Embedding scarcity in urban water tariffs: mapping supply and demand in North Taiwan

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Abstract

Water management is one of the main issues in the water policy agenda. More than a quarter of the world's population will experience severe water scarcity. Although there is board agreement on the importance of incorporating the concept of scarcity into water-management strategies and decision making, the lack of a standardized approach to embedding water scarcity has hindered progress in this direction. In recent years, pricing household water has been proposed as a tool for managing water scarcity in a national context. The objective of this work is to design a water-pricing model that better signals the value of water scarcity by considering water supply and demand at the same time. The proposed scarcity-based pricing model focuses on the variable component of the tariff and follows an increasing block strategy. The case study of the Taipei Water Resource Domain (Taiwan) is used to illustrate the method. It is Greater Taipei's main source of fresh water. By calculating the supply, demand, and budget of water resources in northern Taiwan, this study also determines the visible spatial distribution of water scarcity. The results show that both the supply and demand of water resources changed considerably under three scenarios, namely, low rainfall, average rainfall, and extreme rainfall. This demonstration illustrates a pathway for the implementation of a proposed scarcity-based pricing policy as a signal for users to adjust their water consumption in a proactive manner.

Keywords Water price · Ecosystem services · Integrated valuation of ecosystem services and tradeoffs (InVEST) · Water scarcity · Supply and demand · Urban

Introduction

Limited freshwater use is one of nine planetary boundaries within a changing planet (Steffen et al. 2015). Globally, the total amount of easily accessible freshwater on Earth is 45,500 km³/year. Of this total amount, 3800 km³/year are being withdrawn by humanity (Oki and Kanae 2006). Not only has water supply augmentation options decreased over the last decades, water demand will also sharply rise to 5000 km³ by 2025 owing to an increase in urbanization,

and a upward trend in population. Water scarcity caused by the combination of decreasing water supply and increasing water demand is one of the main issues in water management in urban regions. It is estimated that by 2050 more than half the world's population will live in water-stressed areas (Schewe et al. 2014; Schlosser et al. 2014).

Water resource administrations around the world are struggling to find pathways to promote sustainable water use. The ambitious Sustainable Development Goal (SDG) 6 of achieving availability and sustainable management of drinking water for all by 2030 has been set. The target 6.4, "Ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" is the focus of the SDG 6, and one of the most difficult targets to reach (Vanham et al. 2018). A particular challenge in the achievement of SDG 6 is how to handle urban areas where house over half of the world's population according to UN (2013). In urban regions, compared with water required for agricultural and industrial needs, the total amount of household water

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requirement is small. It seems to be essentially unaffected by water scarcity. In fact, since the majority of the human population is located in urban areas, city regions largely depend on the provision of water and, simultaneously, these areas are the focal impact points of waters scarcity (Cocos et al. 2012).

Water scarcity refers to either physical or social water scarcity (Kummu et al. 2016). Physical water scarcity arises because of low availability of water resources, while social water scarcity is caused by unbalanced or uneven distributions of industrial, agricultural, and residential use. While social water scarcity also highlights important challenges, we focus on physical water scarcity as a first step to examine water shortage, especially increasing population, shifting lifestyles and changing climate are predicted to considerably increase challenges of water accessibility within the following decades (Alcamo et al. 2003). Physical water scarcity has been used to evaluate future water availability at national and regional scales (Jaeger et al. 2013). This study highlights analysis and decision making for water scarcity at a regional scale and enable estimation of water pricing.

Under this scenario, water pricing has received widespread attention and has increasingly been implemented to affect water management in urban regions. To date, mechanisms for pricing household water include a uniform volumetric variable charge, an increasing block tariff, a decreasing block tariff, an increasing rate tariff, a seasonal tariff, a time-of-use tariff, a spatial tariff, etc., (Molinos-Senante and Donoso 2016). Though these ambitious mechanisms aim to reach many goals such as economic efficiency, conservation incentives, equity, and affordability, currently, most water-pricing policies mainly aim to ensure a reasonable rate of return to the water sector (Grafton et al. 2015; Molinos-Senante and Donoso 2016). Although broad agreement exists on a general understanding of water scarcity, prior research has noted that water resource scarcity is overlooked by household water-pricing decision makers (Olmstead et al. 2007; Zhang et al. 2012; Bejranonda et al. 2013; Mamitimin et al. 2015; Sağlam 2015).

Water price is a key economic tool in water resource conservation policies. Although scarcity pricing for freshwater is relatively new for most consumers, studies have linked water scarcity with water prices as a long-term solution. Vörösmarty et al. (2010) noted that water scarcity and the loss of water-related ecosystem services impacts water security for human beings. Their proposed framework addresses the limitations of the water-pricing process by focusing on financially effective water-treatment systems and management of water sectors. Qu et al. (2011) agreed that a water price reflecting water scarcity concerns establishes a long-term incentive for consumers to use water resources more effectively. Macian-Sorribes et al. (2015) showed that water pricing based on scarcity

improves water resource utilization. Sahin et al. (2015) used a system-dynamics method to strengthen water security and recommended that governments should consider temporary drought pricing, placing due emphasis on the scarcity of water resources. Examples from the U.S., Australia and OECD countries indicate when countries suffer from water supply issues in response to actual shortages, the price for scarcity water should fluctuate until a state of balance is reached (Sağlam 2015; Sahin et al. 2018). Recently, to internalize scarcity of water, a water charge structure was developed in Chile, as reported by Molinos-Senante and Donoso (2016). These results addressing urban water-pricing topics have typically promoted taxing water users in a way that reflects the true scarcity value of resource.

Despite the number of water scarcity studies, little research is available for addressing the issue of setting tariff structure. Indeed, finding a pathway to embed water scarcity into the water price structure is of fundamental importance in improving the usage efficiency of water resources and water security. To find a method of incorporating water resource scarcity into water prices, this study proposes a water-pricing model that reflects the scarcity of water resources. Water scarcity, defined as the ratio of water withdrawal to discharge (Falkenmark et al. 1989; Vörösmarty et al. 2000), fulfills needs through its integration of water supply and demand. To integrate water scarcity in achieving a scarcity-driven water price model, aggregate scarcity indices require straightforward computing; moreover, spatial and temporal variations need to be adequately represented.

