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Original Article

Constrained system dynamic modeling for water discrepancy investigations in Bangkok Metropolitan, Thailand

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Abstract

Urban water management plays a crucial role in socio-economic development and each city has its own water demand and water supply patterns. A system dynamics model was then developed to investigate the water demand and supply of Bangkok Metropolitan, Thailand. Influential factors of the water system include economic development, temperature, water conservation programs, waste water treatment, and water infrastructure. Temperature is the main driving force for the water demand, while the pipeline leakage rate is the most impactful factor on the water supply. If no policy intervention is implemented, water deficit will appear in July 2022. The leakage rate at 25% can extend water discrepancy after 2036.

Keywords: urban water management, water deficit, water leakage, Bangkok Metropolitan, system dynamics

1. Introduction

Urban water management is one of the most challenging issues as it plays an important role in socio-economic development (Wei, Lou, Yang, & Li, 2016). The accelerated economic development has resulted in high water demand in many regions across the world and it could lead to water resource problems (Li *et al.*, 2018). Several researchers have then conducted their study to manage water supply and demand systems in order to achieve water security for particular regions. The waste water collection and waste water treatment system can increase the water supply, which can defer water shortage in Tabriz (Zarghami & Akbariyeh, 2012). Yulin city, adding water infrastructures cannot solve the water shortage's problem in the long period. Green water infrastructure to support sustainable water management in five cities was explored namely, Singapore, Berlin, Melbourne, Philadelphia, and Tianjin Eco-city (Li & Jensen, 2018). Although the cities faced similar challenges including water supply threats, environmental protection issues and an emerging threat of flooding risks, each city has its unique target and passages to solutions. Berlin and Singapore had a strong focal point on self-sufficiency of water supply and incorporate with green infrastructure's implementation in the cities, but more environmental protection aspects were addressed in Berlin. While Melbourne and Tianjin Eco-city focused on the reduction of tap water consumption, Philadelphia had a strong concern on environmental protection of rivers to improve both water quality and quantity.

Urban water management system is then rather sophisticated as it is related with detail and dynamic complexity for particular regions (Zarghami & Akbariyeh, 2012). Detail complexity of the system is evolved with several components or factors that could influence the water systems of each city or region differently (Duran-Encalada, Paucar-Caceres, Bandala, & Wright, 2017; Li & Jensen, 2018; Wang *et al.*, 2011; Wei *et al.*, 2016; Zhang, Lu, Zhao, & Song, 2014). To investigate the effects of dynamic complexity, System Dynamics (SD), one of numerical simulation techniques developed by Forrester at the Massachusetts Institute of Technology in the late 1960s, has been applied (Xi & Poh, 2013). It can investigate the behavior of complex systems and dynamic characteristics with changing variables or policy interventions in the feedback structures for visualizing and analyzing the systems (Kojiri, Hori,

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Nakatsuka, & Chong, 2008; Qi & Chang, 2011; Wang *et al.*, 2011). SD has been adopted to investigate several water management systems to simulate or predict water demand/supply variations with various influential components such as economic, social, and environment dimensions (Kojiri *et al.*, 2008; Kotir, Smith, Brown, Marshall, & Johnstone, 2016; Zhang, Zhang, Chen, Chen, & Zhao, 2008; Zhang, Zhang, Zhang, & Liu, 2010).

Bangkok, the capital of Thailand, is the most populated city and contributes the highest gross provincial product (GPP) of the country (NESDB, 2017). The urban water management is crucial to support socio-economic development of the area. The objectives of this paper are to: (1) discover influential factors affecting total water demand and total water supply within the system boundaries; and (2) identify policy interventions to postpone water deficit after 2036.

2. Literature Review

2.1 System dynamics model

SD is a well-developed method to explore system behaviors based on the assumption that the structure of a system consists of connected components and generate their behaviors (Stave, 2003; Sterman, 2004). SD provides feedback loops together with causal loop diagrams (CLDs), stock and flow diagrams (SFDs), time delays, mathematical functions, and nonlinearity to describe interactions among the components of the system studied (Sterman, 2004). CLDs are well known as a tool for system thinking that describe the positive and negative feedback structures of systems. For SFDs, stocks are accumulated or depleted and represent the state of the system such as water level or population. Flows are the rate of inflows or outflows of the stock. Every causal loop should have at least one stock while inflows and outflows can change the stock value over time (Qi & Chang, 2011; Sterman, 2004; Sun, Liu, Shang, & Zhang, 2017). To develop SD consists of the following steps: defining problem and clarifying the boundaries of the system, setting up a dynamic hypothesis, conducting model formulation, running the simulation test, designing policy intervention, and evaluation (Sterman, 2004; Sun *et al.*, 2017).

2.2 Urban water management components

Population is one of major components in urban water management and it affects water consumption of urban residents and increases in water demand (Wei *et al.*, 2016). Population consists of several subcomponents depending on characteristics of regions. In Las Vegas Nevada, the population component contains residential customers and non-residential customers. (Stave, 2003). Manatee country in Florida classified its water supply customers into three groups that are residential users, significant users, and wholesale customers (Qi & Chang, 2011). Migrate rates and emigration rates are involved to reflect the dynamics of the population (Kotir *et al.*, 2016; Zhang *et al.*, 2008).

