relationship between these variables is summarized in **Eq. 6**.

$$DWL = \frac{K^{\dot{m}} P}{1000} + \dot{m}^D + \dot{m}^I - \dot{m}^R \qquad [6]$$

where:

$DWL =$ *average annual daily dry weather pollutant mass loading at treatment plant [kg/day]*

$K^{\dot{m}}$ = *daily per capita loads [g/capita/day]*

P = *population served [capita]*

$\dot{m}^{D}$ = *total daily industrial loading contribution [kg/day]*

$\dot{m}^{I}$ = *loads contributed through dry weather infiltration or unaccounted direct connections [kg/day]*

$\dot{m}^{R}$ = *loads that remain in and/or are removed from the sewer system [kg/day]*

It is possible that per capita loads could change over time due to changes in diet, or changes in the use of load producing fixtures (e.g., garbage disposals) or constituent removal systems (e.g., grey water treatment) (DeZellar and Maier 1980; WEF et al. 2009; Marleni et al. 2012). However, this analysis assumes load per person contributed by residential, commercial and institutional sources remains stable; thus, base sanitary load will only change if population changes. Reductions in total load are accounted for in the term $\dot{m}^{R}$ defined (in **Eq. 7**) as a function of all loads contributed by residential, commercial, institutional, industrial, or infiltrated sources that (i) remain in the sewer system, or (ii) are actively or passively removed from the system.

$$\dot{m}_t^R = \dot{m}_t^N + \dot{m}_t^E \qquad [7]$$

where:

$\dot{m}_t^R$ = *portion of total loads that remain in and/or are removed from the sewer system in time t* [kg/day]

$\dot{m}_t^N$ = *loads that remain in the sewer system under low flow conditions in time t [kg/day]*

$\dot{m}_t^E$ = *loads that are removed from the sewer system in time t [kg/day]*

Loads that remain in the sewer system are a result of settling or biological transformation during low flow conditions. They occur when the velocity falls below the threshold needed for self-cleansing (0.6 m/s), which is a function of diameter, condition, and slope of the sewer pipe and the flow of wastewater through it. Loads are *actively* removed from the system as a result of sewage mining or grey water treatment external to the system. Loads are *passively* removed due to exfiltration from leaks and are a function of Q_t^E.

Industrial loads may also change, due to installation of on-site treatment, stricter regulations, or an increase or decrease in the number of industrial facilities. Industrial loads are modeled to change as a function of flow and concentration of the incoming industrial wastewater. Loads contained in dry weather infiltration are modeled to change in the same manner. **Eq. 8** summarizes the calculation for total dry weather load arriving at the plant over time.

$$DWL_{t+n} = \frac{K_t^L P_t[(1+\rho_t)]^n}{1000} + \frac{(c_t^D \alpha_t^q {Q^D}_t + c_t^D \beta_t^{\dot{q}} {Q^I}_t)}{1000} - \dot{m}_t^R \quad [8]$$

where:

$DWL_{t+n} =$ *average annual daily dry weather pollutant mass loading at treatment plant at the end of time t [kg/day]*

$n =$ *number of years in time period*

c_t^D = expected average daily pollutant concentrations of industrial flows during time period t [mg/L]

c_t^I = expected average daily pollutant concentration of infiltrated flows during time period t [mg/L]

Total dry weather concentration is calculated as the ratio between dry weather loads and dry weather flow at a given point in time.

3.3 Hypothetical Wastewater System Assumptions

This analysis aims to highlight the effect of water conservation practices and other confounding factors (e.g., rate of conservation implementation, population growth, external flows entering the system) on several different types of systems. The analysis provides a methodology to determine if conservation practices lead to positive or negative outcomes for wastewater utilities. With this objective in mind, the mathematical model is applied to a *hypothetical* wastewater system so that several system conditions and scenarios could be examined. Since the system is hypothetical, calibration and validation are not possible, however, these steps could be completed for any real system that has the appropriate data. Input variables needed to run the simulation are described in **Table 1**. An active utility would be able to obtain this information by examining historical records and current operating data. The demonstration of the model here is based on a hypothetical city of 600,000 people (in 2015) that is served by a medium-sized wastewater treatment plant. The collection system (with a presumed area of 30 km^2) is assumed to have 30% combined sewers and 70% separate sewers. Based on assumptions and calculations described in the following section (**3.3.1**), the plant is designed for a maximum dry weather and wet weather capacity of 79 MGD (299,800 m^3/day) and 95 MGD (360,370 m^3/day), respectively.

Table 1. Input variables required to run the simulation

Variable	Description	Imperial units	SI units	Type
K^q	Per capita wastewater production	gpcd	Lpcd	known
ε	Rate of decline of K_q	n/a		forecasted
P	Population served	capita		known
ρ	Rate of change of P	n/a		forecasted
Q^D	Total industrial flow	MGD	m3/d	known
α	Factor of increase/decrease of Q^D	n/a		forecasted
Q^I	Dry weather infiltration	MGD	m3/d	known
β	Factor of increase/decrease of Q^I	n/a		forecasted
Q^R	Removed/exfiltrated flow	MGD	m3/d	known
K^m	Per capita mass loading (BOD_5, TSS)	lb/cap/d	g/cap/d	known
m^D	Total loads from Q^D	kip/day	kg/day	known
m^I	Total loads from Q^I			known
m^N	Loads remaining in sewer in low flow (function of Q)			function
m^E	Total loads removed/exfiltrated from sewer			known

3.3.1. Design conditions (1986)

To assess the interactions among uncertain future conditions, design and current operating parameters must be known, and these would be available for any real system analyzed. For the hypothetical system used in this demonstration, prior condition assumptions were made to enable a more realistic perspective on how wastewater flow would vary given the expected conditions from design. These assumptions are also necessary to describe critical thresholds needed to interpret results (see **Section 3.5**). Consistent with typical planning horizons, the plant was assumed to have a design lifetime of 40 years, and a planning horizon of 9 years for new construction or expansion (Metcalf & Eddy et al. 2003; WEF et al. 2009). The plant is presumed to be at the midway point of its lifetime in 2015, thus to have begun operations 20 years prior to the simulation initiation (in 1995), and to have been designed in 1986, 9 years prior to construction completion.