This study proposes a model embedding water scarcity by combining three innovations. First, this model uses a base charge coupled with a variable water charge element to meet basic domestic water needs while providing incentives to use water efficiently. Second, water scarcity, in terms of the gap between supply and demand, is included in the water-pricing structure. Third, the empirical study is based on historical cases for extreme, average, and low rainfall scenarios at a regional scale. This study is not arguing to replace the existing water-pricing formula, but to transfer focus from using mandatory water restrictions to a scarcity-based option. We suggest that water sectors consider this scarcity-driven water price model.

This paper is organized as follows. A conceptual and operational tap water-pricing model is described in the next section. Section 3 demonstrates a water scarcity model for water supply and demand using a visible map and quantified data by conducting a case study in Taiwan. Section 4 highlights the challenges and opportunities of this water-pricing framework. Lessons learned and suggestions for future work are detailed in the conclusion.

Water-pricing model

Integrating scarcity in water-pricing policy to reach equilibrium between water supply and demand has been applied by a number of researchers to improve water conservation. For example, Grafton and Kompas (2007) and Grafton and Ward (2011) used a dynamic model based on historic supply and demand data estimating freshwater demand and supply conditions to determine the time to augment water supplies in Sydney, Australia. Pesic et al. (2013) presented a model of seasonal water pricing determined based on monthly temperatures and precipitation. Their model conveys a signal to consumers regarding water resource scarcity because weather extremes and droughts create water supply problems. These authors suggested that freshwater operation sectors use this approach in response to supply shortages to curb demand instead of using mandatory water restrictions.

The advantages arising from a combination of fixed and variable water prices provide both steady and flexible incomes for water operation sectors (Rogers et al. 2002). Thus, this paper does not use a new formula. Instead, it uses the current fixed and variable pricing model and focuses on developing a modified pricing structure that includes water scarcity. A model that uses basic and variable water charge elements is hereby proposed. A water scarcity index (SI) serves as the key variable for a water charge formula because it determines whether consumers will face higher water tariffs:

$$P = P_{B} + P_{U} \times (1 + SI), \tag{1}$$

where P is the domestic water charge; P_{B} is the fixed and basic charge based on basic demand for water; P_{U} is the volumetric charge, presented as (unit price)*(volume) − (accumulated difference); and SI is the water scarcity index, a factor lower than 1. This is the variable introduced in the water tariff reflecting water scarcity value. The factor is approximately 0 for a sufficient water supply, in which case a normal price is charged for water use. The factor approaches 1 for significant water supply shortages. It is calculated according to the following formula:

$$SI = \frac{WD}{WS}, \tag{2}$$

where SI is the water scarcity index; WD is water demand for household consumptive water use; WS is water yield from fresh surface water or groundwater for household use. Since this analysis focuses on physical ratios in water scarcity, we use yields rather than withdrawals in estimating WS, such that water supply means that water volume is decided by ecosystems rather than affected by infrastructures.

SI represents the demand-to-supply ratio that compares the consumptive use to the estimated natural runoff on an annual basis. The thresholds and definitions for different levels of water scarcity used in this water-pricing model follow the thresholds of Falkenmark et al. (1989), Raskin et al. (1997), Vörösmarty et al. (2000), and Hoekstra et al. (2012), which have been classified into three levels of water scarcity as follows:

(a) low water scarcity, where the water scarcity factor, in terms of the demand/supply ratio, is lower than 0.2;
(b) moderate water scarcity, where the water scarcity factor, in terms of the demand/supply ratio, is higher than 0.2 but lower than 0.4;
(c) extreme water scarcity, where the water scarcity factor, in terms of the demand/supply ratio, is higher than 0.4.

To use this model effectively, it is necessary to provide an explanation of what exactly the resultant water scarcity scores mean. This is an important research question in the development of the model. Various studies have increased the understanding of water scarcity by assessing current water scarcity from different disciplines (Alcamo et al. 2003; Smakhtin et al. 2004; Oki and Kanae 2006; Hoekstra et al. 2012). The majority of these studies have highlighted the important aspect of physical water scarcity, analyzed the trajectories of past changes, and addressed how it may develop over time into the future. Water scarcity is often measured as a relation of demand and supply. This demand-to-supply ratio is often demarcated by a threshold level, where values lie in the range of 20–40%. One of the most commonly used measures of water scarcity is the Falkenmark indicator. This method defines water scarcity in terms of the total water availability per capita per year. It defines water scarcity as the amount of freshwater that is available for each person each year. Values of 1700 m^3, 1000 m^3, and 500 m^3 of freshwater were proposed as the thresholds for water scarcity. Below these mean values the system is experiencing water stress, water scarcity, and absolute scarcity (Falkenmark et al. 1989). To focus on a more accurate assessment of water scarcity, Raskin et al. (1997) defined water scarcity in terms of water demand compared to the amount of water available for each country. Using this use-to-resource ratio, if the amount of annual withdrawals is between 20 and 40% of the annual supply, that country is said to be experiencing water scarcity; exceeding 40% it is said represent severe water scarcity.

This relation (WD/WS) was adopted by the UN report and consequently widely used in global to regional literature including global level (Hoekstra et al. 2012), country level (Seckler et al. 1999), river basin level (Munia et al. 2016), or grid level (Islam et al. 2007). This criticality ratio as a relationship between annual supply and demand for water is used for various global analyses of water scarcity. For example, based on Raskin et al. (1997) and Vörösmarty et al. (2000) a water scarcity index was estimated by mapping the domestic and industrial sectors, agriculture sectors, and their

combination on a mean annual basis. Values on the order of 0.2–0.4 indicate medium-to-high stress, whereas those greater than 0.4 reflect conditions of severe water limitation. Here, the water scarcity index is determined by comparing the actual current empirical situation with this preset standard. Such a method has already been used as a framework for estimating water scarcity under climate change (Vörösmarty et al. 2000), sustainability (Vörösmarty et al. 2010), and as global analyses of water scarcity (Hoekstra et al. 2012; Cosgrove and Rijsberman 2010).

In this research, we define demand/supply ratios of 0.2 and 0.4 as reference ratios. Three scenarios are considered according to the relationship between water demand and supply to determine the water scarcity factor. This approach is summarized in Fig. 1. In this model, the higher the ratio of demand/supply, the higher the degree of the water scarcity index. Table 1 is a numerical example to illustrate two different water scarcity scenarios. This comparison shows that although the physical assessments of water supply volume in year A and B are the same, less water demand in year A shows water scarcity is less of a problem in that year than in year B. In contrast, year C has a greater degree of water scarcity than year D because of the low water supply. Quantifying water scarcity in this way helps to determine which year faces more scarcity problems in water provisioning.

