International Journal of GEOMATE, March, 2020, Vol.18, Issue 67, pp. 71-77
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.67.5758
Special Issue on Science, Engineering and Environment

IMPACTS OF WEATHER VARIABLES ON URBAN WATER DEMAND AT MULTIPLE TEMPORAL SCALES

* Chinnapan Makpiboon[1], Adichai Pornprommin[2] and Surachai Lipiwattanakarn[3]

[1,2,3]Department of Water Resources Engineering, Faculty of Engineering, Kasetsart University, Thailand

*Corresponding Author, Received :14 June 2019, Revised: 07 Nov. 2019, Accepted: 30 Dec. 2019

ABSTRACT: Population growth and urban development have contributed to increase in base urban water demand in a long-term temporal scale. However, if we consider a short-term temporal scale, weather variability is an important factor affecting daily, monthly and seasonal water demands. This study examines the relationship between urban water demand in the service area of the Metropolitan Waterworks Authority (MWA), Thailand, and two important weather variables: temperature and rainfall at various temporal scales. The growth of water demand was detrended and then normalized. The multiple linear regressions were used for analyzing the relationship. As a result, temperature has a strong significance to the demand that higher temperature causes higher demand, and the impacts are stronger for larger time scales. On the other hand, rainfall has a weak significance to the demand, but higher rainfall causes lower demand. Also, the impacts are more intense for larger time scales. As climate changes will affect both temperature and rainfall, MWA should consider the weather variability for a better management of water production and distribution.

Keywords: Unban Water Demand, Water Consumption, Multiple Temporal Scales, Weather Impact

1. INTRODUCTION

The global water demand for domestic uses is expected to increase significantly, especially in cities and countries with developing economic growth [1]. In 1900, the global population lived in urban areas just 13% and has been rising to 49% in 2005. According to the United Nations (UN) [2], the global population living in urban areas was predicted to rise up to 60% in 2030. Also, UN estimated the population living in Bangkok and its surrounding suburbs was around 18 million people, ranking the 22nd-23rd in the world, but people in the Bangkok area registered to elect the Bangkok governor only had 6 million people [3]. Thus, non-registered population and tourists may affect water demand and pattern in Bangkok significantly.

Metropolitan Waterworks Authority (MWA) provides potable water for Bangkok as Thailand capital city and its two vicinity provinces (Nonthaburi and Samut Prakarn). The water demand in this MWA service area has increased from 4.76 million cubic meters per day (MCM/day) in 2007 to 5.38 MCM/day in 2016 (+13% in 10 years). Thus, understanding and forecasting the water demand is one of the challenging tasks for MWA.

Urban water demand is influenced by many variables based on whether it is analyzed on temporal or spatial bases. The common explanatory variables for temporal analysis are temperature, precipitation, wind speed, evaporation, water price, weather related variables. Among them, temperature and precipitation are the most significant ones [4]. Urban water demand is also sensitive to time scale, especially seasonal time scale [5]. However, most of the studies were in the temperate zone [6,7,8], where the temperature varies widely in summer and winter.

In this study, we studied the impacts of temperature and precipitation on water demand of the MWA service area in the hot and humid tropical zone. The temporal effects on urban water demand, daily, monthly and seasonal time scales, were explicitly studied in the large metropolitan water demand of Thailand. The time series linear regression model was used for time series data analysis [9].