Following design standards at the time, per person wastewater flow was expected to remain stable at 100 gpcd throughout the design lifetime of the plant. Thus, the minimum and maximum populations served would have determined the upper and lower bound of *design* dry weather flows expected throughout the lifetime of the wastewater system. It is assumed that the plant was *designed* for a minimum population of 500,000 people in 1995 (start of operations). The minimum flow requirement necessary to maintain self-cleansing velocities in the sewer system was presumed to have been calculated as a total of 55 MGD (500,000 people, 100 gpcd, industrial flows 10% of BSF), with sewers at an average of 50% capacity under these conditions (which is not uncommon for average dry weather flow conditions (DeZellar and Maier 1980)). Consistent with the average rate of national annual population growth from 1980 to 1985 (prior to design) of 0.92% (World Bank Group 2017), it is also assumed that population was expected to rise to 600,000 by 2015 and reach 720,000 by 2030. The maximum flow requirement to treat dry weather flows at the end of lifetime (2030) was estimated to be 79 MGD (299,800 m^3/day) (720,000 people, 100 gpcd, industrial flows 10% of BSF). This design average dry weather flow would have been combined with a peaking factor (1.2) to reach a required wet weather capacity for the plant of 95 MGD (360,370 m^3/day). These assumptions are summarized at the top of **Figure 2**.

3.3.1. Historical conditions at start of operation (1995) and initial conditions (2015)

As noted in the introduction and background (**Sections 1** and **2)**, most utilities in the U.S. have already experienced some decreases in per capita wastewater flows. However, early wastewater systems would not have been designed to accommodate this decline due to conventional wisdom at the time. Thus, different assumptions were made to estimate the "*historical*" dry weather flow in 1995 and the "*initial conditions"* in 2015, since they would differ from flows predicted using the design assumption of 100 gpcd made in 1986. Also listed at the top of **Figure 2** are the hypothetical "*historical*" conditions at the plant in 1995, and "*initial conditions"* in 2015.

These conditions were estimated in four areas: per person wastewater production, population served, industrial flow, and system infiltration. Based on U.S. trends, we assumed that our hypothetical system had already implemented water conservation or efficiency measures and that per capita flow would not remain stable at 100 gpcd. It would instead decline at the same rate that per capita flow declined nationally over this time period. These national values, reported by DeOreo et al. (2016) and Mayer (2016), are 70 gpcd (264 Lpcd) and 58.6 gpcd (222 Lpcd) for 1995 and 2015, respectively. The *historical* and *initial* flows use the same assumptions for population that were used in design assumptions (a minimum population of 500,000 people in 1995 and a rise to 600,000 by 2015). With these assumptions, base sanitary flow (BSF) in 2015 is calculated as 35 MGD (132,490 m^3/d) – the product of 2015 population (600,000 people) and per capita flow (58.6 gpcd). Industrial flows were assumed to be equivalent to 10% of the BSF, equating to a value of 3.5 MGD (13,249 m^3/d) in 2015. Infiltration was assumed to be 9 MGD in 1995 and several infiltration scenarios were assumed for *initial conditions* in 2015, which are discussed in Section 3.2. Total dry weather flow was estimated to be 48 MGD (176,020 m^3/day) in 1995 and 41 – 73 MGD (155,201 – 276,334 m^3/day) in 2015, depending on the infiltration scenario.

