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A new multiple regression model for predictions of urban water use

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ABSTRACT

Shortages of freshwater have become a serious issue in many regions around the world, partly due to rapid urbanisation and climate change. Sustainable city development should consider minimising water use by people living in cities and urban areas. The purpose of this paper is to improve our understanding of water-use behaviour and to reliably predict water use. We collected appropriate data of daily water use, meteorological parameters, and socioeconomic factors for the City of Brossard in Quebec, Canada, and analysed these data using multiple regression techniques. The techniques represent a new approach to predictions of daily water use; its base use component is predicted using a function of socioeconomic factors, as opposed to a function of time as in existing approaches. The quality of the new approach is quantitatively demonstrated. Time series of predicted daily water-use captures observed characteristics very well, and improves the results of the weighted coefficient of determination, the relative index of agreement and the root mean square error from the existing approaches. Water use in the city exhibits a downward trend possibly due to an increasing annual charge for water use. Water use increases due to weekend effect. It decreases in the occurrence of rainfall; the decrease is more sensitive to previous-day than current-day rainfall. The analysis procedures reported in this paper can be applied to analyse water use in any other cities. The new approach would be a useful tool for decision makers to manage water use by adjusting water consumption policies and price.

1. Introduction

Sustainable city development should consider minimising freshwater consumption by people living in cities and urban areas for two simple reasons: 1) the proportion of people living in urban areas has been increasing rapidly (United Nations, 2014); 2) sources of safe freshwater for urban consumption are actually quite limited. It will become increasingly difficult to meet the new higher levels of water demand. What factors actually influence water consumption in the urban environment? Can one obtain reliable predictions of water demand for urban consumption? These questions are of importance and relevance to sustainable urban planning and development. The purpose of this paper is to quantify the dependence of water use on pertinent influence factors and to further develop a prediction model of water demand.

Many urban activities depend on an adequate supply of freshwater. However, finite freshwater resources do not equally distribute globally. Traditionally, freshwater shortages have been deemed as an issue for urban centres located in drier regions. Now, they have become a global concern, even for water-abundant countries. For example, Canada has one fifth of the world's freshwater. However, a large amount of it is trapped inside distant glaciers and ice caps, or is found in remote water bodies that are not easily accessible to populated urban regions, making it very costly and difficult to exploit, as reported in Brandes and Ferguson (2003). The authors also suggested that the perception of freshwater abundance in the society had resulted in an increase in the rate of water consumption. In order to avoid/alleviate problems related to water shortages, it is necessary to establish and implement scientifically sound measures, which requires a good understanding of water use behaviour.

Researchers have made efforts to identify influence factors of urban water use and evaluate their relative importance. Adamowski, Chan, Prasher, Ozga-Zielinski, and Sliusarieva (2012) included daily maximum temperature, precipitation, and water demand for the current and previous days as influence factors. Stoker and Rothfeder (2014) formulated urban water use as a function of climate, built environment, and demographic variables; they investigated whether or not their relative importance would change for different types of land use. In addition to temperature and precipitation, Romano, Salvati, and Guerrini (2014) included water tariff, income, altitude, and population as influence factors. They concluded that an increase in water tariff reduced

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Notation

The following symbols are used in this paper

B	Average household annual payment for water consumption (CAD/household)
D_r	Relative index of agreement
E_{rms}	Root mean square error (litre per person per day)
I	Average household income (CAD/household)
J	Rainfall occurrence dummy variable
K	Number of harmonics
P	Precipitation amount (mm)
P_c	Rainfall threshold (mm)
P_o	Population
R	Daily water use residual (litre per person per day)
R^2	Coefficient of determination
R_w^2	Weighted coefficient of determination
S	Weekday/weekend dummy variable
T	Daily maximum air temperature (^oC)
T_c	Threshold of air temperature (^oC)
T_n	Normal daily maximum air temperature (^oC)
W_b	Daily base water use (litre per person per day)
W_c	Daily calendrical water use (litre per person per day)
W_{max}	Highest volume of daily water use (litre per person per day)
W_{min}	Lowest volume of daily water use (litre per person per day)
W_s	Daily seasonal water use (litre per person per day)
W_T	Total daily water use (litre per person per day)
$\hat{W}_b$	Estimated base water use (litre per person per day)
$\hat{W}_{ce}$	Estimated water used due to climatic effects (litre per person per day)
$\hat{W}_{pc}$	Estimated persistence component of water use (litre per person per day)
$\hat{W}_{sc}$	Estimated water use with seasonal cycle (litre per person per day)
$\hat{W}_w$	Estimate water use due to weekday/weekend effect (litre per person per day)
a_j, b_j	Fourier coefficients
d	Daily time index
m	Month number
n	Order of polynomial function
p	Order of autoregressive procedure
y	Year number
α_0, α_1, α_2	Regression coefficients (litre per person per day)
γ_0, γ_1, γ_2	Regression coefficients (litre per person per day)
δ_0	Regression coefficient (litre per person per day)
δ_1	Regression coefficient (litre per person per day normalised by income)
δ_2	Regression coefficient (litre per person per day normalised by water-consumption charge)
δ_3	Regression coefficient (litre per person per day normalised by population)
ς_0	Regression coefficient (litre per person per day)
ς_1	Regression coefficient (litre per person per day per degree celsius)
ς_2, ς_3, ς_4	Regression coefficients (litre per person per day per millimetres)
ς_5	Regression coefficient (litre per person per day)
η_0, η_1	Regression coefficients (litre per person per day)
φ	Autoregression coefficient