2. STUDY AREA AND DATA

MWA is a sole water utility agency providing potable water for Bangkok and its vicinity areas with more than 10 million population. MWA provides approximately 1,800 million cubic meters of potable water in 2018. Our study area is the MWA service area covering Bangkok, Nonthaburi and Samut Prakan provinces [10]. MWA provides water demand dataset consisting of daily water discharge and monthly water demand. To obtain daily demand, we assumed daily water loss by subtracting monthly water discharge with water demand and averaging it for daily water loss. According the MWA annual reports between 2007 and 2017, the average percentage of water loss was approximately 30%. The monthly and seasonal water demands are then based on these daily data. Seasonal data are sum of the daily data during a

Table 1 Detailed Information of Urban Water Demand Temporal Scales Dataset

Urban Water Demand Dataset	Daily	Monthly	Seasonal		
			Summer	Rainy	Winter
Period	1 Oct 2007 - 30 Sep 2017	Oct 2007 - Sep 2017	Winter 2007 – Summer 2017		
Number of Data	3,424 days*	116 months*	30 seasons*		
Water Demand					
Max (MCM/Day)	4.30	4.11	4.03	3.90	3.80
Min (MCM/Day)	3.04	3.23	3.54	3.42	3.32
Average (MCM/Day)	3.67	3.67	3.81	3.68	3.58
Temperature					
Max (^{o}c)	34.15	31.90	31.10	29.90	29.02
Min (^{o}c)	18.20	25.12	28.72	29.06	26.80
Average (^{o}c)	29.17	29.19	30.24	29.47	28.05
Rainfall					
Max (mm/day)	115.90	17.65	5.89	10.75	3.50
Min (mm/day)	0.00	0.00	0.72	6.33	0.69
Average (mm/day)	5.09	5.16	2.81	9.00	1.86

Note:* exclude long holidays and during a 2011 mega flood (229 days)

range of seasons.

Weather dataset was obtained from five Thai Meteorological Department (TMD) stations, namely Bangkok (455201), Khlong Toei Port (455203), Bangna (455301), Don Muang Airport (455601) and Samut Prakarn (429301). TMD provided daily temperature and rain data. According to TMD, Thailand weather can be divided into 3 seasons. Summer is between 16 February and 15 May, rainy season is from 16 May to 15 October, and winter is from 16 October to 15 February [11]. The period of the data used in this study was between 1 October 2007 and 30 September 2017 (10 years).

According to the demand data, we found extremely low water demand during October 2011-January 2012 caused by the Thailand mega flood in 2011. We also found that during long holidays (more than 3 days) water demand was significantly lower than usual. Therefore, we did not include these abnormal demand data in our study. Detailed information of urban water demand temporal scales dataset is described in Table 1. Since our study is in the tropical zone, the daily temperature was between 18.20^{o}c and 34.15^{o}c, and the seasonal water demand and temperature did not vary greatly like those in the temperate zone. However, in the rainy season, the amount of rainfall could be 3-5 times higher than that in other seasons.