Economic development is a vital aspect for water management. Industrial sectors including primary, secondary, and tertiary industry sectors consume a significant amount of water. In developing countries, industry sectors consume water up to 80% of the total urban consumption (Wei *et al.*, 2016). GDP, the industrial development rate, the production value, and the level of industrial technology were determined as their significantly affect water demand (Cheng, 2010; Sun *et al.*, 2017; Wei *et al.*, 2016;).

Climate change is correlated with surface water and groun water (Sun *et al.*, 2017). The effect of global warming could lead to more severe water resource problems in Europe and North America, while more water resources could be increased in Asia (Kojiri *et al.*, 2008). The changes of temperature and rainfall conditions result in the variation of quality and quantity of water resources (Duran-Encalada *et al.*, 2017; Zarghami & Akbariyeh, 2012). In Macau, some degrees of relationship between temperature and water demand are explored (Wei *et al.*, 2016). Climate change could influence both the volumes of water supply and demand.

Water supply resources are one of main components in urban water management systems such as desalinated water (Hadadin, Qaqish, Akawwi, & Bdour, 2010; Xi & Poh, 2013), rainfall, surface water, ground water, imported fresh water, and treated waste water (Cheng, 2010; Li *et al.*, 2018; Wang *et al.*, 2011; Zarghami & Akbariyeh, 2012; Zhang *et al.*, 2014). Sustainable water resources management has become a significant aspect as the growing of water demand due to population and economic development while water supply resources are limited (Zhang *et al.*, 2008). The use of treated waste water has contributed to increasing water supply and environment protection (Hadadin *et al.*, 2010; Zarghami & Akbariyeh, 2012; Zhang *et al.*, 2014). In addition, an increasing of water usage efficiency can accommodate limited water resources with growing water demands. The results are promising as the total water demand could be decreased by 17.5% if water conservation programs are utilized (Wei *et al.*, 2016).

3. System dynamics development

3.1 Overview of the study area

To support social and economic development of Bangkok, one state-enterprise is responsible to manage the water system of Bangkok and Bangkok's surrounding areas namely, Nonthaburi and Samut Prakarn called as 'Bangkok Metropolitan' as shown in Figure 1. In this study, SD was applied for the Bangkok Metropolitan. The spatial boundary covered 3,195.3 km^2 and total population was 8.2 million (BORA-DOPA, 2017). The area is a relative humidity between 63% and 80% (TMD, 2019). Thailand's average annual rainfall is 1,552.1 mm (TMD, 2020) mainly occurred from May to October, and a mean air temperature at 29.5 °C, (Metropolitan Waterworks Authority [MWA], 2018a). The water consumption in 2017 was 1,408.6 million m^3 (MWA, 2018d). Chaopraya and Maeklong rivers are the water resources of the study area. Royal Irrigation Department (RID) allocates water to the area in the dry season with some limitations (Royal Irrigation Department [RID], 2018). The water infrastructures, the water allocated, climate changes including temperature, rainfall, conductivity, Chaopraya river level are investigated their effect on the water supply system. The water demand is not only influenced by the growth of economic development that is the number of users, but also temperature that is annually increasing (MWA, 2020). In

Figure 1. Map of the study area

addition, water conservation programs and water treatment programs would be beneficial to explore theirs fruitful if the programs can be implemented. To analyze and extend water shortages after 2036, the system boundaries are defined as exhibited in Table 1.

Table 1. System boundaries

Endogenous	Exogenous	Excluded
Supply 1. Capacity - Untreated water Pumping station - Water pumping at water treatment plants - Water treatment process - Water distribution centers 2. Loss infrastructure	Supply 1. Allocated water 2. Conductivity 3. Wastewater Treatment 4. Chaopraya River Level 5. Precipitation 6.Temperature 7. Supply Management Demand 1. GPP 2. Temperature 3. Water conservation willingness and measures 4. Number of users (Household, economic, and industry) 5. Demand management	Supply 1. Maintenance period 2. Climate Change 3. Rivers Demand 1. Population

3.2 Total water supply component

Total water supply component consists of seven factors as shown in Figure 2a. Firstly, Allocated water is the amount of water allocated from water resources to Chaopraya and Maeklong Rivers. About 22% of total water resources has been allocated to the water system and 46% of total water resources is in natural reservoirs and available for usages (RID, 2018). The two rivers will allocate water to the fourth water plant with the limitation at 890 and 420 million m^3, consecutively in the dry season (RID, 2018). Secondly, Chaopraya River level factor, not only the allocated water affects the river level, climate changes including precipitation and temperature are also correlated with the river level.