The demand/supply ratio provides useful information that supports a different approach for water scarcity assessment. Under the formula's assumptions, the scarcity factor approximates or equals 0 when supplies are adequate. In contrast, it approximates or equals 1 when the water supply is insufficient; in these conditions, consumers would be charged an

Table 1 Water price calculation integrating water scarcity

	Water demand (million m^3)	Water supply (million m^3)	Water scarcity index (demand/supply ratio)
Year A	150	1000	0.15
Year B	500	1000	0.5
Year C	500	1000	0.5
Year D	500	2000	0.25

extra water scarcity fee. The water charge is then increased to incentive water conservation by consumers. Furthermore, with additional revenues generated from increased tariff, the water utility must invest water conservation measures or environmental education campaigns. Compared to the other dynamic water-pricing models, the outcome of our proposed model might be described as relatively simple to implement, as it has relatively easy-to-access data input and information requirements. Therefore, our model might be useful for water sectors or companies with low-level managerial skills.

Case study

Research area

While considerable data on water supply and demand are available from some databases such as World Bank Open Data and AQUASTAT database, comprehensive data sets for specific countries are relatively rare. For those countries
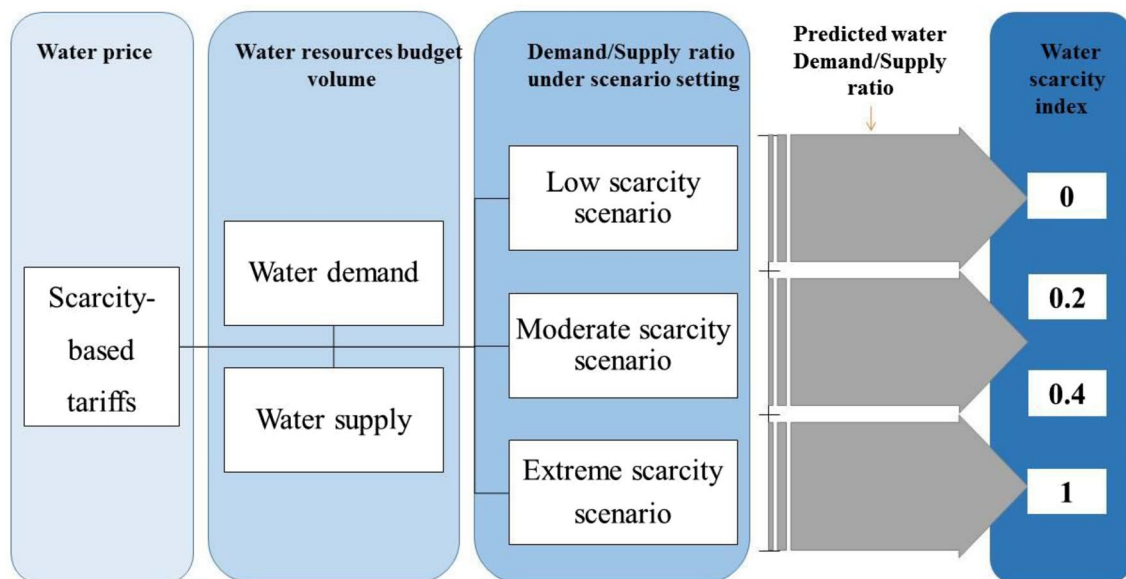

Fig. 1 Water scarcity and demand-to-supply ratio scheme

such as Taiwan where data are lacking, it is necessary to capture the needed in-country.

In Taiwan, household water is provided by public utility companies. The Taipei Water Department (TWD) supplies water to northern Taiwan. Its residential water supply and delivery area include all areas of Taipei City and parts of the New Taipei City. This region, like most Taiwan cities, predominantly relies on surface water. Such a rain-dependent supply sources means the Greater Taipei area is particularly susceptible to the effects of global climate change. Currently, in this greater Taipei area, almost all domestic water sources come from the Taipei Water Resource Domain (TWRD). At the end of 2018, TWRD served a total population of 5 million, which is nearly a quarter of Taiwan's total population. The geographic position and land use land cover of the TWRD are shown in Fig. 2. It is located in the southeastern of Taipei Metropolitan with an extensive area of around 717 km^2 within five main townships of the New Taipei City administration area. Much of undeveloped land is covered in forest which plays pivotal roles in improving the water quantity and quality in the catchment area of the TWRD. This district with supply and purification of the fresh water for greater Taipei area consists of three surface water sources, including the Pei-Shih Creek, Nan-Shih Creek, and Hsin-Dian Stream with a water collecting Feitsui Reservoir. This

reservoir was built in 1981 and stores up to 220 million m^3 of raw water annually for resident's daily use. The TWRD is Greater Taipei's main source of surface fresh water. For this reason, over 95% of the watershed lands that surround the district are protected from development to keep the water clean and clear. New construction and tree felling are prohibited for conserving and protecting these regions. To manage and maintain water quality of the city's daily water needs, the TWRD is the first and only water-source protection district and is under the administration of a dedicated agency. The authority integrates the usually fragmented government responsibilities for TWRD management into a single authority responsible for hydrographic governance.