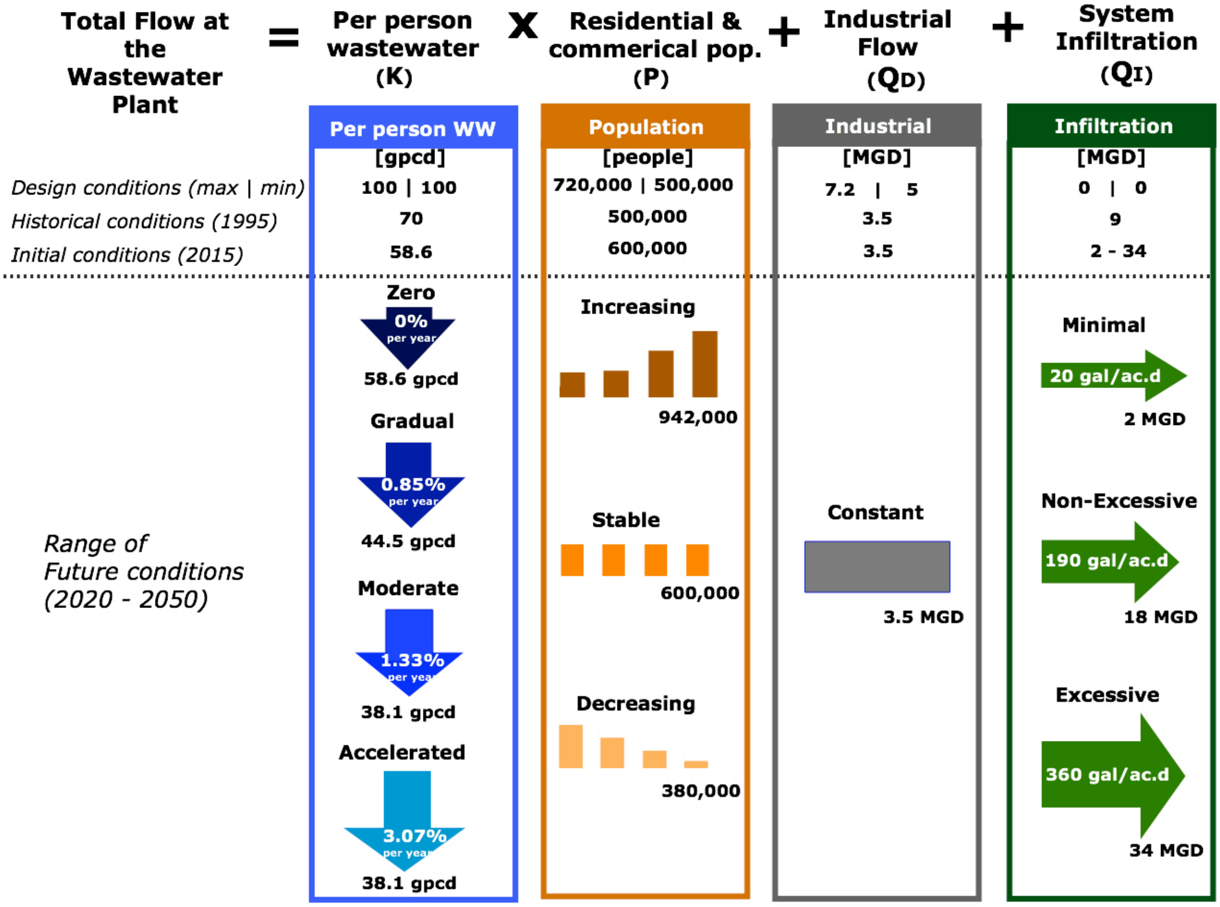

Figure 2. Design, historical, initial, and range of future conditions for modeling of average daily dry weather flow

3.3.2. Initial dry weather infiltration conditions (2015)

Three cases for initial system infiltration were examined: minimal, non-excessive, and excessive (far right of **Figure 2**). **Section S1.1** of the Supplementary Information (SI) presents the assumptions needed to develop these three scenarios, which are summarized in **Table 2.** It is important to note that each of these different assumptions results in a different initial dry weather flow at the start of simulation. The non-excessive scenario is consistent with a doubling of dry weather infiltration from 1995 to 2015; however, it is also possible that infiltration was higher or lower than this midpoint value, hence the other two scenarios are also analyzed. As noted previously, in active systems, estimates of I&I may be available from flow studies. If data are not available, similar ranges of estimates can be used in the model and the results for the initial conditions compared with plant data to ensure the starting point for simulations is reflective of active conditions.

Table 2. Assumptions and values for infiltration scenarios

Infiltration Scenario	MGD	gal/ac/d	Assumption
Minimal	2	20	Lower bound of range of gal/ac/d from Metcalf & Eddy
Non-Excessive	18	190	Mid-point between minimal and excessive
Excessive	34	360	Just above the 120 gpcd definition of "excessive infiltration" by EPA

3.3.3 Initial mass load of BOD_5 and TSS (2015)

In this analysis, per capita load is assumed to remain stable at 85 grams of BOD_5 and 105 grams of TSS per person per day, consistent with average values reported by Metcalf & Eddy et al. (2003). For the simulations in the present work, we assume that industry in our hypothetical city will contribute heavy loads of BOD_5 and TSS. Using data from a service area in the Northwest U.S. with high load industrial units, we assume for this study that the treatment plant will receive approximately 930 g of BOD_5/m^3 of industrial wastewater, and 760 g TSS/m^3 of industrial wastewater. Given that industrial flow is assumed to be 10% of base sanitary flow, the total load contributed by industry is 12,378 kg/day BOD_5 and 10,115 kg/day TSS at the initiation of the simulations. Finally, we assume that infiltration does not contribute additional BOD_5 or TSS load. As noted previously, in currently operating systems, data may be available for all these values or sampling could be undertaken to estimate them. Simulations of active conditions could be compared with observations in the system to adjust assumptions regarding mass loads as needed.

3.4 Future conditions and scenarios (2020 – 2050)

The following section introduces the assumptions used to project average DWF over a 35-year time horizon (from 2015 to 2050). Summarized in **Figure 2,** various scenarios were assumed for the conservation rate (which leads to changes in per capita wastewater flow), population growth rate, industrial flow, and dry weather infiltration. Scenarios for BOD_5 and TSS load are linked to those for flow. Only per capita flow and population are assumed to change over time; industrial flow and system infiltration are assumed to remain stable. Different levels of system infiltration are accounted for by varying the initial conditions (see **Section 3.3.3**).

3.4.1 Conservation scenarios

The rate of decline of per capita flow due to conservation, ϵ, was developed using three scenarios: gradual, moderate, and accelerated adoption of water efficiency measures (far left of **Figure 2**). All of the conservation scenarios assume that per capita flow will eventually reach a minimum per capita flow of 36.7 gpcd (139 Lpcd), which was calculated in the 2016 U.S. Residential End Uses of Water study (DeOreo et al. 2016). Each conservation scenario assumes that the minimum flow is reached in a different future year, which in turn affects the rate of conservation.

The “gradual” scenario assumes that the minimum per capita flow value is reached 20 years after the end of the time horizon - by 2070. This equates to a 0.85% annual decline in per capita flow, reaching a value of 43.4 gpcd (164 Lpcd) by 2050. The “moderate” scenario assumes that the minimum per capita flow is achieved by the end of the time horizon (2050), which is equivalent to an annual linear decline of 1.33%. Finally, the “accelerated” scenario assumes that the minimum per capita flow is reached 20 years *prior* to the moderate scenario, by 2030, resulting in an annual decline of 3.07% until 2030, after which per capita flow remains stable until 2050. These conservation rates are compared to a scenario that assumes no change in per capita flow from 2015, meaning that all reductions had already taken place from 1995 to 2015, and the minimum of 36.7 gpcd is not reached in the simulation. The predicted per capita flow over time, based on the rate of decline from each of the four conservation scenarios, can be found in **Section S1.2** of the SI.

3.4.2 Population and additional flow scenarios

Population growth rates were modeled following predictions for a moderate-sized city in the U.S. (Metro 2009). Population is projected to increase annually by 2.07% until 2020, when the rate of increase gradually declines to reach 1.03% annually by 2040, where the rate remains constant until 2050. Two additional population scenarios were considered: stable and decreasing. The stable population scenario considers that population served will remain constant at 600,000, and the declining scenario assumes that the rate of decline of the population mirrors the population growth rates considered in the increasing scenario. The population rates and the population end points for the different scenarios are summarized in **Figure 2** (middle left).