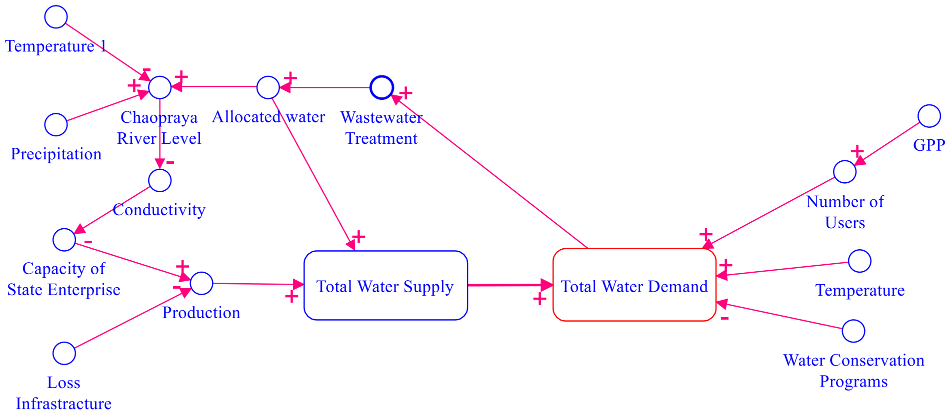
Thirdly, conductivity factor is the contamination of seawater in Chaopraya River and negatively related with the river's level. If the conductivity is over 0.07 S/m, the water pumping rate must be reduced to a flow rate of 60,000 m^3/hour. No conductivity occurred in Maeklong River as it passes through higher land.

Fourthly, water from Chaopraya River at untreated water pumping stations will be pumped and sent to Prapa canal and conveyed to three water treatment factories with the maximum capacity at 5,760,000 m^3 /day, while the water from Maeklong River will flow to the fourth water treatment plant. Total water production capacity is 6,440,000 m^3/day with having reservoirs that can reserve water of 644,000 m^3. Fifthly, tap water will then be distributed to fifteen water distribution centers and water users with total distribution capacity at 13,372,360 m^3/day.

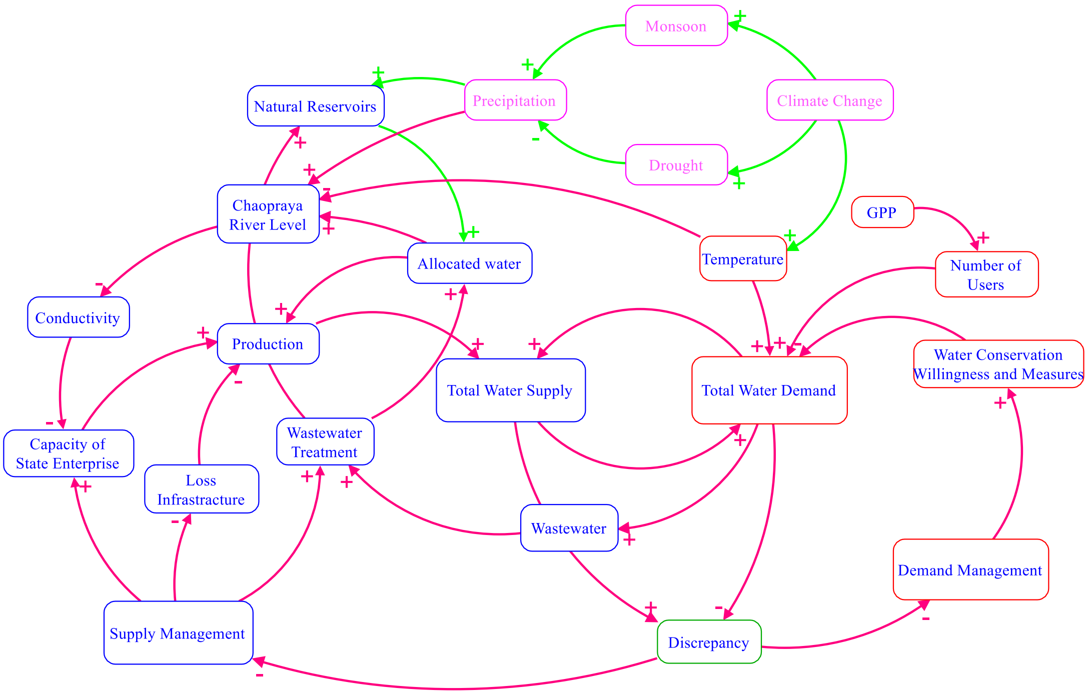
Sixthly, loss infrastructure at the pipelines was 27% of total water supply in 2017. An increasing trend of leakages has been investigated as they have been used about 20 years and maintaining high water pressure in the pipelines leads to a great amount of water losses. Finally, waste water was about 2.5 million m^3/day or 65.1% of the water demand/day while the treatment system's capability was 1.14 million m^3/day (PCD, 2017). Waste water subsystem by Li *et al.* (2018) was applied in the study as Zhengzhou China and the study area have some common characteristics such as highly populated city and having industrial area. About 90% of waste water can be reversed to treatment processes and 80% of them can be treated to supply for agricultural, industrial, and municipal (Li *et al.*,2018). The waste water treated of the study areas is then set at 17.2% of the average water demand and sending back to the two rivers.

