Environmental Modelling & Software 101 (2018) 204–217

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Municipal water planning and management with an end-use based simulation model

Kai Wang, Evan G.R. Davies*

Department of Civil and Environmental Engineering, University of Alberta, 9211 − 116 St NW, Edmonton, Alberta, T6G 1H9, Canada

ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form
13 October 2017
Accepted 26 December 2017

Keywords:
Water demand model
Municipal water conservation
Decision-support tool
Scenario analysis
System dynamics
Calgary

ABSTRACT

This study introduces an end-use-based system dynamics model to support municipal water planning and management over the medium-to long-term. The Calgary Water Management Model (CWMM) simulates water demand and use to 2040 at a weekly time step for ten municipal end-uses, as well as the effects of population growth, climate change, and various water management policies, and includes policy implementation costs for assessment of conservation versus economic trade-offs. The model was validated against historical water demand data for Calgary, Alberta. A series of scenario simulations showed (1) potentially large changes to both seasonal and non-seasonal water demands with climate change and population growth, (2) a need to enhance historical water management policies with new policies such as xeriscaping and greywater reuse to achieve water management goals, and (3) the value of an end-use based model in simulating management policy effects on municipal water demand and use.

Software availability

Software name: CWMM (Calgary Water Management Model)
Developers: K. Wang and E. Davies, University of Alberta
Year first available: 2017
Program language: Vensim
Hardware requirements: No special requirements
Software required: Vensim Model Reader, Ventana Systems Inc.
Availability and cost: Please contact the corresponding author for a free copy

1. Introduction

Population growth and climate change present challenges for water resources planners and managers (McDonald et al., 2011), and water security is increasingly of concern to urban authorities (Grafton et al., 2011; Yigzaw and Hossain, 2016). On the water supply side, a variety of studies have investigated effects of changing precipitation patterns, glacial retreat, and sea level rise on hydrological variables (cf. Dibike et al., 2016; Eshtawi et al., 2016; Scalzitti et al., 2016) as well as urban hydraulic infrastructure expansions and management (Padowski and Jawitz, 2012; Mays, 2002). Water authorities also recognize the value of managing water demand – the focus of this research – which is less time-intensive and more cost-effective and environmentally-friendly than supply-side management (House-Peters and Chang, 2011; Gleick, 2003).

Municipal water systems serve residential, industrial, commercial, institutional and public clients (Mayer et al., 1999), whose demands are affected by both long-term impact factors – population change, economic conditions, and water conservation activities – and short-term impact factors, including seasonal weather patterns and the associated summer peak demands (March and Saurí, 2009). In most urban systems of North America, the total water demand increases with population growth, while per capita water use decreases with water conservation efforts such as adoptions of “low-flow” fixtures and appliances, educational campaigns, water metering and consumption feedback, leak detection programs, economic incentives, xeriscaping, and water treatment and reuse (Billings and Jones, 2008; Sønderlund et al., 2016; DeOreo et al., 2016).

Reliable water demand modeling and forecasting provides the basis for both the short-term (operational) and long-term (planning) aspects of urban water management, in terms of capital investment, infrastructure expansion, conflict mitigation, policy analysis, and system optimization, and it can improve

---

* Corresponding author.
E-mail address: evan.davies@ualberta.ca (E.G.R. Davies).

https://doi.org/10.1016/j.envsoft.2017.12.024

understanding of the underlying factors and dynamics that affect water demand and use (Billings and Jones, 2008). However, accurate demand forecasting and analysis are challenging because of, (1) the limited quantity and quality of data (Brown, 2002), (2) the numerous variables and drivers that affect demand (March and Saurí, 2009), (3) the high uncertainties associated with climate change, economic conditions, population growth, and conservation activities (Gober et al., 2011), (4) the complexity of a quantitative analysis of water conservation options and their implementation costs (Billings and Jones, 2008), and (5) the different model horizons required for short-term and long-term purposes, both of which affect water security (Donkor et al., 2014).

