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Novel bottom-up urban water demand forecasting model: Revealing the determinants, drivers and predictors of residential indoor end-use consumption

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ABSTRACT

The purpose of this comprehensive study was to explore the principal determinants of six residential indoor water end-use consumption categories at the household scale (i.e. namely clothes washer, shower, toilet, tap, dishwasher, and bath), and to find an overarching research design and approach for building a residential indoor water end-use demand forecasting model. A mixed method research design was followed to collect both quantitative and qualitative data from 210 households with a total of 557 occupants located in SEQ, Australia, utilising high resolution smart water metering technology, questionnaire surveys, diaries, and household water stock inventory audits. The principal determinants, main drivers, and predictors of residential indoor water consumption for each end-use category were revealed, and forecasting models were developed this study. This was achieved utilising an array of statistical techniques for each of the six end-use consumption categories. Cluster analysis and dummy coding were used to prepare the data for analysis and modelling. Subsequently, independent *t*-test and independent one-way ANOVA extended into a series of bootstrapped regression models were used to explore the principal determinants of consumption. Successively, a series of Pearson's Chi-Square tests was used to reveal the main drivers of higher water consumption and to determine alternative sets of consumption predictors. Lastly, independent factorial ANOVA extended into a series of bootstrapped multiple regression models was used for the development of alternative forecasting models. Key findings showed that the usage physical characteristics and the demographic and household makeup characteristics are the most significant determinants of all six end-use consumption categories. Further, the appliances/fixtures physical characteristics are significant determinants of all end-use consumption categories except the bath end-use category. Moreover, the socio-demographic characteristics are significant determinants of all end-use consumption categories except the tap and toilet end-use categories. Results also demonstrated that the main drivers of higher end-use water consumption were households with higher frequency and/or longer end-use events which are most likely to be those larger family households with teenagers and children, with higher income, predominantly working occupants, and/or higher educational level. Moreover, a total of 14 forecasting model alternatives for all six end-use consumption categories, as well as three total indoor bottom-up forecasting model alternatives were developed in this study. All of the developed forecasting model alternatives demonstrated strong statistical power, significance of fit, met the generalisation statistical criteria, and were cross-validated utilising an independent validation data set. The paper concludes with a discussion on the most significant determinants, drivers and predictors of water end-use consumption, and outlines the key implications of the research to enhanced urban water planning and policy design.

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1. Introduction

1.1. Urban water security and demand management

Availability of water is becoming more variable due to the rising severity of climate change conditions. Consequences of such changing conditions are the unpredictable changing rainfall patterns and the increasing frequency and severity of droughts. This coupled with growing populations and expanding economic development, results in escalating urban water demands, making water a scarce resource in many regional and urban centres (Gleick, 2011; Jorgensen et al., 2009; Willis et al., 2010a, 2011b). Therefore, scarcity of water and the ability to meet future water demands is one of the greatest concerns for many governments and public utilities, considering the costs associated with sourcing new water supplies. This issue necessitates water being very carefully managed on both the supply and demand sides across the residential, commercial and industrial sectors. This is a common concern in South East Queensland (SEQ) where this study took place, most of the dry Australian continent and also to many other water scarce or variable regions internationally (Bates et al., 2008; Beal and Stewart, 2011; Commonwealth of Australia, 2013b,c; Inman and Jeffrey, 2006; Jiang, 2009; Turner et al., 2010).

Residential water consumption represents a significant component of overall water consumption (Sadalla et al., 2012), forcing water authorities to invest significantly in the development and implementation of a range of integrated urban water management (IUWM) strategies and programmes in an attempt to ensure urban water security (Beal and Stewart, 2011; Correljé et al., 2007; Stewart et al., 2010). Such strategies include the initiation of water-saving measures, imposing water restrictions, rebate programmes for water-efficient fixtures, dual-supply schemes (Beal and Stewart, 2011; Mitchell, 2006; Price et al., 2014; Willis et al., 2011b), visual display shower monitors (Stewart et al., 2011; Willis et al., 2010b), the installation of rainwater tanks (Beal et al., 2011a, 2012c; Coultas et al., 2012), source substitution for toilet flushing and laundry (Anand and Apul, 2011; Chen et al., 2013; Mourad et al., 2011; Stewart et al., 2010), promoting water efficiency labelling schemes, pricing, and conservation awareness programmes (Arbués et al., 2010; Inman and Jeffrey, 2006; Mayer et al., 2004; Nieswiadomy, 1992). These strategies and programmes aim at improving urban water security through wiser, more conservative and sustainable water consumption to enable future water demands to be met (Beal and Stewart, 2011).