3.3 Total water demand component

Total water demand component includes four factors: GPP, number of users, temperature, and water conservation programs. Firstly, GPP, it reflects the result of economic development and can identify commercial water demand (Wei *et al.*, 2016). GPP will then be used to predict the number of users. Secondly, the number of user factor contains household users, industry users, and economic users. Household users are accounted for 80% of total water users. The water consumption of household users was 656.80 million m^3 while that of economic users and industry users was 751.8 million m^3 in 2017 (MWA, 2018b). The number of users is classified into eighteen subareas to predict the water demand. Thirdly, temperature factor impacts both the water demand and supply volumes. Temperature is positively associated with the water demand and negatively related with the river level. Finally, water conservation programs will be explored based on the water conservation programs of Wei *et al.* (2016) as Bangkok and Macau are both highly populated city, and not having agriculture activity. Total water demand component exhibited in Figure 2b and the system diagram with water infrastructures' capacity of the water system is exhibited in Figure 3.



(a) Factors in the water system



(b) Causal loop diagram

Figure 2. Components of the water system

3.4 System dynamics modeling

A CLD of the water system is exhibited in Figure 2b. The growth of economic and the effect of temperature positively influence total water demand. The effect of conservation programs can reduce the water demand. For water supply, the river's level is positively associated with allocated water volumes and precipitation but negatively related with temperature. Conductivity is negatively varying with the river level and the production capacity is negatively correlated with conductivity. The water allocation from the rivers passes to water infrastructures including pumping stations, production plants, reservoirs, and pipelines. The leakage rate negatively affects total water supply. Water discrepancy is then calculated as the differences between total water demand and total water supply.

The SD model was developed with IThink1.3.1 software. Mathematical equations used to calculate the variables for each step time are exhibited in Figure 4. The equations of input variables are shown in Table 2. Total water supply will be the minimum value between the production capacity and the volumes of allocated water and waste water treated including a reduction of total water supply by the loss infrastructure rate. The production capacity will be varied according to the conductivity value that is related with allocated water, temperature, and precipitation.

Total water demand equation includes water demands of household users, economics users, and industry users including the water saving ratio under the water conservation program. GPP of every province shows an increasing trend and positively influences the number of economic users in three areas namely Bangkoknoi, Pasijaroen,

