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An intelligent pattern recognition model to automate the categorisation of residential water end-use events

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ABSTRACT

The rapid dissemination of residential water end-use (e.g. shower, clothes washer, etc.) consumption data to the customer via a web-enabled portal interface is becoming feasible through the advent of high resolution smart metering technologies. However, in order to achieve this paradigm shift in residential customer water use feedback, an automated approach for disaggregating complex water flow trace signatures into a registry of end-use event categories needs to be developed. This outcome is achieved by applying a hybrid combination of gradient vector filtering, Hidden Markov Model (HMM) and Dynamic Time Warping Algorithm (DTW) techniques on an existing residential water end-use database of 252 households located in South-east Queensland, Australia having high resolution water meters (0.0139 L/pulse), remote data transfer loggers (5 s logging) and completed household water appliance audits. The approach enables both single independent events (e.g. shower event) and combined events (i.e. several overlapping single events) to be disaggregated from flow data into a comprehensive end-use event registry. Complex blind source separation of concurrently occurring water end use events (e.g. shower and toilet flush occurring in same time period) is the primary focus of this present study. Validation of the developed model is achieved through an examination of 50 independent combined events.

1. Introduction

1.1. Advanced role of sensor technology and 'big data' analytics in water resources management

Sensor technology and the 'big data' they generate combined with advanced machine learning techniques provide numerous opportunities for enhancing outdated approaches covering all the various segments of water resources management (Schimak et al., 2010; Usländer et al., 2010). Reported studies demonstrate that such technologies and techniques are increasingly influencing how we better monitor and manage large-scale water basins (e.g. White et al., 2006; Quinn et al., 2010; Murlà et al., 2010), river stream flow (Lindim et al., 2010; David et al., 2013), drinking water reservoir quality (Glasgow et al., 2004), water treatment plant operations (Storey et al., 2011), water distribution system networks (Dorini et al., 2006), consumer water end use consumption (Nguyen et al., 2013a; Willis et al., 2011c), and wastewater plant operations (Dürrenmatt and Gujer, 2012). The research focus of this paper is on the application of sensors (i.e. high resolution smart meters) and 'big data' analytical techniques at the urban water scale; specifically the residential water consumer and their end use water consumption. This frontier area of water end use or micro-component analysis research is beginning to attract research attention. Froehlich et al. (2011) conducted a study using pressure sensing devices to infer water usage events in households in Washington State, USA. CSIRO (2012) have recently combined an acoustic sensor with smart water metering systems in order to disaggregate residential water consumption into end use categories. The authors (Nguyen et al., 2013a) utilised machine learning techniques such as HMM and DTW to disaggregate remotely collected high resolution water flow data received from smart meters into single end use event categories, which is the precursor to this present paper seeking to disaggregate concurrently occurring end use events. With these technologies becoming commercially viable, the vision of an intelligent expert system, which can perform autonomous water end use analysis and provide feedback and decision support to both water consumers and authorities, is rapidly becoming a reality.

1.2. Vision of an advanced urban water management system

The era when urban water planning focused only on how to build and supply water has been replaced by a new paradigm,

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where the precise accounting and management of urban water consumption is deemed essential to maintenance of a sustainable water future. Lower water yield reliability, from traditional water supply sources, and the increasing demand for water in urban areas, requires the development of a more adaptive and innovative water resource management approach, fed by robust real-time information. As a consequence, an increasing number of smart water metering technologies have been introduced to the market. Such metering devices embrace two distinct elements: meters that use new technology to capture water use information; and communication systems that can capture and transmit real-time water use information (Stewart et al., 2010). While current forms of smart metering technology can provide total consumption data to the customer and utility at high levels of resolution, they fail to disaggregate this data into its end-use use categories. This study envisions and provides the architecture for an advanced smart metering system that enables customers and utilities to actively monitor, through web-portal interfaces, real-time information about what, when, where and how water was consumed at their meter connection (e.g. 56 litre shower occurring between 06:55–07:15 Tuesday 25 May 2012). The proposed system allows individual consumers to log into their user-defined water consumption web page to view their daily, weekly, and monthly consumption tables, as well as charts on their water end-use patterns across major end use categories (e.g. leaks, clothes washer, dishwasher, tap, toilet, shower and irrigation). It can also rapidly alert them of occurring leak events so that they can immediately address them instead of the current slow feedback process from current metering technology (e.g. monthly or quarterly alert at best).