Supply of water resources

As water becomes more scarce, the importance of how it is managed grows vastly. Our concept is similar to that of Pesic et al. (2013), who considered the impacts of temperature and precipitation on water prices. It is important to notice that physical and biological conditions also have great influence on the water supply service in basin regions (Geng et al. 2014). Thus, we include plant root depth, soil depth,
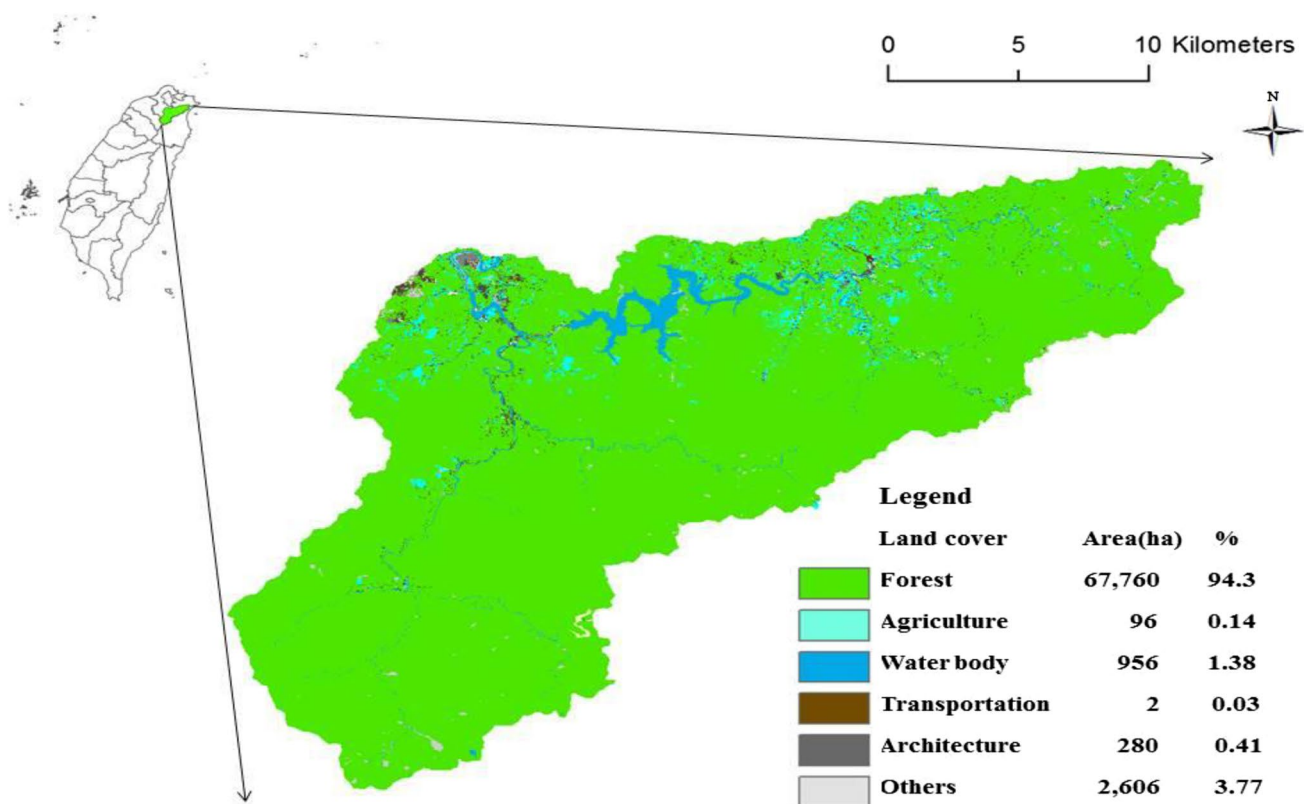

Fig. 2 Geographic location and land cover mapped for the Taipei Water Resource Domain (TWRD) for 2017

evapotranspiration, land cover, and watershed area for water yield estimation (see Table 2 for data source).

To demonstrate the viability of the proposed household water-pricing model, an ecosystem services assessment tool is used to estimate the supply of water resources. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was applied for determining changes and estimating water supply volumes. InVEST was developed by the World Wildlife Fund, the Nature Conservancy, and Stanford University and is widely used to evaluate ecosystem services by various sub-models. InVEST's advantage is its output ability to present a spatial map that is relatively informative, especially for decision-makers equipped with an insufficient knowledge base (Daily et al. 2009). It is a work in progress and can be downloaded at https://www.naturalcapitalproject.org/invest/.

Among sub-models of InVEST, water yield: reservoir hydropower production 3.0 was selected for the assessment. It generates and outputs the total water yield volumes at the sub-basin level. With reference to Trisurat et al. (2016), this study examines scenarios, namely average rainfall, low rainfall and extreme rainfall. The input for the InVEST water yield model includes average annual precipitation, annual reference evapotranspiration, root restricting layer depth, plant-available water content, land use and land cover, root depth, and basin area (see Table 2 for data source). Arc GIS 10.1 is used to pretreat the figures before input. The output is presented both as a mapped spatial distribution and a water yield volume of the case study basin. There is not yet direct measurements of water in the catchment area of the TWRD, we use a Budyko curve.

Annual water yield (Y_{xj}) for each pixel (indexed by $x = 1, 2, ..., x$) with land use j on the landscape is calculated as follows:

$$Y_{xj} = \left(1 - \frac{\text{AET}_{xj}}{P_X}\right) \times P_x, \tag{3}$$

where Y_{xj} is the water yield of pixel x, AET_{xj} is defined as the annual actual evapotranspiration for pixel x, and P_x is the annual precipitation on pixel x.

$\frac{\text{AET}_{xj}}{P_x}$, the evapotranspiration portion of the water balance, can be estimated as follows:

$$\frac{\text{AET}_{xj}}{P_x} = \frac{1 + w_x R_{xj}}{1 + w_x R_{xj} + \frac{1}{R_{xj}}}, \tag{4}$$

where R_{xj} is the ratio of potential evapotranspiration to precipitation as follows:

$$R_{xj} = \frac{k_{xj} \text{ET0}_x}{P_X}, \tag{5}$$

where K_{xj} is the plant evapotranspiration coefficient with land use j on pixel x.

Where w_x is a non-physical parameter that characterizes the precipitation-soil properties during the year. According to Zhang et al. (2001), it is calculated as follows:

$$w_x = Z \frac{\text{AWC}_x}{P_x}, \tag{6}$$

where AWC_x is the volumetric plant-available water content (in mm) that can be held and released in the soil for use by a

Table 2 Data used to quantify water supply and demand

Data	Time steps, time series stand	Source
Administrative borders of municipalities	2017	National Land Surveying and Mapping Center, Ministry of the Interior, R.O.C. (Taiwan)
Water supply		
Soil map including usable field capacity and actual root depth	2017	Taiwan Agricultural Research Institute Council of Agriculture, Executive Yuan, R.O.C. (Taiwan)
Precipitation	2012, 2014, average of 2005–2017	Water Resources Agency, Ministry of Economic Affairs, R.O.C. (Taiwan)
Soil survey map as reference PAWC	2017	Taiwan Agricultural Research Institute Council of Agriculture, Executive Yuan, R.O.C. (Taiwan)
Evapotranspiration	2017	Central Weather Bureau, R.O.C. (Taiwan)
Land use and land cover	2017	National Land Surveying and Mapping Center, Ministry of the Interior, R.O.C. (Taiwan)
Watersheds	2017	National Land Surveying and Mapping Center, Ministry of the Interior, R.O.C. (Taiwan)
Sub-watersheds	2017	Taipei Water Management Office, R.O.C. (Taiwan)
Water demand		
Water consumption of households	2012, 2014, average of 2005–2017	The Taipei Water Department (TWD)

plant, Z is an empirical constant that represents the seasonal distribution and depth of local precipitation.