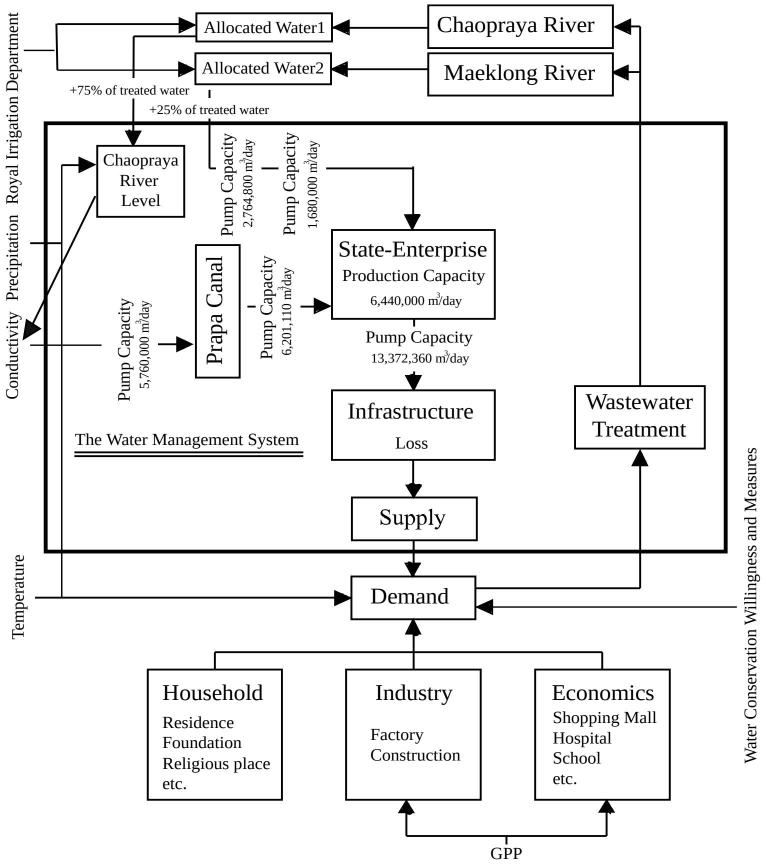


Figure 3. System diagram

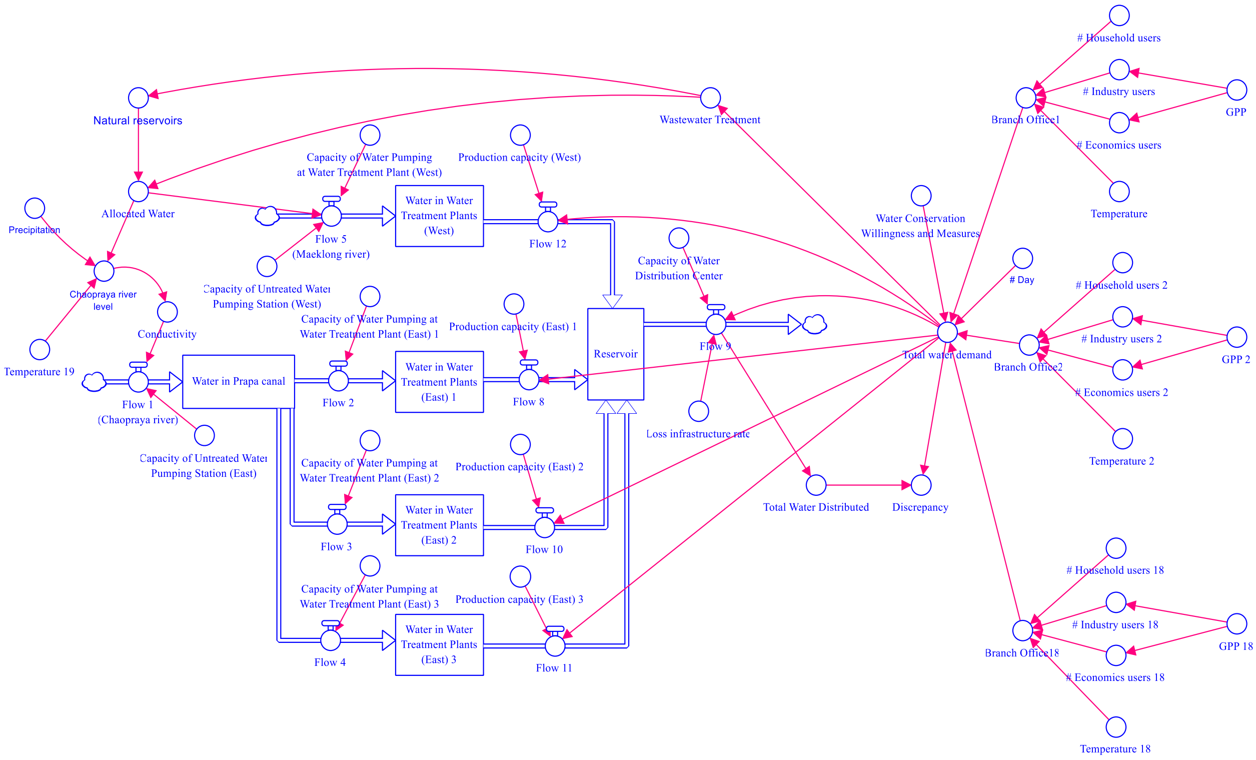


Figure 4. Stock and flow diagram for Bangkok metropolitan water system

Table 2. Time series and regression equations derived with regard to the system dynamics model