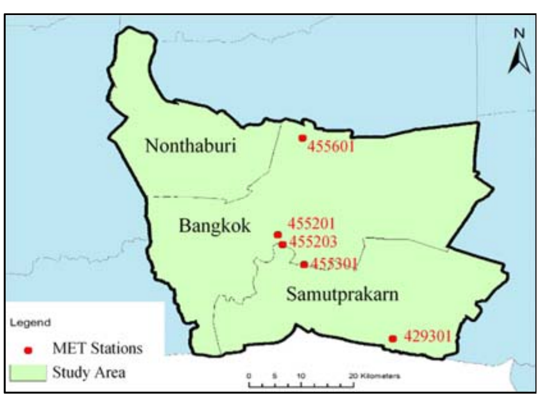


Fig. 1 Study area and weather stations

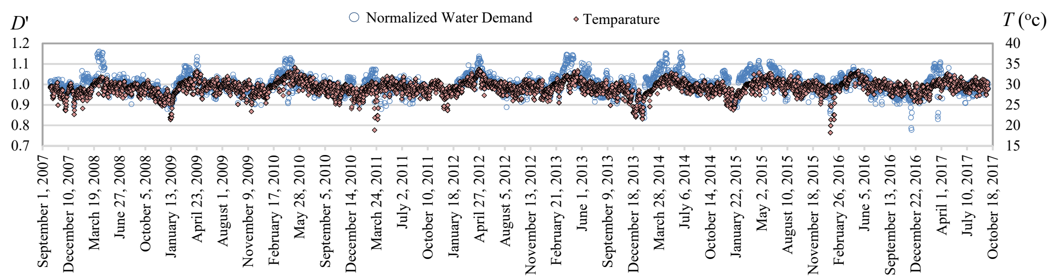
3. METHODOLOGY

3.1 Normalization

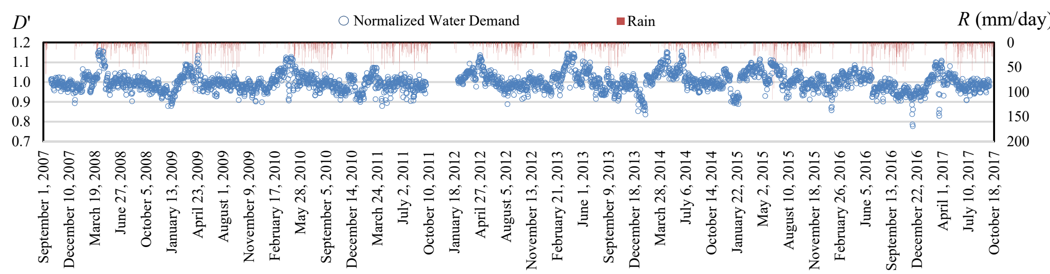
To investigate the impact of weather on water demand, we assumed that all other major variables except weather-related variables present in the water demand as a long-term time series trend. After removing this trend, we then can relate weather data to urban water demand. The time series model of urban water demand can be expressed as:

$$D_t = \alpha_0 + \sum_{j=1}^{v} \alpha_j t_j \quad (1)$$

where D_t is water demand at time t, α_0 is the regression intercept and j is a polynomial term in the trend component, v is a polynomial order and α_j is for a linear trend component. We considered that all the trend coefficient. For our model, we used v as 1 growth-related variables such as population, economics, and an urban growth are included in the trend. After the model is constructed with daily data, we removed this trend by subtracting it from water demand such that

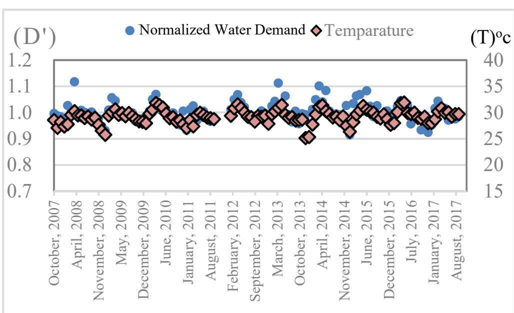


(a) Normalized water demand (D') and temperature (T)

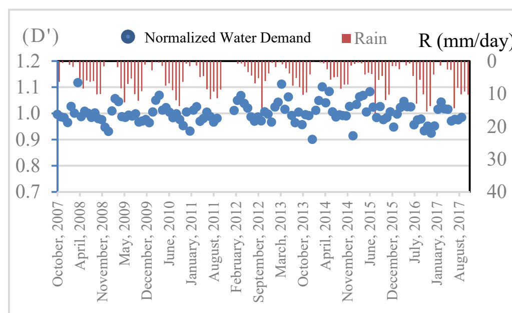


(b) Normalized water demand (D') and rainfall (R)

Fig. 2 Temporal changes of daily normalized water demand with (a) temperature and (b) rainfall

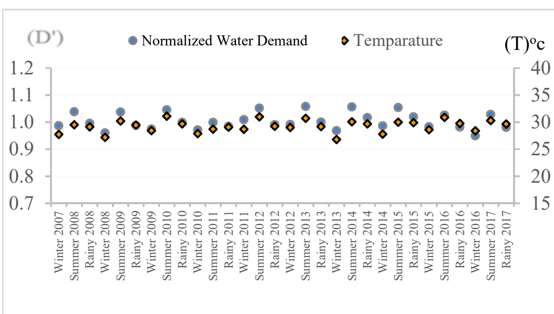


(a)