Taiwan is characterized by annual rainfall variability. With high humidity and abundant rainfall year-round, Taiwan has one of the highest levels of average annual rainfall in the world. However, because rivers and streams are fast-running, Taiwan is a seriously water-depleted country. To estimate water yield volumes under normal and extremal conditions, three scenarios are used in this assessment. The quantification and mapping of water scarcity has been carried out for three points in time: 2012, 2014 and average of 2005–2017 reflects the scenarios of low rainfall, extreme rainfall, and average rainfall. An overview of the data used is given in Table 2. Input figures are shown in Fig. 3. The output is shown in Fig. 4. Water yield volume is approximately 2.36 billion m^3 per year for an average rainfall scenario. For the low rainfall scenario, water yield volume is reduced to approximately 1.96 billion m^3 per year. Water yield volume increases to 2.76 billion m^3 per year for the extreme rainfall scenario. The map shows significantly variable results for these rainfall scenarios.

Demand for water resources

Households are the main beneficiaries of water yield ecosystem services (Fisher et al. 2009; Burkhard et al. 2012; Sigel et al. 2012). In this study, we use data obtained from TWD

(see Table 2 for data source). Volumes of water demand by district are shown in Table 3. The spatial distribution of the household water demand map under the low rainfall scenario is shown in Fig. 5. Here, the greater water demand can be found mainly in the urban districts: Districts 1 and 2 of Taipei City and Districts 13, 14, and 15 of New Taipei City. The industrial and commercial districts have the largest water demand per year. These districts show greater demand for water because of their high population density and booming economic development. In contrast, because of the lower population density, Districts 11 and 12 in Taipei City have lower demand for water. In addition, we see that the water demand was increasing even in the high-scarcity year as consumers neglected perception of water scarcity.

Budget for water resources

In the previous section, this study constructed individual supply and demand maps in TWRD. To describe the corresponding gap between supply and demand, an exploration of budget using the same units is necessary (Burkhard et al. 2012; Bejranonda et al. 2013; Wang et al. 2015). This study uses a single unit of volume (m^3) for water supply, demand, and budget. The comparison of water demand in urban areas and supply from corresponding rural regions provides essential information and arguments for water scarcity. Table 4 summarizes the water demand and supply
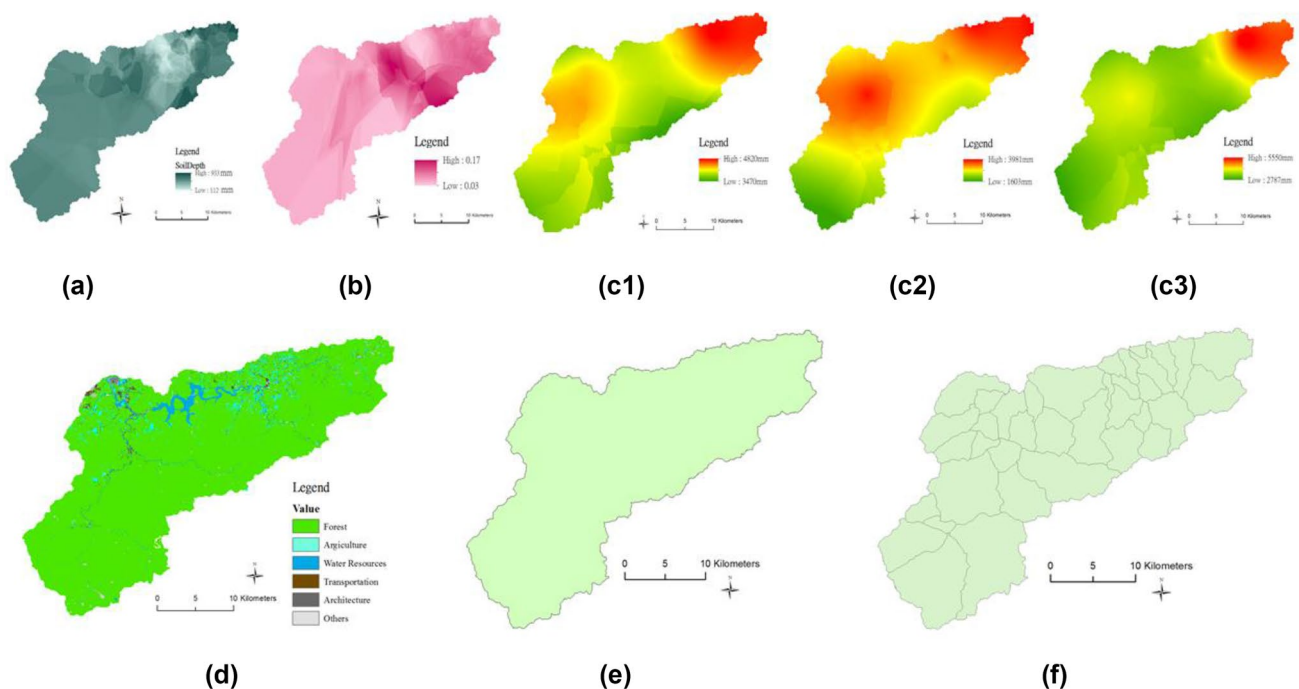