Input variables		Parameters / Equations
Total water demand (cubic meters)		(Household demand$_t$ +Economics demand$_t$+ Industry demand$_t$) *Water Conservation Programs$_t$
Total water supply (cubic meters)		min [Capacities$_t$, (Allocated water$_t$ + Wastewater treatment rate$_t$)] *(1- Loss rate$_t$)
Chaopraya River level (m)		37.216 + ($8.429 * 10^{-9}$ * Allocated water) + (-0.094 * Temperature) + (0.001* Precipitation)
Capacity of Untreated Water Pumping Station: East (m^3/h)		$\begin{cases} 240{,}000\text{ ; Conductivity } \le 0.07\text{ S/m} \\ 60{,}000\text{ ; Otherwise} \end{cases}$
Allocated Water (m^3/month)		$\begin{cases} 1{,}310\text{ million / 6 ; Drought} \\ 6.44\text{ million} * \text{day ; Otherwise} \end{cases}$ + treated water
Loss infrastructure$_{t+1}$ (%)		L_{t+1} *seasonal factor for the period or $[0.416*\frac{\text{Loss infrastrucutre}_t}{\frac{\text{Average for the period}}{\text{Overall average}}}+0.584*L_t]*\frac{\text{Average for the period}}{\text{Overall average}}$ When $L_1 = 20.692$
Precipitation$_{t+1}$ (mm)		$(L_t)*\frac{\text{Average for the period}}{\text{Overall average}}$ When $L_1 = 85.763$
Temperature$_{t+1}$ (°c)		$[0.249*\frac{\text{Temperature}_t}{\frac{\text{Average for the period}}{\text{Overall average}}}+0.751*L_t]*\frac{\text{Average for the period}}{\text{Overall average}}$ When $L_1 = 29.127$
Number of hour (Conductivity >700)		1578.240+(-43.379* Chaopraya River level$_t$)
Wastewater Treatment (cubic metros)		(0-0.172) * Total water demand$_t$
Water Conservation Programs (cubic meters)		(0-0.175) * Total water demand$_t$
GPP (Million Baht)	Bangkok	211608.067(t) + 2413948.556
	Nonthaburi	17685.5(t) + 110270.833
	Samutprakan	15663.75(t) + 551664.028
Household users$_{t+1}$ (users)	Branch Maensri	$W_t*User_t + W_{t-1}*User_{t-1} + W_{t-2}*User_{t-2}$ When $W_1 = W_2 = 0$ and $W_3 = 1$
Economics users (users)	Branch Bangkoknoi	-205.732 + (0.005 * Bangkok's GPP$_t$)
	Branch Prachachuen	7287.281 + (0.002 * Bangkok's GPP$_t$)
	Branch Pasijaroen	$W_{t-1}*User_{t-1} + W_{t-2}*User_{t-2} + W_{t-3}*User_{t-3}$ When $W_1 = W_2 = 0$ and $W_3 = 1$
Industry users (users)	Branch Suwannaphum	-1949.480 + (0.006 * Samutprakan's GPP$_t$)
	Branch Samutprakan	-33.204 + (0.005 * Samutprakan's GPP$_t$)
Total Economics & Industry users$_{t+1}$ (users)	Branch Prakanong	$W_t*User_t + W_{t-1}*User_{t-1} + W_{t-2}*User_{t-2}$ When $W_1 = W_2 = 0$ and $W_3 = 1$
Total Household & Economics users$_{t+1}$ (users)	Branch Bangkhen	$W_t*User_t + W_{t-1}*User_{t-1} + W_{t-2}*User_{t-2}$ When $W_1 = 0.016$, $W_2 = 0$ and $W_3 = 0.984$
Water demand for each branch (cubic metres)	Branch Bangkoknoi	-1925629.575 + (Temperature$_t$*155348.308) + (Economics users$_t$*136.707)
	Branch Minburi	878608.243 + (Temperature$_t$*151100.675)
	Branch Sukhumvit	3426726.244+ (Temperature$_t$*182566.262)
	Branch Prakanong	-5831127.291 + (Temperature$_t$*157482.008) + (Total industry & Economics users$_t$ * 429.282)
	Branch Samutprakarn	-306977.292 + (Temperature$_t$*266094.890) + (Industry users$_t$*1145.125)
	Branch Phyathai	3845249.914 + (Temperature$_t$*140377.816)
	Branch Thungmahamek	2544069.046 + (Temperature$_t$*94344.301)
	Branch Maensri	-7164963.478 + (Temperature$_t$*88844.916) + (Household users$_t$*380.530)
	Branch Ladprao	2908903.458 + (Temperature$_t$*143837.452)
	Branch Prachachuen	-7285972.972 + (Temperature$_t$*117480.501) + (Economics users$_t$*610.614)
	Branch Bangkhen	-3914884.082+(77328.572*Temperature$_t$) + (53.145*Total household & economics users$_t$)
Water demand for each branch (cubic metres)	Branch Suwannaphum	-6174702.133 + (Temperature$_t$*223710.457) + (Industry users$_t$*2712.979)
	Branch Taksin	2499520.085 + (Temperature$_t$*149638.294)
	Branch Pasijaroen	-2954127.037 + (Temperature$_t$*152584.192) + (127.808* Economics users$_t$)
	Branch Suksawat	898455.750 + (Temperature$_t$*166467.535)
	Branch Nonthaburi	1250623.817 + (Temperature$_t$*150486.452)
	Branch Bangbuathong	409854.810 + (Temperature$_t$*101401.710)
	Branch Mahasawat	289331.446 + (Temperature$_t$*127545.736)

and Prachchuen. For the industry areas, namely Suwannaphum and Samutprakan, the number of industry users is positively related with GPP. For the other subareas, the number of users is almost stable because those areas have reached their maturity state. The numbers of users and temperature were analyzed to identify total water demand for each subarea by the regression analysis and collinearity was tested to avoid the redundant of input variables such as the number of users at Bangkhen and Prakanong branches.

The data of annual reports and statistics record of the state-enterprise from January 2014 to September 2017 are used to construct time series or regression models in order to predict the variables from October 2017 to December 2036. As the volumes of water demand and water supply are highly fluctuated, the simulation model is focused in a monthly basis.

3.5 Model validation

The SD model was validated with historical data as shown in Figure 5. The MAPE of total water demand and total water supply is at 3.35% and 3.05% consecutively. In addition, the water demand of household users could approximately represent the same trend as that of Voelker & Sakulsri (2019) household water demand from 2018 to 2038.

3.6 Case setting

The validated model was used to develop seven cases to investigate and evaluate water shortage from 2018 to 2036. Case 1, As-Is or base case maintains the current parameters. Water demand is generated based the SD model developed. The leakage rate is uncontrolled. None of building capacity, water conservation programs, and waste water treated are implemented. No policy intervention is deployed as it is to discover the effects of the base model on the future volumes of water demand and supply. Case 2 is to explore the water discrepancy if the total water demand is increasing and ranging from 1% to 5% from the base case, but no policy intervention is implemented.

From case 3 to 7, to investigate the effects of policy interventions if they could be implemented from January 2018. Case 3 is to explore the effects of leakage rates. The leakage rates are set to decrease by 1% per year until it reaches the maximum leakage rates at 20%, 25%, and 30% respectively. Case 4, increasing the water production capacity has a potential to include in the state-enterprise's action plan to cope with the increasing of total water demand. One water tank can enhance the supply rate with 200,000 m^3/day. Increasing water tanks from 1 to 6 tanks are then explored.