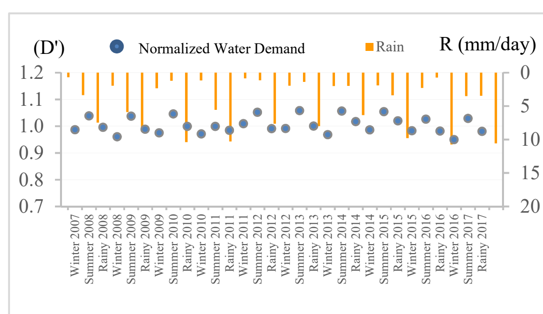


(b)

Fig. 3 Temporal changes of monthly normalized water demand with (a) temperature and (b) rainfall



(a)



(b)

Fig. 4 Temporal changes of seasonal normalized water demand with (a) temperature and (b) rainfall

$$\widehat{D}_t = D_{obs,t} - \alpha_1 t \quad (2)$$

where $\widehat{D}_t$ is the detrended water demand at time t. We then tested the stationarity of $\widehat{D}$ by using an Augmented Dickey-Fuller (ADF) test [12]. The test is aimed for an unknown lag time autoregressive-moving average model. However, for this study, a k-lag autoregressive model, AR(k), is considered and can be given by the equation:

$$\Delta\widehat{D}_t = \alpha\widehat{D}_{t-1} + \sum_{j=1}^{k-1}\beta_j\Delta\widehat{D}_{t-1} + e_t \quad (3)$$

where Δ is the difference operator, e_t is a white noise sequence of random variables, α and β_j are the coefficients. The null hypothesis of the unit root test is that the time series data has a unit root and is not stationary. If the null hypothesis is rejected then the time series data is stationary.

After proving for its stationarity, we normalized the detrended daily water demands by dividing them with α_0 from Eq. (1) to analyze the demands as a ratio. This would give an easy understanding on impact of weather variables to the water demand.

$$D'_t = \widehat{D}_t/\alpha_0 \quad (4)$$

3.2 Multiple Regression Analysis

A multiple regression is a simple linear regression extension used when we predict two or more the value of a variable. The variables we predict are called dependent variables or target variables. A linear relationship is assumed between two variables. Linear regression is a commonly used statistical analysis in water demand while nonlinear regression is used to various growth models [13]. Results in one variable can be predicted from the others [14].

After removing the long-term trend and normalizing the detrended data, the influences of weather-related variables on normalized water demand can be described by a multiple linear regression model which is based on the basis of relationship between water demand and its determinants. Our model can be expressed as:

$$D'_t = \beta_0 + \sum_{i=1}^{n}\beta_i x_{i,t} \quad (5)$$

where D'_t is the normalized water demand at time t, β_0 is the regression intercept and i is an index of i^{th} independent variable, n is the number of variables# and $x_{i,t}$ is a value of i^{th} independent variable at time t. Our independent variables are temperature (i = 1) and rainfall (i = 2).

4. RESULTS AND DISCUSSION

4.1 Normalized Water Demand

To find the urban growth trend of daily water demands, a simple time series model (1) was adopted. We found the relationship based on the start of our data (October 2011) to be

$$D_t = 3.3846 + 1.5696 * 10^{-4}\ t \quad (6)$$

where α_0 = 3.3846 MCM/day and α_1 = 1.5696x10^{-4} MCM/day^2. Thus, the yearly average growth of water demand of MWA for 2007-2017 was roughly 0.0573 MCM/year (+1.7%).

We removed this trend for a zero-slope adjustment by subtracting it from water demand to obtain the detrended water demand $\widehat{D}_t$ in Eq. (2). We then normalized $\widehat{D}_t$ by dividing it with α_0 in Eq. (4). Consequently, we have the normalized water demand D'_t that ranged between 0.8 to 1.2 due to temperature (T) and rainfall (R) as shown in Fig.2.