(a)　　　　**(b)**　　　　**(c1)**　　　　**(c2)**　　　　**(c3)**

(d)　　　　**(e)**　　　　**(f)**

Fig. 3 Hydrology-related spatial distribution for the TWRD: **a** root-restricting layer depth; **b** PAWC; **c1** precipitation in average rainfall; **c2** precipitation in extreme rainfall; **c3** precipitation in low rainfall; **d** land use and land cover; **e** watersheds; and **f** sub-watersheds
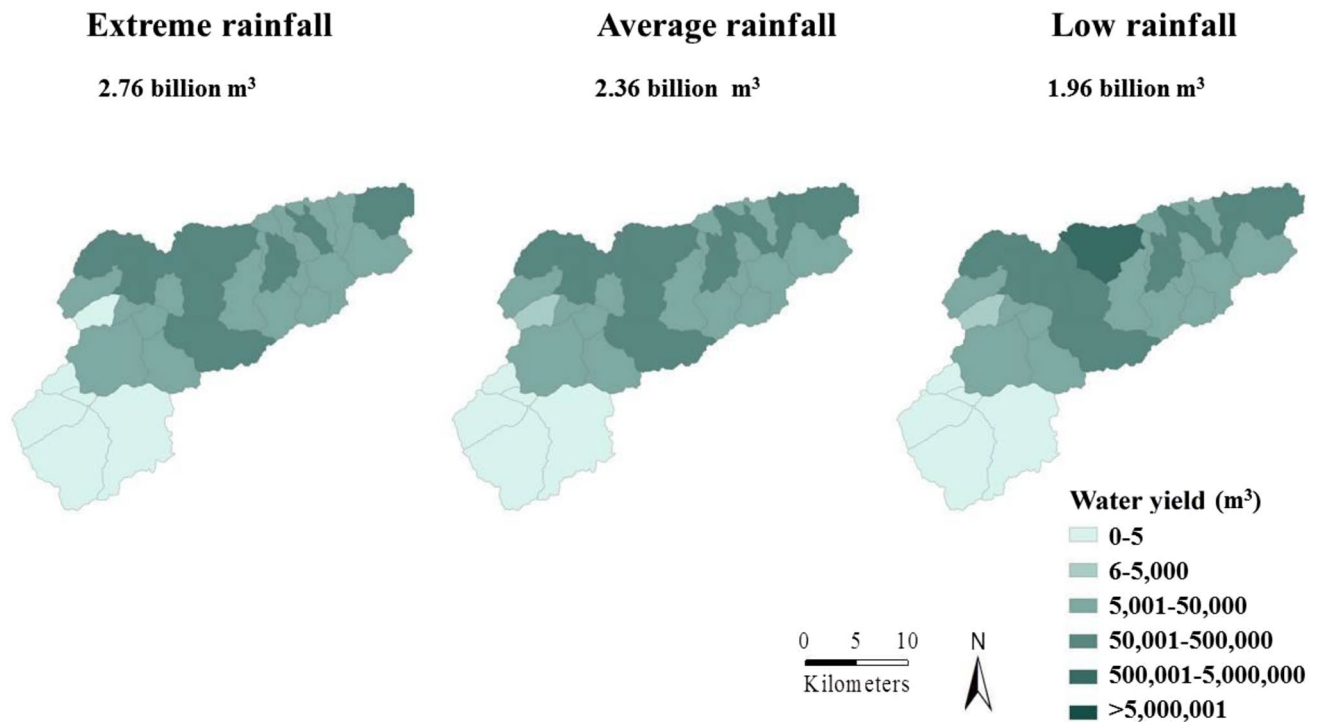
Extreme rainfall
2.76 billion m³

Average rainfall
2.36 billion m³

Low rainfall
1.96 billion m³

Water yield (m³)
- ☐ 0-5
- ☐ 6-5,000
- ☐ 5,001-50,000
- ■ 50,001-500,000
- ■ 500,001-5,000,000
- ■ >5,000,001

0   5   10   N
Kilometers

Fig. 4 Water-yield projections for the Taipei Water Resource Domain (TWRD)

Table 3 Volumes of water required to supply regions of Taipei Water Department

	District	Yearly		
		medium scarcity (million m³)	High scarcity (million m³)	Low scarcity (million m³)
Taipei City	District 1	40	40	41
	District 2	39	40	39
	District 3	32	33	33
	District 4	32	32	32
	District 5	28	28	28
	District 6	28	29	28
	District 7	28	27	28
	District 8	25	25	25
	District 9	25	25	25
	District 10	21	22	21
	District 11	15	15	15
	District 12	14	14	14
New Taipei City	District 13	42	42	42
	District 14	41	41	41
	District 15	37	38	37
	District 16	24	24	24
	District 17	3	3	3
	District 18	011	0.09	0.11
	Sum	475	479	475

for low, average, and extreme rainfall scenarios over the entire case-study area. Notwithstanding the greater than 1 billion m³ volume in the water budget, the estimations for the demand/supply ratio show variable gains of 0.17–0.24, which demonstrate unsteady water supplies and demand.

Figure 6 shows the spatial allocation of water supply and demand. This map reveals geographic mismatch between freshwater demand and supply in the case-study area. We found that although the TWRD is not located close to the core part of Taipei City, it supplies not only this region but also Greater Taipei.

Water supply and demand data in the given period are suggested to estimate the water demand/supply ratio. In Taiwan's case, under a low rainfall scenario, such as a drought year, the water demand/supply ratio increases to 0.24, reflecting water resource shortages. This increasing shortage increases the scarcity factor and additional price, resulting in a reduced demand threshold for water consumers. Using the proposed model, a reasonable water price of volumetric charge will be increased 24%. Once the water scarcity index is lower, water price will be reversed slightly to reflect behavior efficiency trends. In our case, 17% and 20% additional charges accrue under low and average rainfall scarcity factors 0.17 and 0.2. Our work enables upward and downward adjustment by combining water demand threshold and residential water charging.
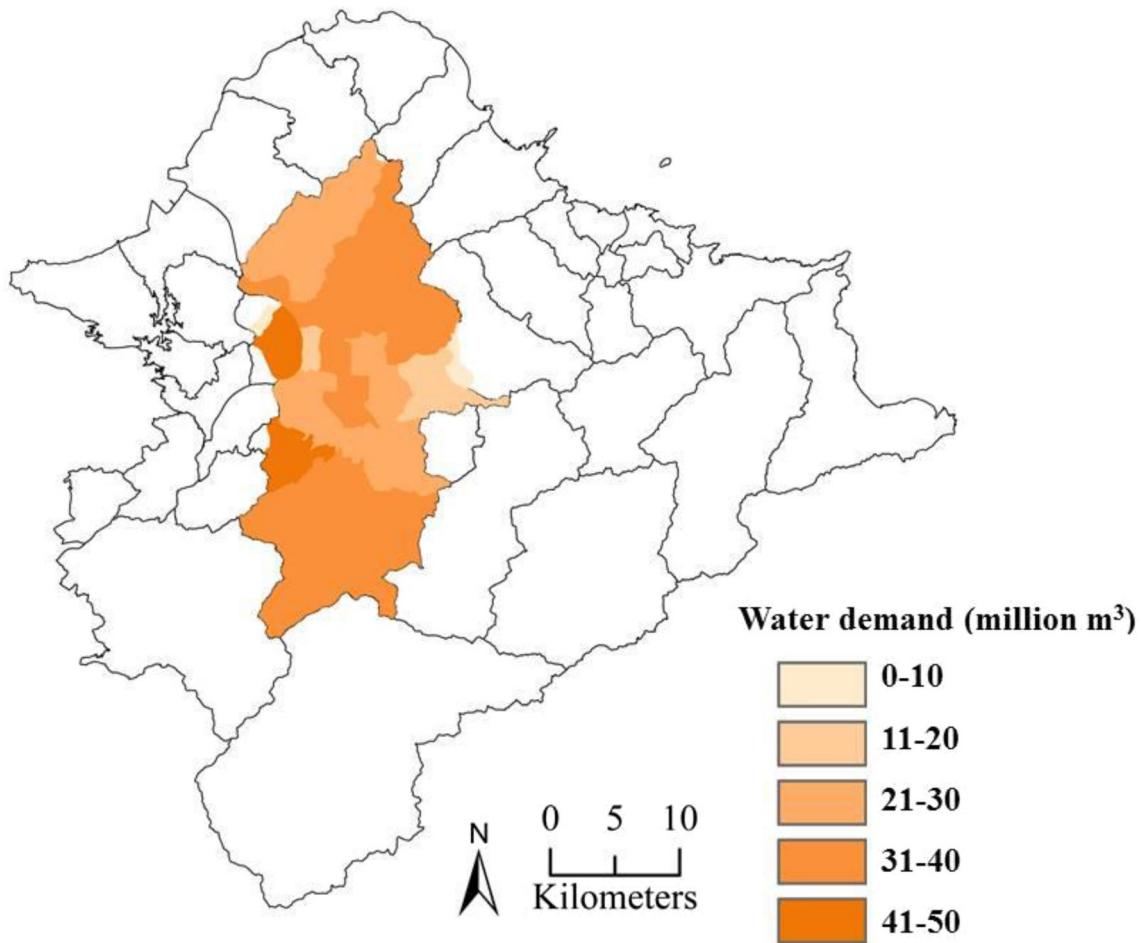
Fig. 5 Spatial volume distributions of household water demand for the high-scarcity scenario