Case 5 adds water conservation programs onto the water system as it can reduce total water demand and leading to a sustainable urban water system. Total water demand will be continuously reduced at the rate of 1% per year until it reaches 17.5% (Wei *et al.*, 2016). The 12.5% and 22.5% water demand reduction rates are added to explore their sensitivity on the water system. Case 6 is a scenario where a waste water treatment process is taken place. The motivation of this case is to minimize the waste water and natural resources could be increased. The waste water treated is set to increase by 1% of total water demand per year until it reaches 17.2% of total water demand (Li *et al.*, 2018). Moreover, the 12.2% and 22.2% of water treated rates are included. Case 7 is an ultimate alternative as it can reduce water loss, water waste, and also water demand. Leakage rate, waste water treatment, and water conservation programs are determined their effects on the water system. The summary of the seven cases is exhibited in Table 3.

4. Results and Discussion

4.1 Results

To analyze the effect of each case, Table 4 shows the water supply and demand ratios (S/D ratio) calculated at 2036, monthly water deficit points and yearly water deficit points.

Case 1, total water demand is gradually increasing about 0.6% per year, while total water supply is a rapidly decreasing trend as a result of the increasing of the leakage rate and the effects of climate changes. As the limitation of water allocated volume, high temperature, low precipitation, low river level, and conductivity in summer and the beginning of rainy season, the production rate must be reduced to maintain the quality of tap water. Therefore, water deficit will firstly appear in July 2022. When total water demand and supply is yearly calculated, the water deficit will be occurred in 2036 and its S/D ratio is 0.8599.

Case 2, the 1% demand growth can accelerate the water deficit to July 2021. At the 5% demand growth in 2036, water supply is required to increase about 310 million m^3 as shown in Figure 6, water availability that is calculated by total water supply minus total water demand. It can be said that the water system will be collapsed if no intervention policy is implemented to increase the water supply or to reduce the water demand. Case 3, the reductions of leakage rates can defer water shortages and also increase water availability from 18 – 253 million m^3 in 2036. The leakage rate can be determined as the most impactful on the water system. Case 4,

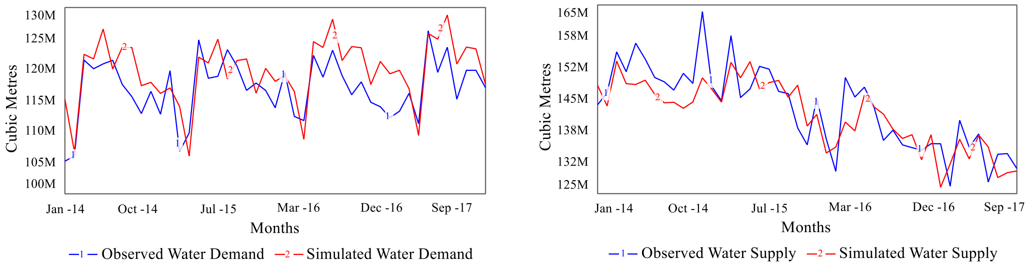


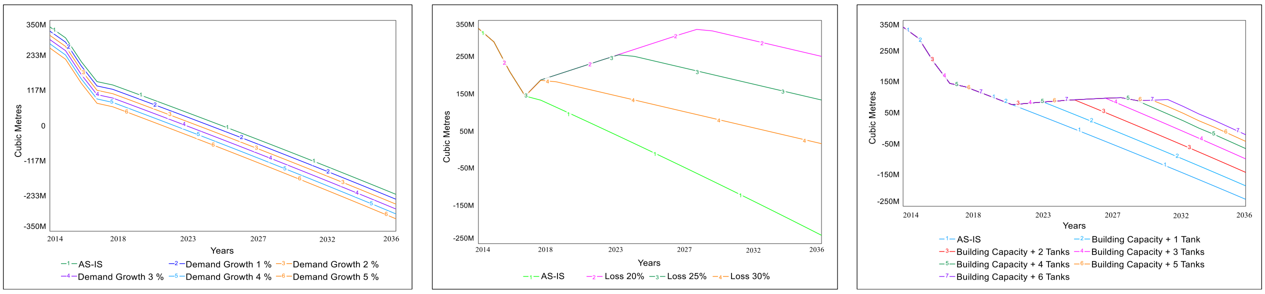
Figure 5. Water demand and supply validation results