Fig. 2(a) shows the temporal variation of daily normalized water demand and temperature for 10 years. It is found that the water demand pattern follows the temperature pattern very well. The temporal variation of daily normalized water demand and rainfall for 10 years is shown in Fig. 2(b). The rainfall seems to have a negative impact on water demand that higher rainfall causes lower water demand. However, the impact is not clear in the winter time periods, where there is less rain. This may be due to the effect of lower temperature.

After averaging daily variables to monthly values, we found that the ranges of water demand, temperature and rainfall became narrower as shown in Fig. 3. Again, the temporal change of the monthly normalized water demand is consistent with that of the temperature in Fig.3(a). Comparing the water demand with the rainfall, we also found a possible relationship between them as shown in Fig. 3(b).

Fig. 4(a) shows the comparison between the seasonal normalized water demand and the temperature. A clear trend shows that the water demand of each season reduced or increased in accordance with the change of the temperature. For example, in the summer when the temperature is the highest, the water demand rises up, it goes down in the rainy season and becomes the lowest during the winter. In Fig.4(b), the rainy season showed the highest rainfall, following with the summer and winter. It is found that water demand in the rainy season is lower than that in summer. This may be due to the effect of rainfall. However, water demand in winter is the lowest even with less rainfall. This should be the effect of the temperature as described earlier.

Table 2 Results of multivariable linear regression of the normalized water demand (*D*') to the average temperature (*T*) and the rainfall (*R*) in the daily, monthly and seasonally temporal scales.

Normalized water demand	Coefficients			t Stat		P-value	
	$\boldsymbol{\beta_1}$ for *T* (1/°c)	$\boldsymbol{\beta_2}$ for *R* (day/mm)	$\boldsymbol{\beta_0}$ as intercept	*T*	*R*	*T*	*R*
Daily	0.0152	-0.00017	0.5571	40.5224	-2.9464	1.23E-293	0.0032
Monthly	0.0187	-0.00189	0.4656	7.6667	-2.8275	8.54E-12	0.0056
Seasonal	0.0238	-0.00291	0.3224	8.6211	-3.3784	3.09E-9	0.0022

Note:*Significant at the 0.01 level

4.2 Weather Variability Analysis

The impacts of weather variables, temperature and rainfall, were analyzed using a multiple linear regression in the following equation:

$$D_t' = \beta_0 + \beta_1 T_t + \beta_2 R_t \tag{7}$$

where $\boldsymbol{T_t}$ is temperature and $\boldsymbol{R_t}$ is rainfall.

Table 2 shows the results from the regression. The statistics in the table are composed of coefficients of the regression variables, t Stat and P-value. The coefficient values show how strong the impact of each variable on the normalized water demand. From the results, an increase in 1°c of the temperature caused an increase in 1.52%, 1.87% and 2.38% of the water demands in the cases of the daily, monthly and seasonal time scales, the rainfall caused a decrease in 0.017%, 0.189% and 0.291% of the water demands in the cases of the daily, monthly and seasonal time scales, respectively. In conclusion, temperature generates a higher demand while rainfall leads to a lower demand. Also, the time scale became larger, the impact was stronger.

We tested the significance of the independent variables, the temperature (*T*) and the rainfall (*R*) using t stat and P-value at the 0.01 significance level as shown in Table 2. The t stat values show how large the coefficients compare to the standard error. The larger value of t stat indicates the more significance of the variable. The P-value is the probability that the variables have no effect on the dependent, the normalized urban demand in this case.

For temperature, the T-stat value for daily is much higher than monthly and seasonal values, indicating that the model for daily tends to be more accurate. Also, the P-value for daily is significantly lower than those for monthly and seasonal, indicating the same message. The t Stat and P-value results show that rainfall is less significant than temperature. In addition, the daily, monthly and seasonal models with rainfall tend to have the same accuracy.