The contributions to additional flows from industrial flows and infiltration are considered to be constant, meaning that the ratio of increase or decrease to average annual daily flows (α and β) are assumed to be 1. Exfiltration and removed flows are assumed to be negligible.

3.4.4 Mass load of BOD_5 and TSS conditions

Unlike flow, mass loadings per capita of BOD_5 and TSS are likely to remain stable when water efficiency increases, except in specific cases of grey water reuse that include on site treatment, and when regulations limit the use of garbage disposals to save water (DeZellar and Maier 1980; Marleni et al. 2012). Industrial loads, however, can vary tremendously depending on the type of industry in the service area. For utilities with extensive information on their industrial loads and estimates of anticipated future changes, these can be incorporated directly into the model. For the present simulation, industrial load is assumed to remain constant. BOD_5 and TSS loads from infiltration are considered to be negligible in this analysis. However, this assumption should be revisited if the model is to be used to describe nutrient loads.

Total load received at the wastewater plant may be smaller than loads received from municipal, commercial, industrial, and infiltrated sources that enter the collection system, either due to settling and storage in pipes, or to biological or chemical transformations that occur during transit to the plant. Based on findings from DeZeller and Maier (1980), reductions in load were observed after decreases in flow by as little as 15%. The four plants in the study that experienced the highest flow reductions (of over 30%) saw decreases in per capita BOD_5 and TSS load that ranged from 14 to 38% for BOD_5, and 22 to 54% for TSS. It is unclear, however, whether these reductions are attributed to reduced garbage disposal use, solids settling, in pipe transformations, or a combination of these effects. Without additional information, for the present analysis we assume that these load reductions affect the total load received at the plant, including load received from industrial units. A piece-wise linear function was fit to the limited data, which estimates that after flow has decreased by 1/3, for every subsequent 2% decline in flow, BOD_5 load will decrease by 5% and TSS by 4%. Once flow is reduced by 40%, BOD_5 reductions stabilize, and TSS reductions slow to a 0.5% decline for every 1% decline in flow. These reductions are applied to flow decreases from the non-excessive infiltration scenario, consistent with lower bounds derived for risk levels during low flow conditions, discussed in the following section. While these assumptions were necessary for demonstration of the model and simulation of results for the hypothetical plant, utilities with extensive data for flow and load reaching their plant could use these data to improve estimates of the effect of future changes.

3.5 Critical thresholds

Two critical points are considered to bound the simulations. The first is the maximum flow at the plant that would trigger planning by the utility to make capital expenditures (e.g., plant expansion, repairs to decrease the amount of infiltration entering the system, or campaigns to increase the rate of conservation). The second is the minimum flow at the plant, corresponding to collection system flows that are low enough to cause settling, corrosion, and odor problems, which would necessitate utility action (e.g., addition of corrosion inhibitors, system flushing).

3.5.1. Threshold triggering expansion planning

To allow time to design, permit, and implement capital expenditure projects, strategic planning of these projects would be initiated approximately 6 - 8 years prior to their completion. This would ensure that sanitary sewer overflows (SSOs) or combined sewer overflows (CSOs) would not result from system surcharge as populations or infiltration increased in the remaining lifetime of the plant. To account for an additional 50,000 people to be added during this time (growth rate 0.134%), an additional 8 MGD (30,280 m^3/day) in capacity would be required to avoid surcharges. The threshold triggering expansion planning (referred to as the “threshold for expansion”) is estimated as 72 MGD (~250,000 m^3/day), consistent with the threshold for excessive infiltration in 2015 (and on for the stable population scenario), as well as the design BSF. For a specific utility, this threshold is likely already known and incorporated into long term planning. The goal of the present work is to simulate how the model’s approach can aid in projecting timelines for reaching such critical points.

3.5.2. Risk levels for settling and corrosion

For the lower bound, there is insufficient information to determine a value independent of additional sewer system characteristics. For the purposes of demonstration, we calculate several “risk levels” that correspond to the potential risk of dropping below the self-cleansing velocity under low flow conditions in the sewer system. To determine these thresholds, it is assumed that a reduction in flow at the plant corresponds to a similar reduction in flow in the sewer system. Assuming the sewers were designed according to standard practice, the minimum design plant flow (55 MGD) would equate to 50% of the carrying capacity of the pipes (to prevent settling under low flow conditions), and the wet weather design flow of 95 MGD would represent pipes that were 86% full, on average. Consistent with findings in the literature, we assume that negative changes (as a result of not maintaining self-cleaning velocities) would occur at 40% of full pipe flow, which arrives when dry weather flows are reduced by 20% from minimum design flows (DeZellar and Maier 1980; Cook et al. 2010).

However, since not all pipes in the sewer are the same size, it is possible that negative changes could occur before or after this 20% threshold. Thus, four risk levels are identified, corresponding to a reduction of 10%, 20%, 30%, and 50% from minimum design flow, as reported in **Table 3**. While these assumptions were necessary for demonstration of the model and simulation of results for the hypothetical plant, utilities with specific information regarding collection system pipe capacity and volumetric loading during dry weather could use these data to improve the selection of the minimum threshold values.