This paper presents a novel end-use-based model as a decision-support tool for municipal water management that addresses many of the challenges above. Intended for tactical (1–10 years) and strategic (long-term) use (see Table 1 in Donkor et al., 2014), the model simulates short- (weekly) and long-term (>10 years) municipal water demand and use patterns under various climate change, population growth, and water conservation scenarios, and reveals management trade-offs such as the potential water savings and economic costs of alternative water management policies. It includes ten specific end-uses with seven residential end-uses (six indoor and one outdoor use), and three non-residential uses, and simulates per capita water demand based on the number of water fixture uses per day and their associated water requirements, which are affected by water conservation policies, as well as appliance and fixture characteristics. Called the Calgary Water Management Model, or CWMM, the model runs fast (a single simulation on a Windows desktop takes a fraction of a second), is easy to use, requires relatively few input data, and matches the historical municipal demands in Calgary, Alberta, while also permitting exploration of various plausible water scenarios into the future. A system dynamics model, CWMM can be adapted to other municipalities by changing model inputs stored in a MS Excel file, and refined from a whole-city scale to represent individual neighborhoods or city regions.

The paper is structured as follows. First, municipal water modeling methodologies and models are reviewed. Then the research area and data availability are presented in terms of water supply, demand, and management conditions. The model is next described and validated using data for Calgary, and sample results such as per capita water demand, management policy conservation effectiveness, and policy cost are presented. Finally, the paper closes with conclusions, a discussion of model limitations, and potential next steps for the research.

2. Municipal water management and modeling

A wide range of methods can be used for municipal water management and modeling, with the selection depending on modeler skill, available resources and data, and accuracy requirements. Methods such as time-series analysis, regression analysis, stochastic modeling, artificial intelligence (AI), and system dynamics (SD) are discussed in this section, as well as modeling concerns related to water customer disaggregation, modeling time step, economic considerations, and climate change. Note that many of these methods, such as time-series and regression models, or artificial neural networks and regression models, are often used in combination to produce "hybrid models" that typically improve water demand forecasting performance over the use of the individual methods (Donkor et al., 2014).

2.1. Available modeling methods

Water demand projections rely on estimated population growth and per capita water demands, and modeling methods differ primarily in their treatment of the latter. Time-series models predict per capita demand based on historical trends, using moving averages, exponential smoothing, or autoregressive integrated moving-average methods (Billings and Jones, 2008), and with fine-temporal scale data can "reveal significant temporal trends in water consumption correlated with economic variables … as well as weather and climate factors" (House-Peters and Chang, 2011: 4). Regression models have also been used extensively historically (Donkor et al., 2014) and employ social and economic factors, called explanatory variables, including water price, house and lot size, water-saving technologies, family income, education, and gender to estimate per capita or family water consumption through linear, log-linear, or exponential models (Billings and Jones, 2008). These drivers are analyzed in terms of temporal and spatial scales (House-Peters and Chang, 2011), direct and indirect impacts on water demand (Jorgensen et al., 2009), and economic and non-economic factors (March and Saurí, 2009). Both approaches require typically modest computing power (House-Peters and Chang, 2011) but do not generally account for population growth or water conservation efforts; therefore, they are usually applied to short-term demand prediction (typically less than a year) for small utilities. See Qi and Chang (2011), House-Peters and Chang (2011), and Donkor et al. (2014) for examples.

Stochastic models may take several forms. Stochastic Poisson rectangular pulse (PRP) models generate rectangular pulses that represent sub-daily scale residential water demands, and are typically applied to water quality modeling in drinking-water distribution systems; they simulate pulse arrival time, intensity (flow), and duration (Creaco et al., 2017). Although such models require (expensive) flow measurements at short time intervals to determine PRP model parameters (Blokker et al., 2010), their results have been shown to closely match observed household and aggregated (21-household) water demands at short time scales of 1 s to 1 h (Creaco et al., 2017). PRP-based models can also reproduce specific residential end-uses of water (Blokker et al., 2010) and offer the potential of projecting the results of changes both in appliance efficiencies and in human behavior over the longer term (Creaco et al., 2017). Stochastic models for long term projections can be generated, for example, from Monte Carlo simulations of daily temperature and precipitation values and combined with a deterministic water demand model (Yung et al., 2011), or simpler multiple linear regression models that generate monthly demands over several decades (Haque et al., 2014).

Artificial intelligence methods include artificial neural networks (ANN), fuzzy inference systems, agent-based modeling (Qi and Chang, 2011; House-Peters and Chang, 2011), Support Vector

Table 1
Sample changes in North American municipal water use from 1999 to 2016 (DeOreo et al., 2016).

Category	Toilet	Shower	Faucet	Dishwasher	Laundry
Fixture uses per capita per day in 1999 (number)	5.05	0.66	15	0.09	0.81
Fixture uses per capita per day in 2016 (number)	5.00	0.69	20	0.10	0.78
Average per capita daily use in 1999 (lpcd)	70	44	41	3.8	57
Average per capita daily use in 2016 (lpcd)	53.8	42	42	2.6	36