Environmental Modelling & Software 72 (2015) 198–214

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Benefits and challenges of using smart meters for advancing residential water demand modeling and management: A review

A. Cominola [a], M. Giuliani [a], D. Piga [b], A. Castelletti [a, c, *], A.E. Rizzoli [d]

[a] Department of Electronics, Information, and Bioengineering, Politecnico di Milano, Milan, Italy
[b] IMT Institute for Advanced Studies Lucca, Lucca, Italy
[c] Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
[d] Istituto Dalle Molle di Studi sull'Intelligenza Artificiale, SUPSI-USI, Lugano, Switzerland

ARTICLE INFO

Article history:
Received 2 April 2015
Received in revised form
21 July 2015
Accepted 21 July 2015
Available online xxx

Keywords:
Smart meter
Residential water management
Water demand modeling
Water conservation

ABSTRACT

Over the last two decades, water smart metering programs have been launched in a number of medium to large cities worldwide to nearly continuously monitor water consumption at the single household level. The availability of data at such very high spatial and temporal resolution advanced the ability in characterizing, modeling, and, ultimately, designing user-oriented residential water demand management strategies. Research to date has been focusing on one or more of these aspects but with limited integration between the specialized methodologies developed so far. This manuscript is the first comprehensive review of the literature in this quickly evolving water research domain. The paper contributes a general framework for the classification of residential water demand modeling studies, which allows revising consolidated approaches, describing emerging trends, and identifying potential future developments. In particular, the future challenges posed by growing population demands, constrained sources of water supply and climate change impacts are expected to require more and more integrated procedures for effectively supporting residential water demand modeling and management in several countries across the world.

1. Introduction

World's urban population is expected to raise from current 54%–66% in 2050 and to further increase as a consequence of the unlikely stabilization of human population by the end of the century (Gerland et al., 2014). By 2030 the number of mega-cities, namely cities with more than 10 million inhabitants, will grow over 40 (UNDESA, 2010). This will boost residential water demand (Cosgrove and Cosgrove, 2012), which nowadays covers a large portion of the public drinking water supply worldwide (e.g., 60–80% in Europe (Collins et al., 2009), 58% in the United States (Kenny et al., 2009)).

The concentration of the water demands of thousands or millions of people into small areas will considerably raise the stress on finite supplies of available freshwater (McDonald et al., 2011a). Besides, climate and land use change will further increase the number of people facing water shortage (McDonald et al., 2011b). In such context, water supply expansion through the construction of new infrastructures might be an option to escape water stress in some situations. Yet, geographical or financial limitations largely restrict such options in most countries (McDonald et al., 2014). Here, acting on the water demand management side through the promotion of cost-effective water-saving technologies, revised economic policies, appropriate national and local regulations, and education represents an alternative strategy for securing reliable water supply and reduce water utilities' costs (Gleick et al., 2003).

In recent years, a variety of water demand management strategies (WDMS) has been applied (for a review, see Inman and Jeffrey, 2006, and references therein). However, the effectiveness of these WDMS is often context-specific and strongly depends on our understanding of the drivers inducing people to consume or save water (Jorgensen et al., 2009). Models that quantitatively describe how water demand is influenced and varies in relation to exogenous uncontrolled drivers (e.g., seasonality, climatic conditions) and demand management actions (e.g., water restrictions, pricing schemes, education campaigns) are essential to explore water users' response to alternative WDMS, ultimately supporting

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[*] Corresponding author. Department of Electronics, Information, and Bioengineering, Politecnico di Milano, Milan, Italy.
E-mail address: andrea.castelletti@polimi.it (A. Castelletti).

http://dx.doi.org/10.1016/j.envsoft.2015.07.012
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strategic planning and policy design.

Traditionally, water demand models focus on different temporal and spatial scales. At the lowest resolution, studies have been carried out, mostly in the 1990s, to model water demand at the urban or block group scale, using low time resolution (i.e., above daily) consumption data retrieved through billing databases or experimental measurement campaigns on a quarterly or monthly basis. The main goal of these works is to inform regional water systems planning and management on the basis of estimated relationships between water consumption patterns and socio-economic or climatic drivers (e.g., House-Peters and Chang, 2011).

The advent of smart meters (Mayer and DeOreo, 1999) in the late 1990s made available new water consumption data at very high spatial (household) and temporal (from several minutes up to few seconds) resolution, enabling the application of data analytics tools to develop accurate characterizations of end-use water consumption profiles. Similarly to the recent developments in integrated smart solutions (Hilty et al., 2014; Laniak et al., 2013), the use of smart meters provides essential information to construct models of the individual consumers behaviors, which can be employed for designing and evaluating consumer-tailored WDMS that can more effectively modify the users' attitude favoring water saving behaviors. In particular, smart meters themselves constitute technologies that promote behavioral changes and water saving attitudes via tailored feedbacks (Fielding et al., 2013).