Table 3. Definitions for critical thresholds used to bound the simulation

Threshold	Flow level	
	MGD	m^3/day

Dry Weather Capacity	79	299,047
Threshold for Expansion	72	272,549
Minimum Design Flow	55	208,197
Risk Level 1 (10% decrease)	49.5	187,377
Risk Level 2 (20% decrease)	44	166,558
Risk Level 3 (30% decrease)	38.5	145,738
Risk Level 4 (50% decrease)	27.5	104,099

4. RESULTS AND DISCUSSION

As expected (and intended), assumptions regarding the rate of adoption of conservation efforts within the service area alter the predicted wastewater produced per person. In the absence of other changes, a decline in per capita wastewater produced would lead to declines in the average wastewater flow reaching the plant over time. **Section S2.1** in the SI presents results and discussion of projections of average annual dry weather flow reaching the wastewater treatment plant under the different conservation scenarios, assuming infiltration remains non-excessive and population does not change. Whether declining per capita wastewater production caused by conservation results in average annual dry weather flow surpassing critical thresholds depends on the level of infiltration present in the system (minimal, non-excessive, or excessive), the rate of population growth, and the actual rate of conservation-associated declines in per capita wastewater generation. This is illustrated in **Section 4.1** for an increasing population. **Section 4.2** illustrates how changes in the rate of population growth can play a role in how quickly declines in average annual dry weather flow take place, or if they take place at all. Detailed results describing flow conditions for other scenarios (e.g., minimal and excessive infiltration) can be found in the SI (**Section S2.2** to **S2.4**). **Section 4.3** presents a summary of how all scenarios could influence future planning. **Section 4.4** shows how changes in flow and load could lead to changes in concentration. More detailed results for load under minimal infiltration are found in **Section S3** of the SI.

4.1 Conservation with different levels of system infiltration and increasing population

This section illustrates how the initial level of system infiltration influences the desired rate of conservation when population is assumed to be increasing. Ultimately, the goal is to manage wastewater flow over time so that it remains below the threshold for expansion and above the level that would lead to low flow conditions associated with corrosion and odor issues. For an increasing population, systems with excessive infiltration are primarily concerned with timing for expansion; whereas systems with minimal infiltration are only constrained by low flow issues. Systems with non-excessive infiltration are exposed to both upper and lower bounds, where attainment of one or the other depends on the rate of conservation and population. **Figure 3** shows the simulation results for average annual flow for the four conservation rate assumptions at three points in time (2015, 2030 and 2050) for an increasing population. Average annual flows are shown for base sanitary conditions (green bar), minimal infiltration (red outline), non-excessive infiltration (light blue bar) and excessive infiltration (dark blue bar). A black, dashed horizontal line indicates the threshold triggering plant expansion plans, and a brown, dotted line indicates the threshold for increasing risk of settling and corrosion problems in the collection system (corresponding to a 20% flow decline from minimum design flow). The first group of bars shows assumptions for design conditions and the average conditions in the U.S. in 2015.

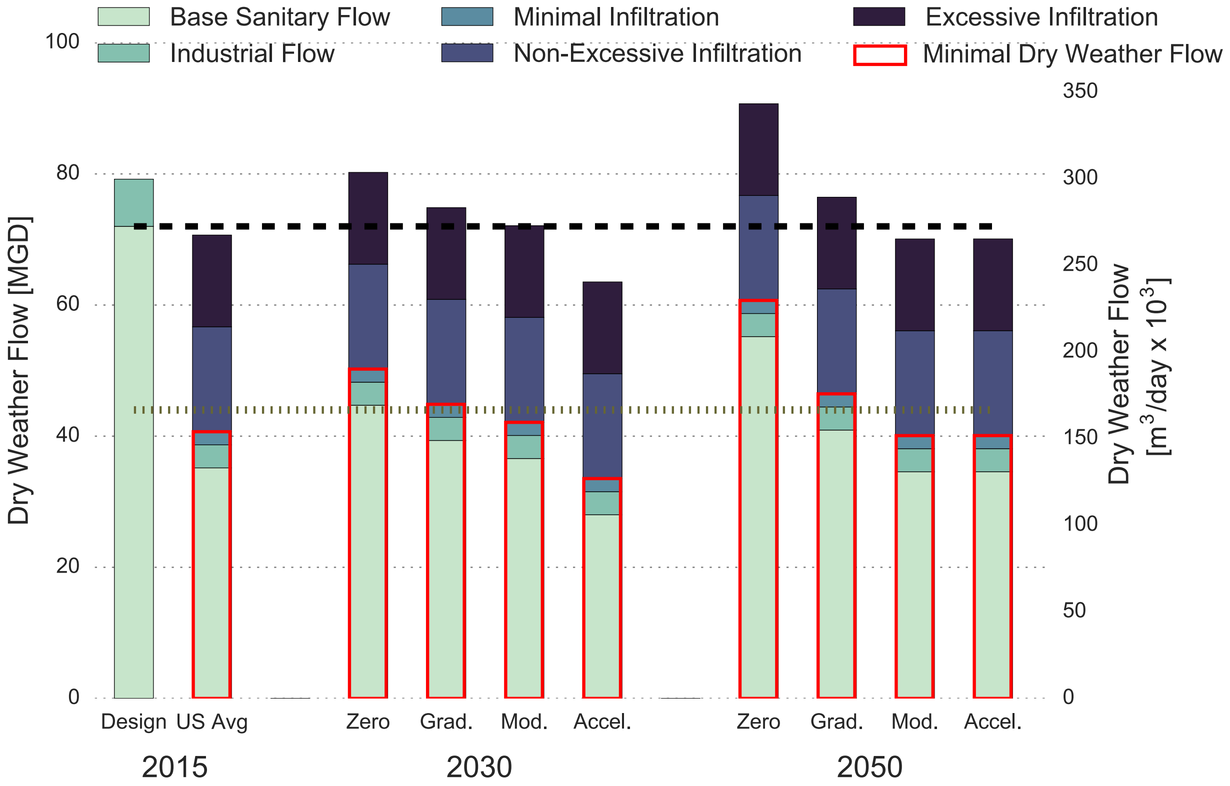

Figure 3. Dry weather flow for design and initial conditions (first group of bars) and for two time points: 2030 (second group of bars) and 2050 (third group). Projections shown for each conservation scenario. Threshold for plant expansion is represented as a black, dashed line. Risk level 2 (20% decrease) is shown as a brown, dotted line.