4.3 Impact of Weather Variables on Demand

The results of multiple linear regression for daily, monthly and seasonal were compared with the datasets in Fig. 5, 6 and 7, respectively, showing the impacts of temperature and rainfall on MWA water demand.

In Fig. 5, the normalized daily water demands ($\boldsymbol{D'}$) ranges between 0.8 and 1.2 with the daily temperature between 21°c and 34°c. A clear trend between temperature and water demand can be seen. We separated the data into three groups to analyze the effect of rainfall as follows. The blue circular dots show the data with rainfall between 0 and 4 mm/day. The red triangular dots represent the data with rainfall between 4 and 8 mm/day, and the green diamond-shaped dots mean the data with rainfall higher than 8 mm/day. Using Eq. (7) with the coefficients in Table 2 for the daily data, the lines of rainfall equal to 2, 6 and 10 mm/day are used to compare with the daily data of three groups. It is found that the data are too scattered and not related to the lines very well. It implies that the daily water demand is not corresponding to the daily rainfall clearly.

Many previous research studies in the temperate climate have found the temperature and rainfall thresholds for urban water demand. For example, [4] show that residential water use for East Doncaster, Victoria, Australia is not affected by temperature changes at 15.3°c or below and at rainfall level of 4.8 mm or higher. For our study area in the tropical climate, however, we cannot find those thresholds. It is possible that our lowest temperature is still higher than the threshold value.

Fig. 6 shows the monthly water demand related to temperature and rainfall. The range of temperature decreases to be between 26°c and 32°c due to monthly averaging. Similar to the daily analysis, water demand depends on temperature. To consider the effect of rainfall, the rainfall lines at levels 2, 6 and 10 mm/day using Eq. (7) with the monthly coefficients from Table 2 were plotted against the three groups of water demand as done in

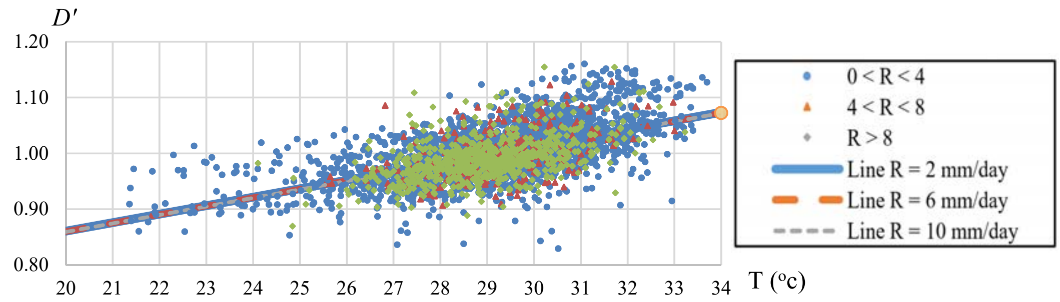


Fig. 5 Relationship between daily normalize urban water demand dataset, temperature and rainfall dataset during winter 2007 – summer 2017