A general procedure to study residential water demand management relying on the high-resolution data nowadays available can be structured in the following four phases (see Fig. 1): (*i*) data gathering, (*ii*) water end-uses characterization, (*iii*) user modeling, (*iv*) design and implementation of personalized WDMS. In the literature, a number of tools and techniques have been proposed for each of these steps, with many works focused either on the data gathering process (e.g., Cordell et al., 2003; Boyle et al., 2013) or on the analysis of WDMS (e.g., Inman and Jeffrey, 2006). Yet, to the authors' knowledge, a systematic and comprehensive review of residential water demand modeling and management is still missing. This review contributes the first effort of classification and critical analysis of 134 studies that in the last 25 years (Fig. 2) contributed new methodologies and tools in one or more of the steps of the above procedure (see Table 1).

The review is structured according to the procedure shown in Fig. 1: the current status, research challenges, and future directions associated to each phase are discussed in Sections 2–5, while the last section reports final remarks and directions for follow up research.

2. Data gathering

Residential water consumption data gathering (box 1 in Fig. 1) represents the first step needed to built the baseline upon which the water demand is estimated and management strategies are designed. Depending on the sampling frequency, we distinguish two main classes, namely *low-resolution* and *high-resolution* data, which delimit the type of the analysis that can be performed.

2.1. Low resolution data

Periodically billed data are characterized by a low level of resolution and recording frequency. Although water consumption is detected with the precision of kilolitres, readings are generally recorded with the frequency of the quarter of year at most (Britton et al., 2008). This low resolution restricts the use of these data to regional planning, where statistical analysis estimating the amount of domestic water consumption can be used to forecast the aggregated water demand at the municipal or district level. In particular, such data have been widely used to study the effect of economic variables and seasonality on the water use at the regional scale since the seminal works by Howe and Linaweaver (1967); Young (1973); Berk et al. (1980); Howe (1982); Maidment and Parzen (1984); Thomas and Syme (1988) (for a review see House-Peters and Chang, 2011, and references therein). Those approaches relied on simple econometric models and time series models based on multivariate regression, and required limited datasets and low computational resources. Their main drawback is related to their limited capability of representing the spatial and temporal heterogeneity of residential water demand, which can be understood and modeled using higher resolution data. While data

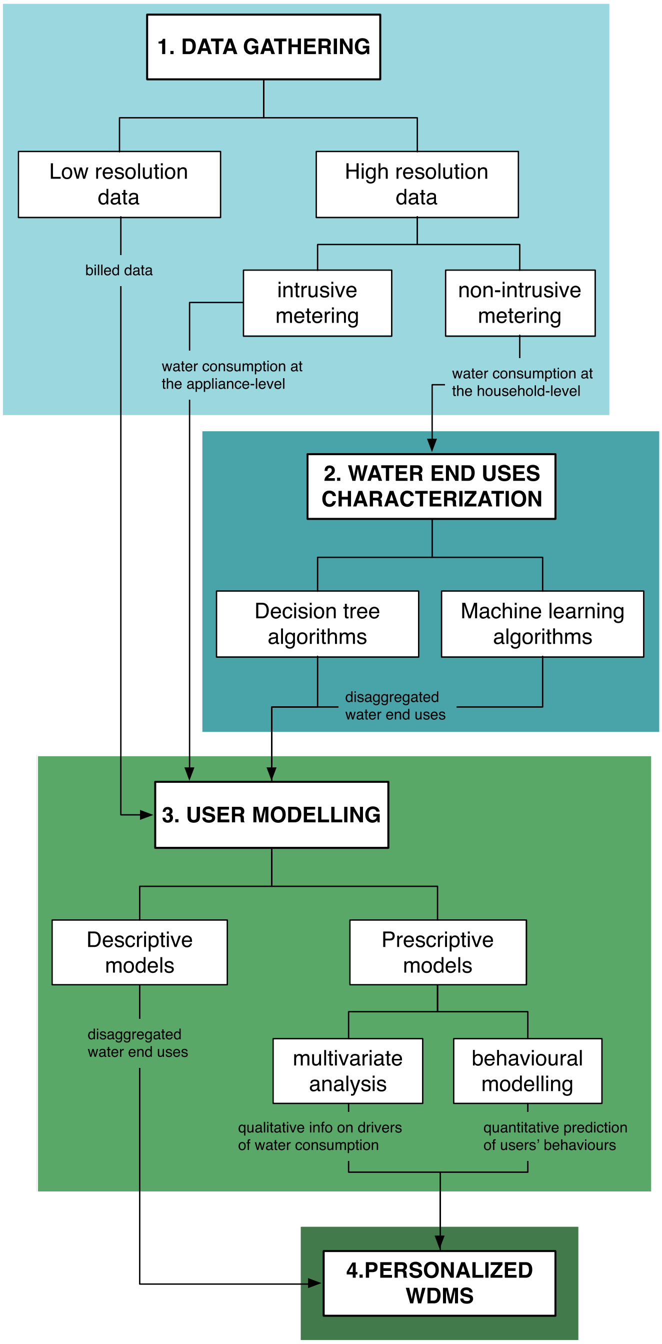

Fig. 1. Flowchart of the general procedure for studying residential water demand management.