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Development and application of weather-normalized monthly building water use model

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ABSTRACT

This study proposes a new monthly whole-building water use regression model for weather-normalized water performance evaluation: a combination three-parameter multi-variable regression (3-P MVR) cooling model using outdoor temperature in a change-point model and precipitation amount/occurrence as an additional independent variable. To select appropriate weather variables influencing a building's water use, previous studies on the water use models at the municipal level were reviewed. The selected weather variables were then tested using the multi-year monthly water use data collected from the two separate water meters (i.e., the main building meter for indoor water use; and sprinkler meter for landscape water use) of the case-study office building in central TX. The proposed water use model is based on twelve monthly, building-level water use data, which should be available for most buildings that are supplied water from a municipal provider. This model allows a year-to-year, weather-normalized comparison for self-referencing as well as savings calculations from various water conservation measures. This new method will reduce uncertainty about reported water savings from water conservation measures applied and improve the credibility of water conservation programs.

1. Introduction

Water is an energy-intensive resource because of its treatment and distribution. The energy intensity of water use reported by Carlson and Walburger [1] varied from 250 kWh/MG (million gallons) to 3500 kWh/MG for water supply (i.e., production, treatment and distribution) and from 1000 kWh/MG to 3000 kWh/MG for wastewater treatment. Water management is now becoming recognized as an integral part of energy management. All water conservation strategies involve reducing the volume of water for a given task to be performed, which results in water savings and energy savings for the pumping, distribution, heating, and treatment to provide supply water as well as treat wastewater from buildings [2].

Few studies have been conducted to quantify the water use in buildings. Although studies have investigated the savings from water-efficient products such as plumbing fixtures, the savings were examined at a product-level not a whole-building level. At the whole-building level, most water savings were simply estimated rather than measured [3]. The International Performance Measurement and Verification Protocol (IPMVP) [4] provided Measurement and Verification (M&V) procedures for building water use, including the metering instrumentation as a part of an energy management program. However, due to the difficulty of estimating the user behavior of water-consuming equipment, Retrofit Isolation methods with an assumed usage profile are suggested to be used for an estimation of the water savings.

However, there are numerous publications about water conservation in commercial applications. These publications often include recommendations about water auditing or sub-metering as one of the strategies [5–8]. The publications by California Department of Water Resources [5] and Schultz Communications [6] provided the water auditing procedures as a part of water conservation strategy. Both publications suggested more than one-year of utility water meter readings and measurements of the amount of water used by major water-consuming equipment using a temporary ultrasonic flow meter or permanent water sub-meters. The EBMUD [8] suggested a sub-metering of individual unit (tenants), major water-consuming systems or landscaping as a water conservation strategy and examined the benefits of sub-metering. However, in all three publications, there were no discussions about how to analyze the data once it has been collected.

Recently, as the need for water conservation has increased, there are few discussions about data analysis methods of building water use in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) publications [9,10]. The ASHRAE/Chartered Institute of Building Services Engineers (CIBSE)/United States Green Building Council (USGBC) Performance

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Measurement Protocols (PMP) for Commercial Buildings [9] identifies the performance metrics and measurement and evaluation methods at three levels of cost/accuracy for several building performance areas, including water use.[1] However, there are no detailed analysis techniques or modeling methods to analyze and evaluate a building's water performance beyond a log of the calculated water use indices.[2] For example, since the ASHRAE PMP water protocols do not require normalizing water use data for weather, it is hard to confirm whether any increase or decrease in building water use was affected by changing weather conditions or other operation and maintenance (O&M) issues.

The revised ASHRAE Guideline 14-2012 working draft, Measurement of Energy and Demand Savings [10] developed a section that discusses regression analysis methods of calculating water savings from water conservation measures. However, unfortunately, it does not provide any advice on suitable independent variables to be used for a baseline model of the whole-building water use.

Therefore, this paper proposes a new monthly whole-building water use model: a combination three-parameter multi-variable regression (3-P MVR) cooling model using outdoor temperature in a change-point model and precipitation amount/occurrence as an additional independent variable. The new model was developed based on a review of previous studies on the water use models at the municipal level. The advantages of using the developed 3-P MVR model to analyze and evaluate a building's water performance are discussed compared to a log of the calculated WUIs, which are the water performance metrics required at the ASHRAE PMP Intermediate Level water protocols.

2. Previous studies on the water use model at the municipal level

At the municipal or community (i.e., residential) level, numerous studies have been conducted to develop reliable water use models either to forecast demand for supply-side water management purpose or to examine community-wide water savings achieved from water conservation programs. The water use models that were proposed typically consist of base and seasonal water use parameters, including: various demographic (i.e., population), economic (i.e., water price, income, or house value), and policy (water conservation or restriction) variables as well as weather variables (i.e., outdoor temperature, precipitation, or evapotranspiration). The statistical approaches adopted, included multiple regression or time-series analysis. The weather variables were typically regarded as the major factor influencing seasonal water use, while other factors contributed to the base level adjustment.