The figure shows that when population is increasing, the desired rate of conservation will depend on the level of existing system infiltration. In a system with excessive levels of infiltration (dark blue bars), the goal is to decrease dry weather flows so they are below the threshold for expansion. Moderate conservation will achieve this goal by 2030; accelerated conservation will achieve it sooner. In a system with non-excessive infiltration (medium blue bars), the goal is to stay below the threshold for expansion. In this case, accelerated conservation is unnecessary; a moderate conservation rate (annual decline of 1.22%) would stabilize wastewater flows over time. In a system with minimal conservation, flows are never at risk of exceeding the threshold for expansion; however, they are at risk of low flow conditions if conservation measures are implemented too rapidly. In this scenario, conservation measures should be implemented gradually with system monitoring for changes in flow over time.

4.2 Sensitivity of conservation choices to stable or declining population

Population may not always increase, even if it is expected to do so. The following section examines the results in the system when conservation measures are implemented when population is stable or declining. **Figure 4** presents the average dry weather flow over time for increasing, stable, and declining population (different colored lines) for non-excessive infiltration and gradual to moderate conservation (different line thickness).

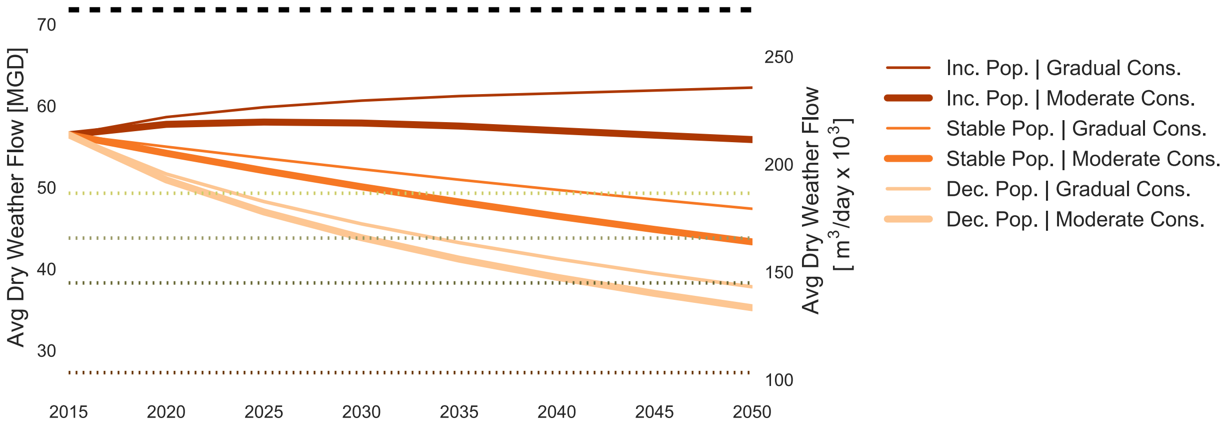

Figure 4. Total wastewater flow over time with moderate conservation for each population scenario and non-excessive infiltration. Threshold for plant expansion is represented as a black, dashed line. Risk levels 1 to 4 are shown as dotted, horizontal lines from top to bottom, respectively.

Figure 4 presents the sensitivity of the results to the rate of population growth under non-excessive infiltration conditions. If the population did not grow as expected, and instead stabilized or declined, the system would be at risk of settling and corrosion within 10 to 20 years if conservation was implemented at a moderate pace. If conservation measures are instead implemented gradually, the declines in wastewater are reduced by half, and the risk of low flow conditions is decreased. Results indicate that a more gradual implementation of conservation is the most robust strategy to implement if infiltration is non-excessive and population is uncertain. Gradual conservation would only lead to slight increases in wastewater flow if population growth increased; yet also minimizes risk to the system if population growth did remain stable or decline.

4.3 Threshold exceedance for flow amid all drivers

Findings indicate that *if* and *when* thresholds for expansion or settling will be crossed depend on: (i) existing levels of infiltration in the collection system; (ii) the rate of population growth or decline; and finally, (iii) the pace of implementation of conservation measures. **Figure 5** summarizes these changes over time for the three infiltration scenarios (minimal, non-excessive, and excessive), three population rates (decreasing, stable, and increasing), and four conservation rates (zero, gradual, moderate, and accelerated). White fill indicates that no thresholds have been exceeded for a particular scenario and time period, labeled as the "safe zone" in the figure. Grey lined fill indicates that the threshold for expansion was exceeded, and solid black fill indicates that plant capacity was exceeded. Light tan to dark brown, dotted squares indicate increased risk of settling and corrosion, from low to high, respectively.

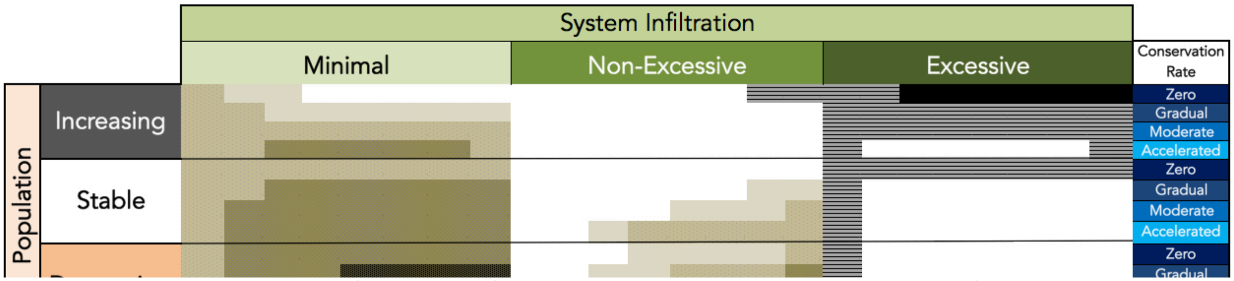

Figure 5. Predicted exceedance of thresholds for all population scenarios (outer rows), infiltration levels (outer columns), and conservation scenarios (rows within boxes).