water consumption. Panagopoulos (2014) analysed the influences of demographic, socio-economic, and climatic variables on urban water use.

The focus of the previous studies was on correlating urban water use to selected influence factors. No attempt has been made to decompose urban water use into suitable components, which would be less complicated to analyse, and no consideration has been given to temporal changes in urban water use. These are two limitations of the previous studies. Also, due to a large set of influence variables involved, correlation analyses need input data over a long period of time (Siauw & Bayen, 2015, Chapter 13). Such input data is often unavailable. Maidment and Parzen (1984b) suggested to perform time series analyses to obtain temporal patterns of urban water use.

Daily water use may be considered as the sum of stochastic, periodic and trend components (Araghinejad, 2014, Chapter 4; Hyndman, 2014). The question is how to realistically decompose a time series of water use into the components mentioned above. A realistic decomposition provides key information needed for the development of models for predicting water demand.

Recently, the trend component of urban water use has been recognised as a significant component (Araghinejad, 2014), which has received a great deal of research attention. Previously, researchers considered the trend component of water use as the base water use. The so-called base water use is a component of water use that changes gradually over a long period of time, as a result of changes in socioeconomic factors such as population and water price. The base water use is believed to be insensitive to climate. This is in contrast to the seasonal water use, which is a component of water use that depends on climatic change (Gato, Jayasuriya, & Roberts, 2007; Maidment & Parzen, 1984a; Zhou, McMahon, Walton, & Lewis, 2000).

A number of researchers (House-Peters, Pratt, & Chang, 2010; Maidment, Miaou, & Crawford, 1985; Syme, Shao, Po, & Campbell, 2004; Zhou et al., 2000) considered the average or lowest water use in the winter season (equal to indoor water use) as the base water use, and obtained seasonal water use by subtracting the base water use from the total water use. Other researchers argued that the indoor water use in the winter season depended on weather and seasonality. For example, in an investigation of seasonality influence on indoor and outdoor water uses in Melbourne, Australia, Rathnayaka, Malano, Maheepala, George, Nawarathna, Arora, and Roberts (2015) showed that there were significant differences in shower (the main indoor use of water) and irrigation (the main outdoor use of water) between winter and summer. Specifically, shower water use could increase with extreme weather conditions; cooler weather increased shower duration, whereas hot weather increased shower frequency. Also, there are cases where water use in winter months includes outdoor use such as garden watering (Gato, Jayasuriya, & Hadgraft, 2003). Thus, the amount for indoor water use in the winter season does not give a best estimate of the base water use.

Gato et al. (2007) assessed the performance of two different methods for calculating the base water use. The first method selects the month with the lowest monthly-averaged use of water for each year and expresses the base water use as a polynomial function of time, using the lowest monthly-averaged use as input. This is a traditional method of calculating the base water use. The method was used in Maidment et al. (1985), Salas-La Cruz and Yevjevich (1972), and Zhou et al. (2000). The second method determines temperature and rainfall thresholds, at which water use is no longer sensitive to actual temperatures and rainfalls. The first method will not produce base water use that is insensitive to temperature and rainfall, but the second method will.

In a modelling study of urban water demand, Wong, Zhang, and Chen (2010) introduced calendrical use as a component of total water use in Hong Kong; the other components were the seasonal use and the base use. Again, Wong et al. (2010) equated the base water use with the lowest monthly use of water in the winter, and