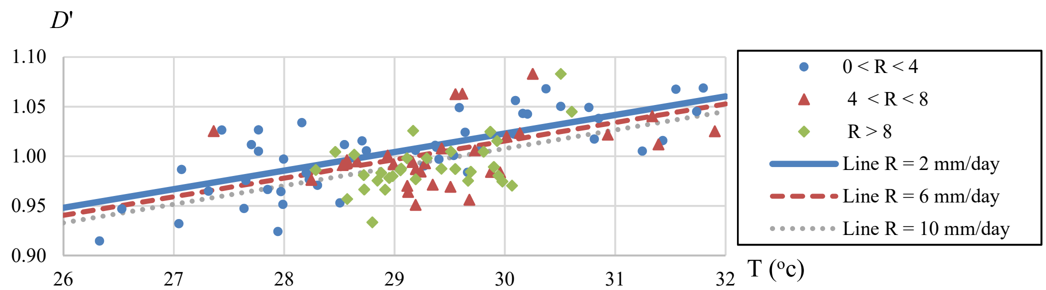
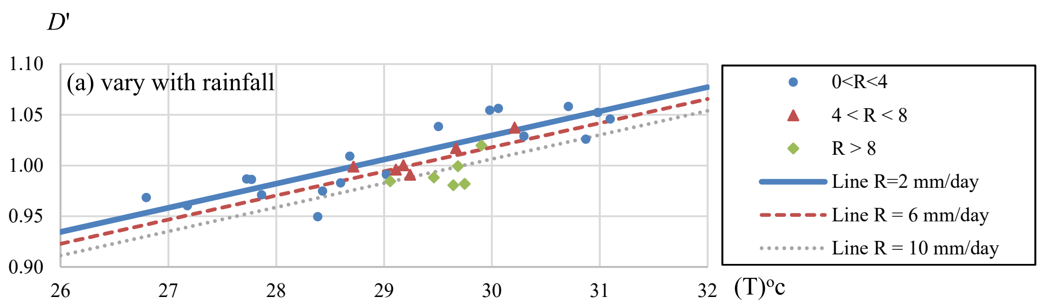
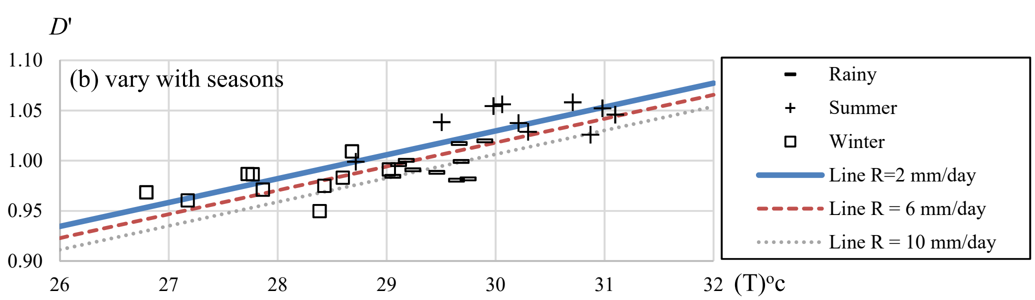


Fig. 6 Relationship between monthly normalize urban water demand dataset, temperature and rainfall dataset during winter 2007 – summer 2017 in the MWA service area



(a) vary with rainfall



(b) vary with seasons

Fig. 7 Relationship between seasonal normalize urban water demand dataset, temperature and rainfall dataset during winter 2007 – summer 2017 (a) and show the amount of rainfall of each season. (b) them, and a better tendency of an inverse relationship between water demand and rainfall can be seen.

Again, we averaged the data into the seasonal time scale in Fig. 7. A clear relationship between temperature and water demand can be seen. In Fig. 7(a), using the same idea to create three lines and three groups of water demand, the effect of rainfall can be found clearly. In Fig. 7(b), three groups of the seasonal data were divided according to seasons. It is clear that temperature and rainfall in each season are different. In summer, high water demand is due to high temperature while, in winter, low temperature causes low water demand. As the temperature in rainy season is moderate, water demand is low due to rainfall.