Weather variables such as outdoor air temperature as well as precipitation have been identified the influential variables that affect seasonal water use [11–21]. Some studies introduced an alternate indicator such as net evapotranspiration (i.e., potential evapotranspiration (ETp) minus actual precipitation, in cm/day), which can be indirectly estimated from outdoor air temperature, humidity, or solar radiation [11,22–25]. However, despite a vast amount of published work, only a few studies focused on the weather variables due to their relatively lower impact on the water use compared to the other socioeconomic variables. Thus, this study reviewed five selected studies in 1970s to 1980s that closely examined the relationship between seasonal water use and climatic variables [11–14,23], which may be applicable to the building-level data consisting of twelve monthly observations with a fairly constant level of other socioeconomic variables.

Morgan and Smolen [11] compared three different seasonal water use models based on different climatic variables, including outdoor temperature and total precipitation; net evapotranspiration (i.e., ETp–Precipitation) computed by the Thornthwaite method [26][3]; and monthly binary dummy variable. The comparison was made using data from twelve monthly municipal water deliveries for each of 33 cities in Southern California. They found that a seasonal water use model based on temperature and precipitation performed marginally better than the model using net evapotranspiration. Thus, they concluded that the use of temperature and precipitation appeared to be an appropriate method for calculating weather-normalized water demand.

To estimate weather-normalized savings from lawn watering restrictions in Fort Collins, CO, Anderson et al. [23] used multiple regression models that predicted water use at the municipal level from net evapotranspiration (i.e., ETp – Precipitation) computed by the Jensen-Haise equation [27].[4] For precipitation, they set upper and lower thresholds between 0.25 cm (0.1 in.) and 1.52 cm (0.6 in.), which were termed effective rainfall that would actually impact the water usage. In addition, they found the inclusion of a one-day lagged precipitation would improve the model. By comparing the predicted consumption against actual water use, they concluded that about one half of the total reduction in water use could be attributed to the imposed restrictions.

Hansen and Narayanan [12] proposed a multivariate monthly municipal water demand model that calculated seasonal water use from four climatic indicators: monthly average temperature, total precipitation, percentage of daylight hours, and a non-growing season dummy variable. The model was determined empirically using a multi-year monthly data set (1961–1974) for Salt Lake City, UT, that yielded a high coefficient of determination (R^2) value. The calculated model was validated using the data from 1975 to 1977. The authors concluded that the proposed model adequately predicted seasonal water use. They also tested the inclusion of a one-month lagged monthly temperature and precipitation in the model. However, these two variables appeared to be statistically insignificant at the monthly level.

Maidment et al. [13] and Maidment and Miaou [14] developed a daily water use model that predicts seasonal water use from the outdoor air temperature as well as precipitation occurrence and amount. Using the multi-year daily data (1975–1981) for Austin, TX, Maidment et al. built a piecewise-linear function between seasonal water uses against the weekly average of daily minimum and maximum outdoor air temperatures. The proposed model was applied to nine cities in FL, PA, and TX using the weekly average of daily maximum temperatures instead of daily minimum and maximum outdoor air temperatures [14]. Both studies found that there was a threshold limit of outdoor air temperature (i.e., 13.3 °C (56 °F) daily minimum and maximum outdoor temperature

[1] The ASHRAE/CIBSE/USGBC PMP covers the following six performance categories: energy use, water use, thermal comfort, indoor air quality, lighting and acoustics.

[2] The water performance metrics required at the ASHRAE PMP water protocols are: (1) Basic level: an annual total site water use index (WUI) and water cost index (WCI); (2) Intermediate level: an annual and periodic (i.e., monthly) WUIs separately for a total building, landscape, and wastewater; and (3) Advanced level: an annual and periodic (i.e., monthly) WUIs separately for a total building and major end-uses (i.e., landscape, HVAC/process, wastewater, gray water, and hot water).

[3] The monthly potential evapotranspiration was computed using the Thornthwaite method which requires an input value for monthly mean temperature: $e = 1.6 \times (10 \times t/I)^a$, where: e = unadjusted potential evapotranspiration (cm/month); t = monthly average temperature (°C); I = annual heat index, which is the sum of the 12 monthly heat indices i where $i = (t/5)^{1.514}$; and $a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 0.01792 \times I + 0.49239$.

[4] The daily potential evapotranspiration was calculated using the Jensen-Haise equation which requires input values for daily mean temperature and daily solar radiation: $ETp = (0.014 \times T - 0.37) \times Rs$, where: ETp = potential evapotranspiration (cm/day); T = daily mean temperature (°C); and Rs = solar radiation, in evaporation equivalent (cm/day).