The analytical report generated by the new advanced integrated water management system will help utilities identify the water consumption patterns of their various consumer types and assist with a range of urban water planning and management functions (Stewart et al., 2010). However, such a system requires a robust analytical model to automatically and accurately disaggregate the flow trace data into individual water end-use event categories. Current end-use disaggregation processes used by the authors and their aligned research teams requires extensive manual data collection and analysis as summarised in Fig. 1 (Beal et al., 2011a). Automation of this resource intensive process is essential to developing the proposed advanced water management system that has commercial viability. The design and verification of an automated flow pattern recognition model that has good accuracy is the ultimate aim of this study.

1.3. *Review of reported water end use studies and analysis approaches applied*

In recent years, a number of residential water end use studies have been completed using a range of single or mixed methods, such as household auditing, diaries, high resolution smart metering and pressure sensors, with a diverse range of per capita end use summaries. Jacobs (2007) and Blokker et al. (2010) provided summaries on a good proportion of the end use models developed from stochastic techniques, contingent valuation approaches (CVA), modelling, and metered methods. The introduction of advanced technology has enabled the direct capture and classification of water end use events. Table 1 provides a summary of reported end use studies that have applied high resolution smart meters, data loggers or pressure sensors completed internationally in the last 15 years.

As displayed in Table 1, from a direct measurement and water end use recognition approach which is undoubtedly the future of this type of problem, the two main approaches presently reported include using smart water meters in conjunction with a decision-tree based analysis tool such as Trace Wizard or Identiflow or as more recently published, the inclusion of pressure sensors at individual appliances (i.e. HydroSense) along with a HMM based decision tool. Each approach has its own strengths and weaknesses, which were discussed in detail in (Nguyen et al., 2013a).

In summary, the ideal approach that is most amenable to city-wide application is installing smart water meters at the property boundary in conjunction with intelligent end use pattern recognition algorithms either in-built into the meter software or within a processing module at the utilities data centre. This is the lowest cost and non-intrusive approach to water end use disaggregation. However, for such widespread implementation, the following summarised limitations of the existing models (i.e. Trace Wizard and Identiflow) have to be overcome:

- inability to analyse collected data without human interaction and manual reclassification (i.e. main disadvantage);
- inability to accurately distinguish different end use categories which have similar water flow characteristics (e.g. shower, bathtub and irrigation);
- inability to classify an end use category that has various physical parameters depending on appliance models (e.g. dishwasher, clothes washer and toilet); and
- inability to deal with multi-layer combined events (i.e. cannot handle three or more concurrent events).

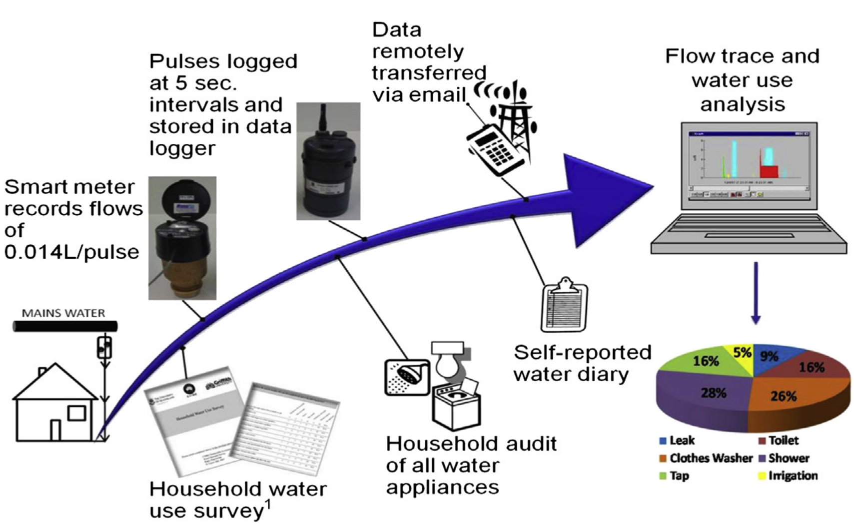

Fig. 1. Schematic illustrating the water end-use analysis process (Beal et al., 2011a).