5. CONCLUSIONS

The average global temperature is constantly rising. Thailand is also affected by global warming. Over the past 40 years, between 1970 and 2009, the average temperature in Thailand rose about 0.024 ^{o}c per years, especially in the metropolitan areas, where the urban temperature is higher than other places due to a dome heat island effect [15]. This impact may cause and increase in urban water demand. Our statistical analysis of urban water demand for Bangkok, Nonthaburi and Samut Prakan provinces of Thailand showed that temperature and rainfall influence the urban water demand in the daily, monthly and seasonal time scales. An increase in 1°c of the temperature caused an increase in 1.52%, 1.87% and 2.38% of the water demands in the cases of the daily, monthly and seasonal time scales, respectively. However, an increase in 10 mm/day of the rainfall caused a decrease of 0.017%, 0.189% and 0.291% of the water demands in the cases of the daily, monthly and seasonal time scales, respectively. Using t stat and P-value, temperature is a more significant variable than rainfall, especially in the daily time scale. Unlike in the temperate climate, we could not find the temperature and rainfall thresholds for urban water demand in our tropical climate study area. The weather effect to water demand with different time scales provides a better water demand prediction for the short-term, medium-term and long-term planning and management. These weather factors should be accompanied with other urban growth factors, such as population density, immigration or expansion, type of urban land use, the network of transport routes and etc.

6. ACKNOWLEDGMENTS

The data provided by Metropolitan Waterworks Authority and Thai Meteorological Department were greatly appreciated. Makpiboon was supported by the PhD scholarship by the Faculty of Engineering, Kasetsart University.

7. REFERENCES

[1] WWAP (United Nations World Water Assessment Programme) (2014), The United Nations World Water Development Report 2014: Water and Energy (Paris: UNESCO)

[2] United Nations, (2018), World Urbanization Prospects: The 2018 Revision [Key Facts]. United Nations.

[3] Pongtat, M., (2018) Greater Bangkok, Thansettakij newspaper, Year 38, Issue 3,349, 18 – 20 March 2018 https://www.thansettakij.com/content/269208

[4] Gato, S., Jayasuriya, N. and Roberts, P. (2007), Temperature and rainfall thresholds for base use urban water demand modelling. Journal of Hydrology 337 (3-4), pp.364– 376

[5] House-Peters, L. A., & Chang, H. (2011). Urban water demand modeling: Review of concepts, methods, and organizing principles. Water Resources Research, 47, 15

[6] Goodchild., C. W. (2003). Modelling the impact of climate change on domestic water demand. The Journal.

[7] Miaou, S., (1990), A Class of Time Series Urban Water Demand Model with Nonlinear Climatic Effects, Water Resources Research, Vol. 26(2), 169-178.

[8] Toth, E., Bragalli, C. & Neri., M. (2018), Assessing the significance of tourism and climate on residential water demand: Panel-data analysis and non-linear modelling of monthly consumptions, Environmental Modelling & Software, 103, 2-61.

[9] Donkor, E. A., Mazzuchi, T.A., Soyer, R., & Roberson, J.A., (2014), Urban Water Demand Forecasting: Review of Methodsand Models, J. Water Resour. Plann. Manage., 140(2): 146-159

[10] Metropolitan Waterworks Authority. (2018),Website of Metropolitan Waterworks Authority (Thailand), Topic "About MWA:The Metropolitan Waterworks Authority's History" https://www.mwa.co.th/ewtadmin/ewt/mwa_internet_eng/ewt_news.php?nid=349

[11] Meteorological Department. (2018), Website of Meteorological Department (Thailand), Topic "Academic: Meteorological Book "Season of Thailand" https://www.tmd.go.th/info/info.php?FileID=53

[12] Said, E.S. & Dickey, D.A. (1984), Testing for unit roots in autoregreive-moving average models of unknown order, Biometric, 71, 3, pp. 599-607.

[13] Statistics Solution. (2018), website Complete Dissertation by Statistics Solution, http://www.statisticssolutions.com/what-is-multiple-linear-regression/

[14] Indian Agricultural Statistics Research Institute (IASRI), (2018), Regression Analysis Library Avenue, PUSA, New Delhi - 110 012 (INDIA) www.iasri.res.in/ebook/win_school_aa/notes/Regression_Analysis.pdf

[15] Limsakul, S. L. a. A. 2012. Atmospheric Research: Trends in Thailand pan evaporation from 1970 to 2007. ELSEVIER: 6.