░	Risk level 1 (10% decline)	▒	Risk level 3 (30% decline)	■	Exceeds Plant Capacity
░	Risk level 2 (20% decline)	▓	Risk level 4 (50% decline)	☰	Exceeds Threshold for Expansion
				☐	Safe Zone

These results highlight the influence that infiltration levels have on the initial state (i.e., in 2015) of the system. With minimal infiltration, the system is already at risk of settling, and with excessive infiltration, the threshold for expansion planning has already been passed. Whether the system moves to an improved state, an inferior state, or stays in the existing state will depend on the rate of population growth and the rate of conservation achieved. There is a risk of settling and corrosion under all population conditions if infiltration is minimal and conservation is implemented. The risk increases as population growth decreases or conservation practices accelerate. If population is decreasing or stable, the risk would be more effectively abated through deliberate increases in I&I, or chemical additions, rather than slowing the rate of conservation. However, if population is increasing and infiltration is minimal, delaying conservation or slowing its implementation could be an effective measure to reduce risk to sewers and avoid the costs associated with flushing or chemical addition.

When infiltration is non-excessive and population is stable or declining, systems are at risk for settling and corrosion problems over time. For a declining population, flushing will likely be required even if conservation is not implemented, but the amount of flushing required decreases as conservation is minimized. Stable populations with non-excessive infiltration should avoid conservation to reduce risk to the sewer; however, other drivers (such as reduced water availability) may require conservation. In these cases, interventions to prevent corrosion will be needed and should be included in planning. Increasing population and non-excessive infiltration is an ideal candidate for conservation, since water savings will avoid plant expansion and the threat to sewers is minimized under all conservation rates.

For systems with high levels of infiltration, conservation has the potential to be used in lieu of or in conjunction with pipe repair (for I&I reduction) to avoid plant expansion or meet regulations limiting overflows. If population is stable or declining, gradual or moderate conservation could avoid expansion and allow for high levels of infiltration to reach the plant for treatment. Increasing population and high infiltration would require pipe repair to reduce flows to the plant; however, conservation could accelerate the pace of flow reductions.

<u>4.4 Changes in concentration amid all drivers</u>

As the results demonstrate, population, infiltration levels, and conservation choices interact to alter the flow of wastewater arriving at the treatment plant. These changes could also shift the amount of load arriving to the treatment plant, and the concentration of the wastewater. Load increased at the rate of population change in all cases except minimal infiltration (see SI), when low flow conditions were assumed to have led to sedimentation. This section presents the results for changes in concentration among all drivers, considering changes in both flow and load.

Figure 6 presents the projected incoming dry-weather concentration of BOD_5 and TSS for minimal infiltration (left panels), non-excessive infiltration (middle panels), and excessive infiltration (right panels) for 2015, 2030, and 2050. Conservation and population scenarios are captured in the ranges shown with error bars. Unlike load, concentration is driven primarily by system infiltration, which dilutes the concentration as more water enters (since it was assumed that infiltrated water does not add additional load). Thus, concentrations are highest under minimal infiltration (350 to 600 mg/L), lowest under excessive infiltration (200 to 400 mg/L), and in between for non-excessive infiltration (300 to 510 mg/L). Concentration is less affected by changes in population since load changes along with population, unless low flow conditions occur to remove load in the collection system.

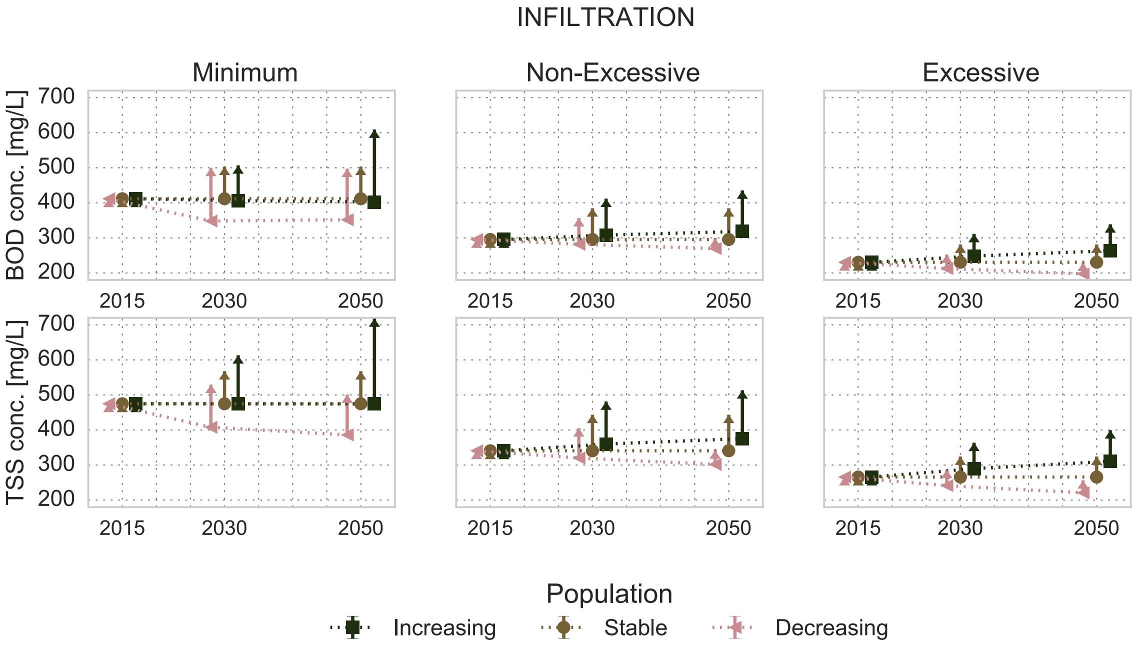

Figure 6. Predicted BOD_5 (top) and TSS (bottom) concentrations for all infiltration scenarios (represented in columns) and all population scenarios (represented as different colors). The markers, connected by dotted lines, represent what the concentration would be with zero conservation. The vertical line increasing from each marker represents the range of concentrations under increasing conservation. The vertical triangle represents the concentration under the accelerated conservation scenario.