Table 3. Summary of simulated cases

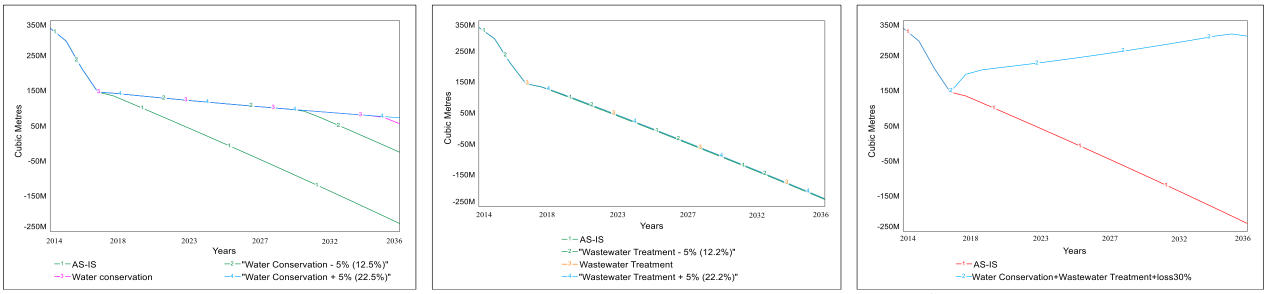
Case	Demand	Leakage rate	Building capacity	Water conservation programs	Waste water treatment
1: As-Is or Base case	Base	Base	Base	Base	Base
2: Demand growth	1% - 5%	Base	Base	Base	Base
3: Leakage rates	Base	20%, 25%, 30%	Base	Base	Base
4: Building capacity	Base	Base	1 Tank – 6 Tanks	Base	Base
5: Water conservation programs	Base	Base	Base	12.5%, 17.5 %, 22.5%	Base
6: Waste water treatment	Base	Base	Base	Base	12.2 %, 17.2 %, 22.2%
7: Water conservation + waste water treatment + leakage rate 30%	Base	30%	Base	17.5 %	17.2 %

Table 4 Water deficit.

Case		Water deficit point (monthly)	Water deficit point (yearly)	S/D ratio (2036)
Case 1: As-Is		July 2022	2025	0.8599
Case 2: Demand growth	1%	July 2021	2025	0.8514
	2%	July 2021	2024	0.8431
	3%	July 2020	2023	0.8349
	4%	July 2019	2022	0.8268
	5%	July 2018	2022	0.8190
Case 3: Leakage rates	20%	>Dec. 2036	> 2036	1.1559
	25%	>Dec. 2036	> 2036	1.0837
	30%	April 2034	> 2036	1.01152
Case 4: Building capacity	1 Tank	July 2024	2028	0.8867
	2 Tanks	July 2026	2030	0.9134
	3 Tanks	July 2028	2032	0.9402
	4 Tanks	July 2030	2034	0.9607
	5 Tanks	January 2031	2035	0.9750
	6 Tanks	January 2031	2036	0.9882
Case 5: Water conservation programs	12.5 %	July 2031	2035	0.9828
	17.5 %	July 2035	> 2036	1.0423
	22.5%	July 2035	> 2036	1.0557
Case 6: Waste water treatment	12.2 %	July 2022	2026	0.8614
	17.2 %	July 2022	2026	0.8614
	22.2%	July 2022	2026	0.8614
Case 7: Water conservation + waste water treatment + leakage rate 30%		>Dec. 2036	> 2036	1.2283



(a) Demand growth (b) Leakage rates (c) Building capacity



(d) Water conservation programs (e) Waste water treatment (f) Water conservation + waste water treatment + leakage rate 30%

Figure 6. Water availability charts

building 6 water tanks can postpone yearly water deficit to 2036, but it cannot cope with high total demand and low water supply due to water allocation and climate changes in summer and the beginning of rainy season. The first deficit is then in January 2031. Water tanks may not help to balance the water system as the main point is to face with scarcity of water including climate changes in summer.

If water conservation programs have been implemented and total water demand reduction rate is more than 17.5%, the water availability can be increased up to 56 million m^3. However, waste water treatment implementations cannot significantly increase the total water supply. The water discrepancy cannot be postponed. Case 7 can effectively postpone water shortages and increase the water availability by 305 million m^3 and it can stabilize the water system in a long run.

4.2 Discussion and Conclusions

The economic factors and temperature positively affect the water demand while Thailand water allocation policy, water infrastructure, and climate changes including precipitation, temperature, conductivity, and the river level influence the water supply system. The model developed does not include Thailand water allocation policy that is to manage water resources to support residential area, economic area, agricultural area, and industry area of the country. Although the water allocation volume used in the model is gathered from the current policy, it could be changed in the future if drought and temperature are extremely increased. In addition, drought, high temperature, conductivity, and the limitation of water resources mainly appear in summer until the beginning of rainy season. To manage the water supply in the mentioned period is rather challenging and could lead to temporarily water shortages if unexpected changes of drought are occurred.

The most impactful policy intervention on the water system is the leakage rate reduction as it can stabilize the water system. Moreover, implementing conservation programs to reduce the water demand rate more than 17.5% could keep balancing the water availability until 2036. To effectively maintain the water system in a long run, the leakage rate reduction together with conservation programs and waste water treatment projects should be further studied to implement and measure their success towards the sustainable urban water management system.

This study has enlightened the factors affected the water discrepancy of the study area with some limitations. Some emerging uncertainties such as the unexpected of drought should be later investigated to reflect more real world situations. Thailand water system should be explored to analyze the impact of the current water allocation policy and propose suggestions that can optimize the water allocation policy to support socio-economic development of the country.

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