Table 4 Supply and demand for water resources 7 in the Greater Taipei region

Rainfall scenarios	Average rainfall	Extreme rainfall	Low rainfall
Supply (million m^3)	2359	1955	2765
Demand (million m^3)	475	479	475
Budget (million m^3)	1884	1477	2290
Demand/supply ratio	0.20	0.24	0.17
Scarcity scenario	Moderate water scarcity	Moderate water scarcity	Low water scarcity

Obviously, the water supply shortage in the TWRD was mainly due to finite precipitation caused by climate change. Otherwise, the freshwater supply was different among land cover and land use. From the perspective of land management, sectors would be able to focus on forests and rivers management (Fig. 4) because they contribute the most compared with other land use types. Furthermore, the natural water supply in the Greater Taipei district has become one of the limiting factors to water supply management. Due of natural conditions, political reasons, and other factors, water abstraction and impoundment capacity is about 59–83% of net water supply in the catchments area in Taiwan (Fig. 7).

Water supply form construction capacity will be an important key constraint of Taiwan for a long time to come; thus, the increase in infrastructure treatment water supply is one choice we should make for the moment to alleviate water stress in the future. In response to water shortage, measures focusing on increasing the efficiency of water withdraw should be taken to increase water availability.

In Taiwan, the water sector is governed by public utility companies. The current household water charge in Greater Taipei was first determined in 1994. It has been revised recently from an average of 9.2 TWD per m^3 in the last decades to 12.14 TWD per m^3 in 2016. It is recognized as
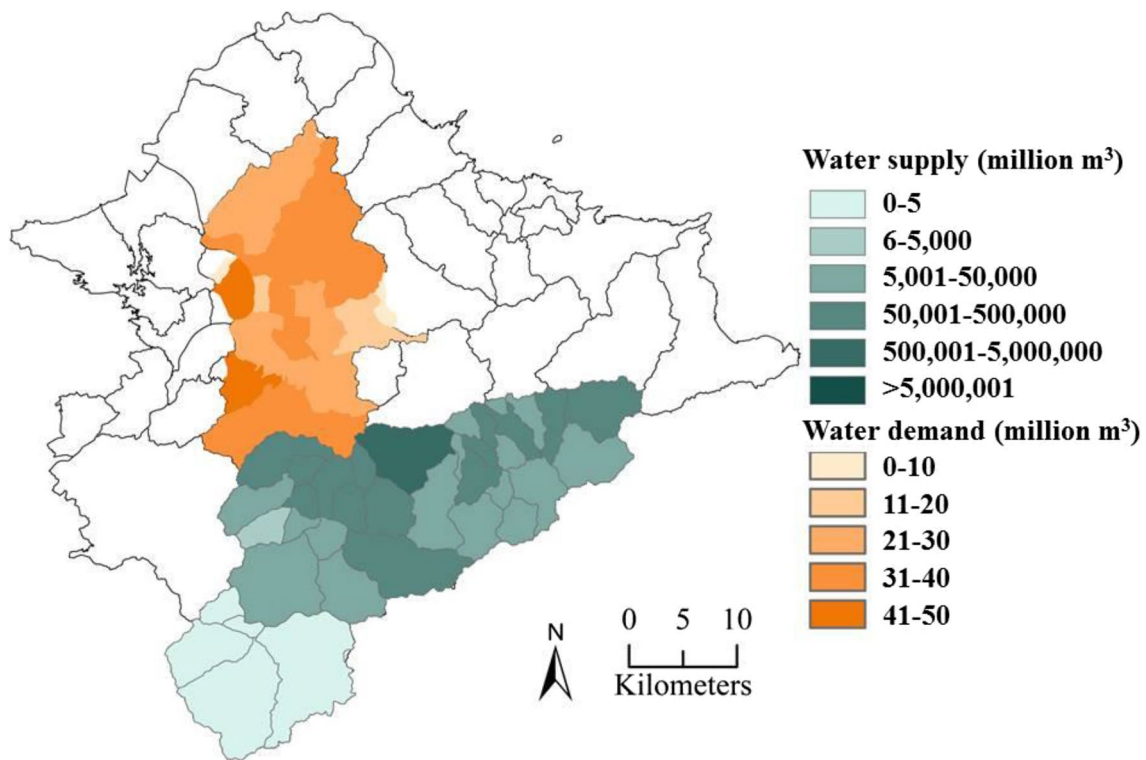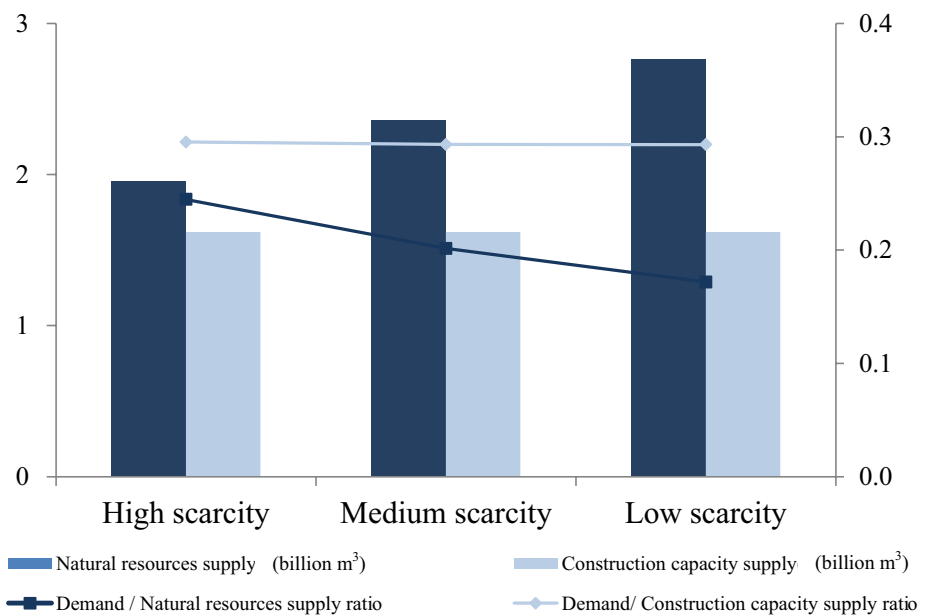
Fig. 6 Spatial distribution of water supply and demand in the research area