Changes in concentration do occur as a result of conservation practices. For all scenarios except decreasing population, average concentration increases as time passes and per capita flows decline. These increases are largest for the minimal infiltration scenario (since the flow is less dilute) and smallest when infiltration is excessive. For decreasing population, concentration could increase or decrease, depending on whether the declines in load outpace the declines in flow. For instance, declines in flow due to conservation could be larger than declines in load from population decreases, causing concentration to increase. This is because conservation focuses on reduced water use, and not on changes that alter waste loads. However, once the minimum per capita flow is reached, load continues to decline (from decreasing population) but flow remains stable. This would cause concentration to decline again.

In all scenarios (conservation, population, infiltration), BOD and TSS influent concentrations never surpass 600 and 700 mg/L, respectively. The concentrations also never fall below 200 mg/L. This range equates to a geometric standard deviation of 1.73 for BOD and 1.87 for TSS, which is outside the typical range expected for influent concentrations at intermediate wastewater treatment facilities (40,000 – 400,000 m^3/day) of 1.3 to 1.6 for both BOD and TSS (Metcalf & Eddy et al. 2003). However, if the excessive infiltration scenario is excluded, concentrations range from ~300 mg/L to 600 mg/L (for BOD) and 700 mg/L (for TSS), which is within the typical geometric standard deviation range. Nonetheless, changes are expected to be within the design tolerances of the wastewater plant (reported by Metcalf & Eddy et al. 2003), as long as infiltration is not drastically increased or decreased.

4.5 Sensitivity of all findings to different initial assumptions

To determine the robustness of these findings, a simple sensitivity analysis was conducted on several of the initial assumptions, while holding the design and threshold assumptions constant. Overall, we found that the results are more sensitive to the rate of change than to the starting point (with the exception being system infiltration). For instance, if initial population in 2015 was 16% larger (population of 700,000 instead of 600,000), yet it grew at the same rate, the system would still not reach the threshold for expansion under gradual conservation assuming non-excessive infiltration. Similarly, if industrial flows were decreased by half or doubled, these cases would have very little influence on the result. This is because the amount of industrial flow relative to infiltration and municipal flow is small, thus halving or doubling this amount is still small in comparison. Only cities with very large flows coming from industry (30% or more) should be concerned with declines in these flows due to conservation. Results would be similar to the case of high infiltration. Changes in concentration would be case specific, and depend on whether the concentration of the industrial flow was changing proportionally to the declining flow.

An interesting finding arises when the initial per capita flow is changed. If the initial per capita flow in 2015 was higher than assumed (for instance, 65 gpcd instead of 56 gpcd), the minimum per capita flow was still reached at the same time period (2030 for accelerated, 2050 for moderate, and 2070 for gradual). This is because the rate of conservation is larger after 2015 than before 2015, leading to the same result. If the initial per capita flow was higher in 2015, and the conservation rate remained the same as in the initial assumptions (see **Figure 2**), then the findings do change. Assuming non-excessive infiltration, the threshold for expansion will be crossed sooner than if more efforts to conserve had been accomplished prior to 2015. This means that utilities should carefully consider how much conservation has already been implemented before considering future conditions. Alternatively, if the minimum per capita flow was reached earlier than 2030, the system could be at risk of low flows for the next 10 to 20 years. Since the rate of conservation in this case would be so rapid (4 – 8% decline per year), the flows would decline rapidly regardless of the rate of population.

The final analysis examined the results under increasing infiltration, and further confirmed the sensitivity of the system to infiltration levels. If initial infiltration was non-excessive, yet infiltration increased by 10% every 5 years, the threshold for expansion would be crossed by 2040 under gradual conservation. However, this threshold would not be crossed if infiltration only increased by 5% every 5 years. Alternatively, if initial infiltration was minimal, any increase in infiltration would be welcome in order to decreases the risk of low flows. Overall, the sensitivity analysis verifies the overall findings, and further confirms that actual results will be unique to the operating and design conditions of each system.

5. CONCLUSIONS

This work presents a structured model for analysis of the interactions of declining per capita water use and changing population on average annual dry weather sewer flows, loads, and concentrations under various levels of infiltration. The model could be used by wastewater utilities to understand how interacting influences (e.g., rate of conservation, growth or decline of population, system infiltration) could result in a benefit (deferring plant expansion) or challenge (risk of low flow conditions) to the wastewater system as a result of conservation practices. Since the model is generic, it could be applied to biological or nutrient loads to the sewer system.

General findings using a hypothetical city show that infiltration is the largest driver in determining whether conservation practices would have a positive or negative effect on the system. Systems with high levels of infiltration (~30% or more of total dry weather flow) will benefit the most from conservation practices since declines in flow from reductions in per capita flow could delay the need for plant expansion or decrease the need for repairs due to I&I. Thus, systems with average to high levels of I&I would benefit from incorporating expected declines in per capita use to utility planning documents and may even want to incentivize conservation efforts at the household level.

Systems with minimal levels of infiltration (less than 5% of dry weather flow) are most at risk of negative effects from implementing conservation practices. These systems may be at risk of low flow conditions in the sewer, which could lead to settling and corrosion issues if the velocity falls below the level needed for self-cleansing. This risk increases as population growth slows (or declines), or conservation practices accelerate. These utilities will need to pay careful attention to ensure that sewer systems are not experiencing worsening deposition and corrosion due to low flow conditions from conservation, and may want to slow the rate of conservation efforts at the household level when possible.

In general, declines in per capita use lead to an increase in average dry weather pollutant concentrations; however, increases are expected to be within the design tolerances of the wastewater plant (Metcalf & Eddy et al. 2003), as long as infiltration is not drastically increased or decreased. Utilities should be less concerned about long-term changes in concentration as a result of conservation practices, and more concerned with impacts resulting from declines in flow.

6. ACKNOWLEDGEMENTS

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