In SEQ, the implementation of such IUWM strategies and programmes has resulted in large water consumption reductions and in greater social awareness of the value of water as a precious resource. However, water-regulating authorities usually follow a reactionary-based approach in the design and implementation of water-regulating strategies, such as setting a target consumption value to reduce water consumption during insecure water periods (Beal and Stewart, 2011). The effectiveness of such approaches depends on differences in location, community attitudes and behaviours (Corral-Verdugo et al., 2003; Turner et al., 2005). In addition, due to the lack of data at the end-use level, water savings associated with their implementation are often estimated on the basis of limited evidence and with many assumptions, leading to understated or grossly inaccurate values (Beal and Stewart, 2011; Stewart et al., 2010). This highlights the need for more detailed information about residential water consumption at the end-use level (Stewart et al., 2010).

Disaggregation of residential water use improves understanding about how water consumption is proportioned in households, and identifies determinants of water consumption to allow an analysis of links between them based on subsets of consumers and end-use consumption (Beal and Stewart, 2011). Further, improved understanding about spatial and temporal residential water consumption variability at the end-use level enables the development and implementation of more effective IUWM strategies, programmes and forecasting models (Beal and Stewart, 2011, 2013). This can provide useful insights enabling water authorities to pursue more proactive approaches to better manage urban water demand and resources.

1.2. Water smart metering

More detailed information about how and where residential water is consumed (e.g. shower, washing machine, dishwasher, tap, bathtub), is an essential requirement for the development of more effective IUWM strategies and programmes, and for a better evaluation of water savings associated with their implementation (Beal and Stewart, 2011; Cole and Stewart, 2012; Willis, 2011; Willis et al., 2011b, 2013). Moreover, such detailed knowledge about water consumption can improve understanding of the key determinants of each end use to form the basis of water consumption predictions and the development of improved demand forecasting models (Blokker et al., 2010; Stewart et al., 2010). The development of such forecasting models at an end-use scale is vital, but essential micro-component level models created from detailed empirical water end-use events data registries (i.e. micro-level bottom-up models) (Kenney et al., 2008; Willis et al., 2009c) are currently lacking. Improved forecasting of total urban residential connection demands will be possible using the models presented in this study.

The emergence of advanced technologies such as water smart-metering enables the creation of the required detailed data registries through real-time or near-real time-monitoring, high-resolution interval metering, automated water meter reading (e.g. drive by GPRS) and access to data from the Internet (Beal and Stewart, 2011). Smart water metering technology comprises high-resolution data capturing, logging and wireless communication technologies, which facilitate the collection, storage, wireless transfer and subsequent analysis of abundant and detailed data (i.e. water consumption flow quantities and time of disaggregated end-use events) using computer software (Beal and Stewart, 2011; Cole and Stewart, 2012; Willis et al., 2009e; Nguyen et al., 2014, 2013a,b). Such detailed and accurate water end-use data, when combined with socio-demographic, water stock inventory, and residential attitude and behavioural factors, will facilitate the creation of models capable of identifying determinants of residential water end-use consumption. Knowledge of these determinants and consumption of each end use will explain aggregate residential consumption and form the foundation for more robust demand forecasting models.

1.3. Water end-use studies

Due to the emerging necessity for residential water consumption disaggregation, a number of end-use studies and forecasting models have been developed, aiming at quantifying and predicting water demand for each end-use category (e.g. shower or washing machine). Such studies and models have been mostly developed using mixed method approaches with some degree of technology for water volume data capturing and social surveys and/or sourced statistical information from available documents (e.g. historical billing data, existing statistical reports or technical information from stock appliance manufacturers) to estimate water end-use consumption using mathematical modelling methods (Beal and Stewart, 2011). Despite the undeniable usefulness of such studies and models in water demand management and prediction, their ability to disaggregate consumption into water end-use categories is limited in accuracy, thereby limiting prediction accuracy. Therefore, utilising a combination of long-term actual measurement