Fig. 7 The comparison of water supply and demand in Taiwan

not only a poor incentive mechanism for water consumers, but also a lower affordable tariff compared with the global average water price. The resulting large deficits of the water sector are filled by government subsidies. Furthermore, for regions with high water demand stress, the combination of increasing demographic growth and improving living standards is the main driving forces of rising residential water demand. For this region, our proposed scarcity-driven water structure charges for these water demanders, thereby relieve regional water consumption and water scarcity. Additionally, water authorities would obtain extra revenue to implement water conservation measures.

Discussion

Water is not only a key component of the natural capital, but also is an essential resource for all life on the planet. As a result of increasing population and climate change, water become increasingly scare worldwide. This study proposes a water rate structure that integrates water scarcity focuses on the variable component of the tariff and follows an increasing block tariff strategy. We developed an approach to calculate water scarcity which integrates water supply, demand, and budget into a single framework as water scarcity index in the second block of water rate structure. Such a combined approach could provide more complete information on water pricing. An empirical application is developed for the Greater Taipei district in Taiwan. According to the results of this study, the water demand/supply ration varied in different years. The average demand/supply ratio in the Greater Taipei district is 0.2. This is consistent with the finding of about 0.2 of moderate water stress (Raskin et al. 1997). The demand/supply ratio is 0.24 during the drought year, which also indicates a moderate water scarcity. Giving this scarcity in a pricing setting, there is an urgent need to include tragedies from perspectives for both water supply and demand management.

Up until now, in Taiwan and elsewhere, household water pricing has mostly been charged as a valid instrument to recover water provision costs of the water sector, including management, taxes and depreciation of water companies (Letsoalo et al. 2007; Guerrini and Romano 2013; Farolfi and Gallego-Ayala 2014; Sibly and Tooth 2014; Barbosa and Brusca 2015). This existing pricing model focuses on a balance among construction, water delivery and maintenance of a freshwater supply system. Unfortunately, water scarcity, in terms of the difference between supply and demand, is not included in the water-pricing structure. A growing number of researches support the idea that higher water scarcity regions should pay higher water prices for their shortages. Studies by Hughes et al. (2009) and Grafton and Ward (2008) have proposed staged scarcity pricing system as a potential alternative to demand management policy of water restrictions. These articles estimate the socially optimal demand management and investment policy functions of the urban water utility. Sahin et al. (2015) have incorporated a system dynamics approach so that water pricing is able to respond to water security. A scarcity-based pricing mechanism, temporary drought pricing (TDP) are set inversely with available water resource supply benchmarks. Our researches support the arguments of these prior studies. The volumetric price of water should be increased to reflect water scarcity when required. Indeed, our analyses of the water scarcity index are likely to be a lower bound of the demand-to-supply ratio as we do not take seasonal differences into account.

The water scarcity index was used for the water-pricing calculations in this study. While useful for our method, our model has some distinct disadvantages that should be noted. First, this model does not take into account seasonal variations of water resources supply or water consumption. The incorporation of seasonal variations is an issue for further discussion. Second, it does not reflect the extreme variability of rainfall in future water supply due to climate change. Third, using a physical water scarcity index in the model, it does not include the aspects of social drivers such as population growth. Thus, with increasing pressure on existing water infrastructure from population growth and climate change, managing the water system optimally, and taking into account its resilience and sustainability by considering possible changes in climate and population are necessary in the future.

Conclusions

This paper proposed a more effective and equitable water-pricing formula. Our work adds to the literature in two ways. First, regarding the literature on water scarcity, we consider both supply and demand links, so the freshwater prices reflect the water scarcity. Second, we perform an estimation of water supply and demand for household utility, and then examine the proposed model using data from Taiwan. Lessons learned from the practical case study demonstrate a method of incorporating water scarcity considerations into a water-pricing structure.

This cleverly designed scarcity-driven water-pricing formula is tailored to serve not only Taiwan, but is adjustable to apply to other water supply–demand systems functioning in similar climactic conditions. Decision-makers might raise the volumetric water price if a drought occurs. This adjusted price would drive consumers to reduce quantity demand. Drought-year prices are thus able to flatten water consumption peaks.

The current study sets the stage for water scarcity-embedded water price. Future improvements in assessing water scarcity can potentially be achieved by more accurate accounting for the effect of seasonal precipitation patterns. New attributes, such as better details on water supply volume affected by climate change, can be incorporated into water price structure. Moreover, future water scarcity studies should include social water scarcity related to water demand from population growths that have not been included in the current study.

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